THE SURVIVABILITY OF UNDERGROUND COMMUNICATIONS SYSTEMS FOLLOWING MINE EMERGENCY INCIDENTS

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SUMMARY

Emergency communication systems can play a crucial role in effecting appropriate responses to mine incidents. However the impact of fires, flooding, explosions and cave-ins can render some communications systems inoperable - just when they are needed most. This paper presents the results of a study that compares the survivability of leaky feeder cables with a proposed radio network. It is demonstrated that cabled systems are vulnerable to disruption and that the radio network has the potential to provide substantially improved survivability.

INTRODUCTION

In recent years, a number of emergency mine incidents have occurred, involving multiple fatalities and a major loss of mine infrastructure. Clearly a lack of effective communications during emergencies has prevented rescue efforts. The occurrence of mine emergency incidents such as those documented in [1] have prompted the development of a new solution to the emergency underground communications problem.

The paper outlines a communications network that is able to survive mine hazards. Each component of the network is independent of the other components yet remains connected to them via multiple redundant routes. The objective is to ensure that there is not a reliance on any component, so that if any part of the network is destroyed, the remainder continues to function.

It is important to examine whether a new solution can offer significant benefit over existing ones. In the case of emergency underground communications, the key factor is survivability. The contribution of this paper is the presentation of a model based comparative study into the survivability of underground communications following mine emergency incidents.

PROBLEM STATEMENT

In Australia, multiple-fatality mining incidents involving explosions, cave-ins and flooding have occurred about every 4 – 5 years. In a recent review of rescue and mine recovery activities [2], three rescue phases are discussed: *self rescue*, *aided rescue* and *mine recovery*. An emergency underground communications system should support these activities. In the support of *self rescue*, underground staff need to be made aware of safe exit paths for self escape. In the *aided rescue* phase, the emergency management team need to know where people are trapped in a mine by a physical impediment or injury. Finally, in the *mine recovery* phase, data about prevailing conditions is desired in order to minimise the exposure of risk to workers while attempting to stabilise the situation in a mine.

A survey of communications systems for underground mines is detailed in [3]. A difficulty faced by conventional communications systems however, is surviving the mine incidents. The very conditions such as rock falls, tunnel collapse, fires, explosions and flooding, during which communications are needed most, can also render them inoperable. An emergency underground communication system needs to be robust with respect to the potential hazards. The factors that can improve survivability include: *hardening*, *redundancy* and *autonomy*. *Hardening* refers to a tolerance of communications components to harsh environmental conditions. For example fibre optic cables [3] are susceptible to being severed by moderately light rock falls. Leaky feeder cables [3,4] are far more resilient but they too can be damaged during cave-ins, fires and explosions. The practice of embedding twisted (wire) pairs within three phase power cabling [5] is probably the least prone to failure. A problem that can plague cable based systems is the requirement to maintain a nominal termination impedance: accidental disconnection can result in severe performance degradations. Inbuilt *redundancy* is highly desirable, this permits some capabilities to be sustained in the event of outages.

Indeed the review paper [2] concludes that "The system should be able to survive a section being taken out so systems with a single high capacity backbone are vulnerable." Here *autonomy* may be defined as an ability to function independently of any strategic infrastructure. For example a system is described in a subsequent section which can provide service in the presence of mine power supply failures.

In summary, the requirements for emergency underground communications include: indicating exit paths, locating trapped miners and if possible, mine condition monitoring. A solution is required to be reliable and robust with respect to various mine hazards. This may be achievable via a mix of hardening, redundancy and autonomy. Above all, any candidate communication systems must be feasible to implement. With up to hundreds of km of communication paths per mine, an implementation decision is invariably based on the cost per km.

A NEW SOLUTION

An emergency system is being developed for Location And Monitoring for Personal Safety (LAMPS). The system, based on radio communications between low-cost, self-powered beacons, provides the location and key vital signs of all underground staff, and, in an emergency additionally provides information on optimal evacuation pathways via primary and/or secondary egress. It also provides a capability for monitoring the location of equipment.

