NIOSH-Sponsored Research in Through-the-Earth Communications for Mines: A Status Report

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***Abstract*—This paper presents the results of recent contractual research sponsored by the National Institute for Occupational Safety and Health that aimed at demonstrating the feasibility of through-the-earth (TTE) wireless communication in mining. TTE systems, developed by five different contractors, are discussed with a focus on technical approach, prototype hardware, and field test results. System features include both magnetic and electric field sensing, loop and line antennas, digital and analog processing, noise filtering and cancelation, and direction finding. The systems were demonstrated at commercial mine sites. The results of these tests are characterized by transmission range and power levels. This paper concludes with a discussion of issues that remain to be resolved as TTE communications are implemented. These include text versus voice format, acceptable time delays, portability, ease of deployment, an interface with existing communications systems, permissibility, and the effect of geological variations.**

I. Introduction

THE Mine Improvement and New Emergency Response Act of 2006 (MINER Act) [1] mandated that each underground coal mine in the U.S. develop an emergency response plan within three years. The plan must provide for two-way wireless postaccident communications between underground and surface personnel as well as electronic tracking of underground workers. Communication between rescuers at the surface and miners in underground mines is particularly important during emergencies including explosions, fires, inundations, and entrapment from rock falls. In an emergency, conventional communication systems may be interrupted if sufficient infrastructure is damaged. An alternative is to directly communicate to the surface through the overburden. Typical high-frequency wireless technologies cannot penetrate significant distances through the earth. However, signals at frequencies below 10 kHz can penetrate the earth and offer promising capabilities to establish through-the-earth (TTE) connections. Proposed TTE communications applied to mining typically involves inducing an ultralow frequency (ULF) signal into the earth through an antenna and receiving that signal through an antenna. The transmission path may be from underground to surface or vice versa. A major advantage of TTE technology is that it requires much less underground and surface infrastructure than higher frequency mine communication systems.

Although TTE has long been considered a desirable technology for mine emergencies by safety experts, research conducted by the U.S. Bureau of Mines (USBM) in the 1970s determined that it would be technically difficult to establish TTE transmitting capability from inside a coal mine since the transmitter power must be limited to meet permissibility requirements [2]. However, recent advances in receiver and signal processing technology have led to better sensitivity and offer new possibilities for TTE communication.

In June 2006, the Congress allocated Emergency Supplemental Appropriation funding for improvements in mine emergency response, including communications and tracking, to the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR). The funds targeted technologies that could be mine-ready in 24–36 months. This led to a series of contracts and grants including those reviewed in this paper, which were awarded via Broad Agency Announcements (BAAs) [3], [4].

II. TTE Communications

Discounting antennas and transceiver hardware, TTE systems have the potential to provide true wireless communications between underground and surface personnel, meeting the intent of the MINER Act. With less infrastructure than traditional communication systems require and typically stored or cached until deployment, TTE systems are more likely to survive an underground explosion and provide a communications link to the surface for trapped or escaping workers. These systems typically operate at frequencies less than 4 kHz, with the electromagnetic signals characterized by wavelengths measured in thousands of meters. The path for transmitted signals may be vertical through the overburden or horizontal through the coal seam. The half-duplex systems provide communications in both directions but only one direction at a time (not simultaneously). They can provide voice in real time, voice, or text messages or emit a periodic beacon signal, which can be sensed on the surface and allows rescuers to estimate the location of its origin. These modes are characterized by different signal transmission rates. For example, rates as high as 2.5 kb/s permit real-time digitized voice, whereas rates as slow as 10 b/s only allow text at one keystroke per second. Obviously, real-time voice is desirable, but TTE transmission is affected, and many times limited, by a number of factors.

The factors that affect signal transmission include the frequency, transmitter power, and the nature of the overburden, such as its electrical conductivity, its depth, and any geologic variations that present changes in the overburden electrical properties. The reception of a transmitted signal is also affected by the presence of electrical noise, both underground and on the surface and both natural and man-made. The ability of the system to communicate is dependent upon the remaining energy of the transmitted signal, after attenuation through the earth, being sufficient to overcome the noise at the receiver location. Finally, the antenna configuration (e.g., loop or linear) can impact transmission and reception.

