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Deliverable	Final Report
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UNIVERSITY OF CANBERRA

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Executive Summary

Coal Services Pty Ltd (CSPL) Health and Safety Trust, under Project No. 20632 - UAV Communications, tasked the University of Canberra (UC) to validate that no currently commercially available technology meets the size, weight, performance, and cost required for a capable communications platform to operate a compact UAV underground. In addition, if no commercially available device is available, to develop a Software Designed Radio (SDR)[1] system as a proof-of-concept communications platform for operating an Unmanned Aerial Vehicle (UAV) in the coalmine environment.

The UAV communications system will be based on an advanced, battery-based, ad-hoc, wireless communication system. The proposed architecture will be an on-the-fly deployable network design that does not rely on any pre existing infrastructure. The UAV (developed by Areal Photography Specialists in Adelaide) will carry additional nodes and when network signal strength degrades – the UAV will deploy a communication node to extend the network. If necessary, the UAV will return to base to pickup additional nodes to further extend the network. This feature necessitates that the communication nodes are lightweight and small, such that the UAV can carry multiple nodes.

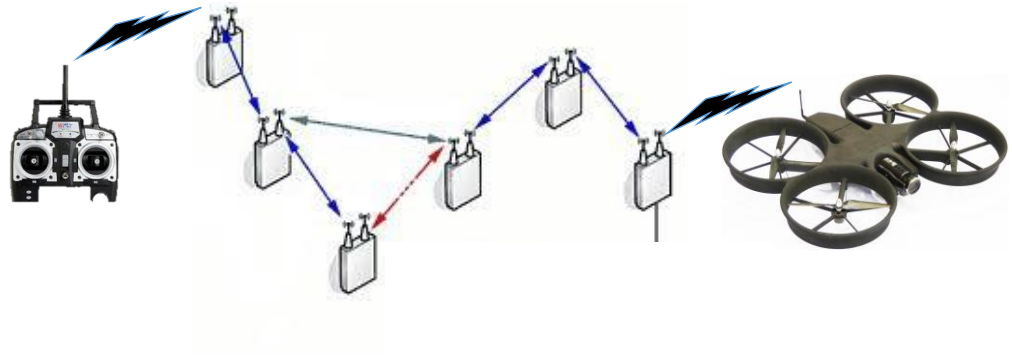
Benefits of our Solution:

- Ease and speed of deployment
- On-the-fly configuration (self-configuring)
- No dependence on infrastructure
- High bandwidth (video transmission capability)
- No interference with other equipment in mines
- Greater range and robustness than traditional below ground communications
- Capable of interworking with the existing heterogeneous network

[1] Software-defined radio (SDR) is a radio communication system where are implemented in an FPGA (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are implemented in hardware though a hardware description language (http://en.wikipedia.org/wiki/Software-defined_radio)

1. Introduction

The UAV communications system will be based on an advanced, battery-based, ad-hoc, wireless communication system. The proposed architecture will be an on-the-fly deployable network design that does not rely on any pre existing infrastructure.



The UAV will carry additional nodes and when network signal strength degrades – the UAV will deploy a communication node to extend the network. If necessary, the UAV will return to base to pickup additional nodes to further extend the network. This feature necessitates that the communication nodes are lightweight and small, such that the UAV can carry multiple nodes.

As illustrated above, each node participates in routing by forwarding data from other nodes. The operation of the proposed system will allow transmission of video data. In addition, we will use COFDM (Coded Orthogonal Frequency Divisional Multiplexed) wireless technology to allow communication signals to travel underground and through small (<5m) obstructions. The main reason for our decision to use COFDM is its ability to overcome multipath effects. When a signal is transmitted, it is met with obstructions such as tunnel corners, equipment, cave-ins, and even people, which scatter the signal causing it to take two or more paths to reach its final destination. The late arrival of the scattered portions of the signal can cause ghost images of the video. COFDM is resistant to multipath effects because it uses multiple carriers to transmit the same signal. Instead of the signal scattering when met with an obstacle, it flows around the obstacle like a river flows around a rock.

In addition to routing, ad hoc networks use flooding for forwarding data, which makes the network high resilient. The proposed wireless networking platform will be heterogeneous and be able to self-configure and interwork with existing wireless networks. With appropriate mesh routing protocols, a highly robust networking solution for underground mines, tunnels, and other confined space environments will be achieved. The communication system will be a secure, robust, resilient, wireless link, capable of transporting data, video, audio, sensor and tracking information from below ground to the surface. A communication network will be formed using COFDM IP nodes, which could run the length of the main mine shaft and also strategically placed at the entrance to the lateral tunnels, and will providing connectivity for the UAV from the mine head to above or below ground remote monitoring stations.

