FLINDERS UNIVERSITY

PHD THESIS

Improving the performance of low-bandwidth communications networks for disaster zones and remote areas

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Declaration of Authorship

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university, and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

(Ghassan Al-Nuaimi, 2022)

FLINDERS UNIVERSITY

Abstract

College of Science and Engineering

PhD Computer Science

Improving the performance of low-bandwidth communications networks for disaster zones and remote areas

by Ghassan Al-Nuaimi

Telecommunications forms a vital part of many aspects of modern life. However, telecommunications access is not available to all. In particular, maintaining access to effective telecommunications following disasters is particularly problematic, as the infrastructure on which it demands may be damaged, destroyed or overwhelmed. Similarly, people who live in small isolated communities are often not able to access telecommunications, because it is not cost-effective to extend cellular coverage to these communities.

This is particularly true in logistically difficult environments, such as in Pacific Island Nations, where communities may live on islands that are many kilometres from the next nearest island or community, and where the islands may be mountainous. Add the difficulties of frequent cyclones, the risk of tsunami, the corrosive tropical maritime climate and the relatively small economies of Pacific Island Nations, and it is no surprise that many people in the Pacific do not have reliable access to telecommunications, even before a disaster strikes. The problem, of course, becomes much worse when a disaster does strike, and may contribute to the loss of life.

One particularly troubling aspect of this is when the lack of access to telecommunications services means that coastal communities in the Indo-Pacific do not have access to a reliable tsunami early warning system. The lack of effective early warning to tsunamis is a frequent contributor to the loss of many lives when tsunamis do occur.

This thesis seeks to mitigate these problems by enhancing the Serval Mesh, in particular, the Low-Bandwidth Asynchronous Rhizome Delivery (LBARD) component, to support the automatic relaying of mobile-phone originated messages via long-range HF radios, as well as overseeing many internal improvements to LBARD, that improve its efficiency, such as the inclusion of the new TreeSync bundle list synchronisations protocol.

Further, in the case of the need for tsunami early warning systems a design is proposed for a low-cost, small and easily maintainable tsunami early warning system based on a combination of the Serval Mesh and an innovative satellite receiver. A proof-of-concept for this system is presented, where a ground-station is used to feed low-latency messages for broadcast delivery using a geostationary satellite, which can be received using a small dish-free and easy to aim receiver. This concept is then further developed to envisage a complete low-cost multi-hazard early warning system that is not dependent on any fixed terrestrial infrastructure, and in particular, is composed entirely of small, low-cost devices that are much easier to work with under the logistical challenges that exist in Pacific Island Nations.

Collectively, these innovations pave the way towards the provision of free and resilient basic telecommunications services – including both text messaging and early warning of disasters like tsunamis – using only low-cost systems, and building on the past pedigree of the Serval Mesh, including past field trials in the Pacific.

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Chapter 1

Introduction

1.1 Motivation

The need for communications techniques in our daily activities is essential, where we need to exchange information or ideas about all manner of things, or request assistance from others. Communications services have rapidly improved toward fast and multimedia transmission between individuals, and with considerable competition between developed countries to provide the best services. A good example of this is the race to provide super fast 5G cellular coverage, where the resulting communications capabilities can even exceed the needs of many users.

However, the situation is different in low resources countries and regions, particularly in the Pacific region. In these situations, people are often struggling with old or obsolete services. Further, in many cases, such as in remote and isolated islands, it is not uncommon for there to be a complete lack of communications infrastructure and services. This then forces many low-income residents to travel between communities to do face-to-face communications [221, 73]. This scenario is not merely inconvenient. Rather, it can result in tragedies when natural disasters strike, and there is a lack of communications links to inform people about an approaching disaster. Tsunamis are particularly problematic in this regard, as there are many coastal communities which may have only minutes to hours to be warned before destructive waves strike. Unfortunately, many people have lost their lives as they have been impacted by such natural disasters, precisely because they could not receive early warning or timely assistance [170].

It is the primary goal of this thesis to research and develop potential solutions to this problem.

This thesis explores several complementary avenues to providing reliable disaster-tolerant communications and early warning systems in isolated and logically challenged low-resource settings, with Pacific Island Nations used as the canonical example. The research presented in this thesis falls into two broad categories:

- Improving the Serval Mesh technology, so that HF and other long distance radio systems can be integrated with it, to enable distributed and resilient communications networks to be built in very isolated areas; *and,*

- Low-cost disaster early warning systems that are both economically and logically feasible for isolated, logistically challenged and low income settings, such as outer islands in Pacific Island Nations.

These approaches stand in stark contrast to the existing practice of post-disaster communications, which tends to be reliant on expensive solutions such as satellite telephones and temporary radio installations [130, 222], which then fall into disrepair after the resolution of a disaster, as they cease to provide an ongoing value between disasters, typically because they are too expensive to allow unrestricted use by communities throughout the year. Rather, the focus in this work is on methods for providing communications systems that can be used year-round including in the lead up to, and following disasters and that are therefore much more likely to be in place and operational when disasters do strike.

This focus on the prior placement of resilient telecommunications systems is important because it is extremely difficult, and much more expensive, if possible at all, to attempt to provide these facilities in the immediate aftermath of a disaster [244, 218], since it can be nearly impossible during and immediately following a disaster to deliver new hardware, to deploy expert employees and other labour required to reinstall or repair the damaged cellular and other communications networks.

The events of the COVID19 pandemic have added a further impetus to prior-placement of disaster mitigation capabilities, as the restrictions on the global movement of people are dramatically restricting the ability of response organisations to enter countries when disasters do strike. This was seen clearly in Vanuatu when Cyclone Harold caused wide-spread damage when it made landfall as a Category 5 cyclone. However, as one of the few COVID-19 free countries at the time, Vanuatu had closed its borders, judging the impact of COVID19 to be worse than the reduced ability to mitigate the effects of the cyclone [153].

One of the worst-case scenarios for the absence of communications services is when natural disasters strike suddenly, like tsunamis, that leaves insufficient time for residents of coastal areas to evacuate themselves to a safe location. This can be because either the Early Warning System (EWS) fails to warn people before the disaster [177, 234], or it simply doesn't exist, particularly in remote islands. The consequences can result in people remaining in the danger zone, and unfortunately, we have witnessed multiple such tsunamis recently, particularly in Indonesia, that have led to high death tolls, precisely because of the failure in EWS. One of the challenges that has led to this situation is that traditional tsunami EWS systems consist of large warning towers and other supporting infrastructure that require regular maintenance, and that may be subject to vandalism or other causes of damage.

Providing a standby communication technique that can be accessible by all individuals within the effected or remote areas based on existing available devices, or small cheap devices that can be more easily pre-positioned and maintained, would not only save lives, but also has the potential to lead to many other positive social and economical outcomes [10, 229, 16]. This is the motivation for, and the basis for the research presented in this thesis: To push the envelope of both knowledge and potential practice, so that lives and livelihoods can be saved and improved.

1.2 Scope of thesis

Many people who live in remote communities and disaster zones, particularly low-resources countries in the Pacific region, have big challenges in communicating with other communities due to the lacking of communications services. Also, the available communications options are often relatively expensive and difficult to afford for many people on low-incomes. The lack of communications links become life-threaten when people in disaster zones have no early warning system for natural disasters installed, or it failed before a potential disaster occur because the maintenance is expensive to be done. This situation leaves people without any protection from the various dangerous actions caused by natural disasters. This is in addition to the general increased vulnerability and limitation of opportunities that result from lack of means of communications with the outside world.

What should be done in these scenarios is looking for communications techniques that can connect members of remote communities with other communities, and that should also be cost-effective and cheap to install and use by low-income members. Also, for the people in natural disaster zones, there is the need for cost effective EWSs, that don't require expensive hardware or expert labour to install or maintain is required. This is especially of concern in the Pacific, where natural disasters are very common, including cyclones, earthquake, tsunami and volcanic activity.

In this research, the focus is on the existing Serval Project, a communications platform that has been designed to provide effective solutions to many challenges in remote areas and disaster zones, primarily through the ability to form islands of devices that can communicate with one another, even if cut-off from the outside world. Thus the work in this thesis takes is based around identifying the need for, describing the requirements of, and implementing a set of improvements to Serval Mesh protocols and related technologies.

Guiding this exploration and extension of the Serval Project, is the context of Pacific Island Nations, and their particular combination of high natural hazard risk, relatively low incomes and small to very small economies, together with the presence of very small communities on outlying islands who may be separated from the next population by tens to hundreds of kilometres of open ocean. This leads to an interest in both short and long-range communications solutions, post-disaster communications, and Early Warning Systems that can be cost-effectively deployed and maintained in such circumstances where there is little to no local communications or energy infrastructure.

More concretely, this research aims to improve:

- The synchronisation process of messages between pairs of peers;
- The range of communications links of Serval Mesh network into the hundreds of kilometres; and
- The cost effectiveness, maintainability and thus availability of effective EWS in the Pacific region.

The potential benefits from this research to the communities in remote areas and disaster zones are huge: It will facilitate people there to be able to communicate freely with one another as often as they wish, and without cost, and thus help enable many communities to be closer to each other, and to reduce their individual vulnerability. Moreover, a level of protection from natural disasters can be granted to the members of costal communities, especially those in small communities on outlying islands, which can save people's lives when installing Serval based EWS on shorelines.

1.3 Research questions

From the background and scope described in the preceeding sections, the following research questions are considered in this thesis:

1. Is it possible to provide a cost-effective and free-to-use communications solution to low-income remote community members?
2. What is the current state of the Serval Mesh's message synchronisation process, and can this be improved?
3. Can we extend the communications range of Serval Mesh network to hundreds of kilometres? Can HF Radio be a solution to this problem?
4. HF data links have very low bandwidth. Can we manage such low-bandwidth links effectively, to enable very isolated communities to communicate with one another?
5. Can we design a low-cost and rapid response early warning system against natural disasters that can fit the circumstances of low-resource countries?

1.4 Contribution to knowledge

The contributions of this thesis are:

1. Design, implementation and validation of a new efficient message synchronisation algorithm for high-latency and low-throughput communications links.
2. Integration of HF radios into the Serval Mesh framework, making it possible to communicate over very long distances.
3. Analysis and optimistion of the Serval Mesh protocols, to improve the efficiency of communications over high-latency and low-throughput communications links, in particular, HF radios.
4. Design and validation of improved HF radio communications under the Serval Mesh, demonstrating the feasibility of using HF radios to provide operator-free communications between entire remote communities, free of usage charges, and with acceptable latency.

5. Design and conceptualisation of a new simple, compact, portable, low-cost, maintainable and sustainable Early Warning System, that is much cheaper and more appropriate for the Pacific Island Nation setting than traditional Early Warning Systems deployed in the region.

Thus, this thesis sets out a number of advancements of the state of the art of communications, that have the potential to improve the lives of millions of people living in Pacific Island Nations. Further, these innovations have the potential to be applied into many other contexts, such as high-population low-income coastal communities, such as in the Asian region, where effective early warning of tsunamis remains an open challenge.

During the time of research, three papers have been published by the author, and a fourth has been co-authored. These papers as follow:

1. G. Al-Nuaimi et al. "Scalable telecommunications over ultra-low-bandwidth radio backbones". In: 2017 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2017

2. G. Al-Nuaimi et al. "Making HF useful 365 days a year, to make sure it works the one day you need it". In: 2018 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2018.

3. G. Al-Nuaimi et al. "Demonstrating a low-cost and zero-recurrent-cost hybrid mesh & satellite based early warning system". In: 2018 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2018.

4. P. Gardner-Stephen et al. "Reducing cost while increasing the resilience & effectiveness of tsunami early warning systems". n: 2019 IEEE Global Humanitarian Technology Conference (GHTC). IEEE. 2019

The contributing publications are explained in more details in chapters (8), (9), (10) & (11), and discuss the performance concerning some exciting techniques.

1.5 Thesis structure

The reminder of this thesis is structured over eleven chapters as follow. The first part is a background to the main components in this research. In chapter (2), it presents a background information about role of communications in remote communities and disaster zones, and what are the challenges against improving communications in such areas. Chapter (3) is continuing to introduce more background information about the communications device in use, in particular, radios and Serval Mesh, and how they are employed to serve communities in remote areas and disaster zones. Literature review presents recent research and products in the field of providing alternative techniques of communications outside the standard and widely-spreaded cellular networks and internet services. In chapter (4), it focuses on the HF radio as the main communications technique for long distance, where it been used, what are the man challenges in widely deploying this device, and the benefits of HF radio over other techniques.

The second part of the thesis is about improving LBARD. In chapter (5), challenges and limitation of LBARD protocol has been introduced, and how can LBARD plays an important role in establishing short, medium, and long-range of communications in remote communities. Chapter (6) introduces the Treesync algorithm and how can this technique save the time and bandwidth over links between nodes inside Serval Mesh network. This chapter presents testing results of applying Treesync between two nodes at different conditions. Chapter (7) highlights the information about LBARD modular driver framework, and what is the structure of this protocol. it explains how to automatically detect and link of new driver to LBARD, and what are the steps to add new driver in the future to the mesh network.

Chapter (8) presents the remote communities' challenges in getting communications with others, and how can HF radio has been utilised as a long-rang carrier of data bundles within Serval Mesh network in the Pacific islands. It also explains some heuristic technique to assist LBARD in transmitting bundles over HF radio links. In chapter (9), an improvement to the performance of bundle transmission over Codan HF radio is introduced, and how can the data modem assist in increasing the number of exchanged bundles over the link. The performance proof that the system can be used on a daily basis to serve remote communities. Chapter (10) presents a novel method of Serval based, low-cost hybrid early warning system that can be so powerful in protecting people against tsunami and other natural disasters in coastal communities. It employees satellite links to rapidly broadcast warning to mitigate the effects of danger. As a continue to that, chapter (11) present a complete low-cost tsunami early warning system that can be deployed in the Pacific islands. The system has three parts, undersea detection, decision support and rapid warning dissemination to remote communities.

The last one is chapter (12), which presents conclusions notes about the research and what are the future steps to improve the performance in different context.

Part I

Background

Chapter 2

The current status of communications systems

2.1 Introduction

Despite the importance of communications technologies worldwide, there are different challenges to provide people in many remote areas and disaster zones to exchange information with others. Where some information or news are vital to save life at the time of natural disaster, or performing daily activities of locals, there is a noticeable failure to provide individuals and communities with such a basic human right and support them against the threats from natural disasters.

The existence of infrastructure, cost and low income are among the main challenges in providing communications solutions in the Pacific, and the available ones are hard to apply. Therefore, this chapter discusses the current status of communication systems, and what it can be done to find new solutions in this scenario.

2.2 The role of communications in remote areas and disaster mitigation.

Many remote communities suffer from the absence of traditional communications services, such as cellular phone coverage, or internet and satellite communications during the normal and emergency time. As a result, physical travel of individuals to nearby communities or cities is often the only way of requesting assistance or exchanging information with them. This results in some combination of physical, financial and time costs. These costs represent barriers that result in people in such situations remaining out of contact with others much of the time [74, 156].

This situation in remote areas in many low-income, low-resource countries of the Pacific region is worse than in most developed countries, because extending the communications services infrastructure is not economically feasible for either the private or public sector. This region is also subject to frequent natural disasters, which puts more pressure on the residents and the economy to cope with their necessities to survive [158, 174]. This in turn makes it more difficult for such communities to both afford and to maintain communications systems that can provide essential communications during disasters.

More work in the direction of assisting people in remote areas, and the related issue of natural disaster mitigation needs to be done. There are considerable challenges that must be overcome in order to achieve this. Yet this area is not without opportunities or other supports. The following sub-sections briefly introduce some of these challenges and opportunities, to provide the reader with further context.

2.2.1 Need for remote communications

Remote areas in many parts of the world receive relatively little investment from their respective national governments and commercial companies in the field of extending the communications services infrastructure. One reason for this is the low economic density of these areas, and financial infeasibility of deploying existing communications technologies to provide coverage in these areas. That is, since there are relatively few people living in these areas compared with the cities or other larger settlements, they are less financially rewarding to service. Alternatively, the population may be so small with respect to the cost of service provision, that it becomes economically infeasible to provide and/or maintain a service at all [213].

Even if there are communication services available to the residents in such areas, then they are typically less developed than those in crowded cities, in order to make them economically or logistically feasible [120, 164]. Also, because communications is not the only service that is challenging to provide in these logistically difficult and resource-deprived environments, historically, governments have applied their limited resources to providing immediate life-critical services, such as the provision of drinking water, causing investment in communications infrastructure to often be (quite understandably) deprived of sufficient funds to be developed and maintained. The distressing fact is that many remote areas remain out of coverage, which means that making the process for people to get in touch with their friends and families is very hard if not possible, and increases their vulnerability in the face of disasters.

Communications options in the remote areas that are suffering from lacking of cell phone overage, or after a natural disaster strikes are very limited. Typically the only feasible options are HF radio and satellite phone, and they both have some challenges that make them not so popular among residents [95, 138] – although they can still make useful, if limited, contributions.

The need for remote communications becomes vital, particularly at the time of emergency or natural disasters when human lives are at stake, and any failure or delay may lead to a tragedy.

Conversely, maintaining communication links in remote areas can create many positive benefits to the community members in the social, health and economic sectors. Thus there are strong motivations to both avoid the lack of effective communications in these areas, as well as in the positive sense to provide these services.

2.2.2 HF radio for long communication distance

One of the techniques to establish a long-range communications link between humans is employing the HF radio, and it is a powerful communications tool in many parts of the world [253]. It provides a point to point link with hundreds of kilometres distance between terminals, as shown in Figure (2.1). Historically in Australia, many people who lived in rural areas owned HF radios, because it was the only way to do different activities, such as communicating with friends and family members, requesting medical assistance and enrolling in the school of the air for educating children. However, the availability of satellite telephones and satellite internet have significantly reduced the demand for this technology not only in Australia, but around the world.

Nonetheless, HF radio is a good and popular option to use in remote areas or around the time of the disaster, particularly if the disaster causes great damage to the existing communications infrastructure, like cell phone towers, because installing HF radio is a fast way to reconnect two users together over very far distance without any need to based on other communications infrastructure, which makes getting any possible means of help to the effected areas very efficient [238, 10].

FIGURE 2.1: This image has been removed due to copyright restriction. Available online from[243]. HF signal propagation over long distance around the earth, which provides communications links between countries or even continents.

Many Humanitarian organisations like National Disaster Management Organisations (NDMOs), Non-Governmental Organisations (NGOs) and the Red Cross that work in the South-West of the Pacific region have their own HF radio networks to facilitate communication among staff members and remote communities in the field [84, 98]. When disasters strike, the on-ground campaign members of any humanitarian organisation need to collect more information, and send it quickly to headquarters to be assessed, so that the exact means of relief can be collected, and send quickly to the people in the targeted locations [33]. HF Radio can provide one such means of providing this, although it is typically limited to voice communications in the Pacific, due to the lack of investment in digital HF system, the increased cost of purchasing and maintaining them, and increased complexity and training of these systems. Difficulties with vendor interoperability have also not helped to drive digital HF interoperability.

The key enduring benefit of HF radio remains very obvious; however, it can provide rapid communications into remote and disaster impacted areas, where no other option may be possible – even if the quality and capability of the service are limited.

2.2.3 Satellite communications

One of the more recent communications technologies that provides extensive global coverage, especially compared with cellular networks, is satellite-based services, and in particular, the satellite phone [182, 126]. The satellite phone connects directly to one of the satellites around the earth via a wireless link, and provide a voice call service or exchange data with another node.

Satellite telephony became attractive after multiple companies launched satellite constellations that are capable of providing telephony services. Initially these systems were largely restricted to government and large corporate users in relatively few countries. Now, however, satellite telephony service is relatively easy to access around the world, and at much more affordable prices than in the past – although cost remains a considerable barrier. A multitude of satellite communications providers, including Iridium, Globalstar, Thuraya and Inmarsat all create the possibility to place mobile telephone calls from mostly any part in the world to any landline or cellular phone provider in any country.

Each provider has many satellites around the earth that provide a wide area of network coverage worldwide (Figure 2.2), and this network is connected with the on-ground landline or mobile service provider to provide more flexible two way of communications.

Satellite communications is considered the easiest way to make a call from a remote or isolated location, whether the participant is located in the mainland or in the ocean [186]. However, it is limited in low-resource and low-income settings by the high cost of terminal hardware and subscription plans. As a result, even where satellite phones have been deployed into South Pacific Island Nations, it is not uncommon to hear stories of them being locked away to prevent the risk of incurring an expensive bill that the custodial organisation cannot afford. As a consequence of the cost of satellite phones, they are also relatively uncommon in this place, which further complicates deploying them in the event of a disaster, as local stock may be very limited.

FIGURE 2.2: This image has been removed due to copyright restriction. Available online from[215]. Globalstar satellites coverage show a wide range of coverage over many continents so that users can know which regions are covered by this service, and which areas have weak signal.

2.2.4 Various disasters and remote areas

With the ongoing unresolved political response to climate change, there is little being done to mitigate the root cause of several types of disaster, in particular, cyclones. However, even without the impacts of climate change, many natural disasters occur every year. Despite all of the developments and modern technology that we have, we can not protect all humans from being effected by all kinds of natural disasters. However, we are frequently able to mitagate the damage or loss caused by these catastrophic events [147, 168, 136]. Tsunami, cyclones and floods, are examples for these natural disasters, and we all have seen the amount of damage caused by these in numerous parts around the world.

If we succeed in warning people ahead of time of a forming disaster event, and/or provide the necessary help to them post-disaster, then the humanitarian job has met its goal by saving the lives [225, 89, 117]. To achieve this goal, effective communications systems should be available 24/7 to all residents, and they must be able to access the provided services.

Another point of interest is that it is typically in the remote areas in many parts of the world, where only tens to hundreds of people are living in small villages or communities, that are suffering from lack of mobile connectivity. While this problem exists, then it prevents residents from gaining many benefits of exchanging information with other people, even the important economic and social sides are very low in these areas.

This reduced socio-economic development level interacts with the problem that a lack of communications services can people who live in remote and isolated areas with an elevated vulnerability to natural disasters. That is, they live with a higher risk than people in other areas, precisely because they have not been provided with communications services, that can warn them of, and help them respond to disaster events [103].

In low resources countries, particularly in the Pacific region, almost all people have been affected by multiple natural disasters, in both urban and rural islands. Thus the need for reducing the losses caused by these events is still a goal for many humanitarian efforts around the world [62].

2.2.5 Serval Project

Serval Project (often called Serval) is a peer-to-peer software that can be installed as an application on many Android and Apple smartphones to provide a communications link, and exchange information between peers, without requiring a cellular network. It is a stand-alone and independent communication system that can be used as an alternative method of communications when the user is unable to get the services from the traditional techniques, like cell phone operator, for whatever reason, such as the cellular network having been damaged due to a disaster, or the network simply not covering their location, or where the network is available, but overwhelmed or unaffordable [79, 80, 88, 30, 84, 240, 252, 81].

The phone establishes connections with other nearby peers using the Wi-Fi interface to make an ad-hoc wireless network that is used to transfer data in between, as shown in Figure (2.3). Also, a small radio unit, the Serval Mesh Extender, can be utilised to extend the range of mesh network beyond the Wi-Fi range of tens of metres to few kilometres [98, 133, 83]. The Mesh Extender device is essential, because it acts as a media-translator between the Wi-Fi of mobile telephones, to other longer-distance radio types.

Suppose there is an active link between participants in the mesh network.

FIGURE 2.3: Serval forms a wireless short-range mesh network based on Wi-Fi coverage of tens of metres long to exchange data between peers.

In that case, Serval can be used for voice call, and text message exchange using the Store-and-Forward technique, that allows delivering messages whenever the user is reconnected to the mesh. Serval can also provide other services such as file sharing and mapping to the users.

Serval project is free software, and anyone can download it without any cost. It was designed originally from the many funded organisations to assist the disaster relief efforts and recovery process, as well as it can be very useful to people in remote areas.

2.3 Challenges to communications in remote areas and disaster zones

People who live in remote areas and disaster zones face various challenges related to communications services. It is very important to highlight the challenges that are standing against providing communications services in remote areas and disaster zone.

Saving lives, reducing property loss and increasing social and economic bonds can be achieved if we succeed in creating communications links where they do not exist or out of order. The provided links should be available to anybody who wants to join without any cost or restrictions to get the maximum benefits.

Each communications technique mentioned earlier does not consider as an optimal solution in every scenario in the normal or emergency situations because of its limitations. HF radio, satellite communications and Serval app work as a separate pieces, and each one works independently within its scope without cooperating with others.

The challenges that face the popularity of each communication techniques are quite different according to different criteria like cost, portability and range, which they are examined in the next section.

2.3.1 HF radio limitations

Although HF radio is excellent in long-range, and there are many in use around the world by individuals, organisations and governments, It has a number of restrictions that make it less attractive [159, 46]. Users prefer a communication device that is neither big nor expensive, and does have a high audio quality, which is hard to be satisfied with HF radio.

HF radio is not a communication option to use inside or around the city because there are other cheaper and easy to use options, like mobile or landline phones; however, some amateur, companies and governments are using the radio to communicate with friends, staff members and expeditions in areas where there are no other means of communications. More limitations about the HF radio will be explained later in section (4.6).

2.3.2 Short to medium distance Serval Mesh network

As it is under development, Serval Mesh is a useful communications tool that provides voice call and data exchange; however, it can be used for short to medium distance only or up to few kilometres of coverage. Serval Mesh can be utilised locally within a small village or town where small group members can establish links between them using the Wi-Fi range, or Mesh Extender range of few kilometres.

As shown in Figure (2.4), the Mesh Extender is considered the backbone of the medium-range mesh network, and the scale of mesh network depends mainly on the range of VHF/UHF radio, that is deemed to be the main component in the Mesh Extender. So if we want to stretch the range for extra few kilometres in a specific direction, then we should install another Mesh extender and so on, which is the only way of expansion [84].

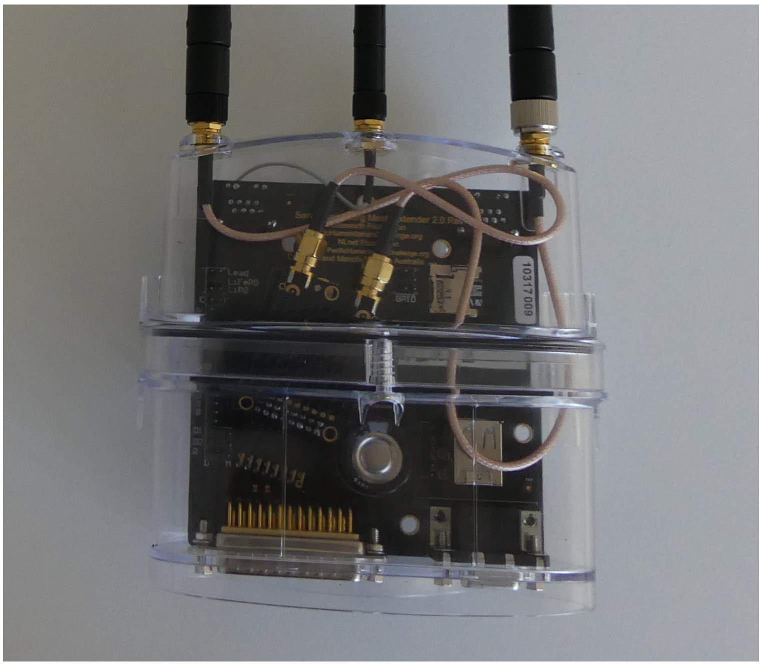


FIGURE 2.4: Mesh Extender Ver 2.0 with a transparent plastic shield that protects the internal components. There are three antennas of the UHF/VHF radios at the top and they are connected to the board via cables.

Previously, Serval Mesh was unable to provide communications over a long distance, even with the utilising of Mesh Extenders because of the limitations of the radio ranges to only tens of kilometres. The key to improve the performance of Serval Mesh, and provide communications over a long distance is thinking of a new device for long range of communication, and at the same time can be integrated into the Serval. Actually this is the core of this research that will be discussed in later Chapters.

2.3.3 Expensive satellite phones

Satellite communications systems, particularly satellite phones are considered to be one of the greatest and reliable techniques in humanitarian applications because it does not rely on any ground communications infrastructure that may be affected by any means of destruction, and participants can make a call from almost anywhere in the world [2].

However, these capabilities come at a cost, the high capital cost of launching and operating satellite services, combined with the limited number of companies who have succeeded in doing so, contribute to satellite services being relatively expensive [138, 7].

If we look at the prices of satellite phones, we see a significant difference between this technique and terrestrial communications systems, like cellular phone networks. The cost of satellite phone handsets is also relatively high, especially for these devices' capabilities. For example, an entry-level satellite phone costs more than AU$1,000, and usage charges are typically above AU$1 per minute. This is extremely expensive compared with cellular networks, where an entry level handset costs less than AU$100, and unlimited calling is possible for about AU$10 per month [23, 233]. The lack of affordable unlimited calling plans for satellite phones is one of their most significants weaknesses because the fear of "bill shock" prevents many organisations in low-income countries from deploying them.

Also, the usability of the satellite phones is another limitation of this technique. There are several reasons for this. First, it is not allowable to use it in some countries, such as North Korea or China, and the governments have a major concern about the national security unless if they are able to intercept the calls [185, 143]. So, in some countries, if anyone wants to use a satellite phone service, they must first obtain a special licence. Second, as already discussed, the fear of "bill shock" is also a significant barrier, that often results in satellite phones being locked away, so that they are not available when required. Third, the latency of satellite phone calls also makes them relatively uncomfortable and inefficient to use.

These barriers all act to limit availability during the acute phase of disasters.

Satellite phones typically have low bandwidth of between 2.4kbit/sec to 60 kbit/sec, making them significantly slower than 3G or 4G cellular phone, comparable with 2G cellular networks, but still faster than HF radio. Thus while they are suitable for voice calls, they are not typically preferable for data or files exchange [129, 138].

2.3.4 Failure of early warning systems

In many parts of the world, Early Warning Systems (EWS) have been deployed to provide maximum warning time for various disasters. This is especially the case for coastal areas to mitigate the threat posed by tsunamis [227].

Tsunamis are generated by a marine disturbance that is caused by different geological events, such as earthquakes, volcanic eruptions or submarine landslides [224, 69, 223]. For this reason, the power of tsunamis can be extremely large, and they can destroy everything in their way [4], with the largest mega-tsunami in the 20th century having been recorded as flowing over a 500-metre tall ridge, and stripping all vegetation and soil away, leaving behind only bedrock [90]. While it is very hard to stop the destruction to physical assets, people's lives can be saved if they evacuate to a safer locations, which in turn requires sufficient warning time before the tsunami makes landfall.

Thus the safety of people in disaster zones, especially those prone to tsunami and similar hazards, depends heavily on having an EWS to provide a timely warning. However, even where an EWS has been deployed, it can occur that the EWS can become non-function or compromised in service for many reasons. Lack of maintenance, vandalism and the logistical challenges of maintaining an EWS in a corrosive tropical maritime environment in remote areas are common causes of the failure of EWS to trigger when required [199, 200].

2.4 Opportunities to improve communications in remote areas and disaster zones

Despite the fact that there are many challenges with communications techniques in remote areas and disaster zones, there are opportunities to improve these techniques, and make them more beneficial to the people. This requires to look closely at many good characteristics that can be found in different techniques, and then either try to improve the techniques that have weak characteristics to be in a good position to provide a good communications links, or the improvement process can integrate two or more techniques into one body to gain the good characteristics from the combined devices.

While the second option is more realistic to achieve, it is necessary to look for the platform that is able to recruit other communications device(s) or techniques without any problems, so that it becomes possible to assist remote communities by introducing a flexible and powerful system to every member.

In general, any improvement to any communications system should take into consideration the following characteristics that satisfy the maximum benefits to the users:

1. Maximum coverage: Any scalable technique that provides communications coverage to community members living in the same area whether they are tens of metres or many kilometres away from each other will be a preferable option for them to use, and it should provide communications with other remote communities.

   Keeping people in remote areas in touch with others over long distances will create many positive benefits in these areas. The number of participants of any communication technique will be dependent on the range of communications, and the total area that can be covered. Thus increasing the geographical coverage will increase the population that can be served by a given approach [179, 230].

2. Automated: Any communications system should work automatically without the need for any expert person to operate it locally. If the technique depends on human intervention to be operated, then its adoption and effectiveness will suffer. The HF radio is an example of this problem, because it requires skilled operators to communicate with others. Thus, it sees relatively limited use, despite its ability to communicate over great distances.

3. Minimum cost: The cost of using any communication technology has significant effect on its popularity since people will naturally seek out and prefer less expensive methods. Many telecommunication companies worldwide continuously advertise new offers with lower prices to attract new customers to join their communications networks since many people care about price above all else. This can be seen with internet-based text and phone calls, where users have rapidly moved to platforms such as WhatsApp and Viber, attracted by the prospect of free calls [150]. Therefore it is important to make sure that any new service is as low cost as possible.

4. Independent: There are many communications techniques that are dependent on various forms of infrastructure, such as cellular communications towers or in-ground cable networks. But these techniques can not be used in remote areas where there is no such infrastructure, or where they suffer outages when natural disasters damage the infrastructure on which they depend [84, 108]. Therefore, any approach that can avoid the dependence on infrastructure is highly attractive.

5. Mobility: The advance of technology has brought pervasive mobility to telecommunications, and makes it easy for users to utilise their own devices anywhere within the range of signal [99]. Cellular and satellite phones have this advantage over landline phones and fixed HF radio installations, making the users very comfortable with utilising their devices. But more importantly, this flexibility allows people to keep their devices with them whenever they want to move from one place to another, and still be able to use them. Thus mobility has become expected, and in many cases, a required function for new telecommunications technologies, including those relating to disaster preparedness, mitigation and response.

6. Interoperable: The integration of communications technologies with one another means that they can be bridge or interface with other technologies, and can communicate or exchange information between them, even if they have different architectures and systems [137, 149]. For example, with the satellite phone, you can make a call to a cellular phone, but you can't ordinarily make a call to an HF radio because they are not integrated with one another.

   The feature of interoperability allows the combination of all of the advantages of the integrated techniques in the hands of the users, and thus can help to mitigate the weaknesses of the various individual solutions.

7. Ease of use: Ease of use has a strong impact on user's willingness to use a given system. If a system is sufficiently easy to use, it expands the potential user-base. Conversely, if a system is too difficult or complex to use, it can contribute to user boredom and frustration, and significantly supress adoption and continued use [205].

8. Size: Advances in technology have allowed ever smaller devices, with modern multi-functional mobile telephones being perhaps the canonical example, and the one against which new technologies are likely to be measured, both in terms of function and size. Such devices have many practical advantages, and now compactness has become a characteristic that is expected, and in many cases required for a communications technology to succeed.

Thus, small, simple and portable devices and systems are much more likely to encourage adoption and continued use than large, complex and non-portable alternatives.

The improvement to the communications techniques can be extended further to imply integrating the Early Warning Systems (EWSs), where essential and high priority information can pass via traditional communications techniques across to the EWS in disaster zones. This creates both opportunities and risks: On the one hand, robust infrastructure such as satellites, or in some cases, HF radio, can be used to forward EWS alerts to a variety of kinds of devices, strengthening the resulting system. However, on the other hand, some EWS systems may be dependent on terrestrial infrastructure, which may be prone to failure during the events the system is intended to warn against. A recent example of this was a tsunami that followed an earthquake in Indonesia, where the earthquake damaged the cellular networks, resulting in reduced ability to deliver an EWS notification about the tsunami [181].

Chapter 3

Literature review

In the previous chapter, current status of communications systems was presented. This chapter shifts attention to the relevant background information, and contextualises the project into the body of published literature.

3.1 The importance and purpose of communications technologies in the humanitarian context

Modern communications technologies have progressively adopted more pervasive and vital functions in many activities of people's daily lives, and there are many examples for these activities, like family and friends communications, online studying and working, online shopping and keeping remote workers safe in a risky environment. This positive role is increasing together with a high and growing demand for these services in various sectors, particularly social, economic and humanitarian fields. Communications services are not restricted to phone or radio communications, but they also extend to include high-speed telecommunications, such as the internet, with a wide variety of use-cases from text messaging to video streaming and file sharing.

The vital role of communications services becomes clear when considering how many activities require at least one communications service to be able to be completed efficiently, or at all. This need can not be overstated in critical scenarios, like the current events of the COVID19 pandemic have caused communications services to become in many cases the only remaining way to study, get supplies, or access government and other services.

In the humanitarian sector, which is the primary sector considered in this thesis, sometimes it is necessary to perform certain actions very quickly. A good example of this is the delivery of early-warning of an approaching disaster situation, such as a cyclone or tsunami. Another common example is the need for people to communications following a disaster, in order to obtain help, determine where supplies need to be delivered, or to report damage to critical infrastructure. Put simply: Communications services support rapid action at a distance, which makes them indispensable for humanitarian applications, as well as every-day life [79, 88, 84]. In the humanitarian context, communications play particularly prominent roles in facilitating the coordination of various activities between effected sites, field teams and coordinating centres.

The beneficial role of communications is not limited only to responding to disasters, but as hinted above, communications systems can be create that can provide early warning of approaching disaster situations. This can allow time to prepare and to mitigate the effects of the impending event, saving both lives and money. In low-resource countries, like Pacific Islands Nations where there are many remote coastal communities distributed over a considerable distance, communications techniques can rapidly warn people who may have a very short time before the occurrence of a disaster, in particular tsunami, and provide a level of safety to local residents. However, while the potential is there to provide such early warning to these remote island communities, the current situation is that many of these island communities lack access to such early warning systems, precisely because of their remote location and small populations.

In the economic sphere, the contribution of Information and Communications Technology (ICT) is essential and substantial [77]. Recent research have shown the affirmative effect of computer, mobile telephone and internet access on GDP [77, 79]. In the USA, ICT sector contributed over $340 billion in 2013 or about 2% of GDP, while in Australia, it contributed about $79 billion or 5.1% to annual GDP in 2013-14. On the other hand, many countries are struggling with low economic growth. While it is unlikely to be the sole factor, a lack of ICT infrastructure likely retards economic growth from what it would otherwise be, if the ICT infrastructure situation was better.

Socially, communications contribution is visible as we go about our daily lives: it permits both individuals and communities to interact socially on occasions and in ways that were not possible before. Social networks that have advanced during recent years have been growing and expanding due to increasing both number of participants and interest in these networks, which reflects on the popularity of numerous Online Social Network (OSNs) like, Twitter, Facebook, WhatsApp, and Instagram [6, 133, 239]. While these innovations have not been without negative effects, it is also clear that they bring many benefits, helping to reduce isolation and vulnerability, especially during pandemic situations such as have been endured due to COVID19.

The overriding purpose of the use of communications technologies in the humanitarian field is to reduce the losses due to disasters. This can include prevention of disasters from occurring through effective preparation, education or other activities. Alternatively, it can take the form of early-warning or responding to the disaster. Such actions, such as instructing the population to seek safe shelter or take other appropriate actions can, and does save lives [241, 236, 9]. For this reason, governments and other authorities around the world use all manner of communications media for this purpose, including television, radios, loudspeakers and SMS to mobile phone.

In the specific case of tsunamis, the need for early warning systems is very important, as many millions of people live in tsunami-prone coastal areas. Unfortunately, as we have witnessed in recent years, tragedies continue to occur where thousands of lives are lost, in part due to lack of timely warning of approaching tsunamis [210, 191, 157].

3.2 Resilience

Resiliency for any system, in general, is the capability of that system to remain functional under abnormal conditions, such as following a natural disaster, or other adverse event. The term is also used in a related manner to describe a community's ability to continue to meet their need in such circumstances [135, 66].

Maintaining communications links in disasters is a significant challenge for governments, humanitarian organisations, and also for the manufacturers and designers of communications systems. There are a variety of factors that contribute to the widespread lack of resilience in communications systems, and as a result it is very common for communications systems to fail following disasters [135, 96]. Some of the contributing factors to the lack of resilience in communications systems are:

1. The difficulty of repurposing digital devices to solve the emerging challenge:

   For the digital part of resilience, the logistical challenges of a disaster often make it impossible to import meaningful quantities of new equipment into the disaster zone [204, 8]. Therefore it is often necessary work with what is already in the zone, i.e., to repurpose existing digital devices. However this is non-trivial, and may require distinct series of steps, or even different software for each model or class of device. Also, the existing devices may not have the necessary properties to allow them to be repurposed in this way, or to be effective in these different roles. For example, some devices do not allow the introduction of third-party software, or are not adequately documented to allow this. Even where these are not barriers, if the software has not already been created and made available in some disaster-resilient manner, it may not be possible to use. Mobile phone apps fall into this category, where although modern mobile phones are highly amenable to meeting new use-cases, Apple devices cannot side-load applications in the absence of internet access, and except in some low-income countries, most users of Android phones are not familiar with the process for side-loading applications, i.e., loading them from another device without relying on internet access.

2. Assumption of availability of communications:

   Related to the previous point, it is very common for communications infrastructure to be damaged or disabled during a disaster. Many software applications, including a distressing number of those intended for disaster response, are designed and implemented in ways which make them dependent on cellular, internet or other communications infrastructure [97, 43]. This can be intentional, i.e., to ensure that users must pay subscription services, or accidental, such as using libraries that rely on internet connectivity.

3. Resilient devices often less profitable:

   Resilience can be counter productive to the vendor's desire to maximise their profit. Resilient devices may last longer, and thus create a risk of decreased sales due to longer replacement schedules [141, 268]. Also, truly resilient communications systems need to be able to operate fully in the complete absence of communications infrastructure. This reduces the degree of control a vendor has over the ways in which users choose to make use of their products. This can in turn decrease the ability of a vendor to extract subscription or other revenue from the users of a given device.

   The ability to cost-effectively repair or otherwise modify physically damaged devices is a variation on this challenge. Many large vendors, like

Apple, have been recognised for making it progressively harder for users to independently repair or modify their devices, demonstrating that this is not merely a theoretical problem.

Similarly, making devices more resilient may result in the cost of design and manufacture of a device increasing, further reducing the profitability, and potentially competitiveness of the resulting device [208]. Again, vendors risk management and profit maximisation interests are often best served by not attempting to create resilient devices.

Therefore there remain considerable challenges to enabling communications devices to be as resilient as possible, and for which there are often active disincentives for vendors to attempt to address. This leads to the need to create purpose-designed resilient communications devices, which can fill the void created by the consequences of these complex issues.

3.3 HF, VHF, UHF and Microwave radio communications

Wireless telecommunication technologies varies in their characteristics and relative strengths and weaknesses to establish communications links between devices. This is because of employing different radio technologies to send/receive the wireless signal, and each radio technology has powerful and limited points in this field [41]. The radio frequency band used has a strong influence on the properties of a given radio system. The four most common broad frequency bands used for terrestrial-based communications are discussed below.

The previous presented telecommunications techniques, including Serval, acquire the positive sides of the recruited radio technology, and become restricted to the design limitation from this technology. So the characteristics of any telecommunications service are actually based mainly on the characteristics of the radio technology.

3.3.1 High-Frequency (HF) radio communications

HF radio technology employs frequencies from 3 – 30 MHz, as shown in Figure (3.1), and this range of frequencies has the ability to travel for hundreds of kilometres, which is its primary strength. However, HF radios typically operate at higher power levels compared to other bands, typically 25W to

100W. HF radios are also typically relatively large, expensive, suffer interoperability problems with one another, require considerable user training and typically support very low data transfer rates of between 1 and 1,000 bytes per second [151].

There are multiple vendors of HF radios. Two of the most common in the humanitarian sector are those from Codan and Barrett. Figure (3.2) depicts a pair of HF radios from these vendors, that were used in the previous HF integration proof-of-concept work for the Serval Project.

FIGURE 3.1: This image has been removed due to copyright restriction. Available online from [35]. A diagram shows the range of frequencies and the wavelength for various radio communications techniques including Wi-Fi, UHF, VHF and HF transmission.

FIGURE 3.2: Two brands of HF radio, Codan and Barrett that involved in the experiments of integration these radios into Serval at the telecommunication lab, Flinders University.

3.3.2 Very High Frequency (VHF) radio communications

VHF radio employ higher frequencies beyond the HF range, between around 30MHz – 300MHz, as shown in Figure (3.1). These frequencies tend to go around small obstacles, such as buildings, but not large geographical features, such as hills. Their communications range tends to be limited to a few tens of kilometres, but can operate at lower transmit power levels of between 5W – 25W, and support slightly higher data-rates, typically in the hundreds to thousands of bytes per second. Compared with HF radios, their small size, lower power consumption and lower costs and user training requirements are important advantages [41, 152].

3.3.3 Ultra High Frequency (UHF) radio communications

UHF radio transmits signals at the range of frequencies between 300MHz – 3GHz, as shown in Figure (fig:radfrequencies). This radio consumes less power than VHF radio between 0.5 – 5W, and it has a lower communication range limited to few kilometres only. This radio is favoured to use inside buildings or campuses due to its capabilities to propagate through building structures and windows [54, 127], and it provides a data rate higher than VHF around tens of thousands of bytes per second. Other advantages to this radio are the small size device, small antenna required to transmit signal and lower cost than other radios. One of the main components in Mesh Extender is RFD900, which is originally a UHF radio.

3.3.4 Microwave radio communications

Microwave radio communications are widely employed in wireless communications due to the amazing characteristics of this type and small wavelength that requires a small antenna for transmission and low power consumption [263, 29]. Wi-Fi transmission, which exists in almost all smartphones and other personal devices employ microwave signal to establish links among devices, and it consumes small amount of power of less than 1W [75]. However, the range of communications is limited to tens of metres long. Wi-Fi card and antenna is small and can fit inside smartphones easily. Also the cost of the radio is the cheapest among other radios, and doesn't need any training to use it.

3.4 Serval Project

This thesis extends the Serval Project's off-grid communications protocols and related technologies. It is therefore important to understand the motivations, intent and properties of the Serval Project and the technologies that have been created as part of it.

3.4.1 Brief overview of the Serval Project

Before explaining the Serval Project in more detail, it is helpful to gain a high-level understanding of the system: The Serval Project in the simplest definition, is a communication system that provides communications links between smartphones, without requiring cellular coverage [67, 79, 80, 57].

The Serval Mesh is a group of technologies that can be installed and used by smartphones that run either Android or iPhone operating system, as shown in Figure (3.3). It requires at least two phones to operate, and in its most simple form, does not require any additional equipment. Where more than two phones are running the Serval Mesh software, they will form a multi-hop wireless ad-hoc network, which can span much greater distances than the communications range of any given pair of phones. Also, because it supports delay-tolerant networking, phones don't need to be in constant contact with one another for communications to occur.

The Serval Mesh employs the Wi-Fi or Bluetooth signal on the smartphone to form the mesh network with other phones that are near one another. For longer range communications, relay devices, called Serval Mesh Extenders, can be used, and that contain or connect to a different radio type,

FIGURE 3.3: The interface of Serval Mesh ver. 0.92 afters installing it of a smartphone, and it shows different services that are provided to the users, such as messaging, share files and maps [57].

that is capable of longer range communications. The standard configuration of a Serval Mesh Extender contains a 4W ISM 915 MHz band packet radio, which is capable of line-of-sight communications at a range of up to a few kilometres, as shown in Figure (2.4)

This open-source software and hardware gives mobile phones the freedom to communicate with each other and exchange different kinds of data format for free like text, images, locations, and phone calls without relying on supporting infrastructure.

3.4.2 Goal and motivation

Every year, many natural disasters occur around the world. It is very common for communications infrastructure to be impacted by these events. In the Indo-Pacific region, cyclones, earthquakes and tsunamis regularly cause significant damage to infrastructure [42, 219]. This is a problem for both low-income and high-income countries. For example, Cyclone Debbie in Queensland in 2017 caused considerable damage [20], while in Indonesia 2018 where two tsunamis that caused significant damage [93] and in Vanuatu 2018 when both cyclone and tsunami happened at the same year [121].

The consequences of the damage of such events may causes a huge delay to the restoration of any provided services at the effected sites [195], like electricity, transportation infrastructure and telecommunication services, and sometimes a restoration process for an essential service like telecommunications can not be triggered unless completing another one like electricity or road.

After a disaster, responding requires functioning communications links to manage the complex actions of the various parties involved [86]. However, when communications infrastructure is damaged, it is necessary to provide some alternative means of communications that are independent from the infrastructure that has been damaged.

This is exactly the role that the Serval Mesh network was designed for, i.e., providing communications links to disaster affected areas, without the depending on any existing infrastructure [87, 80]. Serval was also designed so that community members in disaster zones can utilise Serval, and keep connected in post-disaster situations, rather than only personnel who are part of official responses to a disaster. This recognises that the general public living in a disaster zone play a significant role in disaster response, even if it informal. Also, the affected communities desire and need to communicate with one another, including to know if loved ones are safe or not. This personal connection function often has to be otherwise provided by relief organisations, such as the Red Cross. Thus it is a valuable service of itself. Fulfilling this need is also isometric with providing effective communications channels for people living in remote areas, poor communities or any places where the cellular infrastructure does not exist, or cannot be effectively or affordably accessed. This has the potential to bring significant benefits to these communities.

In short, the primary goal for the Serval Project, which is the same for this research, is to provide survivable means of communications between people regardless of which part of the planet that they live in, or in which circumstances that they find themselves, including adverse events, such as disasters [207].

The huge amount of destruction caused by the Great Haiti Earthquake in 2010, as shown in Figure (3.4) were the initial motivation of Serval Project [57]. The percentage of the affected people is about one third of the total population, and the massive destruction to premises has prevented the government and international humanitarian organisations from relieving the people, and has made them struggling to restore the basic services, like pure water and telecommunications services [145, 15].

The first demonstration of the Serval Project was in late 2010 as an achievement of a small academic team supervised by Dr Paul Gardner-Stephen in the Resilient Networks Lab at Flinders University [88].

FIGURE 3.4: This image has been removed due to copyright restriction. Available online from[37]. Map and degree of the destruction after a massive earthquake in Haiti in 2010, where the percentage of destruction reached to 90% in some areas.

3.4.3 Serval as an emergency network

Currently, Smartphones with cellular coverage of 4G or even the newer version 5G occupy the most common method of communications. However, as has been discussed above, this service is not resilience against different many different disaster scenarios, which in turn can result in loss of service, and reduced effectiveness of disaster responses, and ultimately in lives and livelihoods being damaged or lost that could otherwise be saved.

Thus, there is an imperative to find a solution that is feasible to people who are unable to get the regular communications services, particularly in emergency scenarios. The Serval Mesh is designed to do this, resulting in advantages for use in disaster situations, including infrastructure-indepdence, resilience, and avoidance of the need for user-charges, which all support its applicability to emergency and disaster situations. However, the existing work on the Serval Mesh is limited to short-range communications of not more than a few kilo-metres. Many disaster zones are much bigger than this, and for this reason, this research considers how the range of the Serval Mesh can be extended to provide a reach of many hundreds of kilometres.

Serval can be easily employed on the ground post-disaster, or when there is no coverage at all like in a remote area. Many operations in the affected regions run by humanitarian NGOs can get the benefits of using Serval. In this context, Serval team have worked with many humanitarian organisations like Red Cross and UN World Food Programme to develop a backup plan for communications during the emergencies, and when the communications links are vital for saving lives.

A new deployment strategy of Serval is to utilise as an early warning system for a potential natural disaster, tsunami in particular, since it is believed that this remains an open problem, as the existing systems are very expensive to install and maintain, and the recent events following the tsunamis in Indonesia in 2018 showed that as they often cease to be operable before they are needed [258], resulting in considerable loss of life.

3.4.4 How Serval works

Simply, anyone who intends to use the Serval Mesh has to install the app from the internet or from any nearby smartphone that already has a copy of Serval installed, then the interface, as shown in Figure (3.3) displays various services for the user like sharing files, text message, maps and make a call, which can be shared with other Serval participants. The ability to replicate itself from phone to phone is purposely built into the app, to ensure that it can be deployed widely by the community itself, even in the complete absence of internet access or other communications infrastructure.

The Serval Mesh doesn't need a cellular network or internet to communicate, since it is an entirely stand-alone and fully distributed system. When activated, it automatically looks for other devices running the Serval Mesh software, and begins exchanging data with them.

Data is stored on each node, creating a delay tolerant network [196, 180, 209], so that even only intermittent connection of devices can be made use of to deliver data over arbitrarily many hops. That is, there is no need for a direct and immediate path between the sender and receiver of a particular communications. This approach makes the system extremely resilient. The trade-off is that delivery time cannot be guaranteed, as it may depend on the movement of other users and their devices. Delivery time may also be affected by other factors. For example, the file size, number of hops between sender and receiver, and the type of wireless link between two hops can significantly impact the delivery time of a communication.

If only mobile phones are involved, the communications link between any two devices will be either Wi-Fi or Bluetooth. Communications over longer distances can occur in one of three ways:

1. The two devices move within range of each other at some point in time, allowing the communications to occur at that point in time.

2. Additional mobile phones are participating in the network, and at some point some sequence of pairs of devices come into contact with one another over time, allowing the communication to be progressively replicated onto more devices, until it reaches the destination device.

3. Specialised communications relay devices, such as Serval Mesh Extenders are participating in the network, and receive the communications from any mobile phone on which it is stored (including if it has been automatically replicated to it, as described above), and then forwards it to another communications relay device, which is able to eventually deliver it to the destination device, or causes it to be replicated onto another device, whether a mobile phone or a communications relay device, which in turn allows delivery to complete as described above.

The Serval Project team has developed the Serval Mesh Extender communications relay device precisely to facilitate the more rapid and reliable deliver of communications, and over greater distances, than would be possible using only mobile phones. It also allows mobile phones running the Serval

Mesh software to operate in Wi-Fi Client Mode, which results in considerable energy savings. Empirical testing in the Resilient Telecommunications Lab indicates that one Mesh Extender and two phones running the Serval Mesh app consume less power than two mobile phones running the Serval Mesh software in ad-hoc Wi-Fi mode. Also, as modern mobile phones do not support ad-hoc Wi-Fi mode, the Serval Mesh Extender ensures that the Serval Mesh can be used on newer handsets.

A common use case for the Serval Mesh Extender devices is to have one each in two neighbouring villages or neighbourhoods, as shown in the example Figure (3.5). The Mesh Extenders form a direct link to each other, and large numbers of mobile phones running the Serval Mesh app can be used near either Mesh Extender, and communications will be delivered automatically to any other user in the network. This can allow two nearby communities to communicate with one another resiliently and without cost. Where the villages are too far apart, or separated by difficult geography, additional Mesh Extenders can be deployed, to make a simple and self-organising backbone link between the locations.

However, in some cases, such as islands separated by many kilometres, this may not be possible. Therefore there is a need to provide Serval Mesh Extenders with some means of much longer range communications. Some islands in the Pacific are separated from the next nearest by up to several hundred kilometres. Ideally such a solution would be found that would enable such isolated island communities to link up. Preliminary work on integrating long-distance HF radios into the Serval Mesh has demonstrated that this should be possible, in principle [11]. However, that proof-of-concept system was too slow, requiring more than 15 minutes to deliver each message, was too slow to be useful. Exploring ways to improve the performance of Serval over HF radios is thus warranted, and is given considerable attention in this thesis.

3.4.5 Serval Mesh components: Protocols, Software and Hardware

The Serval Mesh mainly consists of three main parts: protocols which are then implemented in software, and which run on appropriate hardware. The Serval Project has created all three of these, designing the protocols, writing the software, and designing and manufacturing the hardware.

The Serval Mesh embodies several key protocols:

FIGURE 3.5: This image has been removed due to copyright restriction. Available online from [33]. A two neigh-boured villages with a few kilometres distance between them, and they could be connected by Mesh Extender.

1. Mesh Datagram Protocol (MDP) and Mesh Streaming Protocol (MSP), for use on Wi-Fi connections [217].

2. Voice over Mesh Protocol (VoMP), for telephony over Wi-Fi connections [30].

3. Serval Rhizome, a delay-tolerant networking protocol that allows text messaging and other services, even when the network is highly partitioned, and lacks real-time end-to-end connectivity between participants [88, 30].

4. Low-Bandwidth Asyncrhonous Rhizome Delivery (LBARD), for the efficient syncrhonisation of Rhizome payloads over slow and/or high-latency links [136, 240].

