Control and Monitoring via Medium-Frequency Techniques and Existing Mine Conductors

HARRY DOBROSKI, JR. AND LARRY G. STOLARCZYK

***Abstract*—Medium-frequency (MF) techniques have been successfully pplied to the problem of radio voice communications in both coal and etal and nonmental mines. Long range is achieved by taking advantage f existing mine conductors that carry and propagate the signal over vast reas. It is very likely that in the near future such systems will become the referred method for general mine communications. MF techniques can lso be applied to the areas of in-mine control and monitoring. Preliminary work in this area is described. In a western mine, locomotives are being operated under MF remote control in a loading operation. In several eastern mines, MF has been evaluated as a method for monitoring the status of devices in remote areas of the mines. All control and monitor information uses existing mine conductors.**

INTRODUCTION

OVER THE LAST several years, numerous attempts have been made to develop radio systems useful in underground environments such as mines. Such systems would provide to the underground environments the same advantages that radio offers to surface operations, namely instant communications to key personnel, resulting in improved safety and productivity, and direct managerial control. Unfortunately, undergound radio propagation is extremely difficult, and conventional approaches have not been successful. The problem clearly calls for unconventional approaches.

The first of these unconventional approaches is based upon guided wave techniques where radio signals (VHF or UHF) are impressed upon special cables called leaky feeders that accept signals from and radiate signals to portable radios in their immediate area. By the use of repeaters and base stations, communications with and between the portables are possible, but only in the vicinity of the leaky feeder cable [1], [2]. A tremendous advantage would result if a system existed that could take advantage of existing mine conductors (power lines, control lines, etc.) to achieve the same effect. Coverage would be extensive, and no special cables would usually be needed. Medium-frequency (MF) techniques offer such advantages.

Comprehensive theoretical and experimental studies showed that MF (300 kHz–3 MHz) signals could effectively be coupled into existing mine conductors from either magnetic dipole antennas or special line couplers. Once impressed upon a conductor, the signals would propagate long distances, reradiating along the way [3]. The effect very closely simulated that of the leaky feeder cables at VHF or UHF. The advantage was that existing mine conductors could be used. Although certain existing conductors were clearly better than others, all were effective at MF to some degree. In addition, signal energy interchange exists between conductors not physically connected. Therefore, signals impressed upon one conductor are transferred to other conductors, achieving extensive coverage.

Based upon this research, an experimental MF voice communication system was designed, constructed, and evaluated [4]. It consisted of base stations and repeaters that used line couplers to inject signals onto, and receive signals from, existing mine conductors. Mobile transceivers for vehicles and personnel were also designed. The overall system made it possible for mobile transceivers to communicate with each other, or with the base station, by using the existing mine conductor networks. Fig. 1 shows the general system concept.

APPLICATION OF MF TO UNDERGROUND OPERATIONS

The obvious application of MF to underground operations, and the one for which it was originally conceived, was for operational mine communications. By the use of a system similar to that shown in Fig. 1, it is possible for a mine to establish quickly an extensive MF radio network for safety, productivity, and managerial decisionmaking and control. Therefore, the benefits associated with communications between key persons in any complex managerial hierarchy can be extended to the underground mining industry. The other benefits to safety, maintenance, etc., are quite obvious.

A second application, and one in which the Bureau of Mines has a keen interest, is that for postdisaster scenarios. Not only can MF provide an effective communications link for rescue teams in search and recovery operations, it can also provide an in-mine beacon to pinpoint the location of trapped or injured miners, if these personnel are equipped with small transmitting devices.

A third application is that of data telemetry. Because of the favorable propagation characteristics of in-mine MF that result in good signal-to-noise (S/N) ratios on existing conductors, MF offers interesting possibilities in this area. The balance of this paper will expand upon this third application.

