Pilot Project:

Proof-of-Concept for a High-Resilience,

Under Ground, Heterogeneous, Wireless Mesh Network

Prepared For:

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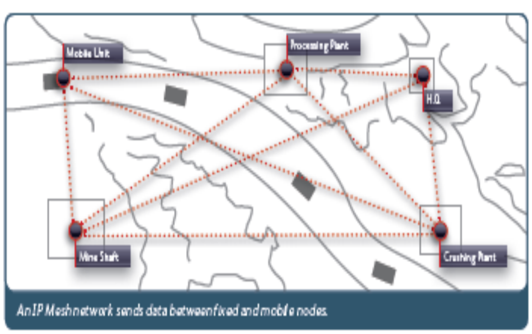
Executive Summary

Coal Services Pty Ltd (CSPL) Health and Safety Trust has enhanced its stellar reputation in health, safety, and mines rescue services by providing commitment to Australian Research Grant (ARC) Linkage Grant entitled “Safety & Medical Monitoring For Mining Operations”. Under the Linkage project, a high-resilience, battery-powered, heterogeneous wireless mesh network suitable for an underground coal mine will be designed, developed, and tested. The CSPL Health and Safety Trust commitment includes funding a pilot de-risking project at the University of Canberra (UC) in 2014. UC has developed a proof-of-concept device based on Software Defined Radio (SDR) technology that allows for the development of new wireless systems and protocols using software tools and APIs critical to the success of the Linkage project.

Testing of the UC proof-of-concept device was undertaken to determine the relative difficulties in implementing various technologies and required features for the final deployable device. Test results indicate that the UC proof-of-concept device has the ability for transmitting messages with minimal loss through 50cm of rubble using two different frequencies. The majority of the work focused on the practical development of various protocols including the ability to send basic messages using a multiplexing scheme named Coded Orthogonal Frequency Division (COFDM)[1].

The proof-of-concept stage of the project achieved the required aims of de-risking the technology development of a smart, battery powered, and heterogeneous mesh network. To complete the larger Linkage Grant project, a significant amount of work still remains to be done but this current effort identified the critical technology development focus areas. The work undertaken in the area of IEEE 802.15.4 ‘Zigbee’ transmitting through rubble was successful and the issues related to Wi-Fi development, COFDM, and mesh capabilities were identified.

With the knowledge and expertise gained in completing this proof-of-concept portion of the project, the successful development of a high-resilience, heterogeneous wireless mesh networking device/access point suitable for an underground coal mine has been substantially de-risked.



An IP Mesh network sends data between fixed and mobile nodes.

Self-healing mesh wireless technology will allow mines to monitor personnel health status from above ground to the mine face

[1] COFDM is a modulation scheme that divides a single digital signal across 1,000 or more signal carriers simultaneously. The signals are sent at right angles to each other (hence, orthogonal) so they do not interfere with each other. COFDM is particularly effective at minimizing multi-path effects.

INTRODUCTION

The underground communications system is the lifeline of a mine, especially during a mine emergency for rescue and recovery. In the event of a mining catastrophe, it is extremely important to find out the health status of any trapped miners. Based on this vital information, rescue or recovery operations will be planned. Having a robust, resilient communications platform plays a crucial role when the safety of a miner is concerned.

In response to this demand, a number of technological solutions have been proposed for underground mine communications. Nevertheless, due to the hazardous conditions of an underground mine, the biggest drawback faced by conventional mine communications systems is their survivability in the event of a catastrophe. In the event that the existing mine communications systems is damaged, the ability for the mines rescue team to deploy a temporary emergency mine communications systems is essential. Consequently, it is a critical health and safety requirement for the mining industry to have a high-resilient, rapidly deployable, compatible, underground communications network.

AIMS AND OBJECTIVES

In this report we have documented work completed on a proof-of-concept stage of a larger mine communications systems development project. The aims of the overarching project are to develop a smart, resilient, robust, self-configuring, infrastructure-less, decentralized, ubiquitous underground communications platform for coalmine monitoring and rescue operations. At its core, this project will save lives by advancing the knowledge base of wireless mesh networks (WMN) and interworking techniques of heterogeneous networks for use in the mining industry. The project will focus on the following objectives:

1. Develop a rapidly deployable, decentralized, heterogeneous WMN capable of operating in an underground mining environment.
2. Develop multi-standard, self-configuring and self-healing routing techniques to make the network resilient and fault tolerant.
3. Develop a Coded Orthogonal Frequency Division Multiplexing (COFDM) communication system, the proposed modulation technique for enabling communications through cave-ins and confined spaces.

In the larger project, in partnership with CSPL Health and Safety Trust, University of Canberra (UC) have proposed to the Federal Government to develop an adaptive device that develop a device to meet the above objectives in the potentially chaotic and hazardous underground mining environments pre and post incident. The proposed network will be designed in such a way that, it will act as a platform for two-way communications for day-to-day as well as post-catastrophic mine operations. In the event of a catastrophic mining disaster, the nodes of the WMN will be able to self-organize and self-heal and additional nodes will be able to be deployed by rescue workers to provide vital health and safety data of the trapped miners. The decision support system will be able to assist in the rescue/recovery operations via Artificial Intelligence (AI) based data analytics.

