# Medium-Frequency Signal Propagation Characteristics of a Lifeline as a Transmission Line in Underground Coal Mines

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***Abstract*—Underground coal mines in the United States of America are required to install lifeline (LL) cable inside escapeways to guide miners out of a mine when visibility becomes poor due to heavy smoke. Some LLs consist of single or multiple steel conductors covered with a protective plastic outer layer. Research has shown that this type of LL can be a good conductor to guide a medium-frequency (MF) communication system signal to travel over large distances. To understand the MF propagation characteristics of an LL, National Institute for Occupational Safety and Health researchers took measurements on a section of LL in a coal mine, and obtained propagation parameters for analysis. The measurement data show that MF signals have a low attenuation which can enable the use of an LL for communication throughout a mine. The propagation parameters measured are presented in this paper.**

***Index Terms*—Attenuation measurement, communication systems, electromagnetic propagation, impedance measurement, mining industry, propagation losses, propagation measurement, RF signals, transmission line (TL) measurements.**

## I. Introduction

To ENACT the Mine Improvement and New Emergency Response Act (MINER Act) passed by Congress in June, 2006, the Mine Safety and Health Administration (MSHA) issued the final rule on Emergency Mine Evacuation on December 8, 2006. According to Sections 75.380 and 75.381 Lifelines (LLs) in Escapeways, the final rule "requires that durable, continuous lifelines (LL) be installed and maintained in both escapeways leading from the working sections or areas where mechanized mining equipment is being installed or removed. The lifelines must be continuous throughout the entire length of each escapeway to the surface escape drift opening, to the escape shaft or slope facilities to the surface, or to the surface, as applicable" [1].

Some LLs consist of one or two steel conductors covered with a protective plastic insulation to withstand a heavy pulling force. Steel conductors may also be coated with copper. Plastic cones are installed at a fixed distance interval along the LL to indicate the direction of travel to the surface. Optical reflectors also hang on the LL at certain points to indicate the LL position within the escapeway.

An escapeway is an entry designated on mine maps as the route to facilitate miners in an underground coal mine to exit the mine in the event of an emergency. The LL is hung from the roof or rib of escapeways, and reachable by the hands of miners. In a case when visibility of escapeways becomes poor due to heavy smoke following an accident, the trapped miners can hold on to the LL, and walk out by following it to the surface.

To further explore the medium-frequency (MF) characteristics of an LL as a transmission line (TL) in an underground coal mine environment after first reviewing underground coal mine communication systems and related research, this paper describes measurement taken on a section of LL in a coal mine and analyzes the obtained propagation parameters.

### A. Underground Coal Mine Communication Systems

The MINER Act requires all US underground coal mines to install wireless communication systems for postaccident communications. There are several types of communication systems currently approved for use in underground coal mines. These include page phones, which use a wired communication system merely for voice signals similar to ordinary land phones (300–3300 Hz); node-based wireless systems with ultrahigh frequency (UHF, 300 MHz–3 GHz); leaky-feeder-based systems with very high frequency (VHF, 30–300 MHz; MF systems with frequencies of 300 kHz–3 MHz; and through-the-earth (TTE) systems with extremely super or ultra low frequencies (3–4000 Hz, ELF, SLF, or ULF) for both data and voice wireless communications. Legacy mine trolley systems once used a mobile frequency-modulated communication system operating at a frequency between 88 and 100 kHz. These technologies fall into two categories based on their bandwidth capabilities. The page phone, node-based, and leaky feeder systems are generally used as primary communications systems for day to day operations. MF and TTE systems can be considered secondary or redundant communication system, to be used in emergency situations or used when the primary system is not operational. Page phone systems in particular can be vulnerable to physical damage and can be disrupted in an emergency situation.

One of the benefits of MF communication systems is that they are considered a parasitic technology, which means that an MF communication transmitter can wirelessly couple its signals

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to existing conductors, such as metal-cored LL, ac power cable, trolley wire, page phone cable, and other long conductors often found in a mine entry, and the signals can passively travel along the conductor for extended distances. This can often be accomplished in the order of several kilometers.