It is known that the lower the frequency of a transmitted signal, the lower the signal attenuation through the earth. However, at very low frequencies, data transmission rates are limited and only text messages or preprogrammed messages may be possible. The lowest practical rates generally allow the greatest depth penetration and are typically used to generate beacon signals underground. The beacon signals can be detected by rescuers on the surface at long ranges for which data and voice transmissions are not possible, and can help determine the approximate location of the transceiver underground.

Given these limitations, it is desirable to have multiple transmission frequency capability to optimize range and mode for a given set of geological conditions. Transmission range is proportional to transmitter power but, underground, consideration must be given to the safe use of electrical equipment in potentially methane-laden atmospheres. Consequently, transmitter power underground can be limited.

Turning attention to the hardware anticipated for a TTE communications system, large loop antennas may be used to transmit and receive small magnetic signals. ferrite core windings may be employed in receiving antennas to conserve space for portability. To optimize coupling and, consequently, signal transmission, both sending and receiving loops should be oriented in the same direction (see Fig. 1) [5]. Multiple ferrite windings may be placed in an X–Y–Z configuration for receiving antennas. Antenna outputs can be then vectorally added to obtain a resultant signal. Underground transceivers can be used for communication both between surface and underground and from point-to-point (horizontally) within the mine. The transceivers may be transportable or in a fixed location, but they must be limited in power to ensure safe operation in potentially hazardous atmospheres.

Surface antennas may theoretically consist of large loops of wires, which are thousands of meters in circumference and encompass most of the mine. However, from a practical standpoint, they may be limited in size by the terrain and by limited access to property above the mine. Alternatively, smaller antennas on the surface may be placed above stationary antennas underground or deployed during an emergency. Much greater power may be used on the surface to transmit a strong signal to the underground environment, with higher frequencies and higher data rates for voice transmission. For the greatest

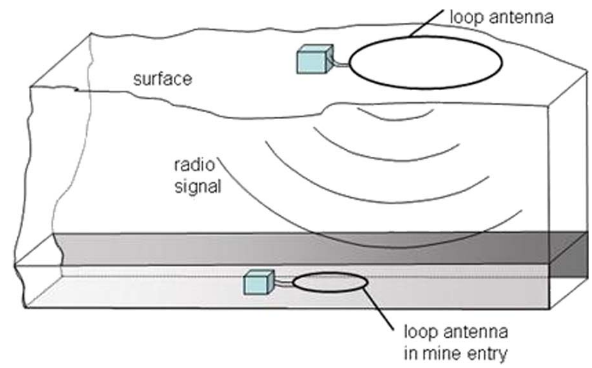

Fig. 1. TTE communications system.

signal, i.e., maximum coupling between antennas, the surface loop antenna should be above the underground antenna. Signal reception on the surface will generally decrease if the surface antenna is not directly above the underground transmitting antenna or if the separation distance increases.

Projects with five firms were funded through NIOSH to investigate the feasibility of applying TTE technology to mining. All contracts resulted in the development of prototype or preprototype systems. System features include both magnetic and electric field (E-field) sensing, loop and line antennas, digital and analog processing, noise filtering and cancelation, and direction finding. The systems were evaluated in tests at various commercial mine sites. The following summaries describe principles of operation, hardware, and test results. Mention of commercial names does not constitute endorsement by NIOSH.

III. Alertek, LLC

The objective of Contract 200-2008-25720 awarded to Alertek, LLC was to design, build and demonstrate a battery-powered TTE wireless voice communications system for overburdens up to 183 m [6]. The technical approach was to establish magnetic coupling between separate loop antennas underground and on the surface. Voice communication is the key feature of the system. The signal from a handheld microphone is amplified, processed, and entered into a digital signal processor where it undergoes further conditioning (see Fig. 2). A single sideband is applied to a magnetic loop antenna. The magnetic flux linking the receiving antenna generates a voltage replicating the transmitted voice, along with noise being picked up at the receiving end. The voice message is extracted, and the baseband is amplified and applied to a speaker or optional earphones. The technology does not use speech compression, avoiding the errors and inherent delays associated with error correction.

The system can also send and receive digital text messages by using phase-shift keying. Incoming text messages are displayed on a liquid crystal display (LCD). The system also has beacon signal capability, which is treated similarly to a text message, except that only a single tone is transmitted and that the received signal is applied to a speaker.