The CSPL Health and Safety Trust funded a proof-of-concept stage of the larger project to develop the core knowledge and components of the larger project. The primary goal of the proof-of-concept stage is to de-risk the technology of the larger project and hence improve the possibility of receiving Federal funding. The objectives of this proof-of-concept stage of the project where to:

1. Show that the concept of a heterogeneous network can be made to work in actual hardware via Software Defined Radio (SDR) technology and prove that hardware can be

made to support multiple networking protocols and be upgradeable within a broad range of radio frequency domains.

2. Show that radio signals can be sent from an antenna system through debris while buried.

3. Develop understanding of the required self-configuring and healing techniques and learn what would need to be done to improve these for a multi protocol and frequency system.

4. Develop COFDM capability concepts with the aim to integrate into a full wireless protocol implementation.

Motivation

Health and Safety is the number one priority of the mining industry, in order to facilitate a safe and productive working environment. This project proposes a smart resilient platform for managing miner health and safety as well as facilitating rescue/recovery operations. A crucial factor for ensuring the safety of a mine is its communications infrastructure. Furthermore, a mine's communications platform also plays an important role in its day-to-day operations.

Despite the advances in communications and health monitoring technologies, there isn't a single complete certified networking, health, safety and rescue managing solution available for the mining industry.

We are confident that the outcomes of this proof of concept will contribute to the improvement of the safety and wellbeing of mining industry employees, and increase the commercial sustainability of the mining industry in Australia and internationally.

DESCRIPTION OF EQUIPMENT ITEMS

Software Defined Radio

Software Defined Radio (SDR) is a radio system where many of the components traditionally implemented in hardware are implemented in software running on an embedded processor. With the rapid recent advancement of computer processors and the increase in the capabilities and speed of these systems, the functional capabilities of an SDR system have never been higher. Using SDR systems, old assumptions about the spectral and functional capabilities of a radio system become obsolete. A SDR transceiver is not as limited as a traditional radio when it comes to the use of the radio spectrum, allowing for spread spectrum transmission and ultra wideband transmission for minimizing multiple channel defects. Capabilities such as wireless mesh networks and cognitive radio become possible with this approach.

The Nuand BladeRF Software Defined Radio is a software defined radio platform incorporating a 40KLE FPGA device and a 200MHz ARM9 processor with wideband RF transceiver[2]. The transceiver uses direct conversion for reception resulting in perceived DC spike within the device and this must be factored into any calibration or transmissions. Due to the inclusion of both the FPGA and ARM9 processor, the device is able to run headless for many applications.

SDR systems such as the BladeRF incorporate a direct conversion transceiver and a field programmable gate array (FPGA) to create and receive radio signals. The inclusion of the FPGA allows for a hybrid approach to radio frequency development whereas the hardware driven radio signals can be generated in the FPGA and software defined radio signals can be sent from a computer. It was chosen for this project due to its full feature set that matched the goals of the project.

Field Programmable Gate arrays

Field-programmable gate arrays (FPGA) are integrated circuits that are capable of being re-configured by a customer after they are manufactured[3]. The chip can be configured to become almost any complex logic device. The programming of FPGA devices is generally done using a hardware description language (HDL) allowing for a device with performance equivalent to an application-specific integrated circuit.

Within an FPGA are reconfigurable logic blocks and a hierarchy of reconfigurable interconnects allowing the blocks to be connected in an almost endless number of ways. Each logic block is capable of performing both simple and complex logic operations. FPGAs can be used to create versatile hardware devices that can be reconfigured without changing the actual hardware.

By integrating FPGA devices with the SDR it is possible to overcome the limitations of a software only approach. Even though SDR technology is extremely versatile, it is unable to match the speed of a dedicated hardware device. An FPGA is able to match the performance of dedicated hardware and the mixing of the SDR and FPGA technologies allows for a device that can be a fast, flexible communication system.

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[2] Nuand | bladeRF Software Defined Radio. 2015. Nuand | bladeRF Software Defined Radio. [ONLINE] Available at: http://nuand.com/. [Accessed 30 January 2015].
[3] FPGAs. 2015. FPGAs. [ONLINE] Available at: http://www.altera.com/products/fpga.html. [Accessed 30 January 2015].

DE0-Nano 22KLE FPGA development board

The DE0-Nano Development board developed by Altera as a Development platform based on the Cyclone IV 22KLE FPGA[4]. The DE0-Nano's Design allows it to be powered via a USB cable connected to any computer or by a battery for a duration of time. With the capability of being mobile and easy to program via the USB-blaster circuit designed specifically for programming the FPGA installed, it allows for easy testing and development for FPGAs.

Wireshark

Wireshark is a packet sniffing and packet-analyzing software developed to organize the headers, data and footers within packetized data to ease the examination of transmitted information over any given medium[5]. Intended majoritally for Ethernet based transmissions (TCP/IP protocol stack), multiple plugins and 3rd party additions allow wireshark to register headers from other protocol stacks and organize packets into an easily readable format. Wiresharks native flagging of errors and other issues also make it useful in understanding issues in specific transmissions, while not always accurate, provides some organized insight into the specifics of what was collected from a given transmission. Its abilities to also save and read Packet Capture (PCAP) files also allows for sharing the results of a Packet Transfer.

