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OPTICALLY-POWERED UNDERGROUND COAL MINE COMMUNICATIONS

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ABSTRACT: Emergency underground coal mine communication networks are discussed. Emergency communication systems should continue to operate following an explosion, major fire, roof collapse, or water inundation without relying on internal batteries or underground mine power. Optical fibre cables support Ethernet communication networks and power underground communication devices are proposed. The results of some tests with power-over-fibre technology have confirmed that 40 mW to 35 mW of power can be made available over a 0.5 km to 1 km length of fibre optic core, respectively. This is sufficient to power an underground SMS or email device.

INTRODUCTION

During 2006, a *Mine Safety and Health Administration (MSHA)* committee in the USA evaluated communication and tracking system technologies for use in underground mines. This effort was in response to the *Sago* and *Alma* mine accidents which indicated that functioning communication and tracking systems would benefit search and rescue efforts. *MSHA* received more than 100 proposals and selected six systems for underground mine testing. The committee reported that the tested systems lacked communication range and were susceptible to radio interference.

In 2008, *NIOSH*, *ACARP*, Australian mining industry and *CSIRO* representatives attended a meeting and agreed to support mine emergency communication collaborative R and D. *NIOSH* subsequently advertised a Broad Agency Announcement that solicited research proposals for communication systems that could result in improved safety for mine workers. *NIOSH* advised that the communication system should satisfy the following requirements: the system should operate in underground coal mines, and can be used during routine operations as well as continued operation following an explosion, major fire, roof collapse, or water inundation; and the system should provide sustained operation without relying on internal batteries or underground mine power.

Currently installed underground communication systems and underground power supplies are not designed to withstand explosions, fires, roof falls or floods. Battery-powered communication devices are unlikely to operate for more than a week, whereas in the *Beaconsfield* Mine collapse of 2006, two miners were rescued two weeks after being trapped. Most recently, 33 Chilean miners were rescued after being trapped underground for 69 days.

In response to the above-mentioned *NIOSH* announcement, *CSIRO* researchers were tasked to investigate options and conduct lab tests for underground coal mine communication networks. This investigation established that direct-burial fibre optic cable buried at a depth of 0.6 m and subjected to pressures many times that exerted by a loader did not exhibit performance degradation. This observation was confirmed independently by *NIOSH*. That is, the same direct burial cable that is ploughed-in by telecommunication providers across Australia can be trenched within underground drives.

The trenched cable would be protected from fires, rock falls and floods. Trenching is done routinely within longwall mines for water drainage. For example, *Hydrapower* can supply a rock saw for developing 70-mm-wide underground trenches at a typical rate of 200 m per hour. A rock saw for cutting 600 mm deep trenches is estimated to cost about AUD \$25,000. An approximate operating cost is AUD \$20 per hour for wear and fuel usage.

The results of *CSIRO* tests with new power-over-fibre technology established that approximately 30 mW of power can be safely delivered to a communication device over a 1 km length of fibre optic core. The maximum optical power of the light source was sufficiently low such that any light energy that escaped the fibre (due to an unterminated cable or breakage) would be incapable of igniting explosive gas mixtures or coal dust (refer IEC 60079-28) which is consistent with intrinsically safe design. The

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authors are proposing a system for underground SMS or email communication that is powered exclusively by a few fibre optic cores connected to equipment at the surface.

This paper summarises the results of the underground coal mine communication investigation done for NIOSH (Einicke, *et al.*, 2009). The communication system requirements are canvassed in Section 2. Options for underground and surface communication infrastructure are discussed in Sections 3 and 4, respectively. Section 5 outlines some candidate underground communications devices. Some remarks about the feasibility of the proposed approach are provided in Section 6 and the conclusions follow in Section 7.

COMMUNICATION SYSTEM REQUIREMENTS

Copper cable requirements

It is envisaged that separate copper cable is used to distribute power to emergency mine communications equipment. The cable's conductor size would be chosen such that it could provide sufficient voltage and current to all connected emergency communications equipment, some of which may be kilometres from a power source. Non-emergency communication equipment would need to be independently powered.

During mine emergency incidents, in which the underground AC supplies are switched off, an IS supply having an internal uninterruptable power supply (UPS) may sustain connected communication equipment for up to several hours. Suppose instead that AC supplies together with IS power supplies were installed at the surface. Assume also that a satisfactory copper conductor was available and the cables were installed down bore-holes to support underground communication equipment. Under these conditions, underground emergency communication devices could continue to operate indefinitely during emergencies.