While there is need for a comprehensive system capable of all modes of communications from face to surface, LAMPS does not pretend to be the solution to all underground mine communications problems. It is a sensible, practical step targeted at progressing emergency communications and location. LAMPS works like a cellular radio system except that the individual beacons are implemented in hardware and do not require computers. This results in a installed cost per beacon in the hundreds of dollars compared to thousands of dollars for other cellular systems.

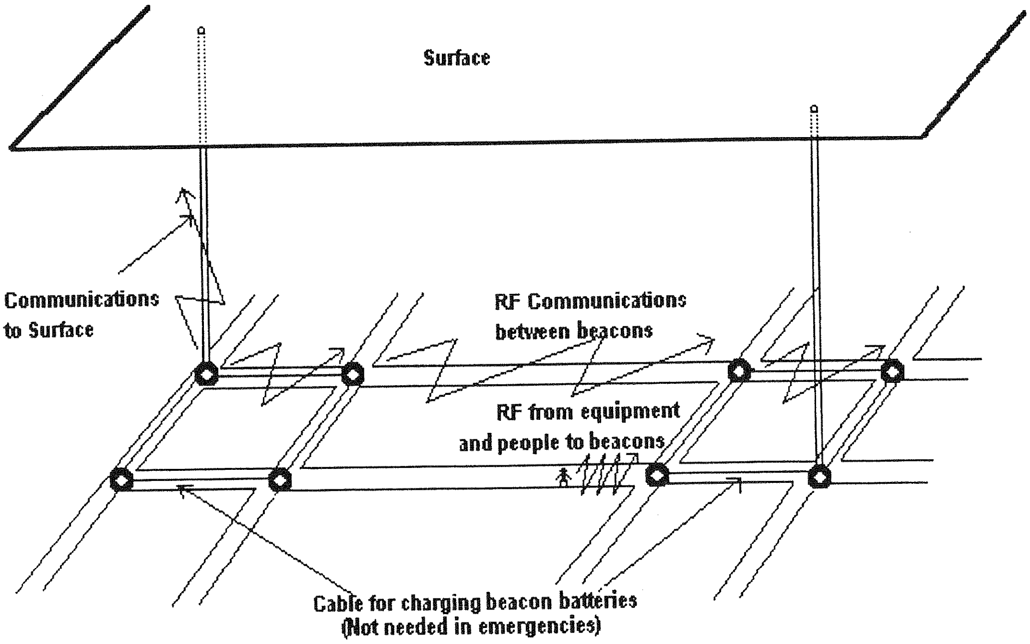

Fig. 1. A depiction of the LAMPS mesh network.

The LAMPS features a totally new protocol that permits communications to automatically find every other beacon in the system. Each beacon contains complete current information on the location and status of all monitored personnel and equipment within the mine. In conventional approaches to survivable or self-healing networks, the nodes are arranged in hierarchical ring architectures (for example, see the tutorial papers [6,7]). The LAMPS beacons are configured in a mesh-like arrangement as depicted in Figure 1. There is no communication backbone or hierarchy; each beacon is autonomous.

The LAMPS beacons are independently battery-powered. Wires are used to trickle charge the batteries in each beacon, but are not relied upon during an emergency as the system uses battery powered short-range radio frequency (RF) communications. Other communications infrastructure such as wiring can optionally be used to enhance the redundancy further. The beacons are identical and thus interchangeable. As a minimum, they need to be installed in areas where miners are deemed to be at risk, and, along multiple access routes to those risk areas. The beacons can be located within primary and secondary egress paths to indicate safe escape and rescue exit paths. In addition, LAMPS could be applied to reporting the location of various assets (such as vehicles) permitting improved effectiveness to increase availability of underground mining equipment. LAMPS has the potential to communicate sensor data such as: the detection of fires, explosions and gas monitoring, provided appropriate sensors are available.