Fig. 2. Alertek surface transceiver.

Fig. 3. E-Spectrum subsurface transceiver shown on surface.

The prototype system was first tested at the NIOSH Experimental Coal Mine in Pittsburgh. The system delivered two-way real-time-voice TTE communication between surface and underground at approximately 30.5 m depth. This was achieved when the transmitting and receiving loop antennas, oriented horizontally on the earth, were directly inline vertically, as well as when the surface transceiver was moved about 91.5 m off the vertical axis. In a follow-up demonstration, real-time two-way voice and text communications were successfully established horizontally between a point outside the drift portal of the experimental mine and a point inside the mine, approximately 305 m away.

Further tests of the prototype communication system were conducted at a commercial coal mine in southwestern PA. The mine depth was approximately 177 m with a surface transceiver located directly above the underground unit. Two-way communications were established via beacon, text, and real-time voice at relatively low power levels (antenna currents were approximately 1.5-A RMS). Electrical noise sources were nearby both underground and on the surface. The transceiver on the surface was in proximity to the mine elevator and power lines approximately 30.5 m away. The underground transceiver was located near a trolley line with the 122-m loop antenna encircling a coal pillar. Voice reception without delay at 3150-Hz resonant frequency on the surface was of such quality that the voice of the person speaking underground could be identified. Underground voice reception was intermittent, with the poor performance attributed to a design deficiency in the underground receiver. The potential impact of this work is that it offers a real-time voice option for relatively shallow mines. However, the system is currently not approved as permissible.

IV. E-Spectrum Technologies

The goal of Contract 200-2008-26818 with E-Spectrum Technologies was to analyze an existing ULF TTE system and to adapt and test it for communication with underground mine personnel [7]. The basis for the adaptation was an E-field sensing system used for oil and gas drilling that was modified to include remote and surface units, appropriate software, and worker interfaces. System specifications addressed suitable carrier frequencies, bandwidth, data format, modes of operation, antenna topology, power requirements, and packaging.

A critical element was developing and testing the transmitting and receiving electrical field antennas. Both antennas require low-resistance earth connections. On the surface, these antennas can take the form of a wire connection to earth via a driven-rod ground bed. Fences with metal conductive posts that are strung with wire conductors were also found to be excellent transmit and receive antennas when coupled with the prototype system. The most challenging aspect of implementing the system in a coal mine is providing an E-field antenna for the underground transceiver unit. One possibility is the installation of roof bolts with conductive epoxy at regular intervals in the mine. These roof bolts could be connected with conductive braid or wire, or with wire roof mesh to further minimize the system impedance to earth.

E-Spectrum Technologies tested the prototype system (see Fig. 3) at NIOSH's Safety Research Coal Mine in Pittsburgh for underground-to-surface communications. The surface E-field antennas were composed of two driven-rod ground beds separated by 30.5 m. The subsurface system relied on a series of interconnected roof bolts to establish a relatively low resistance connection to earth. Text communications were achieved at frequencies of 10 and 22 Hz with an estimated surface to underground diagonal separation distance of 366 m. The contractor also successfully achieved two-way text communications (in prior testing) at approximately 610 m using practical antenna configurations in relatively low-conductivity limestone rock formations.

Further evaluations demonstrated that the ULF system was technically feasible for text communications from underground to the surface diagonally up to 1.6 km in a commercial mine. Ranges of this magnitude were achievable because the system operates at such low frequencies. The performance tradeoff is the low data rate, which limits communications to text messages. The prototype subsurface transceiver unit was fitted with a Bluetooth interface that would allow miners underground to use a handheld unit, such as a cell phone or a personal digital assistant, as the user interface for text messaging to the surface. The handheld device can be up to 30.5 m away from the transceiver.

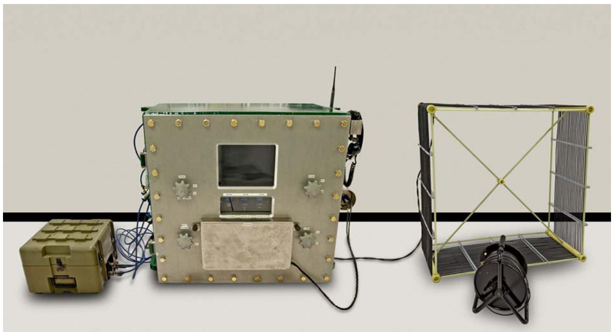

Fig. 4. Lockheed Martin underground prototype.