Benefits of the Solution:

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Intrinsic safety (IS) is a protection technique for safe operation of electrical equipment in hazardous areas by limiting the energy available for ignition. In communication circuits that can operate with low currents and voltages, the IS approach simplifies circuits and reduces installation cost over other protection methods.

2. Technology Review

Regarding the requirement for a readily deployable communication system for use in the underground space, there are only two technologies at present that are able to be used for the wireless transmission of data in the communications space, both based on standard wireless protocols, which are:

Open 900 MHz band and, 2.4 802.11 Wi Fi system.

There are currently a number of approved systems (for use in coal mines and other explosive risk atmospheres) commercially available in Australia. All other systems for communications utilise either leaky feeder or copper / fibre connections, which are not wireless or readily transportable.

While all wireless systems suffer from loss of signal over distance, they also suffer from loss of bandwidth (size of the data transfer "pipe) over distance. This reduces the ability to send large packets of data between one node and the next, as the distances between the nodes increases.

2.4 GHz 802.11 Wi Fi

- Tried and tested system with multiple deployments and pieces of equipment that may be interfaced. (phones, cameras, tablets etc)
- Works well in line of site, does not like to "go around corners" and is seriously impacted by obstructions and infrastructure. (belt structure, seals and restrictions in the roadway)
- Relatively power hungry, requires typically 40+ VA, so ability to use small battery pack is not possible.
- Bandwidth drops off relatively quickly (depends on mine parameters and obstructions), reducing the ability to use say live camera and data streaming, though ability to use voice comms is possible over longer ranges.
- Approved systems for use underground, but not battery powered.
- Able to use for tracking, but accuracy low (typically 100m).

900 MHz band.

- This is an open band (in Australia, + 918 MHz), which has allowed for a number of devices being developed for use in this range, though the number of cameras etc. is not that extensive at the 2.4 GHz band.

- Good for line of site and far more able to go around corners and less impacted by infrastructure than the 2.4 GHz band. In a straight line, has approximately 1/2 the range of 2.4 GHz.
- For relatively simple data transmission (Text and small data packages) the system is able to be battery powered (typically AA, or D cells). Overall not large bandwidth system.
- Bandwidth does not drop off as quickly, allowing for easier deployment in the underground space.
- Approved battery powered systems for use underground.
- Able to be used for tracking, but accuracy typically to 10m.

Using the MSRA approved electronics list, Internet search, and industry contacts; the following table of commercially available communications platforms that potentially could be used to operate a compact UAV underground was developed. Please note, that only Commercial-Off-the Shelf (COTS) battery-operated systems are presented. Powered systems were excluded.

Company	**Name**	**Battery**	**Mesh**	**Size**	**Weight**	**Freq**	**IS**
Strata Worldwide	CommTrac	12 months	Yes	300 mm 150 mm 60 mm	1.9kg	900Mhz	Yes
Rajant	Breadcrumb ME4	3 Hours	Yes	189 mm 95 mm 51 mm	1.2kg	900MHz 2.4GHz, 5 GHz	No
Northern Light Technologies	Netport-able is node	24 hours	Yes	295 mm 339 mm 152 mm	6kg	2.4GHz, 5 GHz	Yes
NewTrax	NTX-WN-300	12 months	Yes	120 mm 120 mm 90 mm	2.5kg	900MHz	No
American Mine Research	MN-6400 Nodes	240 hours	Yes	356 mm 356 mm 178 mm	30.8kg	2.4 GHz	Yes
IWT	Sentinal	~200 hours	Yes	~350 mm 350 mm 180 mm	~30kg	2.4 GHz	Yes
Active Control Technology	AM2000 FaceNode	30 hours	Yes	250mm 250mm 290mm	~12Kg	2.4GHz	Yes

Two technologies were technically very promising; Rajant Breadcrumb ME4 and the NewTrax NTX-WN-300. However, they are not IS compliant and engagement with the companies highlighted that IS was not on their roadmap for the next 12 months. Northern Light Technologies, American Mine

Research, Active Control Technology, and IWT are all good products and certified IS, but are too big and heavy for UAV control.

The only system approved for use in the Australian underground space is the CommTrac system from Strata, which has over 230 systems deployed in mines worldwide. (Each system typically has +50 nodes and +400 tracking and communication devices).

The Strata CommTrac is a truly wireless, battery powered mesh communications and tracking system for underground mining. It is compliant to provide two-way communications and location tracking in day-to-day as well as post-accident situations. Strata CommTrac is intrinsically safe and MSHA approved. However, CommTrac is designed for fixed location data transmission and currently does not have the bandwidth available for video transmission.