SURVIVABILITY COMPARISON

Modelling Assumptions

The objective of the study is to investigate the merits of redundant communication paths. Two panels of a *board and pillar* mine were selected, namely panels 510 and 520 at Moura No. 2 Underground Mine.

Some simulations were conducted which are based on a number of Modelling assumptions that are described below. For convenience of analysis, the communication paths within the panels are partitioned into *cells*. Here a cell denotes each tunnel intersection and midway between each tunnel intersection. The tunnel intersections shown in Figure 2 occur at approximately 50m intervals. Thus along a tunnel, the cells are spaced approximately 25m apart.

Our approach is to examine the availability of communication paths between the two individual panels and the intersection after supposing that a number of cells have failed. The model is restricted to the case where no cell failures are considered within the panel intersection (where 510 and 520 meet), in which the communication sources are presumed to be located.

Three communications options are modeled: a continuous leaky feeder cable, two branched leaker feeder cables and the proposed RF network. It is assumed that the maximum operating range between a hand held transceiver either a leaky feeder cable or a network beacon is 40m. Some possible layouts of cables and network beacons that result in 100% communication coverage are shown in Figure 3. In the single cable layouts of Figure 3(a), it is assumed that there is only one communication path between each panel and the intersection. Figure 3(b) shows example cable layouts that possess some redundancy in which each panel has two branches connected to the intersection. It is assumed that RF beacons exist within the intersection of Figure 2 and are networked to panel beacons, located at every tunnel intersection as shown in Figure 3(c).

We are interested in the fraction of cells that have communication available (with the sources in the intersection) after a number of cells are presumed to have failed. In other words, the task is to count the residual cells that are adjacent to any communication systems which remains connected. This is easily calculated, since it governed entirely by cell adjacency and connectivity. The results are dependent on how failures are assumed to be propagated, which is discussed in the next section.

Failure Propagation

The study is confined to investigating cell availability when up to about 10% of a panel's cells have failed. For panels 510 and 520, it turns out that the number of cells are $n=198$ and $n=312$ respectively. The selected number of failed cells are $N_f \in \{1,2,5,10,15,20\}$ and $N_f \in \{1,2,5,10,15,20,25,30\}$ for panels 510 and 520 respectively.

There are many possible ways in which failure propagation could be modeled. A convenient approach is the random walk

$$x_{k+1} = x_k + u_k \qquad (1)$$

and

$$y_{k+1} = y_k + v_k. \qquad (2)$$

where x_k and y_k represent the coordinates of the k^{th} failed cell in the horizontal plane, in which $u_k, v_k \sim \mathcal{N}(1, N_f)$. That is, gaussian processes of unit mean and variance N_f governs the propagation of failures from one cell to another. The initial values x_1 and y_1 are selected randomly within the panel.

