Simulation and Measurement of Medium-Frequency Signals Coupling From a Line to a Loop Antenna

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***Abstract*—The underground-mining environment can affect radio-signal propagation in various ways. Understanding these effects is especially critical in evaluating communications systems used during normal mining operations and during mine emergencies. One of these types of communications systems relies on medium-frequency (MF) radio frequencies. This paper presents the simulation and measurement results of recent National Institute for Occupational Safety and Health (NIOSH) research aimed at investigating MF coupling between a transmission line (TL) and a loop antenna in an underground coal mine. Two different types of measurements were completed: 1) line-current distribution and 2) line-to-antenna coupling. Measurements were taken underground in an experimental coal mine and on a specially designed surface test area. The results of these tests are characterized by current along a TL and voltage induced in the loop from a line. This paper concludes with a discussion of issues for MF TLs. These include electromagnetic fields at the ends of the TL, connection of the ends of the TL, the effect of other conductors underground, and the proximity of coal or earth. These results could help operators by providing examples of these challenges that may be experienced underground and a method by which to measure voltage induced by a line.**

***Index Terms*—Medium-frequency (MF) communications, parasitic coupling, transmission line (TL).**

I. INTRODUCTION

THE Mine Improvement and New Emergency Response Act of 2006 (MINER Act) [1] mandated that every underground coal mine in the United States develops an emergency response plan within 3 years that includes two-way, postaccident, wireless communication and tracking. The plan must provide for communications between underground and surface personnel, and electronic tracking of all underground mine workers. A survey completed in 2014 showed that all active underground coal mines have installed a system that operates in the very-high-frequency (VHF) or ultrahigh-frequency (UHF) bands [2].

Communication between rescuers at the surface and miners underground is especially important during emergencies such as methane or coal dust explosions, belt fires, or entrapments from a large ground fall or pillar burst. In such circumstances, conventional communication systems might be interrupted because their infrastructure may be damaged. Communication signals are subsequently blocked by the surrounding strata, attenuate on existing conductors once they are damaged, or power is lost. One of the major benefits of medium-frequency (MF) signals is that they couple to any existing mine conductors and travel for considerable distances underground without the need for additional power provided along the way.

MF communications typically involve inducing an electromagnetic field in close proximity to metallic conductors. The MF wave is then carried along those conductors where it can be received by another MF radio. The major advantage of MF technology is that it can couple into many different types of conductors and travel, in some cases, for several kilometers. Possible conductors include single- and multiple-wire insulated cables, power cables, rails, support mesh, and other continuous conductors present in a mining environment [3].

Since 2006, there are currently four approved MF systems. These four include peripherals, and all four are developed and marketed by the same manufacturer with the capability to function as MINER Act compliant communications and tracking systems [4].

II. MF COMMUNICATIONS

Medium frequency is designated for the band 300 kHz to 3 MHz, with wavelengths up to 1 km long. This band also includes the AM radio band. Permissible MF systems currently only support a single channel for voice, text, or data. This limitation may force permissible MF systems into the role of an emergency system for a larger mine which may require more channels or data for daily operations. However, MF does have its advantages; it may not require any additional specific conductors.

On the surface, MINER Act compliant MF radios cannot communicate farther than 30 m apart from each other through air in some cases. The power used by these MF radios has to meet permissible power levels for U.S. underground coal mines. Nonetheless, it has been observed that permissible MF signals can travel over 8 km underground aided by a conductor, acting as part of a transmission line (TL). For MF systems,

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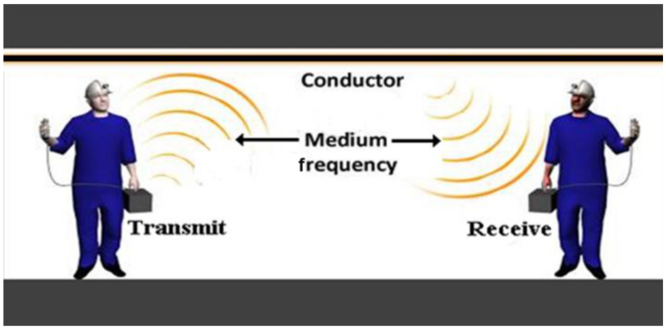

Fig. 1. Simple MF communications system.

the conductor plays a substantial role in the performance of this system.

