A WHOLE-MINE MEDIUM-FREQUENCY RADIO COMMUNICATION SYSTEM

by

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ABSTRACT

A medium-frequency (MF) communication system has been built and has been tested in underground mines. It provides radio coverage to vehicles and personnel anywhere in the mine via parasitic coupling into existing mine conductors. The system consists of base stations, repeaters, and vehicular and personnel transceivers. Air-core antennas for vehicles and clamp-on antennas for base stations and repeaters were designed for maximum coupling efficiency using existing mine wiring. Personnel transceivers are of a unique vest design that features a low physical profile, good user comfort, and efficient antenna design.

In-mine tests show impressive results. Range between rubber-tired vehicles and base stations is often measured in miles. With repeaters, greater range is possible.

INTRODUCTION

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, Bureau of Mines experiments showed that radio propagation in mines was possible but not practical. Equipment was bulky and insensitive, and only very large antennas could be used. The desire for in-mine radio communications is obvious. Such a system would permit mine personnel to receive or initiate messages without physically going to a telephone. The benefits would be safer and more productive mining operations.

RADIO PROPAGATION IN MINE ENVIRONMENTS

Although radio transmission on the surface of the earth is well understood, transmission in an underground environment generally is not. Complex interactions occur between the radio wave and the environment. Characteristics of the geology (stratified layering, boundary effects, conductivity, etc.) and the mine complex (entry dimension, conductors, electromagnetic interferences, etc.) had to be measured and understood before a practical mine radio system could be built. To this end, considerable research has been directed(1) [1].

In a confined area such as a mine, radio waves can propagate useful distances only if the environment has the necessary electrical and physical properties. The "environment" takes into account the natural geology and manmade perturbations such as the mine complex itself. As an example, if the wavelength (λ) of a radio wave is small compared with the entry dimensions, a waveguide mode of propagation is possible. Attenuation depends primarily upon the physical properties of the entry such as cross-sectional area, wall roughness, entry tilts, and obstacles in the propagation path. Secondary effects such as the dielectric constants and earth conductivity also influence attenuation.

Mine radio systems based upon this effect are available commercially. These are UHF systems operating around 450 MHz which provide useful but limited coverage. In high coal [2 m (6.5 ft)], line-of-sight ranges of 300 m (1,000 ft) are often possible. Range is reduced severely in non-line-of-sight, such as when going around a coal pillar. In lower coal, or when obstacles exist in the propagation path, range is reduced even more. For this reason, conventional UHF radio systems require an extensive network of leaky feeder transmission cables and repeaters to become useful. Even so, range from the cable is not usually in excess of 9 to 16 m (30 to 50 ft), and equipment cost is very high. Clearly another approach is desirable.

HISTORICAL OBSERVATIONS

An important contribution to underground radio communications was made by the Chamber of Mines of South Africa. As early as 1948, programs were in place to develop radio systems for deep mines, primarily gold mines (2). The result was that by 1973, an advanced 1-W single sideband (SSB) portable radio system had been developed that apparently worked well. The Bureau of Mines procured several of these units for evaluation. Performance in U.S. coal mines was not satisfactory. There were several reasons for this. First, U.S. mines are highly electrified, producing considerable electromagnetic interference (EMI) not normally found in the South African mines, which completely desensitized SSB radios. Second, 1 W was not enough power. U.S. mines are mostly room and pillar, which means that any radio system would have to have reasonable range from local conductors. Third, geological electrical parameters were less favorable in the United States. For these reasons, the South African system was not acceptable.

The Bureau's approach was to first determine the actual propagation characteristics of MF in U.S. mines, and then to relate the propagation to the underground environment such as the geology, entry size, existing conductors, and EMI. Several exhaustive in-mine measurement and analysis programs (3-5) were conducted. These programs formed the foundation for the first true understanding of how MF propagates in a stratified medium of various electrical parameters, which are often interlaced by man-made conducting structures (rails and power lines) and artificial voids (entryways).