The software part of Serval includes all functions and protocols in the system. It consists of different layers, and each layer is responsible for a specific task, as shown in Figure (3.6) which shows the architecture of the Serval Mesh application for Android.

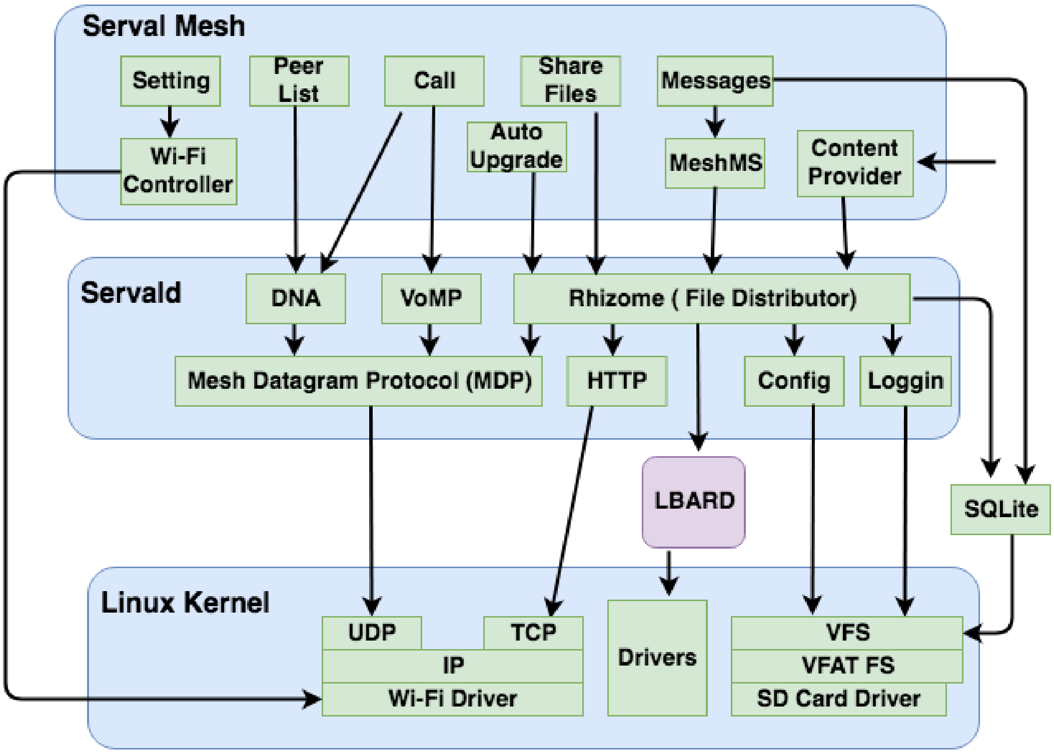


FIGURE 3.6: The architecture of Serval software shows three layers, and each one does several activities. LBARD lies between Serval and Kernel, and it receives data bundles from Rhizome protocol from one side, and connected to drivers modules from the other side to send bundles via a specific driver.

Of particular interest in this thesis are the Rhizome and LBARD protocols, which support the delay-tolerant networking aspects of the Serval Mesh, in particular text messaging. These protocols are implemented in the core Serval software, `servald`, and the LBARD Daemon, `lbard`. All software of the Serval Mesh is open-source, and may be accessed at `https://github.com/servalproject`.

There are different types of hardware devices that have been employed overtime during the developing of the project. Initial testing was performed using computers connected via Wi-Fi, followed by smart-phones running the

Serval Mesh application. More recently, the second-generation Serval Mesh Extender hardware has been developed, which combines a weather-proof enclosure, an ad-hoc Wi-Fi capable micro-controller, UHF packet radio and solar and battery energy management circuitry in a compact and cost-effective package, as shown in Figure (3.7).

The second-generation Mesh Extender also includes a connector that allows the use of an external radio, in place of the internal UHF packet radio. This allows them to interface with other radio types, a property that this thesis relies upon, as it explores the integration of HF radios into the Serval Mesh in later chapters.

3.4.6 Benefits of the Serval Mesh

As has been discussed, Serval Mesh is a communication system that has the potential to provide enormous benefits for people when they need it, particularly in disaster zones and remote areas, or when the existing communications infrastructure is otherwise not available or out of order. Further valuable benefit is obtained when the Serval Mesh helps save the lives of coastal communities by installing Serval based early warning systems, so that the one system can provide both functions. Because the communications function would be used throughout the year, this helps to avoid the problem of early warning systems falling into disrepair, because they do not provide value to the protected communities between disaster events.

Perhaps the canonical scenario where the Serval Mesh is of use is when communications infrastructure fails or is damaged for some reason. Restoring communications can take many days, especially in the aftermath of a disaster, where logistics becomes even more difficult than usual. However, the scenario is much simpler with Serval Mesh to establish communications links again between community members since it doesn't require any infrastructure to operate except downloading the application. Optional use of the Serval Mesh Extender devices can help, but are not necessary. Also, where Serval Mesh Extenders are required, they are small, portable and self-organising, which means that the affected population can easily move these devices to where they are needed most, e.g., as shown in (3.8), thus providing an interim communications solution while awaiting the restoration of damaged communications infrastructure.

In low-resource countries, the cost of telecommunications can often be

(A)

(B)

(C)

FIGURE 3.7: Multiple photos for Mesh Extender version 2 from outside and internal circuit.

FIGURE 3.8: Installing Serval Mesh Extender on a roof of a house during the piloting of Serval Mesh in Vanuatu 2017. The process doesn't require any expensive hardware or expertise, making it possible in a small village. Also, as there is no configuration required, the devices can be moved around based on the needs of the community, without needing to coordinate with, or seek permission of a network operator or other authority.

burdensome, especially for those living in poverty, e.g., those living in rural areas and living by subsistence farming. This can help communities by preserving their limited financial means for other pressing needs, while increasing the benefits that they are able to derive from telecommunications. This includes both economic and social benefits. The social side includes improving the social ties among individuals, families and groups, who are often spread among multiple nearby communities. The economic side includes supporting the farmers with improved efficiencies, e.g., being able to ask a question remotely, rather than having to walk considerable distances to speak to someone, or with better information about supply, demand and pricing in local markets, that can enable them to optimise their income generation capacity.

3.4.7 Challenges for the Serval Project

While the current state of the Serval Project and Serval Mesh is already well advanced, and can be applied to many use-cases, it is also limited in certain important ways, that would be attractive to be overcome, to allow it to be more broadly useful:

1. Communications is limited to a few kilometres between Mesh Extenders, due to the reliance on low-power short-range UHF radios.

2. The very limited HF radio integration that was previously demonstrated as a means to remove this distance barrier suffers from very low throughput, with messages requiring many minutes each to be delivered, limiting message throughput to typically less than 100 messages per 24 hour period. This effectively prevents communities using an HF radio to link with one another, because too few messages can be delivered per day to be attractive. The latency becomes worse as the number of hops are increased, easily approaching an hour or more to deliver a message, which is also highly unattractive. This is partly due to the inefficient use of the HF radio, as well as:

3. Regardless of the radio type, the LBARD programme uses only a crude algorithm to synchronise Rhizome bundles between peers, contributing to high latency and low message throughput, regardless of the type of radio used.

3.5 Literature review of disaster zone communications

Providing communications links in the humanitarian field is a growing interest to many researchers and organisations. These communications links play a vital role in protecting humans, getting necessary supplies and enabling to establish connections between community members [161, 12]. In this context, the need to provide communications links is a high priority to the residents and the humanitarian workers who work in disaster zones, where damage may occur to the telecommunication infrastructure, cellular towers in particular [265]. This need becomes apparent when the residents or humanitarian workers aim to request assistance from others or participate in the relief process, and experience difficulty doing so [206].

Another aspect in the humanitarian field where a lack of communications links is problematic, is in remote and isolated communities. In these locations there is often no communications infrastructure [114, 84], or where such infrastructure does exist, it may be too expensive for local populations to access. In this case, there is a need to establish communications links that suit their circumstances, particularly lower-cost options to people in low-income communities. Going further, in the most isolated locations the cash economy may not be sufficiently developed or pervasive to even allow for making payments at all. Thus, there is a particular attraction for systems that do not involve usage charges at all, but can be freely used once deployed.

These challenges have encouraged researchers, including the Serval Project team among many other groups to develop different approaches to remote areas and disaster zones communications by employing various approaches to communications infrastructure, such as balloon or UAV lofted communications relays, or compact and low-cost Wi-Fi and/or UHF/VHF radios [84, 16]. Each of these approaches share the same goal of providing alternative communication links, but they each have different strengths, weaknesses and characteristics, such as the range of communications coverage that they can provide. The following gives an overview of some of the range of approaches for providing communications links in the humanitarian field that have been considered in recent years:

- Alsamhi and et al. [14] described a tethered balloon network architecture to provide an emergency communication when the entire or part of terrestrial wireless communication infrastructure is out of order for many reasons. The tethered balloon provides broadband wireless communications services for all individuals, authorities and rescue teams within a big area around the balloon. This technique can be implemented to provide different wireless services like WiMAX, Wi-Fi, 3G, LTE and LTE-A services.

- Panda and et al. [176] have introduced a prototype technique for utilising a UAV to provide communication in post-disaster emergency scenario. The technique based on forming an Ad hoc network of many UAV's, and each UAV can be equipped with a Raspberry PI and Wi-Fi access point so that each one can provide communications to people within the range of mobile access point or the UAV here, which means that anyone on the ground will be able to get the internet service if the UAV is within the tens of metres range. The Ad hoc network of UAV's connects to a static access point on the ground which is connected to a rescue coordinate centre to manage the process.

- Askoxylakis and et al. [21] have introduced a Rapid Emergency Deployment mobile Communication (REDComm) node, which provides different types of wireless telecommunication services that can be provided to the users. Each node takes the form of a towable car or truck trailer, and it is equipped with a computer, satellite transceiver for internet access from the satellite, GSM base station for voice and text message, ISDN primary rate Interface to connect public telephone, FM radio transmitter, VHF/UHF Transceiver and access point for providing internet. The trailer is outfitted with a hybrid power source for both renewables like a solar panel and wind turbine and nonrenewables like power generator and batteries. The REDComm also has IP camera for broadcasting the videos to other people, and a telescopic mast for long distance of coverage.

- Sujoy and et al. [198] have introduced hybrid ad hoc network infrastructure for post-disaster communication. The authors describe a four-tiered planned hybrid architecture using Information dropbox, communication balloon, data mules and long-range Wi-Fi communication to provide internet to the users in different scenarios.

- Abdul khaliq and et al. [118] presented a prototype for an emergency response system based on Global Positioning System (GPS) and Vehicular Ad hoc Network (VANET). This system collects information form volunteers, individuals and rescue teams in the disaster area and coordinate the service according to the request. It has a dedicated interface for client-side to send a specific request depending on the situation on the ground, like requiring first aid, ambulance food supply, shelter or sending a voice message.

- Pal and Kant [173] described a smartphone-based disaster recovery network using Wi-Fi tethering. Information can be transferred from one phone to another until it reaches a mobile or fixed access point, like helicopter, UAV, satellite gateway or radio interface, then it transfers through the satellite to the emergency command centre. This network can help individuals or rescue team to send photos, text and recorded voice in the affected area.

- Deruyck and et al. [56] have proposed a new tool for large scale disaster scenario, based on Unmanned Aerial Vehicle (UAV)-aided wireless emergency networks to be utilised in high population areas. Numbers of UAVs fly at low altitude to provide communications to residents, and each one carries an LTE femtocell base station that can operate within the resrictions of the UAV form factor, including physical size, weight and power consumption.

The commercial sector has also developed various communications products that can be applied to humanitarian contexts, such as GoTenna, Gotoky, Beartooth, Sonnet and PowerTALKIE, that could be utilised to provide communications links in the humanitarian field.

These products share many ideas with the Serval Project in providing the communications independently from cellular coverage. However, they are significant differences with the Serval Project and other approaches, the commercial offerings must be maximally profitable for the vendor, and competitive in the market place. This often results in the focus shifting from optimisation for humanitarian use-cases towards more profitable use-cases. For example, many of the commercial offerings have limited communications range, require access to some form of centralised infrastructure, and/or other properties that limit their practicality for the humanitarian context.

The following list presents some of the commercial offerings that have been made available in this space:

- goTenna: This device provides off-grid communications independently from the cellular network using an application on the smartphone [91]. GoTenna device employs the Bluetooth signal to pair with user smartphone, and connects this end-user from one side to other users on distance ends. It builds a mobile mesh network platform to transfer data, such as text messages or a user's location over multiple hops, as shown in Figure (3.9). A piece of information can transfer securely from one node to the next until it reaches its intended destination.

  The goTenna device consists of a UHF/VHF radio to extend the range of communication up to a few kilometres line-of-sight, and with multiple hops, the range can go extend to many kilometres, which is an

FIGURE 3.9: This image has been removed due to copyright restriction. Available online from [91]. The PRO-X version of goTenna and the interface on smartphone. The device is connected via Bluetooth to the mobile, and transfers data to the goTenna devices within the range.

attractive proposition. However, because it uses exclusively small integrated UHF or VHF radios, providing coverage between distant points is not possible. Its primary targeted use-case is hikers, specific operation for security forces and small groups or teams working near one another in remote areas.

Also, while goTenna can be employed in the humanitarian field, a single goTenna device cannot be shared by large numbers of users in an area, thus increasing the effective cost compared with technologies like the Serval Mesh that can do this.

- Gotoky: This commercial device provides the users with a suite of off-grid secure communication services, like text messaging, voice recording, navigation information and locations [92], as shown in Figure (3.10). To make a connection with other users, both parties have to connect to nearby Gotoky device through Bluetooth, then the Gotoky devices are connected together directly within a range of few kilometres, or connecting through another hop if they are beyond the range, which creates a mesh network among the existing users to extend the range.

FIGURE 3.10: This image has been removed due to copyright restriction. Available online from [92]. Gotoky application and communication device that connects to smartphone via Bluetooth from one side, and nearby Gotoky devices on the other side.

The range of Gotoky is similar to GoTenna, and it is restricted to the range of mesh network. Only users within few to tens of kilometres in maximum can exchange information between them.

Gotoky is useful in different scenarios and personal activities, like adventure or humanitarian operations, and anyone can buy it from the official website of Gotoky. This product is not free, and its range is lower than the recent version of Serval Mesh, and like goTenna, a single unit cannot be shared among many simultaneous users, increasing its effective cost.

- Beartooth: Beartooth is utilised to provide communications among dedicated Beartooth network users when there is no cellular phone service, and it works independently from any cellular provide [31]. The

Beartooth device (Figure 3.11) connects with the users' phone through the Bluetooth and with other Beartooth devices to transfer data to other users.

FIGURE 3.11: This image has been removed due to copyright restriction. Available online from [31].Beartooth communication device and the interface on smartphone. These devices communicate within the UHF radio range and can form an independent network to exchange a limited set of data type.

The device consists of a UHF radio that works in ISM915 band (902-928 MHz) which means that the range of communications between any two participants is limited to few kilometres, which is similar to GoTenna's range of communications. The device is commercially available for purchase, and anyone can buy the device from the official website of Beartooth [31].

Beartooth can exchange messages, photos, locations and voice with friends, and it tends to be used more in leisure time than emergencies.

The Beartooth device is almost equivalent to Mesh Extender as a short to medium range of communications device, in terms of its use of the same UHF radio band. However, Beartooth doesn't provide a long-range of communication like in the recent version of Serval Mesh, nor does it allow sharing of a single device among many users, and thus like goTenna and Gotoky, has a much higher effective cost than the Serval Mesh.

- RightMesh: It is an application on Android phones, and provides communications among different nodes that could be a smartphone or IoT [194]. RightMesh doesn't need a communications infrastructure to work, except Wi-Fi signal, Bluetooth or the internet connection because it creates a mobile mesh network independently from the cellular network or any other supportive devices. Any node can connect to the internet to download any data from the internet for itself or any other node within the mesh network, as shown in Figure (3.12).

FIGURE 3.12: This image has been removed due to copyright restriction. Available online from [194]. A diagram shows how can RightMesh create a mobile mesh network and access the internet from certain points to send date through.

RightMesh, similar to Serval, is a free application to provide communications for people especially in developed countries who can't afford the bills for traditional cellular services. Also, it can be utilised in natural disaster situations or even in remote areas.

The main drawback in RightMesh is the range of communication since it is bounded to the range of Wi-Fi or Bluetooth up to few hundred metres in best cases, and is primarily oriented around sharing an internet connection, and requires an internet connection to function.

- Sonnet: This device provides an off-grid mobile mesh network that can be employed to exchange text message, images, voice recording and GPS locations separately from the cellular network, internet or satellite [111].

FIGURE 3.13: This image has been removed due to copyright restriction. Available online from [111]. Sonnet device used to form an off-grid network, and it transfers data from smartphone to another one within the range of UHF radio.

To start the communications, the mobile phone connects to Sonnet via the Wi-Fi range, then Sonnet establishes a link to another Sonnet device that belongs to another user within the UHF radio range of few kilometres in range. Sonnet device mainly consists of a UHF radio and a Wi-Fi card for this purpose.

Data can traverse through different Sonnet devices until it reaches the final destination, extending the range beyond few kilometres. Sonnet can be hired for individual use or humanitarian purpose when the communications infrastructure is out of order for a variety of reasons.

This ability to allow multiple devices to connect via Wi-Fi coupled with a longer-range radio makes it more similar to the Serval Mesh than the other products described above. However, it is not able to use different radio types, and the Sonnet device is not built for long-term outdoors installation and operation.

- PowerTALKIE: This device is for commercial use, and can be easily purchased; however, it can be fitted in different useful cases including post-disaster situation, when there is no cellular network available or there is congestion within the network like flooding, bushfire, camping, remote area, hiking [187].

  PowerTALKIE, similar to Serval, enables chatting, voice recording, GPS and map sharing among the mesh network participants.

  PowerTALKIE extends the range of communications from the Bluetooth range (with smartphone) to up to 8 kilometres in best cases between two devices based on a UHF radio link of 462.55 - 462.725 MHz. It forms a mesh network to extend the range and the number of participants within one geographical area. Again, however, it does not allow many devices in an area to share a single unit, and is not suitable for long-term outdoor installation. Thus, the system will suffer the same high effective cost challenges of many of the other commercial offerings.

- Fogo: It is a stand-alone device that provides a few communications services including text messaging, GPS tracking and Walkie Talkie option [60]. It doesn't require a smartphone as an interface between users, which reduce the complexity and the need for different devices to be involved in communicating with others, as shown in Figure (3.15).

  Unlike Serval, Fogo can't create a mesh network, or transfer digital information over multiple hops. It provides only private point to point message delivering, or broadcast like a walkie talkie, without the ability

FIGURE 3.14: This image has been removed due to copyright restriction. Available online from [187]. A commercial product of PowerTALKIE device that can be bought from Amazone, and two devices can form a bridge between two smartphones in few kilometres range.

to resend the data through an intermediate hop. Again, devices cannot be shared by many users, and together with the lack of multi-hop networking, has very limited range.

These products and approaches and the Serval Mesh each differ from one another, and offer various relative strengths and weaknesses, which are summarised below:

1. Services provided: All these techniques can exchange information between two nodes, similar to Serval, and this information could be a text message, voice call, map or photo, but some of these techniques, like Fogo, can exchange only a limited set of files. Also, none of them overcomes Serval's ability in exchanging a special format of file or providing a service not exist in Serval Mesh.

FIGURE 3.15: This image has been removed due to copyright restriction. Available online from [60]. Fogo device to exchange messages with other devices in the range without the need to a smartphones.

2. Range: All these techniques provide few to tens of kilometres range of communications in maximum, if multiple devices have been employed in between, like Beartooth and Gotoky, and many of them utilise UHF/VHF radio for this purpose. This point restricts the use of these techniques to a small area only. In the previous version of Serval, before this research, it had the same range of communications, and there were gaps between Serval and other techniques. So, one of the main goals in this research is to extend the range beyond tens of kilometres range to provide better services.

3. The cost and availability: Many of these techniques are not free, and it has to buy it from the company. Also, some techniques may not be available to everyone or in any place to buy, like goTenna, since there are some restrictions to purchase the product. With Serval, it is different since it is free and can be utilised in the humanitarian operations in many places. Therefore, this point makes Serval in a better position among these techniques.

3.6 Summary

This chapter has explored the challenging context in which disaster mitigation and response activities in the field of humanitarian endeavour exists. In particular, while there is a pressing need for improved communications solutions, and a general increase in resilience of these systems, this is very unlikely to occur under the influence of market economics alone, as increasing the resilience of systems very often works against the market interest of the vendors.

Fortunately, the area is not without hope: First, at a purely technical level, there are radio types that can meet the fundamental requirements of being able to link people in remote areas. Second, considerable work has already been undertaken in the non-profit open-source sector, including by the Serval Project, to design and implement communications systems that are resilient, and able to operate in profoundly infrastructure deprived contexts, such as immediately following disasters and adverse events.

However, the Serval Project is not currently a complete solution. In particular, it lacks effective and scalable long-range communications options. This deficiency is the focus of considerable attention in this thesis. The potential of HF radios to provide this long-range capability, in particular, is explored in the following chapter, by considering the characteristics, strengths and weaknesses of HF radios and HF radio communications.

Part II

Adapting LBARD for HF Communications

Chapter 4

HF radio as a digital carrier

4.1 Introduction

It was argued in the previous chapter that including High Frequency (HF) communications into the Serval Mesh would help to address the challenge of providing long-distance communications. However, before it can be incorporated to provide effective and efficient services, it is important to first understand HF radio, its characteristics, capabilities and limitations.

Although early models of HF radios supported only analog voice communications, most modern HF radios now support digital communications in some way. This has allowed the attractive features of HF radios, such as very long range communications, and the ability to operate in the absence of supporting infrastructure, to be better leveraged in the information-dominated 21st century. Thus HF radios are now capable of high-quality digital audio, as well as the exchange of files, and transmission of bi-directional data streams – albeit at rather low speeds. Despite these low speeds, the ability of HF radios to operate when other communications infrastructure fails or is absent had lead them to play an important niche role for governments, commercial operators, militaries, non-governmental organisations and humanitarian response organisations of many kinds. In the defence space in particular, HF is seeing a kind of resurgence as the vulnerability of satellites has become more apparent.

For this thesis, it is the ability of HF radio to facilitate communications over long distances, and in the absence of other communications infrastructure that is particularly interesting. However, the first step towards meaningful integration of HF radios into the Serval Mesh is to better understand the strengths and weaknesses of HF radios.

4.2 Theoretical background about HF radio

4.2.1 HF wave propagation

High-Frequency radio frequencies lie approximately between 3 and 30 MHz, corresponding to wavelengths of between 10 and 100 metres. These very long wavelengths allow HF signals to propagate over great distances. As HF radio signals refract and reflect off the ionosphere, they can propagate beyond the visible horizon, and thus provide much longer range communications than VHF and UHF radio systems.

Like any other radio wave, HF radio waves are subjecting to many physical phenomena, such as reflection and absorption, and it is important to understand, at least at a high level, how HF radio waves propagate in the atmosphere, because of the effect of these phenomena on the range and quality of the signal.

As described above, one of the key advantages of HF radio signals, is that can be reflected by the ionosphere, which spans from around 50 km in altitude to around 500 km [59, 101]. The molecules in the higher layers of the atmosphere are subjected to solar radiation, which ionises large fractions of these particles, that is, removes one or more electrons from them, causing them to become electrically charged. As the ionisation is dependent on incoming solar radiation, it varies with the day-night cycle. The day-night cycle and other phenomena also affect the effective height at which HF signals of a given frequency are reflected. The higher the reflection point, the greater the distance over which communications are possible, as the reflected signal is able to travel a greater lateral distance at a given angle of incidence.

Also, the amount of absorption of HF radio waves in the ionosphere layer varies with the day-night cycle, and is also dependent on the frequency of the signal. In general, lower frequencies are absorbed, i.e., attenuated more than are higher frequencies [59]. However, if the frequency is too high, then there is a cut-off point at which reflection ceases to occur, causing the signals to propagate into space, rather than be reflected back to earth. This limits the upper frequency – which, again, is dependent on the day-night cycle and prevailing space weather conditions – at which long-range HF radio communications are possible.

Whereas the above explanation has focussed on the propagation of HF radio waves via ionospheric reflection, there are also other modes of propagation of HF radio signals that can be used, depending on the circumstances, as listed below and illustrated in Figure (4.1).

1. Ground wave: HF radio waves can propagate near the surface of the earth for both land and sea. The wave travels for tens of kilometres, and the attenuation to signal is higher over land than sea. Over the open ocean, the range may reach to a few hundreds of kilometres. This mode is often used for marine communication. It is also of interest for communications links between isolated islands in the Pacific.

2. Direct wave (line-of-sight): HF wave can propagate directly from the ground to a flying object in the air, from air to ground, or between nearby objects on the ground, without the need of a reflection from the ionosphere. However, the range of communications is greatly reduced, especially where both communicating parties are on the ground, where local topographical obstacles may further limit the propagation of signals. Thus this mode finds more use in aviation, such as for communications between aircraft, and between aircraft and air traffic control.

3. Skywave (ionospheric reflection): This is the mode that was first discussed. It typically has a minimum range of several tens of kilometres, because of the large lateral distances the signals typically traverse before reaching the reflection altitude in the ionosphere. Range is typically between 40 km to several hundred kilometres, although under favourable conditions communications may be possible over thousands of kilometres.

4. Near Vertical Incidence Skywave (NVIS): Where an HF signal is aimed almost vertically at the ionosphere, the reflection will be detectable at relatively near distances. This is often used to provide communications between nearby locations where direct line-of-sight is blocked by some major topographical obstacle, such as a hill or mountain range.

4.2.2 HF radio as a digital carrier

The initial HF radios were restricted to analog communications, primarily analog voice. The analog transmission of information via HF radio has many limitations. One of the most significant of these issues is the quality of the audio transferred over the HF link. The difficulty of understanding HF analog audio varies considerably with ambient conditions, and inexperienced operators often have considerable difficult understanding the received signal. Improving how easily the audio from an HF radio can be understood, even

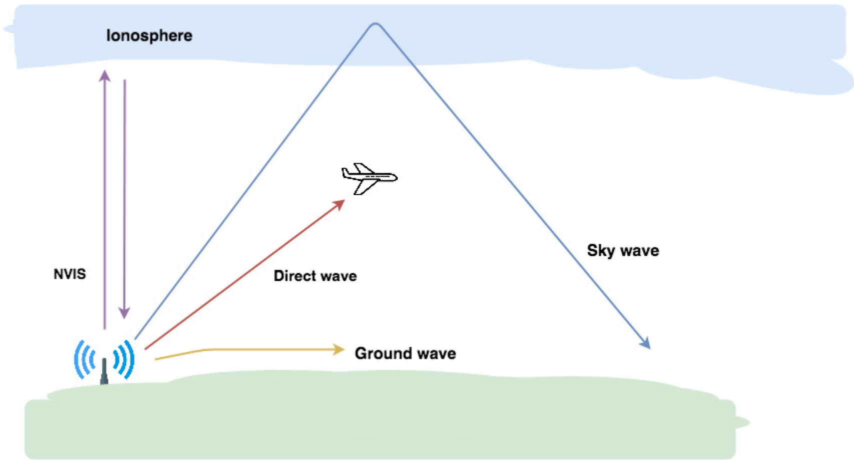


FIGURE 4.1: Four types of HF signal propagation, and which one is reflected by ionosphere layer.

by inexperienced operators, was one of many goals of HF digital transmission. Error-correcting audio codecs can be used on digital systems to obtain much clearer audio, including in conditions when analog audio would be completely incomprehensible.

The analog HF signal simply is a transferred electronic signal over the space, as a continuously modulated wave. While such a simple modulation scheme is quite possible to be utilised for HF communication, it is rather susceptible to multi-path fading, channel fade, and other sources of interference, which can both increase the background noise, and attenuate or distort the desired signal. Digital HF radio systems use advanced signal processing techniques to mitigate these problems.

Most digital capable HF radios, even those that do not support digital audio, support a standard called Automatic Link Establishment (ALE). With ALE, an HF radio unit continuously scans a set of channels for calls from other remote units. They also and periodically transmit sounding and identification signals that help the radios to determine the channel conditions, and select the best channel to use when attempting to establish a radio call to another HF radio. This provides an analogous service to the telephone system, where the operator needs only to know the ALE number of another party to establish a radio call with them. ALE also supports the transmission of text messages, however the effective data rate of this is very low, often as low as 1 to 10 bytes per second. Nonetheless, it represents a data channel that is available on many HF radios.

One challenge with ALE is that vendors implementations are not always fully interoperable. For example, in testing of Codan and Barrett HF radios, it was possible to establish ALE calls in one direction, but not the other.

4.2.3 Signal modulation

HF signals, like many radio frequency signals, is transmitted by modulating a continuous sine wave at a specific frequency. The analog or digital signals to be carried are then superimposed, i.e., modulated, over this signal, often using one of several common methods, such as amplitude modulation (AM), frequency modulation (FM) or phase modulation (PM). However, such simple modulations are limited in their information capacity on a given channel. Modern digital HF radios use more complex modulation schemes, which may, for example, use multiple narrow-band carriers, each of which may then be encoded using some variant of AM, FM or PM.

The particular methods used are not important for this thesis, only that these modulations allow higher speed communications, typically between 100 – 1200 bytes per seconds under good atmospheric conditions. Also of importance is that digital HF modes typically provide error detection and correction, providing the abstraction of a bi-directional serial data stream, similar to that of dial-up modems and other radio modems.

4.2.4 Benefits of digital HF radio

There are numerous benefits of digital-enabled HF radios compared with earlier analog-only HF radios, including those described previously:

1. Higher audio quality and improved ease of understanding of the audio.
2. Higher availability of service, as audio remains intelligible under more heavily degraded channel conditions than with analog audio.
3. The ability to transfer data, thus allowing more flexible, effective and efficient use of the medium.
4. Integrated error-correction, allowing for more reliable communications, especially under poor channel conditions.
5. The ability to automatically select from available channels, and to make automatic connection, such as to deliver email, results in greater utility and utilisation of the radios. Some systems also support QoS or other prioritisation techniques to support simultaneous mixed use-cases.

6. Many digital HF radios support robust encryption of both digital voice and data communications. Common encryption algorithms for HF radios include AES-256 and CES-128 [119, 178, 17].

7. Digital resources, such as images, audio and text can be transferred over many hundreds of kilometres using digital HF radios.

8. IP Network Connectivity: Some newer digital HF radios also provide IP capabilities and thus "internet over HF radio". However the data rates remain very slow, even compared with dial-up internet of the 1990s. Nonetheless, where such connectivity is required, it provides a robust fall-back solution.

4.3 HF radio as a way of long-distance communications in remote areas

Although mobile phones and satellite based communications are now globally widely available, HF radio communication is still has a part to play in the global telecommunications systems, because of its ability to work when other solutions fail.

Residents who live in the cites have many options to utilise any traditional communications technique to be in touch with others. The most popular technique is the cellular phone telecommunication service that is available extensively in almost every city in the world.

However, the communications options available to residents in remote areas are so limited, and it is tough for those in the remote areas to communicate with nearby community members or with their friends in big cities hundreds of kilometres away from where they live.

In a big country like Australia where the population density rapidly drops off away from the few major cities, especially in the outback, HF radio was the traditional telecommunication solution used by remote communities, owners of 4WD vehicles in the outback and others working in these remote areas. HF radio was used to fulfil this role long before the availability of satellite phones, and there are many communities for HF radio owners who communicate continually to provide help to someone in need, social relationship, items delivery, and even requesting emergency medical treatment like Royal Flying Doctor Service that still operates an HF radio channel for requesting medical help [107, 184].

HF radio provides historically provided much useful information to the residents in the Outback, and it is free of charge except paying for the licence [98, 24]. Even today, there are still HF radio to telephone gateways in Australia, that make it possible to use an HF radio to call any mobile or landline phone number, or even a satellite phone. However, although such solutions exist, they are significantly handicapped in their utility by privacy, as the telephone call is broadcast without encryption over many tens of thousands of square kilometres, and also by the limited number of simultaneous phone calls that these gateway systems can support.

4.4 Application of digital HF radio in remote areas

Besides the ability of HF radio to providing voice communication over a long distance, digital HF transmission adds another dimension to the HF communication solution space, because it is quite possible to exchange various digital formats via the HF link, which increases the range of applications to the individuals who live in remote and isolated areas. This provides important advantages in a number of use-cases, which is why one of the goals in this research is to allow the Serval Mesh to take advantage of this capability. Some of the potential use-cases include:

1. Humanitarian aid communications: Many humanitarian agencies and non-governmental organisations perform various relief activities to support the communities affected by natural disasters of many kinds. In such situations, existing communications infrastructure is expected to be damaged or destroyed, making it hard to coordinate the relief process on the ground. Thus, HF radio becomes attractive to deploy in these areas, and rapidly facilitate basic communications within and into and from such areas.

   HF radio can fit the operational requirements, and it bridges the gap between residents, field teams and emergency response centres for better exchange of information and managing of rescue and relief operations.

   Also, humanitarian teams can form a kind of independent digital network-based HF radios between them to rapidly exchange urgent requests for help or provide remote communities with necessary food, medicine and live saving tools.

   Team members and volunteers need to exchange information like text, photos, data sheets with remote offices, and fortunately, this can be achieved via the Serval Mesh network, with digital HF radios offering the promise of being able to do so over much greater distances.

2. Healthcare services: People who live in remote areas also need health care services, and they need to keep their doctors updated with current health status, but the communications become very hard, if not impossible, when there is no coverage for the cellular network. Again, HF radio can, and has historically taken this place, in Australia and elsewhere. For example, HF radio has been employed by Royal Flying Doctors Service for a long time to provide Telehealth consultations to many rural areas over analog HF radio [146]. Patients employed voice radio to describe where does it hurt based on a chart to better guide the doctors on the other end, as shown in Figure (4.2)

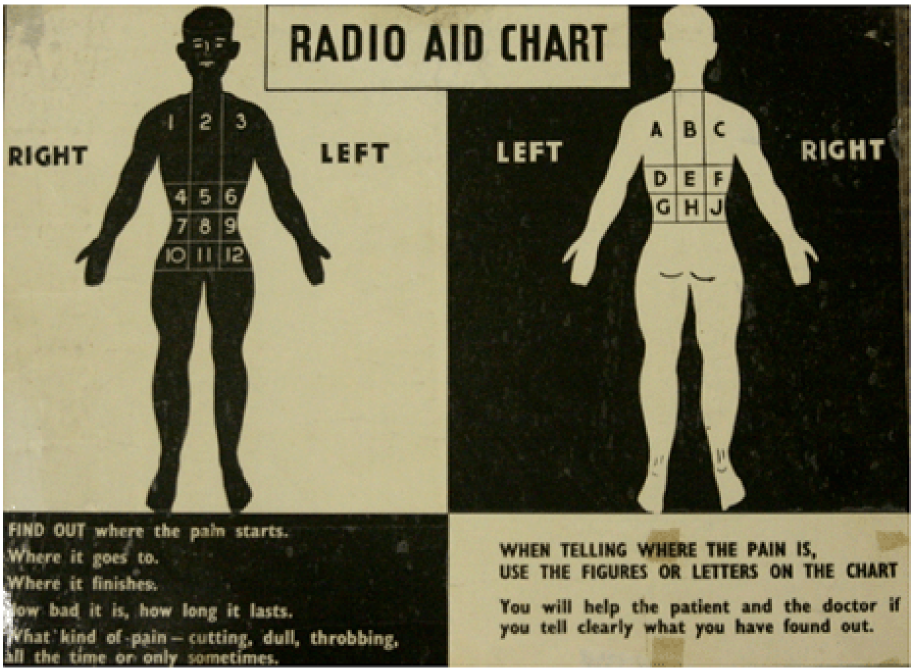


FIGURE 4.2: The "Where does it hurt?" chart, which was presented in 1951 by a member of Royal Flying Doctor Service to allow patients to describe via HF radio where is the location of pain in the body [146].

Now that digital communications technology has become both ubiquitous and highly capable. Many services, including healthcare, are connected to the internet, and many medical staff members utilise many online applications to communicate with patients or store their medical data. Digital HF radio can provide access to the internet and for limited applications, and can improve the quality of health service and the response to the life threatening situations [47, 34], although the very low transmission speed of digital HF links do create problems for modern interactive web-based interfaces that assume orders of magnitude faster transmission.

3. Bushfire fighting and rescue efforts: Bushfires cause severe damage to both the environment and infrastructure. As we have seen in Australia in the bushfires that raged between December 2019 to January 2020, where various remote areas that where cellular coverage was disabled by the bushfires. Residents are now often warned by authorities that there will likely be no cellular coverage when bushfires comes to an area, which also leaves the rescue and response teams without reliable telecommunications services.

   Digital HF radio can also contribute to relieving these situations. For example, it can be used to broadcast graphics images and graphics weather maps about the geography of the affected areas, establishing links between air and land rescue teams, manage firefighting operations in different places, keep both authorities and rescue teams in contact and reduce the time of responding to bushfire [110, 167]. Here the lack of wide-spread use of HF radios limits its effectiveness, making integration with the Serval Mesh particularly appealing, as it would allow people based in such situations to use their existing smart-phones to receive such data, without requiring each person to have a functioning digital HF radio.

4.5 Well-known HF radio vendors and products

There are many vendors of HF radios, who produce a wide variety of devices with differing capabilities and targeting markets. Some of them are focussed on military markets, including in the Pacific, but which are rarely seen in civilian use, such as Harris. However, others, such as Codan and Barrett who will be discussed below, are much more prominent in the Pacific and in the humanitarian sector generally. There are several other vendors, including Icom, Yaesu and Samyung, which are also rarely seen in the Pacific, which we will not focus on for this reason.

The newer generations of HF radios are digital devices. HF radios began as relatively simple analog devices, with what might retrospectively be called Hardware-Define Radios (HDR). Now, however, almost all HF radios are based on Software Define-Radios (SDR), and contain embedded processors. These innovations allow both digital communications modes, as well as more sophisticated features, such as remote interaction via Wi-Fi.

4.5.1 Codan HF radio

Codan was established in South Australia more than 60 years ago, and it is one of the global leading innovating manufacturers in HF technology. Codan has historically placed considerable resources into producing highly capable, reliable and innovative devices, which has helped them to maintain significant market share in the harsh Pacific environment [50].

Codan's target markets reach into many sectors, including defence, NGOs, security forces and civilian communications.

Codan launched its Envoy smart software-defined radio series in 2012, which includes both 2G and 3G ALE features. The Envoy can be see in Figure (4.3). The Envoy radio is a very reliable voice and data communication device, and it comes with many digital HF radio features. This includes a 2,400 bit per second software-based modem that can be activated with the appropriate license from Codan, and does not require the addition of any further hardware to operate.

Codan have kindly supported the work in this thesis, through the loan of two Envoy radios.

4.5.2 Barrett HF radio

Barrett company is another Australian HF radio company, established more than 40 years ago. In the intervening time, Barrett have introduced many HF and VHF radio products that meet different long and medium radio communications. Barrett devices are often somewhat lower priced than those from Codan.

Barrett have included internet connectivity and other advanced features into their radios in recent years.

Barrett radios are now in use in more than 150 countries around the world, and Barrett's clients include governments, militaries, civil security, coast guard, humanitarian organisations and individuals [49]. The combination of voice, fax, data and personnel tracking capabilities at an affordable price has helped to make Barrett's devices popular with customers, such as their model 2020, 2060 & 2090 radios. Figure (4.4) shows a Barrett 2060 radio with a telephone interconnect.

FIGURE 4.3: This image has been removed due to copyright restriction. Available online from [48]. Codan Envoy HF radio is one of the Codan products, and this type can be integrated into Serval Mesh.

Barrett have kindly supported the work in this thesis, through the provision of two of their HF radios.

4.5.3 Harris HF radio

Harris, now known as L3Harris following their merger with the L3 company is one of the largest manufacturers of HF radios. It has a long history in providing many governments, aid organisations, space agents and militaries around the world with more tactical communication solutions and devices [132].

L3Harris has a wide range of HF radio types, and they are mostly targeting the defence sector. USA army is the primary client for many types of Harris HF radio, and the products are equipped with the most up-to-date and sophisticated technologies to provide an excellent performance to armed

(A) This image has been removed due to copyright restriction. Available online from [1]. Barrett 2060 HF telephone interconnect.

(B) This image has been removed due to copyright restriction. Available online from [28]. Barrett 2020 email fax and internet connectivity.

FIGURE 4.4: Different models of Barrett HF radios.

FIGURE 4.5: This image has been removed due to copyright restriction. Available online from [131]. L3harris Falcon III HF/VHF radio with high data transmission capabilities.

forces at different extreme situations, like Falcon III HF radio (Figure 4.5) [131].

Harris radios do not seem to be widely used in the civilian space in the Pacific, and sensitivities around their primarily defence markets meant that it was not practical for us to make use of Harris radios in the work described in this thesis.

4.6 Key challenges against utilising HF radio

Like many technologies, HF radio has both strengths and weaknesses. Its strengths are fairly obvious: The ability to communicate over very long distances, without depending on any other terrestrial infrastructure, and the long-term role it has played in the Pacific means that there are many HF radio installations in the Pacific, and that donors are well accustomed to installing and upgrading HF radio installations in the region. However, it is also important to consider the relative weaknesses of HF radios for use in the Pacific, in particular:

1. Expensive: The HF radios are relatively expensive communication devices, in the context of the small economies and low incomes of the Pacific. An HF radio typically costs between $5,000 and $15,000 [151], and then typically requires a small building with batteries, solar panels and antenna masts. Complete installations often cost between $15,000 and $30,000, after these factors are taken into account.

   This greatly limits the number of deployed HF radios in the region, compared with, say, mobile phones or hand-held UHF radios, which can be purchased for a few hundred dollars or less.

2. Size & weight: HF radios are relatively large and heavy compared with many other communications devices, such as mobile phones, UHF or VHF hand-held radios [44].

   Typically, the weight of HF radio is between 5 and 10 kilograms, up to 50 times heavier than a typical mobile phone. "Portable" HF radios typically come in the form of a large and heavy back-pack, and are generally only practical for militaries, where a soldier can be given the task of carrying it around.

Even ignoring the weight of HF radios, their relatively large size can be problematic, especially as many houses and buildings on remote islands in the Pacific in particular are very small.

3. Training: Effective use of HF radios requires more training than does a mobile phone or UHF or VHF hand-held radio. Also, it takes some practice to be able to readily understand analog voice carried over HF radios, due to the narrow channel bandwidth and substantial distortion of the signals that is caused by many factors [148].

4. Licence: Unlike mobile phones and many hand-held UHF or VHF radios, a special license is required to operate in the HF radio bands. This introduces costs, as well as complexity that together add to the barriers of use for HF radio [5].

5. Quality of communication: The HF radio uses the ionospheric reflection to facilitate communications over distance, as shown in Figure (2.1). This mechanism is prone to a variety of forms of interference and distortion. Solar activity, and the day-night cycle significantly impact on the behaviour of the ionosphere, including the reflection and refraction of HF signals. This means that users can't simply select fixed radio channel to use at all times, but must take make informed decisions about the best channel to use at any particular time, and even then, may still have to suffer poor audio quality [197].

6. Difficult to Share: In contrast with cellular networks where the towers can be used by many people at the same time, HF radios can typically be used by only one person at a time. Related to this, this means that in comparison with cellular networks where if you wish to call someone, they are probably able to pick up their phone and answer, calling someone on an HF radio requires that both of you arrange to be at the radio at the same time, or for there to be an operator at the radio who can send for the called person. Also, it is possible that the operators of HF radios may be reluctant to share the radio they control for a variety of reasons [134]. All of this tends to limit the utility of HF radio for private correspondence among members of the public.

7. Low bandwidth: Even where HF radios support digital communications, the available bandwidth is typically abysmally small compared with other communications systems. For example, Wi-Fi or 4G cellular typically provides hundreds of megabits per second, 3G cellular

up to tens of megabits per second, and even 2G cellular systems are able to approach 1 megabit per second, but the fastest civilian HF radio systems are limited to between 2,400 and 9,600 bits per second [139]. That is, HF radios are typically around 10x to 100x slower than even 2G cellular systems, and many thousands time slower than more modern communications channels.

Newer ALE communications capabilities mitigate this slightly, such as 3G and 4G Automatic Link Establishment (ALE). However, these capabilities, which should not be confused with 3G and 4G cellular connections, are still typically limited to less than 10 kilobits per second in practice.

8. Antenna Size: HF radio typically use wave lengths of between 10 and 100 metres. This means that very large antennae are typically required, especially for long-range communications [232]. These large antennae are also a liability when cyclones strike, as they must be lowered to the ground to avoid damage – a task that is not infrequently overlooked, resulting in the destruction of antennae at precisely the time that they are needed most.

9. Portability: As already discussed, HF radios are not particularly portable in comparison with many other radio types [13]. Their large size and mass makes them portable more in the literal sense of the word, meaning that they can fit through a door way, rather than in the idiomatic sense of being easily carried around.

   For the best performance, HF radios require not only large antennae, but also require relatively large amounts of energy, up to 125 Watts, which means that either large batteries are required, or that they must be recharged very often if an HF radio is to be used frequently. For this reason most HF radio installations in the Pacific tend to be fixed installations in buildings, rather than portable [52], which further limits their utility for the general public.

10. Unattractive: These problems together work to very much limit the appeal of HF radios to the general public, compared with smaller, lighter, faster, more powerful and flexible solutions, such as mobile phones [58].

4.7 Aid agencies and NGO's still supply HF radios

Although HF has several weaknesses and strengths, we observe that foreign aid agencies still routinely deploy HF radios in many areas of the world to coordinate operations and mitigate the effects of the disaster. This is particularly apparent in Pacific Island Nations where there is often no alternative obvious to the funders that can meet their requirements. This is partially driven by the funding cycle of foreign aid, where high capital cost is more tolerable than committing to many years of even modest ongoing funding. This makes buy-and-forget (from the aid agency's perspective) HF radios much more attractive than subscription-based satellite services, even if the total lifetime cost of the satellite solution were lower.

For this reason, it makes sense to find ways to make HF radios more effective in this role, so that these purchases can have greater effectiveness and return on investment for the donor organisations and their funders. We believe that it is possible to maximise the services of HF radio provided by aid agencies to support the relief operations and the residents of affected communities if we can integrate Serval Mesh with the HF radio, which we have successfully accomplished at the end of the research.

4.8 Rise and fall and rise of HF radio

Following its initial introduction, the use of the HF radio grew for many years as there were no competitive alternatives. However, the widespread accessibility to cellular telephony, Internet access, satellite-based communications and other advances in telecommunications has greatly diminished the appeal of HF radio. The vendors of HF radios have managed to protect their markets to some degree by improving the capabilities of HF radios, including through adding digital features, such as email over HF and digital voice. However, this has been only partially effective. Then, more recently, there has been a limited resurgence in interest in HF radio, primarily among military users, who have come to realise the vulnerability of satellites. However, the slow but steady decline of the use of HF radios in the humanitarian space is continuing. This sequence of rise and fall and rise of HF radio is now considered in a little more detail.

4.8.1 HF was initially the only solution

For many decades, HF radio was the only effective choice for over-the-horizon wireless telecommunication, for both "normal" and emergency situations [253]. It was quickly adopted as an effective solution to a wide range of problems, and many services were built upon HF radio. For example, in Australia, the Royal Flying Doctor Service (RFDS) that provides medical services to people in rural areas since 1928, has been receiving calls and providing medical assistance using HF radios since its inception, and continues to do so to the present day. The school of Air, also in Australia, even provided school education for children living in remote areas of Australia until the early 2000s. HF radio enabled these applications, as it was the only practical technology for these use-cases for several decades.

4.8.2 The evolution of HF radio

During the intervening years, HF radios have not remain unchanged, however. HF radios have generally passed through four generations since their introduction, as shown in Figure (4.6) [253]. Each generation delivered one or more significant improvements, e.g., through improved voice quality, or the ability to transmit data. The four generations of HF radios are:

1. First generation (1G): This earlier generation of HF communications covers the approximately between the 1920s to 1970s. The very first of these used spark gap transmitters, and were thus limited to morse code, rather than voice. These then evolved into the narrow-band heterodyne and similar HF radios that supported analog voice. Power consumption at the beginning of this generation was very high, often in the kilo-Watt range, before gradually reducing to between 10 and 200 Watts [115, 18]. These radios typically required highly trained operators to operate these complex early devices.

2. Second generation (2G): This generation appeared in the 1980s and 1990s. These radios were typically hybrid analog/digital devices, often with a digitally controlled analog front-end to the radio. In the later part of this time, Automatic Link Establishment (ALE), and the 2nd generation version of ALE in particular, became available that greatly simplified the process of establishing an HF radio call [267, 162]. This was in large part due to the ability of these radios to scan the conditions

FIGURE 4.6: This image has been removed due to copyright restriction. Available online from [253]. Four generations of HF radio.

on the various channels available to them, so that a call could be automatically placed on the best channel at that time, and that the receiving radio would also be scanning all of the available channels, allowing it to detect and receive the call. These factors, together with digital controls on some units, helped to reduce the complexity of use of these radios. Some 2nd generation HF radios supported the use of simple data modems, to allow the transfer of digital data.

3. Third generation (3G): The third generation of HF radios is primarily focused with the transition to fully digital radios, where waveform generation is performed by software defined radios (SDRs), which facilitates the use of advanced digital waveforms. This is the first generation where digital voice became practical, which greatly improved the end-user experience. It also bought with it the 3rd generation of ALE, which reduced the time required to make a call, as well as greatly improved

the data capabilities of these devices [253, 261]. 3G ALE allows transfer of data at up to 9,600 bits per second. This generation of HF radio also often includes either an optional or built-in data modem capable of 2,400 to 9,600 bits per second. The use of advanced digital waveforms and digital signal processing enabled them to support communications even during relatively poor channel conditions, by improving the extracted signal to noise ratio (SNR), and/or using waveforms that required a lower SNR to operate [267, 32, 115].

Many models also use their relatively high-performance digital data transmission to provide advanced digital services, including effective email over HF, or even (rather slow) internet access [65, 262].

4. Fourth generation (4G): The fourth generation of HF radios include features such as cognitive radio, wide band receivers and/or wide-band transmission [260, 188]. These features enable much higher data rates, up to 64 kilobits per second, and the ability to simultaneously receive transmissions from multiple channels [166]. 4G ALE smart radios acquire knowledge about the geographical environment, and compares it with the internal state policies, then makes the necessary adjustments to the protocols and operational parameters to gain the best transmission performance [248, 166].

4.8.3 Competition from satellite

In the past 20 years, HF radios have seen increasing competition from satellite-based services, as the use of geostationary satellites provides many of the same advantages of HF radio, primarily the ability to communicate from very remote locations. However, the cost of satellite-based services is often much lower than the cost of an HF radio. Also, satellite-based services typically use much higher frequencies, and thus require much smaller and simpler antenna equipment, and are able to support digital services with thousands times more bandwidth than HF radios. The advent of satellite mobile telephone networks further eroded at the remaining use-cases where HF was dominant.

Yet despite this situation, HF radios continue to be used and deployed in the Pacific for various reasons. One key reason is that foreign aid agencies like to buy equipment and then not be obligated to provide on-going subscription costs, even if it would be cheaper overall. This dysfunction in the humanitarian aid system means that HF radios continue to have a competitive advantage over satellite-based services in the Pacific region.

Also, separately from the humanitarian use-cases, the demonstration of several geo-political rivals of their ability to attack and destroy satellites has created an resurgence of interest in HF radio as a fall-back capability for military use.

4.9 Summary

This chapter has explored HF radio, its strengths, weaknesses, and some of the history of its use. This history has shown how HF radios have evolved into digital communications devices, although they remain profoundly limited in comparison with various alternatives. However, the combination of their ability to facilitate communications without dependence on other terrestrial infrastructure means that they remain suitable for use in remote area and post-disaster communications.

Further, because of the vagaries of the international humanitarian aid system, it remains easier in many cases to obtain funding for the purchase or upgrading of HF radio installations, compared with the various alternatives. This means that it is attractive to find ways to make better use of HF radio in the Pacific region. In particular, this thesis is concerned with the potential of marrying the long-range communications and fundability of HF radio infrastructure, with the ability of the Serval Mesh to make it easy and cost-effective for people in remote areas and following disasters to be able to communicate using their mobile phones.

Therefore the following chapter begins to explore the frameworks in the Serval Mesh that exist to support the use of low-bandwidth radio systems, like the 3rd generation digital HF radios that are commonly found in the Pacific, in preparation for adapting LBARD for integration with HF radios.

Chapter 5

Serval LBARD and its intended use-cases

5.1 Introduction

Before the adaption of the Serval LBARD framework to support HF radios can be considered, it is important to first review exactly what Serval Rhizome is, and what its intended use-cases are. Low Bandwidth Asynchronous Rhizome Demonstrator (LBARD) is one of the protocols that included in Serval, and it works with other protocols to assist bundles transfer between two or more nodes in the mesh network environment.

5.2 Addressing the challenges of low-bandwidth unreliable packet radio interfaces

As its name suggests, LBARD was designed to deal with transport situations where the bandwidth is very low, like UHF or VHF packet radio links, where the bandwidth is too low to support the Serval Mesh's existing mechanisms for delivering Rhizome bundles.

Those existing mechanisms are primarily based around encapsulating Serval Mesh Datagram Protocol (MDP) packets in Internet Protocol (IP) packets, and using normal IP-based links, primarily Wi-Fi, in the case of the Serval Mesh phone app. The approach of encapsulating MDP in IP packets works in that case, because the bandwidth of Wi-Fi is high enough to support this, typically many mega-bits per second.

In contrast, the UHF and VHF packet radio links that are feasible to incorporate into the Serval Mesh, are typically capable of no more than a few tens of kilo-bits per second, i.e., no more than a few kilo-bytes per second. Often the available bandwidth is much lower, either because the channel must be shared by many devices, or because the channels have even lower usable bandwidth than this. As a result, it is not uncommon to find links that are capable of perhaps a few hundred bytes per second per node, or even less. At these low data rates, the overheads of IP encapsulated MDP packets becomes substantial, and it is desirable to reduce this overhead.

A further problem that occurs when using distributed packet radio links, is that the probability of packet loss is often very high, especially when nodes are near the limit of their communications ranges. In prior testing of the Serval Mesh Extenders, for example, it was not uncommon to see packet loss rates between 25% and 75%. Wi-Fi in contrast includes mechanism that act to prevent and to mask packet loss, precisely because such high packet loss rates significantly interfere with many networking protocols. For example, TCP often interprets packet loss as network congestion, resulting in the progressive reduction of usable bandwidth.

It is not simple, however, to implement the methods used by Wi-Fi on these kinds of low-bandwidth and peer-to-peer packet radio bearers. For example, Wi-Fi uses access points to coordinate, among other things, the dynamic reservation of time slots in which packets, so that the probability of simultaneous transmission is greatly reduced, thus helping to eliminate this significant source of packet loss on unregulated wireless networks. However, distributed packet radio networks are not able to use this approach, as there is no "controller" to perform this coordination. Also, even if such a controller could be elected, the network topologies are more complex, and the hidden sender problem becomes significant, making it very difficult to prevent packet loss through collision.

However, these packet radio links also enjoy certain natural advantages. Unlike Wi-Fi, which attempts to conceal the broadcast nature of radio communications, it is possible to use this broadcast characteristic to allow all nodes to listen to transmissions by all other nodes on the channel, to more rapidly replicate Rhizome bundles. That is, it is possible to broadcast the pieces of a Rhizome bundle, and have it received by all nodes that can receive those transmissions. Only those packets which could not be received by each specific node need be separately transmitted. This helps to maximise the performance that can be extracted from the channel.

Enabling such broadcast reception on a reliable basis in the face of high rates of packet loss requires specialised protocol design that can accommodate the peculiarities of this, again pointing to the need for a purpose designed protocol that can exploit the natural advantages of such packet radio links, while mitigating their weaknesses as much as possible.