Based on this market research, UC established a professional relationship with Strata and a Confidential Disclosure Agreement (CDA) was executed by the parties. A face-face- meeting in Brisbane occurred and in summary:

- Strata is interested in working with UC on this project – especially in the area of IS
- The size, weight and throughout of the CommTrac are all a function of the battery life requirement. Smaller systems are technically possibly.
- UC will leverage the Software Designed Radio (SDR) system currently under development at UC for the Mine Rescuer health monitoring system project and working with Strata will upgrade the SDR to be a self-configuring, deployable communications platform to allow UAV communications from above ground directly to mining face. The SDR radio will be able to control the UAV, stream thermal and normal video, and transmit gas sensor data from the UAV back to the surface. The nodes will be small enough to be carried and deployed by the UAV and will provide at least 3 hours of battery life.

3. Prototype UAV Communications System

Mesh node design

We have developed a fully functional mesh router to support the operations of a UAV within the mine. This mesh router uses 10 Intel Edison SoM as it is the main processor module used in the heterogeneous device design.

Figure 1 - Intel Edison and LiPo battery

The Intel Edison has been modified to run on a customised version of the poky Linux environment unique to our system. Recent developments such as the custom operating system has allowed for link aggregation and multiple transceivers, Increasing Bandwidth and reliability of the network, whilst allowing for a more stable connection. These recent improvements have solved the UAV video issues experienced in the test site.

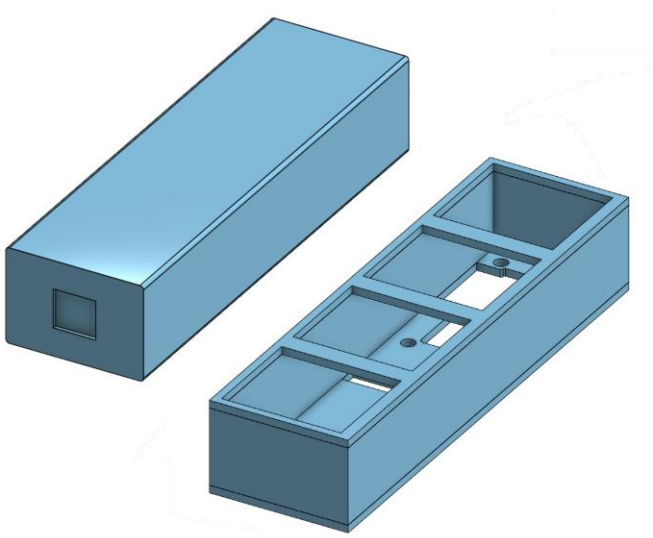

Figure 2 - Custom cases have been designed to minimise weight and space of our devices

Routing Algorithm Design

A self-configuring energy efficient routing algorithm for the mesh communication system has been developed for each node. The mesh network was setup initially with the batman-adv mesh routing protocol, however but with time constraints and several problems that were encountered with testing the mesh. The alternative chosen was the batman routing demon. This provides many of the same features as batman-adv but operates at layer 3 of the TCP IP stack. This protocol worked fully with all the existing network test tools and allowed the mesh to be built on top of an existing IBSS ad-hoc network connection.

```
root@edison:~# ./batmand/batmand wlan0
Interface activated: wlan0
Using interface wlan0 with address 137.92.223.76 and broadcast address 137.92.223.255
root@edison:~#
```

Figure 3 - Batman routing demon protocol.

Batmand has provided for the fast routing and self-healing features needed for future work with the mesh. Each of the Edison devices were configured to create a full mesh, with a standard laptop providing the initial DHCP settings for the network.

```
cspl@cspl-Latitude-3540-2: ~

root@edison:~# wpa_cli -iwlan0 disconnect && wpa_cli -iwlan0 remove_network all
&& wpa_cli -iwlan0 add_network && wpa_cli -iwlan0 set_network 0 frequency 2412 &
& wpa_cli -iwlan0 set_network 0 mode 1 && wpa_cli -iwlan0 set_network 0 ssid '"C
SPLMESH"' && wpa_cli -iwlan0 set_network 0 auth_alg OPEN && wpa_cli -iwlan0 set_
network 0 key_mgmt NONE && wpa_cli -iwlan0 set_network 0 scan_ssid 1 && wpa_cli
-iwlan0 select_network 0 && wpa_cli -iwlan0 enable_network 0 && wpa_cli -iwlan0
status && udhcpd wlan0
```

Figure 4 - Example launch script for mesh nodes.

UAV configuration

Once the mesh had been setup and initial testing was completed a UAV was configured for use on the Mesh. This involved configuring an Edison to relay drone commands over the mesh. Once the Edison was configured it was installed into a UAV and connected to the drone's flight control board. The autopilot was then configured to accept the Edison as an off board control interface. With this completed the Edison redirects controls sent as UDP packets via the mesh directly to the flight control board.