GNU Radio Interface

GNU Radio is a open-source software development toolkit that provides signal processing blocks to implement software-defined radios and signal processing systems. It can be used with external RF hardware to create software-defined radios, or without hardware in a simulation-like environment. It is widely used in academic environments to support wireless communications research. The GNU Radio software allows the user to view a Fast Fourier Transform (FFT), Waterfall, constellation number and scope plot of both sent and received signals.

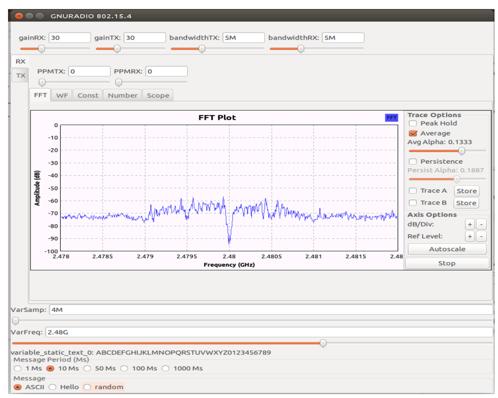


Figure 11- GNU Radio WX interfaces

The interface also provides the option to adjust the transmission and reception frequencies, bandwidth and gain as well as a common sampling rate.

[4] DE0-Nano Development and Education Board. 2015. DE0-Nano Development and Education Board. [ONLINE] Available at: http://www.altera.com/education/univ/materials/boards/de0-nano/unv-de0-nano-board.html. [Accessed 30 January 2015].
[5] Wireshark · Go Deep.. 2015. Wireshark · Go Deep.. [ONLINE] Available at: https://www.wireshark.org/. [Accessed 30 January 2015].

Device Development

Coded Orthogonal Frequency Division Multiplexing

Coded Orthogonal Frequency Division Multiplexing (COFDM) is a method of encoding digital data on multiple carrier frequencies this data is protected by using a forward error correction scheme[6]. The first step to develop COFDM is the development of Forward Error Correction (FEC) schemes to determine their suitability for rugged and hostile environments. In addition to pure loopback modes, over the air testing was also completed.

Forward Error Correction

A file-to-file FEC system was created in GNU Radio and tested to evaluate *repetition FEC*, where a message is repeated several times, and *correction coded FEC*, where a message has added error correction codes. In both of these cases, the FEC is made more robust by the inclusion of a cyclic redundancy check system. By using two simultaneous layers of FEC, the majority of errors was detected and corrected resulting in a low error transmission.

The FEC code scheme is shown in Figure 2 and consists of both block and convolutional coding schemes.

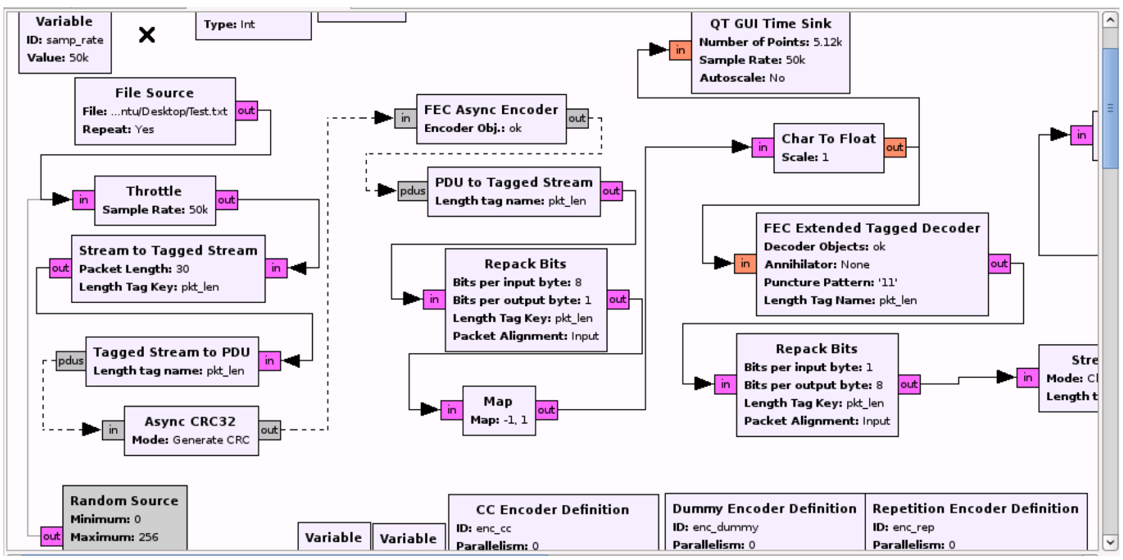


Figure 2- GNU Radio Companion - Loopback Forward Error Correction

THIS CRG SCRIPT IS AN EXAMPLE OF FORWARD ERROR CORRECTION WORKING WITHIN AN INTERNAL LOOPBACK. THIS SCRIPT TAKES TEXT INPUT FROM A FILE AS A STREAM BEFORE PACKETISING THE STRING, ENCODING, DECODING AND APPENDING TO A TEXT FILE AS A STRING.