Optical fibre cable requirements

A mix of cable types is advocated, such as a multi-core optical fibre cable for Ethernet communication, and a two-core copper cable for power. Optical fibre cable is proposed due to its inherently low signal loss per kilometre. In comparison, copper Ethernet cable is limited to 100m in length, which is not consistent with the communication distances that exist within underground mines.

Optical fibre is considered intrinsically safe, provided the light energy transmitted down the fibre is at or below a certain power level. For intrinsically safe optical devices in Group I hazardous areas, the IEC 60079-28 standard applies. It specifies a maximum optical power of 150 mW for continuous-wave radiation in the 380 nm to 10 μm band. Note that further research is being done into single-mode fibre. Due to its extremely small core size and the nature of the light exiting the fibre, optical power density can be significantly higher than in multi-mode fibre. Hence only IS-certified devices with an optical power output at or below 150 mW and in the specified wavelength range may be attached to the optical fibre. The optical fibre cables will need to be suitably armoured so they remain operational under the following conditions: routine underground vehicular traffic; underground roof collapse; underground water inundation; and pressure waves resulting from underground explosions.

Power-over-fibre (POF) technology can be used to power small electrical loads. That is, laser diodes at the surface could be used to transmit power via fibre-optic cables installed down bore-holes to support IS emergency communication devices situated underground. Access at the surface should be possible in flat rural areas where mine operators have arrangements to enter leased or neighbouring farming land. Cable length design trade-offs may preclude the supply of power over copper cables for the deeper bore-holes within inaccessible terrains. The bore-holes would require sealing to minimise impact on underground ventilation performance.

Self-escape and mine rescue requirements

Communications are required to support two rescue phases. The first is the *self rescue* phase when people underground become aware of an incident and they use their own resources and systems available to them in the mine to leave the mine. The second is the *aided rescue* phase, where people are trapped in the mine by a physical impediment, fire or injury. Communication technology is required to support an emergency management team's underground navigation and rescue activities. In the event of

an underground fire or flooding, the underground mine power supply will almost certainly be switched off. Therefore, the technology of choice is that which supports two-way communication and operates independently of underground mine power.

UNDERGROUND COMMUNICATION INFRASTRUCTURE OPTIONS

A configuration involving underground node switches and power supplies is shown in Figure 1. Briefly, a trunk cable, which includes a fibre optic core bundle, is connected to underground nodes having IS Ethernet switches and IS power supplies. It is envisaged that the trunk cable would be routed to the core Ethernet switch situated next to the control room at the surface. The lengths of gate roads within longwall mines can vary from 3 - 5 km. Thus, the distance from a control room to the current working face may be 10 km.