### B. Underground MF Communication Research

Research conducted by the U.S. Bureau of Mines in the 1970s found that an MF signal could travel along a conductor for many kilometers in a coal mine. Measurements of current and current simulations confirmed a low signal attenuation along a conductor, as a TL, hung in a coal mine entry in the 1980s [2]–[4]. Since then, the Bureau of Mines, the National Institute for Occupational Safety and Health (NIOSH), and other researchers have continued to develop MF communication and monitoring systems for underground coal mines [5]–[7]. Recent TL simulations using a simplified entry model have yielded results similar to those from the 1980s studies [8]. These simulations confirmed the low signal loss previously observed. In addition to the attenuation parameters, evaluation of the propagation behavior of MF signals as electromagnetic waves on a TL generally requires an entire set of the propagation parameters. These parameters include characteristic impedance, signal propagation attenuation constant, and phase constant. As shown in [8], these TL propagation parameters can be obtained from simulating a simplified tunnel TL model [8].

The propagation parameters of a TL are determined by many environmental factors in an underground coal mine. Among those factors are the electrical properties of the surrounding coal and rock, entry dimensions, and the position of the conductor. As shown in [9]–[13], the electrical properties of coal and rock can vary widely with frequency and location in an entry, which influence the values of the propagation parameters of a TL in the entry. Because of the complexity of the underground mine environment which is different from mine to mine, the direct measurement of a TL can be a more accurate method to obtain the propagation parameters. The direct measurement is able to yield the parameters which take all environmental factors in a given entry into account rather than just a few in a simulation. The measured parameters allow researchers to evaluate and understand the impact of each of these environmental factors. The measured parameters can also serve as the references for validation of simulation results.

Recently, NIOSH researchers developed an underground TL measurement method, called the open ($Z_{\text{oc}}$) and shorted ($Z_{\text{sc}}$) line impedance measurement method, which can produces a complete set of MF propagation parameters as a function of frequency. These parameters include characteristic impedance $Z_0(f)$; propagation constant $\gamma(f) = \alpha(f) + j\beta(f)$, where $\alpha(f)$ is the attenuation constant and $\beta(f)$ is the phase constant; power loss rate; and velocity factor VF($f$). VF($f$) is the ratio of the signal velocity to the velocity of light in a vacuum [9]–[11]. Power loss rate in dB/m can be an important parameter in determining the ability to communicate and how a system should be designed in a particular mine. The measured MF propagation parameters for some underground TLs using the method can be found in [9]–[13].

### C. Communication Research on LL

The two-conductor LL TL can be used to serve as a wired telephone line in mines as shown in [14] and [15]. Each of the two conductors from the terminal of a page phone can be connected to each of two core conductors of an LL, and miners can communicate to surface personnel on the page phone system.

If an LL consists of one or two metallic conductors, the LL can also be used to serve as a TL for an MF communication system, and there may then be no need for an additional infrastructure for a communication path. Using an LL as an MF communication path would establish another method for trapped miners to communicate with personnel on the surface and thus increase their chance to be rescued following a mine accident.

There are two ways for an MF communication system to couple its signal to a metal LL: 1) wired and 2) wireless. For wired communication, the system directly connects its two terminals to two LL conductors like a regular land telephone communication system. In this case, the LL serves as a two-conductor TL system. The communication signal can also be wirelessly coupled to both conductors of an LL simultaneously with no need to physically connect to it, and the signal can be coupled to the LL at any location. In this case, the LL electrically acts as a single conductor. This equivalent single-conductor line and the surrounding coal/rock in the entry together forms a single-conductor TL system which allows MF electromagnetic signals to propagate along it in the space between the LL conductor and the entry walls for many kilometers. It needs to be pointed out that this paper only focuses on the discussion on the MF propagation characteristics of a LL with an absence of signal coupling characteristics between a transmitter and the LL.