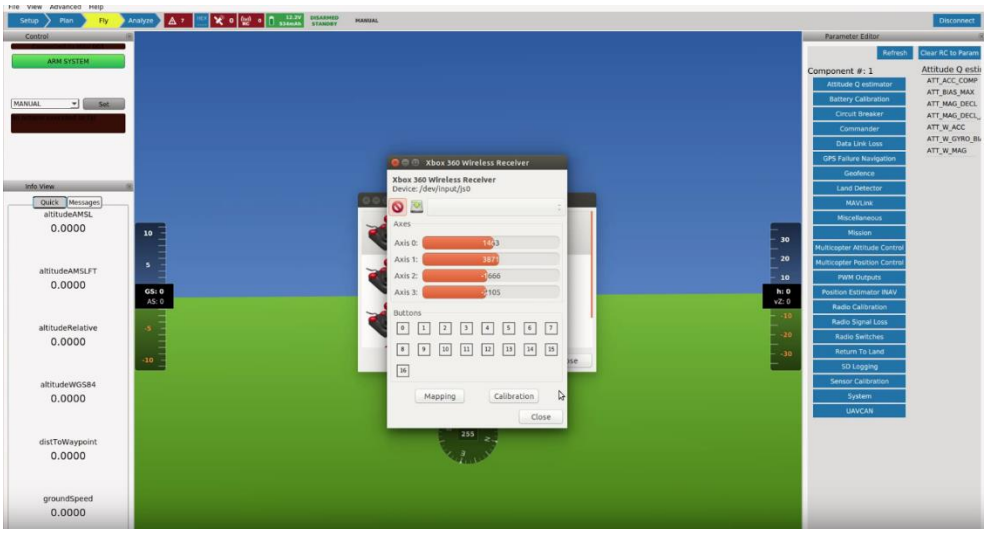

Figure 5 - UDP controls visualised in Qground control

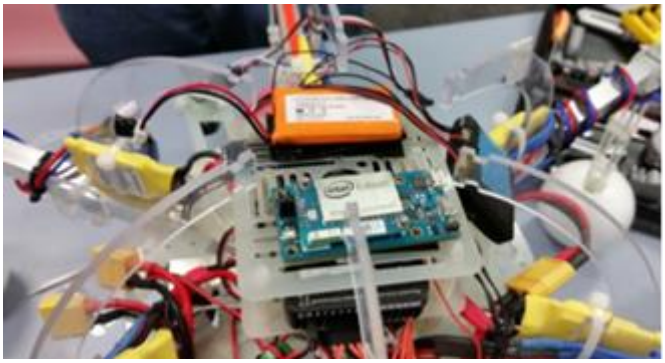

Figure 6 - Our Test mesh and UAV, running on an Intel Edison

Once the ground control station is connected to the mesh, control devices such as joysticks to be used to control the drone. In addition the drone can be set into full autopilot mode and made to navigate to waypoints or by GPS.

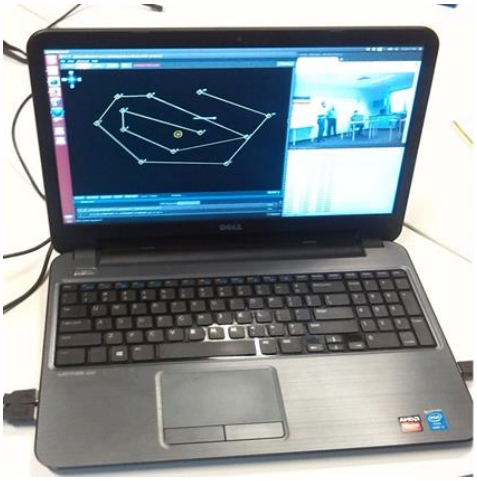

Figure 7 - Ubuntu laptop with Qground control's auto flight planer and live webcam and sensor feed

The flight controller is connected to the Edison using a serial connection to telemetry 2 port. The settings for port and destination on the Edison are set at this point. With this done via the PX4, it will automatically offload some of its lower priority tasks onto the Edison. The Edison is also able to function as a redundant flight processor for the PX4.

Figure 8 - 3DR PixHawk flight control board

4. Prototyping Testing and Demonstration

In-House

Mesh testing

To test the mesh, each node was powered from a single 3.7 volt 2000 mAH lithium polymer ion cell. This allowed the node to run for several hours of a single charge.

The nodes where arranged in line of sight or near line of sight to the adjacent nodes in the mesh, normally at a corner or similar junction point, throughout a four (4) story university building to deliberately create the need to multiple hops.

This system allowed us to ensure each node could connect to the one before and after it in the planned path. This also meant that nodes would have difficulty if a single node was removed from the network during the test. Additional routes where sometimes created during testing to see if signals would find the most optimized path.

