Low-cost Leaky Feeder Communication for Mines Rescue

Author details:

Michael D Bedford (corresponding author), Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall, TR10 9FE, UK, +44 7732 665700, m.d.bedford@exeter.ac.uk

Angel J A Rodríguez López, Robotics Lab, Universidad Carlos III de Madrid, Leganés Campus, Av. de la Universidad, 30, 28911 Leganés, Madrid, Spain, +34 619 10 90 84, angrodri@ing.uc3m.es

Patrick J Foster, Camborne School of Mines, University of Exeter, Penryn Campus, Penryn, Cornwall, TR10 9FE, UK, +44 1326 371828, P.J.Foster@exeter.ac.uk

Abstract:

A low-cost, low-weight leaky feeder system is proposed for mines rescue communication, for use when the mine's permanent communication infrastructure has been compromised by an incident. Unlike the leaky feeders that are permanently installed in some transport tunnels and mines, which are very expensive, bulky and heavy, the system described here relies on the fact that some ordinary coaxial cables leak signal unintentionally. Experimental evaluation of the two main types of low-cost coaxial cable identified a suitable cable and an optimal frequency of 27MHz. Longer range tests characterised the real world underground performance of a system. A range of around a kilometre is achievable but this could be increased substantially by using in-line amplifiers. In comparison to low frequency guidewire systems that have previously been produced for mines rescue use, the method outlined here does not force rescuers to clip handsets to the cable, thereby allowing them much more freedom of movement.

Keywords: Mines rescue, Emergency, Communication, Radio, Leaky feeder

Funding Details: This work was carried out as part of the INDIRES project which has received funding from the Research Fund for Coal and Steel under grant agreement No 748632.

Introduction

Studies have revealed (Jones, 1998; Kowalski-Trakofler *et al*., 2010) that lack of information is one of the main hindrances to the timely and effective response to an emergency incident in a mine. Drawing on the experiences of those involved in several high-profile disasters in American mines – including those at Sago Mine, West Virginia, in 2006, Aracoma Alma No. 1 Mine, West Virginia, in 2006, the Darby No. 1 Mine, Kentucky, in 2006, and Crandall Canyon Mine, Utah, in 2007 – Kowalski-Trakofler *et al*. cite poor communication as their second main hindrance after preparation and planning. Indeed, communication is essential in the preparation and planning process, further emphasising its key role.

Despite the importance of communication in any mines rescue operation, the requirements for a communication system for use by a rescue team are not adequately met by the systems that are used in the day-to-day operation of a mine. This is because a mine's permanent communication infrastructure could be rendered inoperable by accidents including fires, explosions, falls of rock or flooding. For this reason, mines rescue teams cannot rely on a mine's permanent communication system so, ideally, they need to deploy their own communication system which is taken into the mine as part of the rescue response. Several technological options are available for mines rescue communication, but none are without their drawbacks. While it is probable that no one system will provide the optimal solution in all circumstances, it is suggested that the novel, low-cost, low-weight leaky feeder system described here has several benefits and, for this reason, it could play an important role in mines rescue in the future.

Overview of Communication Methods

A brief overview of communications methods applicable to underground mining is provided here with particular reference to rescue use. For a fuller review of mine communications, see (Yarkan *et al*., 2009) and (Forooshani *et al*., 2013).

The permanent communication systems that are used in mines for operational purposes, are based on hard wiring to a lesser or greater extent. Most telephone-type systems are entirely wired; WiFi-based communication at a coal face, waiting area, or in other busy areas such as the shaft bottom, rely on wired links to the associated access points; and leaky feeder systems are reliant on cabling, even though the handsets operate wirelessly. Needless to say, the cables and the permanently wired equipment that is connected to them are at risk from many of the incidents that necessitate a rescue operation. For this reason, reliable rescue communication systems must either be entirely wireless or, if wiring is used, it must be deployed as part of the rescue action.

Through-the-earth (TTE) radio, which usually operates at LF (low frequency, 30-300kHz), VLF (very low frequency, 3-30kHz), ULF (ultra low frequency, 300Hz-3kHz),or sometimes at an even lower frequency, can provide a wireless link, either between the surface and underground, or between two points underground – see (Gibson, 2010) for a detailed introduction. Following the passing of the 2006 MINER Act in the USA, a resurgence of interest has been seen in research into this method – see, for example, (Carreño *et al*., 2016). However, in many cases, and especially in coal mines, because of the high electrical conductivity of coal-bearing strata which causes a high degree of signal attenuation, this is far from ideal for rescue use. This is due to the very high cost of the surface infrastructure, and the large, heavy and barely portable nature of the underground equipment. (Yenchek *et al*., 2012), which presents several designs that were developed for mines rescue, illustrates the ergonomic drawbacks of this approach. More favourable TTE communication can be achieved between two underground locations in a coal mine if both stations are located in the same coal seam (Sacks & Chufo, 1978; Stolarczyk, 1991). This results from the fact that coal has a much lower conductivity than the rock immediately above and below the seam and relates, typically, to MF (medium frequency, 300kHz – 3MHz). However, because of the constraints on location imposed by coal seam mode communication, this is not considered viable for rescue communication in the general case.