In support of MF communication research on LLs, NIOSH researchers recently conducted experiments in an active underground coal mine, and obtained the measured MF propagation parameters for a section of LL. The measurements were taken in two configurations: 1) a two-conductor TL configuration and 2) a single-conductor TL configuration. In the two-conductor configuration, one of the conductors served as the forward signal path and the other as the return path, while in the single-conductor configuration, both of the LL conductors were shorted at both ends and served as the forward signal path, and the surrounding coal and rock of the entry served as the return path.

## II. Measurement Method

In the experiments, the open ($Z_{\text{oc}}$) and shorted ($Z_{\text{sc}}$) line impedance measurement method introduced in [9]–[11] was used to obtain the propagation characteristics of the LL TLs in both configurations. The general derivations of the formulas for this method can also be found in [16]–[19]. As shown in Fig. 1, the open line impedance of the TL $Z_{\text{oc}}(f)$ as a function of frequency can be obtained at the input end of the TL with the far end open. Similarly, the shorted line impedance $Z_{\text{sc}}(f)$ can be obtained with the far end shorted. In Fig. 1, $x$ denotes the distance from the input end of the TL with a total length of $l$. The propagation parameters of the TL, as a function of frequency,

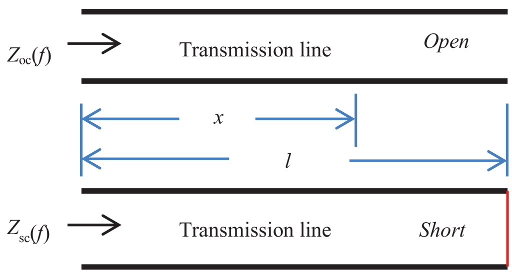


Fig. 1. Open and shorted line impedances of a TL.

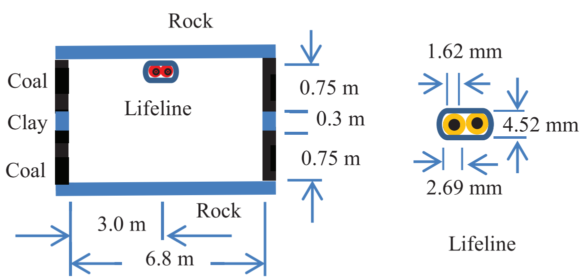


Fig. 2. Average entry cross-sectional dimensions, the LL position, and the cross section of the LL.

can be derived from the $Z_{oc}(f)$ and $Z_{sc}(f)$: the characteristic impedance $Z_0(f)$ can be obtained, as the geometric mean of the $Z_{oc}(f)$ and $Z_{sc}(f)$, from (1), the attenuation constant $\alpha(f)$ from (2), the power loss rate from (3), the phase constant $\beta(f)$ from (4), the signal velocity from (5), and the signal velocity factor VF($f$) from (6). Equations (7) and (8) are the voltage $V(x)$ and current $I(x)$ wave propagation expressions as a function of distance measured from the reference point of the incident end of the TL, where $V_0^+$ denotes the sinusoidal incidental voltage at the input end, $V_0^-$ denotes the reflected voltage at the far end, and $\gamma(f) = \alpha(f) + j\beta(f)$ denotes the propagation constant

$$Z_0(f) = \sqrt{Z_{sc}(f) \cdot Z_{oc}(f)} \text{ (Ohms)} \tag{1}$$

$$\alpha(f) = \frac{1}{2l} \left| \frac{1 + \sqrt{Z_{sc}(f)/Z_{oc}(f)}}{1 - \sqrt{Z_{sc}(f)/Z_{oc}(f)}} \right| \left( \frac{\text{Nepers}}{\text{Unit length}} \right) \tag{2}$$

$$\text{Loss}(f) = 8.686\alpha(f) \left( \frac{\text{dB}}{\text{Unit length}} \right) \tag{3}$$

