MEDIUM FREQUENCY VEHICULAR CONTROL AND COMMUNICATION SYSTEMS FOR UNDERGROUND MINES

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ABSTRACT

Theoretical and experimental research sponsored by the U.S. Bureau of Mines shows that medium frequency (MF) electromagnetic (EM) signals propagate great distances in an underground environment such as a tunnel or mine. This propagation is enhanced by different mechanisms associated with the geology, and with the existence of metallic conductors in the entryways.

In stratified geologies, a transverse electromagnetic (TEM) mode of signal propagation is possible if a low conducting layer is bounded above and below by higher conducting layers. In general, the difference in conductivities must be at least several orders of magnitude. Such geological waveguide conditions often exist in underground mines. Propagation via the waveguide effect is known as the "seam mode" of propagation.

Another mode of propagation, the "tunnel mode," exists in underground entries with electrical conductors such as power cables, metal pipes, and phone lines. A monofilar mode of propagation exists when signals are impressed upon conductors and return via the surrounding rock. A bifilar mode of propagation exists when all signals exist only on local conductors. In a given location there is a combination of monofilar and bifilar modes that make possible an interaction between the conductors and a transmitting device in a tunnel or entryway. Signals can be impressed on or received from local conductors via magnetic dipole antennas (loops) or line couplers.

OBJECTIVE

This paper describes an MF narrowband communication system consisting of base stations, repeaters, mobile transceivers, and personnel transceivers and their evaluation in both mining and nonmining applications. The base stations and repeaters induce signals into existing conductors via line couplers. Because of this, special distribution cables are not required. The existing conductors distribute the signals that can be received by mobile or personnel transceivers in the vicinity of these conductors. The vehicular transceivers are used on any kind of vehicle that requires direct, two-way communications. The personnel transceivers are of a unique vest design, suitable for use in tight quarters. They have been approved for use in methane atmospheres.

The MF system paves the way for further advances in mining technology. It provides a reliable data link for the remote control and monitoring of vehicles, it can be used in wireless environmental monitoring, and it can increase the effectiveness of search and rescue teams. The system can be used in special applications such as inside high-density concrete and steel structures found in nuclear and thermo-electric power generating stations, large office buildings, prisons, and sub-surface military facilities.

INTRODUCTION

Almost everyone has experienced poor radio reception in underground parking lots and tunnels associated with the national highway system. Poor communications in these circumstances result in minor inconveniences in most situations, but the inability to reliably communicate becomes a serious matter for people working in high density concrete and steel structures and tunnels below the surface of the earth. Poor communications within the Three Mile Island facilities have been frequently cited as a contributing factor in the nuclear accident. Excellent radio coverage is essential in mining for increased safety and productivity.

Ever since the emergence of radio for practical surface communications, attempts have been made to apply it to underground mining. The Bureau of Mines was one of the early researchers in this area. As early as 1922, experiments showed that signal propagation was possible but not practical. Equipment was bulky and insensitive and only very large antennas could be used.

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important contributions to underground communications were made by The Chamber of Mines of South Africa who conducted much research and evaluated many prototype radio systems in underground coal and gold mines (1)(2). Both Bureau and South African researchers came to a similar conclusion that radio propagation in the MF band (300 kHz-3 MHz) showed good promise.

Parallel research was also conducted in the U.S. and Europe (3)(4) that showed that frequencies above the MF band (VHF, 30-300 MHz/UHF, 300 MHz-3 GHz) were also useful, but only in unique situations. In general, VHF/UHF is greatly affected by tunnel geometry and obstacles, and is useful only in less than line-of-sight conditions. In addition, a very elaborate system of leaky feeder cables and repeaters was needed to be practical. The time was clearly right to take a serious, in-depth second look at MF.

MF PROPAGATION RESEARCH

The Bureau initiated a series of programs to theoretically study the mechanisms of underground MF propagation in mining areas with and without conductors (5). The theoretical studies were supplemented by exhaustive in-mine measurements to compare theoretical and measured results (6)(7). Modes of propagation in tunnels with electrical conductors were studied in a series of theoretical investigations and tests. Radiating loop antennas were used to induce signals into nearby conductors which behaved like open multiple-conductor transmission lines. Radiation from the lines complete the communications path to the receiver. Research work indicated that bifilar and monofilar modes of propagation existed.