The simplest underground MF communication system consists of only two MF transceivers separated by some distance and a single-conductor TL with return through ground (the earth). An electromagnetic field generated by one transceiver can couple to a conductor and then can be received by another transceiver within range of that same conductor (Fig. 1). Currents excited on a wire from an incident electromagnetic wave to a wire have been of interest to the research community for several decades [5]. One method calculates the induced currents by integrating over the product of the tangential electric field and the Green's function. This method has been applied to multiconductor systems [6] as well as systems including a dissipative medium [7], [8]. Furthermore, when transmission-line equations can be used approximately, a simplified coupling model can be developed [9]–[11] based on the telegrapher's equation.

III. FEKO LINE SIMULATION

There are several electromagnetic software simulation tools on the market. FEKO is an electromagnetic-simulation software tool for the analysis of 3-D structures. It offers multiple numerical methods for the solution of Maxwell's equations, enabling users to solve electromagnetic problems encountered in various industries. In this study, this software was used to simulate measurement values for comparison.

A TL was created using FEKO to simulate two parameters:

1) line-current distribution (LCD);
2) line-to-antenna coupling.

A. LCD Simulation

A FEKO model was created to simulate LCD, or more plainly described as the current along the TL from the beginning to the end. LCD is useful for simulation and modeling because it can be referenced when correlating measurements to models.

Figs. 2 and 3 show plots of the current at a given location along a 300-m TL. The TL was composed of a single 1-mm-radius wire positioned 1.68 m above a lossy earth ($\sigma = 1e-2$ $\mathrm{S/m}, \epsilon_r = 10$). These values of earth properties were chosen as representative values found in testing. The TL was excited by a 1-W power source for six selected frequencies. Notice that the line-current-distribution plots contain shapes that show resonances in the line due to standing waves. For the open-circuit TL (Fig. 2), the current approaches zero at the remote end (a null at 300 m); for a shorted TL, there is a maximum in the current at the remote end (Fig. 3). The first resonance occurs for one-quarter wavelength equal to 300 m (for an open circuit). The next resonance would be for one-half wavelength equal to 300 m (for a short circuit).

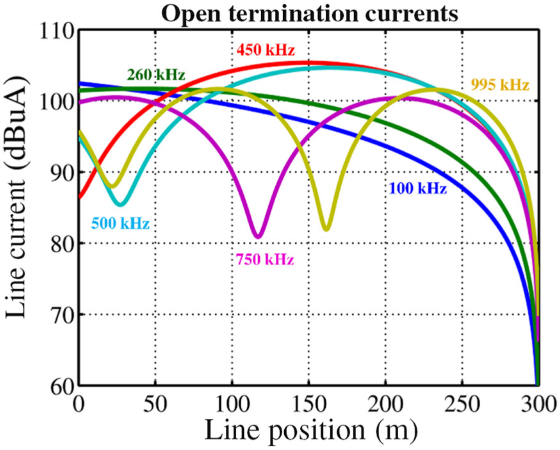

Fig. 2. Simulation result of LCD for an open TL.

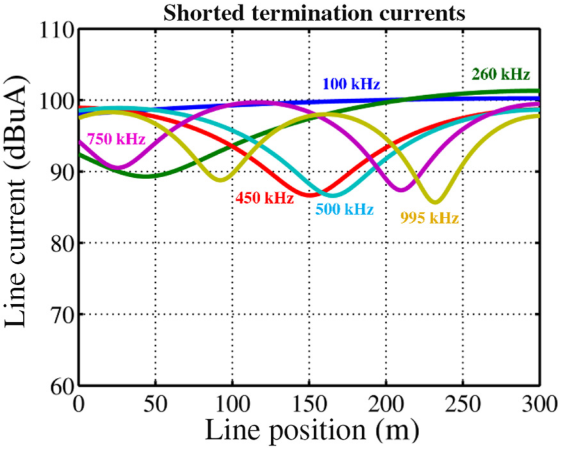

Fig. 3. Simulation result of LCD for a shorted TL.

B. Line-to-Antenna-Coupling Simulation

Using the same TL parameters from the LCD simulation, coupling was simulated by placing a 10-cm radius antenna loop constructed with a 1-mm-radius wire 3 m away, oriented in the plane parallel to the plane of the driven wire and the earth return. The antenna was translated along the length of the TL to simulate the coupling variation between the antenna and the TL along the length of the TL. When the far end of the TL was connected to ground, the simulation yielded Fig. 4.