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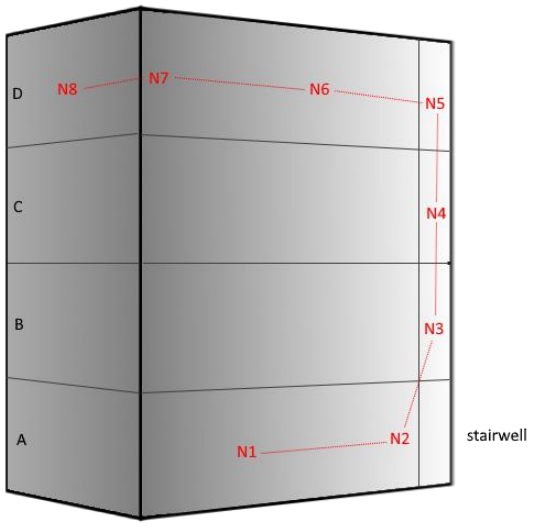

Figure 9 - Diagram of the testing building used at UC

Once this was done the ping utility, tracepath and mtr were was used to measure the delay hops and latencies between them. A total of 8 hops was created and tested. During the test individual nodes where disconnected and the mesh was forced to rebuild without that node.

```
root@csip-Latitude-3540: /home/csip/batmand
root@edison:~/batmand# arp
root@edison:~/batmand# arp
Address                  HWtype  HWaddress           Flags Mask            Iface
10.42.1.21               ether   78:4b:87:a5:88:9a   C                     wlan0
10.42.1.1                ether   34:23:87:20:ed:11   C                     wlan0
root@edison:~/batmand# ping 10.42.1.31
PING 10.42.1.31 (10.42.1.31): 56 data bytes
64 bytes from 10.42.1.31: seq=0 ttl=62 time=40.889 ms
64 bytes from 10.42.1.31: seq=1 ttl=62 time=49.069 ms
64 bytes from 10.42.1.31: seq=2 ttl=62 time=27.523 ms
64 bytes from 10.42.1.31: seq=3 ttl=62 time=36.085 ms
64 bytes from 10.42.1.31: seq=5 ttl=62 time=37.417 ms
64 bytes from 10.42.1.31: seq=6 ttl=62 time=31.999 ms
64 bytes from 10.42.1.31: seq=7 ttl=62 time=36.931 ms
^C
--- 10.42.1.31 ping statistics ---
8 packets transmitted, 7 packets received, 12% packet loss
round-trip min/avg/max = 27.523/37.130/49.069 ms
root@edison:~/batmand# traceroute 10.42.1.31
traceroute to 10.42.1.31 (10.42.1.31), 30 hops max, 38 byte packets
 1  10.42.1.21 (10.42.1.21)  2.467 ms  2.690 ms  2.691 ms
 2  10.42.1.38 (10.42.1.38)  5.593 ms  8.590 ms  5.048 ms
 3  10.42.1.31 (10.42.1.31)  38.391 ms  27.917 ms  12.631 ms
root@edison:~/batmand#
```

Figure 10 - Batmand routing depicted via arp, ping and tracepath

Initial test results show that the mesh is able heal itself when a node or multiple nodes are removed in most cases. Nodes can be moved within an active mesh provided they remain in range of stationary nodes that are a currently connected. Mobile nodes sometimes require higher originator intervals in the mesh setup software to allow for higher mobility. The ideal candidate for this is the UAV deployed on the mesh. During testing it was found the mesh averaged 37.13 milliseconds roundtrip time for a four hop section.

The mesh also averaged 53.794 milliseconds over 8 hops round trip time. This is length of time is insignificant in drone control especially considering drone control messages are single direction only. The mesh test results show that at this stage of development the mesh is capable of self-healing and

of reasonably high speed communications. The mesh is capable of finding new paths and will often skip nodes that are redundant or unnecessary to communications due to two being in range of each other.

Drone control testing

Initial drone testing was done with the drone being in the same room as the QGC computer. This was done to check that the drone was capable of receiving commands over a single hop connection. Once the drone was shown as being able to receive commands over the mesh via a single hop, the controller for the drone was calibrated and configured to allow for simple flight. The drone was walked around and held during a large part of the test to evaluate mobility on the mesh due to safety.

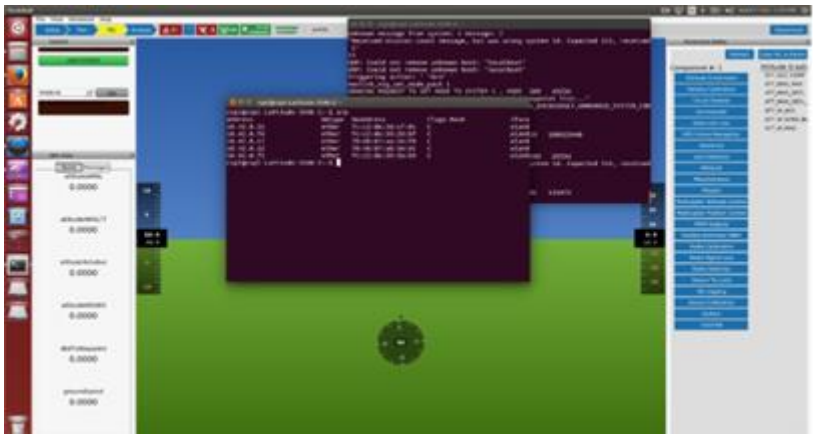

Figure 11 – Qground control interface and an apr table containing node addresses

During this testing it was shown that the drone can be fully controlled over the mesh. Even over multiple hops the drone is able to receive command and telemetry with little latency gain.