The system will need to be modified before it can be submitted for approval by MSHA as permissible. This may entail selection of appropriate explosion-proof housings and design of antenna barriers. The potential impact of this work is that it offers an alternative approach (E-field sensing versus traditional magnetic field sensing) for TTE communication, which holds promise for long-range communication.

V. Lockheed Martin MS2

The purpose of Contract 200-2007-22843, awarded to Lockheed Martin, was to develop and demonstrate a two-way TTE communication system for mines that applies state-of-the-art communications technologies to overcome subterranean wireless communication challenges while meeting acceptable industrial safety standards [8]. In subsequent Contract 200-2009-32021, Lockheed enhanced key features of the TTE prototype to improve its usability, investigated design changes to comply with mine safety standards, ruggedized the hardware, and demonstrated performance at coal mine sites [9].

Lockheed Martin developed a wireless TTE prototype communication system based upon magnetic field generation and sensing. The system consists of surface and underground transceivers. The receiving antennas are made up of three ferrite core windings arranged orthogonally and housed in a portable case. Variously sized single- and multiple-turn air-core antennas are used for transmission from underground to surface, including a single loop of wire that can be deployed around a coal pillar. Voice and text messages are possible at signal transmission frequencies of 3200 and 330 Hz, respectively. Reception of either channel is automatic regardless of the transmission frequency selected. The surface and underground receivers have noise cancelation capability.

The durability and reliability of the original prototype system were improved by making the hardware resistant to humidity, mechanical shock, dust, and water (see Fig. 4). The power usage of the amplifier was reduced to increase battery life while maintaining transmission range, and features were incorporated to enhance usability. A beacon mode was developed. A collision avoidance protocol was used to minimize message collisions involving multiple active transceivers, i.e., having the underground transceiver trying to broadcast when the surface transceiver is also trying to broadcast. A radio relay capability allows for interoperability with conventional handheld radios. The voice message is stored and then transmitted at low frequency through the earth. Another TTE unit receives and stores the message, after which it is replayed.

The system was tested at the NIOSH Pittsburgh facility and at several coal mines in southwestern Pennsylvania, northern West Virginia, and Virginia. Prototype evaluations demonstrated ranges of 472.5 m for text, from the underground mine to the surface. In these tests, the surface transceiver was directly above the underground unit with the underground transmitting antenna operated at relatively low power comparable to intrinsic safety restrictions.

With the prototype operating at higher power levels, Lockheed demonstrated ranges, from the mine to the surface, of 305 m for voice and 594 m for low-rate text. Tests have also been conducted between two distant points, both within the mine. The maximum range achieved for the through-the-mine testing was 1494 m for text and 640 m for voice. Greater ranges are anticipated for the beacon mode signal. A surface direction finder was also demonstrated to estimate the origin of the underground beacon signal. The angular direction of the beacon signal was measured at multiple locations on the surface, and through triangulation, the approximate location of the transmitter antenna underground could be determined.

VI. Stolar, Inc.

The objective of Contract 200-2009-32117 with Stolar, Inc. was to design and build a two-way TTE communication prototype system and then conduct field tests at several underground mining operations [10]. The system developed employs low-frequency transceivers, relatively low-power instrumentation, and simple portable hardware. It was field tested at several hard rock and coal mining sites. Preliminary testing in a western U.S. noncoal mine proved that Stolar's TTE technology could provide communication through a variety of rock types, with depths ranging from 213 to 396 m, depending on the location in the mine. The most recent demonstration achieved two-way text messaging at a vertical range of nearly 244 m in a commercial coal mine in southwestern Pennsylvania with signal strength in reserve. The maximum vertical range at this mine was extrapolated to be nearly 335 m.

The antennas used for this project were rigid air-core loops of either 1.2- or 1.8-m diameter (see Fig. 5). The antennas can be used as either vertical or horizontal magnetic dipoles (VMD or HMD, respectively) lying flat or standing upright, as shown in Fig. 5. The VMD mode is predicted by the vendor to be optimal for low-noise environments where TTE signal sensitivity can be high, permitting the range of signal penetration into the earth to exceed 60% of the maximum capabilities of the system. The HMD mode is predicted to be optimal for higher noise environments since less noise from horizontal power lines can couple to the vertical antenna. However, the HMD mode has less signal sensitivity and will reduce the depth of penetration to less than 70% of the maximum capabilities.