At frequencies above a threshold, that is referred to as the cut-off frequency, and which depends on the cross-sectional dimensions of the tunnel, radio communication is possible along tunnels via a mechanism referred to as a lossy waveguide mode of propagation – (Emslie *et al*.,1975; Zhang *et al.*, 2001). In mine galleries, frequencies in the UHF (ultra high frequency, 300MHz-3GHz) and SHF (super high frequency, 3-30GHz) portions of the radio spectrum are suitable, and communication over a range of hundreds of metres or even kilometres has been achieved in transport tunnels, under ideal conditions (Kennedy & Bedford, 2014). However, while this method provides a viable solution in perfectly straight tunnels with relatively smooth walls, the loss of a line-of-sight path is problematic. In practice, communication is negatively influenced by a single bend (Jacksha & Zhou, 2016) and, at the levels of attenuation quoted in that paper, would typically be lost completely along a path containing two or more bends. This can partially be overcome by installing passive reflectors at each bend (Isberg & Chufo, 1978), but these have to be accurately aligned so this wouldn't be viable for rapid installation during a rescue operation. A much better way of overcoming the problem caused by bends is to place active repeaters at bends (Souryal *et al*., 2009), indeed a string of such repeaters could be installed temporarily by a rescue team as they progress. However, since a high density of repeaters might be needed – for example, up to nine repeaters were needed in the highly non line-of-sight test area described in (Souryal *et al*., 2009), despite the area measuring only 57m x 166m on two levels – this could be an expensive solution, and would require the rescuers to carry a significant amount of equipment into the mine. While still imposing some of these drawbacks, using repeaters to form a mesh network can provide a degree of resilience to equipment failure because signals can be re-routed over a different path if a repeater fails. Equipment using this principle has been produced for mining use. The RESYS system (Buchwald *et al*., 2017) for example, was designed specifically for rescue communication, while the IWT Sentinel system (Anonymous, 2020) is intended for normal operational use but safety is considered a key motivator.

Communication along mine galleries is also made more practical by the presence of a wire to guide the signal, even though the equipment doesn't have to be directly connected to the wire. This mode of communication, which can loosely be called guidewire communication, is not affected by bends and it does not depend on the frequency being above the cut-off. This has been achieved using parasitic coupling to a mine's cabling or other metallic infrastructure at MF (medium frequency, 300kHz - 3MHz) – see (Dobroski Jr. & Stolarczyk, 1982) – but this cannot be relied on for rescue use because the integrity of the infrastructure cannot be guaranteed following an incident. For a dedicated guidewire system that is not reliant on the resilience of mine infrastructure, wires can be laid along mine galleries (Delogne, 1982), but such systems commonly only operate efficiently if the wires are kept away from the walls or floors, which is not viable for wires that are installed rapidly as part of a rescue operation. Frequencies in the LF portion of the radio spectrum have been found to be more immune from rock proximity, though, and the m-Comm system (Pollei*et al*., 2010), which is intended for mines rescue use and was developed as part of the pan-European initiative, relies on this fact. However, because of the LF operating frequency, it is necessary either for the handset to be clipped to the line, albeit without making an electrical connection, or if operation further from the line is required, by use of Bluetooth repeater units, which the rescue team would need to clip onto the line at appropriate locations.

Superficially similar to a guidewire system, even though the principle of operation is quite different, is a leaky feeder system. As the main emphasis of this paper, this is described in the next section in some detail.

The purpose of the work described here was to overcome some of the drawbacks of the currently available systems. In particular, the aim was to provide a system which, like the m-Comm rescue system, uses some sort of guiding cable, so it can be used along mine galleries irrespective of their cross-sectional dimensions and the presence of bends, but does not require equipment to be clipped onto the line. It will, therefore, allow rescuers to communicate when they are more distant from the line and, therefore, without their movement being unduly constrained. This is achieved using the leaky feeder principle, but at much lower cost and greater ease of installation than permanent leaky feeders.

Low-cost Leaky Feeder Approach

Because the system described here for mines rescue communication is a special type of leaky feeder, it is necessary to provide some introductory background information on this method of communication. Coaxial cable is a type of cable that is used primarily as a so-called feeder, that is for connecting a radio transmitter or receiver to an antenna. Its purpose is to transmit as much signal as possible between the radio equipment and the antenna, by minimising losses. The basic structure of a coaxial cable is shown in the top part of *Figure 1*.

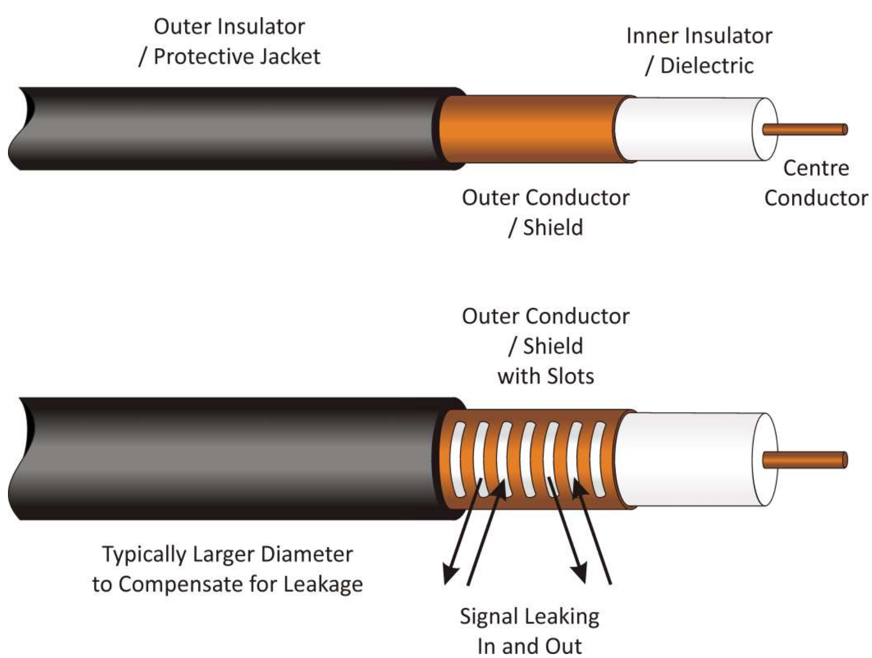

Figure 1 – Ordinary coaxial cable (top) contrasted with leaky feeder cable (bottom)

Instead of using parallel conductors as used, for example, in domestic mains power cables, or twisted conductors, as used in telephone or networking cables, the two conductors are coaxial, that is they share the same axis by virtue of one conductors being wrapped around the other. The outer conductor, which is called the shield, has the effect of preventing the leakage of a signal from the inner conductor, while also preventing external signals from entering the cable and, thereby, causing interference. To act as a good shield, the outer conductor is normally designed to provide a high degree of coverage around the inner conductor, although the percentage coverage might be reduced for the purpose of cost reduction.