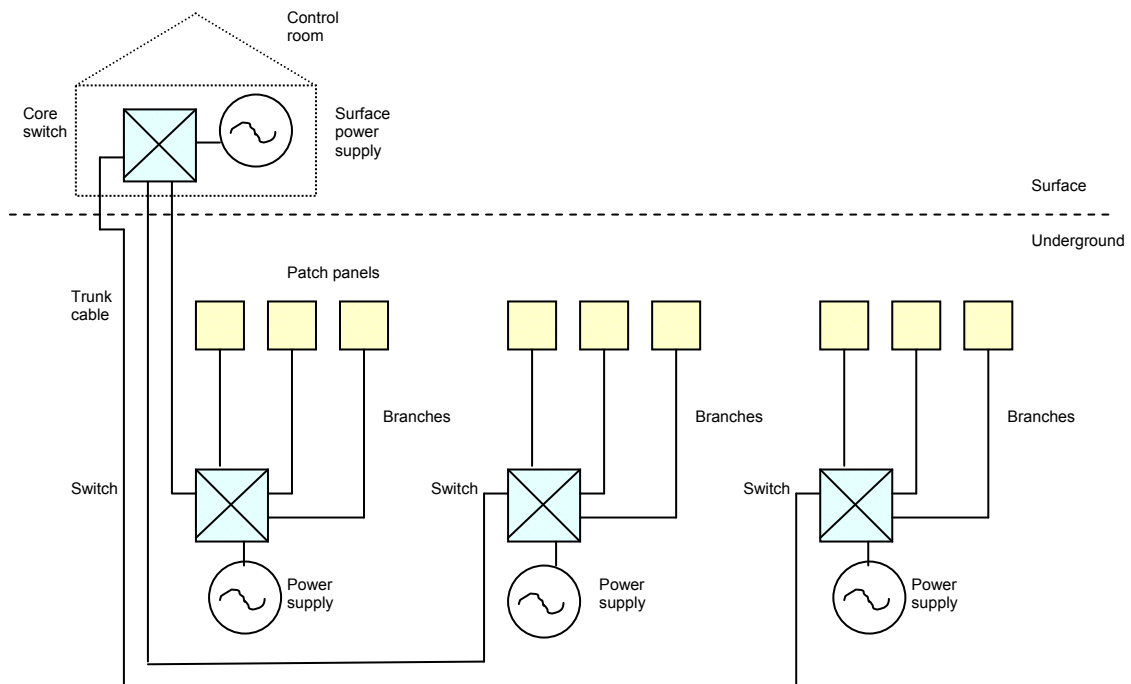


Figure 1 - A star configuration of underground unmanaged switches and power supplies. The network is susceptible to failure unless the underground trunk is protected from fire, floods and roof-falls.

Underground patch panels are suggested for connecting mine-powered communication devices such as 802.11x WiFi equipment. That is, high-bandwidth communication is supported during routine production conditions. In the event of mine emergency conditions involving localised fire, flooding or roof-fall, equipment within some regions may be destroyed. However, the trunk will need to be protected so that communications elsewhere within the mine are supported. For example, as discussed previously, the trunk could be buried in the floor of roadways.

A 110 V AC supply is usually available near existing underground infrastructure. An off-the-shelf 110 V AC to 12 V DC IS power supply could be used to support an IS Ethernet switch. For example, the entity parameters of a 7 AH *Holville* IS power supply are $U_o = 12.6$ V, $I_o = 2.34$ A, $P_o = 29.48$ W, $C_o = 9.6$ μ F and $L_o = 0.05$ mH. The entity parameters of an *Ampcontrol* IS Ethernet Switch are $U_i = 15$ V, $I_i = 2.5$ A, $P_i = 37$ W, $C_i = 0$ and $L_i = 0$. Suppose that this Ethernet switch draws 2 A at a minimum input voltage of 12 V and that the resistance of available copper cable is 5 Ω /km. Then the maximum permissible length of power cable is 0.6 V / (2 A * 0.005 Ω /m) = 60 m. Assume that the IS Ethernet switch was installed underground and the IS power supply was located 500 m away at the surface. Then the available voltage would be 12.6 V * 6 Ω / (6 Ω + (500 m * 0.005 Ω /m)) = 8.9 V, which is insufficient to power the switch.

To minimise the voltage drop over the copper, the cable resistance would need to be very low (less than 1 Ω /km), which would require a cable with a large cross-sectional area (25 mm² or greater). Such a cable would have a very high mass and would not have sufficient tensile strength to support its own weight over

hundreds of meters. Additionally, the L/R ratio could be too high to be safely connected to any IS power supply. These example calculations demonstrate that an underground IS Ethernet switch requires its power supply to also be situated underground. This limitation applies irrespective of whether the power cable is installed within conduit or trenched under the drive.

SURFACE COMMUNICATION INFRASTRUCTURE OPTIONS

It is common practice to install IS Ethernet switches underground where other communication equipment is situated. The power supply cable to the IS Ethernet switch is typically installed in conduit. Although burying this cable under a roadway would provide extra physical protection, it is still within an explosive risk zone and so the power supply is required to be IS. The example calculation (above) demonstrates that a switch cannot be installed underground and powered by an IS supply on the surface. Therefore, it is proposed instead that the switches are located on the surface.

The IS certification process for communication equipment can take 2 – 3 years. Consequently, the capabilities of IS communication equipment tends to lag state-of-the-art technology. For example, managed IS switches having dual power supplies are not yet available in the marketplace. A ring topology involving managed switches at the surface is shown in Figure 2, which is more robust than the star topology of Figure 1. For example, if failure occurs within a fibre optic cable or a switch, a rapid spanning tree protocol (RSTP) can automatically reroute all communication traffic via the redundant paths. Switches supporting dual power supplies are advocated since they can tolerate a failure in one supply.