In the bifilar mode, all signals are confined to local existing conductors. Although small leakage fields exist, the main EM energy is confined between the conductors. This condition makes it more difficult to couple energy into such conductors, but once done, propagation losses are low (3 dB/1,000 ft) because of the metallic propagation path.

In the monofilar mode, any signals induced into local conductors return via the surrounding rock, coal, etc., which results in higher propagation losses (23 dB/1,000 ft). However, it is easy to couple energy into the conductors because of the nature of the fields. In practice there is a complex assortment of bifilar and monofilar modes in a typical mine entry because of variations in line spacings, changes in entry cross sections, etc.

Both bifilar and monofilar coupling to a conductor increase with frequency, but so do propagation losses. In addition, mine-generated electromagnetic interference (EMI) decreases with frequency. These combined frequency effects result in a favorable window of operation that extends from 300 to 800 kHz with due consideration to avoiding conflict with other services occupying this part of the spectrum.

In certain stratified geological formations, natural waveguides exist. Coal, trona, and potash seams that are surrounded by more conductive rock are examples of this. This mode of propagation is known as a "seam mode." For this mode to exist, the seam conductivity (σ_c) must be several order of magnitude less than that of rock (σ_r). A loop antenna that is at least partially vertically oriented produces a vertical electric field (E_z) and a horizontal magnetic field (H_ϕ). In the rock, the field diminishes exponentially in the Z-direction. In the seam, the fields diminish exponentially at a rate determined by the attenuation constant (α), which in turn depends upon the electrical properties of the seam. An inverse square-root factor also exists because of spreading. The effect is that the wave propagates between the highly conducting rock layers bounding the lower conductivity seam. The fact that the seam may have entries and crosscuts is of minor consequence.

The electrical parameters of natural materials depend upon frequency. As a general rule, the conductivity increases and the dielectric constant decreases with frequency. Both increase with water content. They also depend on pressure. Excluding rock with high concentration of ferromagnetic metals, the permeability is close to that of a vacuum. Measurements show that operating range decreases for frequencies below 300 kHz and above 800 kHz.

The tunnel mode and seam mode propagation mechanisms permit good communicating range in the lower MF band in underground environments.

SYSTEM DESIGN AND CONFIGURATION

An MF system was designed and evaluated that could operate either in the tunnel mode (use of existing conductors) or seam mode (waveguide in the strata). The system consists of base stations, repeaters and line couplers, vehicular transceivers and antennas, and a personal transceiver configured into a vest design. Fig. 1 illustrates a tunnel mode configuration. Existing mine conductors serve not only as the transmission lines but as the distribution antennas as well. Unit to unit communications are conducted on frequency f_1. Standard repeater action is conducted by use of frequency f_2. The use of a base station and repeater results in very long range. The base station and repeater use toroidal radio frequency (RF) line couplers to efficiently couple signals into and receive signals from the existing conductors. The couplers are impedance matched and tuned, and can be quickly clamped to most conductors. Transfer impedance is approximately 10 ohms.

An important human factor problem was solved by the design of a vest transceiver (fig. 2). By placing the radio circuit modules in pockets in the vest, the weight and bulk of the transceiver has been evenly distributed on the miner's body. The loop antenna is sewn into the back of the vest. Since the area of the loop does not change with movement of the miner, it remains tuned at all times. The control head has been designed to match the natural movement of the hand. The thumb can comfortably operate all control functions. The vest design allows the miner to maneuver in tight quarters and perform normal mining tasks without the danger of entangling the transceiver in mining equipment. The vest transceiver design has been approved by the Mine Safety and Health Administration (MSHA) for use in a methane atmosphere.

The repeater uses loop antennas to radiate and receive seam mode signals (fig. 3). This permits radio communications with miners working in conductor-free areas that are the focal points of most mining activity. Since the repeater services a "cell" (local working area) in the mine, it is called a cellular repeater. It may be connected to the local pager telephone system to enable communications with other distant miners and with the surface communications center.