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[1]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

Figure 1 is a simplified geometry of an in-mine site that illustrates one of the most important findings of the measurement program, the "coal seam mode." For this mode to exist, the coal seam conductivity (σ_c) must be several orders of magnitude less than that of the 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 ($H\phi$). In the rock, the fields diminish exponentially in the Z-direction. In the coal seam, the fields diminish exponentially at a rate determined by the attenuation constant (α), which in turn depends upon the electrical properties of the coal. 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 coal seam. The fact that the coal may have entries and crosscuts is of minor consequence.

In the presence of conductors, the picture changes considerably. In this case, the effects of these conductors can totally dominate the effects of the geology. In general, the presence of conductors (rails, trolley lines, water pipes, air lines, phone lines) is always of advantage.

MF can couple into, and reradiate from, continuous conductors in such a way that these conductors become not only the transmission lines, but also the antenna system, for the signals. The most favorable frequency depends to some extent on the relationship between the geology and existing conductors. The frequency effects are quite broad. Anything from 500 kHz to 800 kHz will usually be adequate.

SYSTEM DESIGN

The MF system described here is based upon vehicular and personnel transceiver units, base stations, and repeaters. It applies prior fundamental research in the area of MF and utilizes the existing mine wiring network (power cables, trolley line, etc.) to achieve whole-mine coverage. The basic system configuration is shown in figures 2 and 3.

Figure 2 illustrates a minewide repeater/base station concept known as the global maintenance net. In this configuration, mobile units (persons using transceiver vests and/or vehicular transceivers) can maintain local communications by operating at frequency f_1. The range of communications in this case is solely dependent on point-to-point radio propagation, aided by parasitic coupling. A transmission on f_2 causes repeater action to occur, permitting the two mobile units to be separated very large distances. To achieve this repeater action, it is only necessary for the transmitting unit to reach the repeater, either directly or by parasitic effects to the repeater line coupler. Communications with a base station are also possible.

Figure 3 illustrates a local repeater concept constituting a local cellular net. This local repeater is known as a "cellular repeater" because it illuminates a "cell" or area of the mine, such as a working section, only. The antenna for the cellular repeater is a dual wire loop attached to timbers or the rib. An interface to the mine telephone system permits communications "off section."

The system design is distributed in the sense that each net can be operated independently of the other. In practice, a net can be easily installed by coupling a base station (at the portal) to electrical conductors in the wireplant (phone lines, power lines, etc.). Mobile transceivers operating on the assigned net frequency communicate with each other and the base. Other nets use different frequencies and are installed in the same way.

Mobile Transceivers

Two types of mobile transceivers have been developed for the system. These transceivers consist of vest units for individuals and vehicular units for rolling stock. Functionally the two are equivalent, differing only in power levels and physical configuration. These transceivers are shown in figures 4 and 5..

An important human factor problem was solved by the vest design. By placing the radio circuit modules in pockets on the vest, the weight and bulk of the transceiver have been evenly distributed. The loop antenna is sewn into the back of the vest. The pockets are located where medical records show less frequency of injury. Sound is directed toward the ears from epaulet speakers. A hinged control head is conveniently located on the front. The design allows the miners to maneuver in tight quarters and perform normal mining tasks without catching the radio on obstructions.

The vehicular unit can be conveniently placed on any mine vehicle. It is used in conjunction with a special loop antenna of advanced design that produces high magnetic moment. Mechanically, the antenna is enclosed in high strength lexan and is attached to the vehicle via special brackets. The lexan will not break even if severely flexed by impact.

Fixed Station Antennas

Besides the mobile transceivers discussed above, the system also consists of fixed transceivers such as repeaters and base stations. (See figures 2 and 3.) For proper system operation it is necessary that these fixed transceivers have very efficient antennas so that the local wire plant can be properly illuminated and signals on the wire plant are properly received. This efficiency is paramount for whole-mine coverage.

The cellular repeaters use dual-loop antennas (for transmit and receiver) attached to the rib or posts in such a way that there is little danger of damage in normal mine activities. The transmit antenna produces a large magnetic moment that provides the signal for local cellular coverage, which is usually aided by parasitic coupling and reradiation effects. The receive antenna is similar.

The global repeater and base station use a newly designed RF line coupler (see figure 6) that permits very efficient coupling to the mine wireplant. Like a current probe, the coupler can be easily clamped around local conductors. MF signal current flowing through the wireplant conductors produces a coupler output signal (V_0), which is applied to the input of the base station or repeater.