By way of contrast, a leaky feeder cable (Martin, 1975) is a type of coaxial cable that has a deliberately reduced coverage shield so that, although it still acts as a moderately efficient feeder, some of the signal will leak out along its length, while external signals can leak in. This way, users in the vicinity of the cable are able to communicate, but the requirement to be in very close proximity to the cable, that applies to the LF guidewire approach, is relaxed. It is intended to provide communication in confined spaces such as mine galleries or transport tunnels, and is unaffected by bends. For example, users in trains in a subway tunnel equipped with a leaky feeder are able to use mobile phones. Although there are several different designs, one common type of leaky feeder is shown in the bottom part of *Figure 1*. It can be seen that the shield has periodic apertures cut in it to allow some signal to leak both in and out. However, to compensate for this loss, and therefore allow an acceptable amount of signal to progress along the cable, the cable often has a significantly greater diameter than ordinary coaxial cables, and is therefore much more expensive. Typical leaky feeders are 16mm-50mm in diameter, they weight 220kg – 1,120kg per kilometres, and they cost thousands of pounds per kilometre.

Although they offer good performance in a wide variety of tunnel environments, leaky feeder cables of the type used in transport tunnels are too bulky and too heavy to be laid by a rescue team during a rescue operation and this is even true of systems intended for mining applications. For example, the Becker Smart Com mining leaky feeder system, that operates at VHF or UHF, uses cable that weighs 320kg/km. Standard leaky feeders are also far too expensive. This assertion takes into account the fact that the rapid deployment of such a cable, as part of a rescue, would require it to by placed on the floor with little attention being given to optimal positioning, so it would be at risk from footfall or falls of rock. For this reason, it would be necessary either to discard the cable following the rescue, or else to carry out extensive and potentially expensive inspection and testing to confirm the integrity of the cable before permitting it to be reused in another rescue.

The system described here works in the same way as a leaky feeder system with an important difference: the cable that was chosen was not designed for use as a leaky feeder. For this reason, it is significantly smaller in diameter, and hence significantly lighter and more portable than dedicated leaky feeder cables, and it is sufficiently cheap that it can be thrown away after being used. This research was prompted by reports that cavers had successfully used some low-cost ordinary coaxial cable (i.e. cable that is not designed to leak) as a leaky feeder cable for communication along cave passages (Marincola, 2013). However, because there are no reports of this being trialled more generally, for example in a mining context, and apparently nothing has been published in the academic press, it was decided to conduct more extensive tests on inexpensive coaxial cables to assess their suitability as leaky feeders.

Cable Selection and Evaluation

Rationale

The cables that were reportedly used in caves were low-cost cables, which, since they don't adhere to specific standards such as the American military RG cables, are often identified as just "low-loss", although this phrase isn't really an accurate description since they tend to have a higher loss than most similar RG cables. These cables are intended for use with domestic TV antennas.

The cables used for cave communication had a shield comprising both a metallic braid, i.e. woven thin wires, and metal foil. Although the combined shield appears to have 100% coverage, the reports of leakage are certainly credible because of the skin effect which allows signals to penetrate thin conductive barriers to varying degrees, depending on the frequency.

Another type of low-cost "low loss" cable has a copper clad aluminium braid shield but no aluminium foil. Commonly, the percentage coverage of the braid is very low, with the obvious potential for leakage. A coverage of 40% is typical.

Cables of both these types were chosen for evaluation. Both cables are approximately 6.5mm in diameter, they weigh about 34kg per kilometre, and they cost just over £100 per kilometre, characteristics which are considered acceptable for temporary use in a rescue scenario. They are shown in *Figure 2*.

Figure 2 – Low-loss cables tested in this study: braid and foil (top), low coverage braid (bottom)

The majority of leaky feeder systems operate in the UHF or SHF portions of the radio spectrum, these being the frequencies used by the mobile phone and WiFi systems they are designed to operate with. For a mines rescue system, that is intended primarily for analogue voice communication or low speed text and data, fewer frequency constraints apply. However, the manufacturers' quoted attenuation figures show that these "low loss" coaxial cables have relatively high attenuation at microwave frequencies. For this reason, to characterise the performance of these cables for use as leaky feeders, frequencies in the HF (high frequency, 3-30MHz) and VHF (very high frequency, 30-300MHz) portions of the radio spectrum were chosen for experimental evaluation. In particular, frequencies close to 3.5MHz, 7MHz, 14Hz, 28MHz, 50MHz and 144MHz were used, the choice of the exact frequencies being made because of the availability of amateur radio equipment which operates in these frequency bands.

Test Equipment and Procedure

Prior to each test, the cable was connected to the transmitter and reeled out along the ground. The test procedure involved measuring the signal strength at 5m intervals along a 100m length of cable using a handheld receiver and compact antenna, which was at a separation of 2m from the line. This process was carried out for each of the frequencies identified above. Once the frequency that offered the best performance had been identified from the results of the above tests, signal strength measurements were also made at a distance of 40m from the transmitter, at various separations from the cable, ranging from 0m to 15m.

The transmitter was a Yaesu FT-857D amateur radio transceiver. It was configured to transmit a CW (continuous) signal with an output power of 5W. The cable was hard wired to the transmitter and the end of the cable distant from the transmitter was terminated with a 75 ohm "dummy load" resistor, this being the characteristic impedance of the cables. This corresponds to normal practice with leaky feeders, and is necessary to provide an acceptable match between the transmitter and the cable. The receiver was an Aeroflex 9103 spectrum analyser which was used with a 1.5m whip antenna in a vertical configuration. The effective noise floor of this configuration, taking into account background noise, varied from -65dB at 7MHz to -73dB at 144MHz.