[6] Orthogonal frequency-division multiplexing - Wikipedia, the free encyclopedia. 2015. Orthogonal frequency-division multiplexing - Wikipedia, the free encyclopedia. [ONLINE] Available at: http://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing. [Accessed 30 January 2015].

Orthogonal Frequency Division Multiplexing

To further the development of COFDM, an OFDM transmitter and receiver blocks were developed and tested to test its efficacy when using different base modulation schemes (Figure 3). This allowed for a simple testing mechanism to test the BPSK and QPSK modulation schemes for header modulation and 8-PSK and QPSK for payload modulation. Results showed that QPSK was superior compared to BPSK for header modulation (Figure 4). Payload modulation was preferably done with 8-PSK.

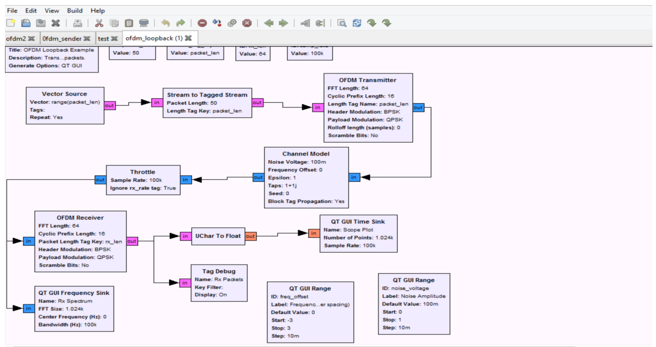


Figure 3: GNU Radio Companion - OFDM Transceiver

THIS CRG SCRIPT WAS USED TO TEST DIFFERENT OFDM MODULATION SCHEMES AND THEIR COMPATIBILITY WITH THE HARDWARE AND ENVIRONMENT.

Orthogonal Frequency Division Multiplexing with Forward Error Correction

Finally, the FEC work and the OFDM system where combined to produce a COFDM system (Figure 4). Testing was for header modulation completed in a loopback mode with a channel model included that added distortion and noise to the system to cause defects in the signal similar to that experienced when actually transmitting. This COFDM system was evaluated to determine the errors that would occur (Figure 5).

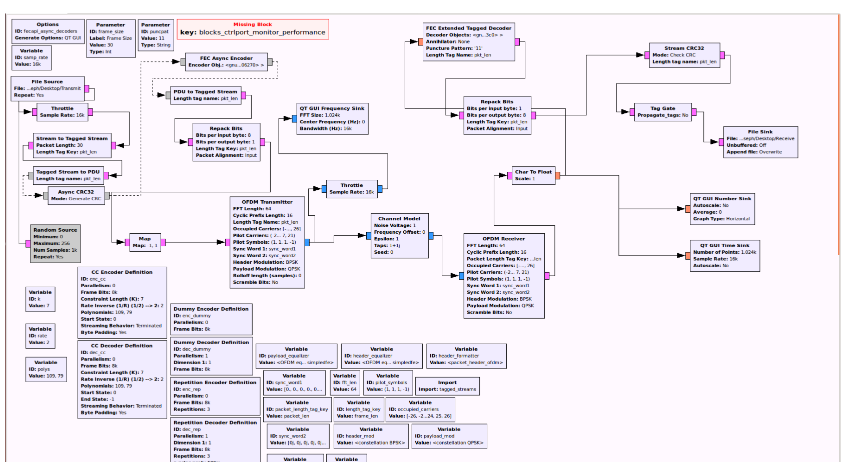


Figure 4- GNU Radio Companion - OFDM With Forward Error Correction.

THIS CRG SCRIPT IS IMPLEMENTED ON FROM THE STANDARD OFDM STRUCTURE, ADDING FORWARD ERROR CORRECTION TO THE TRANSMISSION PROCESSES.

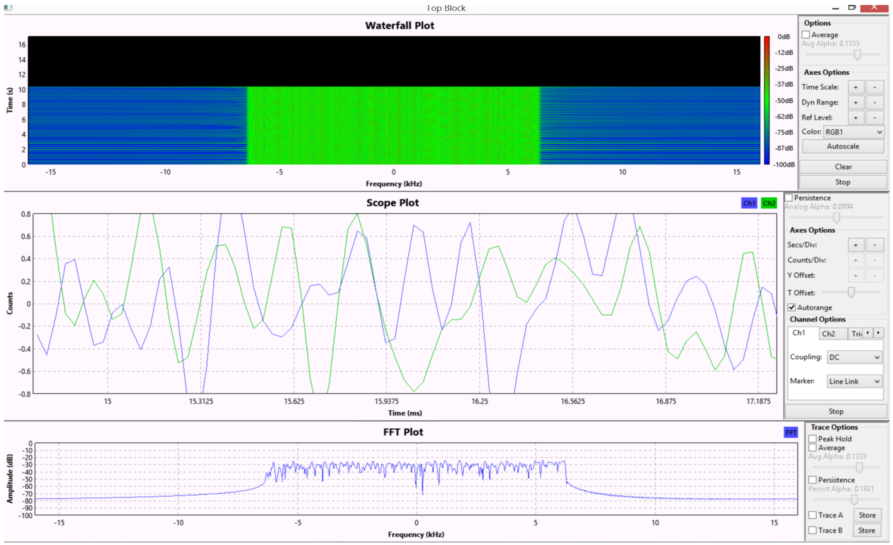


Figure 5- GNU Radio Companion - OFDM Transceiver Loopback Plots

THIS IS A WX GUI BASED DISPLAY OF THE COFDM SYSTEM RUNNING IN A LOOPBACK WITH A WATERFALL, SCOPE AND FFT PLOT PROVIDING A GRAPHICAL REPRESENTATION OF THE TRANSMISSION BEING PASSED.