Base Station and Repeater

The base station is intended to be placed where mine management finds it most advantageous, usually in the surface office complex or with the dispatcher. If desired, the base station can be controlled remotely via signal lines that allow the control console to be placed in a surface building for convenience, while the actual base transceiver is placed in the mine where it can more efficiently couple into the local wiring. Both the global repeater and the base station utilize the RF line coupler for maximum efficiency. The cellular repeater is generally located in a working section. It enables the vest to operate as a mobile pager telephone by switching voice signals between the local pager telephone network and the vest. Vehicular radios can also operate in this mode.

The system was developed around an interchangeable set of plug-in radio circuit modules. The same receiver, synthesizer, and transmitter modules are used in the vehicular transceiver, base station, and repeaters. Servicing the equipment only requires troubleshooting to the board level. Since the equipment uses the same radio circuit modules, the performance specifications of all transceivers are similar. The signaling used depends upon the specific network requirements. All receivers are designed with an adaptive noise-operated squelch network that allows every transceiver on the net to hear the same message (party line).

The transmitters are designed with both sub-audible (100 Hz) and in-band (1000 Hz) tone oscillators. A sub-audible tone is used in the vest transceiver to cause the cellular repeater to switch the message (page) to the pager telephone network. The repeater includes both a noise-operated squelch and a sub-audible tone squelch for use in telephone switching. Sub-audible tone signaling is useful in identifying "stuck on" transmitters that that can block the communications net. In-band signaling is useful in emergency situations.

System Specifications

Emissions

Type..Narrowband FM
Occupied BW...10 KHz
RF frequency...60 to 1,000 kHz
Peak deviation...$\pm$2.5 kHz
Mod frequency...200 to 2500 Hz

Receiver

Type...Superheterodyne
Sensitivity.......................................1.0 µV (12 dB Sinad)
Selectivity.....................................8-pole crystal filter
IF BW 3 dB..12 kHz (min)
70 dB..22 kHz (max)
RF BW...60 to 1,000 kHz
Squelch.......................................Noise operated and tone

Transmitter

Type..Push Pull Class B
Output power
  Vest...4.0 W
  Vehicular...20.0 W

Antenna

Magnetic moment
  Vest...2.1 ATm^2
  Vehicular..6.3 ATm^2

RF Line Coupler

Transfer impedance (Z_T)
  1-in Coupler
    350 kHz...10.0 ohms
    520 kHz...11.2 ohms
    820 kHz...17.8 ohms

  4-in coupler
    520 kHz...10.6 ohms

PERFORMANCE RESULTS

To ascertain the actual performance of any mine communication system, it is necessary to install that system underground and measure performance over a long period of time. Short-term testing is unacceptable and inconclusive. The Bureau of Mines addresses this problem by joining with mining companies in Memorandums of Agreement to acquire this long-term performance data.

Four western mines who have agreed to participate in these performance tests are as follows: (a) York Canyon Mine (Kaiser Steel Co., coal); (b) Escalantes Mine (Ranchers Exploration Corp., silver); (c) Star Point Mine (Plateau Mining Co., coal), and (d) San Manuel Mine (Magma Copper Co., copper). Because of space limitations, it is not possible to describe in detail the performance of the MF system in all mines. This will be the subject of a future paper. Instead, system performance will be described for the York Canyon Mine, where the system has been installed the longest time.

York Canyon Mine

The York Canyon Mine is a combination strip and deep operation located near Raton, N. M. The underground operation mines the York seam, which is approximately 6 ft thick. The mining operation is primarily via longwall, and all coal is transported out by belt. The geology in this area is highly faulted with numerous slips that cause considerable productivity problems. The geography is hilly such that the overburden ranges from about 200 to 800 ft. Primary access to the mine is via four drift entries.

Facing these entries, one finds the left one is fresh air intake, the second is a neutral air supply way, the third is a neutral air beltway, and the right is a return airway. Ventilation fans exist in the portal areas and at distant ventilation boreholes. A simplified map of the portal area is shown in figure 7.