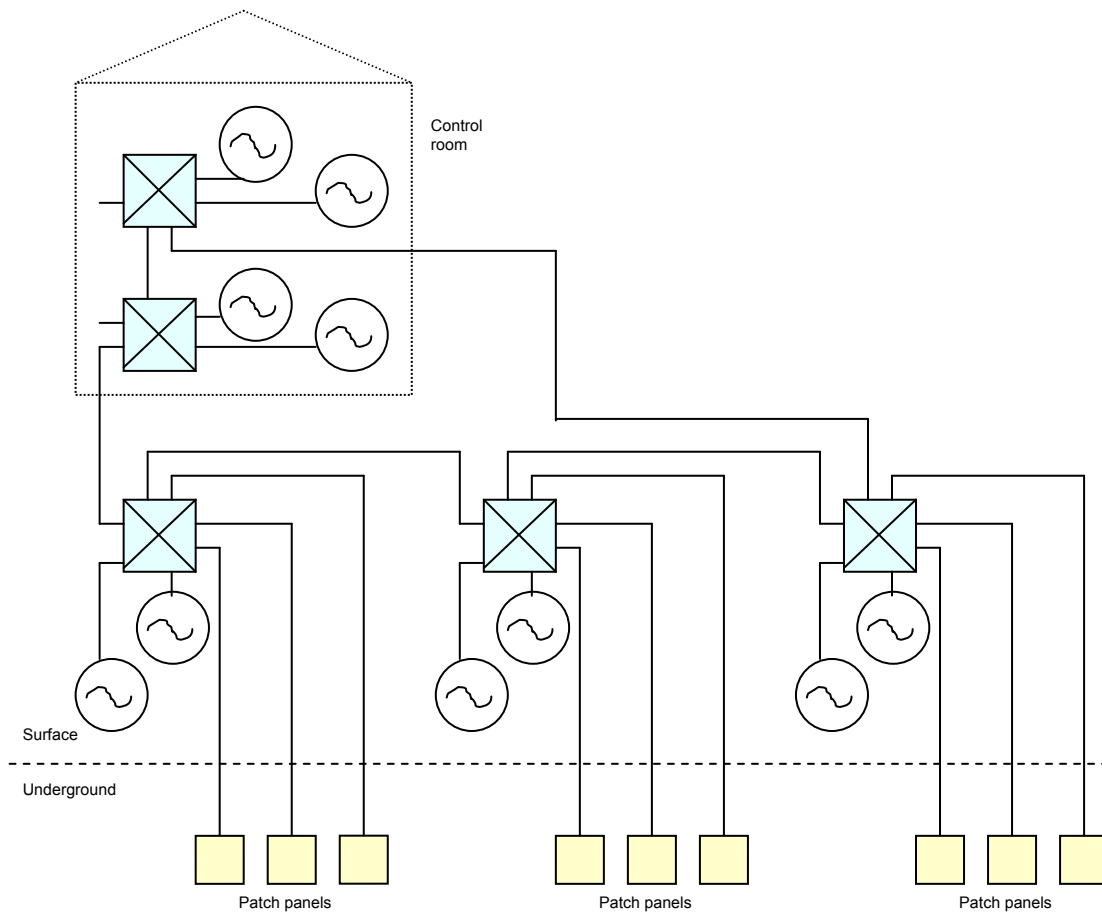


Figure 2 - Configuration of managed switches having dual power supplies. The node communication network will remain operable in the event that a single failure occurs within a connection or switch.

COMMUNICATION DEVICE OPTIONS

Voip telephone

Suppose that an IS VoIP telephone that plugs into an underground patch panel has been developed. The VoIP telephones would enable underground personnel to communicate with personnel in the control room or make outside calls. In the event of an emergency incident in which underground power is not available, the VoIP telephones should be operational for the time it takes able-bodied personnel to walk out of the mine. The phones could remain operational for up to several hours, depending on the state of the UPS. However, any personnel that are confused, stranded, injured or trapped for a longer time would not be guaranteed communications availability.

Assume that an IS VoIP telephone requires 500 mA at 12 V, *i.e.* 6 W. A 500 m cable with a 1.5 mm² cross-sectional area has a typical DC resistance of 7 Ohms and DC inductance of 0.4 mH. For a current of 500 mA, the voltage drop will be 3.5 V at 500 m over 500 m of cable. Therefore the cable could deliver 13.5 V @ 500m A from a 17 V power supply. IS power supplies with suitable entity parameters are available at these power levels. On the surface, an alternative to the IS power supply is to use a large-capacity battery (charged from any non-IS source). The battery would be connected to safety barriers, which would provide IS outputs of appropriate power levels.