The antenna was not specifically cut to resonance at any one frequency but its length was chosen to represent the absolute longest that would be practical on handheld equipment in a mine environment. The implication of this is that its efficiency will differ between the frequencies used, and it will be particularly inefficient at the lower frequencies of 7MHz and 14MHz. However, it would be misleading to attempt to calibrate the results to take account of the differing antenna efficiency for two reasons. First, higher efficiency antennas at 7MHz and 14MHz would be much too long for portable use in a mine environment so any such improvement would not be achievable in practice. Second, as will be seen in the results, the received signal strength at these frequencies was not much above the noise floor, even at short range, suggesting that little headroom was available to provide long-range communication. This would not be addressed by a more efficient antenna. Instead, the key criteria was to achieve a combination of a low level of longitudinal attenuation and headroom above the noise floor, both of which are comparative measures and, therefore, irrespective of antenna efficiency.

The cable evaluation tests were carried out in an outdoor environment for ease of access. It is recognised that, theoretically, a leaky feeder can operate differently in a tunnel than outdoors because, in a tunnel below cutoff, a monofilar mode of propagation can exist in addition to the coaxial mode. However, the monofilar mode has a higher level of longitudinal attenuation, especially for cables in close proximity to a tunnel wall and, as a result, leaky feeder communication is mainly via the coaxial mode which applies to both environments (Delogne, 1980; Hill & Wait, 1976). This choice of test environment was subsequently justified by the very similar values of attenuation that were obtained in the tunnel environment during the field tests.

Results

Graphs of signal strength against longitudinal distance at various frequencies, and against separation from the cable at the optimal frequency, are presented for both cables as *Figure 3 - Figure 8*. Note that a graph has not been provided for 3.5MHz because no appreciable signal could be detected on this frequency with either cable. It should be borne in mind that the plotted values of signal strength are not absolute values because they do not take into account the gain of the receiving antenna which, as already discussed, will vary with frequency.

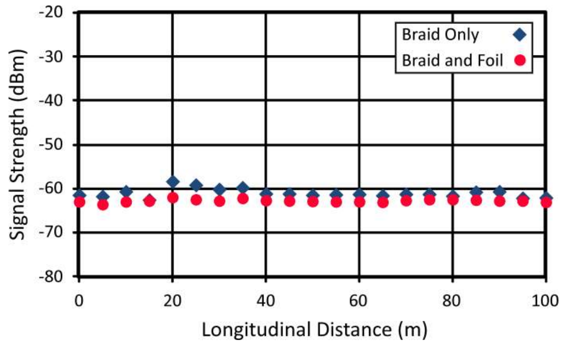

Figure 3 –Signal strength vs. distance, 7MHz

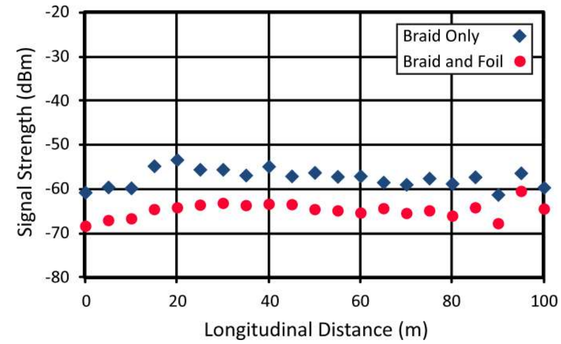

Figure 4 – Signal strength vs. distance, 14MHz

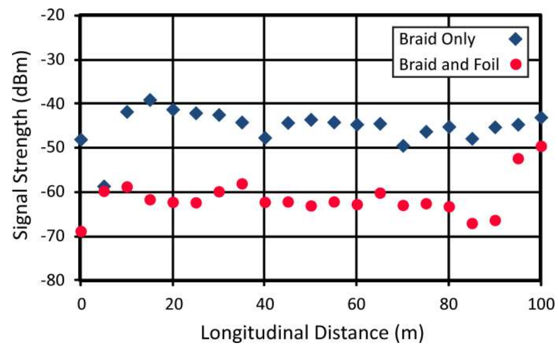

Figure 5 – Signal strength vs. distance, 28MHz

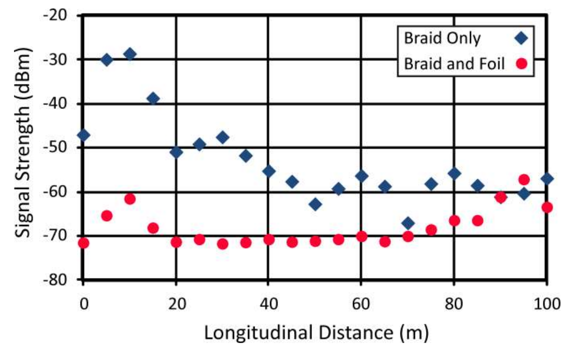

Figure 6 – Signal strength vs. distance, 50MHz

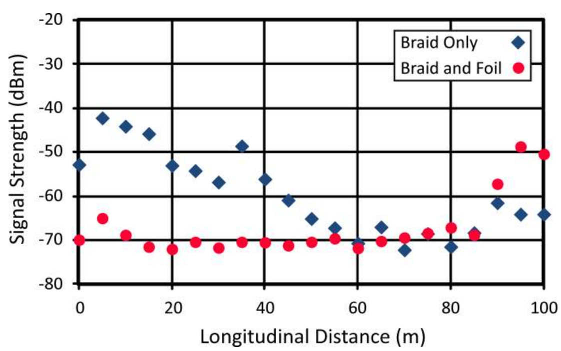

Figure 7 – Signal strength vs. distance, 144MHz

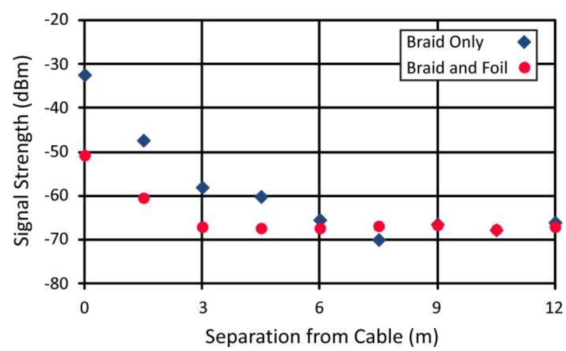

Figure 8 – Signal strength vs. separation, 28MHz

Discussion

It is recognised that the antenna efficiency differs between frequencies, and this could, potentially, have a bearing on the interpretation of the result. This has been discussed in the section on the test equipment.