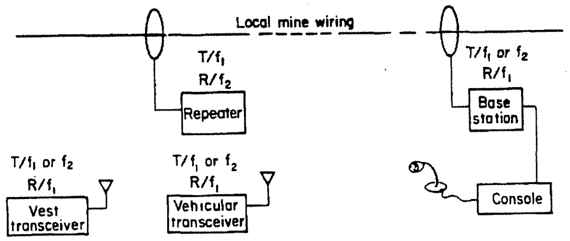

Fig. 1. General MF system concept.

THE CONTROL OF TRAINS IN A METAL MINE LOADING OPERATION

Because of safety and productivity considerations, a metal mine that used block caving mining methods needed to remotely control the locomotives in a loading operation. In this operation, rubbled ore from upper grizzly levels flowed from sub raises and transfer raises to a haulage level where train cars were filled. The transfer raises serve as temporary loading bins for the ore. A working space called a "pony set" is provided above the loading area. By the use of pneumatic gates controlled from the pony sets, the flow of ore from the transfer raises to the cars can be controlled (Fig. 2). The person in the pony set has to have an unobstructed view of the car being loaded. When loaded, the flow was stopped and the locomotive operator was signaled by blinking lights or air horns to advance the train by one car, so the next car would be in position. The operation was labor intensive and inefficient. Two persons were required to perform this single task. When multiplied by the number of other trains and loading operations in the mine, this inefficiency quickly resulted in excessive personnel costs.

A managerial decision was made to streamline the process by putting the locomotive under remote radio control from the pony sets. In this manner the locomotive operator could bring the train into the loading area, leave the train, and go to a pony set, and from there advance or reverse the train under radio control while controlling the loading of the cars. A second person was no longer required. To achieve this, a UHF radio remote control system was installed.

This system was of European design and was commerically available in the U.S. market. A portable transmitter which could be carried by a person, contained numerous control buttons for forward, reverse, stop, etc. When the appropriate button was pushed, a coded digital signal was transmitted to a companion receiver on the locomotive, interfaced with the locomotive controls, which would result in the desired locomotive response. The system operated at a frequency of 452 MHz at a power level of 0.1 W.

From the start, system performance was very poor. As Fig. 2 shows, a person in the pony set is not actually in the entry but is directly above it. Line-of-sight propagation was not possible. In addition, a vast number of cars exist between the pony sets and the receiver on the locomotive. Conditions were such that the cutoff frequency of the panel was too high to permit reliable operation at UHF. Signal attenuation between transmitter and receiver, and other factors introduced excessive signal losses between the transmitter and receiver resulting in a reliable operating distance of less than 100 ft, which was unacceptable. The power level of 0.1 W was far too low for almost any in-mine application, especially one that requires a tunnel mode of propagation to achieve any reasonable range. Although tests were not conducted at higher powers, prior research [2] has shown that acceptable performance could probably never have been achieved at UHF.

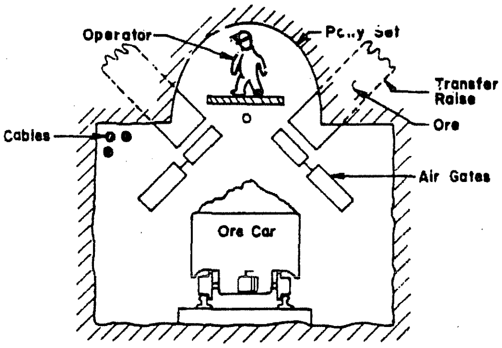

Fig. 2. Ore loading operation.

Since the mine had recently installed an MF system for communications on the main rail haulage which performed exceptionally well, the question was asked whether or not it could also be applied to the problem of train control in the loading operations. Initial experiments in the loading panels showed that MF signals (of magnetic moment 2 $A \cdot T \cdot m^2$) could achieve a propagation distance of 1000 ft in these panels whether or not train cars were positioned between transmitters and receivers. The conductors in the area functioned effectively as the MF distribution system. A decision was made to proceed with the MF train control approach. The following section describes the initial MF system, shows the general system concept, and gives specifications and operating performance.