In the case of a single wire with ground return TL, it is important to consider the termination effects of connecting the wire conductor to lossy earth. Earth is not a perfect conductor; there is a nonzero impedance associated with this electrode

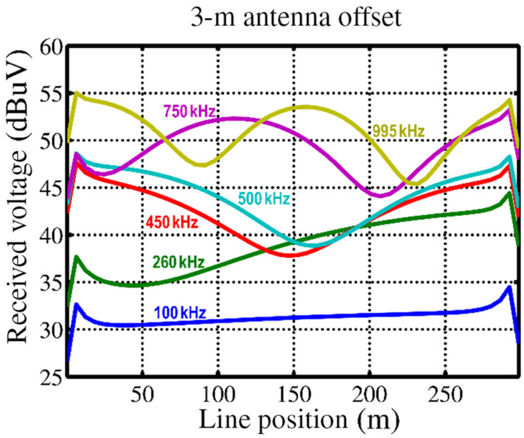

Fig. 4. Coupling simulation of a single conductor connected to ground.

connection to ground. In reality, there are many factors that can affect the earth's conductivity. Hence, for this work, the conductivity used in simulation models was based on experimental findings. For good-conducting (i.e., $\sigma/\epsilon\omega \gg 1$) earth materials, this impedance is mostly real and can be approximated with simple algebraic expressions [12], [13]. As a result, it is not possible to obtain a true short at the end of such a TL. The best that can be achieved is a close approximation to a short by providing $Z_r \ll Z_0$, where Z_r is the contact impedance between the wire and the lossy earth, and Z_0 is the characteristic impedance of the TL.

Permissible MF systems operate around 500 kHz. 995 kHz is about half the wavelength of 500 kHz. The coupling simulation produced a minimum in the received loop voltage about halfway along the length of the line for a 500-kHz signal and two minimums partway along the line for 995 kHz. The correspondence in the minimums in the LCD and antenna coupling plots suggests that current in the line plays a role in the received loop voltage, but since the loop takes into account the entire radiation of the line, the changes appear to be more gradual.

IV. MEASUREMENTS

In order to validate the simulation results and characterize the TL for MF coupling, the same two types of measurements were taken: 1) LCD and 2) line-to-antenna-coupling measurements. Each type of measurement was obtained and compared to the simulation results.

The ultimate goal is to make measurements underground. Rather than measuring an underground TL first, a surface TL was built in a remote area with no other conductors within 50 m. This surface TL served as a baseline reference for future measurements. The surface TL consisted of 14-gauge wire suspended 2 m off the ground using wooden-insulated supports (Fig. 5). One wire was hung on top of another separated by about 15 cm. When earth was connected, eight 15-cm-long, 6.3-mm-diameter, stainless steel bolts were attached in parallel using 14-guage wire and stainless steel clips at each end of the TL. Ground connections or electrodes were measured to be less than 50-Ω resistance from 100 to 1000 kHz at both ends of the TL using measurement methods outlined in previous work [14].

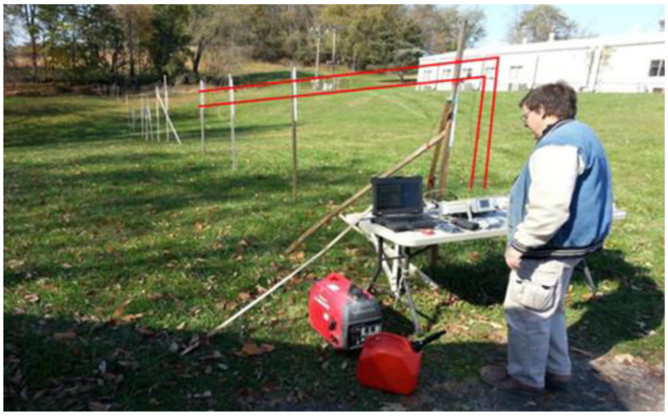

Fig. 5. Surface TL.

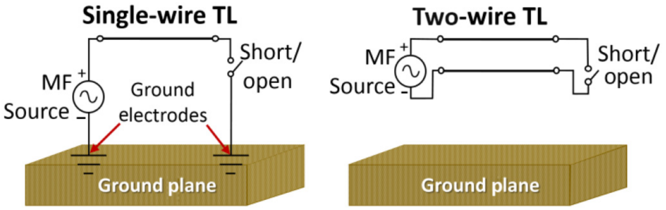

Fig. 6. TL test configurations.