Some anomalous effects were noted in the experimental results. First, on several frequencies, the signal strength very close to the transmitter was lower than it was at a greater distance, even though it then reduced gradually with distance as expected. Because a leaky feeder system would not be used with such minimal separation between the base station and a mobile station, very short range anomalies were ignored in the analysis process. Second, on 144MHz and 50MHz, and on 28MHz with the braid and foil shield cable, the signal strength increased as the end of the cable was approached. It is hypothesised that this was due to radiation from the 75 ohm dummy load that was connected to the end of the cable. It is consistent with this hypothesis that the effect is more noticeable on the higher frequencies at which the dimensions of the dummy load were closer to the wavelength with the result that the dummy load would be a more efficient radiator. Because this only affects the last few readings, and is not noticeable at all on most frequencies, again this anomaly was ignored in the analysis process.

With both cables, and with just a few exceptions, the overall signal strength increased with frequency, as a result of an increasing degree of leakage from the cable. The other notable trend, which is probably a result of the first trend, at least in part, is that the attenuation per unit length also increased with frequency. The implication of this is that there's an optimal frequency, which provides the best compromise between a good overall signal strength (i.e. headroom above the noise floor) and a low level of longitudinal attenuation, as necessary to maximise the range. It was, therefore, a fairly simple task to determine an optimal frequency by eye. For both cables, that frequency is 28MHz.

When drawing comparisons between the two cables, it is clear that the cable with the shield comprising only a braid radiates more signal than the cable with a shield comprising braid and foil on all frequencies. This is particularly noticeable on the optimal frequency of 28MHz, where the signal strength along the length of the cable was about 20dB higher, for the same transmitter power. Despite this, the rate of attenuation along the cable does not appear to be substantially different. For this reason, the coaxial cable with a braid comprising only a low coverage braid is recommended.

From the experimental results presented so far, the attenuation at 27MHz is about 10dB/100m, which is very close to an interpolation to this frequency from the manufacturer's quoted figures, and is the figure that would apply if the cable was connected directly between the transmitter and receiver. As a comparison, interpolated figures ranged from 6.7dB/100m at 7MHz to 17.5dB/100m at 144MHz. It is anticipated, therefore, that the range at 27MHz will be several hundreds of metres, perhaps to a kilometre, although the exact distance will depend on the specification of the radio equipment that is used as part of the system. To contrast this with a standard mining leaky feeder system, the Becker Smart Com system has an attenuation of 4.6dB/100m at VHF and 6dB/100m at UHF, although it is recommended that repeaters re used every 500m or 350m respectively. This suggests that the low-cost coaxial cables compares quite favourably when its much reduced weight and cost are taken into account. However, it is pertinent to point out that this assumes a separation of 2m between the mobile handset and the cable. Although it was an aim of this work to provide much more freedom than LF guidewire systems, by relaxing the requirement for the handheld radio to be almost touching the line, it should be noted that the signal could be boosted by a approximately 20dB by standing at a distance of 500mm from the leaky feeder. This is not considered to be onerous to the rescue team, yet it could improve the range.

Field Tests

Rationale

Further to the previously described tests, which were aimed at characterising the cables and determining the optimal frequency, additional tests were carried out using the braid only cable over a longer distance, in order to better understand the operational characteristics. The purpose of these tests was two-fold. First, it was an aim to measure signal strength against distance for over a longer range than was used in the earlier cable selection and evaluation tests. This would permit a better estimate to be made of the maximum range achievable. Second, it was important not just to make measurements, but also to assess performance in a way that parallels operational use, so bi-directional speech tests were conducted.

Despite the previous observation that, of those frequencies tested, 28MHz offered the best performance, for these tests a frequency of 27MHz was used. This is because CB (Citizens Band) equipment operates at 27MHz so low-cost equipment is widely available and can be used legally in many countries. This, therefore, would very much simplify the adoption of such a system by rescue teams. Preliminary field tests confirmed the expectation that 27MHz would offer very similar performance to the nearby 28MHz.

For ease of access, the field tests were carried out in the underground service tunnels at the Universidad Carlos III de Madrid campus. These tunnels range from about 2.0m to 4.5m high and vary in width from about 2.4m to 6.0m. They comprise straight sections separated by mostly right angled bends. These characteristics make them similar in their basic geometry to typical mine galleries, although leaky feeder systems are insensitive to the gallery geometry or geology.

Equipment & Experimental Procedure

For signal strength measurements, an Elad FDM-DUO amateur radio transceiver with its coverage extended to include the 27MHz CB band, and transmitting at 5W, was used for the base station because it could transmit a continuous signal. An SDRplay RSPduo receiver was used as the portable radio because it could provide signal strength readings on a connected laptop. For the speech tests, two handheld CB radios were used, both of which had been re-housed in ATEX cases to demonstrate the viability of this approach for use in coal mines. When used as a base station with a large car battery, these radios produced a transmit power of 4W, while when used as a handheld, with lower voltage batteries, this reduced to about 2.3W. All handheld radios were used with their standard 195mm base loaded vertical antennas. The antennas used exhibited the highest possible gain at 27MHz, within the constraints of portability in an underground environment, as verified experimentally.

For all tests, the cable was installed along the tunnels, to a maximum length of 800m, the base station was attached to one end of the cable and a dummy load was attached to the other end. This setup was used with one or two portable units that were moved along the cable, as required by each particular test.