The test page file code is included below. This is a simple pattern of common keyboard characters as it is easily verifiable if an error has occurred in transmission.

```
*********************************************************
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
 a b c d e f g h i j k l m n o p q r s t u v w x y z
1 2 3 4 5 6 7 8 9 0
!@#$%^&*(){}:”<>,.>?
1 2 3 4 5 6 7 8 9 0
 a b c d e f g h i j k l m n o p q r s t u v w x y z
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
*********************************************************
```

During loopback transmission testing, the file was sent as a repeating data sequence and the resulting file was checked to see if errors had occurred during transmission. Errors where only found at high transmission rates beyond the data requirements of the health monitoring project, and where the result of bottlenecks in the python software test scripts. Python is an interpreted language where each line of code is compiled individually at run time making it slower than conventional compiled languages. Rewriting the code in C/C++ would resolve this problem and allow for higher data transmission speeds for use in other scenarios such as video transmission.

The system was then tested with a single BladeRF without antennas and the signal was found to present minimal errors in a low gain environment. Without antennas, the system is functioning with minimal ability to transmit and this is an analogue of what would be experienced when the system is subject to a rock fall. Next step is to incorporate the COFDM coding into a mesh topology, network system with addressable communication.

Development of IEEE 802.15.4 (Zigbee)

IEEE 802.15.4 is a communication standard for Low Rate Wireless Personal Area Networks (LRWPAN)[7] and is maintained by the IEEE 802.15 working group. 802.15.4 has been used as the basis for a number of public and proprietary communication standards, including Zigbee, ISA100.11a, MiWi and 6LoWPAN. The design for 802.15.4 was based on work from University of Paderborn, Germany[8] modified to operate with the BladeRF to create a communication environment with a top level design resembling Zigbee with error encoding via Asynchronous 32 bit cyclic redundancy checks (Figure 6). This development resulted in the creation of a custom SDR based, 'Zigbee-like' wireless communication system with improve transmission success rates.

Successful bench top testing showed that SDR technology is capable of handling LRWPAN at reasonable loss rate. Improving these rates will be discussed in the future work section.