SYSTEM SPECIFICATIONS

Emissions

Type	Narrowband FM
Occupied BW	10 kHz
RF frequency (internally selectable)	60 to 1,000 kHz
Peak deviation	± 2.5 kHz
Mod frequency	200 to 2,500 Hz

Receiver

Type	Superheterodyne
Sensitivity	1.0 µV (12 dB Sinad)
IF BW 3 dB	12 kHz (min)
70 dB	22 kHz (max)
Squelch	Noise operated

Transmitter

Type	Push Pull Class B
Output Power	
Vest	4 W
Vehicular/base	20 W

Antenna

Magnetic moment	
Vest	2.1 ATM^2 (Amp-Turn-meters^2)
Vehicular	6.3 ATM^2

COMMUNICATION SYSTEM PERFORMANCE

To ascertain the actual performance in underground mines, it was necessary to install the system and measure the performance over a long period of time. Equipment was installed in the following mines: (a) York Canyon Mine (Kaiser Steel Corp.), coal; (b) Escalante Mine (Ranchers Exploration and Development Corp.), silver; (c) Magma (Magma Copper Co.), copper; and (d) Star Point Mine (Plateau Mining Co.), coal.

The communication system performance was similar in every mine. Base station radio signals could be received wherever electrical conductors existed in the entryways. The talkback range depended upon the distance of the radiating antenna from the conductors. It also depended upon the type of conductors in the entryway. For a radiating antenna-to-line separation of approximately 7 ft, the vehicular-to-base communication range exceeded 30,000 ft along unshielded single-pair telephone cables. At 520 kHz the attenuation rate was 2.4 dB/1,000 ft. It was only 1 dB/1,000 ft at 350 kHz. The range along the shielded 3-phase a-c power cable exceeded 10,000 ft. At each point where the primary path cable connected to sub-stations, the cable path loss increased from 8 to 12 dB. At 400 kHz, the attenuation rate was approximately 4 dB/1,000 ft.

In coal mines, the talkback distance to a base from a vest or vehicular transceiver depends upon the distance from the cable and the distance of the base along the cable. At a range of 1,000 ft, the talkback distance was approximately 80 ft from the cable. It decreased to 40 ft at a range of 8,000 ft. In a conductor-free area the cellular repeater talkback range exceeded 500 ft.

In-mine tests of the system demonstrated that the time to reach key personnel could be reduced from an average of 35 minutes (with the existing mine pager telephone system) to less than a second. A base station could be installed and coupled to the existing mine wiring in less than one hour. The ease of installation is important since the mine management can assess system performance before they buy equipment.

Besides being able to hear messages almost anywhere conductors exist in the mine, the talkback range was measured in miles when the mobile transceiver was within a few feet of the mine conductors. For ranges up to a mile, the received base station carrier/noise (C/N) ratio exceeded 60 dB. This suggested that the system could be used as a high quality data link.

LOCOMOTIVE REMOTE CONTROL USING MF

These MF techniques were successfully applied to the remote control of locomotives in a loading operation in Union Oil's Molycorp Mine near Questa, New Mexico.

This mine uses multiple level block caving methods to mine the ore. The upper ore body is fractured by blasting and ore flows by gravity to the grizzly level where miners fill transfer raises. In the loading process a trolley-powered locomotive is used to maneuver cars below the raise. Powered gates control the flow of ore into the car. Multiple panels of eight or more raises are located directly below the ore body. After loading, the train leaves the panel and enters the main haulage track where it continues to the dump. A conveyor belt is used to transport the ore out of the mine. Fig. 4 shows the loading operation.

Each locomotive used in this operation has been equipped with an MF transceiver modified for two-frequency operation and interfaced with FSK decoders and control circuits. When used on f_1, the locomotives can communicate with other locomotives on the main haulage tracks to coordinate movement to the dump. When used on f_2, the locomotives are on a frequency that permits remote control of the loading process.

In the loading process, the motorman takes the train to a transfer raise location and switches to f_2. He then leaves the locomotive and goes to the gate. At the gate there is a control box connected to an MF base control station. The base control station frequency is modulated by a FSK digital command signal (mark 2070 Hz, space 2500 Hz) which is generated in a remote control modulator (RCM) unit. Depressing the forward/brake release or reverse/brake release switches on the control box (one at each loading point) initiating digital encoding of the command signal. For safety purposes, each locomotive is assigned a unique key. Insertion of this key in the RCM uniquely codes the command signal with the train identification. The FSK signal modulates the base station which induces an MF signal current on the control cable via a line coupler. The train transceiver receives the FM signal from the cable and recovers the FSK digital command signal which is applied to a remote control demodulator (RCD) unit. The RCD pilot relay controls the required contactors in the locomotive control circuit. The RCD unit is designed with double redundant fail-safe circuitry. The digital code includes self-checking features to prevent false operation of the train.