THE GENERAL MF APPROACH

The initial experimental system, shown in Fig. 3, consists of a transmitter under wireline control from fixed control boxes in the pony sets. The control cable (and all other cables in the entry) performs as both the propagation medium and the distribution antenna, producing local magnetic field all along the loading panels. A radio receiver on the locomotive completes the system. Table I gives the general hardware specifications.

THE TRANSMITTING SYSTEM—DETAILS

The transmitting part of the overall system was installed in the loading panels. This consists of various pony set control boxes, a control cable, modulator, MF transmitter, and RF line driver.

At each pony set location, a pony set control box was installed. The box contains three pushbuttons for brake release, forward, and reverse, along with an indicator light emitting diode (LED).

The pushbutton information from each pony set is sent by the cable to a modulator at the base station. Signals from the pony set pushbuttons and a locomotive identification (ID) are encoded into audio frequency shift keying (FSK) and sent to the transmitter. The locomotive ID is generated by a special

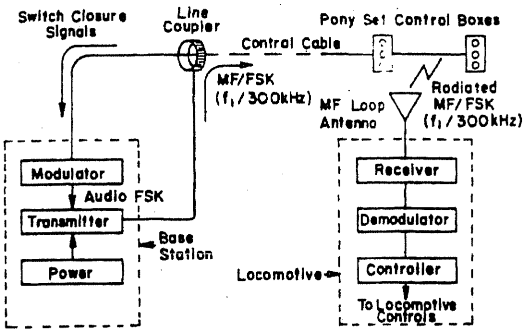

Fig. 3. MF radio control via control boxes and control cables.

TABLE I
SPECIFICATIONS

General	
Frequency	f_1 (300 kHz) remote control mode f_2 (350 kHz) voice communications mode
Power output	20W
Digital signal	Manchester coded baseband FSK
Mark frequency	1070 ± 10 Hz
Space frequency	1270 ± 10 Hz
Baud rate	300 ± 15
Base transmitter station	
Frequency	f_1 (300 kHz) only
Modulator output	0–2 V peak to peak
RF interface	f_1 (300 kHz) line coupler
Transmitter type	f_1/f_2 type set for f_1 only
Locomotive transceiver	
Frequency	f_1/f_2 depending on operating mode
Demodulator dynamic range	>60 dB
RF interface	f_1/f_2 loop antenna

physical key–electronic contactor assembly that permits unique coding. Different physical keys are associated with different locomotives. The audio FSK modulates the transmitter where it is converted to MF at 300 kHz.

The modulator is equipped with a seven-segment visual display corresponding to the ID key being used. It also supervises (as well as decodes) the three command lines for the three pushbuttons in the pony set control boxes. Fig. 4 shows how this is done.

All pushbuttons of a particular function (forward, for instance) are wired in parallel as shown. The last pony set control box also contains an "end of line" resistor. Since $R_1 = R_2$, normally the potential at A is 6 V. Pushing any pushbutton will cause point A to rise to 12 V, indicating a command function. If point A drops below 6 V, it indicates problems with either the 12-V source or the control cable.

When any of the control function detector circuits in the modulator are activated, an LED corresponding to brake/forward/reverse and line open/short will be lit. In this manner the control line is supervised. If a short/open fault is detected, a corresponding LED at each pony set control box is also lit.

The transmitter is simply an unmodified MF transceiver, with an output power of 20 W. It is a two-frequency device (300 kHz/350 kHz) that is automatically locked to 300 kHz when connected with the modulator. The control frequency chosen at this mine was 300 kHz.

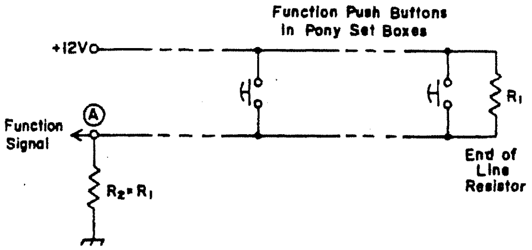

Fig. 4. Supervised command control line circuit.