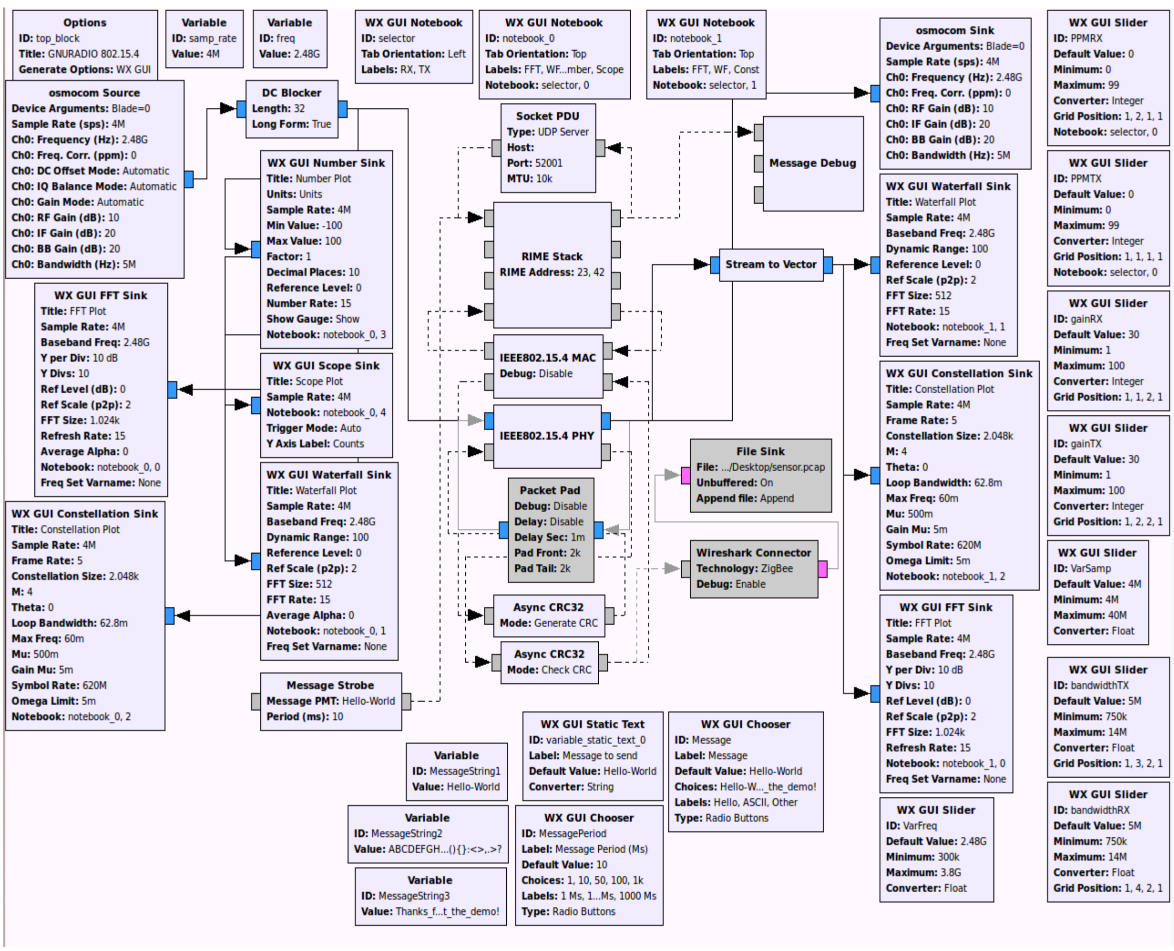


Figure 6 - GNU Radio Companion - 802.15.4 script

GNU Radio companion block view of our modified 802.15.4 transceiver script

[7] IEEE Standard Association - IEEE Get Program. 2015. IEEE Standard Association - IEEE Get Program. [ONLINE] Available at: http://standards.ieee.org/getieee802/download/802.15.4-2011.pdf. [Accessed 30 January 2015].
[8] bastibl/gr-ieee802-15-4 · GitHub. 2015. bastibl/gr-ieee802-15-4 · GitHub. [ONLINE] Available at: https://github.com/bastibl/gr-ieee802-15-4. [Accessed 30 January 2015].

Development of Mesh

Primary work on the development of a mesh networking has focused on the creation of small ad-hoc network using the Quagga routing suite[9] with the BabelD[10] routing Daemon. BabelD is a network routing protocol that uses loop avoidance and link cost estimation to allow for the creation of ad-hoc wireless networks. BabelD was designed to improve upon Destination-Sequenced Distance-Vector Routing, Ad hoc On-Demand Distance Vector (AODV) Routing and Enhanced Interior Gateway Routing Protocol (EIGRP).

The BabelD software proved sufficient for the task of creating a basic mesh network and future development of mesh networking will improve on this functionality. BabelD uses its routing capability to allow for the best routes to be calculated. This allows for the network to self heal as a damaged section will cause the babel routing link state system to assign higher metrics or cost to damaged sections and as such the network should only be sending by the best possible route.

PROOF OF CONCEPT TESTING

Objectives

The core objective of this project is to determine the possibility of transmission for a device that has been involved in a tunnel collapse within a mine. A test environment was developed to determine if the concept SDR is capable of working under these specific conditions.

Components

To give an approximated simulation of a tunnel collapse where rock has surrounded one or more communication devices, tests comprised of two (2) "buried" devices and one (1) "surface" device.

The "buried" device comprises of a BladeRF and two log periodic antennas attached to a laptop for monitoring. The BladeRF is in a waterproof, sealed container with three (3) cable glands, Two (2) for the receiving and transmitting antennas and another for the USB cable. To prevent the Antennas from being crushed, a small plastic basket with perforated top and sides to allow for signal propagation in and out of the encasing was placed on top of the BladeRF and antennas to create a protective cover. This was then placed inside of a half wine barrel filled with river stones were then used to fill the Half Wine Barrel, fully submerging the plastic protective basket. A single USB line runs out from the bottom of the barrel and is connected to a laptop for powering and processing the BladeRF's transmissions. The use of loose stones is to provide a simulated rock collapse that provides space for signal propagation.

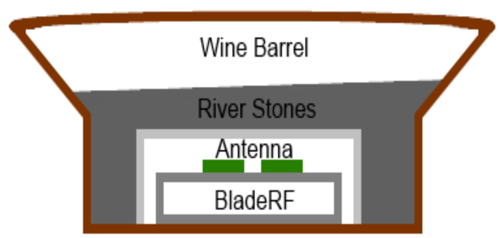


Figure 7- Diagram of buried devices

THIS FIGURE DEPICTS THE INSIDE OF THE BURIED DEVICES. THE OUTER LAYER IS A WOODEN BARREL, FOLLOWED BY A LINING OF RIVER STONES OF VARIOUS SIZES, A PLASTIC BASKET TO PROTECT THE ANTENNA, THE BLADERF AND ITS PLASTIC CONTAINER.

[9] Quagga Software Routing Suite. 2015. Quagga Software Routing Suite. [ONLINE] Available at: http://www.nongnu.org/quagga/. [Accessed 30 January 2015].

[10] jech/babeld · GitHub. 2015. jech/babeld · GitHub. [ONLINE] Available at: https://github.com/jech/babeld. [Accessed 30 January 2015].

The BladeRF were enclosed and Figure 8 shows the process undertaken to create the test environment for the proof of concept SDR device.