In addition to electrode grounding, noise can be a factor for TL measurements as well. A very long TL, acting as an antenna itself, can receive this interference. Because interference from other frequency sources is inevitable, frequencies were chosen to be in between AM radio stations, which are strong interferers on the surface. Frequencies were selected that were not first or second harmonics of each other, so measurements of multiple frequencies could be recorded almost simultaneously for LCD and for line-to-antenna coupling.

TL measurements were taken using two different configurations (Fig. 6). For the single-wire TL, ground was always used as the return path. For the two-wire TL, the second wire was used as a return path and the earth was not connected.

A. Surface-Line-Current-Distribution Measurements

LCD measurements were taken using a clamp-on current probe (model BCP-510 passive current probe from AH systems, Inc.) and a spectrum analyzer (model Spectrum Master MS2722C from Anritsu Corp.) at fixed intervals along the TL. For a two-wire TL with an open termination (Fig. 7), current starts to flow at the source but begins to fall off toward the end of the TL. The opposite is true for a two-wire TL with a shorted termination (Fig. 8). For a single-conductor TL using ground as a return, current begins to flow near the source but does not fall off as it approaches the 300-m mark (Fig. 9).

For these frequencies, there is agreement between the LCD simulation and the measurements. Consider 500 kHz for Figs. 3 and 9. The 500-kHz measurement begins at the source and about halfway down the length of the TL it experiences a minimum before returning back up to a value close to what it was near the source at the end of the TL. There is a very little difference in behavior between the current in the TL

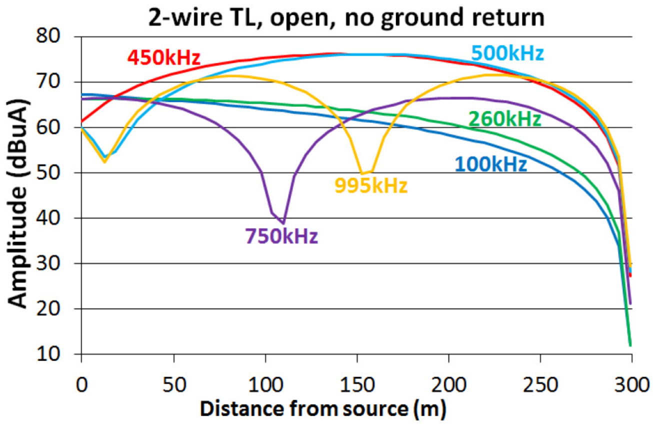

Fig. 7. LCD—two-wire TL, open, no ground connected.

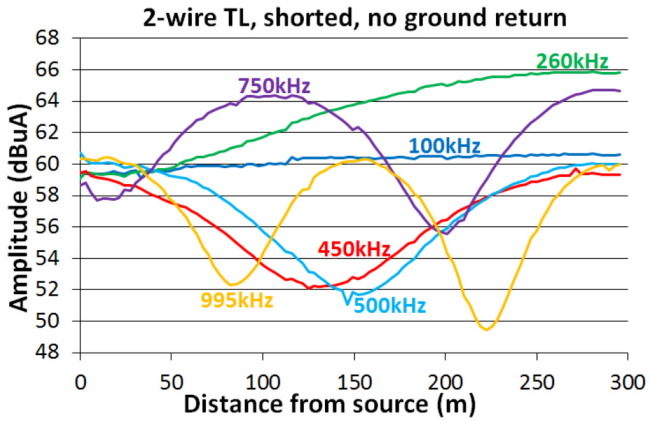

Fig. 8. LCD—two-wire TL, no ground connected.

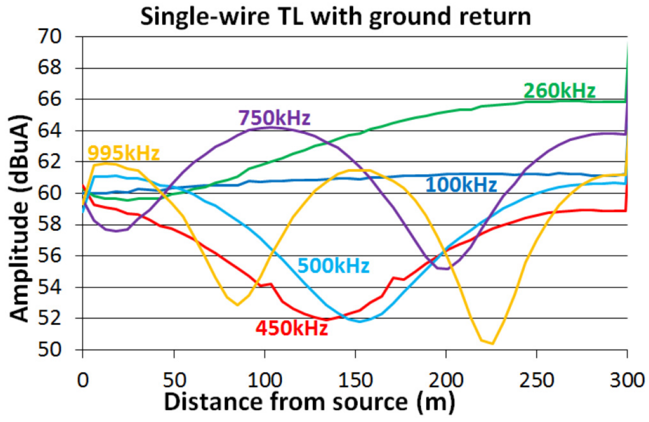

Fig. 9. LCD—single-wire TL, connected to ground.