To monitor the variation of signal strength with range, the base station was configured to transmit a carrier continuously. Then, starting at a range of 50m from the base station, the portable radio was moved along the cable, at a separation of 1.0m from the cable, and the signal strength was recorded at 25m intervals. At selected distances from the base station, signal strength measurements were also made with the handheld radio at separations from the coaxial cable between 250mm and 3.0m.

Two tests were carried out involving voice communication. The first speech test involved communication between the hard-wired base station and a mobile handheld radio. The handheld radio was moved along the cable, at a separation of 1.5m from the cable, and two-way voice communication attempted at 25m intervals. If communication proved difficult, the handheld radio was moved closer to the coaxial cable. The second speech test followed the same procedure except, although the base station was still connected to the coaxial cable, as it would be in a rescue scenario, communication was attempted between two handheld radios. This, therefore, mimicked communication between two mobile members of a rescue team rather than between one member of that team and a stationary controller.

Figure 9 – Handheld CB Radios Re-housed in ATEX enclosures, as used in the Tests

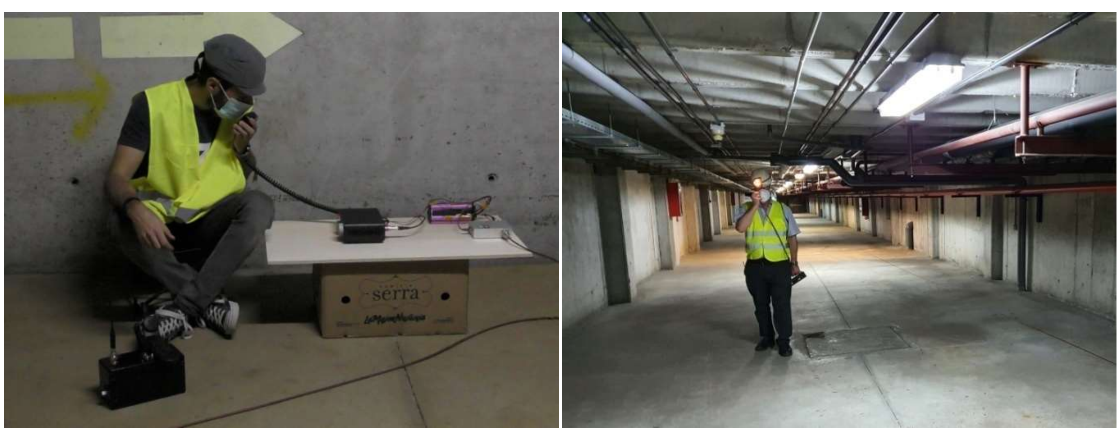

Figure 10 – Tests in Progress in Underground Tunnels

Results

The variation of signal strength with distance is presented graphically as *Figure 11*. A linear trend line is also shown, indicating that the signal decreases linearly with distance.

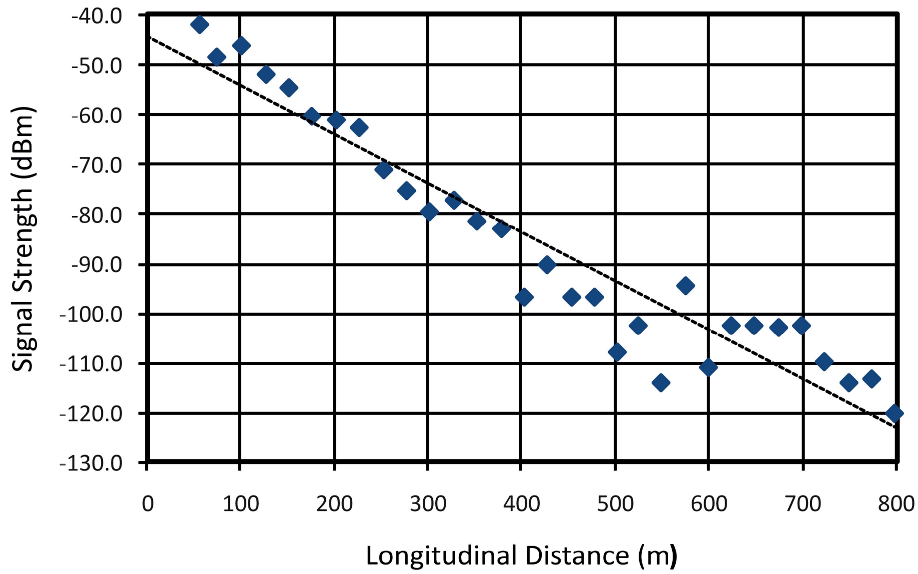

Figure 11 – Variation of Signal strength with Distance in Underground Tunnels

Further tests into the effect of the separation between the handheld unit and the cable were carried out at a few points. The main finding was that, by moving to 250mm from the typical separation of 1.0m which was used for the other measurements, the signal strength increased by about 10dB.

In the voice tests, two-way communication between the base station and a handheld radio was achieved over a distance of 800m, even though it was necessary to move the handheld somewhat closer to the coaxial cable, at a few points, as this range was approached. Speech tests between two handheld radios were also successful to a range of 650m but, again, it was necessary for one or both of the handsets to be held closer to the cable, at some locations, when the range was close to this limit.

Discussion

The results of the signal strength measurements were broadly similar to those of the cable selection and evaluation tests, except that they provided confirmation of the expected results over a distance that would be more typical of use in a rescue scenario. In particular, the average level of attenuation was 10dB/100m, and a useable signal strength was present to a range of 800m. As the end of the cable was approached, peaks and troughs were noticed in the signal and, at a few points, the signal was at the level of the background noise. This is not considered a major problem from an operational viewpoint because it was necessary only to progress a further metre or so to regain the signal. Also, the tests of signal strength against separation between the handheld unit and the cable showed that approximately 10dB was in hand, suggesting that the maximum range would be 900m at the expense of having to hold the handset closer to the cable towards the end of the line, at some points. To reiterate the comparison with a typical mining leaky feeder, the Becker Smart Com system, which uses a cable which is much too heavy for installation as part of a rescue operation (320kg/km compared to 34kg/km for the low-cost coaxial cable), has an attenuation of 4.6dB/100m at VHF and 6dB/100m at UHF, suggesting that the range could be approximately double, even though the manufacturer suggests using repeaters every 500m or 350m respectively.