Figure 8: Construction of Test Environment

Testing Procedure

For the purposes of this proof of concept, the 802.15.4 protocol previously described was used. The coded 802.14.5 protocol is a low power, reduced bandwidth protocol that meets the miner health monitoring system requirement. During initial bench testing, the coded 802.14.5 protocol received consistently good results. In addition, CRC32 FEC was added to provide error correction as broadcasting was used to examine the conditions of one device transmitting and one device receiving.

The 'worst case' condition of buried-to-buried was tested to determine the effects on transmission from two devices with physical obstructions, and with a minimum of 20m of open air between the two 'buried' devices.

To provide message diversity, the following three separate messages were created of varying lengths:

1. "Hello-World"
2. "ABCDEFGHIJKLMNOPQRSTUVWXYZ1234567890!@#$%^&*(){}:<>,.>?"
3. "Thanks-for-looking-at-the-demo!"

Two different frequencies were tested: 915Mhz and 2.48Ghz to inspect the individual performance of the different frequencies. All messages were sent at 10ms second intervals

The "Message Debug" GNU Radio Companion Block was used to approximate the rate of successful transfer, ignoring any lost, incorrect or error containing packets that might be found during CRC32 FEC checking.

Testing Results

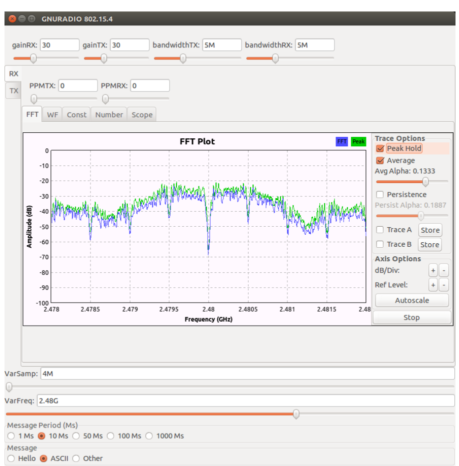
Transmitting	Receiving
	

Figure 9: 2.48 Ghz Transmission Testing

TESTING WITH ALL MESSAGE STRINGS, THE MESSAGES BEING RECEIVED FROM THE BURIED DEVICE TO THE BURIED DEVICE WERE QUITE CONSISTENT WITH ALL THREE MESSAGES.

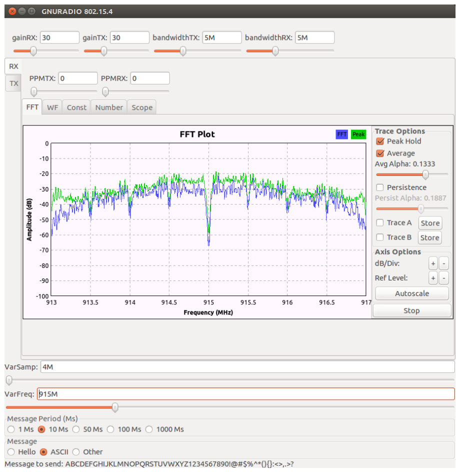
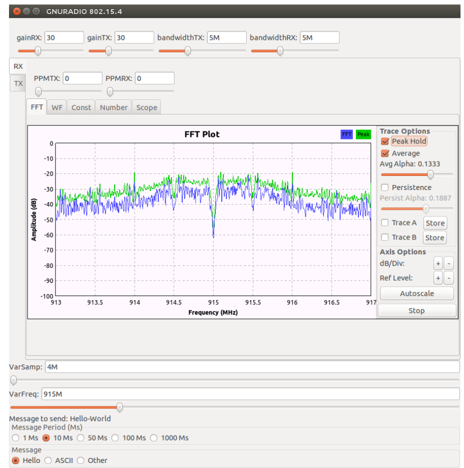
Transmitting	Receiving
	

Figure 10: 915 Mhz Transmission Testing

TESTING WITH ALL MESSAGE STRINGS, THE MESSAGES BEING RECEIVED FROM THE BURIED DEVICE TO THE BURIED DEVICE WERE QUITE CONSISTENT WITH ALL THREE MESSAGES.

The results demonstrated successful transmission of all three messages at 915 MHz and 2.48 GHz. Both frequencies had high stability, high transmission speed, and low errors. The FFT plots of the receiving device showed consistent difference of the signal to the noise surrounding it, creating a clear definition that the signal was being clearly recognized (Figures 9,10).

DISCUSSION

Due to the lower bandwidth and speed requirements of an 802.15.4-based system, the prototype system was successfully implemented with CODFM and mesh capabilities in the SDR. This result was a significant first step in the development of a high-resilience, heterogeneous wireless mesh networking device/access point suitable for an underground coalmine. Results from this proof-of-concept project highlighted the required future development efforts and considerably de-risked the developmental pathway.

Future work focused on ensuring compliance with various different implementations of 802.15.4 protocol (i.e. Digimesh, Xbee) to allow the end user to have flexibility in what other devices will be compatible with our 802.15.4 protocol stack (heterogeneity) is required. Given the excellent performance of the existing 802.15.4 implementation, the remaining work in this area is considered minor.

In a related project, CSPL has asked University of Canberra to investigate the possibility of using this miner heath proof-of-concept communication system in a related UAV project. As originally designed, the miner heath communication system (low data bandwidth) would not be compatible with UAV project due to the increased data bandwidth requirements of the UAV video. Therefore, during development of the 802.15.4-based system for this project, UC investigated the possibility of also implementing the high bandwidth IEEE 802.11 'Wi-Fi' protocol in addition to the low bandwidth 802.15.4 'Zigbee' protocol.