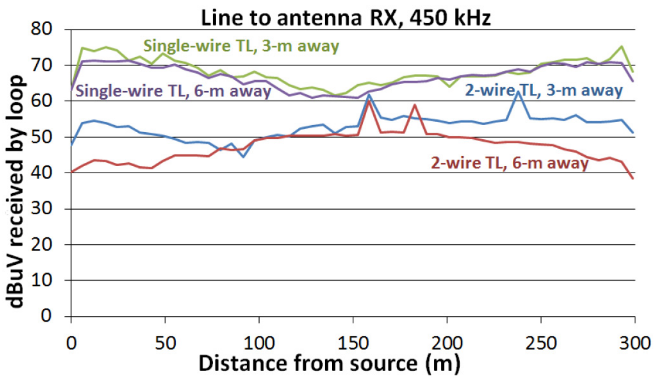

Fig. 10. Surface antenna coupling—450 kHz, single-wire and two-wire TL, loop antenna at 3 and 6 m away from the TL, all shorted.

in the two-wire shorted case (Fig. 8) and the single-wire configuration with return through earth (Fig. 9). Another observation is the decrease in the current at specific locations along the TL for each frequency. These decreases are attributed to standing waves in the TL caused by the reflecting current at the far end of the TL. When comparing the measurements with the simulation results, it is also important to note that the simulation models assumed that the TL is uniform along its length, which may not be true for the section of earth used for transmission in the experiments. It has been noted that this difference can cause modal conversion in multiconductor systems [15], potentially leading to differences in simulation models and measurement data.

B. Surface-Antenna-Coupling Measurements

Surface-antenna-coupling measurements were taken with a calibrated 30.5-cm receive loop (model SAS-563B 12” active-shielded loop antenna from AH systems, Inc.) and the same model spectrum analyzer used for LCD measurements. The loop was positioned with its axis approximately 1.8 m high off the ground. The loop was oriented in the vertical plane parallel to the TL. Measurements were taken at 3 and 6 m away from the TL for its entire length (Fig. 10). The TL’s electromagnetic field induced a voltage in the loop which is proportional to the changing electromagnetic field flux experienced by the loop. The calibration chart of the receive loop allows the user to equate the measured voltage to the electromagnetic field strength at that frequency. The magnetic flux density **B** is related to the voltage V, using the equation as follows:

$$V = -\int_{\boldsymbol{\Sigma}} \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{A}$$

where

B	magnetic field (magnetic flux density);
Σ	surface bounded by a given closed contour;
d**A**	infinitesimal vector element of surface Σ. If its direction is orthogonal to that surface patch, the magnitude is the area of an infinitesimal patch of surface.

The same TL test configurations used for LCD were also used for coupling measurements.

The two bottom plots in Fig. 10 are for a two-wire TL shorted at the end with the 30.5-cm receive antenna positioned 3 and 6 m away from the TL. The two top plots in Fig. 10 are the coupling results for a single-wire TL when ground was attached to both ends of the TL for the same positions. One observation was a 10−20 dBμV increase in received loop voltage when both ends of the TL were connected to ground. Another observation was a 5-dBμV drop observed at the ends of the TL whether ground was connected or not.

A slight increase and then a drop of about 5 dBμV at the end and beginning of the TL was observed for every frequency measured (Fig. 11). This also showed up in the simulation (Fig. 4) and may be attributed to the increased flux due to the vertical

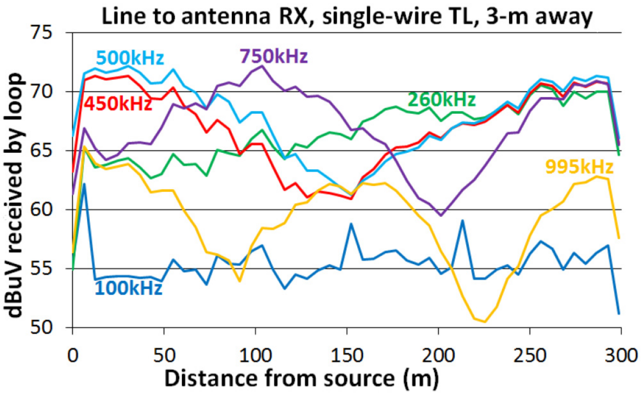

Fig. 11. Surface antenna coupling—single-wire TL, connected to ground.