The primary screen menu on the transceiver's LCD display allows the user to enter custom text messages or turn on a location beacon. Another screen menu allows the user to select from a variety of "predefined" messages. The text messages use a selected frequency of either 2 or 4 kHz. The default lower

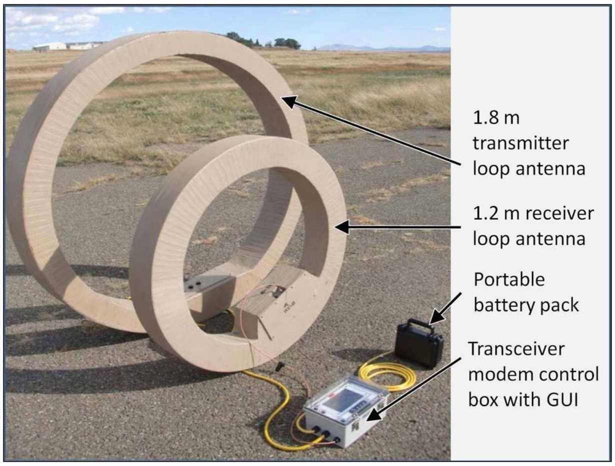

Fig. 5. Integrated Stolar surface transceiver with antennas.

frequency is commonly used for depths of 152 m and deeper. The higher frequency has less penetrating power in the earth (higher attenuation rate) and is typically reserved for short-range applications where background noise at 2 kHz may be higher than normal. In addition to the text message signals, each system also possesses a beacon mode, which allows the transceiver to be used as a continuous transmission source for detection and location by using a surface gradiometer, which triangulates the received signal by sensing the difference in the magnetic field at several locations in space. To help with field testing and data collection, and to assist with the transceiver setup at different sites, a diagnostic program was created that wirelessly links to the individual transceivers for real-time signal analysis, including signal strength, decoding sensitivity and threshold, and background noise. The contractor initiated the MSHA approval process for a system featuring an explosion-proof enclosure for the transceiver.

VII. Ultra Electronics

The goal of Contract 200-2009-31292 with Ultra Electronics was to fabricate and test a previously designed TTE communication system for use in an underground mine [11]. In this system, the voice signal to be transmitted is conditioned and converted to digital form. It is then compressed, using a vocoder, and packetized. The bits in the packet modulate the transmitter output using an orthogonal frequency-shift keying (FSK) approach. The transmit loop antennas consist of flexible wire of several turns. The receive antennas, internal to the transceiver enclosures, feature windings on ferrite rods. The receiver provides selectivity using analog and digital filtering, demodulates the FSK signal, passes the received "voice" data to the vocoder for regeneration of the audio, and finally drives the speaker (or earpiece) with the audio signal. The current system is powered internally by two 12-V lead-acid batteries. The units are not approved as permissible at this time.

The transmitter can also accept serial data from an RS-232C port and text information from an external device (keyboard, suitably configured terminal device, or personal computer). For serial data, the magnetoinductive link employs a packeting approach similar to that for voice mode. The received serial

Fig. 6. Transmitting voice to underground with the Ultra system.

data are made available to the RS-232C port on the receiver. The TTE transceiver operates similar to a two-way radio, using a push-to-talk half-duplex mode. Using the low-bit-rate text mode, the range into the earth is doubled over that for voice.

Six magnetoinductive TTE communication devices were built according to a plan approved by NIOSH. The modules are digital transceivers supporting both voice and text communications. Wideband mode at 4.82 kHz is used for digital voice and data, whereas the narrow band is for data only. Four transmit antennas (3.8-, 12.5-, 26-, and 90-m loop diameter) having different transmission ranges were also included.