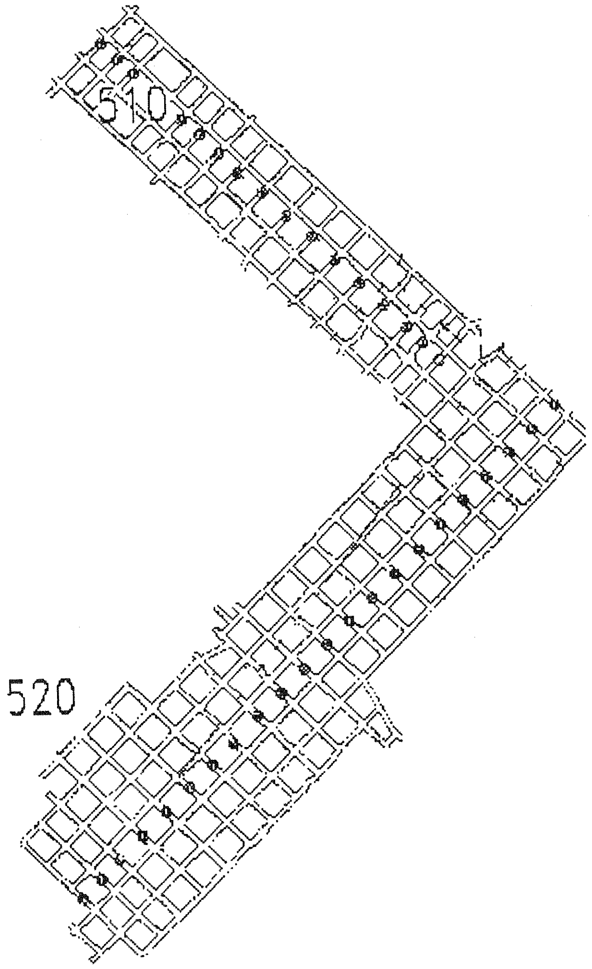

Fig. 2. Panels 510 and 520 of Moura No2 Underground Mine.

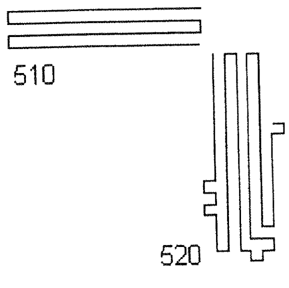

Fig. 3(a). Single cable layout.

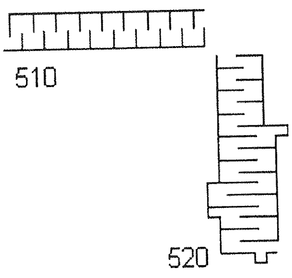

Fig. 3(b). Branched cable layout.

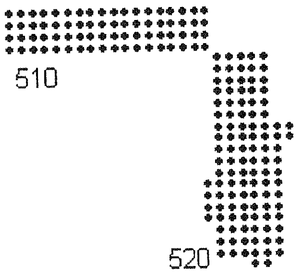

Fig. 3 (c). RF network layout.

Simulation Results

The number of cells that have communication available depend on the particular selection of failed cells. Therefore the simulations were conducted, in which the mean number of available cells, denoted by N_a, was calculated over 1000 realisations of the random processes in (1), (2) for each trial. The probability of cells having communications available, versus N_f, for panels 510 and 520 are shown in Figures 4 and 5 respectively. The dotted, dashed and solid lines respectively indicate the performance of a single continuous cable, two branched cables and an RF network (such as LAMPS).

The data demonstrates the benefits of redundancy. In the case of one continuous leaky feeder cable, the mean cell availabilities degrade quite rapidly, down to around half of the total number of cells, when only two to five cells have failed. This vulnerability is attributable to a lack of redundancy. When there is just one backbone, a failure near the source precludes all communications downstream of the failure. Figures 4 and 5 illustrate that two communication backbones can be better than one (provided that they are sufficiently separated). When N_f is small, the propagation model described in Section 4.3 generates failures that are closely spaced. Consequently, the branched cable arrangements depicted in Figure 3(b), offer greater improvement for small N_f, when it is less likely that both backbones will have been affected by cell failure.

Figures 4 and 5 demonstrate that the RF network can outperform leaky feeder cable solutions. It can be seen that N_a decreases approximately linearly for small N_f. Since there is no backbone in the RF network modeled here, we have $n-N_f \geq N_a$, in which the inequality accounts for any enclosed cells. It can be seen that the network performance degrades at a higher rate for panel 510 because it is narrower and it follows that there are less redundant pathways. In the case of panel 520 for example, it is seen that for 10% cell failures, the RF network can provide about 80% cell availability. This contrasts with about 10% and 30% availability for the single and branched cable arrangements respectively.