OTHER APPLICATIONS

The MF system performance has been evaluated inside a high-density concrete and steel nuclear reactor containment vessel, a large thermo-electric power plant, and a fire-fighting training structure. A large-diameter loop antenna placed on the gangway inside of the containment vessel was excited by a base station via an RF line coupler. In another series of tests, loops were placed around the outside of the electric power generator station and the fire fighting training structures. As in the containment vessel test, the loops were excited by RF line couplers. In these tests, commercially available handheld UHF transceivers were compared with the MF vests. Although the UHF transceivers performed well on all line-of-sight paths, communication problems existed in many areas such as lower level work areas, elevators, and behind steel reinforced walls. In contrast, MF coverage included these areas. When an MF vest was within 4 ft of the loop, the received base C/N was greater than 40 dB.

SUMMARY

A whole mine radio system has been developed that exploits the low loss tunnel and seam modes of MF wave propagation in sub-surface tunnels. This Bureau of Mines program was initiated because of the need for more effective communications for improved safety and productivity. The system reduced the average time to reach key personnel from 35 minutes (pager phones) to less than a second (MF system). The system permits underground personnel to maintain communications almost anywhere in the mine and with the surface communications center. As a consequence, communications are possible to the point of equipment breakdown, a fact of significance in reducing mining costs.

Inductive coupling of signals into the existing mine conductors insures extensive coverage in the underground complex. No special communication cable usually needs to be installed. Base stations and repeaters can be installed in minutes in locations of prime mine power. Backup batteries are included for additional reliability.

Both vehicular and personnel transceivers are available. The vehicular antennas utilize a new antenna design of exceptional efficiency and durability. The personnel transceiver utilizes a unique vest concept that enables miners to maneuver in tight quarters and perform normal tasks without the danger of entangling the transceiver in mining equipment.

Extensive tests in numerous underground coal and metal mines have demonstrated the reliability and ease of installation. The equipment survives and performs well in the hostile mine environment. Since the same equipment can be used for both voice and data transmissions, it forms the basis for further advances in mining technolody. For the case of train haulage, the voice segment of the system enables coordination of rail traffic for reduced haulage costs and improved safety. During loading, remote control of the train frees at least one man to do other mining tasks.

REFERENCES

(1) Nelson, T. U. and B. A. Austin. "A Medium Frequency Radio Communication System in a Coal Mine." Research Report 42/80, Project CS1C10, Chamber of Mines of South Africa, Johannesburg, 1980, 30 pp.

(2) Austin, B. A. "Underground Radio Communication Techniques and Systems in South African Mines." PROC. Electromagnetic Guided Waves in Mine Environment Workshop, 1978, pp 87-102.

(3) Martin, D. J. R. "The Use of In-line Repeaters in Leaky Feeder Radio Systems for Coal Mines." PROC 28th IEEE Conf. on Vehicular Technology, 1978, pp 255-260.

(4) DeLonge, P., L. Deryck, and R. Liegeois. "Guided Propagation of Radio Waves." PROC Thru-the-Earth EM Workshop, 1973, pp 49-53.

(5) A. D. Little Inc. "Modelling and Data Analysis of 50 to 5,000 kHz Radio Wave Propagation in Coal Mines." (Contract H0346045) BuMines OFR 83-80, 1980, 109 pp; NTIS PB-209-455.

(6) Cory, T. S. "Propagation of EM Signals in Underground Mines." (Contract H0366028, Rockwell Intl.) BuMines OFR 136-78, 1977, 158 pp.; NTIS PB 287-757 A/S.

(7) Cory, T. S. "Propagation of EM Signals in Underground Metal/Nonmetal Mines." (Contract J0308012, T. S. Cory) For further information contact James R. Means, Jr., Technical Project Officer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA 15236.