The system was evaluated to determine TTE operating range, electrical noise interference, an interface to other emergency communication subsystems, and repeater functions, as well as ease of use and mechanical ruggedness. Preliminary testing of the equipment in a Pennsylvania coal mine revealed that narrow-band communication of text was successful, but real-time voice was not achieved. Magnetic signal and noise were also recorded for later analysis. High attenuation of the magnetic signal and high electrical noise levels in the mine were determined to be the cause for the reduced performance of the wideband voice communication. In a follow-up test at the same Pennsylvania coal mine (see Fig. 6), a larger transmit antenna was employed to increase signal strength to overcome the attenuation. In addition, a noise-canceling comb filter for 60-Hz harmonics was implemented to reduce the impact of the in-band noise. Successful real-time voice reception on the surface from an underground transmitter, as well as low-speed text communication, was achieved vertically through more than 183 m of overburden. The ability of the triaxial magnetometer to directionally detect underground transmitted signals was demonstrated for possible application in locating trapped miners.

VIII. Summary and Future Challenges

The feasibility of two-way TTE communications in underground mines has been demonstrated in five recent NIOSH-sponsored research contracts. These projects involved development of prototype units that were evaluated at commercial mines. The systems used varied approaches to establish communication through the earth. Most featured magnetic field

TABLE I
SUMMARY TABLE OF TTE PROTOTYPE TESTS

Prototype Manufacturer	Prototype Technology	Operating Frequency	Maximum Vertical Depth[1]	Maximum Distance[2]
Alertek, LLC	Analog Large Loop Magnetic Field	3150 Hz	177 m (voice)	305 m (voice)
E-Spectrum, Technologies	Compact Electric Field	10 or 22 Hz	177 m (text)	610 m (text)
Lockheed Martin MS2	Digital Large Loop Magnetic Field	330 or 3200 Hz	305 m (voice) 594 m (text)	640 m (voice) 1494 m (text)
Stolar, Inc.	Small Loop Magnetic Field	2000 or 4000 Hz	244 m (text)	335 m (text)
Ultra Electronics	Digital Large Loop Magnetic Field	4820 Hz	183 m (voice and text)	183 m (voice and text)

[1] Values listed are the maximum demonstrated vertical distances through the earth for successful one-way or, in some cases, two-way communication.

[2] Values listed are the maximum demonstrated off-vertical-axis distances through the earth for successful one-way communication. That is, where the distance between points on the surface and underground had a horizontal component, or where both points were underground.

sensing, with one design based upon E-field propagation. Both digital and analog signal processing techniques were employed. Loop or line antennas were used for transmission. Noise filters or noise cancelation techniques were found to be necessary for signal reception. Underground-to-surface communication, as well as underground point-to-point communication for voice and text, was demonstrated at ranges that might be applicable for some mines. Range generally increased with power levels. Further evaluations are needed to gauge ranges for systems operating within MSHA permissibility limits underground. Some systems allowed for estimation of the location of an underground transceiver through the reception and analysis of a beacon signal on the surface. In some contracts, prototype hardware was delivered to NIOSH.

Through these BAAs, NIOSH provided companies an opportunity to demonstrate and develop technology solutions that can be applied to solve mine safety and health problems. There was considerable research conducted by the USBM that documented the challenges to TTE communication. Based on their understanding of these challenges, most vendors were initially very confident that they could readily achieve depths in excess of 305 m for voice and up to 610 m for text (see Table I). In all cases, the manufacturers found the challenges to be much more difficult than they had expected. There are several possible explanations. First, the digital signal processing and noise cancelation techniques used for radio, radar, and sonar applications were not designed to be effective on the type of signals and noise experienced at these ultralow frequencies. Second, past USBM research was conducted in the 1970s and 1980s, when equipment typically operated at lower utilization voltages and power than at present. Today's equipment would be expected to generate a different electromagnetic noise profile. Finally, as a result of continued development, the noise levels due to above-ground transmission lines and other man-made sources most likely have increased substantially in the last 30 to 40 years. Whatever the reason, one thing is clear: Additional research will be required to identify the types and sizes of coal mines in which TTE solutions can work and to understand the performance limitation of these systems.

Further, before this technology can be implemented by the mining industry, there are still many questions that remain to be answered. These relate to communication format, time delays, portability, deployment, noise characterization, interaction with other systems, and permissibility. These issues will be briefly detailed here.