IEEE 802.11 is a set of specifications for the creation of Media access control (MAC) and Physical layers for the implementation of wireless local area networks (WLAN). It is most commonly used in the Wi-Fi branded series of compatible devices. Similar to the 802.15.4 'Zigbee' work, early testing and proof of concept work with SDR Wi-Fi was based on University of Paderborn in Germany[11] research. The goal was to determine the hurdles that would need to be overcome for the full realisation of 802.11 compatible components of a heterogeneous wireless networking system.

After modifying the software of the BladeRF to include Wi-Fi capability, initial testing involved the detecting of packets from a Wi-Fi network via the BladeRF. This testing was successful with a significant amount of Wi-Fi packets being successfully sniffed and decoded. Next stage was to test the transmission of data via a Wi-Fi network. Preliminary results showed that a reliable connection to a Wi-FI network using software only GNU Radio was not possible. To overcome these issues it would be necessary to implement the Wi-Fi functionality in the FPGA to generate a Wi-Fi networking controller. As such, a future avenue of work on the UAV project will focus on this implementation. Benefits of this FPGA implementation would include the ability of creating application specific circuits with hardware generated error correction that would allow the Wi-Fi system to function within high noise or multi path environment with minimal loss of throughput.

In addition to 802.15.4 'Zigbee' protocol implementation, the prototype COFDM implementation was also successful, and further development of COFDM will focus on the integration of the correction coding schemes into a 802.11 Wi-Fi based implementation. This will allow for a high level of networking and for the possibility of using existing Wi-Fi hardware devices in the network. Additional focus of future work will the improvement of the correction coding scheme to allow for faster response and greater accuracy including the ability to detect a greater number of bit errors per message then is currently possible. The coding scheme needs to investigate means of splitting and interleaving the signal allowing for the duplication of the signal over multiple bandwidth domains thus minimizing multi channel defects when transmitting in an underground environment. Future error correction schemes will likely use a multi layer FEC scheme to allow for greater resiliency in the transmission path.

A potential downside of using multiple codes will be a decreased average bit rate in the communication path. Future work must find a way to reach a desired level of trade off in the number of missed bits versus the decreased rate of transmission. A primary concern when transmitting in an underground environment however will not be the rate of the exchange of data but rather the reliability of the exchange. The reliability of the system must take precedence.

A significant component of the future work will be the Intrinsically Safe hardware design that will include an FPGA, microcontrollers, accelerometers, and power circuits. A small, lightweight size achievable for this device will be a desirable outcome of the design stage.

A mandatory feature of the final device will be the ability to operate on battery power. This creates a significant engineering challenge. For the device to achieve maximum flexibility and utility (UAV and miner health), it must include FPGA devices and relatively high power transceiver devices. These devices must be able to send significant amounts of data with minimal delay times, meaning they must be online for the maximum time possible.

[11] bastibl/gr-ieee802-11 · GitHub. 2015. bastibl/gr-ieee802-11 · GitHub. [ONLINE] Available at: https://github.com/bastibl/gr-ieee802-11. [Accessed 30 January 2015].

One option to be investigated is to include a secondary low power transceiver to allow for a signal to wake the device up and begin sending and receiving data and power down when not needed. Thus the higher battery drain components could spend significant time powered down and only be woken when needed. The problem with this approach would be achieving the necessary minimum delay between a signal to wake up being sent and the device being fully functional. The challenges of having a device that is capable of being a heterogeneous wireless mesh networking controller (Wi-Fi, Bluetooth, Zigbee), and having that same device run for months on its own internal power supply will high priority in follow-on projects.

To allow for mesh networking across a heterogeneous network it would be necessary to improve on the implemented BabelD routing protocols to create a "cognitive" network that has the ability to route around damaged sections. Babeld will already route around damaged sections but has no ability to detect problems in the hardware level or in the signal itself. An area of improvement would be to allow for the routing algorithm to include signal strength and noise level as metrics in the routing algorithm. In addition, the lost/dropped bits and average hamming[12] distance could be used as metrics for the link state. These additional metrics would ensure that the best possible route is determined when sending data.

An additional feature of the routing algorithm would be the ability to select different radio frequency (900Mhz or 2.4Ghz) and to allow for a link state based metric or hybrid approach to allow for the device to choose from different protocols (WiFi or Zigbee) as the best option to send a piece of data.

CONCLUSION

This proof-of-concept stage of the project achieved the required aims of de-risking the technology development of a smart, battery powered, and heterogeneous mesh network. To complete the larger project a significant amount of work still remains to be done but this project has identified the areas of effort needed. The work undertaken in the area of 802.15.4 'Zigbee' transmitting through rubble was successful and the issues related to Wi-Fi development, COFDM, and mesh capabilities were identified.

With the knowledge and expertise gained in undertaking this part of the project, the successful development of a high-resilience, heterogeneous wireless mesh networking device suitable for an underground coal mine has been substantially de-risked.

[12] Minimum number of errors that could have transformed one string into the other.