It is important to be able to achieve this goal, because while Wi-Fi is a good communications bearer for short-range communications, there is the need for enabling longer-range communications using the Serval Mesh, so that the distances between villages, and ultimately, between widely separated islands in the Pacific can be bridged. This was the motivation for the creation of the LBARD protocol and software, so that the Serval Mesh can facilitate communications over greater distances. It forms an important component of the Serval Mesh Extender devices, which include a 915MHz UHF packet radio, to enable communications over several kilometres, and is the natural choice of Serval Mesh component to be extended in order to support digital HF radio to increase the range of the Serval Mesh to be able to reach between widely spaced Pacific Islands.

5.3 Desire for automatic configuration

The LBARD software is responsible for supporting all of the different low-bandwidth communications bearers that are supported by the Serval Mesh. This means that it needs to know which type of radio is connected to it, at any particular time. While this could be handled through a configuration file or similar mechanism, this is problematic for its use in practice.

First, the Serval Mesh Extenders internal radio bay allows swapping out of the radio module in the field. If LBARD required reconfiguring whenever this was performed, it would complicate this process.

Second, the Serval Mesh Extenders are also designed to be easily connected to external radios using the 25-pin radio and power connector. This is how it is intended that Serval Mesh Extenders would be connected to HF radios, for example. This means that a Mesh Extender, and thus LBARD, may find themselves connected to different radio types at any time. For example, if the Mesh Extender connected to an HF radio were to fail, it may be replaced at short notice by another Mesh Extender. Or alternatively, there may not be enough Mesh Extenders to control both the HF radio, and still provide complete communications coverage within a given village. Thus the Mesh Extender may find itself moved between multiple locations, even on a daily basis.

Third and finally, when deployed in a disaster zone situation, it is highly desirable to keep the system as simple as possible to deploy, redeploy and reconfigure as required. Therefore avoiding the need for any configuration or reconfiguration when changing location or role is highly advantageous, if not an outright necessity.

LBARD was therefore designed from the outset to automatically detect the type of radio it is connected to, so that these problems can be avoided, and the Serval Mesh Extender device can effectively be operated on a "plug and play" basis.

While not specifically an LBARD feature, the combination of LBARD to control radios and the inclusion of the ordinary Serval Mesh Rhizome synchronisation protocol over Wi-Fi, this enables Serval Mesh Extenders to automatically form flexible heterogenous networks, where the Rhizome over Wi-Fi bearer acts as the common interface that allows the exchange of Serval Mesh traffic sent over different communications bearers. Thus LBARD forms the central component in enabling the easy construction and free modification of such networks, as shown in Figure (5.1). This is a considerable strength of the system, as it abstracts away the otherwise significant problems and complexities of interconnecting different packet radio types, frequencies and modulations into coherent, resilient and functional networks.

5.4 Overview of LBARD protocol

The LBARD protocol is designed to deliver Serval Rhizome traffic over low-bandwidth and unreliable communications links.

Serval Rhizome in turn, is the Serval Mesh's store-and-forward delay-tolerant networking (DTN) protocol, that is used primarily in the Serval Mesh for the delivery of text messaging, via Serval MeshMS protocol, and social media and micro-blogging services, via the MeshMB protocol. Serval Rhizome is also used for file transfer and the distribution of software and firmware updates for the Serval Mesh itself, allowing for a rich and evolving set of capabilities on the Serval Mesh [88, 88, 79, 82, 81].

The fundamental data unit of the Serval Rhizome protocol, is the Rhizome Bundle, which consists of a meta-data "envelope" called the manifest, and an optional payload. That is, a Rhizome Bundle always consists of a manifest, and may or may not contain a payload. The manifest must follow strict structural requirements, including that it must not exceed 1 KiB in size. The manifest contains the sender and recipient identities where required, and is cryptographically self-signed to ensure that it cannot be modified by malicious parties in transit.

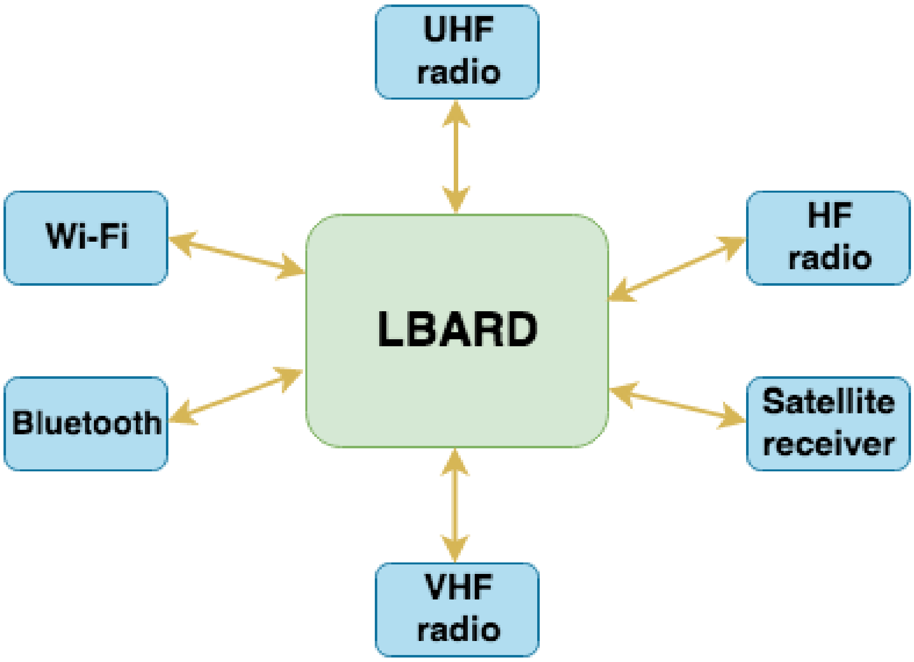


FIGURE 5.1: LBARD effectively acts as the "network glue" that allows Serval Mesh networks to be built using a wide diversity of communications bearers. That is, it abstracts the underlying communications bearer types to provide a single logical view of the network based on Rhizome Bundles. In this regard, it performs a very similar role to that of the Internet Protocol, which allows the inter-connection of many different communications bearer types. The main difference being that LBARD is designed for much lower bandwidth and less reliable communications bearers than the Internet Protocol is typically used for these days.

The overall operation of the LBARD protocol is relatively simple, with the following key functions:

1. The discovery of neighbouring nodes that are directly reachable over the communications bearer.

2. The efficient discovery of the set of Rhizome Bundles that each reachable neighbour has already received, and the version of those bundles, using the TreeSync protocol which is described in chapter (6).

3. The prioritisation of which Rhizome Bundle should be next sent to a given node, potentially taking a wide variety of inputs into the determination of the prioritity [136], to ensure that the most important bundles are delivered as soon as possible.

4. The transmission of Rhizome Bundles over the communications bearer.

5. As the typical communications bearers used by LBARD support only small packet sizes, typically < 256 bytes, LBARD is responsible for the fragmentation and reassembly of Rhizome Bundles that are sent over the bearer. The fragments of Rhizome Bundles are referred to as *pieces* in the LBARD protocol.

6. Tracking of the progress of transmission and reception of pieces of bundles, and managing retransmission of pieces that have been lost due to packet loss, including where bundles are being received by multiple nodes.

7. Optimisation of the case where multiple senders are able to cooperatively transmit a given bundle to a neighbour which has not yet received it.

From an operational perspective, LBARD effectively alternates between listening for arriving packets and processing them, and determining when it is next able to transmit a packet, and when that time arrives, assembling and sending a packet containing a combination of house-keeping and synchronisation data, as well as one or more pieces of the Rhizome Bundle that currently has the highest priority for transmission.

Preventing over frequent transmission of packets plays an important role in this process, as it helps on the one hand to minimise the probability of packet collisions if packets are sent too frequently, but on the other hand to make the most use of the usually meagre bandwidth of the channel by not reducing the packet rate beyond that necessary to avoid excessive packet loss through collisions. This means that the packet rate of LBARD instances on a shared channel will vary based on the number of LBARD instances transmitting on that channel, for example.

5.5 Flag-Ship Use-Case: Connecting Pacific Island communities

LBARD is designed to make it possible to incorporate a wide variety of communications bearers into the Serval Mesh, so that it can be used in a wider range of real-world situations. The primary intended use-cases are enabling communications post-disaster and in isolated communities in the Pacific.

These two use-cases share substantial commonality, in that both are characterised by the need to easily and cost-effectively deploy resilient communications networks in rather difficult circumstances. Indeed, the intersection of these two use-cases is substantial with many remote areas in the Pacific lacking communications in the aftermath of disasters. If resilient communications can be provided to these areas before disaster strikes, then this is all the more advantageous.

It is helpful to make this more concrete, by considering a specific example of where the Serval Mesh could be deployed. The island of Efate in Vanuatu, where previous field work with the Serval Mesh has been performed is used to provide this example, including in the village of Pang Pang, as shown in Figure (5.2).

FIGURE 5.2: Serval team were piloting Serval Project in Pang Pang, Vanuatu, and photos were taken during the process of installing a Mesh Extender at the local community there with the help from the local villagers.

Efate is one of the larger islands in Vanuatu, approximately 40 km $\times$ 30 km in size, with a number of smaller out-lying islands. The capital city of Vanuatu, Port Vila, is located in a natural bay on the southern side of the island, and that faces East. Port Vila has a population of several tens of thousands, and is by far the largest population centre on the island. Dotted around the circumference of the island are a number of villages, typically with a few hundred people each, and spaced several kilometres from one another. The island enjoys a tropical maritime climate, with high rainfall, and is typically impacted by several cyclones per year. The topography is very hilly, and vegetation cover is extensive, dense and tall over most of the island, complicating radio communications.

Many village areas have relatively cleared areas in and around where most houses are located, making Wi-Fi coverage within a village feasible, using one or more Serval Mesh Extenders. However, it is also not uncommon for smaller satellite settlements to be located some distance away from the central area of a village. Also, many villages span distances of the order of a kilometre or so, meaning that Wi-Fi links alone are unlikely to be sufficient. Careful placement of Serval Mesh Extenders with UHF packet radios can in many cases be used to establish links between such isolated houses or satellite settlements, and the main village area. However, even this can be difficult, due to the tall dense vegetation, that effectively limits the range of the UHF packet radios to a few hundred metres, unless they can be located high enough to clear the surrounding vegetation and other structures.

Linking the villages to one another, or to Port Vila, however, requires a different approach, as the distances are too great. VHF packet radios would be an option in some cases, being able to provide a range of upto 10 or 20 km under good conditions, and probably of the order of 1 km if they cannot be placed clear of the vegetation. Thus VHF packet radio is also not a complete solution, and a longer-range communications option, such as HF radio, would be required to ensure connectivity among all communities on the island.

If a long-range communications bearer, such as HF radio, were incorporated into the Serval Mesh, then this would allow the construction of heterogeneous networks that use the lower-cost UHF or VHF packet radio options where possible, and yet allows connection over longer distances as well. For example, Efate could conceivably covered using such a heterogeneous Serval Mesh network, as depicted in Figure (5.3). Again, the ability of LBARD to abstract away the specific details of the different communications bearers, and allow their easy interconnection is a key enabler of this, and one that should not be under-estimated: UHF, VHF and HF radios are already present in Vanuatu in substantial numbers, but are not currently able to form such a comprehensive integrated network.

Breaking this down, there are several sub-cases internal to this use-case:

1. *Communications between one or two adjacent communities.*

   Typically neighbouring communities are less than 10km apart, and there is often substantial relational links between such communities, including relatives of extended families being spread among such communities. For example, on Efate, the villages of Pang Pang and Epao are

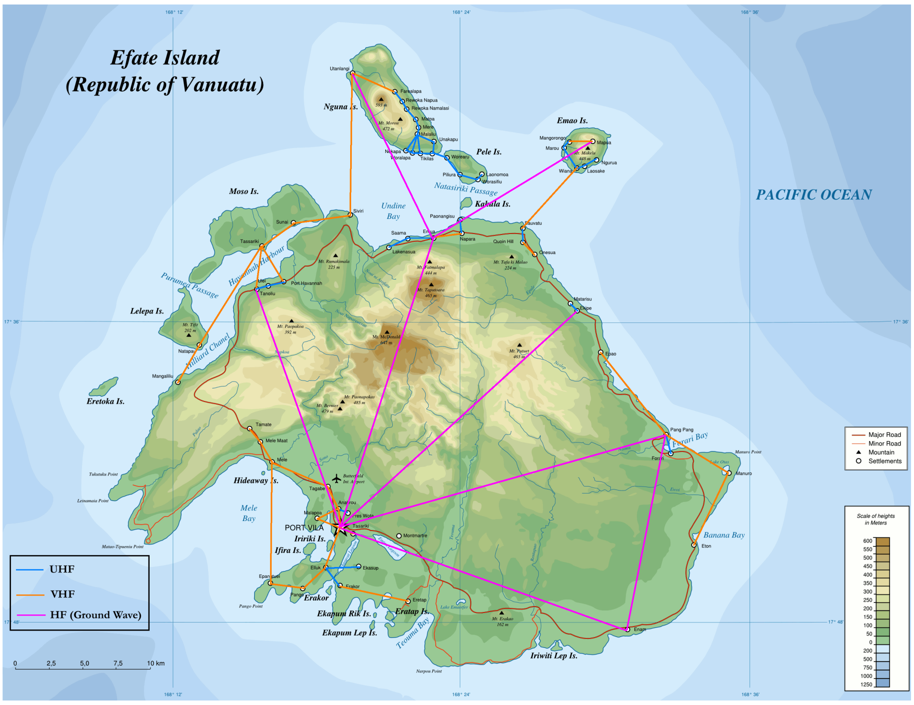


FIGURE 5.3: A suggested UHF/VHF/HF radio communications network on Efate and surrounding islands. It shows a decentralised hybrid links to assist local residents in connecting to any source [98].

located several kilometres apart along the eastern coast. The local topography means that while Epao has cellular coverage, most of Pang Pang is in a cellular shadow, making it difficult for the communities to communicate with one another. It is not an uncommon site to see community members walking the several kilometres between these two communities. The provision of reliable communications between these communities could reduce the need for this time and energy consuming activity, as well as support more regular and convenient communications within and among these communities.

Within each community, Wi-Fi has been demonstrated to be a feasible communications bearer, however the combination of distance, vegetation and topography means that even UHF packet radio is not able to connect these two communities. Careful placement of Mesh Extenders above the vegetation may, however, make it possible to link these communities using VHF packet radio, or failing that, HF radio could be used.

2. *Communications between communities in one island.* More generally, there are multiple communities that are located tens of kilometres from one

another. In these cases, either VHF packet radio or HF radio would likely be required, in order to span these distances – especially where the presence of mountains prevent direct line-of-sight communications.

3. *Inter-Island Communications* Many of the smaller islands surrounding Efate also host communities. These may be similar or longer distances from the nearest community on Efate, as the distance between communities on Efate. Somewhat counter-intuitively, connecting these communities is in many cases easier than connecting the communities on Efate, because the ocean surface presents a clear transmission path, without barriers such as mountains or dense vegetation. Also, as most communities in Vanuatu are located at the coast, there is often line of sight from these villages across the water. Nonetheless, the distances involved are typically longer than can be met using UHF packet radios, and either VHF or HF radio would be required. HF radio in particular, can perform very well over open ocean, as it forms a very efficient ground plane over which the signal can propagate.
4. *Communications across different provinces* The distance between Port Villa, the capital of Vanuatu and other provinces can be up to several hundred kilometres, including considerable distance over the ocean in many cases, which means that the destination is not only not in direct line-of-sight, but is also located over the horizon. For such situations, either HF sky wave, NVIS are the most feasible candidates. Where access to very low HF frequencies are available, these can also be used for over-the-horizon ground-wave communications, as these are favourably refracted over open ocean.

As has been described above, these different sub-cases require a mix of different communications bearers, and that for several of these, HF radio is the most feasible solution, and the interconnection of such different communications bearers is facilitated by the abstraction provided by Serval LBARD.

5.6 Existing work

The previous section has described the flag-ship use-case which LBARD seeks to address. While it is not currently able to support the full complexity of this use-case, considerable progress has already been made with the implementation and testing of LBARD:

1. Support for UHF packet radios, and the RFD900 in particular, has been implemented in LBARD for some time. This has been piloted in Vanuatu, and demonstrated the ability to facilitate Serval Mesh communications over distances of up to 3 km in the humid tropical maritime environment. In that context it was able to demonstrate the delivery of Rhizome bundles.

2. LBARD already implements dynamic throttling of the packet transmission rate, based on the channel capacity, and the existing channel traffic and number of transmitting nodes present. It implements a simple algorithm that seeks to maintain channel utilisation near 20%, so as to minimise packet loss through collision that results from the necessary use of an AALOHA-like random packet transmission timing approach, because of the infeasibility of precisely synchronising all nodes, especially in the face of challenges such as the hidden sender problem.

3. The firmware for the RFD900 UHF packet radio has been re-written to support peer-to-peer ad-hoc communications, thus allowing all nodes within mutual range of one another to receive the packets sent by all other nodes in range [84], and to form effective multi-hop communications paths.

4. Integration into the Serval Mesh Extender devices, allowing the formation of practical heterogeneous Wi-Fi / UHF packet radio Serval Mesh networks, as piloted in Vanuatu.

That is, LBARD is already currently functional, and has been tested in the field, and shown to function substantially as intended.

5.7 Known limitations

While LBARD is already operational, it is not without limitations or issues, with several challenges being identified during the piloting in Vanuatu, or in the consideration of the flag-ship use-case:

1. LBARD lacked support for VHF and HF radios. While VHF radio support is still an outstanding issue, HF radio support is addressed in chapters (8) and (9) of this thesis.

2. Protocol implementation issues were identified during testing in Vanuatu. These problems resulted in intermittent protocol lock-ups and

other problems that prevented the continuing free-flow of Rhizome Bundles. These problems have since been resolved as part of the work to implement HF radio support in LBARD, as documented in chapter (9).

3. The synchronisation protocol used in LBARD to identify the lists of Rhizome Bundles held by each LBARD instance performs poorly in many cases. This problem is resolved in the next chapter, which describes the design, implementation and testing of the TreeSync protocol.

5.8 Conclusion

LBARD plays an important enabling role in the Serval Mesh, by enabling the use of low-bandwidth packet radios and similar communications bearers that are capable of much longer range communications than can be provided using omni-directional Wi-Fi. Importantly those bearers do not require precision alignment of dishes or other equipment, as would be required, for example, to establish long-range directional Wi-Fi links, thus ensuring that rapid and low-skilled deployment and maintenance of the resulting networks is feasible.

The abstraction that LBARD provides over the underlying communications bearers allows the easy formation of heterogeneous Serval Mesh networks that can be used to connect isolated communities in a resilient and cost-effective manner. LBARD has already reached the point where it can be, and has been, tested in the field, including on Efate in Vanuatu. However, it currently lacks support for HF radios, and has identified errata with its operation – both of which are addressed in later chapters of this thesis, thus enabling LBARD to realise its potential for connecting widely separated isolated communities.

Specifically, in the following chapter one of the key limitations of LBARD, the poor performance of its Rhizome Bundle list synchronisation process is addressed.

Chapter 6

Efficient bundle synchronisation process

6.1 Introduction

In this Chapter, we describe an improved synchronisation framework that can be used to efficiently determine which bundles need to be exchanged between pairs of nodes for the Serval Mesh. This builds on the LBARD framework introduced in chapter (5), and which is continued in chapter (7), where the focus turns to a modular approach to support different radio types.

One of the most significant benefits in computer networks is the ability to share resources between different devices, whether files or data, and this feature enables replicating material from one device to another. One approach to updating or sharing a set of files between two devices is to send a full copy of the files, regardless of whether the device has an identical copy of any or even all of the files. This is highly undesirable, as it will consume more network resources and time in order to perform the synchronisation than is necessary. The context for this process in this chapter is the Serval Mesh's store-and-forward Rhizome protocol, where the problem is to efficiently replicate the Rhizome bundles among devices participating in the network [88, 87].

In the earlier versions of the Rhizome protocol, a naive approach was taken, where the lists of bundles held by each node were exchanged in full, and then the differences found by each participating side, and the bundles that they lacked were requested. However, this approach does not scale to large numbers of bundles, especially when considering the low-bandwidth links that LBARD is designed. The naive approach is particularly inefficient for the common case where two peers have an identical set of bundles, except for one bundle newly received by one of the peers.

Improving the performance of this common case over low-bandwidth links is the driving motivation for the design and integration of a new bundle directory synchronisation protocol for the Serval Mesh, and LBARD in particular. The remainder of this chapter describes this process, after first providing background context for this general area of network synchronisation. The result is a tree-based synchronisation process, that represents the directory, i.e., list of bundles held by each peer in a deterministic tree-based structure. This deterministic structure is used to quickly find sub-trees that are either identical or that differ. Those that differ are recursively sub-divided, and the differences exchanged between the peers. This makes the common case where most bundles are shared much more efficient, and greatly reduces the size of the network traffic required to perform the synchronisation process.

6.2 Contributions

The contributions of this chapter are:

1. Analysis of the synchronisation problem facing the Serval Mesh
2. Analysis of the constraints that the high-latency and low-bandwidth links typified by Serval LBARD links places on synchronisation algorithms that can be used.
3. The design of a synchronisation algorithm which reasonably satisfies these needs.
4. The commissioning of the implementation of this algorithm into the Serval LBARD software.
5. The testing of the resulting system, confirming that it is fit for purpose, i.e., that it can efficiently synchronise content between multiple Serval Mesh nodes connected by high-latency and low-bandwidth links.

6.3 Data consistency challenge

The dependence on digital information has become near ubiquitous [246], reflecting the rapid evolution in the digital world that occurred because the use of digital information has enabled vast numbers of people from all walks of life to work more effectively. This has been accompanied by the growing need to facilitate fast and efficient replication of the digital artefacts on which they are working and that they are creating.

A rather mundane of this is depicted in Figure (6.1), where two users have sub-sets of the complete set of files required for some task, and wish to end up with an identical, i.e., consistent, set of files. A similar scenario when a user works on two different computers, and wishes to maintain consistency between these two computers, i.e., ensuring that they have the latest version of each file available on both computers. The value of consistency of data has led to the explosion of available services in this area, including services such as DropBox, Google Drive among many others [183].

The context for the Serval Mesh is similar, in that each node on a Serval Mesh network has the need to obtain copies of the latest version of as many of the Rhizome Bundles on the network as quickly as possible, so as to facilitate the delivery of text messages, as well as facilitating other Rhizome-based services, such as social media functions. A key difference, however, is that the Serval Mesh doesn't strictly need perfect consistency, in that the system will function as best as it can with the data it is able to receive, when it is able to receive it. Nonetheless, perfect consistency is preferable, as it ensures that none of these services will be impaired due to lack of up-to-date data.

Tolerance of imperfect consistency is one of the key features of the design of Serval Rhizome services, because it is accepted and expected that network links will be intermittent, and very likely lack sufficient capacity or continuity of access, or even the storage space, to hold the latest version of every bundle that appears anywhere on a Serval Rhizome network. However, clearly it is highly desirable to obtain the latest version of as many bundles as possible as promptly as possible, especially those bundles which have relevance to the receiver. There are fortunately some natural advantages in such networks, in that local connectivity and local use of the network will tend to result in the production of data relatively near to where it will be consumed on the network. Thus the goal of data consistency, i.e., having the same version of the same digital resources [163] will tend to be more possible for those resources that are produced near to where they are consumed. In the case of the Serval Mesh, this corresponds to the natural locality bias.

Optimising this process, and handling the situation where it becomes impossible to obtain or maintain consistency as the size of Serval Mesh networks grow is beyond the scope of this thesis. The scope is instead restricted to how to solve the problem at the peering level, i.e., how to maximise the number of bundles that can be synchronised in a given time period between a pair of peering nodes.

One common problem with obtaining data consistency is that of conflicts,

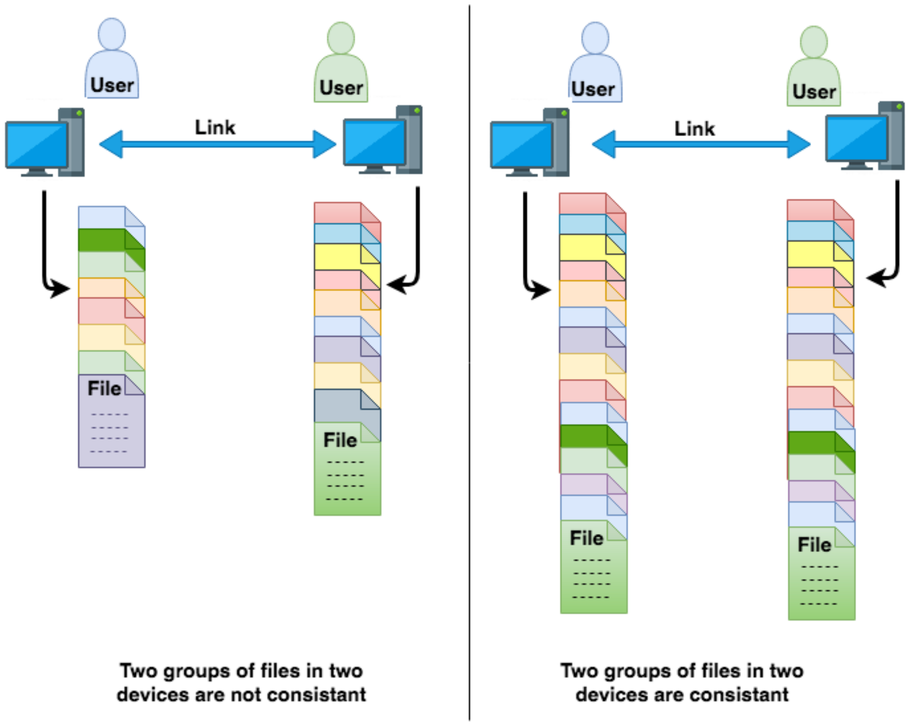


FIGURE 6.1: One scenario of data consistency challenge when two users working on a single project, and both of them have to have an identical set of files.

where changes have been made to a single resource by multiple parties, and where those changes require reconciliation [231, 26]. This problem is avoided with Rhizome, because each bundle is allowed to have only a single author, and the latest numbered version of a bundle is always considered the authoritative version, until such time as a newer version of the bundle is created. This considerably simplifies the problem, by reducing it to synchronising the lists of bundles.

6.4 Approaches to Synchronisation

In general, data synchronisation processes are implemented through the creation of protocols and rules, through which the data is synchronised, and that the correctness of this synchronisation is assured [116, 72, 240]. A copy of updated files are transferred from a source location to one or more target locations. The synchronisation could be either uni-directional or bi-directional. That is, it could consist of synchronising a mirror of a data set, which is not allowed to create new data or modify the data already in that set. Rather, the only changes which can be made are at the source. Alternatively, it may be that the synchronisation allows changes to be made to any replicate, and that those changes will then be propagated to all replicates. It is the latter approach that is required for Rhizome, as there is no sense of a "master copy", but rather each node is a peer seeking to replicate the Rhizome Bundle library of its peers.

Another property to be considered for synchronisation algorithms is whether to use single-round or multi-round synchronisation schemes [70].

6.4.1 Single-round synchronisation

This type of synchronisation is based on only one round of communication between two nodes, where all the differences are calculated and send to another node. There are many protocols of this type, with Rsync being one of the better known algorithms in this space [237]. The idea of Rsync is based on splitting files on the peer on a client into non-overlap slices with fixed size for all slices, then strong and weak checksums are computed for each slice using a hash function. The client sends these checksum values to the server, which also calculates strong and weak checksum of its copies of the files, and compares the result of that with the data it received from the client. Where the results match, the files are assumed to be identical, but where they do not match, this information is used to localise the differences, and reduce the amount of data which needs to be sent to the client [237].

Algorithms like Rsync are well suited to small files, such as are typical for Rhizome bundles, and is also well suited to high network latency, but it is not intended as a synchronisation algorithm for many peers seeking eventual consistency of data. Also, it assumes that connectivity is continuously available during a synchronisation activity, which is not a reasonable assumption for the Serval Mesh.

6.4.2 Multi-round synchronisation

More recent work has shown that by using multiple rounds of message exchange, synchronisation protocols can be made substantially more efficient [113].

In these algorithms, more than one round is needed to complete the synchronisation process, and during these rounds, each node tries to progressively reach consisteny with the the other node, by refining their knowledge of the similarities and differences in the files.

One advantage of this method is that it can reduce the network bandwidth requirements – although at the cost of the number of round-trips required to achieve consistency. This approach is considered to be the more appropriate for synchronising lists of Rhizome Bundles on the Serval Mesh, as available bandwidth is generally more limiting than the number of round-trip times. Therefore the new TreeSync protocol for the Serval Mesh is based on a multi-round synchronisation scheme.

6.5 Treesync synchronisation algorithm layout

The common case for Rhizome synchronisation is where the communicating nodes, of which there may be more than two, have substantially the same set of bundles, with only a few exceptions. The goal is to discover those exceptions as quickly as possible, using as little network bandwidth as possible.

The theory of Linear Network Coding (LNC) is adopted in the synchronisation to transmit data between source and destination. LNC has advantages in improving the network's throughput, scalability and the data transmission efficiency [254] that are highly desirable characteristics in this scenario. While packets in the LNC environment traverse over different nodes until it reaches the destination; these packets are transmitted directly via a direct link to the second node in Serval Mesh network, and this situation is likely to be unicast transmission on LNC. Another approach is in some LNC, XOR operation between packets is adopted at the encoding & decoding process at intermediate nodes, while this operation is applied internally at each node during TreeSync.

6.5.1 Tree Construction

The approach taken is to form a tree structure where the leaf nodes in the tree are hashes of the Rhizome Bundles, and where intermediate nodes are the XOR of the nodes below. This process is applied recursively, to produce a single top-level value for the tree, as depicted in Figure (6.2).

Note that the hashes of the bundles are hashes of the manifest, not the payload, and are typically relatively short, being just 64 bits in length, to minimise communications requirements at the cost of a very small risk of hash collisions. A complete set of bundles can thus be represented by a single 64-bit value.

The use of XOR as the mechanism of combining nodes to produce the intermediate values is highly attractive for four reasons:

1. XOR is wonderfully inexpensive computationally, which helps to minimise the power consumption of devices running this algorithm, which can be an issue in energy deprived disaster zone and isolated community contexts [124, 123, 122, 125].

2. XOR combines the information of its inputs, and is commutable, which makes it possible infer information about sub-trees based on the value of other sub-trees. For example, if some parent node, N, is known, and all but one of its children values are transmitted, the receiver can infer the value of the remaining child, without needing to transmit its value explicitly. This property can be used to reduce the volume of network traffic required to fully discover the set of nodes that another node holds.

3. This approach that produces deterministic trees, is that nodes can listen for sub-tree information from many nodes simultaneously, and use information from one peer to infer information about the bundles held by another peer, further helping to reduce the volume of network traffic required.

4. Finally, it is very inexpensive to modify the tree as bundles are added, updated or removed.

Where two nodes have the same set of bundles, they will be able to immediately infer this by exchanging the 64-bit value at the top level of the tree. Conversely, where there is some difference in the set of bundles, their top-level values will differ. If this occurs, a subsequent round of synchronisation is required where the children of the differing node are exchanged. As the trees are constructed with each branch in the tree describing a fixed number of bits, usually 1 or 2 bits, the position of a set of bundles in the tree is fixed. That is, the tree's structure effectively describes the prefixes of the bundle hashes it contains. This in turn means that the hash of a sub-tree will always be the same if the two nodes have the same structure and be found in the same location in the tree. As a result, identical sub-trees can be quickly identified and ignored, focusing the tree traversal on the sub-trees that differ. This process occurs recursively until all differences in the tree have been identified.

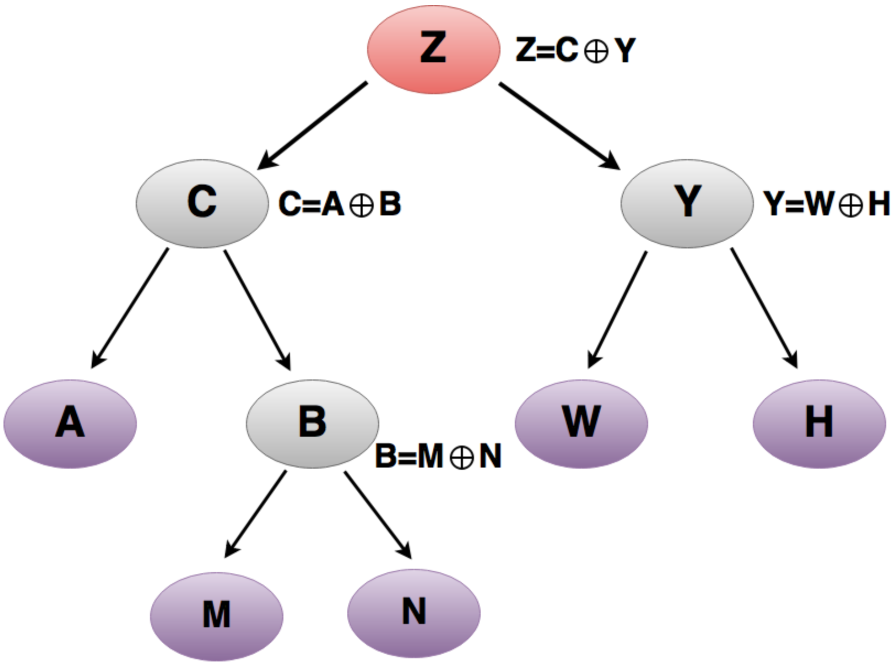


FIGURE 6.2: Sorted tree.

This approach that a single differing bundle will be discovered in O($log(n)$) rounds, where n is the maximum number of bundles that one of the nodes holds. This is overwhelmingly more efficient than a naive list exchange, once the number of bundles grows. Further advantage is gained by including multiple child node hashes in a single TreeSync message in order to reduce the number of round-trips required.

For its use in the Serval Mesh, there is no need to resolve the hashes of bundles that only a remote peer holds, as the nodes that have those bundles will pre-emptively transmit those bundles when it is discovered that the receiving node does not have them. This also saves on network overhead considerably.

The result is sub-linear synchronisation time with respect to the total number of files, thus allowing for very rapid synchronisation of underlying files, and delivery of MeshMS messages to the other end that doesn't have these missing bundles.

After creating the tree, every leave in the tree has an address similar to the prefix part of the key, and all siblings have the same prefix part of the key, as shown in Figure (6.3).

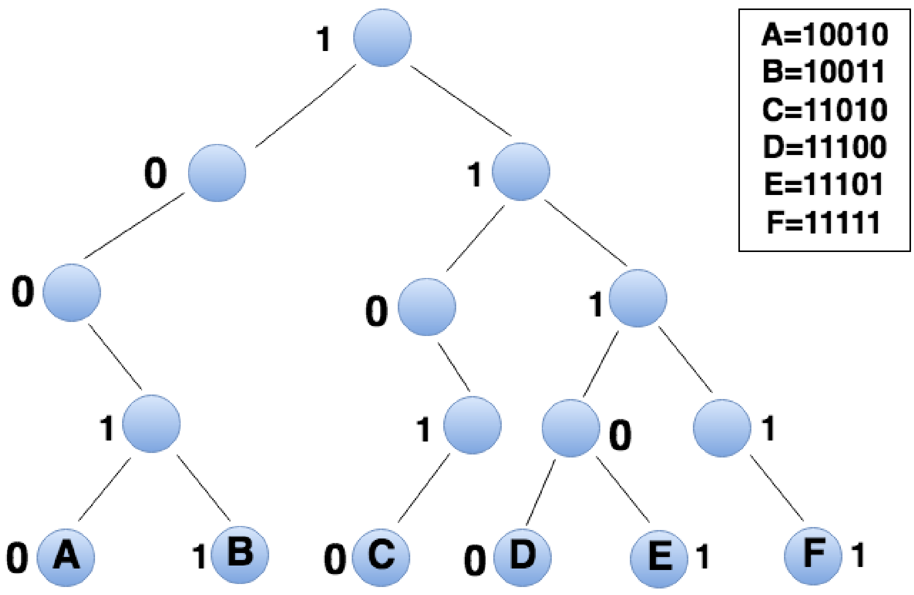


FIGURE 6.3: Binary sorted tree contains six leaves.

6.5.2 Tree analysing and messages exchanging

After each peer has forming its tree, synchronisation starts between two peers, for example A and B. The first step in communication is node A sends a message contains the key or hash value (64 bits) of its root to node B. Node B receives this message, and extracts the key. Next, node B compares the received key with the hash of its own tree's root. Based on that comparison, there are three different scenarios for this comparison between the two hashes as follow:

1. *The two values match*: Then the synchronisation will end successfully at this point because two binary trees in both nodes A and B are identical, regardless of the number and size of the bundles in the tree, because the tree construction process is deterministic, as illustrated in Figure (6.4). This case is expected when two nodes have already synchronised, and no new bundles have arrived to either. Thus in the case where synchronisation has been achieved, no further data exchange is required. Importantly, this single message is all that is required, regardless of the number of bundles that each node is holding.

2. *The two values do not match, but the difference can be explained*: If the XOR combination of the received key and the key of the node's own root exactly matches the value of any single leaf node in the receiver's tree, then the receiver can infer that the only difference between the two trees

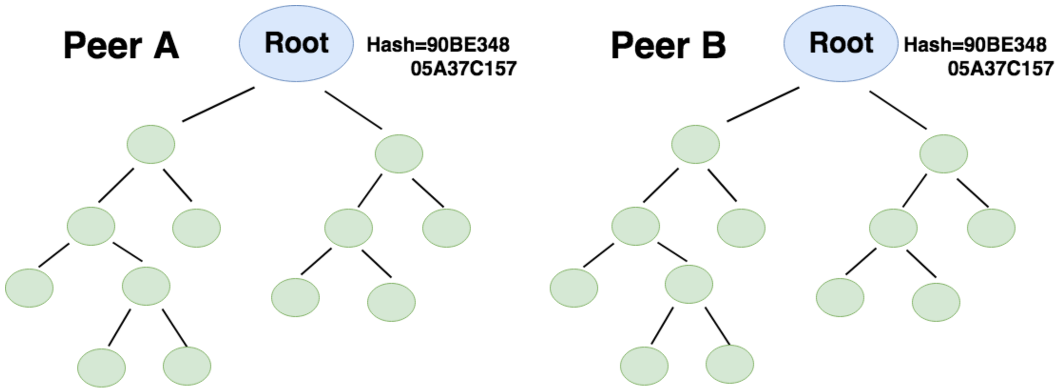


FIGURE 6.4: Root's hash values of two tree are equal.

is that node A is missing exactly that bundle. That is, no further exchange of tree material is required, because the receiver can infer the missing node, and therefore the value at each of the intermediate nodes in the tree, all the way back to the root. This works because in the case of only one node differing between the two trees, the top level hashes will be related according to:

$RootA = RootB \oplus AdditionalBundle$

The reason behind this step is that in case there is only one different node that found in B and not found in A then X will match this different node's value; therefore, the system starts comparing all nodes one by one with X value, and if any matching is found, then the algorithm will stop doing any further comparison, and move to data transfer step to send the actual data represented by this node from A to B.

For example, Figure (6.5) depicts such an example, where Peer B receives the hash 90BE34805A37C157 from Peer A, which does not match its own root hash of 2ABE5440269C30A1. Searching through its own try, it finds that the orange node has hash BA0060C07CABF1F6, and computes that BA0060C07CABF1F6 ⊕ 90BE34805A37C157 = 2ABE5440269C30A1, which matches Peer A root node. Peer B now has complete knowledge of Peer A's tree, and requires no further communications.

3. *The two values do not match, and the difference cannot be explained*: In this case, further information is required about the tree of Peer A. Peer B therefore sends a message to Peer A indicating that it cannot explain this hash. This message takes the form of the address of the unexplained hash in the tree. The predictable nature of the tree's construction means that this address is reproduceable at by both peers. When

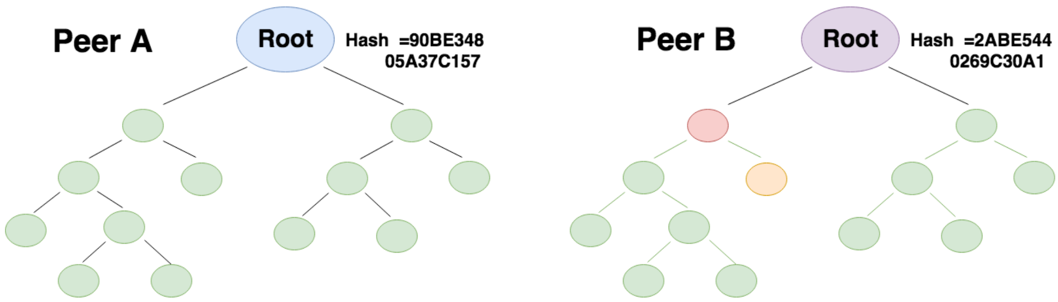


FIGURE 6.5: The trees differ by exactly one node. Because the top-level hash of the tree is formed from the XOR combination of all of the bundles in the tree, Peer B can determine that Peer A lacks bundle BA0060C07CABF1F6, marked in orange. No further communications are required, as even the intermediate node marked in red can be computed by Peer B for both its own and Peer A's tree. Peer B therefore now has complete knowledge of the structure of Peer A's tree, and therefore knows the complete set of bundles that Peer A possesses.

Peer A receives this message, it is able to send the hash stored at that position in its tree in the next round of communications.

From this point, the process continues recursively down the tree. So for example, the next comparison might be of two sub-trees that that differ, as shown in Figure (6.6). On the following round, only one of their sub-trees differ in turn, so only that sub-tree (blue), will require explanation. As a result the tree exploration remains focused only on those sub-trees that contain differences.

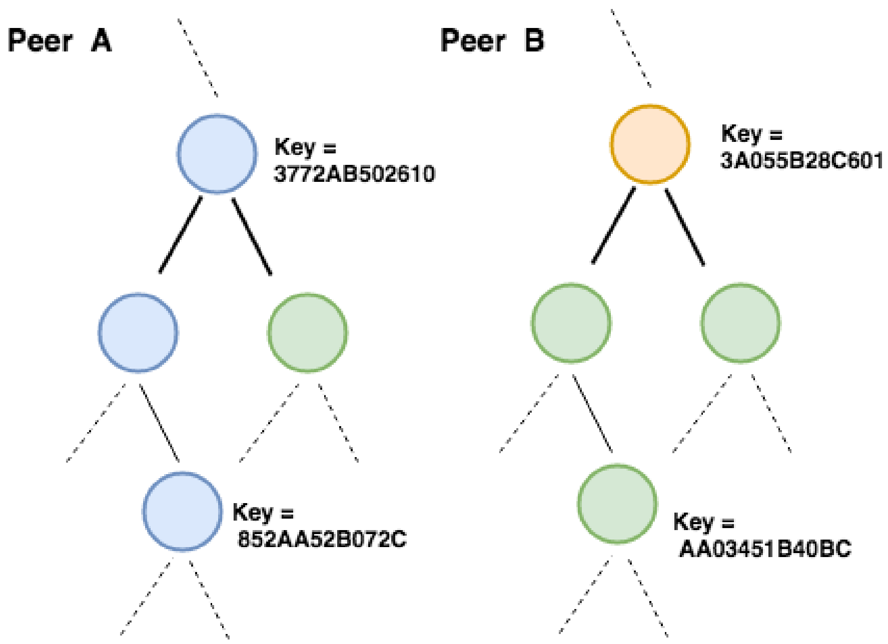


FIGURE 6.6: One node is different.

Eventually some sub-tree will be reached, where there are no more differences, as shown in Figure (6.7), and the exploration of that sub-tree will cease, and any other higher sub-trees with differences will be searched, until all all unknown sub-trees have been resolved.

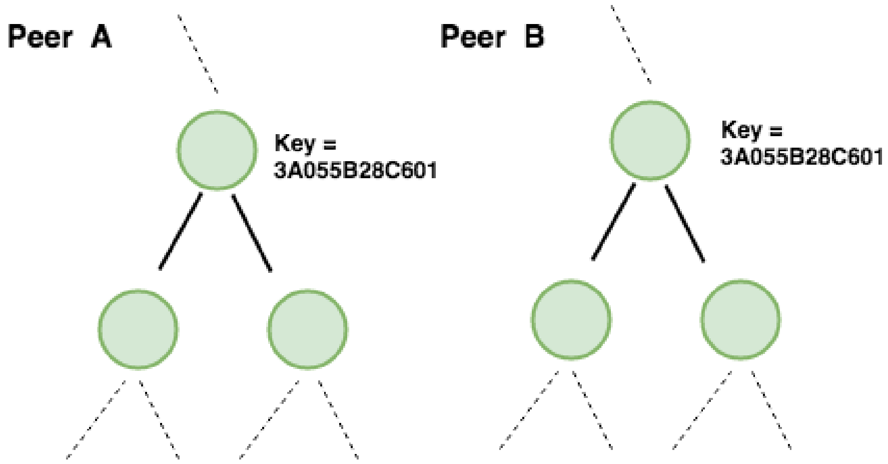


FIGURE 6.7: Two matching nodes.

6.5.3 Data transfer

At the point at which a peer knows the set of bundles that it has, but which another peer is missing, this is all that is required for the Serval Mesh to begin transferring those bundles. In fact, as soon as TreeSync is able to indicate that any single bundle is not held by a peer, this can be communicated to LBARD, to allow immediate transmission to begin. LBARD's dynamic prioritisation system will then allow that bundle to be transmitted until either it completes, or another bundle is discovered that the receiving peer does not have, and that has a higher priority, in which case that bundle will pre-empt it.

That TreeSync is able to progressively communicate this information helps to enable synchronisation of the Rhizome bundles immediately, rather than waiting for the complete bundle list synchronisation to occur. This can help make more efficient use of the limited bandwidth by avoiding the wasting of packet transmission opportunities, and reduce the latency of the delivery of bundles.

6.6 Testing Treesync

The previous sections have introduced the design and operation of the TreeSync algorithm. This algorithm was then implemented in the Resilient Telecommunications Laboratory, and then integrated into the Serval Mesh, including into LBARD, as well as a stand-alone utility to facilitate efficiency testing.

6.6.1 Oracle as performance benchmark

To measure performance, a benchmark was devised, that is based on the minimum information that is required to be transferred, i.e., the set of differing bundles. That is, if the algorithm running on each node had access to an oracle that could answer the question "Does the other node have this bundle?", it would need to send only the hashes for those bundles that the other peer does not have. In this way, a comparison can be made on the basis of optimality of the protocol, and an idea of how much further improvement may be possible

The performance metric is the ratio of the number of bytes transferred in each direction, versus the number required if the algorithm had access to the oracle. From this we can consider the efficiency ($transferredbytes/bytesrequiredwithanoracle$) of the system.

6.6.2 Results and discussion

The initial tests consisted of setting up two nodes, each with 100 Rhizome bundles. At one extreme, the two nodes were given exactly the same 100 Rhizome bundles, while at the other extreme, each node had a different 100 Rhizome bundles. In between those two extremes, tests were performed where there were numbers of unique bundles between the peers between those two figures. That is, for each test there was some, possibly zero, number of bundles unique to each node, and that each node shares in common, as depicted in Figure (6.8).

Due to the variation that random selection of unique manifest identifiers could have, each test was repeated ten times, with the mean being reported.

The results for each of the two nodes (peers) in this test are, as expected, essentially identical, as can be seen in Figures (6.9) and (6.10). Not surprisingly, the number of bytes that are required to be transferred begins near zero, when there are zero bundles unique to each tree, thus showing the power of TreeSync's ability to efficiently detect identical trees. Then as the number

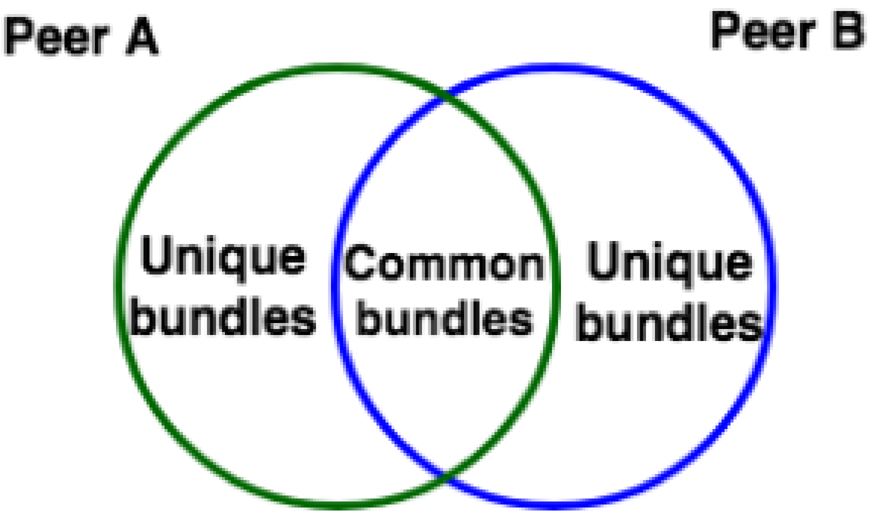


FIGURE 6.8: Peer A and B have unique and common manifests

of unique bundles per tree increases, the number of bytes required to communicate this increases sub-linearly. This most likely reflects the ability of TreeSync to infer the values of missing nodes. The smooth response over the full range provides comfort that there are no major unexpected problems with the approach.

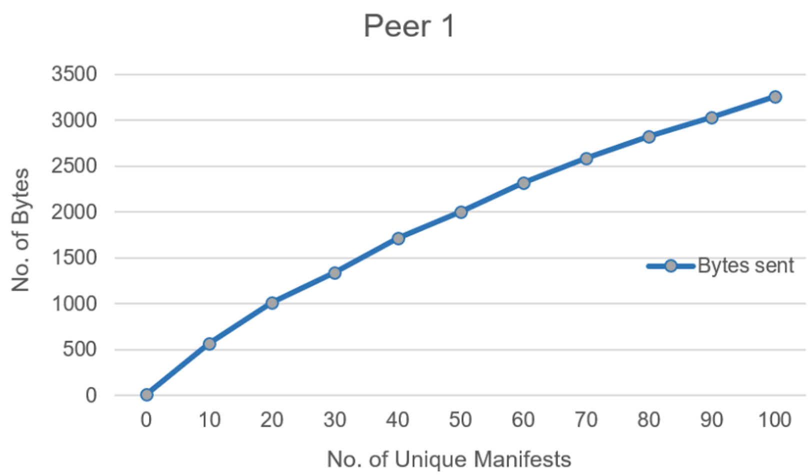


FIGURE 6.9: The total number of bytes sent versus the number of unique manifests for peer 1. It shows that when there are 0 unique bundles, i.e., the nodes start in a fully synchronised state, practically no data needs to be sent, confirming the expected efficiency for this common situation. At the other extreme, where each node have no bundles in common, requires about 3300 bytes to complete the process. In between, the growth in the number of bytes sent is either sub-linear, or perhaps more likely, growth is linear after an initial rapid growth as the fraction of the tree that requires exploration.

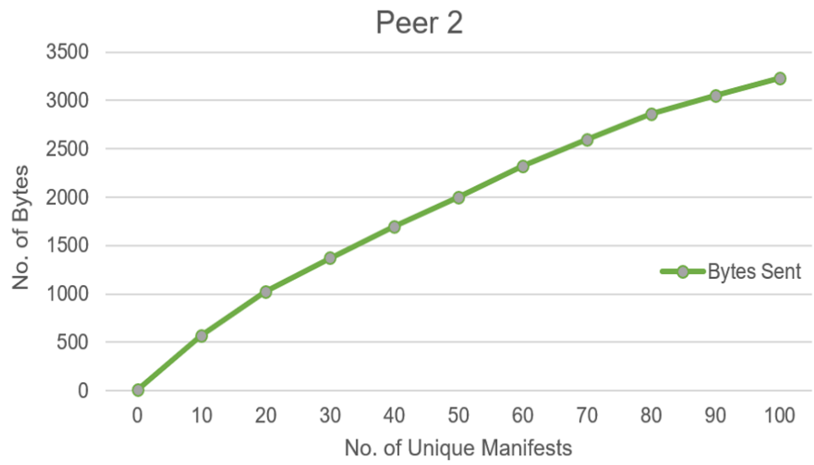


FIGURE 6.10: The total number of bytes sent versus the number of unique manifests for peer 2. The response curve is, as expected, essentially identical to that of Figure (6.9).

Having considered the total number of bytes sent, we now turn to the Oracular Metric, where we consider the overall efficiency of the system, versus the situation where an oracle function is available. These results are presented in Figure (6.11). It can be seen that TreeSync's performance is remarkably close, growing only slightly faster, as the number of unique manifests grows. This is enabled because of TreeSync's use of the information-conserving XOR-based approach, that allows TreeSync to frequently infer the value of leaf nodes, thus avoiding needing to send them explicitly, and thus helping to amortise the cost of having sent the higher-level node values in the tree.

As the preceding test considered only small numbers of bundles, it is beneficial to run tests involving much larger numbers of bundles, as well as repeating the tests for varying fractions of the bundles being unique and in common, with the total number of bundles ranging from 10 to 2,000,000. The results of these tests are presented in Table (6.1).

The number of bytes sent grows very close to linearly as the number of unique bundles grows. An algorithm using the oracular function would be able to send exactly 64 bits, i.e., 8 bytes for each unique bundle, which would result in a growth of $log_{10}(10) = 1.0$ each time the number of unique bundles is increased, from a base of $log_{10}(10 \times 8) = 1.903$ for the case where there are 10 unique bundles. The observed results are initially higher than this, requiring nearer $10^{2.5}$ – $10^{2.9}$ bytes to be sent, based on the number of bundles in common, as the cost of exploring more of the tree must be relatively

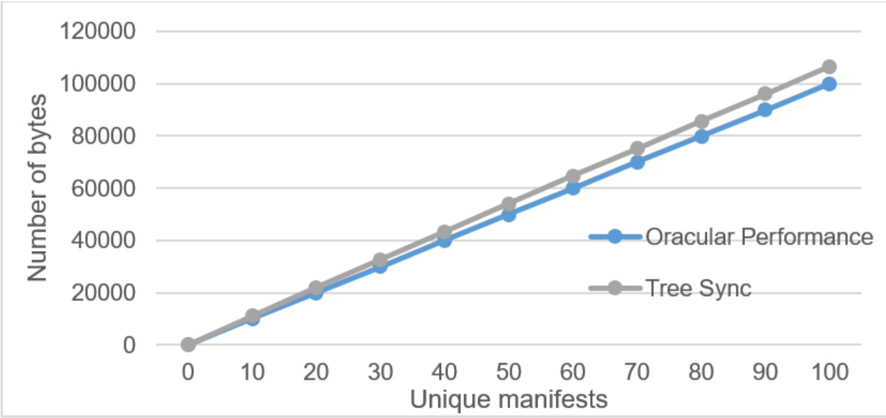


FIGURE 6.11: Comparison of TreeSync's data requirements against that of the case of a hypothetical algorithm that has access to an oracle function that can determine whether a bundle's hash requires sending or not. It can be seen that TreeSync's performance is remarkably close, growing only slightly faster, as the number of unique manifests grows. This is enabled because of TreeSync's use of the information-conserving XOR-based approach, that allows TreeSync to frequently infer the value of leaf nodes, thus avoiding needing to send them explicitly, and thus helping to amortise the cost of having sent the higher-level node values in the tree.

quickly incurred, but after this, the ability of TreeSync to infer leaf node values allows the overall growth rate to reduce back to a figure very close to 1, with the performance when there are 1,000,000 unique and 1,000,000 common bundles requiring only $10^{7.37}/8 \times 1000000 = 3.07\times$ more data than in the case where an oracle were available.

These data are also presented expressed using the oracle metric in Table (6.2). The efficiency is shown as zero for the case where there are no unique bundles, because TreeSync must still exchange the root hash, whereas the oracle implementation realises that it does not need to send any data at all. However, as seen in the previous table, the practical impact of this is simply a fixed 10 bytes of traffic, so the efficiency is less meaningful here than the absolute number of bytes sent.

As the number of unique bundles grows, the efficiency remains apparently rather poor, especially as the number of bundles in common grows. This reflects the relatively constant cost of drilling down through the tree to identify the few changed bundles. Again, the low efficiency at this point is quite tolerable, as the number of bytes involved is quite low. The efficiency then improves, rising, perhaps asymptotically towards a plateau value near 0.5.