One of the tremendous advantages of medium frequencies is the ease at which a well-designed system can "illuminate" the existing mine wiring. Figure 7 illustrates this for the York Canyon Mine. A single line coupler placed around the existing 25-pair telephone line was the only device installed. This coupler was physically located about 25 ft into the entry and connected to a base station in the maintenance shop via a single-pair line.

Measurements show that the line coupler functions as a transformer consisting of "N" turns of primary and numerous single turns of secondary. As an example, if one had several conductors of similar electrical properties and placed one through the line coupler, a current i_1 would be induced into this line. If a second conductor was also included, it too would have a current i_1 induced. If a dozen such conductors were included, each would have i_1 induced. It becomes apparent then that to achieve the best performance from a line coupler, it is necessary to include the maximum possible number of conductors. A 25-pair phone line, like the one at York Canyon, is a bonanza for an MF system. In less favorable circumstances, a little innovation is necessary or multiple couplers can be used. Obviously a reciprocal effect exists on receive.

Precise measurements of signal strength in an underground mine are extremely difficult and time consuming. Therefore, for this report performance of the system was based not on signal strength, but rather on the talk-listen range of the transceivers (between base and vests, vehicle transceivers). This is a more meaningful measure of performance to the mine operator anyway. To relate talk-listen information to more quantitative data, the refer to the section on system specifications.

With the base station and repeater configured as in figure 7, communications between the base station and vehicular or vest transceivers were possible the entire length of the supply way [2,800 m (9,000 ft)]. The vest would occasionally produce a poor transmission, but never a poor reception. The vehicular transceiver never experienced a problem. In the adjacent entries (fresh air on left, belt line on right), the vest would experience slightly more transmission problems to the base but rarely any reception problems. Within a few feet of mine conductors (phone line, belt fire control line, etc.), the vest would experience no problems. Ranges of 4,700 m (15,000 ft) with the vest were achievable in this manner. Substantial improvements are anticipated with the installation of a repeater.

The MF system has been in operation at the York Canyon Mine since late 1981. Various hardware improvements have been continually made, but performance is essentially as stated. The mine personnel use the system on a daily basis and have found it to be reliable and time-saving.

Problems so far have been mostly nuisance in nature. For example, lead-in cables on vehicular transceivers would often break. Sometimes when vehicles were brought outside in the rain, the enclosures would leak, causing circuit failures. These and similar problems are being solved.

CONCLUSIONS

A whole mine radio system has been developed for underground mines based on medium frequency principles. The program was initiated because of a need for more effective communications for improved productivity and safety. The system permits underground personnel to maintain communications almost anywhere in the mine, and with the surface complex. As a consequence, communication is possible to the point of equipment breakdown, a fact of significance in improving productivity by reducing downtime.

Parasitic coupling into existing mine conductors insures extensive coverage. No special communications cable need be installed. Base stations and repeaters can be installed in minutes in locations of prime mine power. Backup batteries are included for additional reliability.

Portable units consist of vehicular and personnel transceivers. The vehicular transceivers utilize a newly designed antenna of exceptional efficiency and durability. The personnel transceivers utilize a unique vest concept that permits a low profile and affords excellent user convenience.

Extensive tests have been run in numerous underground coal and metal mines. Performance has been very good in all cases. These tests will continue into 1983 to ascertain how well the design performs under long-term conditions of the harsh mine environment.