Wireless messaging

Underground mine equipment relies heavily on Ethernet communications. An underground wireless local area network (WLAN) could be established by connecting wireless access points to underground patch panels, provided that: the WLAN equipment is IS; fibre optic Ethernet connections are used; and independent power supplies are installed

Northern Light Technologies offer IS wireless access points and a cap-lamp-powered wireless messaging system. An IS messaging capability would aid underground workforce productivity and safety. The access points need to be installed underground. After the loss of underground mine power, the WLAN operating time will depend on the state of their IS UPS. Similarly, the availability of the messaging system will depend on the state of a worker's cap-lamp battery.

Wired messaging / Email devices

Currently, underground communications equipment relying on batteries are unable sustain operation for a week or more. There is clearly need for a survivable communications system to respond to such situations with indefinite operational duration. Consequently, the authors are undertaking the development of an IS email/messaging device.



Figure 3 - Depiction of the proposed low-power email/messaging device. It is envisaged that the device would be powered via a small number of fibre optic cores.

Some theoretical estimates and the results of some tests with power-over-fibre technology are detailed in Einicke G, McPhee R, Munday L and Hainsworth D (2009). Multi-mode components are preferable for supplying power over fibre for distances up to 1.5 km, whereas single-mode components perform better over longer distances. It has been confirmed that with a Class 3 150 mW laser source and a single 500-m-long multi-mode fibre-optic core, a photovoltaic-converter can deliver 50 mW of electrical power. For longer distances, multiple cores can be employed. Similarly to deployment in laser printers, the Class 3 laser could be housed in an enclosure so that the assembly is Class 1. An interlock serves to ensure that the laser automatically switches off whenever the connected cable is severed.

The test results suggest that it should be technically feasible to develop an IS email/messaging device that is powered exclusively by a small number of fibre optic cores. It is envisaged that the device would possess an alpha-numeric keypad and a liquid crystal display (LCD). A sketch of the proposed IS email/messaging device is shown in Figure 3 and is the subject of a patent application - see Einicke *et al.* (2009).

FEASIBILITY CONSIDERATIONS

Cable crushing tests

The ground within underground drives tends to include rocks. Thus, a trencher possessing a rock saw will probably be needed for direct burying of cable in mines. It is also envisaged that a hopper that discharges bedding material may additionally be required for rocky environments. Therefore, the efficacy of candidate bedding material needs to be investigated.

Six 5-m-long direct-burial 6-core SMOF loose-tube cables were obtained from *Optical Fibre Systems* for crush testing. The cores were pre-terminated with ST connectors. A test rig was manufactured so that a cable could be buried at different depths with different sample material and loaded within a press. The main body of the rig consisted of a 720-mm-high vertical section of rolled steel pipe having wall thickness of 5 mm and an outer diameter of 270 mm. The bottom of the cylinder was bolted onto the bench of a 250 kN (*i.e.*, 25 t) *Instron* 1342 press.

Samples of the following material were selected for testing: crusher dust, 1.59 t/m³ density; 5 mm gravel, 1.33 t/m³ density; 15 mm gravel, 1.30 t/m³ density; and 50 mm road-base, 1.26 t/m³ density. Photos of these samples are provided in Figure 4. For each sample material and load setting, an FLS-600 light source (set to 1310 nm) was connected to one end of each core and a WG OLP-18B optical power meter to the other end. The tests were stopped when the piston reached a depth of 200 mm within the bedding material.

Crushing could be heard continuously throughout the tests, and surprisingly, no core failures occurred. The cable crushing test results are plotted in Figure 5. The variations in the attenuation measurements occurred because dust accumulates on the exposed 9 µm fibre cores with each disconnection and connection. The pressure produced by a loader was estimated to be 23.5 t-f/m² (33.4 psi). Thus, with a safety factor of greater than 10, burying the cable together with crusher dust at a depth of 0.6 m should afford adequate protection. The results presented here are spot tests. It is suggested that decision makers need to conduct repeated testing with the actual mix of bedding material and excavated material available at mine sites.

Ball-park cost estimates

Boreholes of 100 mm diameter can be drilled with ±1 m cross-track accuracy for depths up to 300 m and ±3 m accuracy for depths up to 600 m. Anything deeper than 600 m requires "steering" to ensure that the drill accurately reaches the target region. The cost of drilling a 100 mm borehole is about AUD \$100/m. Hence, for our example with an average depth of 300 m, the borehole costs are \$30 000 * 5 = AUD \$150 000. Typically, 100 m boreholes can be grout filled around cables for approximately AUD \$50/m. Thus, the grouting costs for five 300 m boreholes are about \$50 * 300 * 5 = AUD \$75 000.