It is also beneficial to consider how the range compares to that which would be obtained in the same tunnels without the presence of the coaxial cable. Such communication would take place via waveguide propagation which, in a lossy dielectric waveguide such as a tunnel, depends on the frequency being higher than the cut-off frequency which is a function of the tunnel's cross-sectional dimensions. In most of the tunnels used in these tests, cut-off ranges from 37 to 75MHz. For the short section of 6m wide tunnel the figure would be 25MHz but, since the operating frequency is only slightly above this, very high levels of attenuation would result. Calculations indicate a maximum range of less than 10m without the guiding cable. Indeed, even at UHF frequencies well above cut-off, the presence of several right-angled bends along the test path, each contributing an additional attenuation of typically 30-40dB (Jacksha & Zhou, 2016), would have imposed a limit of two bends, in this case limiting the range to about 200m. The fact that the rate of attenuation was approximately the same along the entire route, irrespective of the differing cross-sectional dimensions of the tunnel, further suggests that communication was entirely via the coaxial cable and that performance is independent of these environmental characteristics.

The speech tests were also encouraging, in proving that the signal strength measurements were representative of the use of this system for real world rescue operations. Furthermore, it is clear that the range achieved is significantly greater than that which could be obtained in the same tunnels without the presence of the coaxial cable.

Recommendations

A consequence of choosing 27MHz as the operating frequency is that commercial equipment is readily available and cheap. However, ATEX-certified CB equipment is not available so rescue teams intending to operate in coal mines would have to undertake some development and certification. One option, as illustrated by the equipment used in the field tests, and applicable to organisations requiring a comparatively small number of units, is to base the design on the re-housing of ordinary CB equipment. However, when larger numbers of radios is required, it would be necessary to engage in an electronics design exercise. Although the way in which they are used is novel, the radio circuitry is conventional, so the RF design is not considered to be onerous. However, in the case of systems for use in coal mines, the process of ATEX design and certification should not be underestimated.

In many cases, an operational range of 800m will be sufficient to bridge the gap between the area in which rescue operations are taking place and an area in which the permanently installed communication system is operational. However, in instances where a greater range is needed, several options are available.

The first option, which slightly reduces the convenience of using the system, but is only an issue towards the limit of the range that would otherwise by achieved, is to hold the handset closer to the coaxial cable. This could offer a 100m increase in range.

The second option involves making some incremental changes to the equipment. In the following discussion, improvements are given in decibels (dB), and some indication of the additional range provided can be obtained by looking at *Figure 11*, which shows that the attenuation of the signal is at a rate of about 10dB per 100m. So, for example, if an extra 20dB of signal is obtained, the range would increase by about 200m. It should be noted that some of these recommendations would not adhere to the regulations governing the use of CB radio in some countries. However, in the case of use in an underground mine, the likelihood of any appreciable signal leaking to the surface and causing interference would be negligible and, for this reason, it might be permitted by the regulatory authorities. Note also that, for use in coal mines, ATEX-certified equipment is limited to an EIRP (Effective Isotropic Radiated Power) of 6W (37.8 dBm), this being a combination of the actual transmitter power and the gain of the antenna. The first option for improvement is to increase the power output of the transmitter. Each doubling of the power will provide an extra 3dB of signal. The second option is to use an antenna that has a higher gain than the standard one provided with the handheld radio, and an extra 5dB is easily achievable. Finally, choosing a CB radio which provides speech communication using SSB modulation, instead of the more common FM, as used in these tests, would provide an additional improvement. It is estimated that a combination of these measures, while still using easily portable equipment, could provide a 150-200m increase in range, although some of this improvement might not be permissible in coal mines.

Another option, but at the expense of having to carry and install additional equipment, is to use an in-line amplifier which would be connected to the cable at a point at which signals from the base station are easily readable. Then, a further length of cable would be run after the amplifier, thereby almost doubling the range. Further improvements could be achieved using additional amplifiers. If the power of the amplifier is limited to around 6W, each amplifier and its associated battery would be compact and light, thereby allowing it to easily be carried to the required location.

Tests showed that the range was lower between two handheld radios than between a hard-wired base station and a handheld radio. Another recommendation, therefore, relates specifically to improving communication between two handsets. There is a significant coupling loss between a handset and a leaky feeder but, in the case of a link involving a hard-wired base station, there is only such loss in the complete transmission path. In the case of communication between two mobile handsets, however, there would be two coupling losses and, therefore, a much higher end-to-end attenuation in most cases. A setup that should be considered, if there is a need for communication between mobile stations over a long distance, involves the use of a store-and-forward facility at the base station. This would allow the base station to record and retransmit any message transmitted by a mobile station for reception by another mobile station.

Finally, while not a method of improving the range, consideration could be given to including a feature in the base station to transmit periodic bleeps, when it’s not transmitting speech. Hearing these bleeps would give the mobile team confidence that the communication link is still operable as they progress away from the base station. If this confidence signal is lost, it would prompt the radio operator in the mobile party to walk closer to the coaxial cable.

Conclusion

A novel method of communication, that does not rely on a mine's potentially vulnerable fixed communications infrastructure, has been developed for mines rescue. In particular, we have shown that ordinary coaxial cable, of the type used with domestic TV antennas which has a shield comprising just a low-coverage braid, and which costs about £10 per hundred metres, operates as a leaky feeder. This, therefore, can provide communication along galleries. It is unaffected by obstacles or bends which, together with the limitations imposed by the cut-off frequency, would severely limit the range of non-guided radio communication along galleries, to little more than a couple of hundred metres, except in the case of large perfectly straight galleries. Furthermore, tests have shown that the optimal frequency is very close to the 27MHz band which is used for CB radio, worldwide, which means that low-cost radios are widely available.