That is, the algorithm is most efficient in exactly those situations where it needs to be, i.e., the largest amount of bytes need to be exchanged, and is always within an order of magnitude of what an oracle-assisted algorithm would be able to achieve, and often within a factor of $2\times - 3\times$ the that of the ideal.

In short, the TreeSync offers good performance, without needing to be tuned to the number of bundles in common or bundles unique to each peer. This is important, because those quantities are not knowable until after the bundle list synchronisation has completed. That is, the TreeSync algorithm performs sufficiently well across the range of conditions under which it is required to work.

	Unique bundles						
Bundles in common	0	10	100	1000	10000	100000	1000000
0	1	2.50	3.40	4.23	5.22	6.21	7.21
10	1	2.60	3.42	4.23	5.22	6.21	7.21
100	1	2.75	3.51	4.25	5.22	6.21	7.21
1000	1	2.80	3.68	4.38	5.24	6.22	7.21
10000	1	2.80	3.75	4.61	5.37	6.24	7.22
100000	1	2.81	3.76	4.68	5.60	6.37	7.24
1000000	1	2.84	3.76	4.69	5.68	6.60	7.37

TABLE 6.1: Relationship between number of bytes and the number of manifests (unique & common) for peer A, expressed as $log_{10}(UniqueBundles)$. As expected, the figures are almost identical for Peer B, and are thus not shown. When the number of unique bundles is 0, the data sent is constant and very low (0 unique bundles column), and then grows approximately linearly with regard to the number of unique bundles.

6.7 Conclusion

In this chapter the need for the TreeSync algorithm has been presented, followed by the design and testing of the algorithm using realistic test data. The result is an algorithm which uses very little network bandwidth in the common situation where there is only a very small proportion of unique bundles between communicating peers, and performs very efficiently when there are large numbers of unique bundles between communicating peers. This is achieved without the algorithm having to know or guess the proportion of unique bundles each peer holds.

	Unique bundles						
Bundles in common	0	10	100	1000	10000	100000	1000000
0	0	0.26	0.32	0.47	0.49	0.49	0.49
10	0	0.20	0.30	0.47	0.49	0.49	0.49
100	0	0.14	0.25	0.45	0.49	0.49	0.49
1000	0	0.13	0.17	0.33	0.46	0.49	0.49
10000	0	0.13	0.14	0.20	0.34	0.46	0.49
100000	0	0.12	0.14	0.17	0.20	0.34	0.46
1000000	0	0.12	0.14	0.16	0.17	0.20	0.34

TABLE 6.2: The same data as presented in Table (6.1), but this time expressed using the Oracle Metric, that is, dividing the number of bytes required by an algorithm with access to an oracle function, i.e., $8 \times NumberOfUniqueBundles$, by the number of bytes required by TreeSync. A result of 1 means as efficient as the oracular solution, and with values lower than this indicating proportionately lower efficiency.

Impressively, the efficiency approaches 50% of that of an implementation that had the advantage of an oracle function that would inform each sender of the set of bundles that it holds that are not held by the corresponding peer.

That is, an algorithm has been devised and implemented into the Serval Mesh and LBARD that provides the kind of performance curve required for effective use with very-low bandwidth links, such as HF radios. This sets the scene for the integration of support for HF radios into the Serval LBARD framework. The final preparatory step for achieving this is addressed in the following chapter, where the Serval LBARD software is refactored to make it much easier to add drivers for additional radio types.

Chapter 7

LBARD Modular Driver Framework

7.1 Introduction

In this chapter, a framework for the modularisation of drivers in the LBARD protocol is presented, to simplify the process of adding support for new communications bearers to the Serval Mesh. This is a pre-requisite for the inclusion of support for HF radios into the Serval Mesh, as is covered in the following chapters.

Historically, whenever LBARD has been required to support a new model or type of radio, this has been implemented in an ad-hoc manner. As a result, the structure of the software became convoluted and confused, and it was difficult for people working on the project to be able to add such support. The "technological debt" began to reach the point where it would be more time-efficient to restructure the current code-base, so that the act of adding additional communications bearers would be able to be reduced substantially.

7.2 Motivation

LBARD needs to be able to support a wide variety of communications bearers, because no single model of radio presents a complete solution. On the one hand, different countries have different spectrum allocation laws and policies, which mean that a radio that might be a good solution in one country, or group of countries, may not be legal to use in other countries. Then on the other hand, different radio types offer different data rates, range of communications and other properties. Finally, as newer improved radios become available that improve on the performance and/or cost of existing radios, it is highly desirable to be able to easily integrate support for those devices.

To understand how now single radio type can meet all use-cases, consider the context of providing communications to remote communities in Vanuatu. Geographically, Vanuatu consists of many islands, which are located tens to hundreds of kilometres apart from one another, as can be seen in Figure (7.1). For example, the distance between two islands, Efate, where the capital, Port Vila, is located, and the next major island to the South, Erromango, is close to 100 kilometres, for which only HF radio is a realistic terrestrial communications bearer.

In contrast, to the North, there are many small islands separated by much smaller distances, and where UHF or VHF radios would be likely to be feasible. Where UHF or VHF radios are possible, they are highly advantageous, as they are cheaper, smaller, use smaller antennae that are less prone to damage by cyclones, and can support higher data rates than HF radios can.

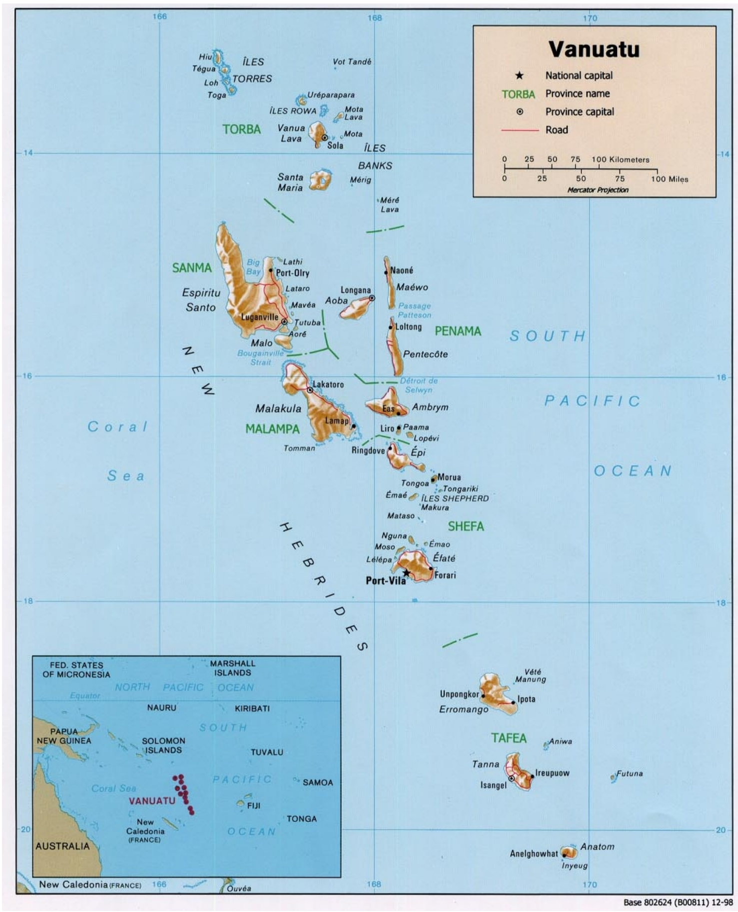


FIGURE 7.1: Map of the Republic of Vanuatu. Many islands are separated from one another by many tens of kilometres [112].

Also, within islands, differing radio solutions may be possible or preferred, based on the particular context. For example, within a village, a high-bandwidth UHF packet radio may be preferable, even if longer-range radios were available. Also, new low-cost packet radios are being released regularly, including those based on new and advanced wave-forms, such as LoRa-compatible radios. Having the Serval Mesh be able to integrate these radios quickly is highly attractive – even if only to test and compare their performance.

The remainder of this chapter describes the process of re-factoring the LBARD software, to make it much easier to integrate new radio types.

7.3 Contributions

The contributions of this chapter are:

1. Elucidation of the motivations and reasons for LBARD to have an improved and more modular radio driver framework.

2. The description of the general requirements of such a modular driver framework, and the approach taken to implement this in LBARD.

7.4 New LBARD directory structure

The first step in re-factoring LBARD was to introduce structure into the previously flat directory hierarchy. This structure is helpful, as LBARD performs a variety of house-keeping functions for Serval Mesh Extenders, as well as having sub-systems to provide various services it requires to perform its functions, such as the interface to the Rhizome Database, the TreeSync algorithm, cryptographic and error correction routines, as illustrated in Figure (7.2).

Within the source directory, a number of subdirectories were created, as shown in Figure (7.3), into which the various existing source files were triaged.

Most important sub-directories in this structure are described below briefly:

1. *drivers*: This folder is the focus of the work described in this chapter, and includes all the files that implement the various radio drivers in LBARD, which will be described later. The only radio function which is not included in this folder are some common utility functions that are applicable to multiple types of HF radios.

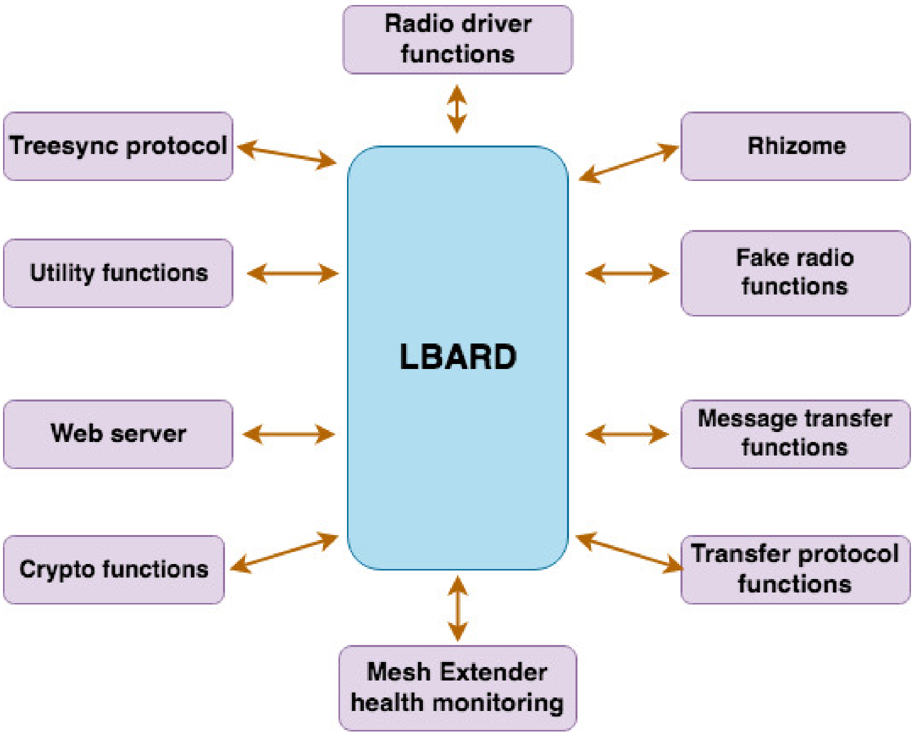


FIGURE 7.2: The LBARD software performs many functions, and contains numerous sub-systems to support those functions.

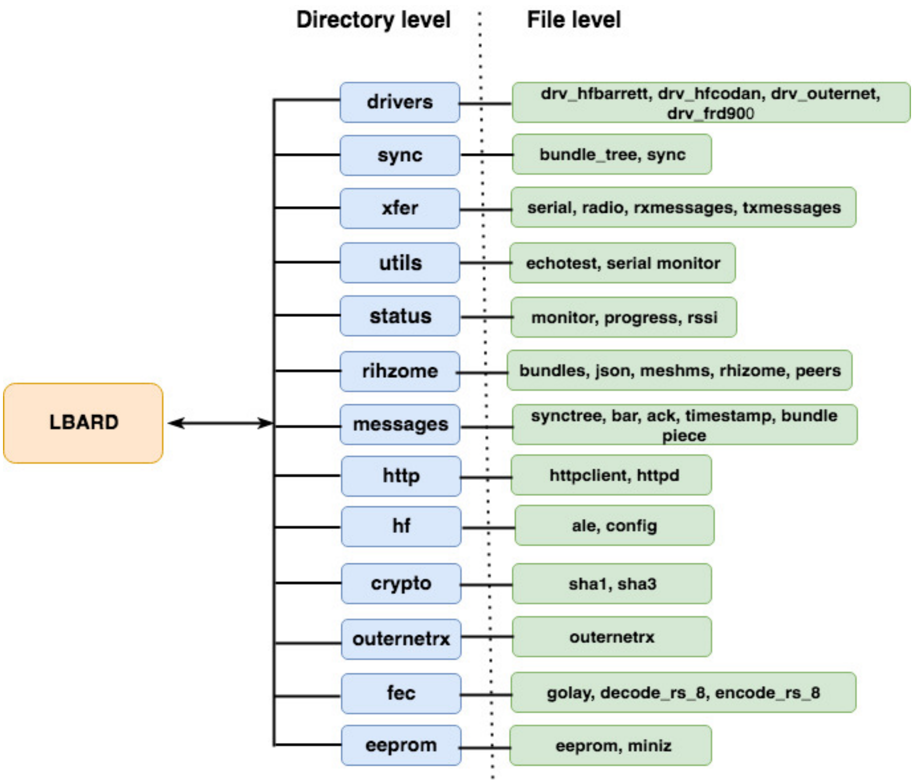


FIGURE 7.3: LBARD new hierarchy structure for directory and file levels. Showing the most important files at the file level classified according to the job required.

2. *hf*: As mentioned above, this sub-directory contains utility functions are of use for multiple HF radio types. This includes `ale.c` and `config.c` that provide helper routines for managing ALE call states, and managing radio configuration, respectively.

3. *sync*: Includes the tree synchronisation protocol that was introduced in chapter (6).

4. *xfer*: This sub-directory contains many of the core bundle transfer functions for LBARD, including the fragmentation and reassembly of bundles, as well as the code that calls the radio auto-detection and initialisation routines. It is in many ways the heart of LBARD.

5. *utils*: This sub-directory contains a variety of utility functions, including time keeping, safe writing of data to serial ports etc.

6. *status*: This sub-directory contains the routines that are used to produce the real-time transfer and status reports that are made available via LBARD's integrated web-server.

7. *rhizome*: This is where the routines that provide the interface to the Rhizome Database are found. These routines allow reading and writing of bundles using the HTTP RESTful API provided by the ServalDNA software component.

8. *messages*: This folder contains the routines that produce and parse the various message types that are supported in LBARD data packets.

9. *http*: Includes both the HTTP client code that is used to access the Rhizome HTTP API, as well as a compact integrated HTTP server that is used to serve the status pages that LBARD produces internally, that are used to monitor the function, performance and health of Serval Mesh Extenders and any active radio links.

7.5 LBARD Driver Framework

Of prime importance to the goals of this chapter is that the separate `drivers` sub-directory was created, into which new drivers could be added. This provides a predictable place for developers to look to find the existing radio drivers, including to use as a template for implementing a new driver, and to know where to place their new driver files when complete.

The driver files now also receive predictable names: Each driver consists of two files called `drv_NAME.h` and `drv_NAME.c`, where *NAME* is the short name of the radio type, for example, for the RFD900 radio, these files are called `drv_rfd900.h` and `drv_rfd900.c`.

7.5.1 Purpose and Function of Radio Drivers in LBARD

LBARD includes the general functions required to exchange messages with other instances of LBARD, using TreeSync to determine which bundles need to be sent to those other instances, prioritise the order in which those bundles are sent, and to fragment and send the resulting pieces of those bundles – together with all of the associated house-keeping required to do these tasks in practice.

The existence of drivers as a discrete entity mirrors their use in many other software systems, and helps to provide an abstracted view of the communications bearers, which helps to reduce the complexity of the software package as a whole [228, 266].

This requires a well-defined, and hopefully, simple interface between the software responsible for interfacing with the radio, and the higher-level functions. From the perspective of a layered networking model, the drivers operate at layers 1 and 2 of the OSI model, and all drivers provide the same common abstracted interface, regardless of the underlying communications bearer.

7.5.2 Driver Software Interface

In LBARD, the radio driver interface consists of the following functions, where RADIO is the name of the driver:

1. `RADIO_radio_detect`: This function is responsible for attempting to detect if the indicated radio type is present. These routines must take care to not cause damage to any other supported radio type, and are perhaps the most complex part of the driver, because of this interdependency. For this reason, some drivers may share a single auto-detect function that can discriminate between multiple radio types. The use of shared auto-detection functions can also help to reduce the time it takes for LBARD to discover the type of radio it is connected to, thus improving start-up time.

2. `RADIO_serviceloop`: This function is the heart of the driver, and implements the state-machine for the radio if required, as well as indicating when the radio is ready to send the next packet. Packets are generated by LBARD just-in-time, so that the bundle prioritisation decisions are made with the latest possible information. This is feasible because the data rate of LBARD links is relatively low, almost always below 100 kilobits per second, and with packet rates that are not faster than a few 10s of Hz.

   The service loop is called regularly by LBARD, and should return after having updated the state of the radio, including the current desired packet transmission rate.

   For HF radios that use ALE to establish point-to-point links, the service loop is also responsible for managing the state-machine for the ALE calls, as for example depicted in Figure (7.4):

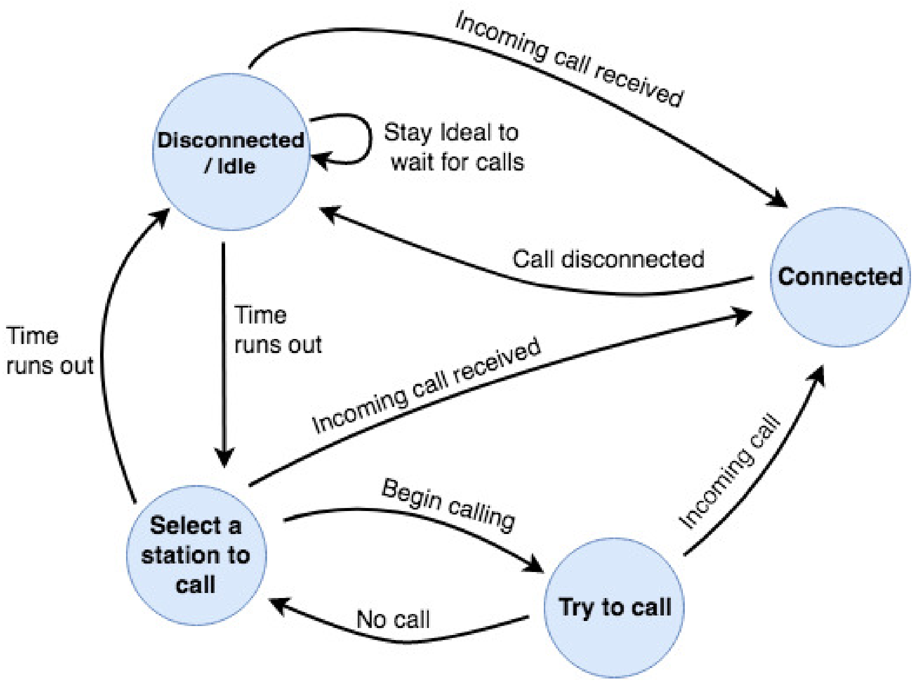


FIGURE 7.4: State machine for HF radio, and it shows different states that spends on a specific action to transit from one to another.

This state machine is usually quite similar, even for different models of HF radios, for this reason, a simple state-machine driver is provided in the `hf` sub-directory, which supports the following call states, and thus makes it simpler to implement HF radio drivers:

(a) *Disconnected*: The radio is idle, and waiting to either make or receive an ALE call.

If the radio is in this state, the radio communications plan is consulted, if one exists, which may result in the instigation of an ALE call to another station, by moving to the *Select a station to call* state. Otherwise this state is only departed when an in-bound ALE call is received, in which case it transitions to the *Connected* state, if and when an inbound ALE call occurs, is accepted, and results in an ALE connection.

(b) *Select a station to call*: This state is transiently entered when considering if a call should be made to another node on the network, which results in a transition to *Trying to call* or back to the *Disconnected* state if the call cannot be made for some reason. Also, if an in-bound ALE call is received in this state, it can result in the transition to the *Connected* state.

(c) `Try to call`: This state covers the period of time from which an ALE call has been requested, until the call either connects, in which case it transitions to *Connected*, or the call fails, in which case it transitions back to *Select a station to call*, to determine if there is another station that can be called.

(d) `Connected`: This is the state in which an ALE call is active, and it is possible for data to flow. This state will persist until it is detected that the call has terminated, or until the radio driver elects to terminate the call itself.

3. `RADIO_send_packet`: This function is called whenever LBARD wishes to transmit a packet. The packet to be sent is supplied as part of the call. This function must then encode and encapsulate the packet in whatever manner is required in preparation for transmission. It then sends the resulting data to the radio itself. For radio types that require fragmentation of packets, e.g., the ALE 2G text messaging transport, that can in practical situations only handle a few dozen 8-bit clean characters, this function is responsible for performing the fragmentation.

   This function is also responsible to make sure that the radio is in the correct state to transmit the packet.

4. `RADIO_receive_bytes`: This function is called whenever one or more byte of data is received from the radio. Thus function is responsible

for implementing any decapsulation of data, packet framing, and error checking of the received data stream from the radio. It is also responsible for the re-assembly of packets that had to be fragmented in order to be transmitted.

5. `RADIO_check_if_ready`: This function can be called at any time by LBARD, and the driver should indicate if the radio is ready to send the next packet, or not.

7.6 Steps to create a driver for a new radio type

To create a new radio driver for LBARD, the `drv_RADIO.c` and `drv_RADIO.h` files must be created in the `src/drivers` directory. The files should be named, such that *RADIO* is replaced by a short name for the radio. An empty driver, the null driver, exists in `drv_null.h` and `drv_null.c`, which can be used as a convenient starting point by making and renaming copies of these files. The function names in both files should then be changed to match the new radio.

Alternatively, if the operation of the new radio is substantially similar to another existing radio type, it may make sense to fork that driver.

The auto-detection routine for the driver should be implemented, and tested with all supported radio types, to ensure that it correctly detects the radio type, and does not interfere with the correct detection of the existing drivers. Following this, the other functions in the driver should be completed, and tested with real hardware, to ensure proper operation of the driver.

7.6.1 Automatic detection and linking of drivers in LBARD

Whether a new driver is created from the null driver or forked from an existing driver, the LBARD compilation process and driver initialisation code needs to know about the new driver. LBARD automates this through creative use of several small scripts that are called by the `Makefile`. This avoids the need for the developer to modify the build process, as well as enabling the drivers to all be compiled into a single LBARD programme, allowing any Mesh Extender device to use any supported radio at any time.

The key to this driver linking process is the creation of a special comment line at the top of the `drv_RADIO.c` file, that has the general format of:

```
/*
```

```
RADIO TYPE: SHORTNAME,"shortname","Long name of radio type",shortname_radio_detect,
*/
```

The words *SHORTNAME* and *shortname* should be replaced by the upper case and lower-case versions of the short-name of the radio driver, i.e., the part that takes the place of *RADIO* in the `drv_RADIO.c` filename. That is, the names of the listed functions should match those in the driver. If the driver uses the auto-detection routine supplied by another driver, the name of the correct `*_radio_detect` command should be used. The 0 at the end of the line is the estimated latency of the link in seconds, if it is an HF radio. If it is not an HF radio, this value should be left as 0. The comment *must* begin at the left edge of the file, i.e., there should be no spaces before `RADIO TYPE:`.

The Makefile contains a script which searches for such comments in the `src/drivers` sub-directory, and from them populates the `radio_types` structure in `xfer/radio_types.c`:

```
 $(INCLUDEDIR)/radios.h: $(RADIODRIVERS) Makefile
echo "Radio driver files: $(RADIODRIVERS)"
echo '#include "radio_type.h"' > $(INCLUDEDIR)/radios.h
echo "" >> $(INCLUDEDIR)/radios.h
echo "#define RADIOTYPE_MIN 0" >> $(INCLUDEDIR)/radios.h
grep "^RADIO TYPE:" src/drivers/*.c | cut -f3 -d: | cut -f1 -d,
| awk '{ printf("#define RADIOTYPE_\%s \%d\n",$$1,n); n++; }
END { printf("#define RADIOTYPE_MAX \%d\n",n-1); }' >> $(INCLUDEDIR)/radios.h
echo "" >> $(INCLUDEDIR)/radios.h
for fn in `(cd $(SRCDIR); echo drivers/drv_*.h)`; do echo "#include \"$$fn\""; done
echo "" >> $(INCLUDEDIR)/radios.h
```

It also populates the set of `#define` statements created for each of the radio types in `include/radios.h`. The result will be two files with content similar to the following:

```
#include "radio_type.h"
#define RADIOTYPE_MIN 0
#define RADIOTYPE_HF2020 0
#define RADIOTYPE_HFBARRETT 1
#define RADIOTYPE_HFCODAN 2
#define RADIOTYPE_HFCODAN3012 3
#define RADIOTYPE_LORARN 4
#define RADIOTYPE_NORADIO 5
```

```
#define RADIOTYPE_OUTERNET 6
#define RADIOTYPE_RFD900 7
#define RADIOTYPE_MAX 7
#include "drivers/drv_hf2020.h"
#include "drivers/drv_hfbarrett.h"
#include "drivers/drv_hfcodan.h"
#include "drivers/drv_hfcodan3012.h"
#include "drivers/drv_lorarn.h"
#include "drivers/drv_null.h"
#include "drivers/drv_outernet.h"
#include "drivers/drv_rfd900.h"
```

The second file (src/xfer/radio_types.c) gets generated in the next piece of script after the first one, with a content something like the following:

```
#include <stdio.h>
#include <fcntl.h>
#include <sys/uio.h>
#include <sys/socket.h>
#include <time.h>
#include "sync.h"
#include "lbard.h"
#include "hf.h"
#include "radios.h"


radio_type radio_types[]={
{RADIOTYPE_HF2020,"hf2020","Clover 2020 HF modem",hf2020_radio_detect,hf2020_servic
{RADIOTYPE_HFBARRETT,"hfbarrett","Barrett HF with ALE",hfcodanbarrett_radio_detect,
{RADIOTYPE_HFCODAN,"hfcodan","Codan HF with ALE",hfcodanbarrett_radio_detect,hfcoda
{RADIOTYPE_HFCODAN3012,"hfcodan3012","Codan HF with 3012 Data Modem",hfcodan3012_ra
{RADIOTYPE_LORARN,"lorarn","First LoRa-type radio",lorarn_radio_detect,lorarn_servi
{RADIOTYPE_NORADIO,"noradio","No radio",null_radio_detect,null_serviceloop,null_rec
{RADIOTYPE_OUTERNET,"outernet","Outernet.is broadcast satellite",outernet_radio_det
{RADIOTYPE_RFD900,"rfd900","RFDesign RFD900, RFD868 or compatible",rfd900_radio_det
{-1,NULL,NULL,NULL,NULL,NULL,NULL,NULL,-1}};
```

These files are shown simply for instruction – a developer creating a new driver need not look in them, as the whole point is that they are automatically maintained for them. The tt radio_types structure is used internally by LBARD to call the auto-detection routines of each radio driver, and to then copy the function pointers for the correct radio driver.

7.7 Simulation of Radios

It is also possible to create a simulation driver for the radio in `fake_RADIO.c` in the `src/drivers` sub-directory. Such a simulation driver functions similarly to that of the radio drivers, with automatic linking. Finally, it is possible to create tests that use the simulated radio to create automated regression tests by modifying the `tests/lbard` file. These activities fall outside the scope of this chapter.

7.7.1 Comparison of different supported radio types

Following the refactoring of the code-base, the various radio drivers implemented in LBARD can be clearly identified in the `src/drivers` directory, as summarised in Table (7.1). The HF radios listed concern the HF radio ALE 2G support that is described in chapter (8), which predates the work of this chapter in time. This table shows that a rather wide variety in radio types with differing properties can be accommodated by this driver framework.

7.8 Summary

Prior to the work described in this chapter, the radio driver system in LBARD was ad-hoc in nature, opaque, and difficult to extend. By refactoring the code-base to support a simple modular driver framework, these problems have been resolved. The inclusion of an automatic driver linking mechanism further simplifies the creation of additional radio drivers, by removing the need to modify the build system when new drivers are added. The wide variety in the properties of the radios supported under this driver framework demonstrate its flexibility.

In short, with this work complete, the last preliminary step has taken in order to add support for higher-bandwidth HF radio systems into the Serval Mesh, a topic that is addressed in the following two chapters.

Radio type vs Properties	HF Codan radio	HF Barrett radio	RFD900 radio	LoRa radio
Transmission speed	182 byte/sec	200	16 KB/sec	<1KB/sec
AT-command based control	Yes	No	No	Yes
Raw packet radio interface	No	No	Yes	Partial
Transmission latency (seconds)	7 sec	unknown	<0.1 sec	2 sec
point-to-point (P2P) or point-to-multi-point (P2MP)	P2P	P2P	P2P + P2MP	P2P + P2MP
Supports hardware flow control	Yes	No	Yes	N/A

TABLE 7.1: Table of properties of the various radio types, demonstrating the wide variety of radio devices that are already accommodated by this driver framework.

Chapter 8

Leveraging ultra-low bandwidth links for the Pacific

8.1 Introduction

Part of this work is published in IEEE GHTC conference, 2017, titled "Scalable telecommunications over ultra-low-bandwidth radio backbones". This chapter presents a considerably expanded coverage than is included in that paper.

This chapter describes the process of the initial integration of HF radios into the Serval Mesh, to facilitate telecommunications in the Pacific in circumstances that currently lack solutions, primarily for remote island communities and disaster-impacted locations. This builds directly on the modular driver framework presented in the preceding chapter. In doing so, this chapter answers research questions numbers 1, 3 & 4, i.e.:

- Is it possible to provide a cost-effective and free-to-use communications solution to low-income remote community members?

  This question is answered in part through the addition of long-range communications to the Serval Mesh, so that it becomes possible for members of isolated communities to make use of it.

- Can we extend the communications range of Serval Mesh network to hundreds of kilometres? Can HF Radio be a solution to this problem?

  This question is answered in that we demonstrate the integration of HF radio into the Serval Mesh, which provides the capability to communicate over hundreds of kilometres to the Serval Mesh.

- HF data links have very low bandwidth. Can we manage such low-bandwidth links effectively, to enable very isolated communities to communicate with one another?

> This question is answered in that we demonstrate the management of type of low-bandwidth link, which is capable of very long-range communications, that has the potential to link very isolated communities with one another.

The following chapter builds on the work of this chapter by improving the performance of the Serval Mesh over HF radios, to achieve increased system capacity, that further improves its utility.

Long-range communications links are highly desirable in many situations, including following disasters, and in a remote area. It can provide tremendous advantages to users. However, providing conventional telecommunications infrastructure that can provide this capability in these situations can be expensive, difficult to sustain, or both. For these and other reasons, long-range telecommunications are not universally available in these situations.

The Pacific region includes many small nations that are distributed over relatively small and isolated islands. Many of these islands have very small populations, and often lack reliable means of communications, especially the more remote islands. Most of these countries have very small economies compared with the logistical cost and difficulty of providing robust telecommunications infrastructure to all of their populated islands. Therefore new thinking is required, if it is to become cost-effective to provide all of these communities with the protective and beneficial mantle of telecommunications that larger populations take for granted.

The geography, including the remoteness of many islands in the Pacific, have a significant impact on their ability to access telecommunications services [71]. This makes planning for disasters particularly difficult in these countries because of the uneven availability of telecommunications services that are likely to be relied upon to warn of approaching disasters, or to respond to disasters after they have occurred. This motivates the need to create telecommunications solutions that are both cost-effective, as well as able to provide communications to these small and isolated island communities.

This chapter answers this need by presenting improvements to the LBARD protocol, by documenting the integration of support for Codan digital HF radios into the Serval Mesh. By doing so, it is demonstrated how the modular driver framework of LBARD can be used to support additional radio types, and in the specific case of the Codan digital HF radios, how this can be used to bring support for very long-range communications to the Serval

Mesh. This work also includes improvements to LBARD to improve its performance when operating over very slow and high-latency connections.

8.2 Contributions

For this chapter, the contributions are:

1. An appraisal of the communications challenges and potential solutions for remote islands and disaster-impacted locations in the Pacific.
2. The extension of the range of communications of the Serval Mesh from kilometres to hundreds, or even thousands of kilometres, by making it practical to use Codan digital HF radios as part of a Serval Mesh.
3. The improvement of the LBARD software to make more efficient use of ultra-low high-latency communications links. The result is the ability to send hundreds of messages per day over a single HF radio link, sufficient to support effective communications between isolated communities linked only by HF radio.

8.3 Challenges of getting communications to outlying Pacific islands

Pacific Island Nations are distributed over an incredibly large area, of approximately 15% of the total surface of the earth [25], as can be seen in Figure (8.1). This huge area has thousands of islands scattered in the ocean, and even within one country, the distance between islands can be many hundreds of kilometres. As a result, the total population of this vast area is only a few million people, and the collective scale of the economy is very low compared with most of the rest of the world. Thus while it is imperative to connect these people, to support their further economic, social growth and resilience, the very same factors make it much more expensive and challenging to provide telecommunications in this region, especially to the smallest and most isolated island communities, of which there are relatively many. The frequent occurrence of disasters, including cyclones, earthquakes and tsunamis, further complicate the long-term provision of services in this area.

The Pacific Island Nations are included in the categorisation of Small Island Developing States (SIDS), a group of small-sized and relatively remote

FIGURE 8.1: This image has been removed due to copyright restriction. Available online from [38]. Map of Pacific islands, showing the national borders, and how the area of the islands is tiny in comparison to the area of the surrounding ocean.

countries that share a similar label and subject to a similar set of development challenges, that are particular to the SIDS. For example, the combination of a low-income based economy, frequent natural disasters, remoteness, small populations, and a high dependency on international trade and support [27].

PICs are highly vulnerable to climate change and disaster risk, making telecommunications between individuals extremely important to help people to access information, ensure community safety, and to increasing public awareness during times of emergency [99].

However, these countries face many challenges to provide telecommunications services to the entire populations, intrinsically linked to the problematic combination of challenges that SIDS face. Some of these challenges are as follows:

8.3.1 Small population in each village or island

The countries in the Pacific Ocean are typically small in both land area and population, and widely scattered over the ocean area, e.g., Papua New Guinea, Fiji, Vanuatu, Nauru, Kiribati, Marshall Islands, Federated States of Micronesia, Samoa, Solomon Islands, Palau, Tuvalu, Tonga). Each of these countries, in turn, typically consists of many islands. The combined number of populations in these countries, excluding Papua New Guinea, is only about 2.3 million people [25, 40], and some of these countries have extremely small populations, with less than 13,000 people each living in Tuvalu and Nauru. Further, in many of these nations, a large percentage of the population lives on one or two of the largest islands, meaning that the remaining population is often spread over a very large area, and divided into many small to very-small villages, many having populations less than 100 [76, 142].

It is also very common to find family members distributed over different nearby villages or islands due to the considerable social and economic interactions among these small communities, e.g., through weather, movement in search of work, or relocation to avoid the effects of various natural disasters. Thus the geographic isolation of each community exists in tension with the desire and need of these isolated communities to be able to communicate with one another.

Life in these small communities is typically some form of subsistence farming, often a combination of agriculture and fishing, both of which can be greatly benefited through access to timely expert advice [106].

8.3.2 The tyranny of distance

Pacific islands' geographical distribution in a vast ocean makes many of these islands suffer from intense isolation, as there are no easy and reliable means for interconnection with other islands.

The large geographical distance between remote islands acts as an effective natural barrier against many humans activities, which contributes to the isolation of the people living there [104, 106]. Typically the only means of travel is via small motorboats, which can only be used in favourable weather conditions. This limits communications, trade and a variety of other beneficial activities, and consequentially increases the vulnerability of these communities, and logistical difficulty and cost of providing services to them.

8.3.3 Lack of cellular network and electrical grids

It is therefore not surprising that many of these remote islands lack cellular network coverage, access to an electrical grid, or both.

These two factors feed into one another, in that the lack of an electrical grid makes it more expensive to provide cellular communications, and the lack of cellular communications tends to be implicated in lower levels of economic activity, which retards these communities ability to build their local economies to the scale where they could support an electrical grid. It is therefore not surprising that the Pacific region is classified as the last place on earth to be covered by cellular network service, precisely because of many of these confounding challenges of small scattered populations, remoteness, and vulnerability to disasters [255, 53].

The lack of cellular coverage in Pacific Island Nations thus leads to many negative effects for the members of these community, leaving them among the most vulnerable people globally [83, 255, 40].

In regards to the provision of electricity, it is typically not possible to extend the electrical grid from urban areas to the remote outlying islands due to the extremely high cost and transmission losses that would result. Thus the focus tends to be on providing local energy generation or harvesting and storage solutions. Many islands are dependent on diesel generators, for example, or use low-voltage DC solar systems to power households or small communities. However, these solutions all remain relatively expensive when compared to the economic means of these communities. Therefore it often falls to governments or foreign aid agencies to underwrite grid extension activities [226, 155].

8.3.4 Expensive telecommunication services

Where telecommunications services are available to small island populations, they are often expensive relative to the financial means of these communities. Another problem is that many of these communities do not substantially rely on a money-based economy, and/or lack easy means to purchase communications services [83, 255]. This creates a kind of catch-22, where the high cost of providing the services, including due to the often vexed logistics of maintaining the equipment once installed, which might include flying in by helicopter, and then hiking through the jungle carrying fuel, tools and spare parts [105], creates a reluctance of mobile operators to extend coverage, because they cannot recoup these costs due to the small population size and limited economic activity, which perpetuates the lack of economic activity in these locations.

Fortunately, there are initiatives around the world to help mitigate these challenges, and support the resilience, safety and prosperity of SIDS. There is a growing interest in providing telecommunications services to many islands in the Pacific region, and foreign aid frequently plays a significant role in this, enabling or even directly supporting the modernisation of telecommunications infrastructure and capabilities in the region [40]. However, these funds are limited in what they can achieve, due to the cost of provisioning traditional telecommunications infrastructure, especially on small and isolated islands. This is why the research described in this thesis focuses instead on the creation of lower-cost approaches to providing basic telecommunications services in these challenging locations.

8.4 Possible communication technologies for Pacific Island Nations

Even though some communications technologies, such as HF radio, were introduced decades ago into the Pacific region, they remain relatively unavailable to small isolated communities. In many cases, communications networks were deployed to key regional centres by colonial governments in the period before many of these nations gained independence [99]. Unfortunately, the situation in remote areas has not changed greatly following the independence of these many countries, again, due to the cost and other challenges of providing pervasive communications solutions, and the limited utility of the traditional manner in which technologies like HF radios were deployed, where only one or a few people were able to make use of the equipment.

However, as communications technologies have evolved and propagated, both urban centres and many islands have witnessed a noticeable growth and adoption of these new technologies, especially over the last two decades. For example, despite the difficulties in reaching the most isolated and smallest of communities, cellular network service and internet are now available in many areas of all Pacific Island Nations [61].

In the following text, we consider a number of the communications technologies that are used in or could be used in Pacific Island Nations, depending on the particular circumstances.

8.4.1 Cellular Telephony

This service is one of the modern technologies which was propagated widely in the Pacific region, and there are many commercial telecommunication companies active in the region, including Digicel and Vodafone.

However, the cellular service provided by these companies in many areas is often 2G or the earlier generations of 3G, as these are typically cheaper to deploy and maintain, and often have a greater range of communications. Thus throughout much of the Pacific, the performance of cellular networks is well below what might be expected elsewhere [105, 53]. In particular, internet access is often very slow, partly because of the use of 2G or 3G cellular protocols, but also because of inherent limitations of local internet connectivity, as is described below. Finally, the physical extent of cellular coverage is often limited by the economics of deploying and maintaining a network into the most remote areas of these nations, where it is unlikely for the carrier to be able to do so profitably [83].

8.4.2 Internet service

Internet access is available through much of the Pacific, using a combination of cellular, satellite, fixed-wireless, dial-up, DSL and fibre-optic infrastructure. However, it is often limited by the availability, capacity and cost of the backhaul links from the Pacific Island Nations to the outside world. While submarine cables now reach many Pacific Island Nations [100, 247], they typically land at only the main island of a given country, and outlying islands often remain dependent on satellite backhaul for internet connectivity, which greatly increases costs and limits bandwidth. Thus effective coverage remains limited or non-existent in many of the most isolated communities.

8.4.3 Satellite communications

Satellite communications links have the advantage that it is possible to cover to even the most remote island communities, because they do not require terrestrial links for backhaul. Also, Pacific Island Nations are generally relatively near the equator, which means that the geostationary satellites are visible very high in the sky, higher than for mid-latitude countries like Australia. Also, the relatively low population of the Pacific basin means that satellite capacity is typically not fully occupied, and that where the funds are available, it is possible to obtain relatively high bandwidth satellite connections.

However, it is the cost of leasing the satellite capacity that remains problematic. This is especially the case where individual solutions are pursued, rather than coordinated national or regional solutions where substantial economies of scale are possible. Also, regional solutions have the advantage that a high-bandwidth link can be obtained, and then time-shared among communities, so that even services like video-based telehealth become possible.

The University of the South Pacific does have a regional solution for its campuses spread throughout the region, demonstrating that such an approach is indeed possible. However, this is the exception, rather than the rule. The result is that satellite internet and telephony services in the region remain too expensive for most remote communities to effectively access [100, 138]. Also, even where cost-effective solutions can be found, satellite services still tend to be more limited in bandwidth than terrestrial solutions, and suffer from much higher latency, which considerably degrades the end-user experience.

There is hope; however, that new LEO (Low Earth Orbit) and MEO (Medium Earth Orbit) constellations, such as the Star Link system will, over time, reduce the cost and latency of provision of satellite-based internet and telephony services in the Pacific, while simultaneously greatly increasing the bandwidth that can be obtained. However, a challenge here is to get companies, like Star Link, to engage with the region because of the very small relative revenues that they will be able to extract from these small and low-income populations. It may well be that the best solution in this regard is for the various governments in the region to come up with a joint approval and management process, so that Star Link is able to reduce their cost of engagement, making it commercially feasible for them to enter the Pacific markets.

8.4.4 HF radio

The potential for HF radio to meet some of the communications needs of the Pacific Island Nations has already been discussed in this thesis, and requires little further comment here, other than to reiterate that HF radio has found productive use in the region dating back to the 2nd World War, and has been used by governments, businesses, non-governmental organisations, relief organisations and individual communities in various ways since that time. HF radios are relatively expensive, but this is somewhat offset by the propensity of foreign aid organisations to be willing to purchase or upgrade HF radio networks from time to time. Thus finding ways to improve the utility of HF radio networks in the Pacific is attractive, as the technology is already well known to the likely funders, and they are comfortable with funding its deployment or improvement.

8.4.5 Serval Mesh

More recently, the Serval Mesh was created to address many of the communications challenges in the Pacific, and in particular for remote and disaster-impacted communities. This work has attracted considerable interest in the Pacific region, as it is rightly perceived as a new approach that can resolve many of the previously insolvable telecommunications challenges that frequently arise in the region, in particular, a relating to the most remote communities, and those areas where telecommunications infrastructure is at risk of damage due to the impact of disasters. For example, the Australian Department of Foreign Affairs and Trade has in recent years funded a pilot of the Serval Mesh in Vanuatu, as evidenced in Figures (8.2) and (8.3). The New Zealand Red Cross, which plays a leading role in disaster communications in the Pacific, has also been strongly engaged in the creation of the Serval Mesh. This interest has expanded to other groups active in the area, such as the UN World Food Programme's regional office for Asia and the Pacific, who are in the process of funding the first deployment of Succinct Data, a derivative of Serval Mesh, to assist in the monitoring of public health in Tuvalu, with a focus on the COVID19 pandemic. Similarly, Serval Mesh forms part of the mandated activity of a UN World Health Organisation Collaborative Centre for Mass Gatherings and Public Health.

However, as previously described, the main challenge for the deployment of the Serval Mesh more broadly in the Pacific has been the lack of a solution for very long-distance communications that would enable the connection of remote island communities with one another and with larger regional or national population centres.

8.5 Appraising communication techniques

The above discussion has introduced a number of telecommunications technologies that are potentially beneficial for Pacific Island Nations. Many are already providing considerable benefits to people living in the region. Having introduced these technologies, the focus now turns to their appraisal. To facilitate this, several criteria are introduced, by which they can be measured

FIGURE 8.2: Piloting Serval Mesh in Vanuatu[83]. Examining Mesh Extender by representatives of NGOs and institutions in Pacific region during a Emergency Telecommunications Cluster (ETC) workshop organised by UN World Food Programme and the government of Vanuatu.

FIGURE 8.3: Piloting Serval Mesh in Vanuatu[83]. A meeting with a representatives from the mobile carriers in Vanuatu.

and compared. It is recognised that no single set of criteria can, however, provide a completely objective analysis, in part because there are many different use-cases, and each technology may excel at particular use-cases, but be unsuitable for others. To resolve this, this thesis continues to focus on the use-cases related to communications support for remote island communities and for post-disaster use.

1. Coverage area: As Pacific Island Nations typically consist of many widely spaced islands and their surrounding seas, the area of coverage of any technology is important. A larger coverage area is better.

2. Cost: As incomes in Pacific Island Nations, and their scales of economies are limited, the cost is a critical factor. This is especially true for remote island communities and disaster-impacted communities, where the cash economy may be very limited or completely absent. The lower cost is better.

3. Capacity: Communications techniques vary in their capacity. This thesis focuses on basic services, in particular, text messaging. Thus an appropriate measure is the number of messages that can be delivered per day. Higher capacity is better.

4. The latency of delivery: Different technologies will experience different latencies for the delivery of text messages. Lower latency is better, especially for disaster early warning and response.

5. Energy requirements: The lack of a robust electrical grid in many areas of the Pacific, especially on remote islands and following disasters makes energy a key factor in sustaining communications. Solutions that can provide their own energy requirements, e.g., through being able to be powered from batteries or solar panels, e.g., as in Figure (8.4), are preferable over those that require a stable mains power supply.

6. Maintenance requirements: Maintenance of equipment is a chronic problem in the Pacific. The combination of low incomes, frequent disasters, corrosive tropical maritime climatic conditions and limited local capacity for the maintenance of telecommunications equipment create considerable problems. It is not uncommon for foreign aid agencies to gift equipment, which then quickly falls into disuse due to the inability to maintain the equipment. Therefore equipment which requires the least and least complicated maintenance is preferable over technologies that require regular, expensive and/or complicated maintenance

(A) (B) (C) (D)

FIGURE 8.4: Installing solar panel to provide power for Serval Mesh Extenders in the village of Pang Pang in Vanuatu, as part of the pilot of the Serval Mesh in Vanuatu. This village lacks access to the national electricity grid, despite being located on the main island of Vanuatu. Such situations are common, because of the small populations in these villages, which are often separated by many kilometres from one another.

7. Infrastructure Dependence: Related to the challenges of maintaining equipment and capabilities in the Pacific, telecommunications solutions which depend on other local infrastructure, equipment or services will be much more vulnerable to failure, than those that are able to operate independently.

8. Disaster Resilience: The Pacific region is impacted by many natural disasters each year, some of which are capable of destroying local infrastructure, especially infrastructure that is not designed to survive such events. Therefore technologies which are more resilient in the face of disasters are highly preferable.

Table (Table 8.1) summarises the assessment of the previously identified telecommunications solutions against these criteria.

8.6 Combining the strengths of HF radio and the Serval Mesh

Table Table 8.1 is very instructive, in that it allows us to see that the more popular telecommunication technologies, such as cellular phone and internet, are problematic for isolated communities and following disasters. It becomes clear that a combination of the Serval Mesh, with the long-range communications capability of HF radio has the potential to have the most positive overall set of characteristics.

HF radio and Serval Mesh are remarkable communications techniques, in that they can be employed immediately in post-disaster situations since they do not require any infrastructure to work. However, individually they have limitations, that limit their current utility: The Serval Mesh has a limited range of communications, while HF radio is limited by human factors, including requiring that users be physically at the HF radio to make or receive calls, and that the audio quality on the commonly deployed analog HF radios is problematic. Also, at peak times, it is neither simple nor time-efficient for many users to share a single HF radio.

However, by combining these two technologies, it is possible to eliminate these disadvantages: First, the Serval Mesh gains the ability to communicate over very long distances, sufficient to connect isolated island communities. Second, the human factors that limit the use of HF radios are avoided: The Serval Mesh allows users to send and receive text messages, and in the future, voice mail messages, from their own devices and wherever they are located in a village that has deployed Serval Mesh Extenders [84, 193]. Having Serval control the HF radio avoids the need for users to sit at the radio, and allows messages to be queued for transmission during busy times and to be delivered as soon as they can be transmitted and received. The result is something that approximates the feeling of an SMS-capable cellular network, but without the challenges that face providing cellular coverage to such remote areas.

This combination is made possible by the provision of a modular radio driver framework in the Serval LBARD software, and the modular nature of the Serval Mesh Extender hardware, that allows connection to an external radio. The remainder of this chapter describes the process by which HF radio support was included into LBARD, to allow this marrying of the benefits of HF radio and the Serval Mesh.

8.7 Challenges and opportunities for LBARD performance over HF radio

Serval Rhizome is a store-and-forward and bundle-based protocol. That is, data bundles, rather than packets are the basic data unit transferred in the network.

Basically, when an LBARD instance, i.e., the LBARD software controlling a physical radio, is willing to transmit a packet, the LBARD program generates a packet that contains both bundle inventory synchronisation information, as well as some fragment of a bundle. The Tree-Sync algorithm introduced in chapter (6) is used for the efficient communications of bundle inventory information, and the encoding of bundle fragments uses LBARD's existing encoding for this. This approach is used, regardless of the radio type being used.

8.7.1 Very small packet sizes and high latency

A key challenge is that although the typical LBARD packet size is already very small, usually less than 250 bytes, including addressing information and all other overheads, it is still too large for encoding using ALE v2 text messaging, and thus each LBARD packet must be fragmented, in order to be able to be transmitted using this mechanism that is available on HF radios.

Sending an LBARD packet in this way may take 30 seconds or more, and as a complete Serval Mesh text message may require several packets in order to be transferred, this means that message delivery is likely to take several minutes. This makes the prioritisation of which bundles to send first all the more important.

Fortunately, LBARD implements a flexible prioritisation mechanism that specifies which bundle is the highest priority to be sent over a given link at a given point in time [136]. It allows priority sorting of bundles based on a variety of factors, e.g., the size of a bundle, the type of bundle, or information about where the sender and recipient are located. This ability to increase the intelligence of the prioritisation function based on situational awareness of the network is expected to be important for improving the performance of the Serval Mesh when communicating over HF radio links.

8.7.2 Local versus remote bundles

As the capacity of HF radio links is very constrained, it is necessary to consider methods by which the number of bundles that must be transmitted can be reduced. One approach to this problem is to consider whether a given bundle is for local or remote consumption. That is, whether the recipient is (or is likely to be) on the near or far side of an HF radio link. If the recipient is likely to be on the far side of an HF radio link, then it should be given a higher priority for transmission over that link, than a bundle whose recipient is likely to be on the near side of the HF radio link.

This method can greatly reduce the number of bundles that require transmission over an HF radio link. It also has the advantage where an incorrect decision is made as to whether a recipient is on the near or far side of an HF radio link, that the worse-case situation is that a bundle has its priority of transmission reduced. That is, the bundle is not dropped or lost, but rather merely delayed. Thus the bundle will still be eventually delivered. Also, if LBARD receives more information that allows it to update its heuristic as to whether it believes a recipient is on the near or far side of an HF radio link, then it can increase the priority of affected bundles, and thus respond dynamically to its awareness of network conditions and the location and movement of users.

By way of example, consider Figure (8.5), where two villages, N and C, are using the Serval Mesh, and linked via a single HF radio. If N1 sends a message to N2, the sender and recipient are both on the same side of the HF radio link, and thus there is no need to transfer bundles over the HF radio link. In contrast, if N1 and C1 wish to communicate, then their bundles must be replicated over the HF radio link, in order to be delivered to the final destination.

However, determining which side of a link the sender and recipient are located on is non-trivial in the general case, especially where users are likely to move from one location to another as they go about their lives. Therefore there is a need to devise some kind of heuristic of locality, which can be fed into LBARD's prioritisation scheme, so that messages can be intelligently prioritised to make the most effective use of the highly capacity constrained HF radio links.

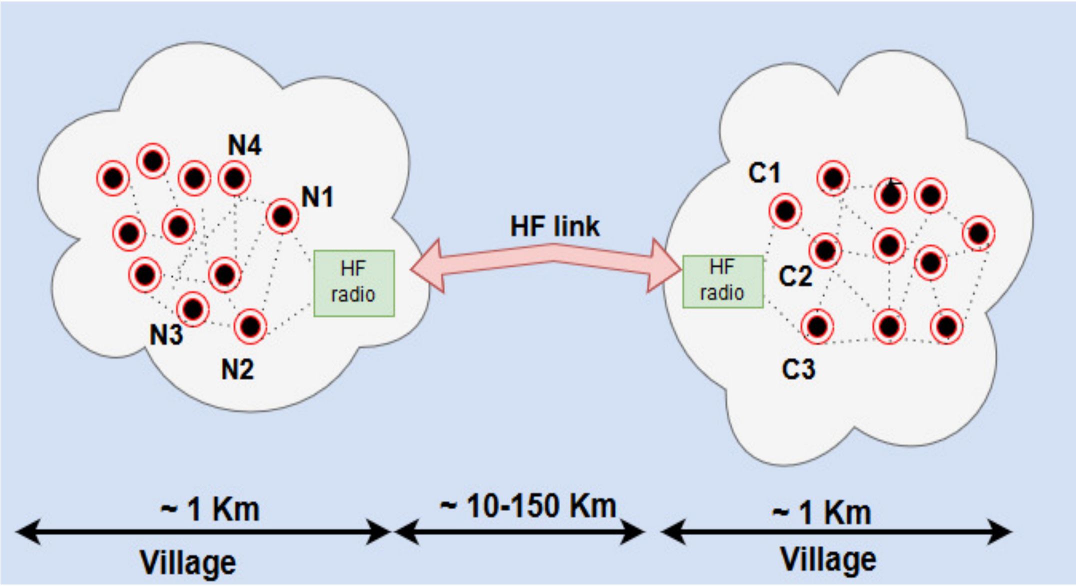


FIGURE 8.5: Two villages using the Serval Mesh located on different islands, connected via an HF radio link.

8.7.3 Inferring Locality

To better understand the locality inference problem, it is helpful to consider some example situations. These examples are based on the fictional network of Figure (8.5). This Figure depicts two villages, each with a Serval Mesh deployment, and that are so far apart from one another that an HF radio link is the only practical option for linking the villages.

The first village has nodes N1, N2, N3 and N4, while the second village has nodes C1, C2 and C3. Thus traffic among the N nodes should ideally not be sent across the link to the other village. Similarly, traffic among the C nodes should also not be sent across the HF radio link to the first village. Only the traffic between the N nodes and C nodes should be transferred across the HF radio link. While these nodes are clearly differentiated in the Figure by their N and C prefixes, in reality, there is no way to make such a convenient distinction between the nodes, which is why some mechanism for inferring locality is required.

It is assumed that all nodes in each village will rapidly replicate the bundles that any node in the village has to all other nodes in the village. Thus for convenience, we ignore the process of distribution of bundles among the nodes in a village.

It is also assumed that an instance of LBARD runs on both sides of the HF link, and it monitors the arrival of any bundles over the link. This instance of LBARD is part of integrated Mesh Extender 2.0, as in Figure (8.7), which is connected to an HF radio. The Mesh Extender will continue to communicate with the other Mesh Extenders in the same village via the combination of Wi-Fi and UHF packet radios that they possess.

One heuristic that is possible, is for the LBARD instance at each end of the HF radio link to monitor the arrival of bundles via all of these means. If a bundle is first observed via the HF radio link, then it can be tentatively assumed to have originated from a sender at the other end of the link. In contrast, if a bundle is first observed arriving via a Wi-Fi or UHF packet radio link, then it can be tentatively assumed to have originated from a sender on the local side of the HF radio link. As the meta-data for bundles contains the sender and recipient's identities, it is possible for LBARD to build a list of identities, and whether it believes that they are local or remote, with regards to the HF radio link.