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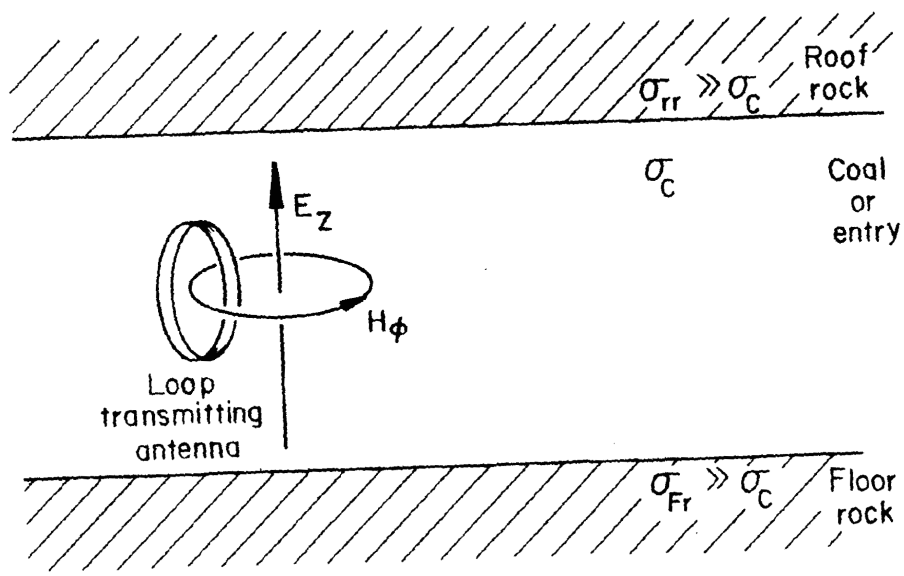