Voice over IP (VoIP)

After hearing feedback from Steve Tonegato and Robert Bull during our second site test, it was decided that a VOIP system operating over our Network would be of great benefit. This has been tested over multi hop and direct scenarios with both Voice and video data and has been proven possible using freely available software, in our case we used RING. There has been some stability issues with this however as there is no SIP server and the call is on an IP2IP basis, this means if the network changes or IP address change the call is dropped.

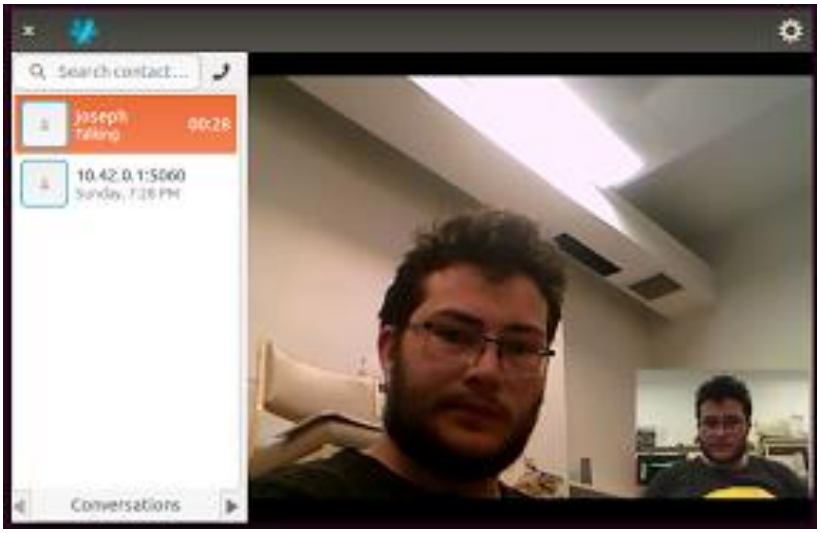

Figure 12 - VOIP Call over single hop mesh network.

SRMS Woonona

After multiple tests both in-house and at the Woonona test site we have seen that the UAV is capable of flight, communication of control and sensor data and HD Video over the mesh network.

The first network test

The first network test and demonstration was carried out at the SMRS Wonoona on the 9th of November with Mr Steve Tonegato from CSPL in attendance. The wireless mesh network and the capabilities of the drone for transferring telemetry, control, video and sensory data was successfully demonstrated above ground. During the above ground tests latency over the mesh over multiple hops was checked and reported to be in millisecond range. However, due to a software issue, the network did not properly mesh in the underground gallery.

Figure 13 - Setting up for a demo at SMRS Woonona

Figure 14 - surface UAV demo at SMRS Woonona

The second network test

The second network test and demonstration was carried out at the SMRS Wonoona on the 20th of November with Mr Steve Tonegato from CSPL present. The wireless mesh network was successfully tested and demonstrated underground. However, due to bandwidth limitation of the mesh network underground, the capabilities of the drone for transferring telemetry, video and sensory data was only limited to a single hop on the mesh. The team agreed to increase the bandwidth of the mesh network and carry on further tests in 2016.