Consider the situation where the instance of LBARD on the left side of the HF radio link in our example pair of villages has received the set of bundles listed in Table (Table 8.2) via Wi-Fi or UHF, i.e., not via the HF radio link.

This LBARD instance has not discovered any remote bundles, as no bundles have crossed the HF radio link yet, and thus there is not yet any information that it can use to make such inferences.

With perfect knowledge, we can, however, see that bundles 8 and 15 should be transmitted via the HF radio link, as it can be seen that the recipients of those bundles exist in the right-hand village. That is, an implementation with perfect knowledge would send only these two bundles, as depicted in Figure (8.6).

However, without perfect knowledge, LBARD would proceed using its normal priority algorithm, where smaller bundles are sent before larger bundles. That is, bundles 7, 14 and 11 would be sent initially, even though this is not required for those bundles to be delivered to their recipients. Then bundle 15 as the next largest bundle after bundle 11 would be sent next. Then LBARD would continue with bundles 10, 16, 19, 1 and 17, before transmitting bundle 8, as it continues to transmit bundles in the order of their sizes. The challenge is to find a way to correct this order, so that LBARD will transmit bundles 8 and 15 earlier in this sequence, so that they are delivered with lower latency.

This example has only a few numbers of bundles, and each bundle is almost small size. However, the reality is typically more complex, with many more bundles, and of much larger sizes. Given that bundles, and newer versions of bundles, will continue to arrive over time, it is possible that the bundles that require being sent over the HF radio link may never reach the front of the queue, and thus never be delivered. Thus it is imperative to improve the order of transmission as much as possible.

The following text considers several possible locality heuristics that could be implemented.

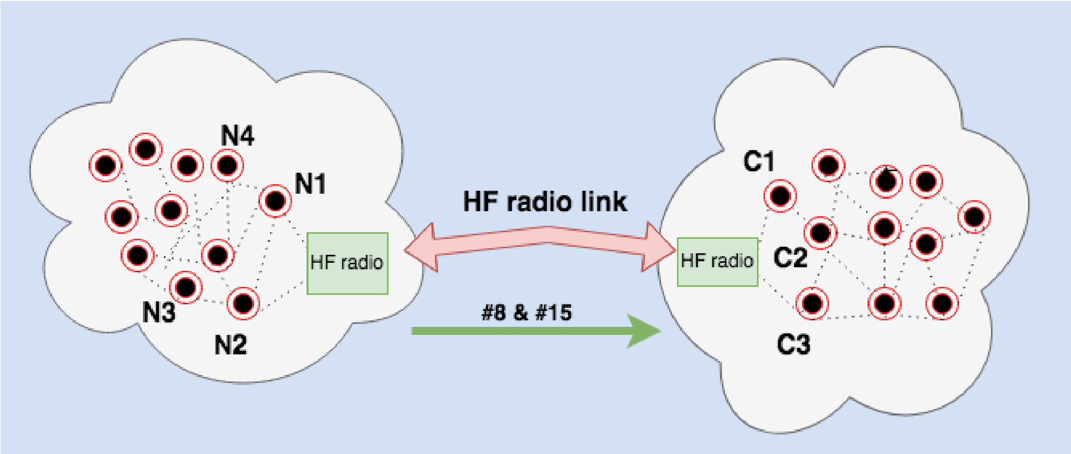


FIGURE 8.6: Only the two remote bundles have to cross the HF radio link

8.7.4 Potential Locality Heuristics

This scenario demonstrates the value that a locality heuristic could bring to realistic traffic flows, allowing latency to be significantly reduced, and the effective capacity of the HF radio link to be increased by only transferring those bundles which require transferring to the other side. With more complex topologies, the situation will become even more complex, and prone to greater inefficiencies if locality heuristics are not implemented. The following describes several locality heuristics that could be applied to this situation, using only knowledge available to each LBARD instance.

Bundle sender heuristic

Each bundle in the Serval Rhizome protocol contains information about the sender and recipient. This information can be used to build statistical models of whether a given sender or recipient is believed to be on the near or far side of an HF radio link. If a bundle from a given sender is first received via the HF radio link, then the probability that the sender exists on the far side of the

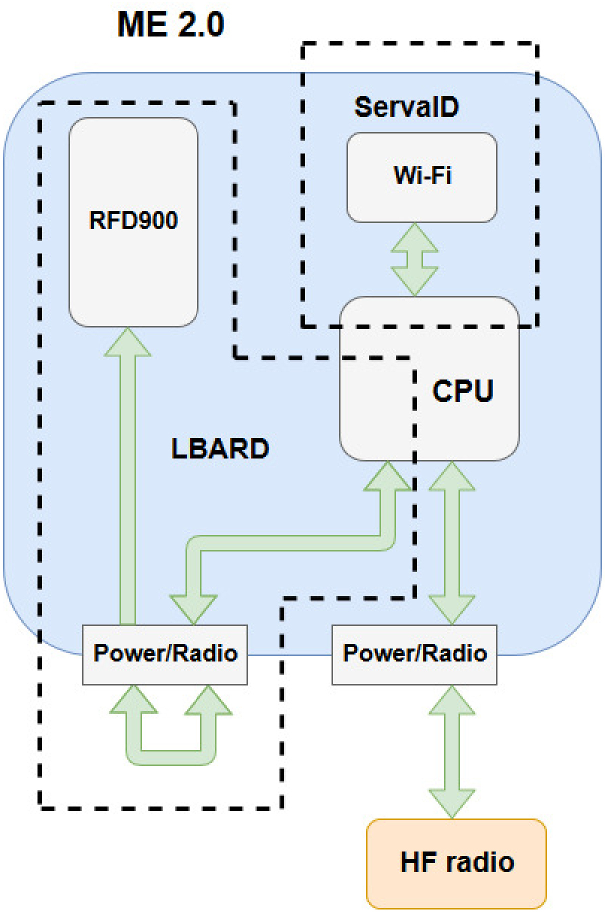


FIGURE 8.7: Block diagram for Mesh Extender 2.0 connected to HF radio via cable, and they both run by LBARD instance.

HF radio link should be increased. Conversely, if a bundle is first received via a Wi-Fi or UHF packet radio link, then it is more likely to have been sent from the local side. Thus such a sender is less likely to be on the other side of an HF radio link.

However, these inferences are not certain, especially if a sender moves location from time to time. Thus it is necessary to integrate such information over time, and the influence of individual events should decay over time, so that the location of senders who have moved from one location to another can be reasonably accurately modelled.

Indeed, a good first approximation is to simply monitor the most recently received bundle from each sender, and use the path by which it arrived to infer if the sender is local or remote with regards to the HF radio link. This has the significant advantage that the information required for each sender can be boiled down to the time of the last bundle from that sender, and whether it is local or remote. The timestamp is required so that the delayed arrival of older bundles from the sender can be disambiguated from the rapid arrival of newer bundles from the sender, thus reducing the potential for falsely believing that a sender is on the remote side of a slow link. This is enabled by the inclusion of timestamp information in most bundle types. This compact representation of the location state makes it possible to track the location of very large numbers of senders.

This approach also has the beneficial side-effect that as soon as a sender who has changed locations sends any bundle, it will allow the location inference information to be corrected. While this information may still take considerable time to propagate over HF radio links in some cases, to inform the remote networks of the new location of the sender, it will immediately quench the sending of bundles addressed to the relocated sender from their new local network.

This problem could be substantially mitigated by sending information about newly observed local nodes in a compact form over HF radio links, so that the velocity of communication of such events is dramatically increased. In particular, sending such information over links where the node was previously believed to be located would be particularly beneficial. Such location update information could be expressed in as little as perhaps 16 bytes, with 8 bytes for the 64-bit timestamp of the latest bundle timestamp observed, together with an 8-byte prefix of the sender's public key. This would result in a false positive rate of $< 2^{-32}$ via the Birthday Paradox. False positives could be completely eliminated by increasing the message size to 40 bytes, so that it can include the entire 32 bytes of the sender's public key.

Bundle recipient heuristic

It is also possible to make use of the recipient information included in the Rhizome bundles. While the sender information gives more direct information about the location of the sender, the recipient information provides only indirect information, in that it hints at where some node believes it is likely to find the recipient. However, because Rhizome uses a smart-flooding approach to message delivery, this information is not entirely reliable. However, it can be used to refine the belief of an LBARD instance as to whether it believes a node is on the near or far side of an HF radio link. This can be achieved because of the flexible dynamic prioritisation framework in the Serval Mesh, where the priority of a bundle to be sent over a given link can be calculated based on an arbitrary number of factors. For example, the inference from the sender ID in a bundle could be given a larger co-efficient than the belief garnered from the recipient ID.

Serval Mesh routing table

Further information is available from the routing information maintained by the servald instance present in each Serval Mesh Extender. This information contains definite information about which senders are physically present on the local network at the current time. Thus whenever the servald instance can see a particular sender on the local side of the network, it knows with certainty that the sender is not on the remote side. Thus bundles addressed to that sender can be given the lowest possible priority for sending over the HF radio link, and the location of the sender can be communicated over the HF radio link to the remote side in the compact format described above. This can allow the remote side to immediately realise that the sender is on the remote side from its perspective, and any bundles addressed to that node should be sent over the HF radio link.

It should be noted that this routing information is not perfect because it cannot bridge partitions in the network. This is because a sender has to be reachable in real-time via Wi-Fi links between Mesh Extenders and the sender's device in order for it to appear in the routing table of the Serval Mesh Extender. UHF packet radio links do not result in senders being added to the routing table, because only the Wi-Fi links can be used for communicating via the Mesh Datagram Protocol (MDP), to which the routing table corresponds.

8.7.5 The mobility problem

The heuristics, described above, work best when senders remain in one location with respect to any HF radio links. While they are capable of taking into account some degree of mobility between locations, they are not perfect in the face of mobility. The decisions are imperfect, based on inferences of location in many instances. Even where definite information is available about the location of a node, it must be transmitted over an HF radio link in order to be useful for the other side. Even though the information per node is very small, it is still a significant burden for HF radio links where data rates are typically between 1 and 100 bytes per second.

Some further improvement would be possible by implementing a mechanism to share the reachability of nodes via UHF packet radio, so that nodes can be identified that are local, but which never come within Wi-Fi range of the Mesh Extender which is controlling an HF radio, or within Wi-Fi range of a Mesh Extender that is directly or indirectly within Wi-Fi range of a Mesh

Extender that itself, in turn, is within Wi-Fi range of the Mesh Extender that is controlling the HF radio. This would come at the cost of increasing the traffic on the UHF packet radio links, so it itself involves a trade-off.

Another possible approach is to tag each received bundle with the number of HF radio links over which it has been transmitted. This can help to identify definitively whether a bundle has arrived via an HF radio link, even if it is some distance away on the network, or whether it is truly local. However, complications arise in that this information can be inconsistent between the various local networks because of the high-latency and distributed nature of the network. Again, resolving this through pre-emptive sharing of such information over HF radio links would add considerable traffic burden to those very bandwidth constrained links.

8.7.6 Data-Mule problem

Further complications come when considering the other implications of senders moving throughout the network. This is because Serval Rhizome is a store-and-forward based protocol. This means that when a sender moves from one area of the network to another, it will carry with it much traffic that was generated in that area of the network. This could easily fool the locality heuristics, particularly those relating to the sender and recipient of bundles that arrive via non-HF links, into thinking that many of the remote senders are, in fact, local.

This problem complicates the modelling of remoteness and locality. There are various possible mitigation strategies for this problem.

First, some mechanisms could be introduced that attempt to recognise when such events occur, e.g., by looking for large numbers of bundles arriving in rapid succession that are addressed to or from nodes that are not in the local network. This could then be used to infer those nodes are not, in fact, local.

Second, the problem is to some degree self-mitigating, in that if senders are regularly moving between two parts of the network connected via an HF radio link, then such data mules represent an alternative path through the network, and it could be argued to be the correct course of action to consider those nodes local, and de-prioritise their transmission via the HF radio link. Again, because LBARD only ever de-prioritised traffic, rather than dropping it, the worst-case scenario is that traffic is delayed, and provided the overall traffic volume is not too great, the system will become eventually consistent.

Also, if the proposed mechanism for communicating locality of a node is used, and the strength of belief is included, in particular when the presence of a sender in the local Serval Mesh routing table makes it certain that a node is currently located on one side or the other of an HF radio link, then the problem can be effectively managed.

Where such definite information is contradicted by the effects of a sender carrying data from one part of the network to another, this can be included in the bundle prioritisation function, so that such bundles still have a higher priority for transmission via the HF link than truly local traffic, but lower priority than for bundles addressed to senders who were not included in the data dump, and thus for which there is no alternate path. In this way, the system can very naturally make intelligent decisions about the relative priority of bundles addressed to various senders, taking into account such seemingly contradictory information.

These mitigations are probably effective enough for the pairs of villages that are connected to one another via HF radio links. However, where more complex topologies exist, they are likely to be insufficient. However, this is an acceptable situation in the first instance, as such complex topologies are likely to take time to emerge, and secondly, because it is also very likely that the use of HF radios in the Pacific will tend to continue to follow a hub and spoke topology, and if necessary, this could be mandated for the user of HF-enabled Serval Mesh networks.

8.7.7 Prioritisation, rather than filtering

This issue has been mentioned several times already, but is worth mentioning explicitly: The method of selecting the order in which bundles should be sent over an HF radio link is based on modifying the priority order, rather than dropping bundles from the list entirely if they are believed to be for local consumption only.

This makes errors from the locality heuristic soft errors, rather than hard errors, which is greatly preferable [55, 257], as they will eventually be recovered from, either when the misclassified bundles eventually reach the head of the transmission queue, or when updated information is received, which enables the priority of the bundles to be corrected, causing them to move higher in the transmission queue.

8.8 HF Proof-of-Concept

The feasibility of integrating HF radios into the Serval Mesh was confirmed by implementing a proof-of-concept system.

This was achieved through the generous provision of access by Codan and Barrett to examples of their radios at a conference. Photographs of these radios can be seen in Figures (8.8) and (8.9). Barrett and Codan were selected as they are the two most widely deployed brands of HF radios in the civilian space in the Pacific region. The mix of these two vendors radios in the Pacific was also the key reason why the decision was to demonstrate an interoperable proof-of-concept between the two, to give humanitarian partners in the Pacific confidence that the scheme would be possible to deploy in practice, without the need to replace their HF radios.

FIGURE 8.8: The Barrett 2050 HF radio set was the first to integrate with LBARD for proof-of-concept.

The first step was to implement simple drivers and auto-detection routines in LBARD to recognise and correctly control these radios.

These radios supported only ALE 2G text messaging as a mutually compatible digital data transport. The ALE 2G text messaging channel offers a theoretical bandwidth of 375 bits per second, i.e., approximately 47 bytes per second. However, it was discovered that there were interoperability problems with this transport between the vendors:

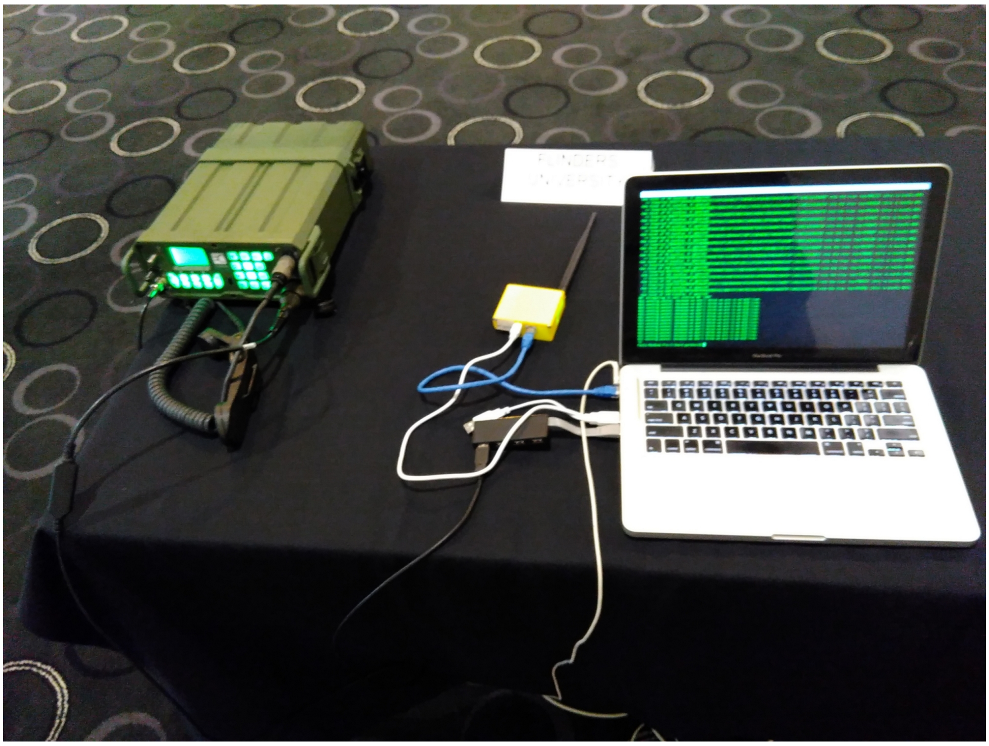


FIGURE 8.9: The Codan Manpack 2110 HF radio set was the integrate with LBARD for proof-of-concept.

1. The ALE 2G text messaging standard supports 6-bit characters. However, the firmware in one of the radios would accept only alpha-numeric characters, limiting the effective data channel to only 5 bits per character. The time pressures of the proof-of-concept, which had to be realised in a 24 hour period at the conference, meant that in practice, only 4 bits per character were possible, resulting in only 2/3 of the bandwidth being usable.

2. ALE calls could only be established from one brand to the other, but not from the other brand to the first. Establishing any ALE 2G link at all required considerable creativity due to various subtle interoperability problems.

Once these problems were resolved, it was necessary to implement a packet fragmentation and re-assembly scheme, as only 43 bytes of data would fit in each encoded ALE 2G message. The considerable signalling overheads of the ALE 2G text messaging protocol, including as a result of the interoperability problems between the two vendor's radios resulted in an overall bandwidth of at most 10 bytes per second, typically taking around 30 seconds to transfer a single 250 byte LBARD packet over the half-duplex link.

Nonetheless, the interconnection between the two radios was established, and the delivery of encrypted Serval Mesh text messages was demonstrated over HF radio, thus confirming the feasibility of integrating HF radio into the Serval Mesh. Figure (8.10) shows the output log of one of the LBARD instances, showing the reception of three ALE 2G messages corresponding to three fragments of a single LBARD message, which was then correctly re-assembled and decoded, resulting in this LBARD instance recognising the presence of the LBARD instance at the other end, having peer ID cee162c5a2a6.

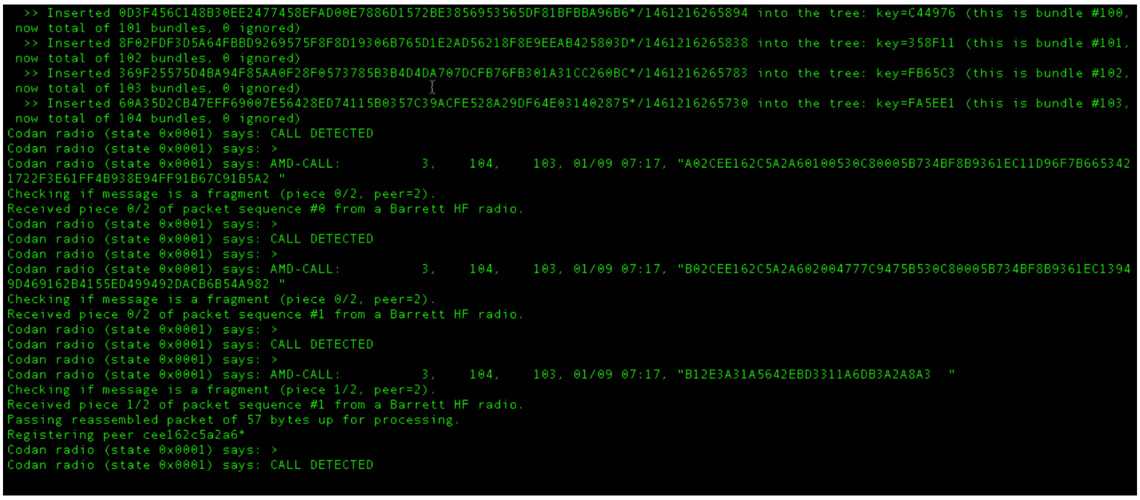


FIGURE 8.10: LBARD console output, and it shows an LBARD instance established a connection to another LBARD peer and identify it over HF radio.

As previously mentioned, the effective bandwidth of the link was only around 10 bytes per second, less than 1/4 of the advertised link rate of 375 bits per second. As the link is half-duplex, this corresponds to approximately 864,000 bytes per day, i.e., approximately 843KiB per day. Assuming that transferring a text message from one peer to another requires around 1KiB of LBARD traffic, this corresponds a daily message capacity of around 843 messages per day, excluding the overhead of the bundle list synchronisation process.

Thus despite ALE 2G's very limited bandwidth, especially when used in this way, it does make it possible to transfer useful amounts of messages per day. Two communities of up to perhaps a hundred people each should be feasible, even if the latency of each message delivery will likely be several minutes.

8.9 Estimating Capacity through Simulation over ALE 2G link

To validate the performance of an LBARD connection over this proof-of-concept HF radio link, a test framework was created to analyse the requirements for transferring one Rhizome bundle over this link and examining how many bytes and packets are required to achieve this, rather than relying on estimation. Many iterations were run, to gather averaged information. The simulation was based on the attempted delivery of bundles with a payload length of 50 bytes, designed to simulate short text messages.

The SMAC short message compression algorithm [81] was applied, as it can compress the size of SMS-like test messages to about 50% of their original size. A corpus of 3 million SMS messages revealed an average length of 92.45 characters per SMS message [201]. SMAC would, on average, reduce the side of such SMS messages to around half that size, which is why the bundle payload length of 50 bytes was chosen.

When the simulations were run, which includes the overhead of the bundle list synchronisation via the Tree Sync algorithm, the mean message delivery time was found to be 180 ± 33. There was considerable variation in message delivery time, between 148 and 266 seconds.

These simulations were based on a channel bandwidth of 10 bytes per second, and using the radio-induced turn-around delays derived from observations of the HF radio equipment at the conference.

By examining the logs of the tests with real radios and the simulations, it was found that the overall channel utilisation ratio was limited to 0.37 ± 0.02. When the full Rhizome overheads, that is, including transmitting the content of bundle manifests as well as the payloads, the average overhead was 228 ± 38 bytes. The inclusion of this data resulted in a protocol efficiency of only 0.21 ± 0.03, because for such small messages, the manifest data is much larger than the message content.

While these results are not particularly spectacular, they have firmly established the feasibility of integrating HF radios into the Serval Mesh.

8.10 Discussion & Conclusion

The challenges for providing communications in the Pacific has been established throughout this thesis, including that there are many small and/or isolated communities that lack access to normal telecommunications services.

HF radio and the Serval Mesh, together, have the best combination of characteristics for resolving this problem, but until now, they have not been able to be used together.

The proof-of-concept work in this chapter has changed this situation by demonstrating that it is possible to integrate the Serval Mesh with various HF radios.

- The continuous improvement of LBARD, specifically the part for the proof-of-concept and the integration of different HF radio vendors into Serval Mesh, has led to the re-factor of LBARD to enhance the flexibility and extensibility of each radio driver framework. It authorised LBARD to perform the auto-detection process to each radio type via the serial interface, and keep Serval Mesh Extender independent from any need to the manual configuration when it is plugged into different ones. Therefore, in case of replacing the Mesh Extender in realistic situations due to any reason, then it removes the need for skilled labour to perform the job, or set up the configurations again.

- A new scheme has been added to support the automatic configuration, and this scheme stores the configuration of an HF radio in the ALE contact list in each radio rather than store it in the Mesh Extender. The reason for this is justified in the previous point, and since the HF radio installations have to be done by a skilled person, then adding one more step to the commissioning process of HF radio will be a simple task, and does not require a great inconvenience. The scheme implies formatting the contact names of all involved stations so that it helps LBARD when it should attempt to contact each one on an automatic basis, and it provides necessary information about what is the preferable time to contact during the day, and the number of times each station is ready to contact. This scheme is ready to evolve based on further understanding of any problem that may appear in the future in relation to the operation of the HF radio network.

However, this proof-of-concept is precisely that: While it has proven the possibility of the concept, and could in principle deliver hundreds of messages per day, it is extremely slow and inefficient. It uses the grossly outdated and ill-suited ALE 2G text messaging facility, rather than, say, a low-latency high(er)-speed HF data modem. HF data modems with speeds of between 2,400 and 9,600 bits per second are available, which offer between six and 25 times the bandwidth of the 375 bit per second ALE 2G text messaging channel – and likely support higher channel utilisations than are possible with ALE 2G, making a higher fraction of that bandwidth available.

Also, the proof-of-concept focussed on very simple scenarios with just a single bundle being transferred, and thus without any meaningful consideration of, or experience of the impact of the bundle list synchronisation algorithms when using LBARD over such low-bandwidth and high-latency connections. These issues will be further explored in the next chapter, which focuses precisely on improving the performance of the Serval Mesh over HF radio links, and in more realistic scenarios where there are many bundles in transit.

Returning to the research questions that this chapter answers, we can conclude:

- Is it possible to provide a cost-effective and free-to-use communications solution to low-income remote community members?

  This question has been answered in the affirmative, in that we have demonstrated the possibility of a solution based on a combination of the Serval Mesh and HF radios, which makes it possible in principle to connect such communities using the kind of HF radio infrastructure that in many cases already exists, or which foreign donors are accustomed to funding.

- Can we extend the communications range of Serval Mesh network to hundreds of kilometres? Can HF Radio be a solution to this problem?

  This question is answered in the affirmative, precisely by demonstrating the integration of the Serval Mesh with HF radio, which creates the means for the Serval Mesh to communicate over hundreds of kilometres.

- HF data links have very low bandwidth. Can we manage such low-bandwidth links effectively, to enable very isolated communities to communicate with one another?

  This question has been answered in the affirmative, in that we have shown that it is possible to extract satisfactory, if suboptimal, performance from HF radio data links. Further work is required to ensure that this result holds for the more general case, where realistic traffic volumes are involved. This will be explored in the following chapter.

In short, the potential for the Serval Mesh and HF radios to be used together to solve some of the very challenging communications needs in isolated and disaster-impacted Pacific Island communities. This is particularly appealing, given that HF radio installations are already common in the Pacific, and well understood and accepted by foreign aid agencies and other supporters of the region. Thus it enables the building on an existing infrastructure and approach, to bring new capabilities and improved outcomes for the region. In particular, the potential for individuals in a community to make easy use of the HF radio infrastructure from their own homes, and without special training is particularly interesting. This is partly because of the impetus that it will create to ensure that HF radio infrastructure is adequately maintained between disaster events due to its increased utility.

These issues around increasing the efficiency of the combined Serval Mesh / HF radio approach, including testing it under more realistic traffic conditions, so that it can indeed be of use to community members year-round, to ensure that it is available when a disaster strikes will all be explored further in the following chapter.

Criterion / Technology	Cellular phones	Internet	Satellite phones	HF radio	Serval Mesh
Coverage area	limited to areas surrounding towers	limited to installed hardware or cables	global coverage	very wide coverage	up to several kilometres per link
Cost	Moderate once installed	Moderate once installed	Very Expensive	Expensive to install, cost-free usage thereafter	Low installation cost, cost-free usage thereafter
Capacity	Sufficient. Usually limited in practice by usage charges	Generally sufficient. Often limited by usage charges or backhaul capacity	Usually limited by subscription and usage charges	Usually limited by human factors	Sufficient
Latency	Low	Low to moderate	Low to moderate	Low	Low to high, depending on network topology
Energy requirements	Mains power or sophisticated generator installations for towers	Mains or local DC generation, depending on solution	local DC generation for recharging	Mains power or local DC generation and battery storage	Local DC generation, optionally with small battery storage
Maintenance requirements	Complex	Moderate	Simple	Moderate	Simple
Infrastructure Dependence	Yes	Yes	No	No	No
Disaster Resilience	No	No	Yes	Antennas must be dropped before cyclones	Yes

TABLE 8.1: Relationship between communication techniques and the the desirable criteria in the PICs.

TABLE 8.2: Bundles received via UHF by left-side HF radio controller.

Bundle ID	*Sender Identity*	*Receiver Identity*	*Size (bytes)*
1	N1	N3	134
2	N2	N7	345
3	N4	N1	345
4	N1	N5	42
5	N5	N2	932
6	N1	N8	322
7	N7	N1	24
8	N3	C1	187
9	N9	N1	634
10	N3	N5	77
11	N5	N1	52
12	N6	N1	756
13	N4	N2	232
14	N4	N6	39
15	N1	C1	66
16	N9	N1	98
17	N2	N5	144
18	N6	N1	242
19	N7	N2	129

Chapter 9

Making HF useful 365 days a year

9.1 Introduction

Part of this work is published in IEEE GHTC conference, 2018, titled "Making HF useful 365 days a year, to make sure it works the one day you need it". This chapter presents a considerably expanded coverage than is included in that paper.

The previous chapter provided a proof-of-concept for integrating the Serval Mesh with HF radio communications. This chapter continues that work by exploring means by which the performance of the Serval Mesh over HF radio can be improved, and presents substantial progress on this front.

As has already been discussed, HF radio has proven its ability to provide long-range communications links over the past 120 years. This, combined with the relatively common use of HF radio in the Pacific region due to the absence of other solutions that solve the double problem of being technically capable and at the same time to be fundable by the various foreign aid bodies who often end up providing remote communications solutions in the Pacific region. While satellite-based services are superior in many ways, the reluctance of the foreign aid donors to pay for the ongoing usage charges of these systems – even where the total cost of ownership over several years would be demonstrably lower. Similarly, the brand, model and precise specification of HF radios in the Pacific region tends to be limited by the choices made by these funders, which places additional limitations on what can be achieved in practice. This context must be taken into account in any attempt to improve the performance of integrated Serval Mesh / HF radio solutions.

While this context may be limiting in various ways, it does not diminish the demand, desire, and survivable universal basic communications in the Pacific: Enabling residents in this region to continue to be able to use their mobile telephones, even when in very remote areas, and/or during and following emergencies and disasters remains a humanitarian imperative. Therefore it is worthwhile attempting to overcome the challenges of these contextual limitations, in order to improve the performance, scalability and user-experience that is achievable. In particular, the key metrics that are sought to be improved are latency and throughput of the system, including under realistic network traffic loads.

Addressing these two factors of latency and throughput is the primary focus of the remainder of this chapter, which considers this through three related activities:

1. Consider potential higher-bandwidth HF radio digital communications options, and enable Serval LBARD to use one of them;
2. Identify any problems with Serval LBARD when using an HF radio transport;
3. Make such changes to LBARD as are required to remedy or mitigate these problems; and finally;
4. Quantify the improvement in Serval LBARD over HF Radio performance compared with the proof-of-concept of chapter (8), using more realistic simulated traffic loads.

We examine the current state of LBARD over HF in Section (8.7), identify problems that require rectifying, and rectify those problems through improvements to the LBARD software in section (9.6.3), and then confirm the effectiveness and impact of having fixed all of those problems in section (9.8).

Improving the data throughput and delivery reliability over the Codan HF radio high-speed data modem link will be focusing on and how can necessary tunings be done to LBARD so that more messages get delivered successfully during the day. The high-speed data modem is introduced in this chapter and how its role can upgrade the overall throughput in the Serval Mesh network toward more realistic performance. The speed of this data modem is higher than ALE 2G modem, and it can deliver more messages per day; however, the speed of data transfer is still very slow overall.

9.2 Contributions

The contributions of this chapter are:

1. Examination of several higher-bandwidth HF radio digital communications facilities than used in chapter (8), to identify those which are most likely to be feasible in practice.

2. Facilitate the integration of the Codan Envoy's internal data modem in order to improve the bandwidth available to the Serval Mesh over HF radio.

3. Identify several problems in the Serval LBARD software that limit its performance.

4. Facilitate the correction of those problems in Serval LBARD, so that its performance is improved.

5. Measure the improved performance of the Serval Mesh over the resulting improved HF radio integration, confirming and demonstrating that substantial latency and throughput improvements are possible.

6. Demonstrate that these collective improvements make it feasible to use HF radio more effectively, to provide a useful and usable service year round for remote communities, helping to ensure that it will be available when disaster strikes.

9.3 HF deployment in the Pacific

It is an observable trend that deploy multiple HF radio networks are deployed variously by National Disaster Management Organisations (NDMOs), Non-Governmental Organisations (NGOs), the Red Cross and other parties in the Pacific, so that to support their respective missions. International aid organisations often purchase these systems. Thus, most of them are high-quality systems, and come with well-supported equipment in term of solar power, appropriate infrastructure, like antenna and mast. Many organisations provide HF radio system installation to villages and other communities, and provide train for an operator in each village on how to utilise the radio and the equipment.

However, when these systems provisioned by organisations, the installations frequently don't include adequate ongoing maintenance support. As a result, these expensive systems that are purchased and deployed precisely because they can support remote and post-disaster communications rapidly fall into disrepair. It is not uncommon for substantial fractions of these systems to not be available when a disaster occurs, undermining the considerable expenditure that was invested.

These failures have many causes, including:

1. Unavailability of a trained HF radio operator, for example because they have travelled to another village or island for work.
2. Lack of refresher training resulting in loss of radio operator ability over time.
3. The requisition of solar panels, batteries or other equipment for higher-priority needs as evaluated by the local community, such as to provide lighting in other buildings.
4. Or where the energy generation and storage facilities remain intact, they may be used for additional purposes, leaving insufficient energy to effectively power the radio equipment.
5. Damage due to lightning strike, failure to drop HF antennae during high winds, or other physical sources of damage.

A contributor to all of these problems is that the HF radios provide little benefit most days of the year. As a result, the maintenance and availability of the equipment is of a lower priority for many of the communities where it is deployed. Rational deployment of their limited resources then results in neglect of the HF radio facility, or the redeployment of usable elements, such as the solar panels and batteries. The result is the lack of availability of long-distance communications when most required. However, if the HF radio system were able to provide benefit year round, then some of these factors may be able to be mitigated, as the maintenance and availability of the HF radio facility would become higher priorities for the communities where they are deployed. Attempting to facilitate this transformation is a key objective of this thesis, and this chapter in particular.

9.4 Practical benefits of using the Serval Mesh to access HF Radios

Long-range communications is the key benefit of HF radio in the Pacific Islands. In seeking to make these radios easily and practically accessible via the Serval Mesh, there are multiple practical advantages that can be realised:

1. The need for a trained human to operate the HF radio is greatly reduced, since the HF radio is managed by a Serval Mesh Extender running the Serval LBARD software.

2. No longer does someone need to sit at the radio to make or receive communications, but members of the community can be in their own homes, gardens, or going about their other normal activities while remaining in contact – much as has long been taken for granted in urban areas around the world.

3. Acts to prevent restrictive or discriminative use of an HF radio by its operator or other custodians, by removing the ability to physically gatekeep access or otherwise restrict access to the facility.

4. Solves the problem of congestion during peak periods by allowing multiple simultaneous users.

5. Again, because no radio operator is required to facilitate communications, an HF radio can be active, 24 hours a day, 365 days a year. This greatly increases the return on investment on the HF radio equipment, as well as improving the service level experienced by communities dependent on HF radio. It is not difficult to imagine several orders of magnitude increased utility of an HF radio when used in this manner, compared to the traditional operator-facilitated use. This can also help encourage funders to deploy more systems, as they can see a greater return on investment, thus further increasing the benefit and impact.

6. As the main cost of operating an HF radio is the capital cost of the equipment, there is no need to charge for use of the system. This contrasts sharply with satellite telephones and other similar options, which are cheap to purchase but have prohibitive ongoing subscription and usage costs that are not practical for small remote communities, or in many cases, for the low-income Pacific Island Nations generally. This ability to effectively eliminate the ongoing costs, apart from periodic maintenance of the equipment, cannot be underestimated in its importance for deployments in the Pacific.

7. By making the HF radio useful year round, communities are more likely to notice, complain and/or make necessary repairs themselves before the next disaster strikes, precisely because they are deriving benefit from it on a daily basis, and thus will miss the service if it fails. Also, because the system will be used continuously, it will be much easier for NDMOs and other organisations to notice from afar when a system fails, so that they can deploy personnel to assess and remedy the situation, well before the next disaster strikes. This is not possible with the

current usage of HF radio, where failures may go for weeks, months or even years, without being noticed.

8. Communications are digital and easily understandable, unlike analog HF audio that can be difficult to understand.

9. HF radio can be affected by the day/night cycle and weather. This can result in frustration for users if they have gone to radio to communicate, but are unable to. Using Serval Mesh delay-tolerant protocols, such events are substantially mitigated, as delivery will occur as soon as conditions improve, and without further action on the part of the people trying to communicate.

In short, it provides a very cost-effective solution to solving the otherwise so-far intractable problems of providing reliable and affordable communications for small isolated communities, and communities impacted by disasters that have knocked out other modes of communications.

The challenge to realising these goals is that the performance of the ALE 2G-based proof-of-concept of integration of HF radio into the Serval Mesh is neither sufficient, nor more adequately characterised under more realistic traffic conditions. The remainder of this chapter seeks to advance the state of the art on both points, by integrating higher-bandwidth HF digital communications into the Serval Mesh, and analysing, and where necessary, improving the performance of the Serval LBARD protocol when used over HF radio links.

9.5 Practical considerations of Serval Mesh HF integration

During the process of integration between the HF radio and Serval, the work was focused on how to achieve a convincing proof-of-concept, that is, to prove that an interface between the Serval Mesh and HF radios was possible. That proof-of-concept work was achieved using only equipment on short-term loan from Codan and Barrett companies, in the context of a conference. A key goal was to demonstrate that it was possible to achieve this capability using radios from different vendors.

In this chapter the goal is rather different: To consolidate on the prior work, by optimising the behaviour of Serval LBARD with a single model and configuration of HF radio, to the point where it will have the capacity and behaviour required to enable the intended use-case of connecting remote communities with one another, or similarly, a single remote community with a regional centre. That is, interoperability between different models or vendors of HF radio is no longer a focus.

The following text describes the process by which the Codan Envoy HF radio, with its integrated internal modem was selected as the hardware to be used for the refinement of the Serval / HF radio integration.

9.5.1 Selection of HF radio vendors and equipment

As the work described in this thesis was performed without significant financial support, it was necessary to select a radio model that we would be able to arrange extended access to two units of. Given the prior work with Barrett and Codan radios, these were the two vendors whose products were considered. The proof-of-concept had opened communications channels with representatives of these organisation. Each were asked to provide us with sample equipment which we could consider for use in this next stage of the project.

Both responded positively, with each providing access to a pair of their radios. Barrett provided access to a 2090 and 2050 radio, as shown in Figure (9.1), while Codan provided access to a pair of Envoy radios, as shown in Figure (9.2). In both cases, a pair of 1.5kW dummy loads were used in place of real antennae, to allow desk-top testing, with leakage from the dummy loads sufficient to establish stable links between the radios.

This frugal development context precluded the option to examine some of the higher-bandwidth HF communications options, such as 9,600 bit per second narrow-band modems, or the newer generation of wide-band HF modems, that are capable of data rates of up to at least 76,000 bits per second [78], and potentially 120,000 bits per second [192]. Were circumstances different, it would have been beneficial and interesting to test these radio types.

That said, such high-speed HF radios are also likely to be very expensive, with suggestions that the US military pays of the order of US$200,000 per radio (including accessories and support) [235]. Thus even if access to such radio equipment had been possible during this research, such radios are very unlikely to be available, let alone common, in the Pacific Island Nation humanitarian context. Therefore the focus on the more affordable and commonly deployed Barrett and Codan radios is entirely reasonable, and does not detract from the goals of this thesis.

FIGURE 9.1: Two Barrett HF radios 2090 and 2050 during a live lab test, and each one is connected to a dummy load and serial interface. Both radios have been provided by Barrett company.

FIGURE 9.2: Two Codan Envoy HF radios provided from Codan company, and they have been utilised in this research.

Codan also offers a MIL-STD-188-110A/B modem, that is capable of 9,600 bits per second [51]. However, financial constraints on the project prevented us from testing this hardware. Also, we are not aware of these more expensive modems being widely deployed in the Pacific, so it was seen as reasonable to remain focused on the 2,400 bit per second internal modem. That said, it should not be difficult to add support for the faster modem, and this could be used to provide a further substantial improvement to latency and throughput in the future.

Initial explorations were made using radios from both Barrett and Codan. In the case of the Barrett radios, these required use of an external modem from HAL communication corporation of model number DSP4200/2K, as shown in Figure (9.3). Through these initial explorations, it was found that the process for communicating reliably with the Barrett modems was more complicated than with the Codan radios. Specifically, the need to perform nested escaping of certain characters made it difficult to obtain a clean 8-bit communications channel. The Codan radios, on the other hand, when correctly configured, provide a separate serial interface for their internal modems. This avoided the need for complex character escaping schemes. Both the Codan and Barrett modems offer data rates of up to 2,400 bits per second. Thus with the only apparent difference being the difficulty of interfacing with the modems, the decision was made to pursue the work of this chapter using the Codan HF radios.

9.5.2 Experimental setup & preliminary work

The test environment setup using to a pair of Codan HF radios, with the antenna connector of each connected to a dummy load rated at 1.5kW. The maximum output power of the radios is 125W, well below the rating of the dummy loads. This allowed testing in an open laboratory setup, without having to work in a restrictive Faraday Cage or similar. By placing the dummy loads within 1 metre of each other, the sensitivity of the Codan radios was sufficient to establish communications from the low-level signal leakage from the dummy loads. A similar configuration using the Barrett radios can be seen in Figure (9.1).

Improve LBARD radio auto-detection framework

Implementing support for the Barrett and Codan modems required that the radio auto-detection framework be improved, to correctly discriminate between the analog and digital modes of communications, and to detect whether the radios included the modems or not. Ensuring that the auto-detection

FIGURE 9.3: HAL HF radio external modem.

framework is robust against the various radio types helps to avoid the need for trained personnel when configuring a hybrid Serval Mesh / HF radio network.

A related change was made that allows the information about which HF stations to call to be stored in the ALE contact list of the Codan radios. This avoids the need for configuring the Serval Mesh Extender to contain this information. This further simplifies the process of configuring and deploying a hybrid Serval Mesh / HF radio network. The current scheme using the ALE contact list is, however, imperfect, and should be improved in any follow-on work to this thesis.

9.6 Codan Envoy HF integrated data modem

As discussed, to overcome the problem of extremely low throughput of the ALE 2G HF radio, the Codan Envoy with its integrated data modem 3012 has been used in this research.

Various operations in this modem can be controlled and managed using industry-standard AT modem commands. This is the mechanism that LBARD uses to communicate with the modem. Further information on the AT commands used can be found in Appendix (A).

The data modem in the Codan Envoy radio that was used in this research is a software-defined modem, that is, does not require any additional hardware [102]. That said, the modem is still logically separate from the rest of the radio, and is controlled via a separate serial line interface, as shown in Figure (9.4).

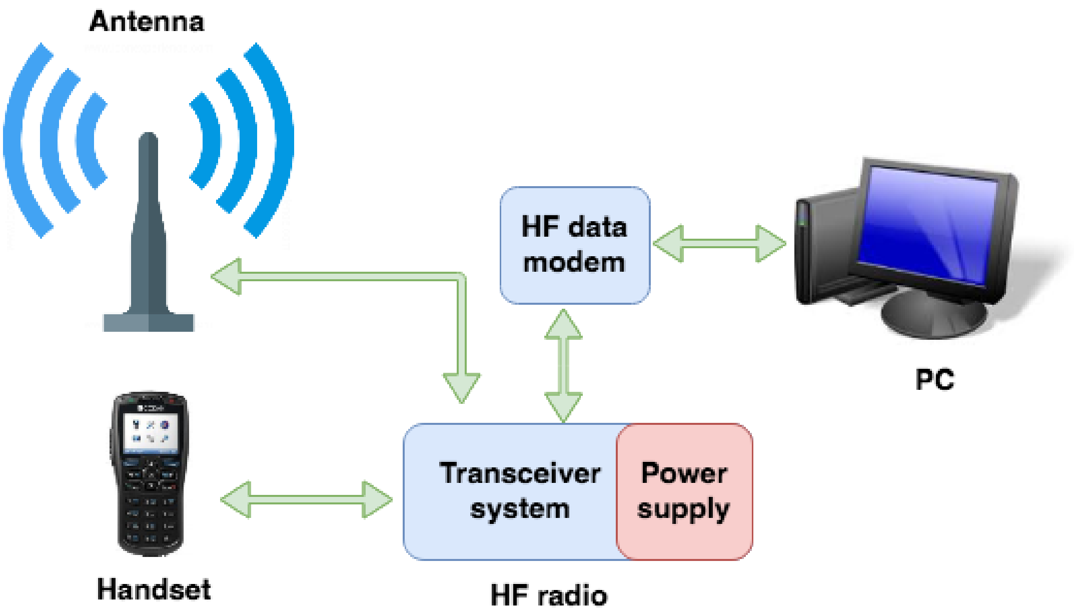


FIGURE 9.4: A basic diagram for installing and configuration of data modem system and how data modem is connected to a computer to exchange information with.

The theoretical data channel for this modem has a capacity of 2400 bps; however, this ideal bandwidth is not achievable in reality. Initial testing sending a continuous data stream in one direction revealed a maximum data transfer rate of only 1,475 bits per second, or about 184 bytes per second. The difference is assumed to be due to the half-simplex nature of the communications channel, the long turn-around time when each modem takes turns transmitting, forward error correction, and any other overheads. Bidirectional tests, where data streams were sent in both directions correlated closely with this, delivering around half that bandwidth in each direction, i.e., around 90 – 92 bytes per second.

9.6.1 Enabling the Codan Envoy Internal Data Modem Feature

While the internal data modem in the Envoy requires no additional hardware, it does require activation through a software license unlock code. The license can be purchased by contacting Codan. You will need the Electronic Serial Number (ESN) for the radio unit, which can be obtained by following the process illustrated in Figure (9.5) from the following menu of the handset:

Menu → Information → Device Information → Hardware Option → RFU ESN

(A) (B) (C)

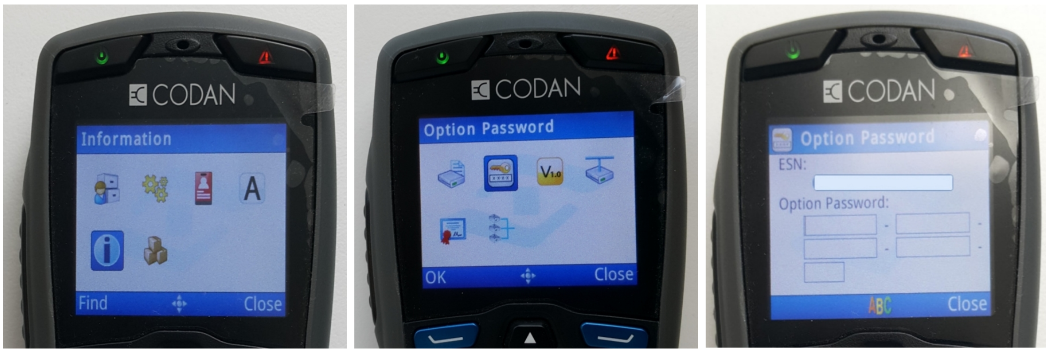
FIGURE 9.5: This sequence of steps can be used to obtain the "RFU ESN", which is the unique identifier of the radio, which is required when requesting license unlock codes for additional features, such as the internal data modem.

Once the user receives the licence code from Codan, the procedure is relatively straightforward to enable the data modem via the following menu sequence on the handset, as shown in Figure (9.6):

Menu → Information → Option Password → *Enter the license code*

9.6.2 Configure the HF data modem through handset

Once the license code has been entered into the Envoy radio for the data modem, the data modem must be configured to connect it to one of the two serial



(A) (B) (C)

FIGURE 9.6: The sequence of steps followed on the handset for Codan HF radio to enter a new license to activate a feature, such as the internal data modem.

port connections on the Envoy. The Envoy has a primary serial port accessible on the RFU15 connector, and a second serial port on the RFU6 connector. The primary radio control interface (CICS command interface) should be configured on the RFU6 connector, and the modem on the RFU15 connector. Problems were encountered if these were attempted to be configured the other way around, so that should be avoided.

Figure (9.7) shows the process of using the handset to configure the data modem to be accessible via the RFU15 interface, via the following menu sequence:

Menu → User Data → Peripherals → RFU GP port → 2.4 kbps Data Modem Interface

It is also necessary to tell the Envoy radio that the device connected to the RFU 6-way is a computer, and not a GPS or other device. This is also performed using the handset, as shown in Figure (9.8), by following the menu sequence:

Menu → User Data → Peripherals → RFU 6way → PC

Following these steps, the Codan Envoy radio should be configured to provide access to the internal data modem. The RFU6 connector should be connected via a serial or USB-serial adapter cable to the computer which is running Serval LBARD.

9.6.3 Codan HF data modem driver for LBARD

The next step was to implement the LBARD driver that is able to auto-detect the Codan internal data modem, and to be able to control it, sending and

(A)

(B)

(C)

(D)

FIGURE 9.7: The sequence of steps followed on the handset for Codan HF radio to make the 2.4kbps internal data modem accessible via the RFU6 connector.

receiving packets, as well as making and answering ALE calls. The source code for this driver is located at:

`https://github.com/servalproject/lbard/blob/codan3012/src/drivers/drv_hfcodan3012.c`

In more detail, the functions of this driver include:

1. *Auto-detection and initialising stage*: The auto-detection stage is the first action before LBARD can control the modem, and establish links with other remote LBARD instances. This generally functions correctly, however a problem was encountered with the Codan USB serial adapter for the RGU6 and RGU15 connectors, that sometimes prevented the radio and modem from being identified. Unplugging and replugging the USB connector corrects this problem.

   Once LBARD detects the modem, it triggers the initialisation routine, and makes the modem ready to operate. The routine issues several AT

(A) (B) (C) (D)

FIGURE 9.8: The sequence of steps followed on the handset for Codan HF radio to tell the Envoy radio that a computer is connected to the 6-way RFU6 cable.

commands that set the address for the HF radio, explained in Appendix (A), and enables the hardware flow control via the `AT&K` command.

2. *Data modem state machine*: All LBARD radio drivers must implement a state machine, that allows LBARD to know when a radio connection exists, and to correctly send and to receive data packets. For HF radios that support ALE calling, the state machine is a little more complex, with states that also include *calling*, *answering call*, *data link ready*, and *online for data transfer*.

3. *Sending and receiving packets*: Once the radio is in the *online for data transfer* state, the driver also includes code for sending and receiving data packets. As the internal data modem conceals the physical packet boundaries, and presents the abstraction of a continuous data stream,

this driver must also provide packet framing, not dissimilar to that used in older SLIP and PPP serial packet encapsulation protocols [203, 128].

As with all LBARD drivers, these routines are also responsible for managing flow-control and congestion, and informing LBARD how often it is able to send packets.

9.7 Codan HF internal modem integration and performance improvment in LBARD

With a driver created for LBARD to recognise and control the Codan Envoy's internal data modem, the focus then shifted to preliminary testing of LBARD when communicating using that device, to understand the initial performance, and to identify any problems that are revealed through the process. That is, before optimising the interaction of LBARD with the Codan Envoy's modem, it is important to get the integration behaving stably, and any deficiencies in the general behaviour of the system corrected, so that the effect of any later optimisations can be properly assessed. The following sub-sections address this consolidation of the LBARD protocol, after providing a reminder of the general structure of the Serval Rhizome bundle transfer mechanics.

9.7.1 Overview of Rhizome bundle transfer

Each Rhizome bundle as a unit consists of a bundle manifest, i.e., meta-data including addressing information, and optional payload. The manifest size is limited to less than 1KiB, and is typically approximately between 350 to 450 bytes long. The payload, in comparison, is not restricted in size, and may be anywhere between 0 bytes to many giga-bytes in size.

As the bundle size can be much larger than the packet size limit of the radios that LBARD makes use of, LBARD fragments bundles. To support this, divides each bundle logically into a number of 64 byte pieces, and keeps track of which pieces it has sent, which have been acknowledged as being received, and which still require sending. A sliding window bitmap representation of the received/not received is maintained by the LBARD instances at each end of a link, to attempt to maintain and communicate this information in an efficient manner, when it must be sent from one instance to the other to update its information about the state of transfer of a bundle.

It is possible for a bundle to be delivered to a Serval instance via other links, while simultaneously being transferred via a HF radio. In such a case, LBARD should stop sending the bundle which has already been received. This is supported by a special ACK message type sent by the receiving side, that tells the sending side that the receiver already has the complete bundle, and that the sender should now send the next highest priority bundle in the transmission queue.

The transmission queue itself is continuously updated as the TreeSync algorithm runs over the HF radio link and discovers the set of bundles that the Serval instance at each end of the link have in their Rhizome database. Both as this process progresses in the normal case, as well as when new bundles become available at each end of the link, the transmission queue is continuously updated. This can mean that part of a bundle might be transmitted, before being bumped by a the availability of a bundle that is given a higher priority. Similarly, the dynamic prioritisation functions that LBARD supports means that other factors may affect the priority order of the bundles being sent. Whatever the cause, it is possible that partial transfer of a bundle can occur, be interrupted by the transmission of one or more other bundles, in whole or in part, before then resuming.

To avoid inefficiency in this case, LBARD instances keep track of the reception status of many bundles, so that resumption of reception of a bundle can take into account the material that has already been received, to avoid duplicating the transmission of the already received material.

The dynamic transmission queue management also maintains only a small number of bundles in the transmission queue. If the queue is exhausted, then it will re-scan the Rhizome database, and refill the transmission queue with the next highest priority bundles that have not yet been transferred. This only happens, however, if the transmission queue has filled, so that the database is not repeatedly scanned after all bundles have been transferred.

With this background in place, attention now turns to problems encountered while testing the initial integration of the Codan Envoy internal data modem.

9.7.2 Intermittent auto detection failures

As previously discussed, it was observed that the auto-detection process for the Codan Envoy internal data modem would fail. Ordinarily when opening the serial port to the Codan USB serial adapter, the Envoy self-identifies by sending an informational message, and then responds interactively to commands issued. In the failing case, the radio does not self-identify, and commands are not responded to by the radio.

This problem seems to be caused by the USB serial adapter not correctly recognising the opening of the port. It was able to be worked around by unplugging and re-plugging the USB serial adapter when the error occurred. In the longer term, this issue should be investigated. Perhaps the simplest long-term solution is to not use the USB serial adapter, but directly connect to the serial port lines from the RFU6/15 connectors of the Codan Envoy.

9.7.3 Serial buffer overflow

It was observed that packet reception errors would occur from a short time after establishing a data connection. Investigation confirmed that the problem was that bytes were being dropped, with the root-cause being serial buffer overflow in the data modem. The data modem has only a relatively small buffer. While the exact size of this buffer was not determined, it is believed to be not larger than a few kilo-bytes.

There are two common approaches to this problem: software flow-control and hardware flow-control. As LBARD requires an 8-bit clean data channel, software flow-control was not suitable, so hardware flow-control was used. However, the use of the USB serial adapter presented a problem regardless of the form of flow-control used. This relates to the well-known problem that the bundling of multiple bytes into a single USB data packet means that it is possible for a single USB data packet to overflow the receive buffer, without any chance for the overflow situation to be communicated back to the sender. As a result some fraction of the bytes in the USB data packet will be lost.

This problem was solved by adding a sequence number to the packets being sent, and having the receiving side acknowledging the packets received. If no acknowledgement was received within a particular time-frame, then the rate at which packets are being sent was progressively backed off, until the buffer had opportunity to drain. The backoff was calculated using a minimum delay between packets, plus a variable factor calculated based on the number of unacknowledged packets. This process was made rather more difficult to implement by the very high latency of the data modem in the Envoy radios, which is discussed in more detail later.