The output of the base transmitter is sent to a line coupler clamped around the control cable. In this interesting arrangement, the control cable performs two functions. It connects the pony set control boxes to the modulator and also acts as the MF distribution antenna. The line coupler induces MF current into the control cable, which produces a local magnetic field all along the loading panel.

THE RECEIVING SYSTEM

The transceiver on the locomotive is equivalent to that of the base station but can operate on either f_1 (300 kHz) or f_2 (350 kHz), depending upon whether it is needed for voice communications on the haulageways or remote control in the loading panels. A two-position switch on the attached demodulator unit provides the selection. In the "manual" position, operation is at 350 kHz for voice communications with the rest of the rail haulage system. In the "remote" position, operation is at 300 kHz, and the locomotive is set for remote control from the pony set control boxes. A vehicular loop antenna on the locomotive picks up and transfers to the transceiver either 300- or 350-kHz signals.

When the "remote" mode is selected, FSK-encoded MF signals are picked up by the antenna-transceiver system from the local wiring and demodulated to FSK audio signals. The transceiver is also locked into the "receive" mode at 300 kHz. The demodulator converts the incoming audio FSK to a digital data stream. These data are an exact copy of those sent from the modulator at the base. The data are decoded, validated, and checked for redundancy. If correct, the data are then sent to control relays that drive the final contactors associated with the desired locomotive functions.

The data field associated with the system contains 15 b. The first 5 b contain the locomotive's ID and are determined by the physical key inserted into the modulator at the base. The last 10 b concern the function to be performed, such as brake release. Each locomotive has its own code preprogrammed in the modulator. In this manner, the decoded output can be valid only for a unique individual locomotive. After each reception of data, the last 4 b of each decoded data word are compared. The data will cause the output relays to activate only if 1) the baud rate is correct, 2) the ID codes match, and 3) data from two decoders are identical. In addition. for increased safety, the MF link from base to locomotive must be intact for the control relays to be activated. The loss of signal for more that 1 s causes time out, and the brakes are reset.

System operation to date has been excellent. Train control is reliable out to 1000 ft from the transmitter in a situation where, of course, there are cars between the two.

The question may be asked why this system represents a significant advance in train control when the same performance could have been achieved (in this mine) by carrier current techniques where the telemetry signals could simply have been capacitively coupled onto and received from the trolley line in the conventional manner, at a standard carrier current frequency of perhaps 88 kHz. The significance lies in several factors.

1) Control is possible to locomotives that do not use dc trolley power, such as diesels and battery units.

2) The locomotives need not be very near any conductors. Many tens of feet separation are possible.

3) The most important feature is shown in Fig. 5. Via a portable MF transmitter-repeater combination, reliable control is possible from the person, wherever standing. In fact, portable vest transceivers already exists (Fig. 6) that permit this feature.

OTHER APPLICATIONS

The Use of MF in a Snapper Operation

One of the most dangerous tasks in a mine with a rail haulage system is that of coupling and uncoupling cars of the train. The person who does this work is often referred to as a "snapper."

The danger usually results from the fact that the snapper and the locomotive operator (motorman) are not in direct contact with each other because of the length of the train, curves in the loading area, and other factors. If the motorman moves the train when the snapper is between cars, the results can be tragic. Although snappers are supposed to adjust car couplers with long bars, and never actually place themselves between cars, they often do enter this area when alignment or other problems occur.

Even under the best of conditions, the operation is clumsy and inefficient. To address this problem, many mines have attempted to establish some sort of communications link between snapper and motorman.

The first attempt made is often to string a series of pager phones in the snapper's and motorman's locations. This approach is usually ineffective. The pager phones at the snapper's location are seldom where they are needed because the coupling–uncoupling point usually changes. The pager phones at the motorman's location are seldom where needed because the train length changes. Even if these problems did not exist, the system does not provide a good solution. If the snapper must physically stand at a pager phone location, he cannot "talk" the motorman into inching the train forward or back as needed.