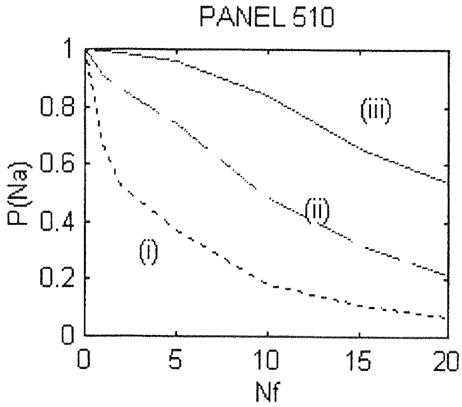

Fig. 4. Probability of cell availability for Panel 510,
(i) Single cable, (ii) Branched cable (iii) RF network.

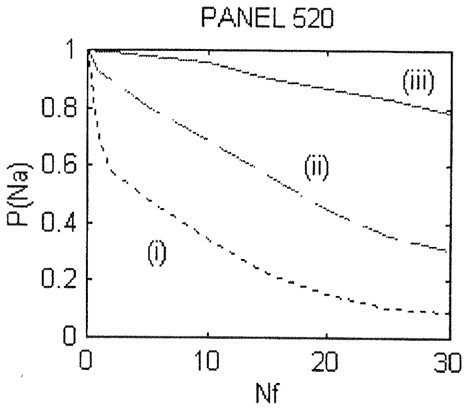

Fig. 5. Probability of cell availability for Panel 520,
(i) Single cable, (ii) Branched cable (iii) RF network.

The above data is indicative only. While panels 510 and 520 are typical of a board and pillar mine, any cell availability calculations depend on the topography at hand and on the Modelling assumptions. The simulations do emphasize the importance of providing redundant communications paths. In particular it is observed that: the performance of a single cable layout can degrade quite rapidly with increasing cell failure; a branched cable layout can yield an improvement; and, an RF network can provide by far the greatest improvement.

Possible Modelling Refinements

There are many possible Modelling refinements that could be included, should a more detailed investigation be warranted. In practice, dead spots are usually abundant because the provision of 100% communication coverage is currently cost prohibitive. The layouts of Figure 3 were prompted by the 40m operating range of existing leaky feeder systems. The range of LAMPS beacons and emergent leaky feeder systems is 50m which permits an increase in reliability.

A number of simplifying (albeit conservative) assumptions have been made to investigate the comparative advantage of redundancy. For example, it is assumed that complete cell failures occur, whereas RF beacons can continue communication through any tunnels that are partially blocked. There are often pathways through to adjacent panels which increase the scope for network redundancy. Cabled systems are acutely sensitive to impedance mismatch and thus are intolerant of accidental disconnections. The failure propagation model of Section 4.3 is severe, but it serves to highlight some worst case scenarios. Nevertheless, this study is tendered as a general approach for the open question of quantifying communications survivability.

CONCLUSIONS

Requirements exist for emergency underground communications systems. There are three roles in which communications support is desired, namely self rescue, aided rescue and mine recovery. Arguably a candidate system should possess some inbuilt survivability to counter the possible hazardous incidents. The factors that can improve survivability include hardening, redundancy and autonomy. However, a mine implementation decision is invariably based on the cost per km.

A new solution for the emergency underground communication problem has been outlined. The

Location And Monitoring for Personal Safety system relies on a network of low cost autonomous beacons to provide redundant communication paths. During emergency incidents the mine power may fail and cables can be severed; to this end, the beacons are battery powered and communications are effected via low power, RF transmissions.
A simulation study has been conducted in an attempt to quantify the advantage of an RF network, versus leaky feeder cable. In a particular case study, in which 10% of mine is deemed to have failures, it is demonstrated that a single leaky feeder cable layout, on average, exhibits only about 10% availability. In contrast, a branched cable arrangement can offer about 30% availability, whereas a RF network can provide about 80% cell availability. While the study does rely on simplifying assumptions, the approach is conservative and certainly does make a case for a RF network.

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