Speech communication over a range of 800m has been demonstrated. This could readily be extended to about 1km by small changes to the equipment which have been identified, and it could be extended significantly by using in-line amplifiers. Notably, it has been shown that, unlike some previous wire-guided rescue communication systems, rescue personnel do not normally have to stand very close to the line, thereby allowing communication without unduly hindering their rescue operations.

While recognising that other communication technologies offer different benefits in a rescue scenario, depending on the nature of the incident and the characteristics of the mine, it is suggested that the system described here could play an important role, as part of the mix of methods available to rescue teams.

References

Anonymous. 2020. Dedication Runs Deep. Coal Age 125(5): 26-28.

Buchwald, P.; Golicz, P.; Śliwa, J. and Kowalik, A. 2017. RESYS – Nowy System Telekomunikacyjny dla Ratownictwa Górniczego (English: RESYS – A New Telecommunications System Designed for Rescue Teams. Systems Supporting Production Engineering 6(2): 31-41.

Carreño, J.; Silva, L.; Neves, S.; Aguayo, L.; Braga, A.; Barreto, A. and Garcia, L. 2016. Through-The-Earth (TTE) Communications for Underground Mines. Journal of Communication and Information Systems 31(1): 164-176.

Delogne, P. 1980. Communications: Radio Goes Underground, IEEE Spectrum 17(7): 26-29.

Delogne, P. 1982. Leaky Feeders and Subsurface Radio Communication, Stevenage, Herts; New York: P. Peregrinus on behalf of the Institution of Electrical Engineers.

Dobroski Jr., H. and Stolarczyk, L. G. 1982. A Whole-Mine Medium-Frequency Radio Communication System. 6th WVU Conference on Coal Mine Electrotechnology, Cooley-WL, ed., Morgantown, WV, Jul 28-30, 1982: 124-136.

Emslie, A. G.; Legace, R. L.; Strong, P. F. 1975. Theory of the Propagation of UHF Radio Waves in Coal Mine Tunnels. IEEE Transactions on Antennas and Propagation 23(2): 192–205.

Forooshani,A. E.; Bashir, S.; Michelson, D. G. and Noghanian, S. 2013. A Survey of Wireless Communications and Propagation Modeling in Underground Mines. IEEE Communications Surveys & Tutorials 15(4): 1524-1545.

Gibson, D. 2010. Channel Characterisation and System Design for Sub-Surface Communications. Leeds, UK: Self-published. ISBN 978-1-4457-6953-0.

Hill, D. A. and Wait, J. R. 1976. Propagation Along a Braided Coaxial Cable Located Close to a Tunnel Wall (Short Papers), IEEE Transactions on Microwave Theory and Techniques 24(7): 476-480.

Isberg, R.A. and Chufo, R.L. 1978. Passive Reflectors as a Means for Extending UHF Signals Down Intersecting Cross Cuts in Mines or Large Corridors. 28th IEEE Vehicular Technology Conference, Denver, CO, Mar 22-24, 1978: 267-272.

Jacksha, R. and Zhou, C. 2016. Measurement of RF Propagation Around Corners in Underground Mines and Tunnels. Transactions of Society for Mining, Metallurgy, and Exploration 340(1): 30-37. doi:10.19150/trans.7324.

Jones, B. 1998. New Technology provides Effective Communications for Underground Rescue Operations. Coal International 246(5): .171-174.

Kennedy, G. A. and Bedford, M. D. 2014. Underground Wireless Networking: A Performance Evaluation of Communication Standards for Tunnelling and Mining. Tunnelling and Underground Space Technology 43: 157-170.

Kowalski-Trakofler, K., Vaught, C., Brnich, M., Janskey, J. 2010. A Study of First Moments in Underground Mine Emergency Response. Journal of Homeland Security and Emergency Management 7(1): Article 39, 31 pp.

Marincola, F. 2013. A Low-cost Leaky Feeder System for Cave Communication. CREG Journal 81: 4-6.

Martin, D. J. R. 1975. A General Study of the Leaky-feeder Principle. Radio and Electronics Engineer 45(5): 205 – 214.

Pollei, U.; Papamichalis, A.; Rodriguez, A.; Espada Moreno, F. J.; Rellecke, R.; Wiszniowski, P.; Brenkley, D.; Bedford, M. D.; Kennedy, G.; Bigby, D. N. 2010. Researching the Applications of Open Innovative Wireless Technologies (RAINOW). Luxembourg: Publications Office of the European Union, 2010, 149 pp. doi:10.2777/78643.

Sacks, H. K.; Chufo. R. L. 1978. Medium-Frequency Propagation in Coal Mines. Proceedings of 4th WVU Conference on Coal Mine Electrotechnology, Aldridge-MD, ed., Morgantown, WV, Aug 2-4, 1978: 27-1–27-12.

Souryal, M. R.; Wapf A. and Moayeri, N. 2009.Rapidly-Deployable Mesh Network Testbed. Presented at GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference, Honolulu, HI, 2009: 1-6.

Stolarczyk, L. G. 1991. Emergency and Operational Low and Medium Frequency Band Radio Communications System for Underground Mines. IEEE Transactions on Industry Applications 27(4): 780-790.

Yarkan, S.; Guzelgoz, S.; Arslan, H. and Murphy, R. R. 2009. Underground Mine Communications: A Survey. IEEE Communications Surveys & Tutorials 11(3): 125-142.

Yenchek, M. R.; Homce, G. T.; Damiano, N. W. and Srednicki, J. R. 2012. NIOSH-Sponsored Research in Through-the-Earth Communications for Mines: A Status Report. IEEE Transactions on Industry Applications 48(5): 1700-1707.

Zhang, Y. P.; Zheng, G. X. and Sheng, J. H. 2001. Radio Propagation at 900 MHz in Underground Coal Mines. IEEE Trans Antennas and Propagation 49(5): 757–762.