FIGURE 1. - The coal seam mode

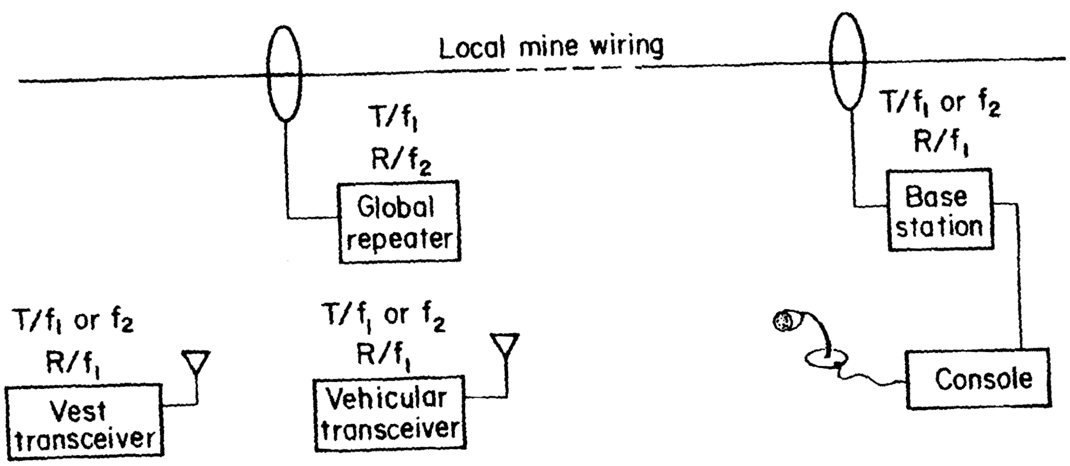

FIGURE 2. - Global repeater concept

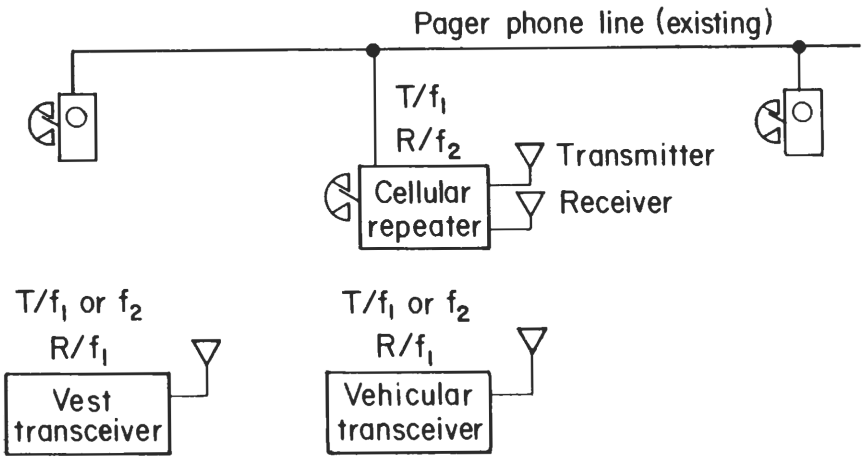

FIGURE 3. - Cellular repeater concept

FIGURE 4. - Vest transceiver for personnel

FIGURE 5. - Vehicular transceiver for vehicles

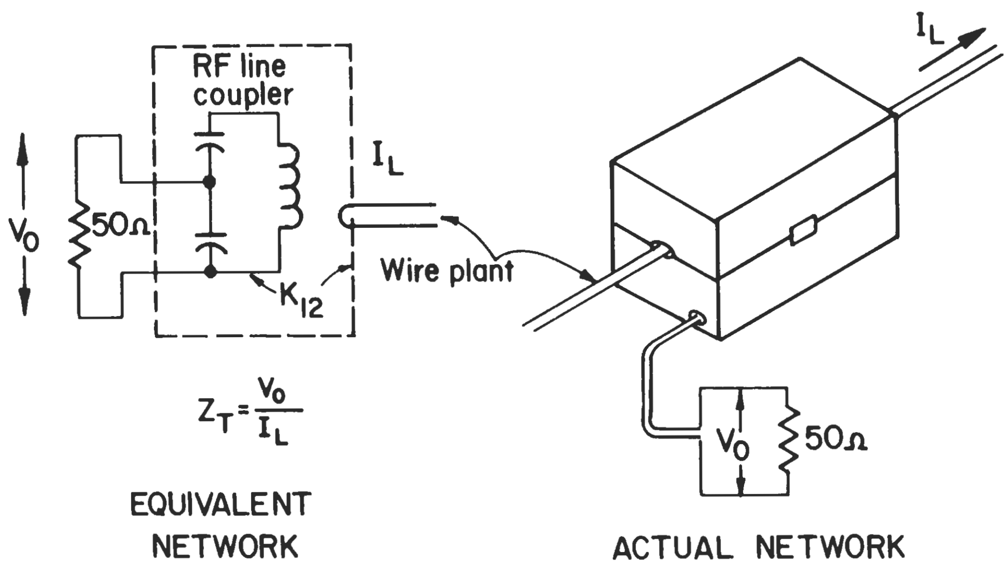

FIGURE 6. - RF line coupler for base stations and repeaters

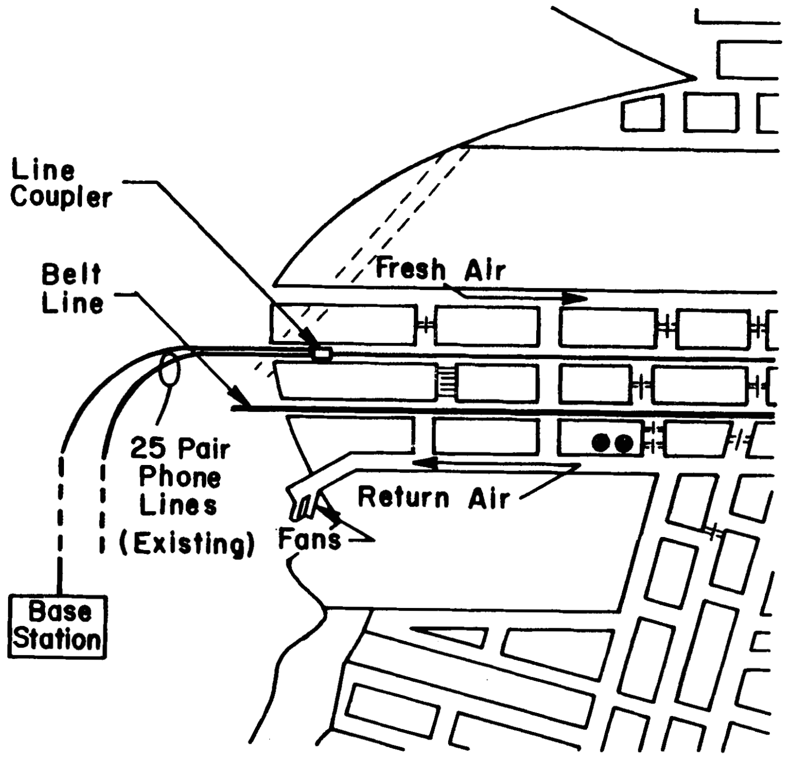

FIGURE 7. - Portal area of the York Canyon Mine