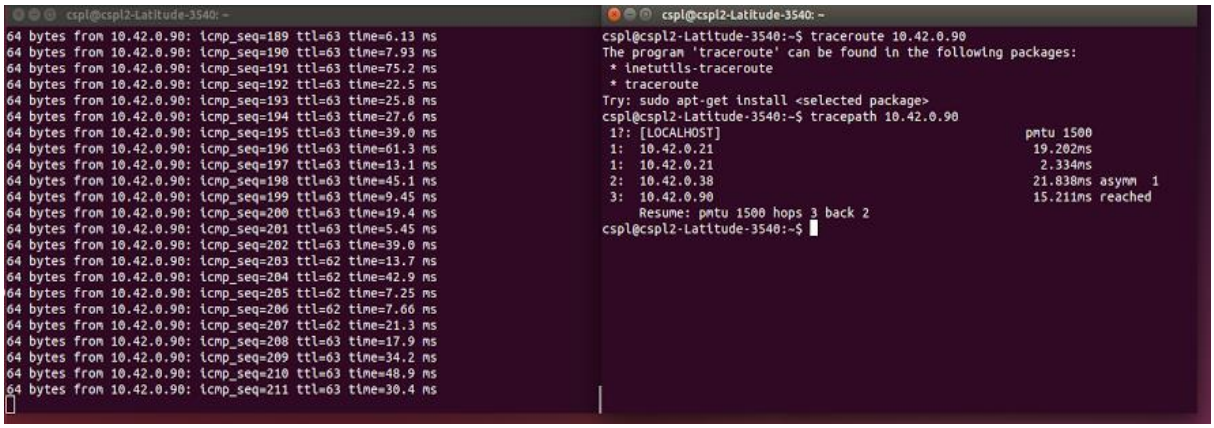

Figure 15 - Multiple hops with path and ping stream to UAV, tested at SMRS Woonona

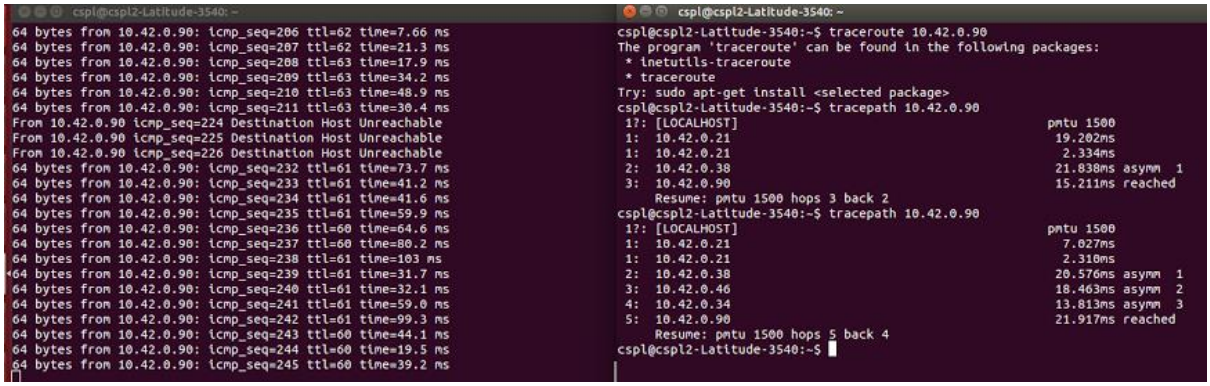

Figure 16 - UAV drop and re-join network with multiple hops.