Other attempts have been made that are equally unsatisfactory. Carrier phones with loop antennas have been given to snappers to permit direct communications with the motorman. In this approach, the snapper is required to carry a 30-lb carrier phone from site to site. If the trolley line does not extend into the snapper's location, communication is impossible. Even if a trolley line or other conductors exist, coupling losses and antenna inefficiencies are great, and performance is again poor.

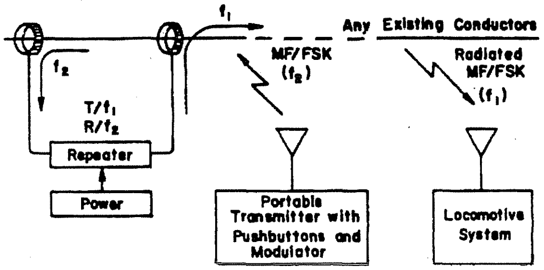

Fig. 5. MF control via portable transmitter repeater and existing conductors,

Fig. 6. Portable vest transceiver with remote control features.

UHF radio has also been tried and shown to be generally unsatisfactory. The long string of cars between snapper and motorman causes large signal attenuations, as do curves in the entryways. The overall result is short range.

An experiment was conducted to evaluate the performance of MF in a snapper operation in a local coal mine that was seeking a solution to this problem. The mine used a looparound-loading point method of loading train cars from shuttle cars. Fig. 7 shows the general layout.

The locomotive was equipped with a standard 20-W MF transceiver and loop antenna. The snapper was given a standard 4-W MF vest, similar to that shown in Fig. 6. The system did not provide any sort of control capability from vest to locomotive, only a voice link between snapper and motorman. The entryways where the snapper worked contained only a trolley line.

The communications range, between the motorman and snapper, was typically 1000 ft when rail cars existed between the two. At 1000 ft, directional effects existed such that the snapper had to be oriented parallel to and within 5 ft of the

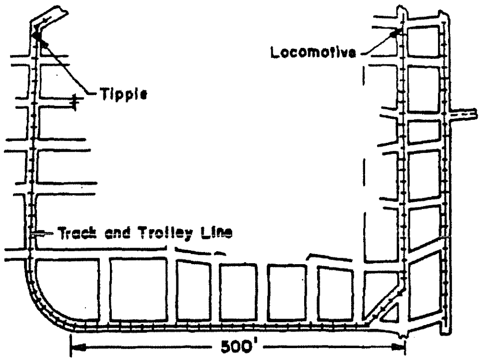

Fig. 7. Use of MF in snapper operation in coal mine.

trolley wire to achieve reliable communications. At separations less than 1000 ft, directional effects diminished, and it was possible to be farther away from the trolley line.

Because the snapper always works near the rail cars which represent a massive metal anomaly in the area, there is little doubt that even at MF these cars increase the signal attenuation. A solution would be to simply use a repeater concept as shown in Fig. 5. If this were done, the vest transceiver would have the benefit of 20 W of power instead of 4 W. Not only would range increase, but directional effects would be eliminated.

Status Monitoring of Mine Devices

In many instances it is necessary to know the condition or status of a critical mine device such as a water sump, motor, etc. Although the information desired is usually simple (is the sump overflowing?) it is also critical. It is usually not practical to run cables between the device and display location because of distance and other problems. Also, the information desired is sometimes temporary in nature. If it were possible to monitor and display this information in a convenient manner, this would be of great advantage. Medium frequencies allows this to be done.

An experimental data telemetry system has been developed that permits the monitoring of mine devices without the need to deploy special cables. It uses existing mine conductors. The general system is shown in Fig. 8.

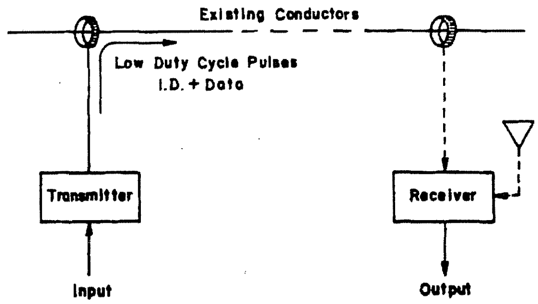

Fig. 8. Simple MF data telemetry system.