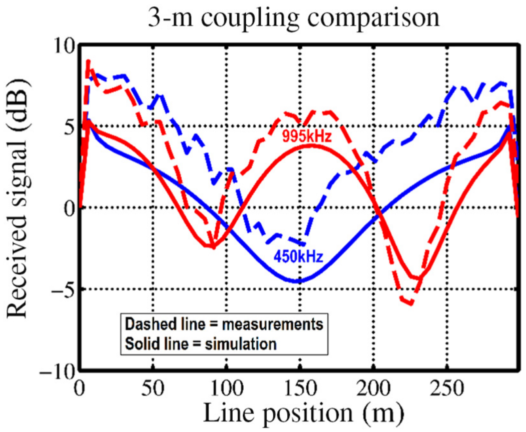

Fig. 12. Comparison of line-to-antenna-coupling measurement versus simulation.

line connecting the return wire or ground as the loop approaches within 5–10 m from the vertical line. Within 5 m, the vertical and horizontal field lines may not couple as well to the loop, thus producing a 5-dBμV drop.

One representative example comparing simulated and measured coupling for two frequencies is shown in Fig. 12. The line-to-antenna-coupling simulation and measurements agree within about a 5-dB margin. There is a slight shift in the minimums for the measured values when compared to the simulation in Fig. 12. This is due to several factors. Other sources were present in the test area adding to our received signal, the ground plane was not completely flat, about 1 m of wire was used to connect the TL to our source as well as the termination, and finally, our resolution of 3 m is larger than the simulation.

C. *Underground-Antenna-Coupling Measurements*

Coupling measurements were taken underground in a nonproducing coal mine. This mine was a small drift mine that contained noise sources and conductors similar to active mines. The TL in this case was a 520-m, 16-gauge solid copper, twisted-pair page phone cable. This type of cable is found regularly in active coal mines and it was one long continuous cable with no interruptions in this case. The cable ran into the mine through the drift opening and followed the perimeter before ending in the back of the mine. The cable was hung using plastic cable ties along the rib at about 1.2 m off the ground. Other conductors ran alongside it at various points. These other conductors shared the same entry as the twisted-pair under test for portions of the 520-m distance. The cable was hung to create a separation distance between it and any large steel structures to prevent direct contact with the TL insulation that may affect MF coupling characteristics.

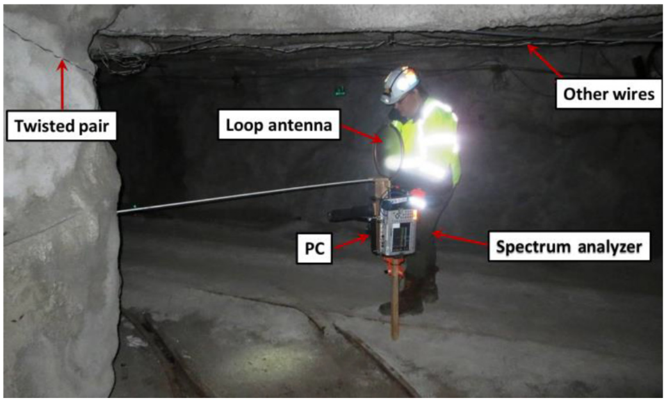

Fig. 13. Underground-transmission-line-coupling measurements.

The receiving loop height was shortened to 1 m on the center to account for low-roof conditions (Fig. 13). The antenna was also positioned 1.5 m away from the TL in order to keep it close to the center of the entry. Any further distance might have exposed the antenna to increased coupling of conductors on the other side of the entry in certain locations.