9.7.4 Bundles stuck in endless loop

Once the transmission of multiple bundles was attempted, a problem became rapidly apparent where the same bundle would be transmitted over and over again, instead of being acknowledged via the previously described mechanism of the recipient sending an acknowledgement message. This problem could occur for multiple independent reasons, as depicted in Figure (9.9), and explained below:

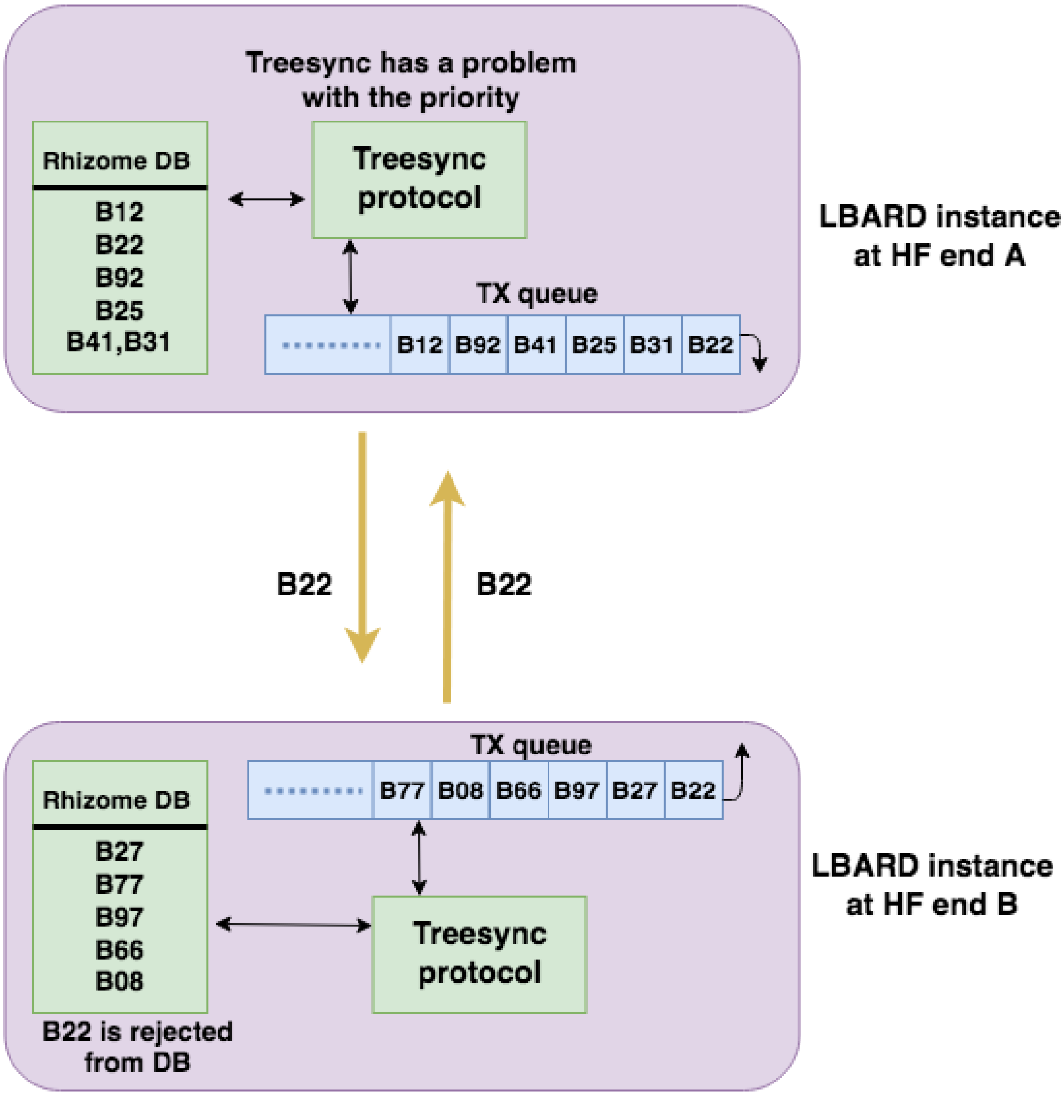


FIGURE 9.9: Bundle B22 is stuck in endless loop between two ends of LBARD instances over HF link due to either a problem with a Treesync priority as in instance A, or it has been rejected from Rhizome DB as in instance B.

1. One problem stemmed from the behaviour of the TreeSync protocol, where a bundle could be mistakenly detected as needing a second time,

resulting in its re-transmission. There was already a mechanism in TreeSync to mitigate this kind of event, where the tree of bundles present at each end is regenerated periodically, typically every 15 minutes or so. However, a bundle could be repeatedly transmitted during that 15 minute time-frame.

This problem was further mitigated by maintaining a persistent list of bundles that had been acknowledged as having been received by the LBARD instance at the other end of the link. The root-cause of the problem in the TreeSync algorithm was separately fixed, once it was found.

2. Another cause of problems was where a bundle was believed to have been correctly received, but for some reason could not be recorded into the Rhizome Database. As a result, the bundle would be transmitted again, as the TreeSync process would (correctly) determine that the bundle had not been received. This turned out to be caused serial buffer overflows, or failure to properly start the Serval Daemon that controls the Rhizome database. In the first case, the problem was corrupted bundles, which failed the cryptographic check when being inserted into the Rhizome database. In the second case, the problem was simply that the software components had not been started in the correct order.

3. When sending bundles, several pieces of each bundle would be sent after the receiver had the entire bundle, and had stored it into the Rhizome database. The problem here was the very high latency of the Envoy's internal data modem when using the default settings. In particular, the setting to allow compression of data would buffer data for some time before sending it, increasing latency to between 10 and 20 seconds. As a result, the time from when the recipient received the last piece of a bundle to when the transmitter received notification of this from the receiver could be several tens of seconds, reducing the efficiency of transfer of small bundles in particular.

   The solution to this problem was to disable data compression, which reduced the latency in each direction to 3 – 5 seconds, and thus the round-trip latency to typically less than 10 seconds, substantially mitigating this problem by reducing the number of superfluous packets per bundle to typically only one or two, instead of potentially half a dozen or more.

4. In some cases, individual bundles were sent and received multiple times by the transmitter. The receiver, however, never sent the acknowledgement message to the sender, informing it that it had received the bundle. As a result, the bundle would be sent again, and in some cases, repeatedly until the TreeSync process restarted, allowing the sender to realise that the bundle had been received. This is related to the problem previously described, where the protocol would effectively lock up on the sending of a single bundle. However, the cause in this case was not in TreeSync, but rather in the mishandling of the return message queue in LBARD: The acknowledgement message would be queued for transmission, and then further processing of the packet would queue an acknowledgement of the specific piece of the bundle received, causing the message acknowledging the entire bundle to be mistakenly discarded, thus preventing the sender from ever realising that the entire bundle had been received.

   A symptom of this problem is that the same bundle would be received multiple times, and be attempted to be inserted into the Rhizome database multiple times, as shown in Figure (9.10). This aspect of the problem was fixed, by having the receiver check if a bundle was in the Rhizome database, before beginning to accurate pieces of the bundle for later insertion into the database. While this did not mitigate the cause of the problem, it reduced its impact. Together with the correction described in the previous paragraph, these corrections resolved this problem.

5. The code that placed the TreeSync Tree Generation ID (GID) into the LBARD packets was incorrect, and was putting this information into the sender address field instead, causing a variety of problems. One of these problems is that the TreeSync re-start process would not always trigger, allowing protocol lock-up to continue, even if the TreeSync process started again. The causative bug was found and corrected.

After these problems were identified and corrected, LBARD was able to transfer bundles reliably using the Codan Envoy's data modem. Multiple tests were run, simultaneously synchronising sets of 100 bundles in each direction, with sizes varying from 50 bytes to 10,000 bytes per bundle, representing a the level of text messaging traffic expected when linking two communities of approximately 100 people each, with synchronisation of these sets of bundles reliably occurring. Nonetheless, compared with the theoretical throughput of 2,400 bits per second = 300 bytes per second, the average

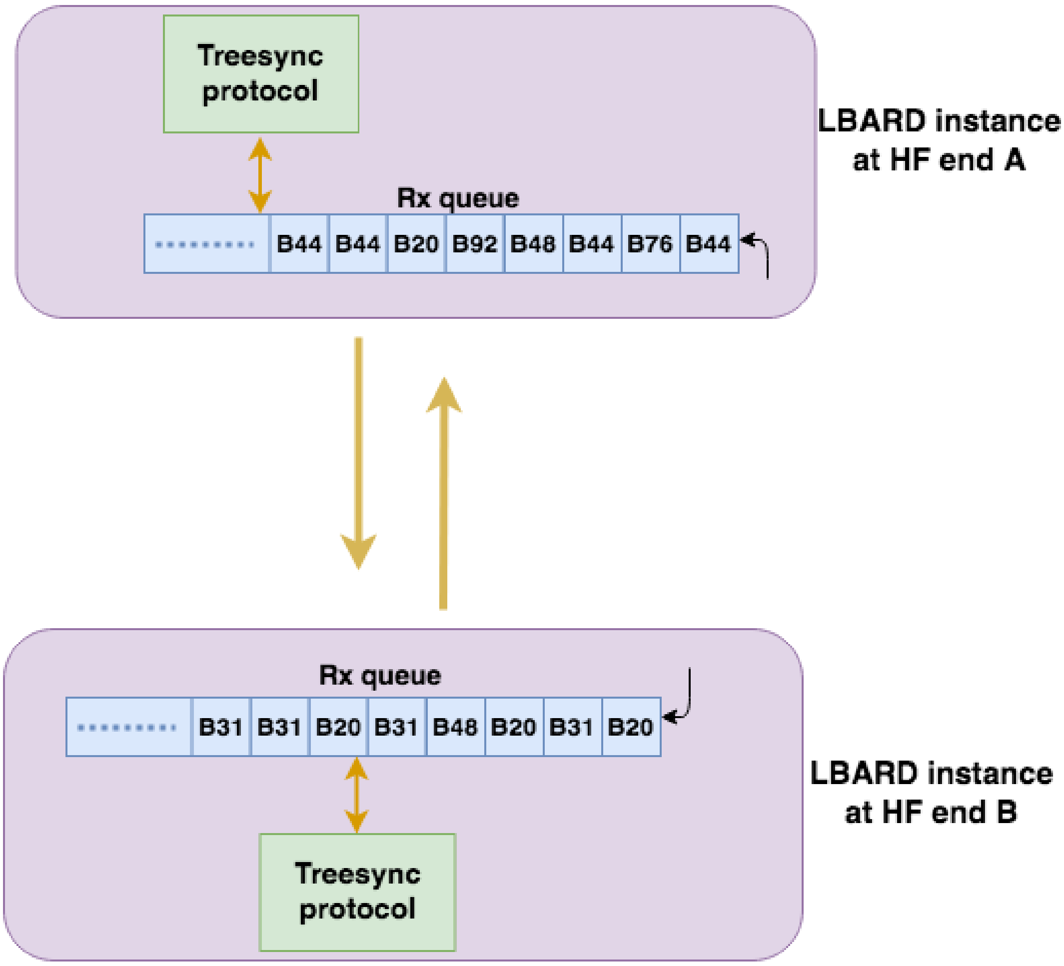


FIGURE 9.10: The same bundles have been received many times over the HF link. In this example, we can see that for the LBARD instance A, that bundle 44 (B44) is received multiple times, and for LBARD instance B, that bundles 31 and 20 are received multiple times. Each bundle should be received by each LBARD instance exactly once.

data throughput achieved was only 20 bytes per second in the best case – less than 7% of the theoretical capacity.

This situation, while disappointing, is not as bad as it first appears. As has been previously discussed, the actual available throughput of the data modem during sustained bi-directional communications is only 92 bytes per second. When consideration that the TreeSync protocol is running over the channel at the same time, as well as the overheads related to cryptographic authentication of the data, and framing of packet data, result is credible. Already, it meant that bundles of size 1,000 bytes can be transferred at the rate of approximately one bundle per minute, i.e., 1,500 bundles per day. This is a substantial improvement on the results described in chapter (8), and certainly demonstrates the feasibility of using such a modem to sustain the kind of traffic throughput required to link isolated villages or communities. However, obviously potential remained to further improve the throughput of the system.

Various causes of the poor throughput were investigated and mitigated in some way, to improve the throughput of the system. There are described in the following sub-sections.

9.7.5 Overhead of half-duplex serial operation

Any transmission operation over the HF data modem 3012 implies an overhead in negotiation between two devices, as they switch back and forth between which device is transmitting and which is receiving.

As mentioned earlier in this chapter, while each Codan HF data modem is theoretically rated to 2,400 bits per second = 300 bytes per second, the actual sustained throughput is only about 92 bytes per sec, less than one third of the theoretical throughput. If data is sent in only one direction, then this increases to 180 bytes per second, i.e., approximately the same ratio of data transmission to theoretical data rate, suggesting that a little approximately $(300 - 180/300)/300 = 40\%$ of the channel time is consumed by the overhead of switching between transmit and receive.

The specific contributions to this are not known definitively, however are believed to be a combination of the relatively slow mechanical switching time tolerances of the radios, as relays are used to switch between transmit and receive, presumably due to the high transmit power levels that would easily damage the receiver hardware if it were not physically isolated during transmission. Also, it is possible, although not confirmed, that the modem assumes a fixed and relatively long turn-around time to allow for propagation of the signals over potentially several thousand kilometres. At approximately 300,000 km per second, a distance of 10,000 km requires approximately 30 milli seconds to traverse. It is possible that the Codan modems are designed to allow for such distances, plus a safety margin in each direction, which would result in of the order of 100 milli seconds turn-around-time, or somewhat more than 10% of the channel time, assuming data packets of 250 bytes.

As these factors are related to the radio, and not the LBARD software's control of the radios, it falls outside of the scope of this thesis to address

– although it may be fruitful to engage with Codan in the future to better understand the contributions to the turn-around time, and explore whether there is scope to reduce it.

9.7.6 Bundles rejected from Rhizome database and error message 422

Some receiving bundles at the destination side could not be insert into the database, with the Serval Rhizome HTTP interface returning error code 422. This error code indicates that either the manifest is too long, or that there is a mismatch between the hash of the payload contained in the manifest and the payload that was supplied. Typically, the bundle would then be sent a second time, at which point it would often, but not always, be accepted.

The first potential cause, i.e., that the manifest was too long, was able to be immediately excluded, as none of these manifests were longer than the 1,024 byte length limit.

This left the second potential cause, i.e., that the payload hash or the payload itself was in some way incorrect. Investigating this revealed a bug in the packet assembly process. Specifically, the problem was found when performing certain optimisations to maximally fill a packet with content from the bundle manifest, that it would incorrectly calculate the offset in the manifest, and thus send incorrect data for the end of the manifest – which would then correctly be rejected. Once this bug was corrected, the problem stopped.

9.7.7 TreeSync and high-latency links

Problems were observed with the TreeSync algorithm once multiple packets were in flight. It would often take tens of minutes for TreeSync to determine the set of bundles present at each end of the HF radio link. For the numbers of bundles involved, this should not have taken more than a few minutes, even allowing for the low speed and high latency of the HF radio links.

On investigation, it was found that the TreeSync algorithm performs poorly when the latency is so high as to mean that multiple TreeSync messages are in flight in each direction at the same time. TreeSync misinterprets this situation as packet loss, and often resets the requested point in the synchronisation tree to the root of the tree, thus causing it to mistakenly re-start the tree traversal many times, and thus increasing the time required to synchronise by an order of magnitude or more.

A related problem caused by this problem, was that the TreeSync traffic was consuming approximately 75% of the available channel bandwidth as it repeatedly re-started the tree traversal and exchanged large chunks of the synchronisation tree. Thus not only was the synchronisation process itself slowed down, the transfer of bundles was also greatly slowed.

This problem was mitigated by managing the HF modem such that only one unacknowledged packet was allowed to be in flight at any point in time. This was implemented by using the sequence number to each packet, and adjusting the packet rate back-off to grow much more rapidly when unacknowledged packets remained. It was necessary to add approximately a 10 second penalty for each unacknowledged packet. Using a back-off like this necessary in stead of simply waiting for acknowledgement because it is possible for the modems to encounter unrecoverable errors in the data stream, e.g., due to bursts of interference.

Once the problem was resolved, the traffic from the TreeSync messages reduced to between 10% and 20% of the total bytes sent, i.e., a reduction of 3$\times$ or better during the synchronisation process, and would complete the synchronisation within a few minutes, after which it would reach a quiescent state where it consumed 5% or less of the link capacity in order to maintain synchronisation. This allowed more of the link capacity to be used for the transfer of bundles, thus improving performance.

9.7.8 High modem latency

The problem described above with TreeSync was primarily caused by the high latency of the Envoy's data modem. Fundamentally, it should be possible for such modems to have latencies of the order of 1 second, when sending 250 bytes at 2,400 bits per second, and allowing for appropriate turn-around time for the half-duplex link.

However, in investigating the TreeSync problem, it became clear just how high the latency of the data modem is: One-way latencies of between 7 and 10 seconds were routinely seen, with round-trip latency typically being of the order of 15 seconds. This latency exists even when sending a single character, so it isn't caused by buffers being filled, for example.

This led to investigation of several possible settings in the modem that might affect latency:

1. The AT*T allows configuration of the timeout before sending a packet. This can be set between 0 and 120,000 ms. It was already set to 0, i.e., to not add any latency, and thus was not the cause of the problem.

2. The AT&M command allows for the selection of behaviours that vary between increased throughput and increased interactivity. This was already set to the most interactive, i.e., lowest latency setting, AT&M=5.

3. The AT%C command enables or disables compression of data over the modem. This turned out to make a significant difference, as described below.

Disabling the data compression setting reduced the latency from 7 – 10 seconds in each direction to between about 3 and 4 seconds, i.e., better than halving it. It was still disappointing that the latency was still that high.

It is suspected that the root cause of much of the remaining latency, is that each modem tells the other modem how much time it will need when sending the following packet, so that the radios know when to talk and when to listen, so that both are never transmitting at the same time. Thus from when data is provided to the modem for transmission, the time of one packet being sent, and one packet being received must elapse, before the data itself can be sent. Thus the total time between data entry on one modem and exit from the modem at the other end is the time required to send 3 packets, not 1. As each 250 byte packet takes 1 second to send, this results in a cumulative latency of between 3 and 4 seconds.

Assuming that this analysis is valid, this remaining latency will not be removable, without developing new modem firmware that can use fixed duration time-slots when the modems are sending sustained amounts of data. It may be worth contacting Codan to implement such a feature in a future version of their modem firmware, so that effective latency can be further reduced. But that falls outside the scope of this thesis.

Nonetheless, substantial improvement in latency was achieved by disabling the compression: With the latency reduced to less than 50% of what it was previously, the packet rate was able to be increased by more than 100%, substantially improving performance. Also, this greatly reduced the delay between sending the last piece of a bundle, and receiving back confirmation that the receiver now had the complete bundle. This quasi-constant per-bundle time penalty was thus reduced to less than 10 seconds, instead of several 10s of seconds originally.

However, even with the reduced latency allowing packets to be sent approximately every 6 – 8 seconds, it was not possible to make full use of the channel capacity: Recall that the effective channel capacity in each direction is 92 bytes per second. By reducing the acknowledgement latency to 8 seconds, this indicates a bandwidth-delay product of up to $92 \times 8 = 736$ bytes. With the packet limited to 255 bytes, this limits results in as little as 255/736 = 34% of channel capacity able to be effectively used. As the latency was in practice still slightly variable, the average channel utilisation was typically a little better than this. However, this combination of measures was enough to limit the number of redundantly sent bundle pieces to a single piece per bundle in most cases, as for example in Figure (9.11).

```
>>> [10:05.27.184928 CEE1*] Saw a piece of BID=d2dd9224845e9689* from SID=c1b231650fb3*: body [2456,2656)
>>> [10:05.27.184934 CEE1*] Piece is for me.
>>> [10:05.27.184949 CEE1*] bundle is recently received.
>>> [10:05.27.184958 CEE1*] We recently received d2dd9224845e9689* version 1600814956191 - ignoring piece.
>>> [10:05.28.010330 CEE1*] There are 200 eligible bytes for a pure data packet.
>>> [10:05.28.807051 CEE1*] Saw a piece of BID=d2dd9224845e9689* from SID=c1b231650fb3*: body [2656,2856)
>>> [10:05.28.807057 CEE1*] Piece is for me.
```

FIGURE 9.11: A screenshot from the log file and inside the blue rectangle is the message "ignoring piece", and the sender had already dispatched this piece into the modem's transmit buffer, before the receiver is able to send an acknowledgement of the entire bundle to the sender. As a result, the sender sends one more (but only one more) piece of the recently received bundle, which is another source of delay in the transmission.

To improve this situation, a new packet type was added to the driver for this modem, which includes only pieces of the bundle currently being sent. This was tuned to use the remaining available channel capacity in each direction. Challenges were encountered in this, in that the small data buffers in the modem initially resulted in data corruption due to dropped bytes in these "pure data" packets.

This tuning was performed using a test configuration where each LBARD instance had a 100 bundles, each with 0 byte payloads. That is, each bundle consisted only of a 200 – 300 byte manifest, after the normal manifest compression was applied. The tests consisted of running this configuration for 1,000 seconds, and counting the number of bundles transferred during that time, and measuring the average data transfer rate, as measured in average number of bytes per second sent over the modem. Several tests were performed, as summarised in Table (9.1).

In short, by sending 200 byte pure-data packets every 3 seconds, the number of bundles that could be delivered in 1,000 seconds was maximised, while the maximum data rate was achieved using 256 byte pure-data packets every

Configuration	Average Data Rate (bytes/sec) (left)	Average Data Rate (bytes/sec) (right)	Bundles Received (left)	Bundles Received (right)
Control (no pure-data packets)	16.66	16.93	13	13
128 byte pure-data packet after each LBARD packet	25.74	25.26	19	21
256 byte pure-data packet after each LBARD packet	33.22	33.06	26	33
200 byte pure-data packet every 3 seconds	48.13	48.18	29	26
256 byte pure-data packet every 3 seconds	78.37	80.62	23	21
200 byte pure-data packet every 2 seconds	68.59	68.86	23	23
256 byte pure-data packet every 2 seconds	>92	>92	0	0

TABLE 9.1: Several configurations were tested to tune the performance of LBARD over the Codan Envoy's HF radio, specifically relating to the addition of pure-data packets in addition to the normal LBARD packets which contain TreeSync and other house-keeping messages. The control configuration used only the normal LBARD packets, resulting in poor performance due to the high-latency of the modems and the requirement that only one unacknowledged TreeSync message, and thus LBARD packet, is allowable at any point in time. Following each LBARD packet with a single data packet of varying sizes increased throughput moderately. However, this was not able to approach saturation of the modem link, resulting in data rates well below the 92 byte second channel capacity. Sending data packets asynchronously to the LBARD packets at regular intervals was able to much better approach the capacity of the channel, or even exceed it in the case of 256 byte data packets every 2 seconds. In that case, the limited data buffers of the modems resulted in lost bytes, and thus failure of the communications protocol. Thus it was necessary to select a setting which retains a comfortable gap between the channel capacity and actual data rate.

2 seconds. Attempting to send too fast resulted in the modems hanging up, and thus must be avoided.

The interactions that lead to this situation are somewhat complex: For example, sending many pure-data packets will likely increase the latency of the LBARD packets, resulting in a longer delay in acknowledging the receipt of a bundle, which might result in additional pure-data packets being sent for that bundle, thus resulting in a lower effective transmission rate.

It is also worth noting that typically the first 120 to 180 seconds of the 1,000 second test period were consumed by the time required for the modems to dial one another, and for the TreeSync algorithm to begin discovering which bundles need to be sent. Thus, in the best cases where 30 bundles were transmitted during a test, this correlates not to 1,000/30 = 33 seconds per bundle, but to closer to $(1000 - 150)/30 =$ 28 seconds per bundle.

9.7.9 Various progress tracking bugs

The performance tests listed in the previous sub-section relate to the sending of bundles with zero-length payloads. When similar tests were attempted using bundles with payloads, a number of problems were found and rectified, including:

1. An out-by-one error when sending pieces of bundle manifests would mistakenly mark the following piece as having been sent. This would prevent that piece from being sent until all other pieces had been sent at least once, thus greatly slowing throughput. This was masked in the manifest-only bundles used in the previous test, as the manifest is small, and so such delays would be rather short, as it would typically be only a few seconds later that the incorrectly marked piece would be correctly sent.

2. Other errors in the code meant that sometimes payload or manifest pieces would be incorrectly marked as the other in the lists of recently sent pieces, causing similar delays before the pieces masked by such errors would be re-sent.

3. The transmission of bundles would sometimes be interrupted, causing it to forget the information about the current state of transfer.

This last problem was not as simple to fix as the previous two. Essentially there were two options for solving it, namely:

1. Never switch the bundle currently being sent; or

2. Remember the state of transfer of bundles when interrupting their transfer, so that transfer can be efficiently resumed later.

The first is not a realistic option, precisely because one of Rhizome's strengths is the ability to prioritise the transmission of newly arrived (or discovered) bundles, so that it is always transferring the highest priority bundle.

Therefore a mechanism was added that allows caching of the transfer status of each bundle, so that they can be efficiently resumed after interruption.

In the process, several other minor problems were found, including the failure to mark the terminal piece of a payload as having been sent. Also, the Generation ID of the TreeSync algorithm was being reset every four minutes, causing the TreeSync process to restart every four minutes. This would cause the interruption of the bundle currently being sent, thus antagonising the above problem. It also meant that more of the channel was being consumed by TreeSync traffic than necessary.

Other problems related to the USB and modem flow-control interaction, errors in the escaping of special characters in the pure-data, and various other bugs were also found and fixed.

9.7.10 Transmission queue mishandling

Further problems were found in the management of the transmission queue. In particular, there were code-paths where a bundle would be bumped from being the currently transmitted bundle, but would not be inserted into the queue of bundles that still need to be transferred. This was masked in most cases, where this happened while there were still more bundles to be sent than fit in the transmission queue, and thus the TreeSync re-start process that would be triggered in that case would give the bundle a further opportunity to be queued. However, if this situation occurred when there were only a few bundles left to be sent, then the TreeSync algorithm would not be re-started, and it would be possible for the bundle in question to not be sent.

This was corrected by fixing the mis-handling of the transmission queue that allowed the bundle to be erroneously removed from the transmission queue to begin with.

9.8 Results & Discussion

Having addressed the various problems described in the previous section, LBARD is now able to reliably deliver Rhizome Bundles with reasonable efficiency. This was tested by running multiple tests where each LBARD instance was configured with 102 bundles with payloads ranging from 0 to almost 7,000 bytes, designed to simulate text messaging traffic. All bundles were delivered in all tests, that is no evidence for any remaining protocol errors that prevented the delivery of bundles was revealed. The results of these tests are summarised in Figures (9.12) and (9.13).

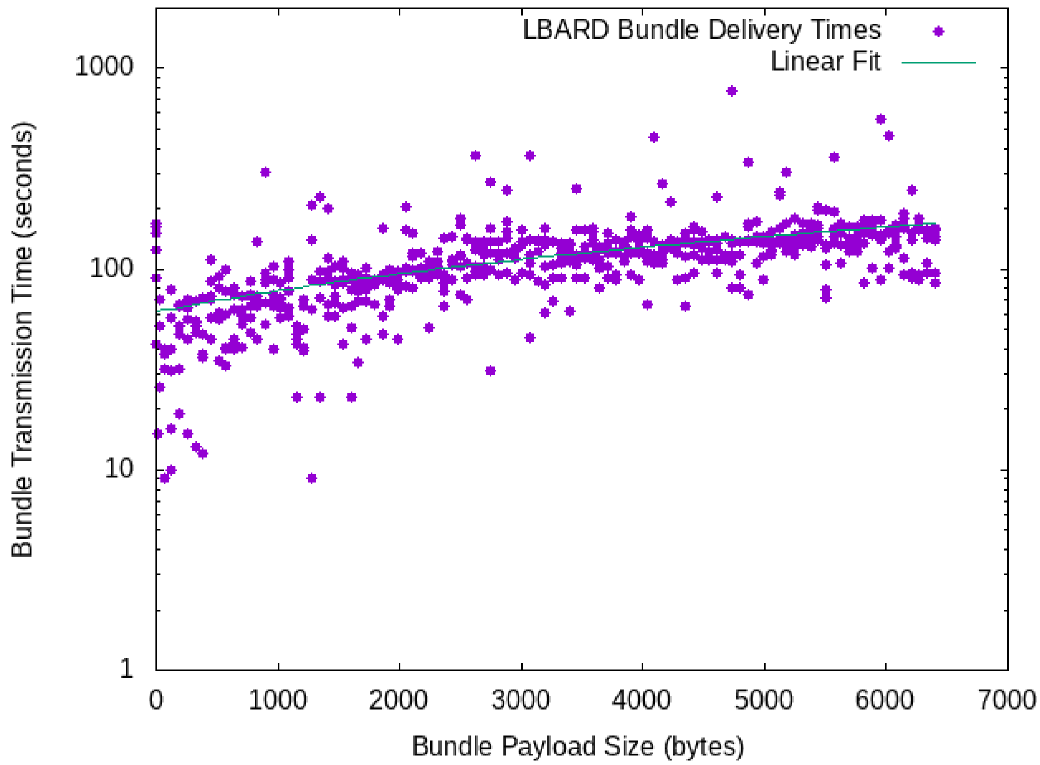


FIGURE 9.12: This graph shows that the delivery time of bundles scales almost linearly with the length of the bundle payload. There is an overhead of around one minute, regardless of bundle payload size, which reflects the time it takes to transfer the bundle manifest, as well as for the bundle synchronisation protocol to inform the sending party that a bundle has been completely received. The relatively linear increase in bundle delivery time is strong evidence that all critical protocol errors have been resolved, and that bundle transfer is occurring relatively efficiently, independent of bundle payload length. In particular, if individual data blocks were being unnecessarily resent, we would see super-linear growth in bundle delivery time instead.

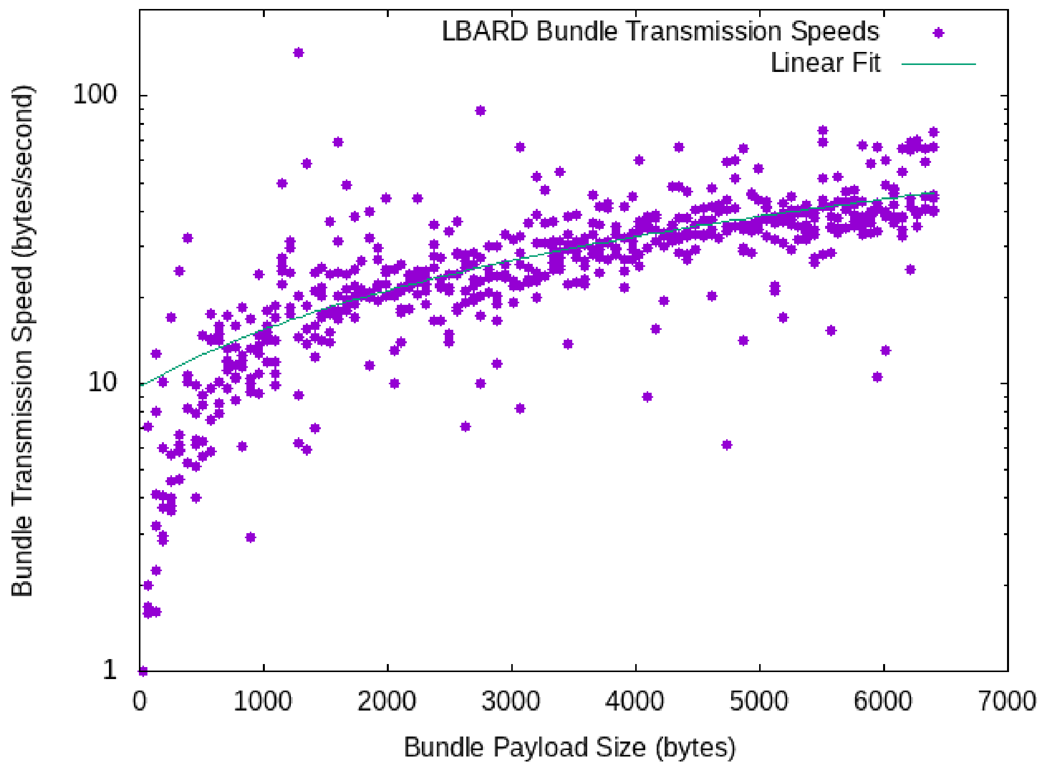


FIGURE 9.13: As previously described, the transmission time of bundles scales linearly with payload length. This graph shows the speed of bundle delivery with respect to bundle payload length. Because of the synchronisation protocol's overhead and the need to send the bundle manifest, the speed of bundle transmission for very small payloads appears slower because these overheads dominate. However, as the bundle payload length grows, we see that the speed increases and plateaus, asymptotically approaching a speed of around 40 bytes per second. This is around half of the effective channel speed of about 92 byte/sec. The difference is due to the synchronisation protocol and protocol headers, as well as significant contributions from the high latency of the modems, and the difficulty of actually saturating the modem links in practice.

These figures show that the transmission speed of bundles tends to increase with increasing bundle size. This is not surprising, as the overheads for the transmission of a bundle are relatively fixed, including the time taken to transfer the manifest of a bundle, as well as the modem-latency induced delay in informing the sender that a bundle has been received in its entirety.

Also, it can be seen that the sustained throughput of bundles now approximates 50% of the 92 byte per second channel capacity. That is, any remaining improvements to the protocol can at most result in a doubling of capacity. This is more than sufficient for proving the feasibility of the utility of hybrid

Serval Mesh / HF radio networks for connecting remote communities.

It is also worth commenting on the outliers in the data presented. Where bundles show transfer speeds that are higher than the channel capacity of 92 bytes per second, this is most likely due to the way that the accounting of time spent transferring each bundle was accounted, and that the transmission of one bundle can be pre-empted by another. This makes it possible for time to be incorrectly accounted. This is more apparent when this occurs to smaller bundles, such as the bundle with a payload of approximately 1,250 bytes that was transferred with an apparent speed of more than 100 bytes per second. A second potential cause in these situations is that the modems do not equally share the channel.

On the other hand, for a small proportion of bundles the transfer speed is well below the average. In these situations again the difficulties of correctly accounting the transfer time for bundles when transmission of bundles is regularly interrupted when higher-priority bundles are discovered is the most likely leading cause. Considerable comfort comes from the fact that the transmission speed does increase on average with bundle payload length, and that even in the worst case scenario, the transmission time for no bundle is more than half an hour.

Indeed, for the vast majority of bundles, the transfer time is in the range of 1 to 4 minutes, with many bundles being transferred in less than 1 minute, especially smaller ones. Given that these transfers occur bidirectionally, this corresponds to several hundred to a few thousand bundles that can be transferred each direction in a given 24 hour period, which should be more than sufficient for small isolated communities to remain in effective contact with one another. Also, the implied round trip latencies of 2 – 8 minutes for sending a message and receiving a reply would seem to be well within the range of acceptability for facilitating effective two-way communications.

Nonetheless, it would be worthwhile to further investigate and analyse all sources of variation in bundle delivery latency and transmission speed, to determine if these figures can be further improved. However, the goal of this thesis is to demonstrate the feasibility of the integration of HF radios into the Serval Mesh, rather than to present an optimal implementation, this falls outside of the scope of this thesis.

9.9 Conclusion

In this chapter, it has produced in-depth technical steps about how HF radio data modem can be rehabilitated by integrated it with Serval Mesh to expand the usage of HF radio beyond the traditional purpose, and give it the opportunity to be as an excellent communications alternative in some cases like satellite phones. The decisive point here is that it is not restricted to few people only, but to all community members, and give them a chance to communicate with other remote communities all year round, improving their resilience, increasing the likelihood that the HF radio will be in service during natural disaster time, and creating many potentials in different aspect of life to whom who live in remote communities.

When these new improvements go into service, it will provide efficient links between individuals at no cost. It will encourage international aid organisations to supply many remote communities in the Pacific region with HF units as the cheapest method to service many residents using one single device only.

The gaining capacity allows for two participants in remote locations to exchange several messages on a daily basis, and this is satisfied to say that there is a basic communications link between communities, which can be employed to express different humans' needs.

9.10 Responding to the research questions

In this chapter it has been shown that it is possible to integrate HF radio into the Serval Mesh, in a manner that is able to facilitate the delivery of hundreds to thousands of messages in each direction per day. To achieve this, various deficiencies and errors in the Serval Mesh software and protocols had to be identified and rectified. The end result is a system that is able to achieve close to 50% efficiency, despite the considerable challenges that the HF data modems present, and provide reliable delivery of Rhizome bundles using this equipment. This is a significant achievement in the context of the first four research questions that are the focus of this thesis:

9.10.1 Is it possible to provide a cost-effective and free-to-use communications solution to low-income remote community members?

This has already been substantially answered in the affirmative by the existence of the Serval Mesh, but is strengthened by the demonstration of the practical capacity of HF radios to facilitate Serval Mesh communications with adequate capacity. It is the integration of HF radios that makes it possible to serve low-income remote community members, by removing the need for individuals to have access to expensive to use solutions such as satellite telephones. The manner in which the Serval Mesh is able to share the benefit of a HF radio installation among all community members who have access to a simple Android-based smart-phone, which are very common in the Pacific Islands, is also a key enabler. This avoids the situation where only a few select members of a community would otherwise have easy access to the telecommunications.

9.10.2 What is the current state of the Serval Mesh message synchronisation process, and can this be improved?

This has been answered throughout the chapter where various problems with the synchronisation process were identified, being a mix of implementation errors, as well as limitations in the face of high-latency communications links, such a the Envoy's data modem. The correction of these deficiencies, resulting in a decrease in bundle delivery latency and increase in bundle transmission speed demonstrate that improvements were possible, and have been achieved.

9.10.3 Can we extend the communications range of Serval Mesh network to hundreds of kilometres? Can HF Radio be a solution to this problem?

This question has been answered in the affirmative by the combination of this chapter, and the previous chapter: The ability to integrate HF radio into the Serval Mesh has been conclusively demonstrated, and by implication, the ability to extend the communications range of the Serval Mesh to hundreds of kilometres.

9.10.4 HF data links have very low bandwidth. Can we manage such low-bandwidth links effectively, to enable very isolated communities to communicate with one another?

This question has also been answered in the affirmative: Compared with the proof-of-concept work of the previous chapter, this chapter has demonstrated the ability to deliver hundreds to thousands of Rhizome bundles per day over a low-bandwidth, high-latency HF radio link. Given the typical isolated community in the Pacific has a population of 200 or less, this is sufficient to allow multiple messages per person per day. This would seem to adequately satisfy the requirement of "enable very isolated communities to communicate with one another".

9.11 Conclusion

In short, this chapter has resolved four of the five research questions, by conclusively demonstrating the feasibility of using the Serval Mesh with HF radios to provide sufficient communications capabilities as would be required to connect isolated communities with one another. That said, there remain opportunities for improving the performance of the system, and better understanding the sources of variation in bundle delivery speed and latency, which can be explored in future works.

This leaves only the fifth research question to be answered, which is the focus of the following two chapters of this thesis.

Chapter 10

Demonstrating a low-cost and zero-recurrent-cost hybrid mesh and satellite based early warning system

10.1 Introduction

Part of this work is published in IEEE GHTC conference, 2018, titled "Demonstrating a low-cost and zero-recurrent-cost hybrid mesh & satellite-based early warning system". This chapter presents a considerably expanded coverage than is included in that paper.

In the previous chapters, the focus has been on how to expand the Serval Mesh, and the LBARD component in particular, to support effective long-range communications, with the goal of connecting isolated and disaster-impacted communities in Pacific Island Nations. In the previous chapter, it was demonstrated that it is possible to use HF radios as one approach to achieve this, and that is capable of transporting hundreds to thousands of messages per day. While that achievement is significant, and will likely have considerable positive impact in the Pacific when deployed, it is still limited by the characteristics of the HF radios on which it is based. Some of those limitations include:

1. Real-time communication is dependent on the state of the ionosphere, and other potential users or interference sources on the radio channels. This means that while over a period of hours to days, communications is typically possible, that at any particular moment, communications may not be possible.

2. The latency of the system is still quite noticeable, typically of the order of one to several minutes.

While those limitations are acceptable for many use-cases, they do present problems for certain use-cases. In this chapter, the implications for the provision of effective disaster early-warning systems (EWS) are considered. For example, while the latency of HF-mediated communications may be acceptable for non-time-critical communications, some disaster events are very rapid onset, and every minute or even second of warning time can make a significant difference to the outcome. This is particularly true for tsunamis, whether caused by earthquake, slope collapse of volcanoes or other causes [264, 256]. In some cases, the effective window for warning may be of the order of one minute, or even less in extreme cases, which HF radio is not capable of reliably meeting.

Therefore this chapter considers an alternative approach to resolve these issues within the Serval Mesh. In particular, what methods might be feasible for providing high-reliability low-latency message delivery into a Serval Mesh installation in a remote Pacific Island context, and how that might then be used to rapidly alert the community of an approaching disaster or emergency event.

Before this can occur, it is necessary to first revisit the Pacific Island context from the perspective of their disaster/emergency early warning system (EWS) requirements and situation.

10.2 Tsunami Early Warning Systems: Need for, and challenges in the Pacific

Tsunamis are caused by the displacement of large volumes of water, which then results in sometimes very large waves that impact coastal communities. A further complication of tsunamis is that they travel very fast, effectively due to the high speed of sound in water, and that tsunami waves are transporting energy, rather than water. This changes as they approach shallow water near land: The wave slows from several hundred kilometres per hour to 10 to 50 kilometres per hour, and the tsunami waves are thus compressed horizontally, causing them to grow in height to compensate for this. This is also why tsunamis are often not noticed in the open ocean, where the wave may be as little as 10 cm in height, and rarely more than one metre in height, and where the wavelength will can be hundreds of kilometres long, making this small vertical movement hardly noticeable. These descriptions of tsunamis are approximate, but serve to give sufficient understanding of the danger that tsunamis present. This danger is not just theoretical, but many people lose their lives to tsunamis on average each year. Pacific Island Nations are surrounded by the Pacific Ring of Fire, which exposes them to a very high risk of tsunamis.

Because of this danger that tsunamis present, it is common for wealthy coastal nations to have sophisticated tsunami early warning systems. These warning systems often consist of a number of complementary elements. These can include integration with the cellular network, so that bulk SMS messages can be sent to all handsets in the danger zone, for example, or the provision of large warning siren towers that can broadcast an audible alert over many kilometres. Figure (10.1) shows the top of such a siren tower in Timor Leste. What is difficult from this image to grap, is that these towers are often very large structures, often 20 to 50 metres in height, and are correspondingly expensive to purchase, and require considerable logistical support to maintain.

These characteristics are all problems in low-income low-population Pacific Island Nations. Often such systems are kindly donated by foreign aid schemes, and pay for the purchase and installation of the early warning towers, but then typically leave operation and maintenance to the recipient nation. This occurs for similar reasons, and with similar consequences to the supply of HF radios into Pacific Island Nations: Many systems rapidly fall into disrepair, because they are not useful year round, it is not immediately obvious when they have failed, and there are many other competing demands for the limited time, money and human resources in these nations in order to address these problems.

It is not only smaller and poorer Pacific Island Nations that have difficulty maintaining these traditional tsunami warning systems. For example, we have seen recently in Indonesia in 2018 that the early warning systems there did not provide timely warning of the approach of tsunamis, which resulted in the loss of lives, infrastructure and livelihoods. Unfortunately, this situation happened twice following two tsunamis within a short period of time [190].

Thus there is an imperative to apply a similar approach to innovating the provision of early warning systems as has been applied in the Serval Mesh to the provision of basic telecommunications services.

FIGURE 10.1: The upper section of a tsunami early warning siren tower in Dili, Timor Leste (Image in the public domain). These towers are typically 20 to 50 metres in height, are expensive to install, and expensive and complex to maintain in remote Pacific Island Nation contexts, especially where they are faced with regular cyclones and a highly corrosive tropical maritime environment.

One approach to this is to apply the recent advances in satellite broadcasting, and integrating that with Serval Mesh to present a low-cost effective solution. The cost of many satellite receivers is less than US$100, and requires only very small antennae, that do not require accurate aiming to receive the broadcast satellite signal. This technique would make it possible to establish a one-way bridge from the outside world to local community members to deliver high-priority messages to them or to a local alert tower. By carefully designing the satellite broadcast service, it is possible to avoid all usage and subscription charges for end-users, thus overcoming an important barrier for adoption by impoverished remote communities. The previous chapters have demonstrated the feasibility of incorporating new telecommunications carriers into the Serval LBARD system.

The exploration of this possibility is the focus of the remainder of this chapter, where a low-cost Ku-band satellite receiver from Othernet [171] is considered for its potential to meet this need. This chapter covers both the implementation of this approach and a demonstration of the resulting system, including its ability to deliver information to isolated areas with very low latency. Importantly we demonstrate latencies of less than one minute, which is sufficient to provide early warning of most tsunamis, including locally generated tsunamis, such as the one that struck Indonesia following the underwater slope collapse of Anak Krakatau.

10.3 Contributions

The contributions in this chapter are:

1. Design of a low-cost Emergency Warning System that avoids the logistical difficulties and related problems that exist for traditional "tall tower" Emergency Warning Systems.
2. Introducing the proof-of-concept of such a system that employs a subscriber-cost-free satellite link to deliver messages into remote Pacific Island environments with low enough latency to be useful for early warning of tsunamis.
3. Demonstration of the proof-of-concept system in Vanuatu, a Pacific Island Nation that is prone to tsunamis, and climatically representative of many Pacific Island Nations.

10.4 Heightened disaster risk for coastal communities

Recent significant events that have happened in coastal areas worldwide have shown the catastrophic effect of what such events are able to cause. The tragic experiences that happened worldwide demonstrate that costal communities are among the most threatening groups by natural disasters. For example, Hurricane Katrina when it struck the southeastern coast of the United States caused massive damage to New Orleans [249], while the significant tsunamis following large earthquakes in Indo-Pacific region resulted in considerable loss and damage in Indonesia [85] and in the case of Fukushima in Japan, triggered a major nuclear disaster [225].

Large coastal cities are often considered attractive places to live, and they often host many entertainment activities, and other popular public facilities.

They are, however, often exposed to considerable natural risks, including that of tsunamis, storm swells and cyclones. While some such locations are at least partially protected by their local geography, such as being based at the top of large cliffs or through the presence of mitigating bathymetric topography [45], many populated coastal areas have no effective natural protection against these events. For larger population centres in more wealthy nations, this risk is typically mitigated by the provision of early warning systems, this is rarely the case for smaller and isolated communities and villages, especially in lower-income countries. This leaves these communities with an elevated risk profile.

Climate change has added to this risk profile, through increasing sea levels, and more significantly, through increased risk of cyclones, storm swells and other extreme weather events, especially in the tropical and sub-tropical latitudes. The evolution of these risks are difficult to predict, highlighting the need for responsive early warning systems to help manage both the well-known and emerging hazards for coastal communities. This adds to the imperative for providing effective early warning systems for coastal communities.

10.5 The role of Early Warning Systems to mitigate the effects of natural disasters

Early warning systems are increasingly deployed as they have proven their abilities to mitigate the threatens posed by natural hazards. It is generally no longer disputed that natural disasters are increasing the loss and damage to coastal communities, nor the ability of early warning systems to aid in the mitigation of those risks [68].

An effective EWS is able to significantly reduce on the death toll and injuries caused by a natural disaster. Early alerts give residents a time to displace from the hazard area, and help authorities in the evacuation process and sheltering the effected people before anything happens, and in some cases, protective actions can be taken to reduce the damage to key infrastructure. For example, boats and ships can be moved out of harbours into deep water, where the impact of tsunamis is greatly reduced, and the risk of the vessels running aground can be minimised.

Effective early warning can also be used to more rapidly mobilise the response to a disaster, by providing early warning to the response organisations of the impending need [189]. Generally this aspect of early warning works well, as it does not normally depend on the availability and serviceability of infrastructure in the affected area. Thus there is little need for improvement in warning those outside of the disaster zone, and the focus of this thesis remains on warning those who are in the path of a disaster event.

10.6 Lack of effective Early Warning Systems in low-resource countries

Despite the importance and benefits of deploying Early Warning Systems in hazard areas, the situation in low-resources countries not particularly positive: The lack of capacity, capability and resilience through advanced infrastructure that comes with higher resource levels makes the availability of effective early warning of disasters all the more critical. However, these same limitations mean that Early Warning Systems are less likely to be deployed, or to be working correctly when needed. The foreign aid system shares part of the blame in this, in that donor nations are typically much more willing to fund the purchase of large infrastructure, like a traditional tower-based Early Warning System, than to provide for the ongoing operating and maintenance cost of the system. This then compounded by difficulties in translating best practices from high-resource settings into the resource-constrained environment of these small low-income countries [109].

For these reasons, there is considerable value and interest in creation lower cost, and more easily maintained and sustained early warning solutions for the Pacific.

10.7 The logistics problem remains unsolved

In the Indo-Pacific region, with its many small islands are distributed over a very large area, has many small and isolated communities, often as little as 100 people. As explained earlier in this thesis in Section (8.3), these small communities are likely to be isolated from the outside world, because of the lack of access to telecommunication infrastructure. Therefore, there is a need to connect these communities with the outside world, which becomes vital and urgent when disasters occur.

Unfortunately, disasters do frequently happen in this region. As a result, many governments there have installed different equipment to detect or alert the population of disasters when they strike, including disaster early warning systems. These equipment have historically been very expensive to purchase, and then require a significant recurring budget to pay for their operation and maintenance, which often requires access to expertise that may not be locally available, further increasing the cost and logistical complexity of doing so.

Thus, even when foreign countries and other foreign aid organisations donate the cost of installing disaster early warning systems, the problem of maintaining them remains a big challenge or even without solution. As a result, there are many non-functioning or partially-functioning early warning systems in a region that witnesses many natural disasters every year. Another factor is that large and visible infrastructure pieces are often subjected to vandalism or "pre-emptive recycling". These factors are further amplifies the problem of maintaining these traditional large infrastructure-based early warning systems. Further, because of the very large cost of these systems, and small population on many out-lying islands, such systems are far from providing complete coverage of all people living in the region.

In short, the current approach is unlikely to ever be able to provide complete coverage for disaster early warning, and even if it were to do so, the cost of doing so would be prohibitive. Thus the primary motivation must be to mitigate these logistical and financial problems suffered by the current approach. This raises two interrelated questions:

1. How can high priority messages be affordably delivered to isolated and remote communities, where there is a lack of telecommunication infrastructure

2. How can such a solution be constructed, such that it is cost-effective and sustainable, both in terms of initial installation and in terms of maintenance maintenance, so that it can remain functional for the long-term?

Before these questions can be answered, it is necessary to consider the types of early warning systems that may be required:

10.8 Types of early warning systems

While the focus so far in this chapter has been on responding to tsunamis and other hazards related to the ocean, these are not the only hazards that are of relevance to the Pacific Island Nations, and that may also require varying responses and warnings to be issued. For example, as 2020 has so clearly revealed, it is also possible for disease outbreaks to create problems that may require effective warnings of varying kinds.

One approach to classify early warning systems and the hazards they correspond to is as follows [245, 63]. Not all of these hazards fall within the scope of this thesis.

1. Geological hazard: This type lies within the scope of work, and it includes those natural disasters that are related to geological activities, e.g.,tsunami, earthquake, landslides and volcanic activity.

2. Hydrometeorological hazard: This includes another set of natural disasters related to extreme weather conditions, whether inland and marine regions. Examples include cyclones/hurricanes/typhoons, tornadoes, floods, and also events such as drought and heat or cold waves. While not all of these hazards are the focus of this thesis, it can be seen how many of these hazards could be served by an early warning system that is fast enough to respond to rapid-onset events such as tsunami, earthquakes or landslides.

3. Health hazard: This type refers to disease, primarily comes from contagious viruses to humans, such as COVID-19 or the Ebola Virus.

4. Biological hazard: This refers to another range of biological risks not included in the health category, such as insect plagues, for example, locust plagues that may pose a risk to crops and food security.

This chapter will focus on geological hazards, and on tsunamis in particular as one of the more challenging examples of this, because of the very low latency requirements for such warnings. It will be assumed that an effective tsunami warning must be able to be delivered within 60 seconds.

Independent of the type of hazard that is being mitigated by the early warning system, it is also possible to consider the scale of the system:

1. International level system: These systems operate globally, available to all nations, and international organisations are typically involved such

systems. For example, the functions of the UN World Health Organisation (UN WHO) for providing warning of epidemics and pandemics, as exercised during the COVID-19 crisis.

2. Regional level system: Similar to the international level, but restricted to certain groups of countries, typically in a particular geographic region, or with a particular affiliation or common uniting element, such as anglophone or Francophone countries collaborating, or Pacific Island Nations to the extent that they cooperate in these matters.

3. Countrywide level system: The next level down is systems that are cover the entirety of a single country, and are typically operated by a government agency or department, or auxiliary organisation, like the Red Cross.

4. Community-level system: Finally, the lowest level is where local communities coordinate and provide their own local early warning system. Such systems may be in response to decidedly local hazards, such as the measures taken by the small communities living on Halligen on the German North Sea coast that are subject to inundation by storm surge, or to provide a local capability for responding to hazards that are more widely relevant, such as a local bush fire spotting and response capability. Community level systems may or may not be integrated into larger countrywide systems.

In this chapter, the focus will be on community-level systems, as the focus is on creating solutions that are cost-effective enough for individual communities to deploy and maintain, precisely because the countrywide approach has, to date, not been able to meet their needs. This does not preclude the solutions from being adopted at a national, regional or international level, however.

10.9 Low-latency broadcast satellite based solution required

In the previous chapters the potential for HF radio to be used in new ways has been explored. Indeed, it was shown that by using HF radio in a more intelligent manner, it is possible to provide basic telecommunications in remote areas in the Pacific. However, also as described, the latency, intermittency and other problems of HF radio make it less suitable for delivering high-importance low-latency warnings of approaching disasters.

In contrast, broadcast satellite services have the ideal properties in most regards:

1. Very low latency, typically of the order of one second.

2. No terrestrial infrastructure required in the disaster zone.

3. A single signal can cover very large areas. Indeed, satellite television is based on precisely this strength.

4. Fundamental cost of access is low, with cost-free access available to services, where this is the intention.

This third point requires some explanation: While satellite telephony and related satellite-based services are very expensive to use, renting capacity on a legacy broadcast television satellite is remarkably affordable, as shall be described later in this chapter. If a system can be based around this concept, it has the potential to be cheaper to operate than existing "tall tower" systems, and importantly, without requiring expensive and logistically complex maintenance of the towers and related infrastructure.

The key outstanding challenges are avoiding the need for a carefully aimed dish, and for translating the satellite signal into a useful alert, for example, a series of tones on a loud speaker or siren. Solutions to these challenges are outlined in this chapter, culminating in the demonstration of a proof-of-concept system based around a Serval Mesh Extender combined with small low-cost broadcast satellite receiver.

Proposing to use satellites as part of an Early Warning System is hardly new or contentious, as satellite communications is used in a variety of existing early warning systems. What is new, is finding ways to do this using small community-scale warning devices, enabling them to use a single low-cost shared satellite broadcast stream, and to integrate this with the Serval Mesh, so that the system can also support year-round basic telecommunications and/or other services, so that it these small systems are more likely to be maintained between disaster events.

10.10 Abstracting radio links

Incorporating broadcast satellite into the Serval Mesh requires the ability to abstract this communications mode along side the existing bi-directional options already supported, including Wi-Fi, UHF packet radio, and most recently as described in this thesis, HF radio.

Stepping back, there is considerable advantages to implementing such an abstraction, as it will allow simple interconnection of different radio types in order to construct useful resilient telecommunications networks. These can of course be useful in the Pacific, but also in other contexts, such as for space exploration and settlements on other planets or moons. Those contexts effectively mirror that of the Pacific, albeit in slightly more extreme form: Limited resources, low populations, and extremely challenging logistics to install and maintain these systems.