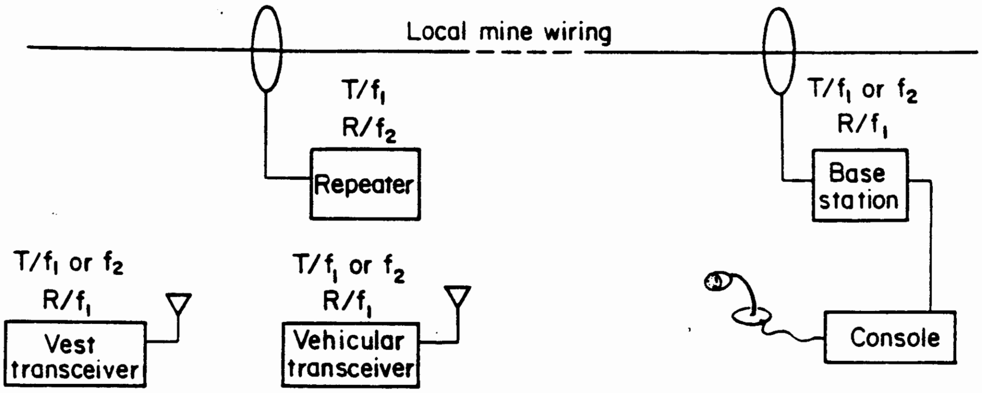

Figure 1. - Tunnel mode concept

Figure 2. - Medium frequency vest transceiver

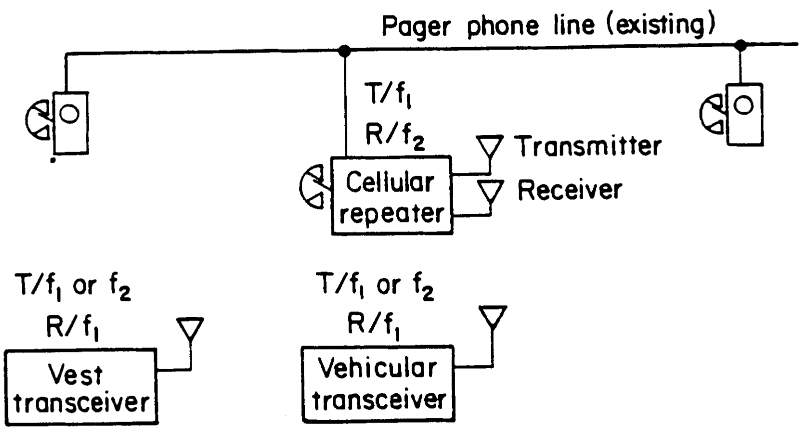

Figure 3. - Cellular repeater concept

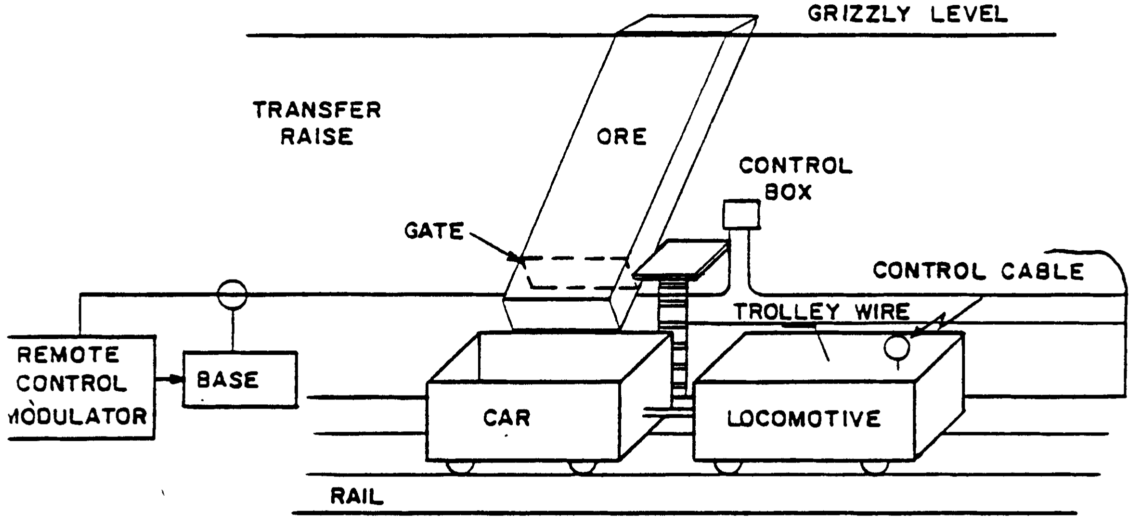

Figure 4. - Train remote control system