The transmitter is a self-contained battery-powered portable MF digital device that can encode and transmit 4 bits of data and a 12-bit address at any desired MF frequency, impressing this digital signal onto local mine wiring by the use of line couplers or other means. When so done, the existing conductors transmit and radiate the data throughout the mine. The receiver, also battery-powered, receives these signals either from line couplers (if the receiver is in a fixed location) or from loop antennas (if the receiver is mobile).

The transmitter transmits the data in short bursts of 40-ms duration followed by an adjustable off time which results in selectable duty cycles. This mode of operation has several important advantages: 1) circuit simplicity; 2) low average power consumption; and 3) low probability of data collision if more than one transmitter is used.

The receiver can be configured to operate in several modes, depending upon the nature of the data being transmitted. In the first mode, if alarm data exists on the four data bits from a particular transmitter, an immediate alarm indication (lights, buzzer, etc.) can be made to occur. In the second mode, the reception of a data word that contains only an address sets an internal timer within the receiver. So long as data are received within the time-out period of the receiver, time out will never occur and no alarm or loss of signal indication will be displayed.

Anything that disrupts the signal from reaching the receiver within the time-out interval will cause this fact to be displayed. The disruption can be caused in several ways: 1) the transmitter is actually shut off by the alarm condition or a transmitter failure; 2) a break in local mine conductors; 3) poor S/N ratio caused by electromagnetic interferences (EMI) or great distances; and 4) a failure in the receiver.

The foregoing mode of operation is nothing more than a supervisory, MF approach where the data consists of only the digital address of the particular transmitters. The Bureau's experimental data system has been designed to operate on the second mode. Limited testing on a mine phone line showed a 95-dB signal margin remaining at a distance of 1 mi from the transmitter. Additional testing has not been done to date.

The obvious application of this technique would be to have numerous in-mine transmitters sending data back to a fixed location such as an underground shop, but an even more valuable (and not so obvious) application exists. By the use of magnetic loop antennas placed on vehicles (such as the maintenance foreman's jeep), data, or status of devices, could be monitored while on the move, an application not practical by other means.

CONCLUSION

MF techniques have been used in a train-loading operation where radio control was required. The MF system worked well in an environment where a corresponding UHF system performed poorly. The MF system was based upon standard commerically available transceivers, interfaced with encoders and decoders. Because of the success of this system, the mine has improved the efficiency of the loading operation, reduced the number of personnel involved, and has enhanced general safety.

The initial system controlled trains via fixed control boxes in the pony sets, connected to a base station. Future plans calls for control from mobile portable transceivers. If very close to conductors, these transceivers could control the locomotives directly. If distant from wires, or under difficult conditions, a repeater system could be used.

Correction to "Control and Monitoring via Medium-Frequency Techniques and Existing Mine Conductors"

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In the above paper,[1] two concluding paragraphs and the references were missing from the manuscript on page 1092. They appear as follows.

In a coal mine, MF was applied to the problem of communications between snapper and motorman in a rail haulage-looparound operation. With standard portable and vehicular transceivers, communications were established between the two with 1000 ft of rail cars intervening. Although not truly a remote control application, the situation is similar to that of the metal mine and performance was equally good.

A simple MF data telemetry system was designed and tested that indicates that the integration of digital and MF techniques could be of benefit in monitoring critical mine parameters or devices. The system provides long range propagation using existing mine conductors.

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[3] R. L. Lagace, A. G. Emslie, and M. A. Grossman, "Modelling and data analysis of 50 to 5,000 kHz radio wave propagation in coal mines," (contract H0346045, A. D. Little, Inc.) *BuMines* OFR 83-80, 1980, 109 pp.; NTIS PB 80-209455.

[4] A.R.F. Products Inc. A Medium Frequency Wireless Communication System for Underground Mines (contract H0308004). For further information contact Harry Dobroski, Jr., Technical Project Officer, Bureau of Mines, Pittsburgh Research Center, Pittsburgh, PA 15236.