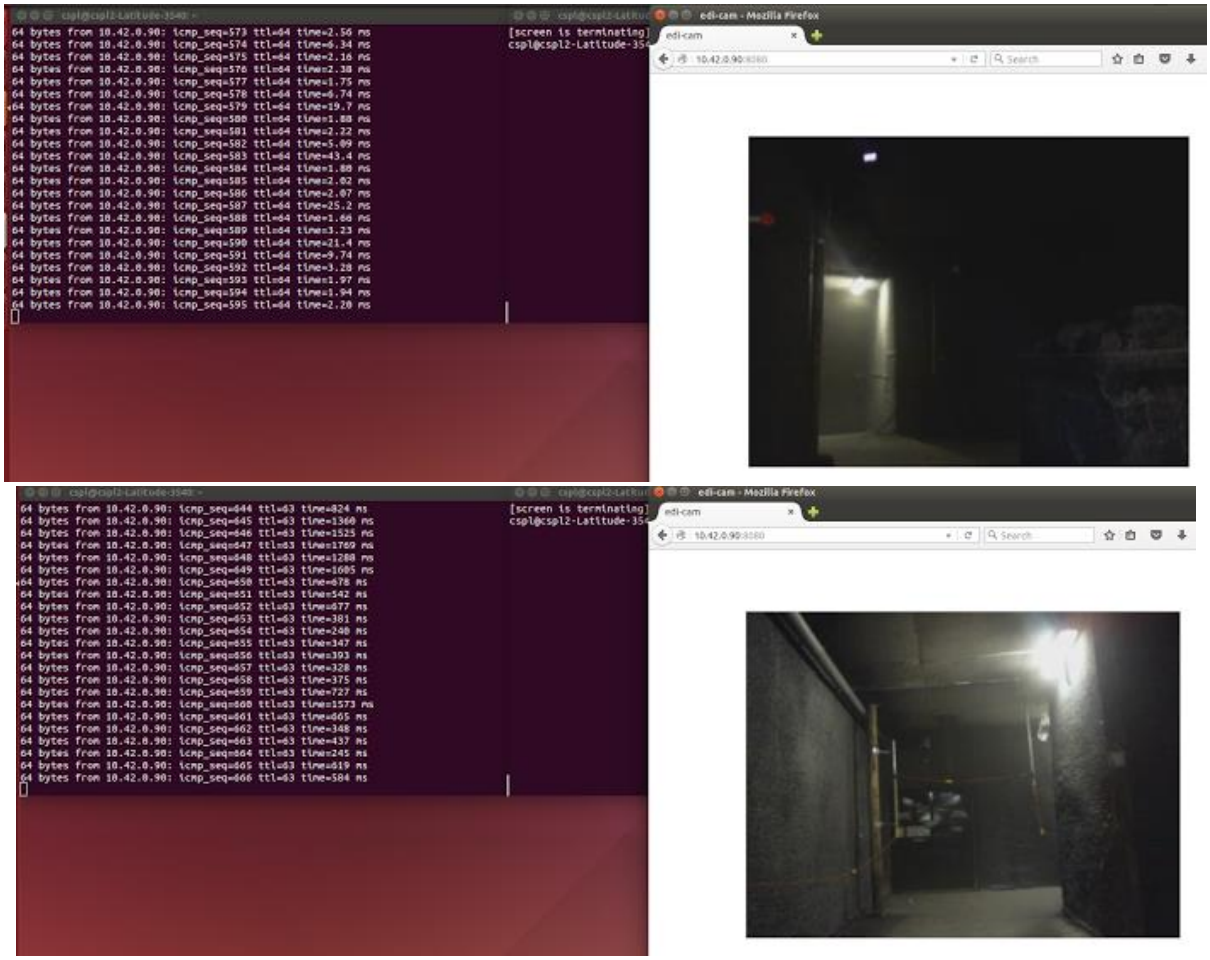

Figure 17 - Video streams tested under the previous system at Woonona

Task 5: Intrinsically Safe Configuration Design

Our heterogeneous wireless mesh device has been designed to be intrinsically safe for an underground mining environment in collaboration with Strata and the Mine Safety Testing Centre (MSTC). Currently our device has not been IS certified

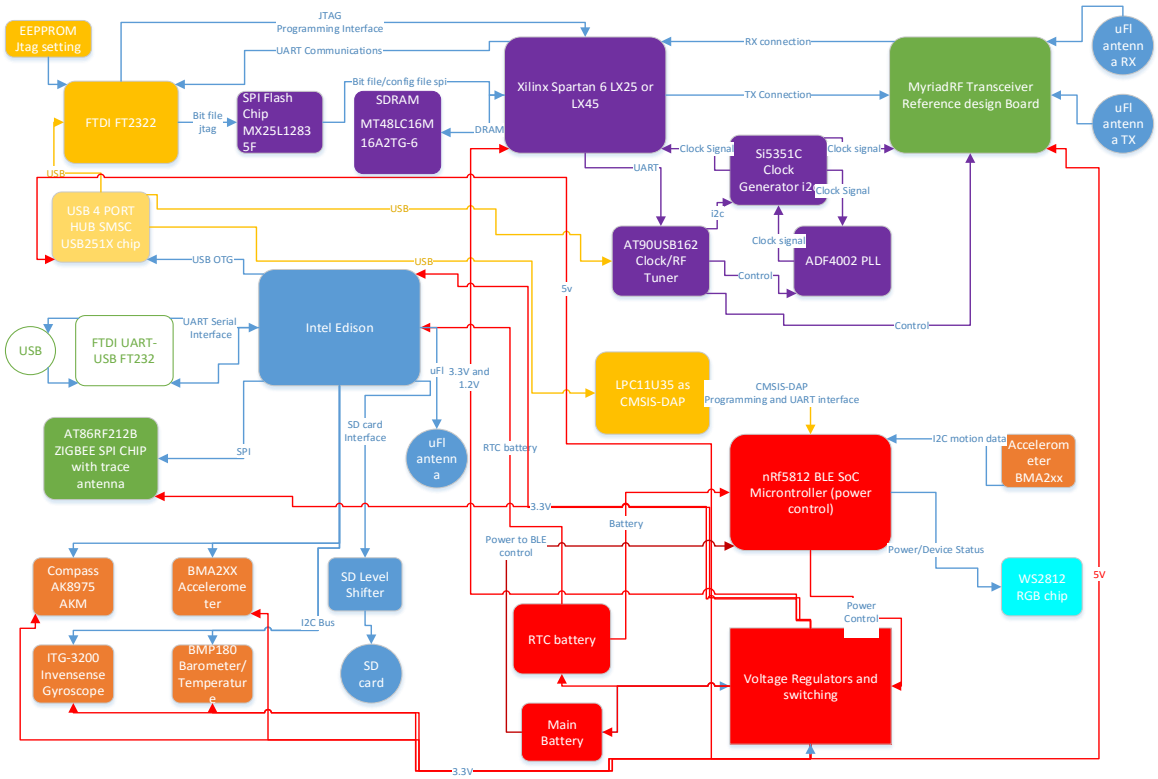

Figure 18 - Intrinsically safe configuration design. Overview and block diagram