This is not dissimilar to the adoption of the Internet Protocol to abstract over the various low-level media over which real-time packet-switched networks can be constructed, e.g., 802.11 Wi-Fi, 802.3 Ethernet and RS232 serial. The success and popularity of the Internet comes from being a common communications protocol, and it abstracts away all beneath layers of different communication systems. This abstraction of the communications details has enabled a wide diversity of applications and communication to be created, and they can be interfaced together easily [250, 251, 94], which leads to interoperability and increases the utility of the Internet.

However, there is the challenge of translating this abstraction from the Internet to the context of Disruption Tolerant Networking (DTN): The Internet Protocol does not directly support disruption or delay tolerant networking (DTN). However, this is critically important for these kinds of remote and disaster zone communications systems, where direct real-time links cannot be guaranteed to be accessible. This is why the Serval Rhizome bundle-based protocol was created.

10.10.1 Abstracting disruption-tolerant radio links

The main difference between the Internet and DTNs is that the Internet is a packet-switching network environment, while DTNs is based on message-switched network, that makes it possible to tolerate significant transmission into consideration where the link to the destination may not be possible at all times. For example, RFC5050 bundle Protocol [202] where a bundle of data is the unit of traffic, typically including any required meta-data. The Serval

Mesh also makes use of the DTN concept, with the Serval Rhizome protocol being a bundle-based protocol [11, 88, 136].

If we can provide Rhizome stack to be utilised by different communication systems, in a similar way to what Internet stacks being provided, it will allow for the interconnection between these systems to happen. What Serval Mesh software and Serval Mesh Extender hardware are facilitating is precisely abstracting away the details of communication systems being employed to facilitate easy inter-networking between different bearer types [83].

Rhizome can inter-connect different communication systems together, and this can be done with little effort and low complexity to support extending the scale of the network by adding new links. A larger network can be formed from a variety of links, e.g., Wi-Fi, VHF, UHF and HF radio links. This makes it is relatively straightforward to deploy, redeploy and rearrange network to fit the potentially dynamic requirements of the owners of the network. Each bearer has particular characteristics which bring advantages and capabilities with them. For example, the UHF packet radio links enables longer range communications between Mesh Extenders in a village, while Wi-Fi allows the connection of smart phones to the network. Meanwhile, as discussed in the previous two chapters, HF radio can be used to facilitate communications over hundreds of kilometres.

The goal of this chapter is to consider a new bearer type that can be brought into the Serval Mesh family, that has the properties required to facilitate long-range, low-latency and reliable delivery of disaster warning messages – and at the same time have favourable economic properties, i.e., that it be cheap to operate the system, not require any subscription fees for users, and finally, that it should not require accurate aiming or a large antenna that would be difficult to transport, install and maintain in extremely infrastructure deprived environments. As previously described, the intended direction is to achieve this using a broadcast satellite receiver. This would be the first unidirectional bearer incorporated into the LBARD framework, which requires some special attention.

The following sections pursue this process.

10.10.2 The criticality of eliminating high operating costs

Satellite communication services are generally associated with higher costs compared with terrestrial services, due to the expense of launching and maintaining equipment in orbit. Indeed, the cost of obtaining a dedicated satellite connection, whether for telephony or internet, is relatively expensive. Certainly those costs would be prohibitive if scaled up across the Pacific.

In contrast, where a single satellite service can be shared among many users simultaneously, this allows the cost of access to be amortised among very many users. For example, broadcasting free-to-air television over satellite has a fixed cost of provision, regardless of how many people watch it. This has two benefits: First, the cost per user is low, but second and perhaps more importantly, the cost of providing the service is constant, regardless of the number of users. This allows the adoption of the service to grow, without increasing operating costs. This makes planning for the cost of operation predictable and feasible.

In the context of the Serval Mesh, and providing a disaster early warning system, the warning messages would be delivered as high priority Rhizome bundles. This allows the warnings to arrive via any possible channel, and to allow the bundles to be sent repeatedly over the available channels, to help maximise the chance of reception, where this makes sense for the bearer type. This is important for a satellite broadcast link, as unlike for the other bearer types integrated into the Serval Mesh, a satellite broadcast transmission is unidirectional, with no means to negotiate and synchronise in a two-way manner.

If we consider a system with a 1KiB per second broadcast signal, this has the capability to deliver 3,600 KiB per hour or 86,400 KiB per day. Assuming an average message size of about 1KiB, then such a link has the potential to deliver tens of thousands of messages per day, which is reasonable to simultaneously support many remote communities communication, as well as to very rapidly deliver high-priority disaster warning messages. That is, such a system could act as a kind of "delivery accelerator" for a Serval Mesh network operating in the same area, to help reduce the latency of message delivery. For example, messages from an urban area to remote communities could be uplinked via an internet-connected ground-station to the satellite, and then received by all Serval Mesh nodes in the region simultaneously. This would allow message delivery in that direction potentially in just a few seconds. Replies from the remote areas may still be dependent on HF radio or other links, but the traffic on those links would be reduced by the off-loading of the out-going traffic onto the satellite bearer. Also, when users move about the network, the messages addressed to them would be much more rapidly delivered.

This ability to use the satellite broadcast signal to support basic telecommunications would act to fulfil the desire and intention that the early warning system would be useful year round, so that it is more likely to be maintained and available when required. For disaster early warning messaging, this would simply be injected as a highest-priority message, and delivered in the same way, again, potentially in just a few seconds. This is where the low-latency of the satellite bearer becomes important.

The challenge is to find a low-cost satellite receiver that can satisfy the requirement for being able to receive hundreds of bytes per second, and that is ideally small, cheap and does not require accurate aiming at the satellite, so that it can be more easily pointed at the satellite.

10.10.3 The Othernet low-cost satellite receiver

The satellite receiver must be able to be installed in remote communities and to be used for post-disaster communications. Therefore, it must satisfy several important requirements:

1. low-cost, so that wide deployment can be supported, and replacement of failed units is affordable for small rural communities;
2. small size so that it can be easily transported to remote island communities where they are needed most;
3. weather resistance to some degree, sufficient to survive for at least a year in a tropical maritime climate; and
4. easy installation and pointed to the appropriate satellite.

Following an investigation of potential options, the Othernet satellite receiver system [172] was found to satisfy these requirements. It consists of a small PCB containing a low-cost radio receiver and embedded processor as shown in Figure(10.2). As well as being sufficiently cheap, of the order of US$100 per unit, it uses a standard Ku-band satellite television receiver horn as the antenna. However, unlike a normal satellite television receiver, it does not require a dish. The entire receiver can fit in a box approximately 20 cm long in each direction

By using a resilient relatively low-bandwidth waveform, using a cheap off-the-shelf LoRa-compatible receiver [140], it is able to receive a signal that is upto 20dB below the noise floor. This allows it to filter out competing transmissions from other satellites that are in view of the receiver. As a result,

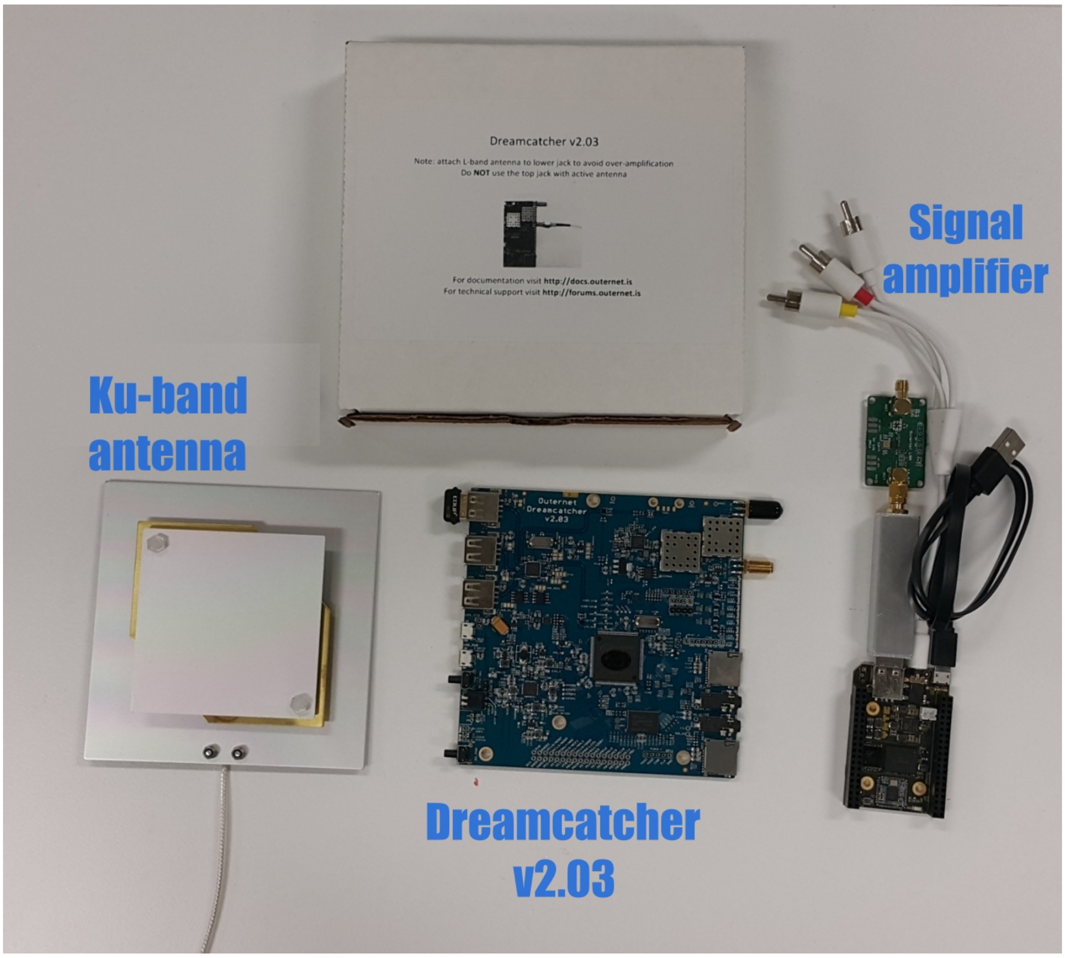


FIGURE 10.2: Othernet receiver components that has been utilised during the tests, and it shows the Dreamcatcher v2.03 board in the middle, Ku-band antenna at the left and the signal amplifier at the right.

it requires only to be aimed to within about 10 degrees of the position of the satellite. This is sufficiently simple as to be performed by an interested user with basic instructions, as shown in Figure (10.4).

Also, as it is based on existing low-cost weather-resistant outdoors satellite television antennae, this satisfies the weather proofing requirement, as well as helping to ensure that the antennae will continue to be available into the future. In short, the Othernet receiver system satisfies these requirements. Being based on a simple Linux-based embedded computer, it is also interface the Othernet receiver board with a Serval Mesh Extender, for example, via Wi-Fi, allowing the receiver to be integrated into a Serval Mesh network, as shown in Figure (10.3).

Thus the physical means of receiving digital communications in remote Pacific Island communities has been found. The next step is to conceive how an effective early warning system can be built on this foundation.

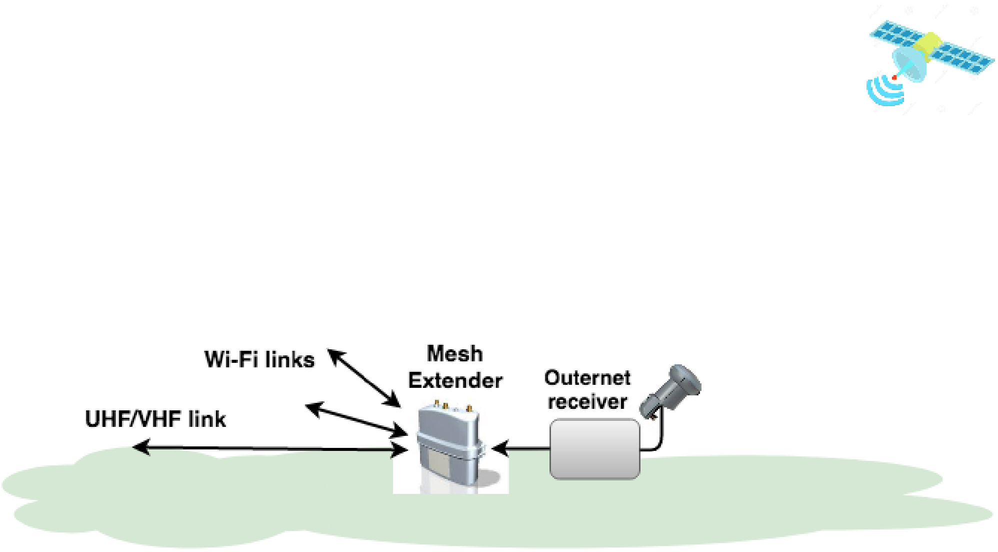


FIGURE 10.3: A diagram shows how Othernet satellite receiver gets data bundles from Ku-band satellite via horn and pass them to Mesh Extender, which broadcasts bundles over Wi-Fi short-range links and UHF/VHF medium-range links to other hops.

FIGURE 10.4: Installing the low-cost EWS at a village in Vanuatu, and a villager is aiming the horn of satellite receiver toward the Ku-band satellite since it doesn't require much experience person to install. Photo is taken by Serval team member.

10.11 Conceptualising humanitarian services

The goal that is the focus of this chapter is to establish a disaster early warning system that can provide early warning of an approaching disaster, as well as facilitating basic telecommunications, and/or other services that can be used to ensure that the system is useful and valuable to beneficiary communities year round, so that it will be functioning when needed to provide an alert for an approaching disaster. A message latency of up to 60 seconds will be considered acceptable.

However, it is possible to use the kind of system described so far to provide further beneficial services to remote communities. For example, it would be possible to use the capacity of the system to also send news, weather, and potentially also music and other entertainment content, to further increase the value of the system.

Software could be constructed that takes the stream of new content from the broadcast stream, and together with Rhizome Bundles that describe a play list, constructs a simulated radio station. While perhaps only one song per day in MP3 format could be accommodated by the system, these would build up over many days of operation, and eventually allow a diverse range of music and other content with which to fill the radio programme.

The receiver could also contain a low-power FM radio transmitter, so that people could listen to the radio station wherever they are. Aside from the direct value of these services to the communities, it would also have the important effect of normalising listening to the content, and thus maximising the likelihood that a disaster alert would be heard promptly on reception. This could be complimented by including a low-cost siren, such as a recycled automobile horn, to provide a general audible warning. The electronics for this would all still fit within a box approximately 20 cm long on each side, and still be very cheap.

The potential of such a system was recognised by the UN World Food Programme's Pacific Regional Office in Fiji in their role as Emergency Telecommunications Cluster (ETC) lead agency, when it was described to them. They were very enthusiastic about the system, and the concept is now known as the ETC Lali system. "Lali" is a word common to many Pacific Island languages, and is the name of the meeting drums used to call a community together, and was chosen by Pacific Islander members of the ETC group in Fiji.

Using such a system, it would be possible to create an integrated community information, entertainment and disaster early warning system, that would be cheap, simple and effective, as shown in Figure (10.5). Again, each receiver would not result in any increase in the satellite link operation or other costs.

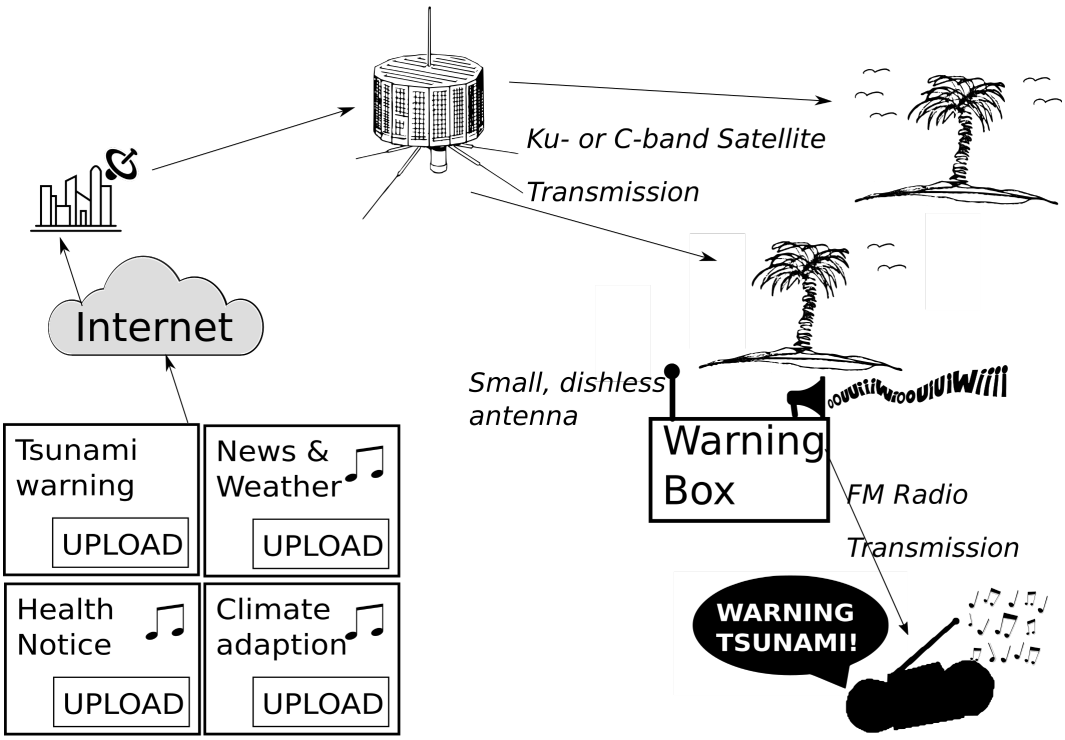


FIGURE 10.5: EWS or ETC Lali system diagram based Serval Project, where information are downloaded from satellite to local radio station or Serval hop, and any tsunami warning will trigger siren or any warning tool to inform people via loud sound or broadcast news from FM radio.

The emergency alert passed via the Serval Mesh software would be configured to be restricted so as to verify the source of the information, e.g., a National Disaster Management Organisation or governmental department, and add any other required data to the message, such as digital signatures, geographical bounding box information, which is quite feasible to fit in 1KiB or less. These organisational and regulatory requirements would need to be required before the system could be deployed operationally. Such activities are outside of the scope of the work described here, which focuses on the technical aspects, i.e., demonstrating that it is possible to transmit such a message and receiving it on an Othernet receiver, and feeding that into a Serval Mesh network.

10.12 Integrating the Serval Mesh and Othernet satellite broadcast services

The integration process between Othernet satellite receiver and Serval Mesh consists of two main parts:

1. Integration with the ground station of Othernet satellite so that Rhizome bundles are able to be injected into the up-link data stream for broadcast by the satellite; and

2. Integration between Serval Mesh Extenders and Othernet receiver, so that LBARD can process bundles received via the satellite down-link data stream

These two parts are explained below.

10.12.1 Integration with up-Link data stream

The integration will depend on the particulars of the ground-station and up-link system employed. For the proof-of-concept, Othernet were contracted to provide the uplink services. However, they did not have access to a ground-station within the foot-print of a geostationary satellite that covered both Flinders University and Vanuatu, our chosen test location in the Pacific.

As a result, the decision was made to recommission a defunct 4.5m diameter satellite dish located at Flinders University, as shown in Figure (10.6), and to co-locate the uplink electronics with it. This involved replacing the electronics, including the LNB among other components, which were non-trivial to locate for this dish, owing to its age. It was also necessary to re-aim the dish to point to the correct satellite, Intelsat 18A, located over the western-Pacific ocean.

Leasing access to a 1MHz wide transponder spot on this satellite cost only a few thousand US dollars per month, and yet covered approximately half of the Pacific Ocean, highlighting just how affordable it can be to provide this kind of service. In comparison, the connection fee a satellite phone is typically around US$50 per month, with high per-minute usage charges. In contrast the broadcast service cost allowed for 24 hours a day of constant transmission, resulting in a much lower effective cost.

LBARD traditionally manages the traffic over UHF, VHF and HF radio links, and this new role required some changes to the LBARD software. Specifically, to act as the feeder for the uplink, it had to be adapted to transmit one or more bundles in a completely uni-directional manner, and to correctly packetise the data in a manner that could be accepted by Othernet's uplink equipment, without feedback from the receiving parties, because there is no direct back-channel. The Othernet uplink hardware provided basic Forward Error Correction (FEC) services, but not interleaving or other delivery reliability services.

FIGURE 10.6: A 20 years old satellite 4.5m diameter dish already installed at Flinders University-Bedford campus has been employed to up-link data to the the satellite, then broadcast data to other remote communities. Considerable work was required to recommission this dish to act as a ground-station

Satellite communications systems must be able to tolerate packet loss due to a variety of factors, including channel fading and elevated noise levels [214, 3, 154]. This is most commonly occurred using some sort of redundancy, so as to overcome the expected packet loss rates, including both sporadic/random packet loss, and clusters of packet loss caused by bursty sources of interference, such as heavy rain, various space-weather effects, or even a bird passing in front of the receiver.

There are different applied techniques that can be used to mitigate against such forms of packet loss, ranging from simple repetition of packets, to RAID-like encodings that can tolerate the loss of some percentage of packets [22]. Another complementary approach is to use interleaving, so that the impact of the loss of a cluster of consecutive packets is spread out over the received data stream. The goal is that with the lower density of packet loss in the de-interleaved stream, that the other Forward Error Correction mechanism can recover from the loss of the packets.

As the intention is provide a proof-of-concept at this stage, rather than a fully-optimised service, a relatively simple interleaving and redundancy scheme was implemented, that can still deliver sufficiently low latency to meet the 60 second latency requirement.

The implemented redundancy scheme is similar to RAID5, and based on the addition of one parity block for every three data blocks. This allows recovery of one in every four packets, thus tolerating up to 25% of packet loss, provided that no more than one packet is lost in each set of 4 packets.

For the interleaving scheme, five data streams were maintained, each using the RAID5-like parity scheme within them. This allows the sending of five different bundles simultaneously. For added redundancy, the same bundle could be transmitted over more than one of these five streams. Perhaps more typically, bundles could be classified according to their size before injecting into the five lanes, with each lane accepting a bundle if it is between the minimum and maximum size threshold, so that smaller bundles cannot be held up by the transmission of a single large bundle, but that larger bundles can also be simultaneously transmitted. For example, bundle size limits could be selected as 1KiB, 4KiB, 16KiB & 64KiB for the first four lanes, and the fifth reserved for bundles larger than 64KiB.

It is fully acknowledged that the described redundancy and interleaving schemes are rather simplistic and sub-optimal compared to best practice. Nonetheless, if the delivery of Rhizome bundles can be achieved in realistic conditions using these schemes, then this proves the overall feasibility of the concept, which is the goal of this study.

Assuming the above encoding scheme, assume a packet of size 200 bytes, and a data bundle size of 1KiB, which contains vital an early warning message for a tsunami or other disaster. Transmission of this bundle would require six fragments to be transmitted, given that $1,024 > 5 \times 200$, this requiring require 6 fragments. However, the addition of the RAID5-like redundancy and interleaving increases ths to $6 \times (n+1)/n \times 5 = 6 \times 4/3 \times 5 =$ 40 consecutive packets to transmit the bundle. Although five such bundles could be transferred simultaneously in this time, the latency of each will still be the time it takes to transmit and propagate 40 packets. Therefore, provided that the rate at which packets can be transmitted is at least 1Hz, this will result in a latency of < 40 seconds, which is comfortably within the 60 second latency deadline set for this use-case.

10.12.2 Extracting bundles from the Othernet receiver

The previous description explains how Rhizome bundles can be packetised and reliably uplinked to the satellite, so that they can be broadcast for reception by an Othernet receiver. The next step is ensuring that the packets can be received and reassembled on the Othernet receiver hardware, and then handed over to a connected Serval Mesh Extender.

The communications link between the Othernet receiver and Serval Mesh Extender was implemented using the Othernet board's integrated Wi-Fi receiver. A modified version of LBARD was run on the Othernet receiver which received the raw data from the satellite receiver, and then processed the received packets to reassemble the Rhizome bundles, by (1) de-interleaving the packet stream; (2) applying the parity redundancy scheme, and recovering any lost packets as required; and (3) inserting the packets into the normal LBARD packet reception service, which takes the fragments and assembles complete Rhizome bundles from them. Once received by LBARD, they are inserted into the Serval Rhizome database in the normal way, from where they are automatically transferred via the Wi-Fi link to the Serval instance on the Serval Mesh Extender.

In this way, the fact that bundles are being received by the new satellite-based bearer is completely abstracted from the end-user, who simply uses the Serval Mesh in the normal way, highlighting the power of this approach.

10.12.3 Othernet supports Two-way communications

It is worth noting that while the Othernet receiver was used in a purely receive-only mode, it is possible, in theory, to use it as a two-way communications channel, even with its small antenna. This could be used, for example, to allow a central authority to determine which nodes are still functioning, and which need repair, in order to aid maintaining an effective early warning capability. It could also potentially be used to relay messages back from isolated communities. However, there are considerable technical and regulatory barriers to implementing this, and it is therefore out of scope for this thesis.

10.13 Results

10.13.1 Verification through simulation

The final stage before field testing is simulating the system to verify the functionality and the performance. To do that, a modification to the simulation framework of LBARD was implemented to allow including the Othernet satellite path. The simulation is performed via fakeouternet program, which allows packet injection at a rate of one per second, and provides a simulated acknowledgement of transmission to trigger the injection of next packet in the queue, matching the requirements of the Othernet ground-station equipment. The geostationary satellite free-space delay was excluded from the simulation as contributes only a fixed 280 milli-seconds to the total latency [212], and the number can be accumulated to the total latency. A further fixed 1 second was allowed to cover latencies of internet carriage of the injected traffic to the ground-station uplink systems. Therefore, delay during space path and transmission process at a fixed rate equals $0.28 + 0.28 + 1 = 1.56$ seconds.

During the simulation, bundle sizes of 365, 765 & 1265 bytes were tested. These sizes were chosen as representative of the smallest possible bundle that could contain the necessary information for a tsunami warning message, as well as two larger sizes that could be used to accommodate more complex information. The time was calculated from the log file between the first packet's arrival until reconstruction of a complete bundle, assuming no packet loss during the simulation. The total latencies from this simulation corresponded to 16, 36 and 56 seconds were, respectively, thus giving confidence that the 60 second latency deadline could be met in practice.

10.13.2 Field Testing

The next stage was to undertake testing with the satellite system in the loop. Liaising with Othernet various data rates were used, to determine where the limit of reliable receivability lay. Initial tests were performed receiving the signal at Flinders University, at latitude 35 South, which was conveniently the most pessimistic of the three locations available for testing. Thus the assumption was made that if the system could function at Flinders University, it should be able to function in the Pacific, where the satellite would be substantially higher in the sky.

Through these initial experiments, it was found that the packet rate could be increased to 1.33Hz, i.e., 33% faster than originally anticipated, which reduces the latency in a proportional manner.

To exclude all possibility of accidentally receiving local re-radiation from the ground-station, the system was then tested at a remote location in the Australian Outback that lacked any form of communications infrastructure, including cellular coverage. For that test, a Toyota LandCruiser was driven to the remote Siller's Lookout at Arkaroola, in the northern Flinders Ranges, almost 700km from the ground-station, as shown in Figure (10.7).

FIGURE 10.7: Proof-of-concept of packet reception test from the back of a Toyota Land Cruiser at Siller's Lookout, Arkaroola, Outback Australia. The signal from satellite was received successfully in the field without any difficulties.

Finally, it was tested from the Island of Efate in Vanuatu. This test was performed in the capital city, Port Vila, as this would be the location with the most RF interference. The climate is generally similar across the whole country, so the humidity and other weather effects were assumed to be representative. Unfortunately, no photographs were taken of that test.

These field tests were limited in that the travel had to occur before the complete bundle re-assembly process was complete, and after which time, the funds for leasing the satellite had been exhausted. Thus the tests that were performed while the satellite service was operating focussed on measuring the packet reception reliability. The packet loss rate was found to be < 1% in all three cases with a packet size of 200 bytes, and packet rate of 1.33 Hz. From this, it can be inferred that the latency for the three bundle sizes of 365, 765 & 1265 bytes would correspond to bundle delivery latencies of 12, 27 and 42 seconds, respectively. That is, the ability to deliver Rhizome bundles containing a tsunami early warning message in less than 60 seconds using such a system was demonstrated through the combination of simulation and field measurement of packet reception rates.

10.14 Conclusion

The work described in this chapter has proven the concept that low-latency delivery of disaster early warning messages using a low-cost broadcast satellite bearer into the Serval Mesh is possible. This was demonstrated through a combination of protocol simulation and field testing of packet reception rates, coming tantalisingly close to demonstrating the reception of Serval Mesh bundles in the field via the experimental system.

Thus the potential of integrating additional bearer types into the Serval Mesh has been highlighted, and the path to creating new low-cost, small, and easy to deploy and maintain early warning systems based on that has been illuminated. The challenge is to now find the means to complete this work, and to operationalise it.

This is remarkable, given that the cost of deploying the traditional "big towers" into the Pacific comes to many millions of dollars per year, while this system was able to be operated for several months for a few tens of thousands of dollars in satellite operation costs – while also providing the potential to access useful communications and entertainment services year round, thus helping to ensure that the relatively modest burden of maintaining the operation of the receiver in a remote community might be more appealing to those communities.

That is, an answer has started to come into view to the fifth research question of this thesis:

Can we design a low-cost and rapid response early warning system against natural disasters that can fit the circumstances of low-resource countries?

This question can be answered in the affirmative, in that a design has been presented for such a rapid response early warning system, and that the resulting system is much cheaper to deploy and to operate, compared with existing practice using large towers that are expensive to deploy, operate and maintain, and are not suited to deployment in small remote island communities, where the cost per person could easily exceed the GDP per capita of many countries in the Pacific.

This chapter has begun to outline how the dissemination part of a tsunami early warning system can be designed in response to this research question, but has not answered how challenges relating to the generation of the tsunami warnings, or considered more deeply the design and construction of a complete tsunami early warning system suited to low-resource countries in the Pacific. These issues are explored further in the next chapter.

Chapter 11

Low-cost tsunami early warning system

11.1 Introduction

Part of this work is published in IEEE GHTC conference, 2019, titled "Reducing cost while increasing the resilience & effectiveness of tsunami early warning systems".

In the previous chapter an approach for providing reliable and low-latency dissemination of tsunami or other disaster early warnings was presented. That method used a novel approach to broadcast satellite reception. This chapter continues and expands on that concept, by contemplating how a complete tsunami early warning system could be constructed, that does not depend on any expensive fixed infrastructure. This would cover not merely the warning dissemination aspect of the system, but also the tsunami detection and decision support systems required to issue the warnings. Such a whollistic approach would help to overcome the challenge of ensuring that a tsunami early warning system would remain operational for when it is required.

The necessity of such work is demonstrated by, for example, the Boxing-day Tsunami and the more recent tsunamis in Indonesia in 2018, where in all cases some aspect of the tsunami early warning system failed, or where the entire system was not present or not available for some reason, impacting on the ability to provide timely warning of approaching tsunamis.

There can be many causes for such failures, ranging from the lack of a deployed system, to accidental or intentional damage of infrastructure, or lack of adequate maintenance of operating budget to maintain the early warning capacity. In the case of one of the 2018 tsunamis in Indonesia, a further vulnerability was revealed, in that the tsunami warning system was not well prepared to respond to non-seismic tsunamogenic events, such as the collapse of an underwater volcanic slope. Also in the case of another tsunami triggered by an earthquake, the cellular-based early warning system was disabled by the damage caused to the cellular network by the earthquake.

These recent tsunamis, especially those in Indonesia in 2018 also acted as a reminder that there is often little time between when an event occurs, and when it makes land-fall. This substantially limits the window of opportunity for providing an actionable warning, which unfortunately, tends to amplify the loss of life and property – in some cases on a massive scale, such as following the Boxing Day Tsunami.

These events all point towards the need for improved tsunami early warning systems that are more resilient to these kinds of failure modes. The remainder of this chapter explores possible approaches to producing such resilient early warning systems, where the detection of events, decision making and dissemination of warnings are all made more resilient, while ideally also reducing the cost and complexity of maintaining the early warning capability.

The proposed resilience tsunami early warning system consists of three main components:

1. Tsunami detection system, based on small low-cost autonomous underwater vehicles;
2. Multi-Hazard warning decision support system concept, that provides a visual interface that provides situational awareness of the regional context, and allows the issueing of warnings for specified geographic areas; and
3. A multi-Hazard warning dissemination system, based on the proof-of-concept work presented in the previous chapter.

The remainder of this chapter presents a further analysis of the tsunami and related risk profile of the Pacific, followed by the conception of the three proposed components that can be used to form a low-cost and resilient tsunami and other hazard early warning system.

11.2 Contribution

The contributions of this chapter are:

1. The design of a low-cost tsunami detection system, that is not dependent on fixed ocean buoys, and that is thus more resistant to various common forms of damage or loss.

2. The creation of an integrated tsunami and other hazard early warning system that incorporates this, and the work of chapter (10), to outline how the provision of a complete low-cost and terrestrial infrastructure independent tsunami and multi-hazard early warning system.

11.3 Tsunamis are threatening coastal communities

Indo-Pacific/ Ring-of-Fire region, Figure (11.1), is a region that contains many active tectonic plate boundaries. The region is vulnerable to a wide variety of natural disasters, including those cause directly or indirectly by this tectonic activity. This includes earthquakes, volcanos and tsunamis [175, 169]. Compounding this issue, the region contains thousands of islands, may of which have populations centres along their coasts, making them vulnerable to tsunamis [144, 19]. There is therefore a need to design and deploy tsunami and other hazard early warning systems that can help to protect these coastal communities. This need exists both in large countries, like Indonesia, as well as for countries with very small populations, like Tuvalu.

Two of the most lethal disaster types are the tsunami and cyclones, which cause deaths in coastal areas, especially where the people who live there have not been warned before the coming of danger. For tsunamis, the precaution procedure globally followed by the governments is to install special equipment to detect it, then warn people as early as possible, e.g., using large siren towers, such as shown in Figure (11.2), to warn people to move away from the the coast and low-lying areas. Unfortunately, tsunamis are responsible for causing large numbers of deaths in coastal areas, if there is no early warning given, for example, because an early warning system has been installed, but fallen into disrepair, or has been disabled by the trigger for the tsunami, or where no early warning system was installed to begin with.

11.4 Brief analysis to the recent tsunamis in the Pacific

Not all tsunamis are the same, or triggered by the same kinds of events. This complicates the detection and warning process. The most common type of tsunami is where an earthquake occurs under water, causing the sea-floor to buckle, displacing huge volumes of water. Other types include those caused by land-slides into water, or under-water slope collapses. Whatever

FIGURE 11.1: This image has been removed due to copyright restriction. Available online from [36]. Map of plate boundaries surrounding the of Ring-of-Fire in the Indo-Pacific region, and which can generate very large earthquakes and tsunamis. The subduction zones adjacent to these plates also result in large chains of volcanoes that create further hazards for the region.

the cause, the result is destructive waves that can reach heights of upto several tens of metres, and that in many cases, can travel great distances at high speed across open water, before impacting on land, often with devastating effect [39].

To help understand the variety of tsunami events in the Pacific, consider some of the more recent tsunamis that have occurred in the region:

1. Boxing day (2004): This is the biggest tsunami recorded in the 21 century. It was triggered by a M9.3 earthquake on the ocean floor. This event was responsible for hundreds of thousands of deaths, as well as massive destruction to the coastal areas of several countries, with the

FIGURE 11.2: This image has been removed due to copyright restriction. Available online from [242]. An installed siren in coastal area in Auckland, New Zealand to warn people from natural disaster like tsunami. Also, this one has been used for daylight saving signal.

damage being obvious for months after, as shown in Figure (11.3). The lack of an effective Indian Ocean Tsunami Early Warning System contributed to the loss of life, and considerable effort and resources were invested by the international community following this event to rectify this problem.

2. Sulawesi and Anak Krakatoa tsunamis (2018): These two tsunamis struck Indonesia, and resulted in thousands of deaths. The tsunami early warning system that is installed in many parts in Indonesia was not fully functioning at that time, due to challenges funding the ongoing system maintenance, as well as other logistical challenges.

   In the case of the Sulawesi tsunami, the tsunami was detected quickly

FIGURE 11.3: This image has been removed due to copyright restriction. Available online from [216]. This photo is taken in January 2005 at Meulaboh town, Aceh province in Indonesia as a result of massive earthquake and tsunami waves.

following the earthquake, however, the delivery of the warning to the residents at the effected zone was impaired, because many of cellular towers had been damaged and displaced due to the wide-spread soil liquefaction that occurred, with eerie videos showing cellular towers moving tens of metres from their original locations [160, 258]. This scenario, were the cellular towers are not available, or similarly where mobile phones are not able to be charged, presents a similar lack of means of communications to that experienced in small remote communities – yet this occurred in a large relatively well resourced city.

In contrast, the Anak Krakatoa tsunami which occurred about two months after the Sulawesi tsunami was caused by the flank collapse of a volcanic cone into the ocean, which transfer immense energy to water and formed tsunami waves. Unfortunately, this tsunami was not detected by the early warning system, and no alert was triggered to the nearby zones [64, 259]. Part of the difficulty in this event, was that the generated tsunami was rather local, and thus was not easy to detect with sparsely placed tsunami sensors, and did not fit the normal signature of tsunamis caused by earthquakes. This combined with the very close proximity of the tsunami to the populated coastal area which it impacted, meaning that the window for issuing a warning was in any case very short – probably less than four minutes.

3. New Caledonia & Vanuatu tsunami: This tsunami occurred in December 2018, between New Caledonia and Vanuatu. The EWS detected this tsunami in the South Pacific ocean, and an alert was triggered in New Caledonia and in Fiji. However, the uncertain in the prediction of wave height meant that no alert was triggered for some parts of Vanuatu that did end up being impacted by the tsunami.

   The resilient telecommunications group under which this thesis was undertaken were present in Fiji at the time, and were on alert for this event. As a result, they were in contact with the coastal community in Vanuatu with which they had worked on previous occasions, and discussed the wisdom of staying away from the coast during the alert period. This turned out to be a sensible precaution, as the local bathymetry and coastal topography resulted in the focusing of the otherwise relatively small tsunami waves into the local bay, even resulting in the tsunami running up the river that runs through the village, swelling to many times its normal size and depth, and damaging some fish drying racks. Fortunately, however, there was no injury or loss of life. This particular event demonstrated the difficulty in accurately forecasting the areas at risk of impact from a tsunami.

11.5 Tsunami Early Warning System (EWS)

In general, the deployment of an Early Warning System is an responsive measure taken to mitigate the effects of various hazards that can lead to adverse events of varying kinds [165]. The goal of an EWS is to save lives and property, by maximising the opportunity to take steps to mitigate the impact of a disaster before it arrives. That is, Early Warning Systems and the UN Emergency Telecommunications Cluster (ETC) play an important role in warning people, to help save lives. The effectiveness of an EWS is significantly dependent on how resilient and rapid it is at delivering warnings of an approaching disaster.

An effective tsunami EWS consists of different components, and they basically are to ensure the detection of tsunami causing events, process the information about these events to determine if warnings are required, and to disseminate warnings where they are required to alert people in affected areas via one or more means of communication. Failure in any these steps will result in a lack of effectiveness and failure to deliver essential warnings to humans. Various such failings are apparent in the tsunamis discussed above, highlighting the need for innovation in this space.

To facilitate innovation in the provision of effective early warning of tsunamis, there are three key stages that must all function correctly:

1. Monitoring and detection of signals: Responsible to detect tsunamis, usually using underwater pressure sensing equipment on the seabed, and buoys equipment for communicating with a ground station via satellite link. These installations are relatively high cost, and many of them need to be deployed in deep ocean waters, so that the tsunami events can be detected sufficiently rapidly. Many such devices are needed to provide adequate coverage, especially for locally-generated tsunamis, such as the Anak Krakatoa event that was triggered by a nearby slope collapse, with the tsunami making land-fall long before the tsunami was detected by the nearest tsunami sensor.

2. Risk assessment and decision making: This is related to how to get raw data from the tsunami sensors, and to process it so that a decision can be made whether to trigger an alert can be made. Each tsunami early warning system seems to employ its own approach to this problem, and typically involves a human-in-the-loop, in order to make the often subjective decisions about the regions to warn, and the exact wording of the warnings. This, unfortunately, also introduces significant delay and risk of decision paralysis, or making decisions based on incomplete information. Ideally decisions should be made based on high-quality models and information, so that more accurate predictions of the size and extent of the tsunami can be made, to help avoid problems similar

to that which occurred with the New Caledonia / Vanuatu tsunami of 2018.

3. Dissemination alerts and communications: When the National Disaster Management Organisation (NDMO) or other competent authority confirms that the information from the tsunami sensors necessitates the issue of one or more warnings, then the next step is determine how to communicate this warning to the people in the affected area, including which communications channels should be used. Typically, this will involve multiple communications methods that deliver important information to the residents, such as cellular SMS or telephone call, automated land-line telephone calls, television, broadcast radio news, tsunami warning siren towers, or other appropriate means. However, most of these techniques are heavily dependant on existing infrastructure, and they may or may not be operational when required. For example, for tsunamis caused by a local earthquake, the shaking may damage or destroy the infrastructure that is being depended on to disseminate the warning.

Figure (11.4) shows a diagram for one of the most significant traditional and sophisticated tsunami early warning systems, which consists of buoy Deep-ocean Assessment and Reporting of Tsunamis (DART) equipment to detect tsunami, that transmits a signal via satellite to a ground station for analysis, where the decision will be made as to whether to issue a warning if the data show that a tsunami has indeed been triggered.

Such a system is very typically used in areas with large populations, since the loss will be high if no warnings are issued. However, there are challenges against deploying this system in a low density population islands. Basically, the cost to purchase the components is very high to buy. But if we look to Into-Pacific region, we find that many of the countries there are classified as low-income, making it difficult for these nations to purchase such systems. These system also require maintenance and the related logistical support, both before and after installation, in order to be deployed and remain operations. This often requires expert personnel, which are not available locally, and have to be accessed from abroad, at considerable additional cost. In short, the traditional approach to tsunami early warning systems is not cost-effective for Pacific Island Nations, and their focus on large expensive infrastructure, such as siren towers, makes them extremely cost ineffective

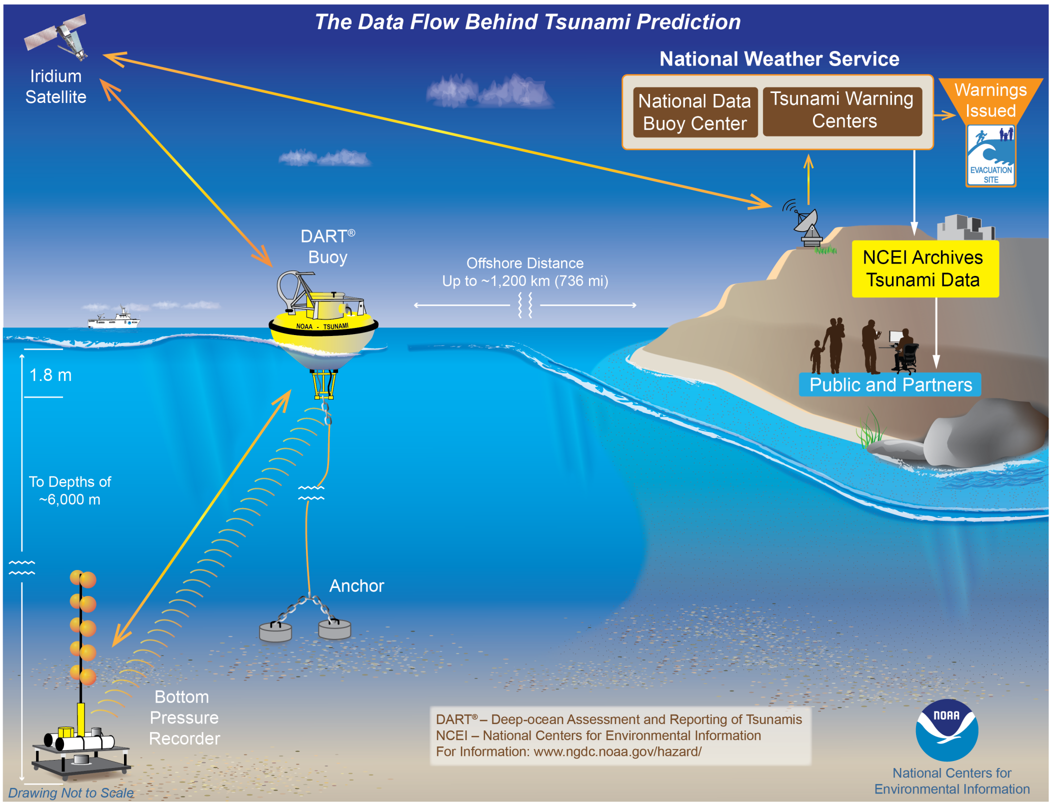


FIGURE 11.4: A diagram shows the data flow and components of a buoy DART Tsunami early warning system and how can it detect tsunami in the ocean and transmit signal via satellite to a ground station, which processes all incoming signal and triggers the alarm to people [211].

for small isolated communities, of which there are very many in the Pacific islands.

Even where an EWS is managed to be installed, it may subject to failure due to many reasons, including both equipment or human-related errors. Lack of maintenance is a potential reason for failure, and it was a contributing factor to the difficulties in providing early warning of the Sulawesi tsunami. Also, the error in the tsunami wave height models can cause such failures, as seen in the New Caledonia / Vanuatu tsunami in 2018. It would be beneficial to mitigate any or all of these challenges, to help improve the resilience, reliability and availability of tsunami early warning systems in the region.

11.6 Emergency telecommunication cluster disseminate warnings for tsunami

To extend the efforts in providing help to people in coastal areas, A new technique of tsunami early warning system is presented in this section, which is intended to mitigate the problems described above, about how low-resource nations struggle to deploy and maintain expensive tsunami early warning systems.

The system is designed to detect and warn people in hazardous areas based on low-cost hardware and low complexity, and it is able to provide a regional warning to maximise the benefits to participating countries.

Simply, this technique consists of three stages, and they are explained as follow:

11.6.1 Underwater signal detector

The first step is to be able the detect tsunami. Rather than expensive and vulnerable buoys and sea-floor pressure sensors, it is proposed to use acoustic detection of tsunamis, using hydrophones, i.e., underwater microphones. The key to this approach is that tsunamis generate very loud and distinctive underwater sound waves. If it is possible to detect the transmitted signals, then the system will be in an advance position to send an alert about this danger. A particular advantage, is that such systems can potentially hear the tsunami long before the wave reaches the sensor, thus potentially increasing the warning time.

This concept is based around around low-cost autonomous underwater vehicles, built to include recent advances in underwater acoustic signal processing, as shown in Figure (11.5). Both the vehicle and detector were built by a collaborating group in France, and they have been tested in the sea. The vehicle equipped with low-cost thrusters that assist in moving or manoeuvring under the ocean, so it can work at different depths under the sea level, and is not necessary to be tethered to the floor. These underwater vehicles are able to operate submerged for long periods, down to depths of 50 metres, which is more than sufficient to protect them from surface weather conditions or intentional or accidental damage by humans. Perhaps most importantly, these underwater vehicles can be produced at very low cost, perhaps as low as US$100 each.

Their low cost means that maintenance can effectively be through progressive replacement, and reliability can be cost-effectively achieved by deploying many such units into predictable ocean currents, and optionally collected at predictable locations for defouling and refurbishing and reuse. This would become a continuous, but relatively simple and low-cost process, thus helping to avoid some of the challenges of performing large, complex and expensive periodic maintenance, which history has shown tends to not always reliably occur in the Pacific.

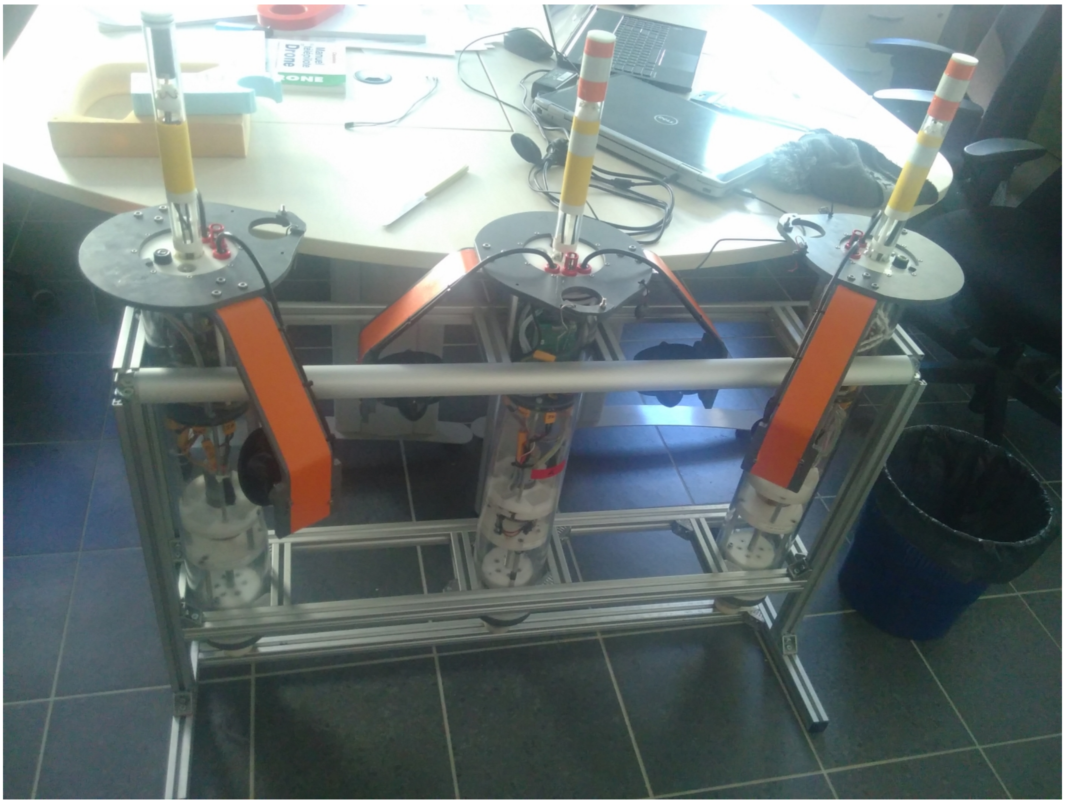


FIGURE 11.5: A photograph of a prototype low-cost autonomous marine vehicle that has been developed, built and tested by a collaborator. It is remarkable for its extremely low-cost and low-technology construction, and yet retains the ability to (slowly) manoeuvre in ocean currents, providing some level of active navigation.

As mentioned above, acoustic detection of tsunamis has the advantage of being able to hear tsunamis a long distance, and long before the tsunami wave itself reaches the sensor, which can give more time to residents to prepare. For example, with the 2011 tsunami in Fukushima, Japan, the seabed rupture that caused it was clearly heard by hydrophones located some 1,500 km away [220].

A system built using such low-cost underwater vehicles has the challenge that the vehicles cannot communicate with a satellite while they are submerged. Thus they must surface from their cruising depth of 20 to 50 metres below the sea surface, whenever they detect a probable tsunamigenic event, so that they can send this information via satellite, perhaps using a low-cost Iridium Short-Burst Data (SBD) transceiver, before again submerging, as showing in Figure (11.6).

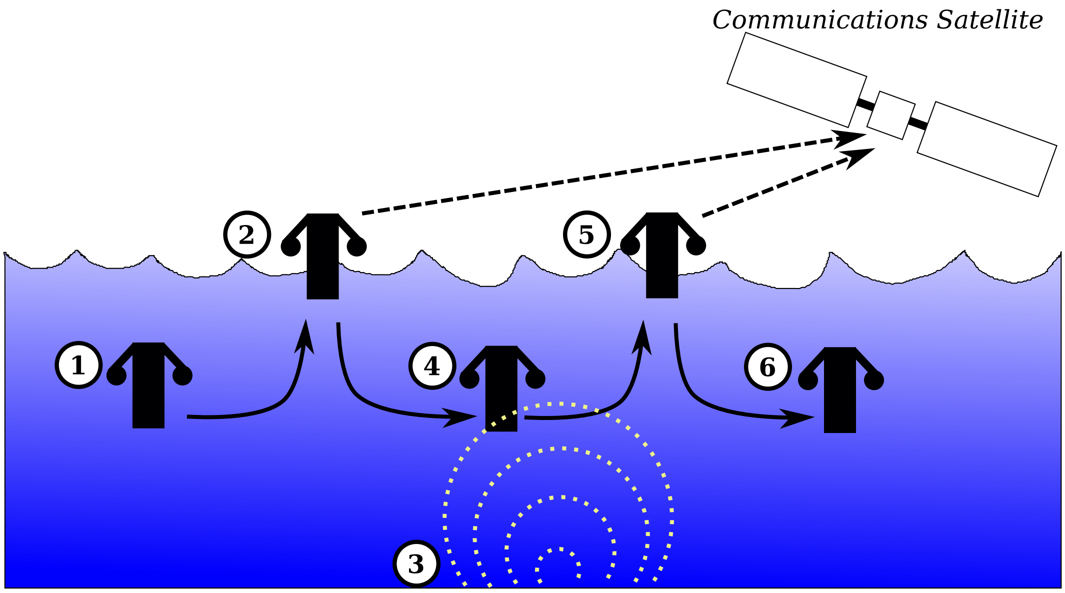


FIGURE 11.6: Activity cycle for the autonomous detector vehicle: On release, it submerges to a cruising depth of between 20 and 50 metres below the sea surface (1). Then as it detects probable tsunamigenic events, or at scheduled intervals to report its health and location, it surfaces and communicates via satellite (2 and 5), before submerging again (1, 4 and 6) where it shows initial depth between 20-50m in number 1,4 & 6. At the end of a mission, it can again surface to report its location and activate a radio-location beacon, to allow it to be collected for refurbishing or disposal. The lack of fixed location of the buoys, and their spending the vast majority of their time below the ocean surface helps to minimise the risk of damage or vandalism, helping to reduce operating costs and increase availability.

11.6.2 Warning decision support system

The need for rapid action is vital when an event is reported. However, each country has its own set of legislation to react to this kind of event. One approach to work around this is to create a portal that is able to collect and make predictions of tsunami impact based on the collective information available in a region, and from that provides recommendations for the issue of warnings. Each national government can then have their own policies and procedures for actually triggering the alerts, which may be partially or fully automated in the portal, to help support rapid decision making and subsequent dissemination of the resulting warnings. The portal could also include direct integration with the various means of disseminating the warnings, again, on a country by country basis, to meet the particular national context.

11.6.3 Warning dissemination system

This part of the system is responsible for distributing alert in remote and isolated areas, and it is an extension to what explained in Section (10.12), where Serval Mesh can be employed to distribute warning via satellite link once it is triggered, allowing rapid delivery of alerts to small and isolated island communities. As discussed in chapter (10), such ETC Lali systems can include low-power FM radio transmitters that help to disseminate warnings to community members who are some distance from the Lali receiver. This approach of using larger numbers of small and cheap early warning alert devices has the potentially be considerably cheaper than the current approach of using smaller numbers of large expensive siren towers, as shown in Figure (11.7). The key to this cost-effectiveness is that on many islands, the communities that require coverage are quite widely spaced, meaning that the vast majority of the coverage of the large towers is incident over unpopulated areas.

A low-cost second-hand car horn on an ETC Lali receiver in each village is a good option to substitute for the large siren towers normally used. This is because the the large siren towers have much greater coverage area than is needed for these small island communities, and cost many orders of magnitude less, and are much easier to install and maintain, compared with the large towers that require cranes and other special equipment, which is logistically and financially difficult to access for small remote island communities or their governments. This also means that the maintenance of an ETC Lali-based system can most likely be undertaken using domestic labour, rather than relying on expensive foreign expert labour, which also results in considerable financial out-flows from the economy.