One question revolves around the choice of communication format, specifically, text versus voice. From a technological standpoint, the signal range for text can be greater than for voice. Text can be transmitted at lower bit rates and lower frequencies, with preprogrammed canned messages having the greatest potential range. Text also has the advantage of being a familiar and well-accepted communication format for a workforce becoming more comfortable with computers. There are concerns over the ability to text under stressful adverse emergency conditions, particularly when smoke hinders visibility. Those same conditions, however, may also hinder voice communications when self-contained breathing apparatus are in use. The solution may lie in software that can convert voice input into text, and/or text into synthesized voice.

Another question focuses on what is an acceptable time delay for a message. Real-time communication without functional delays, as with conventional telephones, is a goal that may not be practically achievable or necessary. It is conceivable that a message can be transmitted and received, and a response is made over several minutes without adversely affecting rescue or escape. As with message format, message delay times and range are impacted by bit rate.

Further questions revolve around the hardware and its deployment. It could be stationary while in use, or it may need to be transportable. It may be used while workers are awaiting rescue or during their escape. Some systems may feature components in heavy explosion-proof enclosures that could only be moved by equipment. Underground antennas could be predeployed by integration into the design of refuge chambers or be carried and deployed as needed by an escaping miner who might also have donned a self-contained self-rescuer. On the surface, antennas may be permanently deployed over dedicated hardened transceivers installed underground or may be installed following an emergency on the surface above a rescue chamber.

It is difficult to predict what mine communications or infrastructure may survive a catastrophic explosion. One possible TTE system configuration that could enhance survivability would employ hardened TTE transceivers and antennas installed periodically along escape routes underground and linked to permanent surface installations. Escaping workers could access the distributed transceivers on their way out, either directly or via a handheld radio interface. TTE systems could relay messages underground from trapped miners to rescue teams or could interface with other existing systems such as a leaky feeder, medium frequency, or wireless mesh. Signal relaying and interfacing mandate that message collision avoidance features be incorporated.

There are many sources of electrical noise underground that may interfere with the reception of a low-frequency signal. These include motors, motor starters, and transformers. However, TTE systems would most typically be used following an incident that requires escape or rescue. Under these conditions, the mine power would often be deenergized, and most low-frequency underground noise sources would be quieted. On the surface, atmospheric conditions and electrical installations may generate noise. However, during rescue operations other noise sources such as from drilling, vehicles, and the media might be present on the surface. The signal captured on the surface must not be swamped by background noise; therefore, noise reduction is important. With conventional techniques, a 20-dB reduction in noise is achievable. Further improvements may be gained with advanced digital filtering. For communication in deeper mines, such reductions will likely be necessary.

Prior to commercialization, systems must be approved as permissible for use in potentially hazardous atmospheres underground. Traditional methods to approach permissibility generally negatively affect TTE performance or system features. For example, one approach to permissibility is to locate hardware in explosion-proof enclosures but that tends to limit portability. An alternative approach is to use intrinsically safe underground components, but the associated energy limitations often limit range, and in some cases, may make designs impractical for any but the shallowest of mines.

Finally, it is known that the geology of the earth transmission path poses further challenges for the designer and user of TTE communication systems. The electrical conductance of the overburden has a great impact on the efficiency of transmission and can vary by orders of magnitude from mine to mine. Signal transmission with minimal loss is most easily achieved through materials with relatively low conductivity, such as air, dry limestone, or sandstone. Higher conductivity materials such as salt or coal can impede transmission. Maximum TTE system ranges can be simplistically extrapolated assuming a homogeneous overburden with uniform conductivity. However, aquifers, salt deposits, and mined-out seams may adversely affect transmission. There could be significant signal reflections at the air–earth interfaces that might necessitate burying or embedding both the surface and underground antennas. Underground, for a point-to-point transmission, multiple entries, solid coal blocks, roof mesh, and gob could significantly alter the range. NIOSH OMSHR plans to characterize the TTE path loss by determining the factors that most affect signal transmission and reception for TTE systems, and to investigate methods that optimize system performance. This will be accomplished through modeling with validation at commercial mine sites, but it may still require that transmission measurements be made at each TTE installation.

Acknowledgment

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH). In addition, citations to Web sites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these Web sites. All Web addresses referenced in this document were accessible as of the publication date. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

The prototypes identified in this paper were not all tested under similar conditions, and the maximum distances reported, in some cases, were influenced by test site conditions in addition to system performance. As a result, any information provided should not be interpreted as an objective system comparison. NIOSH does not endorse any specific manufacturer or technology.

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