Measurements underground were taken using the same configurations and instrumentation as the surface-antenna-coupling measurements. The twisted-pair was used as a TL in the first case, and, in the second case, the twisted-pair shorted at both ends and used as a single-wire TL. For both configurations, the end of the TL (approximately the 500-m mark) was tested under both the short and open terminations. The source was positioned at the mouth of the drift and connected to the TL heading inby. When the source was connected to ground during the single-wire configuration, it was attached to eight 15-cm stainless steel bolts into the earth outside the mine. When the termination at the end of the TL was shorted to ground inside the mine, the end of the TL was attached to eight similar 15-cm stainless steel bolts into the coal rib. Results from tests conducted in this mine show that the impedance achieved from grounding eight bolts does not significantly change when adding more [14]. The results from the coupling measurements are shown in Fig. 14.

From beginning to end, the TL was nearby other energized conductors which continued through the mine. Although there is more interference as evidenced by the fluctuations seen in Fig. 14, there is still agreement with the surface results and simulations. There is still a large increase in the coupling of 10−20 dBμV in the single-wire configuration.

The sudden increase at the termination end of the underground TL may be attributed to other conductors being in the area of the termination. At the very end of the TL, the received

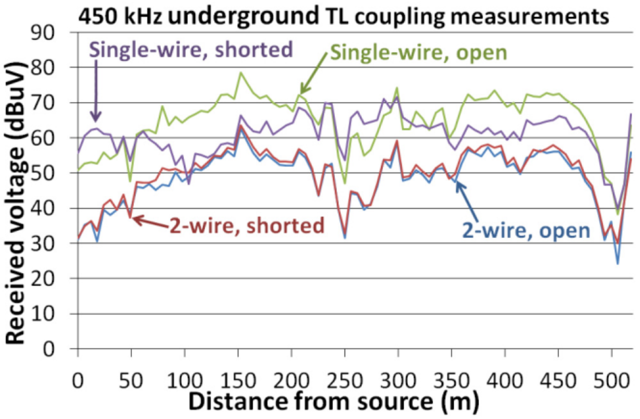

Fig. 14. Underground-coupling measurements at 450 kHz.

coupling for every configuration seems to read nearly the same value regardless of the conductor's termination. A further investigation on the influence of other conductors to the coupling is needed in order to quantify this effect. For a very long MF TL, it is very likely to come in close proximity to other underground conductors, which could produce unintended coupling.

V. DISCUSSION

Based on observations underground, it would appear in certain cases that keeping the TL away from other metal conductors underground may reduce coupling or TL propagation issues. Measurement equipment and modeling similar to what was used in this paper may help determine the source of these types of TL issues and provide general guidance on installation of a TL for MF communication use.

The measurements presented in the paper [16] can serve as a reference to help understand MF coupling characteristics, but only in the context of the described conditions. The measurement results are expected to vary with changing conditions. Among these conditions are current flowing on the conductor, length of the conductor, size of the antenna, orientation of the antenna, and termination of the TL conductors. However, these results serve as a representative example of simulation and measurement comparison.

VI. CONCLUSION

In this study, line coupling was found to correlate with LCD. The line-coupling simulation and measurements do not experience the sharper drops in signal due to resonance of the receiving antenna contribution over a length of line instead of a given point. For the case involving the two-wire open-ended TL, the current will go to zero at the termination. Therefore, the coupling will be poor at the end of the TL in this case.

Both in the TL measurements and in the simulation, it was observed that there is about a 5-dB drop in the signal coupled to the directional MF antenna within about 5–10 m of the end of the TL. These TL end effects are due to the antenna nearing the end of the TL where initially the vertical line used to short the TL to a return wire or to ground increases the flux through the receive loop. When the receive loop moves closer to the end of the TL, there are no horizontal TL lines past the vertical line to produce flux so a decrease occurs.

One solution to either of these problems is to extend the TL beyond the beginning and end points of maximum transmission. This could also be accomplished by extending the TL beyond the maximum desired communication distance. In any case, moving the receiver away from the end of the TL and toward the center of the TL may resolve this issue.

Measurements in this study indicate that a single-wire TL configuration using ground as a return has a greater signal coupling than a two-wire TL (Figs. 10 and 14). This is likely due to the increased size of the area enclosed by a single-wire TL. The stray field from a two-wire TL with the conductors close together is less than that from a single-wire TL spaced relatively far from the earth return; hence, it is easier for the loop to couple in the second case.

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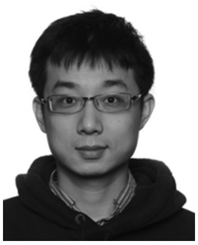

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