A further benefit of the ETC Lali system is that the failure of any one unit does not result in the loss of warning capacity to multiple communities. Where numbers of ETC Lali units are deployed, and owing to their low cost,

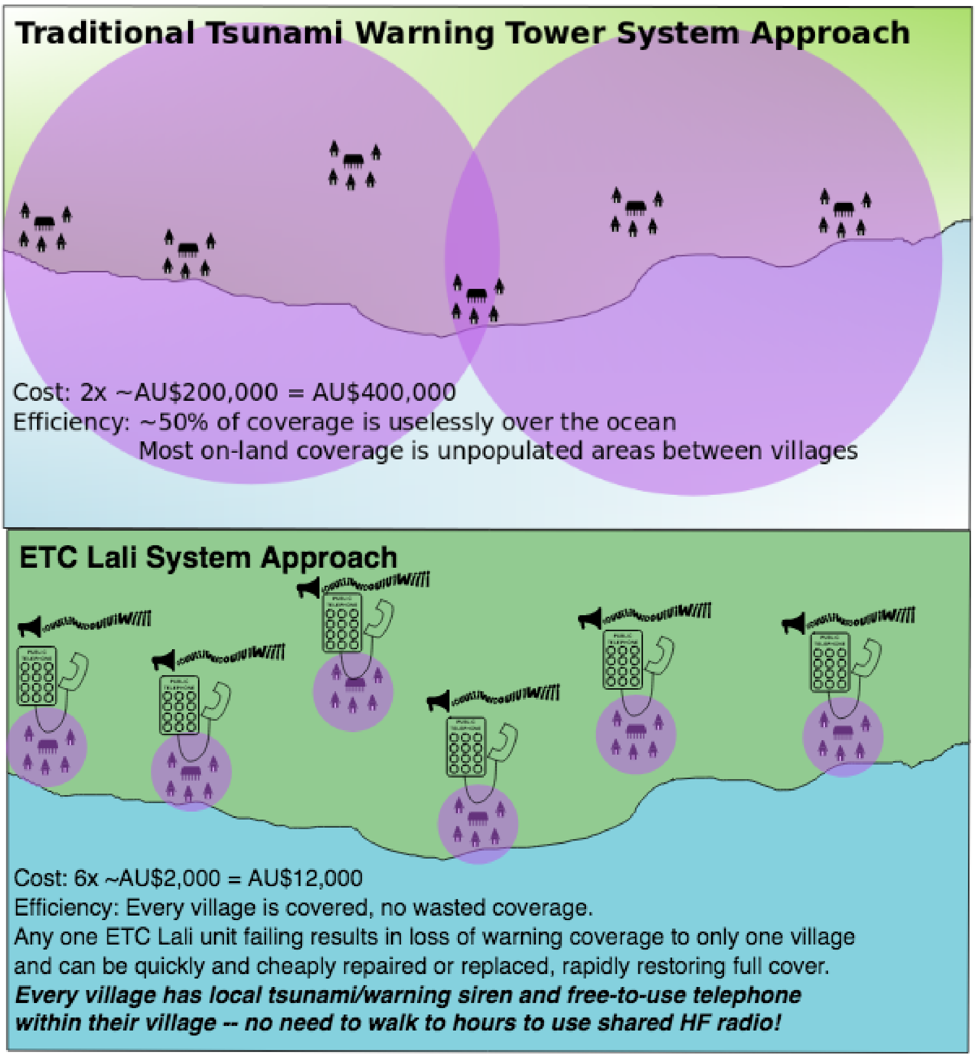


FIGURE 11.7: Comparison between two approaches, for a traditional tsunami warning dissemination at the top, and the suggested ETC Lali system at the bottom. The comparison shows that the traditional approach costs much more than the ETC Lali approach, potentially orders of magnitude cheaper. Because they are very cheap, ETC Lali units can be cost-effectively deployed over much greater areas, potentially providing complete coverage of all small communities on remote islands over time.

it is quite possible for there to be sufficient remaining units that can be redeployed to plug the coverage gap in the short-term, while a replacement unit is sought. Again, because of their small size and low cost, obtaining and installing a replacement unit is a simple process that can be satisfied through the normal inter-island trade and travel systems. In contrast, the traditional large-tower based approach is highly problematic when a failure occurs: The loss of service of a single tower is very likely to leave multiple communities without early warning services, and will take considerable time, expense and logistical effort to arrange for its replacement, leaving the affected communities without early warning services for an extended period of time – assuming that it is ever repaired.

11.7 Conclusion

Despite the fact that the tsunami early warning system has a significant role in saving lives along the hazardous areas, there are many challenges that make them difficult to deploy in the Pacific region. The high cost of hardware, installation and maintenance negatively affect the availability and functionality of tsunami EWS in the region, which means that many people in the region are vulnerable to tsunami and other disasters, due to the lack of effective early warning. Also, the traditional approach to tsunami EWS has several limitations in detection, alert generation and dissemination that likely contributed to the failure to provide effectively early warning following recent tsunamis in the region, and thus the resulting loss of many lives.

This chapter has considered alternative ways to structure the complete tsunami early warning system, spanning from detection of tsunamigenic events, through the process of determining whether to issue an alert, and the dissemination of the resulting alert, especially into small isolated island communities.

This builds on the work of the preceding chapters to design resilient and low-cost communications systems that can provide year-round benefit to these disadvantaged communities, thus encouraging the maintenance of these systems between disasters, to thus ensure that they are available when needed most.

However, realising such a complete tsunami warning system is no small undertaking, and thus falls outside the scope of this chapter and indeed thesis. Nonetheless, the work described in this chapter introduces and argues in support of various new approaches to tsunami early warning system detection, decision making and dissemination, that warrant further exploration in the future.

In doing so, this chapter has answered the final research question of this thesis:

Can we design a low-cost and rapid response early warning system against natural disasters that can fit the circumstances of low-resource countries?

This question is answered in the affirmative, in that precisely such a system has been proposed in this chapter, that addresses considerable financial and logistical disadvantages of the existing approach to tsunami early warning systems, and proposes a complementary that is well suited to small isolated communities, that has the potential to be orders of magnitude cheaper to deploy, and much more feasible to maintain in these difficult environments.

Chapter 12

Conclusion and future work

12.1 Reflecting on the motivation

This thesis was undertaken with the goal of improving the opportunities for communications among people living in remote areas, and those who are affected by natural disasters. These two groups share in common the lack of access to functioning telecommunications infrastructure – no matter whether that is due to it having been damaged or destroyed by a natural disaster, or whether it is simply absent. They also share that their difficulties communicating with the outside world increases their vulnerability, and in many cases contributes to otherwise unavoidable loss of life. This is especially true in the case where the need for communications includes early warning of natural disasters, such as tsunamis.

The intention was to take the Serval Mesh suite of technologies, which were created with exactly these use-cases in mind, to assess their current state, and then to variously propose, commission, implement and assess the potential effectiveness of a number of possible improvements and extensions to the Serval Mesh technology.

At the beginning of this project, the Serval Mesh communicated primarily directly between mobile phones, with only limited assistance from the Serval Mesh Extender devices that had only recently been created. The effectiveness of the Mesh Extenders was limited by performance problems with the LBARD software, and the lack of support for long-range communications. Those problems have now all been resolved, with quite useable performance over Codan digital HF radios, as well as many problems in the LBARD algorithm having been fixed, or otherwise improved. For example, the TreeSync algorithm has been integrated into LBARD, improving its performance over all radio types, as well as various problematic protocol-lockup issues that were an issue during the earlier pilot of the Serval Mesh in Vanuatu.

Further, a proof-of-concept has been implemented for a low-cost tsunami early warning system that extends and complements the Serval Mesh, and is simultaneously much cheaper to deploy and operate than the traditional approach based on large siren towers. This work was interesting, that while there may be alternative approaches to facilitating remote area communications that are used, with the Serval Mesh adding one more horse to that stable, there seems to be a lack of feasible tsunami early warning systems that use small and affordable equipment, and that through additional attractive functions, are likely to be maintained by the small low-income communities that need them most. Perhaps this will provide the most impactful and lasting impact of the work described in this thesis, and help save many lives when tsunamis strike these communities in the future.

12.2 Responding to the research questions

Within these goals of saving and improving lives through the provision of basic communications services in very difficult environments, there were five research questions that were teased out, and which this thesis has worked to answer, namely:

1. *Is it possible to provide a cost-effective and free-to-use communications solution to low-income remote community members?*

   This question has been answered in the affirmative by improving the Serval Mesh to support effective communications over digital HF radios, so that isolated low-income communities can make use of a resource which is well known in the region – namely, HF radios – to extend the Serval Mesh to enable it to overcome the distances between communities and islands that cause so many logistical difficulties for the region. By doing so, this question has been answered by presenting a proof-by-example, that is ready for further verification in the field, once borders reopen.

2. *What is the current state of the Serval Mesh's message synchronisation process, and can this be improved?*

   This question was explored by examining the state of LBARD as the software component of the Serval Mesh responsible message synchronisation over long distances, identifying a large number of problems with it, correcting those, and also improving aspects of the fundamental algorithms, such as by proposing and overseeing the integration of

TreeSync into LBARD, to improve the efficiency of the synchronisation of messages on the Serval Mesh. It is now possible to automatically deliver text messages over hundreds of kilometres using a shared HF radio link in as little as a minute – all without the end user needing to even know how to operate an HF radio.

3. *Can we extend the communications range of Serval Mesh network to hundreds of kilometres? Can HF Radio be a solution to this problem?*

   This question has been simply and conclusively answered by the integration of the Codan digital HF radio system into the Serval Mesh, potentially allowing the Serval Mesh to deliver messages over hundreds and even thousands of kilometres. By achieving this using an HF radio, the both parts of this question has been unequivocally answered in the affirmative.

4. *HF data links have very low bandwidth. Can we manage such low-bandwidth links effectively, to enable very isolated communities to communicate with one another?*

   This question has been answered through the improvement of LBARD to use the efficient TreeSync protocol, combined with the many improvements made to LBARD, culminating in it being able to deliver text messages over HF data links in as little as 40 to 50 seconds, and capable of transferring many hundreds to thousands of messages in each direction over a single shared HF radio link. As these isolated communities are often very small, with perhaps 50 – 200 members each, this represents more than sufficient capacity to enable multiple messages sent to and from each member of such a community.

   This ability to carry hundreds to thousands of communications per day is quite revolutionary, compared with the current practice of using HF radios primarily for voice calls between the operator of each radio, and perhaps a few people in their near circle. The ability for communities to use their smartphones to send and receive text messages for free, over hundreds of kilometres, without even having to know how an HF radio works has the potential to be quite transformative.

5. *Can we design a low-cost and rapid response early warning system against natural disasters that can fit the circumstances of low-resource countries?*

   This final question has also been answered in the affirmative through the proposal and proof-of-concept testing of a small low-cost satellite receiver, and the integration of this into the Serval Mesh, and the conception of a complete low-cost early warning system based around this concept. While further work is required to realise such a system, it can be safely said that such a design is now feasible.

Importantly, the proposed design is based around the Serval Mesh, which can provide year-round communications capabilities to these vulnerable communities, which will encourage them to keep the system operating between disasters, so that it is available to provide early warning when a disaster does occur. The use of small low-cost hardware devices makes it possible for these communities to perform this maintenance themselves.

This all stands in stark contrast to the traditional approach which is not a good fit to the circumstances of island communities, where the high capital cost, high maintenance costs of maintaining large towers in remote areas surrounded by corrosive tropical maritime conditions, and where maintenance is often dependent on international expertise that is both difficult and expensive to bring into country when required – even before COVID19 started closing borders.

In short, this thesis has answered all five research questions in the affirmative, and has markedly advanced the state of the art for remote area, disaster and disaster mitigation telecommunications in the Pacific.

12.3 Future work

Despite the considerable progress made, the work described in this thesis remains primarily in the laboratory, or in controlled field tests. The overwhelming requirement now is to take the work described in this thesis, consolidate it, and move towards a programme of field testing, refinement in response to that and to the input of key stakeholders, culminating in operationalisation of the technologies described in this thesis.

Separately, there are of course many opportunities for further improvement of the technologies and results described in this thesis, including, for example:

1. The Codan Envoy's data modem is capable of somewhat better performance than we are currently able to extract out of it. Also, by further optimising the LBARD system, it may be possible to reduce some of the

overheads currently suffered, thus allowing the average throughput of Rhizome Bundles to be increased from the current 40 bytes per second, to much nearer the actual capacity of 92 bytes per second in each direction.

2. Similarly, the Codan data modem does not expose a raw packet interface, which increases latency, and necessitates the use of escaping of data packets, both of which reduce the effective throughput somewhat. By modifying the firmware on this modem it should be possible to overcome these limitations, and potentially also to reduce the turn-around time to further improve the available capacity of the channel to nearer to the theoretical 2,400 bits per second.

3. Alternatively, it would be possible to investigate the creation of a new low-cost high-performance HF modem, perhaps based on the work by David Rowe in this area.

4. Short-to-medium range of communications is the next step to focus on. A strong candidature is LoRa radio, which will be perfect to support Mesh Extender to become more internationally portable and usable in the humanitarian field. This low-cost, lower power consumption and few kilometres range radio uses Wi-Fi or Bluetooth signal to communicate with other devices, and it can be part of mixed-radio network. The auto-detection and auto-organising of Mesh Extender explained earlier facilitate such addition of new device, and it will be an interesting thing when we see the new performance of Mesh network.

12.4 Closing words

In closing, this thesis embarked on the ambitious goal of improving conditions for vulnerable communities in the Pacific. Achieving real change in the humanitarian sector is no easy undertaking, and as I have discovered, takes considerable time. It will likely be several more years before the work contained in this thesis can begin to make a difference in the field. If in some small way, I have been able to alter the future path of these isolated and disaster-prone communities for the better, then I will be satisfied. Whatever the case, I am satisfied that I have been able to make a measurable improvement of the state-of-the-art in this area, and shown the possibility of outcomes that were perhaps previously not thought possible.

Appendix A

Practical notes and information about the LBARD, Outernet receiver and HF radio drivers

A.1 Introduction

LBARD protocol improvements and the work related to integrating hardware devices or links implies many fine and big details related to in- put code, initialisation of hardware, change settings and install or test Serval on computer. These details are very important to developers newly joint to Serval Project. It is believed that the Appendix will save the time of any future efforts when a roadmap is existing to continue developing Serval.

The technical notes in the Appendix are useful to programmers who want to know how to do many tasks from the beginning, and how to install or connect different components together before running or testing the software. These notes cover many programming and system design details, and they are necessary to follow when dealing with any of the Serval, LBARD, Codan HF radios, Barrett HF radios and Outernet satellite receiver. Unfortunately, there are more details that the author has not had the time to mention them, but he is ready to clarify any ambiguity to any interested person.

The Appendix section is divided into five technical parts, LBARD, test LBARD, Codan HF radio, Barrett HF radio and Outernet satellite receiver. All these parts are vital to achieving tasks, and they have been mentioned across different Chapters of the thesis, but this time, the information is closer to the programming level rather than the academic context.

A.2 LBARD protocol

While the attention focuses on LBARD protocol in this research, it is crucial to talk about some technical notes necessary to install a new copy form GitHub, compile and test it. There are different sections related to LBARD, and the most important parts are explained below. There are more technical notes and advises that can explain to anyone interested by contacting with Serval team.

A.2.1 Install a fresh copy of LBARD

The first thing to do if any developer aims to deal with LBARD is to install a fresh copy from GitHub repository, and it can be accessed easily through this link (`https://github.com/servalproject/lbard`). The installation and initialisation process can be summarised in the following points:

- The developer can utilise either 'git clone' command from git commands list to download LBARD, as shown in Figure (A.1), or chooses the direct download option; however, the git clone is preferable here. All git commands are accessed from a terminal, and they do not exist, then git must be installed first.

```
Ghassan@Pauls-MacBook-Pro:~/GHASSAN$ git clone https://github.com/servalproject/lbard.git
Cloning into 'lbard'...
remote: Enumerating objects: 55, done.
remote: Counting objects: 100% (55/55), done.
remote: Compressing objects: 100% (39/39), done.
remote: Total 5880 (delta 21), reused 42 (delta 14), pack-reused 5825
Receiving objects: 100% (5880/5880), 1.67 MiB | 2.74 MiB/s, done.
Resolving deltas: 100% (4121/4121), done.
Ghassan@Pauls-MacBook-Pro:~/GHASSAN$
```

FIGURE A.1: A screenshot for cloning the content of LBARD from GitHub to a folder on local machine.

  In this example, a folder 'GHASSAN' has been created earlier, then move into this folder to clone and download the content from the GitHub repository.

- After a successful download, the next step is to update the submodule for Serval DNA that exists inside LBARD git repository. The git command `git submodule init` performs this task, as shown in Figure (A.2).

- Update the content of Serval DNA local folder form git repository via the command `git submodule update`.

```
Ghassan@Pauls-MacBook-Pro:~/GHASSAN$ cd lbard
Ghassan@Pauls-MacBook-Pro:~/GHASSAN/lbard$ git submodule init
Submodule 'serval-dna' (https://github.com/servalproject/serval-dna.git) registered for
path 'serval-dna'
Ghassan@Pauls-MacBook-Pro:~/GHASSAN/lbard$ git submodule update
Cloning into '/Users/Ghassan/GHASSAN/lbard/serval-dna'...
Submodule path 'serval-dna': checked out 'e8effa75e473086b1f21254655ec87675573940c'
```

FIGURE A.2: A screenshot for updating the submodule of LBARD at the local folder.

- The final step is to compile LBARD using `make` command, as shown in Figure (A.3) to check if there is an error in the software, and it is the same method followed after each any update to the code of LBARD.

```
Ghassan@Pauls-MacBook-Pro:~/GHASSAN/lbard$ make
echo '#include <stdio.h>' > src/xfer/radio_types.c
echo '#include <fcntl.h>' >> src/xfer/radio_types.c
echo '#include <sys/uio.h>' >> src/xfer/radio_types.c
echo '#include <sys/socket.h>' >> src/xfer/radio_types.c
echo '#include <time.h>' >> src/xfer/radio_types.c
```

FIGURE A.3: A screenshot for compiling LBARD after successful installation. If there is no error, then it will end with nothing; otherwise, if there is an error, then it will appear on the terminal.

A.2.2 LBARD & fake radio

For the future work, if any developer aims to take part in this project without having the necessary hardware (HF/UHF/VHF radio), then it is more comfortable in the first stage to work on the fake model rather than real expensive hardware. This model makes the early integration steps of the new HF radio brand into Serval very easy, where some technical issues with the new hardware may raise without getting rapid feedback from the manufacturer. This model was followed during the research

In real test when the HF radio is full operational and communicates directly with LBARD, then a set of files are responded to LBARD like (`drv_hfbarrett.c` & `drv_hfcodan.c`) depending on the brand of the HF radio, while in the fake model, then there are (`fake_hfbarrett.c`, `fake_hfcodan.c` & `fakecsmaradio.c`) that respond to LBARD. The mechanism for both cases, fake and real radio, are almost similar since the same procedures have to be followed in both cases. The code of all drivers' files is stored inside two folders that can be accessed through (./lbard/src/drivers) and (./lbard/src/fakeradio).

The communications architecture between LBARD and fake radio can be classified into two parts, which are the LBARD side and fakecsmaradio side. These two parts are communicating through the file descriptor (fd) for the test purpose (i.e. if LBARD aims to send a message to fake radio, then it writes the message to the fd. Fake radio is going to read a segment of data from fd and analyses what does it contain).

The below section is an overview of the two sides of communication parties (LBARD and fake radio), and it helps developers gain essential information about the mechanism between these two modules.

The LBARD side

The LBARD main file(main.c) deals with many functions in different files, mainly in(`serial.c`, `radio.c`, `hfcontroller.c` & `txmessages.c`). Also, there is a sequence for executions starts from lbard, and ends with one of the functions in LBARD directory.

In general, when execution attempts to write data to the file descriptor, it means that LBARD at this point wants to send a message to the fake radio, then there is a tiny time break after this line since the fake radio is going to read, analyses and responses to the message of LBARD. The same thing is happening at fake radio side when it comes to writing data to the file descriptor, and hence if we want to know what is going on in both forward and backward data transfer between two parties, we should have understood the content of the exchanging messages.

Fake radio and receiver side

This side is representing two different communications techniques in two files stored in (./lbard/src/fakeradio), which are HF radio and satellite Outernet receiver.

Inside of this communications module, the functionality of real radio or receiver has been represented here, and many functions that distributed over many files simulate the real process of the HF radio and Outernet satellite receiver. The starting point of execution lies in fakecsmaradio that represent the fake radio, or in fakeouternet that represent the Outernet receiver. For fakecsmaradio and before the starting of execution of this file, few parameters need to be initialised like the number of radios and the list of suggested radios whether they are Codan, Barrett or RFD900, then during the execution, the fake model will check the list of radios within its internal functions, and identify them based on the radio type identification functions in this part.

Fakecsmaradio or fakeouternet are not the only files in this module, and there are other files that take part in the process like `fake_hfcodan`, `fake_hfbarrett` and `fake_rfd900`. For the fake radio part, different functions are called to read bytes, analyse messages, identify the radio type, respond to file descriptor (fd), and check the beginning and the end of messages.

Data transfer and process between the LBARD side and fake side continues to both sides through the fd, which plays like a logical link between them. If any error could happen during the communications between two parties, then log files can be examined to find out where the problem is, and what does it cause it.

A.2.3 The interaction between HF radio and LBARD and message exchanging

For each Codan or Barrett HF radio, there is a different behaviour between the two drivers since each radio has its own set of commands which reflects on what the functions in each driver(`drv_hfcodan.c` & `drv_hfbarrett.c`), particularly (`hfbarrett_process_line` & `hfcodan_process_line`) going to do after receiving a specific message. To explain more, let us talk about each HF radio reaction here.

1. Codan interaction: It is effortless to list all actions made by Codan's internal modem, and how the function (`hfcodan_process_line`) deals with it, as shown below. It is also important to know that this function deals with different radio replies, like a direct command from Codan, interaction message from Codan to a specific locally generated command, a response message from the attached radio to a received command or request from a remote radio. Therefore, the following expected events are taking into consideration:

   - To start with the correct command in the communication, the echo commands should be ignored, and the first action is to wait for '>' prompt because the radio releases this prompt whenever it finishes an action, and wait for another command.
   - The message `CALL STARTED` from radio means that the radio has sent a request to connect to a remote radio using the command `alecall`, on the same time, it sends this message to LBARD as a kind of confirmation of the operation. If this function recognises this message, then the correct position of the state machine for the radio, in this case, is `Connecting`, and the function does not change

the state machine for the radio because it is not a command or received message.

- The message `CALL DETECTED` relates to the opposite case of the previous one, or we can say that the local radio has received a call or a request to connect from/with the other remote radio. The local radio generates this message to inform the user or LBARD that a request to call is under the process, and it may end up successfully by engaging with the remote radio, or reject the request of connection if the local radio is busy.

  Mostly, if the local radio within the `Ideal` state machine, it will accept the request of connection. While, if it is in a `Connected` state which means it has been already connected to other radio, it will reject the pairing request.

- The message `ALE-LINK: FAILED` is a reply to the command `alecall` if the remote radio has not responded or agreed to the connection request made by the local radio. This reply also means that the process of connection is failed, and it needs to be started again from the beginning. Similarly, changing the state machine from any state back to `Ideal`.

- The message `LINK: CLOSED` is the next reply message after `ALE-LINK: FAILED` when sending the `alecall` command to the remote radio. This reply officially ends the `alecall` request of connection with other radio as shown in the following part of a real communication's session below:

  01:13:41.973> alecall 111 from 1797

  OK

  CALL STARTED

  CHAN: 2

  CHAN: 1

  ALE-LINK: FAILED

  LINK: CLOSED

- If the connection is established between two radios, then the message `AMD CALL STARTED` from radio appears, which means that the radio has sent a direct data message to the remote radio using the command `amd`, and locally, this radio generates this message to the user or LBARD to indicate the beginning of the process. Also, receiving this message from the radio means that the radio is already in the `Connected` state, and it is possible to change to `TXing` or transmitting state machine. This message does not change the state machine for the radio since it shows the current process's status.

- The message `AMD CALL FINISHED` from the radio is the complement one for the `AMD CALL STARTED` as shown in a real communication's session below:

  02:26:44.128> amd "Hello there"

  OK

  AMD CALL STARTED

  AMD CALL FINISHED

  When the radio sends a data message using `amd` command, then it informs the user or LBARD about the start and the endpoints of the process, and formally, this response message indicates the end of the process of sending one single message from the local radio to the remote one despite the fact that this message has been successfully delivered in full or not. Also, this message does not change the state machine for the radio.

- The message `AMD-CALL: channel number, sender ID, local ID, time and the data message from the sender` is generated by the local radio that has received a message from the remote radio. The set of parameters within the message illustrates which frequency channel, the sender radio ID, our local radio ID, the current time and the delivered data message.

  The status of both radios should be connected (i.e., alecall has been established first), and they both in a `Connected` state.

  An example of receiving a data message from other radio is shown below from real communication's session:

  CALL DETECTED

  AMD-CALL: 3, 111, 1959, 04/03 08:21, "Hello there"

  00:17:41.402>

- The message `ALE-LINK: channel number, caller ID, remote ID, date & time` that comes with many parameters, is generated from the local radio after sending the command `alecall` to the remote radio that accepts the request. This message indicates that the connection is established now between the two radios, and they are connected. The two radios are also ready to exchange data between them when using `amd` command. This message implies changing the state machine for the current radio to `Connected`.

An example below of real communication's session that shows the use of `alecall` and what are the displayed messages from local radio when the connection request is approved:

00:13:49.217> alecall 111 from 1977

OK

CALL STARTED

CHAN: 3

ALE-LINK: 3, 1977, 111, 04/03 08:18

2. Barrett interaction: The internal modem for Barrett has a different list of commands, and it is different from Codan's list. Also, the commands and the engagement of Barrett with LBARD is a little more complex since the commands and messages are about codes, unlike the clear and understood messages in Codan; however; simplify the process between LBARD and Barrett inside the function (`hfbarrett_process_line`) is what is willing to achieve in the next section:

    - The first thing in the modem's raw message is to skip extra characters like ON/OFF, and is a necessary step as it filters out the message line to reach the actual line of command or data.
    - To establish an ALE link, the command AXLINK DD SS is sent to other radio to request the engagement in a link. DD & SS in the command represent destination and source address for the local and remote radio respectively.

      The request may fail for various reasons, and depending on the reason, there are error codes generated by the modem that tells LBARD why the request to connect failed. These error codes are sent from the modem to LBARD, and then each receiving message should be checked by the driver for any types of error. The following are the most common error codes from Barrett that checked by LBARD

        - EV00 & E0: Means that there is a syntax error due to message format (i.e., the command starts with a 'L' to refer to ALE)

  - EV08: Means that there is an ALE error, and it is unknown. This could happen during link set up, trying to make a call or link termination.

  When an error happens, and one of the previous codes has been detected by LBARD, it changes the state machine of the radio form its current state into `Disconnected` state since the occurrence error prevents any attempt to maintain the link or proceed further in any request.

- If LBARD has detected no error, then It necessary to retrieve all address from the modem, and save it in LBARD's list of radios. The command `AIATBL` does that, then LBARD extracts both source and remote addresses, and registers the new remote address in all radios' operational list if it has not been added.
- If an ALE link has been established between two radio without AXLINK, then LBARD inspects the coming message from the modem if it contains any ALE message or `AIAMDA`, which means that there is a data message with a maximum of 90 expanded ASCII byte.
- LBARD can determine any change in ALE status of the radio once it receives the command `AISAT`. Change in ALE status for the radio implies much information like:
  - What is the current ALE system mode (offline, scan, receive or manual mode)?
  - What is the ALE current status (ideal, incoming call, start call transmit, sounding transmit or receive)?
  - What is the current transmitting (transmitting ALE or receiving)?
  - What is the current tuning (active or not active)?

  To give an example about what can single command tell LBARD, the following reply from the radio contains a number, and each digit represents something:

  AISTAT10000100

  The radio says here that the ALE mode is offline (1), ALE process is ideal (0), no transmission receiving (0), no tuning (0), one link only (01) and scan list index (00). The sequence of number (10000100) reveals all these pieces of information and makes LBARD updates the state machine.

- It is important that LBARD knows about any change in the current list of HF radio stations linked to the radio, so that if an attempt failed to connect to a remote radio, then LBARD gives a time frame before re-attempt to connect again to the same remote radio. LBARD checks the radio's reply if it implies the command `AILTBL` and what is the current state machine for the radio so that it waits a few minutes before trying to reconnect again; otherwise, disconnect from this remote radio.

A.3 Test LBARD

There are many scripts related to LBARD protocol responsible for testing different functionality related to, and they are all stored in one of the folders inside the main directory of LBARD. Among these tests scripts, we are interested in few only related to the recent improvements of this protocol with HF radio or satellite links. This section provides information about testing the code of LBARD, particularly the first step of connecting HF radio to LBARD, and how to analyse the output from the test. All files and their locations are stored in the GitHub repository and are included in this section to check the script and save time for the reader.

A.3.1 Test script files location

To get access to the copy of test script files related to many tests with Serval DNA in Serval Project, it needs first to have a look to the information related to different tests, and they are located in Serval DNA repository. The following direct link takes directly to doc folder as below:

https://github.com/servalproject/serval-dna/tree/development/doc

The doc folder contains many different script files about general gaudiness for these tests not specifically for a certain one.

The actual test script files for testing LBARD are located in a different folder, and currently, there are more than 45 different tests distributed over two script files that can be found in (lbard/tests) in the main directory of LBARD, or it can be accessed directly from the following link, then the code for these tests is accessible easily.

https://github.com/servalproject/lbard/tree/master/tests

If the developer prefers to utilise the terminal to deal with the tests, then it can be listed using the bash command inside the lbard folder (tests/lbard -l), and l here means list.

In this section, only one test will be demonstrated and leave the remaining tests to anyone interested in reading about LBARD. The selected test checks all functions in LBARD that are related to HF/UHF/VHF radio connectivity from one side, and the fakecsmaradio on the other side. It simulates the reality of the connection between LBARD and any other device like Codan HF radio, Barrett HF radios, RDF900 radio in Mesh Extender.

The role of this test is to help Serval developer trace any errors in any improvement to LBARD's code like adding new hardware device or alter the response or priority to connected devices.

The first test (LBARD detects radios), which is about running four LBARD daemons, servald & fakecsmaradio, checks the virtual operation of these different components (software), and ensure that they are working correctly, which means there are no software bugs in every c-file of them, and they are logically working together without any problem.

The c-file `fakecsmaradio` was built to simulate the same operation for real HF radios for different brands. All responses from real radios have been considered when it has been built, and it is very accurate and fast.

The first test should also show a link established between the fake radio and LBARD with some few messages as a copy from the original internal messages from both of them, which include what does fake radio response if it receives a VER command from LBARD for example.

To display the script file's content, any bash command like nano, pico or less can be employed here on a terminal for this purpose. Also, many individual tests within the same file can be obvious to the developer to trace any test. This test file can be accessed in the terminal through the following command:

nano tests/lbard

Another important test file is `testframework.sh` in serval-dna folder which has few essential functions that used with (lbard/tests/lbard). It can be access through the command:

nano serval-dna/testframework.sh

A.3.2 Initialising temporary directory

Before running the test, one step is necessary if the workstation is Mac OS based, which is to adjust the temporary directory to adopt with the LBARD since Mac uses a long path for temporary folder, and cause an error during the test if this statement has not been made. To solve that, simply by typing the following command:

export TMPDIR=/tmp

This should be done before running the test, and it is required for one time only; otherwise, it will get an ERROR, and the test will stop from being progressed.

A.3.3 Run the test

Now, there is no obstacle or any further step to perform the test, and to run the test and ensure that everything is OK, execute the following command if the current path in the terminal is ./lbard.

tests/lbard -f 1

Here, -f means run it with force, and 1 means that the user wants to run the first test only and keep other tests without run. The first test takes seconds to finish, and it may take longer time depending on the waiting time commands (delay instructions) with the LBARD's files since the request for connection between LBARD and fake radio implies a waiting time to response for each virtual device.

A.3.4 The output of test

If the first test is executed, then the output can be one of the three scenarios (PASS, FAIL or ERROR), and they cover all possibilities to the connection status between LBARD and the radio.

It is important to mention here that the test takes time to finish up to a couple of minutes since it simulates the reality where LBARD may wait for a time in order to connect successfully to the radio due to many reasons, like the radio itself being busy with another connection, LBARD fails to connect to the radio and waits a time before re-attempt the request.

To remove the ambiguity about the three cases and what they mean, each case will be clarified here as follow.

1. ERROR: Which means that there is/are software error(s) or bug(s) in one/many of the files that have been running. This situation happened

many times during the process of improving the code of LBARD where some errors may exist during the process.

If an error occurs, then the following output message for the first test appears:

Test/bard -f 1

Starting the tests/lbars program

1 [ERROR] LBARD detects radios

1 test, 0 pass, 0 fail, 1 error

In this case, there is definitely an error with code, and to discover the reason behind it and have a closer look, it is better to examine the ERROR log file, which is generated while running the test every time.

The path for this log file is (`./lbard/testlog/lbard/1.DetectRadios.ERROR/log.txt`), and it can be displayed via the command

less testlog/lbard/1.DetectRadios.ERROR/log.txt

The content of the file will display on the screen. Next, search for the word `ERROR` by typing /ERROR within the interface which will show all ERROR messages within the log file. Attention must be given to each `ERROR` message, and trace it back. It is necessary to know which part of software generates it since these ERROR messages have been inserted in the original copies of files to help developers know what is happening.

2. FAIL: If this message exists, then we can say that LBARD works fine with no bugs, but a logical error or something is missing within the structure that prevents the test form having the final result.

   Fail output screen has the same output of `ERROR` except the word FAIL instead of ERROR. Also, the report of FAIL is stored in the generated log file in the path (`../lbard/testlog/lbard/1.DetectRadios.FAIL/log.txt`), and it can be displayed via the following command:

   Less /testlog/lbard/1.DetectRadios.FAIL/log.txt

   To examine the reasons that led to FAIL, check the log file in a similar way to what has been explained in the ERROR log file and know what type of FAIL messages have been generated.

3. PASS: This is the best case from the developer point of view, and it means that there is no problem or bug along all functions in LBARD

or fake radio. Also, there are no connectivity problems during the test, and a successful connection between LBARD and fake radio has been established during the test. The Figure below (A.4) is a screenshot for a PASS test.

```
Ghassan@Pauls-MBP:~/src/lbard$ export DIRTMP=/tmp
Ghassan@Pauls-MBP:~/src/lbard$ tests/lbard -f 1
Starting the tests/lbars program
1 [PASS.] LBARD detects radios
1 test, 1 pass, 0 fail, 0 error
Ghassan@Pauls-MBP:~/src/lbard$
```

FIGURE A.4: Screenshot of the LBARD test for connectivity with HF radio. The word PASS in green means that it is a successful test, and no problems have been found.

A.3.5 Re-compile lbard after fixing bugs

The process of executing a c file is to compile it first after any modification to the code and then run it. With a single c file, a gcc command compiles the file and produce the output file for execution. Then execute the file by typing the output file in a terminal as in the following example.

gcc input.c -o /output

./output

But in LBARD case with so many files and functions, they need to be linked after compilation process, and the best thing to do these two steps safely is to use Makefile and make command to compile LBARD then execute it.

During the development process of LBARD, if any change is applied to any function in LBARD or fake radio, it has to employ the command make & make fakecsmaradio for LBARD and fake radio respectively.

Regarding any change to LBARD (`main.c`) or any other file linked to, the command `make lbard` compiles LBARD since the name (main) is replaced by lbard according to Makefile in the same directory.

A.4 Codan HF Data Modem 3012 and AT commands

Codan HF data modem 3012 is an essential element in this research, and there are many details related to the integration steps between this modem and LBARD. Therefore, it is better to make a section that is continuing to the section of data modem 3012 in Chapter (8), and explain more details about this modem in relation to AT commands are necessary to control the modem. These details would help the developer go through before starting with any improvements to this modem.

A.4.1 Install the HF Data Modem 3012

To connect all equipment together, and make one operational unit, Figure (9.4) shows how we can install the HF data modem with the transceiver together, and connect them to a computer. The green arrows represent different types of cables, and the data modem is connected to the transceiver from one side and to a computer or Mesh Extender on the other side.

The data modem is connected to a serial port of computer through the cable, which is a USB port in this example, and at this point, it should be ensured that all software in both computer and data modem are installed, and working properly. The 9102 Fax and Data Controller Software is the interface between the computer and the transceiver, and it extends the modem with the required setting to communicate with the computer, which is running under Windows or Linux operating system.

A.4.2 Setting up the terminal

Next step after connecting all cables to the equipment is moving now to the computer, and open a terminal to make the necessary setting to the terminal before the actual connection to the HF data modem.

To make a successful connection to the data modem, as shown in Figure (A.5), few parameters must set up in advance, which are Baud rate, data bit, parity check, stop bit and hardware handshaking. The following values must be given to these parameters respectively (9600, 8, no parity, 1 stop bit & RTS/CTS signal).

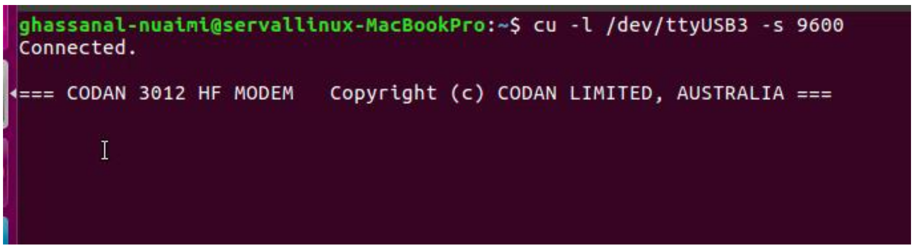


FIGURE A.5: Setting up the terminal to enable connection with Codan HF data modem.

Under Linux environment, we can utilise any command that utilised to connect to a serial port, like cu or screen, and set up the parameters directly, as shown in Figure A.5. The connection process to the modem may take few second, and if it is successful, then a message on the terminal "connected" appears to indicate that it is now connected, and ready to any AT command.

A.4.3 Fax and Data Controller Software

The data modem 3012 comes with Codan 9102 Fax and Data Controller Software, that brings many features to digital HF radio transmission environment, and makes them easy to operate or manage [102]. For example, it implies data compression as in many digital transportations, which is essential to improve the throughput within the link, it provides file and text exchange between any two or more nodes, making sharing information through different applications very comfortable. The software enables the user to control the modem through a set of commands, known as AT commands, and this is done via a terminal.

Also, Codan HF data modem can be utilised to send emails over the HF link as a part of the digital system and when there is no coverage for other communications services.

A.4.4 Types of data transmission

Transmission of digital data among HF data modems 3012 can be achieved in three different ways depending on the type of link(s) between two or more HF units. Each type has advantages and disadvantages, and some of them are explained as follow:

1. Selective or point to point call: In this type of transmission, a link between two data modems only is established, and the data flow in both directions between these two nodes. HF data modem destination address of the callee radio is specified when the caller radio aims to communicate with, and it takes longer time than other types since it depends on the status of the callee HF radio (i.e. busy, ideal).

   Interactive chat mode or live chat is possible in this type in addition to optimised data transfer, and the link can be employed for a variety of things.

   This type of transmission has an advantage over other types since the data transmitted are guarantee error-free, and the installed software is responsible for that. If any error may happen due to poor link condition, then retransmission of payload is applied. Point to point is preferred to use in Serval mesh network due to the automatic retransmission of data without increasing the load on LBARD.

2. Group call: In this type, the caller can send data to a group of stations that have HF radio data modems by specifying the group number within the call request of a maximum of 99 stations in one call.

   The group call is beneficial and time-efficient method since it does not imply a dedicated link between the caller and each callee station. It is possible to utilise this type in Serval Mesh network when a set of bundles are needed to be sent to a group of nodes in a specific area. However, this form of transmission is not error-free since it is subjected to channel status, whether it is good or not in each receiver.

3. Broadcast call: This type of transmission is similar to the group call, except that it is without specifying the receiving stations, which means that any HF radio that can communicate over the selected channel can engage in this transmission as it is broadcasting concept.

   Broadcast call in HF radio is similar to the broadcasting transmission in the computer network, and they have many standard features between them.

   Broadcast call shares the group call of being a non-guarantee error-free data exchange method so that they may imply retransmission of important data to some HF radios. This type can be applied in the Serval Mesh network even if it implies errors in data transmission to some stations, which can be solved by retransmission.

A.4.5 AT commands

AT commands are a list of commands dedicated to handle a wide variety of commercial modems, like mobile phones, GSM & GPRS. The prefix AT is an abbreviation for the word 'Attention' to let the modem knows that this is a command, and action has to be made. The AT commands are fit to the purpose of machine-to-machine communications to establish a link to a computer. These commands are integrated with the recent LBARD improvements to deal with HF data modem 3012, and LBARD sends different commands to the modem to do various tasks.

Every command begins with AT followed by one or few letters. The prefix AT is not part of the command, but the following letter(s) tells what the necessary action to be done is. For example, ATD means Dial, and ATA means Answer.

In general, a wide range of tasks can be achieved with the AT commands when connecting to a modem like:

1. Retrieve basic information from the modem, e.g., model number & name of the manufacturer.
2. Establish a data connection
3. Retrieve the subscriber information.
4. Current status of modem, e.g., modem activity & signal strength.
5. Read, write and send data.
6. Change the configuration of the modem.

Modes of operation

The HF data modem 3012 has two modes of operation: Local Command mode and On-line mode. The modem is generally in the first mode, and can respond to AT commands, while if a link is established between two data modems, then each one switches from the Local Command Mode to On-line mode, which can be used for exchanging data or chatting.

Switching between the two modes can be made through the computer's input commands by hitting few keys or using AT commands for this purpose. For example, if the modem is in the On-line mode and switches back to the Local Command mode, just type the escape characters. The default escape characters in Codan are +++, and the user can set them to another sequence by utilising the command AT&E=followed by ASCII characters. If the switching process is done, OK appears on the terminal as an indicator of another mode.

Switching from Local Command mode to On-line mode is done automatically without sending any other command to the modem after a process of establishing a link is finished successfully. However, to switch manually to On-line mode, the command ATO does that.

Setting the station address

One of the necessary steps before making a call to another data modem is setting the local data modem's address. Any data modem must have an address to be as an identifier among other HF radio data modems, so that any remote data modem can call the local modem depending on the previously specified address.

The address here is a sequence of numbers between 0 and 15, and it is elementary to set it up through the command AT&U, then any remote modem can call the local one based on the given number like when the user calls a mobile number.

Making selective, group and broadcast call

After setting the data modem's address for each station, any call of the three types can be made from the modem utilising the AT command (ATD), which is the same for all three types except the argument part that specifies the call type.

The selective call requires an abstract remote data modem address as an argument with ATD since this type establishes a close link between two known stations as a condition to proceed and exchange data, which is why this call is the most reliable connection over other types. To make a selective call to a station address (43891) as an example, simply by typing (`ATD43891`) in the terminal, and wait for the response from the data modem.

There are three common types of responses for the selective call whether it is a success or not, and for each response, a message is displayed on the terminal to what is the result of sending a request of a call to the remote data modem as follow:

1. If the link is successfully established by being accepted by the remote station, then the message `CONNECT` appears on the terminal, and the data modem mode is switched to On-line mode. The response normally takes less than a minute to complete, and show the result on the screen.

2. If the remote data modem rejects the call or the link simply is failed to establish for any reason, then the message `NO CARRIER` is displayed on the terminal to let the user reduce the scope of the not connecting problem.

3. If the message `NO ANSWER` appears on the terminal, then it means that the dedicated time of establishing a link, which is two minutes, ends without receiving anything from the remote data modem.

To make a group call, all it needs is to put a number between 0 and 99 after the address number in the command ATD, so that the command line consists of three parts, the command, the prefix address of the first station & 00 at the end. The group of stations should have the same prefix part of the address, and they are different in the last two digits to be in the same group; otherwise, and station that has different prefix address cannot be within the group call session. For example, the command `ATD562400` is making a group call to all stations between 562400 and 562499.

The group of stations should prepare to receive the call from the sender station; otherwise, the call will skip the station that is not ready for the data transmitting process. The terminal also displays the message `CONNECT` when is ready to start the process.

To make a broadcast call, which is the easiest one, no argument or address is required to start the one-way data flow link, and just the command ATD is needed to make this call. The terminal shows the message 'CONNECT', and be in the on-line mode when the modem is ready to send data.

Answering the incoming call

If the data modem has set the address, then it can be reachable by other remote data modems. Link establishment between two or more data modems requires two actions to be made by both parties, the first action is making a call from the callee station, and the second action is to answer that call by the caller, then the data can be flown across the link afterward.

When the data modem receives a call, then the message 'RING' appears on the terminal to indicate that someone is calling the data modem, then there are two options to react to this call request, which are either accepted or rejected the call.

The data modem takes no action until a decision made by either answering or rejecting the call through a command sent from the terminal to the data modem. If the call is being answered, then the data modem needs seconds of time before the link is being ready to transmit the data, and to know that, if the message `CONNECT` appears on the terminal, then it is ready now. Any iteration to send data before the message `CONNECT` appears, may result in aborting the link establishment. Figure (A.6) illustrate the state machine for the Codan HF data modem 3012, and what happens when utilising different AT commands on different states.

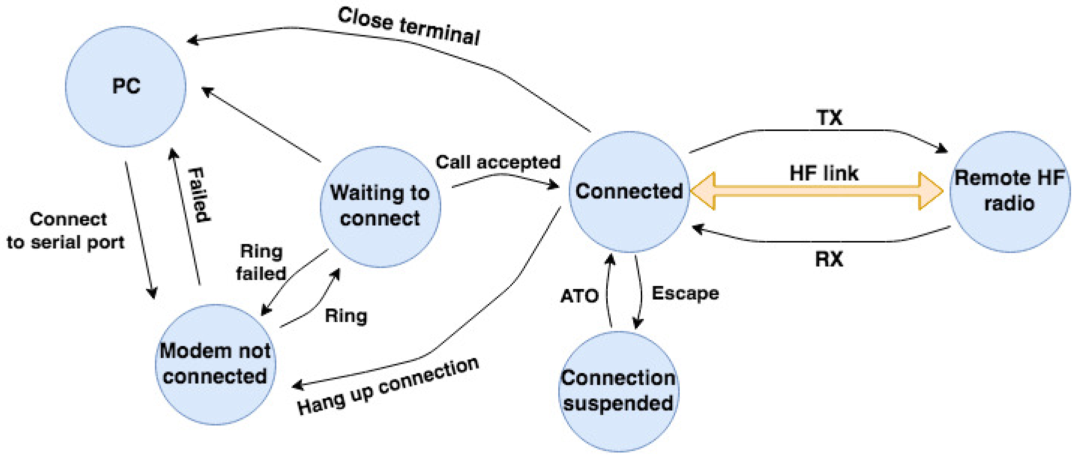


FIGURE A.6: The state machine for Codan HF data modem 3012 when applying various AT commands.

A.5 Barrett Radio

Barrett HF radio is the second brand of HF radios that included in the improvements of LBARD, and it is essential to give more details about the initialisation of the parameters involved in the setting. A new user has to deal with two different parts before preparing the Barrett radio for actual transmission, and in each one, steps have to be followed for successful integration of the radio into Serval Mesh network.

A.5.1 Setting up HF Barrett radio for transmission

When dealing with Barrett radio for the first time, it needs to explain how to set up channels from the beginning based on the connection with a computer. This research has got support from Barrett company by providing two HF radios (Barrett model 2090 & 2050), and a software (2000 series programming software) is included to assist in the first setting of the radio with the computer.

This stage has many different steps, and each step has different points mentioned here to make it easy for non-expert people to set up everything. The following sections have to be applied in sequence, and can be done on both models of Barrett HF radio (2090 &2050).

Software installation and connection to HF radio

Barrett HF radio software is necessary to enable the user to do the necessary setting to the radio before the transmission process. The following points are guiding the user to prepare HF radio and computer to enable ALE mode for successful communicate:

1. All cables from HF radio to the computer are provided and plugged into the computer.

2. Install 2000 series programming software into the computer. This software comes with HF radio, and it is developed by Barrett. This software can be installed under the Windows environment, and just choose the setup.exe file to install it, then go through the installation process until the end.

   A user can select either international, Australian or blank database, which implies different packs for users during the process.

3. After a successful installation, open the software and look to the interface with different columns. At this point, the user is ready to initialise ALE channels for the two Barrett radios, which are connected to the computers at this point.

4. Click on `Add Pack` from Port at the top, then choose `Downloaded pack`.

5. ALE channels can be added to the channel preset, and new preset map, which contains the newly created channel.

6. Initialise new addresses for ALE channels, and adjust them to the newly preset map. After that, it is important to upload the pack to each HF radio to enable it to communicate with other radio according to the new address.

7. Move now from the computer to the HF radio and utilise the radio interface to make the radio adopt the new setting.

8. Go the ALE mode, and enable it, then assign the current scan list to the recently created preset map. After that, the radio is ready to operate in the ALE mode.

Initialise radio channels

The next step is to initialise radio channels to allow both radios to communicate over these channels. Few steps need to be done within the 2000 series programming software interface, not from the radio.

1. Click the pack that has been specified from ALE initialisation stage from different packs.
2. Select edit transceiver option, then channel menu.
3. Here, the user can create many channels by clicking on Add new channels and initialise the values for each new channel like a number, RX frequency, TX frequency and mode. At the end click OK to finish.

Update Channel Presets

After initialising radio channel, another process is required to make the newly created channels be operational. This can be made by updating channel presets as follow:

1. Click on the same pack in step 1 & 2 form main interface, and select Edit ALE option.
2. From the channel configuration interface, click on the tap Channel Presets at the top.
3. Click on Add, and then it is possible to add all recently created channels from step B here. Click OK when finished.

Update Preset Maps

The next step after updating the channel presets is updating the Presets Maps, and to do that, follow the two points:

1. Stay in the same pack, and select another tab at the top, which is Preset Maps.
2. Select the newly created preset map from the left side, and add the recently created channels, then OK.

Assign addresses to the channels

This is an essential step, where the address is assigned to each HF radio, and it should be called according to this input address, and to manipulate HF radio addresses in this stage, follow these two points:

1. Stay in the same pack, and select Addresses tap from the top.
2. Click Add to assign new addresses to the channels. The address is a four digits number, and it is up to the user to select it. However, it should be unique among other HF radios.

Initialise the scan list In ALE mode

This step is to tell Barrett radio to listen to the previously initialised channels in ALE mode, so that Barrett can respond to any incoming signal from any address in the list.

In ALE list, select ScanList or preset map that has been created in the previous steps.

The ALE configuration interface has other features or taps beside Addresses, Channel Presets and Preset Maps. Other taps like Presets Messages and System Settings enable the user to perform a speed test or alter pack setting.

Test the overall setting

This stage is the final, and it tells us whether the previous steps were achieved correctly or not. The test is manipulated from the Barrett radio interface, not the software, after all, setting all values to the new pack. The following steps are to test voice call:

1. Press Call button.
2. Scroll until display ALE call, then select it.
3. Select the address, then call the remote station.

Almost, the same steps are followed to test the messages, but here select ALE message instead of ALE call.

A.5.2 Installing test-based modem controller

After initialising the parameters of HF radio from the interface, the next step is deal with Minimum, which is a text-based modem controller under Linux environment OS. It has a straightforward communication interface that is utilised for some parameters. Minicom enables the dilation process, and it has a dialling directory for this purpose.

Minicom can be utilised to send commands to both Barrett and Codan radios, and wait for any radio reply. If the computer does not have a copy of Minicom, then the following bash command installs it on the computer.

sudo apt-get install minicom

Next, there is a need to set up the link between the computer and the radio modem. It is important to know which port that the radio is connected to, or in other words, what is the port name inside the computer that the cable has been plugged into.

To display all ports on the local machine, we can employ either one of the following commands:

ls /dev/cu.*

Or

dmesg | grep tty

After that, it is very easy to tell which port is connected in /dev directory, since we are going to tell Minicom to initialise the speed over this link as in the following command:

sudo minicom -b speed -D /dev/port_name

Where speed is the specified transmission speed in baud (usually 9600), and `port_name` is where it connected (i.e. ttyUSB1, ttyUSB2).

Next, Barrett commands are ready to employ within the terminal, and the interaction session starts from this point.

To terminate the session between Barrett and Minicom, the same command in ASCII that is utilised to terminate the Barrett ALE session is repeated here, which is \r\n (carriage return and new line feed).

A.6 Outernet/Othernet receiver

Serval Mesh can be extended to include many different nodes, and these nodes can be Wi-Fi, Mesh Extender and HF radio. Also, Outernet or Othernet satellite receiver has joint the Serval Mesh in this research to be one of these nodes that provides free and fast data transfer over a long distance.

To integrate the satellite receiver into Serval, required steps have to be followed to enable Dreamcatcher board to run a copy of Serval, and be able to receive data bundles via satellite link. This can be done over three stages as following.

A.6.1 Install Armbian distribution

With the Outernet satellite receiver, many steps should be followed to make a successful and smooth operation, and the first step is to install Armbian distribution. Armbian is an open-source distribution based on Ubuntu and Debian OS, and it supported the utilising of Outernet Dreamcatcher hardware perfectly. This installation is compulsory as it is the only available option that is compatible with the receiver.

The Armbian image can be downloaded from the below link, and Armbian 5.41version has been adopted in our experimental work, not the 5.67 version, since Outernet hardware does not support the mainline Armbian.

`https://archive.othernet.is/Dreamcatcher3%20Armbian/`

Then copy the downloaded image into the Dreamcatcher board's SD card (Figure A.7). Then start booting the OS which takes time after displaying `Starting kernel` on the LCD panel and a login prompt.

A.6.2 Connect to Outernet board

The board can be connected to a local computer through a serial adapter (or USB to serial adapter cable) to setup a few things. The speed is initialised to a 115200 bps from the interface in the local machine by the following command:

cu -l -s 115200 /dev/ttyUSB1

If it is prompted, then it is OK now to continue, and the connection is established. The first login to the Dreamcatcher from a terminal is performed via the default username & password (root & 1234), which can be changed into another one.

A.6.3 Connecting to Serval Mesh

Outernet Dreamcatcher board comes with many hardware adapters including a Wi-Fi adapter. This adapter can be utilised to connect to any nearby Mesh Extender?s Wi-Fi to be part of Serval Mesh network, but it is required

FIGURE A.7: This image has been removed due to copyright restriction. Available online from [171]. Outernet Dreamcatcher board, and it has many slots.

first to activate this Wi-Fi and specify which Wi-Fi signal is chosen among other ones.

Back to the terminal, two commands are employed here to gain the pairing with Mesh Extender?s Wi-Fi, which are nmcli and nmtui.

1. nmcli (Network Manager Command-Line tool) is utilised for managing network and reporting status, and it can take action in the edit, delete, create and activate/deactivate connection to a network. An example of how to connect to a Wi-Fi network protected with a password is below, where SSID name and password are required to complete the connection:

   nmcli device Wi-Fi connect "SSID_ name" password "password_here"

   In output example, to connect to mesh Extender Wi-Fi, the following command is only what a user needs here.

   nmcli device Wi-Fi connect "ServalProject.org"

2. nmtui (Network Manager Text User Interface) is a command with a simple graphical interface that assist users in network configuration, and it performs many tasks similar to nmcli. This command is required to complete the connection to Serval Mesh by selecting the Mesh Extender Wi-Fi from the interface through `Activate a connection` option, then pick up the targeted ones.

A.6.4 Install Serval-DNA and LBARD into Outernet Dreamcatcher

At this point, Outernet is running by Armbian OS, and it does not have a copy of Serval-DNA and LBARD, so it necessary to install them before doing any further action. The installation process is the same for installing Serval-DNA and LBARD on any other machine by utilising terminal and git commands (Installing LBARD is explained at the beginning of Appendix).

Another important file is required to install into Dreamcatcher, which is demod binary file (Demodulation binary). This file can be downloaded from the official website of Outernet, or it is accessible through this link:

https://github.com/servalproject/lbard/tree/master/blobs

Once it is downloaded, then a copy should be moved into the board, and this can be done via the cable of Wi-Fi. The update command is necessary after this step.

A heterogeneous set of I2C tools package and I2C bus for Linux is installed before testing LBARD. The following command is employed to install the package:

sudo apt install i2c-tools

sudo i2cset -y 0 0x60 0x00 0x8B

The final step is to run and test LBARD, then check if everything works correctly on Dreamcatcher. The process explained above may face some problem related to hardware flow control since the local machine connected to the board runs by a different OS.

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