It will not always be possible to drill a hole to every desired location. For example, infrastructure and other obstructions may exist at the surface or geological faults may be present underground. In this case, some cable may have to be buried within an underground roadway. Since burying cable underground is not common practice, estimating its cost is difficult. An approximate estimate for burying cable can be

obtained by adding a levy of \$250/m for underground coal mine work to the \$100/m drilling costs, i.e., \$350/m.



Figure 4 - Crusher dust sample (top left), 5 mm gravel sample (top right), 15 mm gravel sample (bottom left) and 50 mm road-base sample (bottom right).

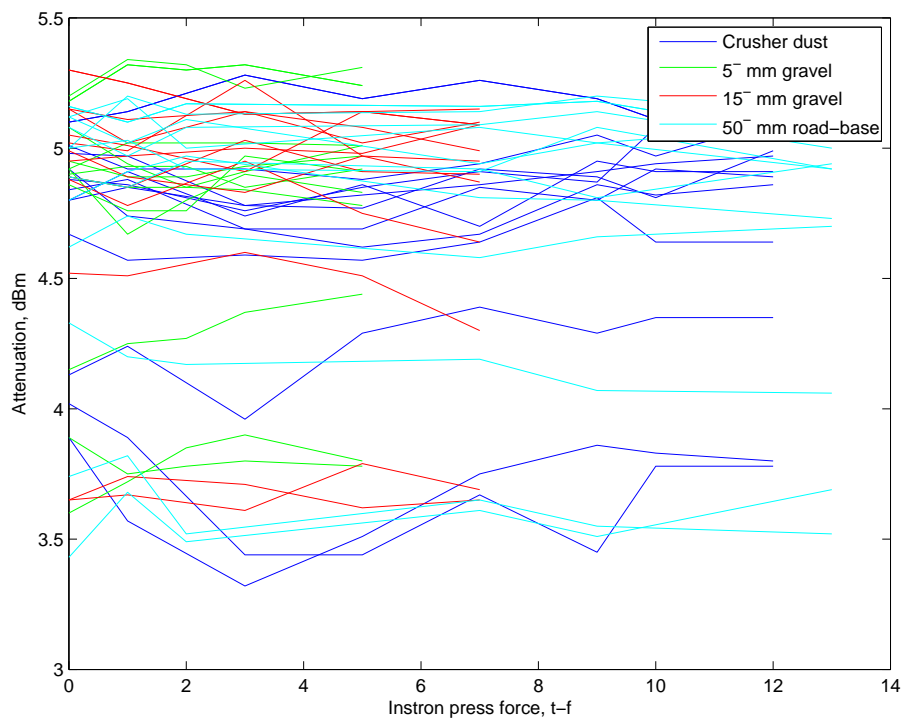


Figure 5 - Cable attenuation versus Instron press force for different sample materials

The cost of optical fibre cable depends on the number of cores, armouring and whether it is multimode or single-mode. For example, typical retail costs of an 8-core single-mode armoured riser cable (that is suitable for aerial use and for direct burial) is AUD \$2.60/m. Industrial-quality managed 24-port Ethernet

switches and 100BaseTX to 100BaseFX media converters can cost around AUD \$2 000 and \$500, respectively. Thus, the estimated cost of two surface switches and 14 media converters is about AUD \$11 000.

The low-powered communications devices are required to be IS and it is expected that they may cost about AUD \$4 000 each. It is estimated in (Einicke G, McPhee R, Munday L and Hainsworth D, 2009) that the start-up cost for installing the proposed network at a new longwall mine is around AUD \$400k. The switches, low-power communication devices and the patch panels can be reused from one longwall to the next.

CONCLUSIONS

This paper has discussed options for emergency underground coal mine communication networks. Underground coal communications systems are required to be intrinsically safe, meet communication needs during both production and emergency conditions, and survive underground mine power outages. Intrinsic-safety design considerations prevent the use of copper cables to supply power from the surface to underground Ethernet switches. Therefore, it is proposed that Ethernet communication networks are installed at the surface.

Some theoretical estimates and the results of some tests with power-over-fibre technology have confirmed that 40 mW to 35 mW of power can be made available over a 0.5 km to 1 km length of fibre optic core, respectively. This is sufficient to power an underground SMS or email device. The surface equipment would employ enclosed 150 mW laser sources, which are no more hazardous than a laser printer. It is expected that similar low-power design techniques could subsequently be applied in the development of IS VoIP telephones. This would involve an end-to-end delay design trade-off, which is consistent with push-to-talk telephones and intercoms that are currently in use.

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