$$\beta\left(f = \frac{f_2+f_1}{2}\right) = \frac{\pi(f_2+f_1)}{2\,l(f_2-f_1)} \left( \frac{\text{Rad}}{\text{Unit length}} \right) \text{ for } f_2 > f_1, \text{ where frequencies } f_2 \text{ and } f_1 \text{ are selected to make } 2\beta(f_2)\,l - 2\beta(f_1)\,l = 2\pi \tag{4}$$

$$v_p = \frac{\pi(f_2+f_1)}{\beta} \left( \frac{\text{meters}}{s} \right) \tag{5}$$

$$\text{VF} = \frac{v_p}{3.0 \times 10^8}, \text{ velocity of light} = 3.0 \times 10^8 \tag{6}$$

$$V(x) = V_0^+ e^{-\gamma(f)x} + V_0^- e^{\gamma(f)x} \tag{7}$$

$$I(x) = (1/Z_0)\left(V_0^+ e^{-\gamma x} - V_0^- e^{\gamma x}\right). \tag{8}$$

## III. Measurement Conditions

The experiments were conducted in an entry of an active underground coal mine with no other conductors present. Fig. 2 shows the average cross-sectional dimensions of the entry with the average height of 1.8 m.

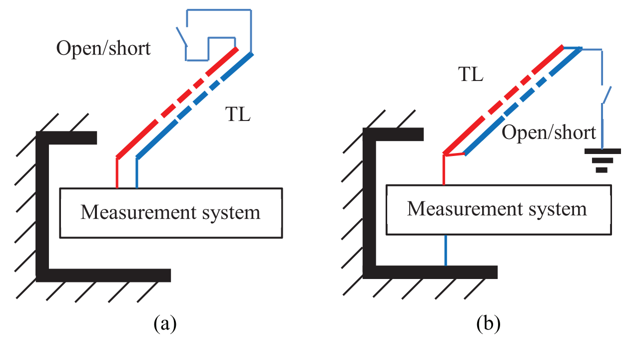


Fig. 3. Measurement configurations for both two- and single-conductor LL TLs in entry. Measurement of (a) two-conductor LL TL and (b) single-conductor LL TL.

The two-conductor LL measured 427.2-m long and hung near the center of the entry at an average of 0.30 m from the roof. The conductors were copper-coated steel cables measuring 1.62 mm in diameter and were individually insulated with plastic insulation then wrapped in a plastic outer layer as shown in Fig. 2 (right). The two conductors in the LL are in parallel.

## IV. LL Propagation Measurements

As stated earlier, the parameters were measured with the LL TLs in two configurations: 1) a two-conductor TL configuration and 2) a single-conductor TL configuration. The same measurement system introduced in [10] and [11] was used for both configurations. Fig. 3(a) illustrates the measurement configuration for the two-conductor TL. In this configuration, the two conductors are connected to the two respective leads of the measurement system that has no physical grounding. The propagation parameters obtained from this configuration can be used for a communication system that uses one conductor of the LL as the forward signal path and the other the return path. Fig. 3(b) illustrates the measurement configuration for the single-conductor TL. In this configuration, the two conductors are shorted at both ends and then connected with one of the leads of the measurement system. The other lead of the measurement system is connected to the ground (coal/rock) return path of the TL. The same grounding method introduced in [10] and [11] was used in this experiment. The propagation parameters from this measurement configuration can be used for a communication system that uses both LL conductors as the forward signal path and the surrounding coal/rock as the return path.

The $Z_{oc}(f)$ and $Z_{sc}(f)$ were measured from 300 kHz to 2 MHz in 1-kHz increments for both TL configurations in this experiment. The propagation parameters were then derived from $Z_{oc}(f)$ and $Z_{sc}(f)$.

### A. Propagation Parameters for Both Two- and Single-Conductor LL TLs

The measurements of $Z_{oc}(f)$ and $Z_{sc}(f)$ of the two- and single-conductor TLs are given as a function of frequency in Figs. 4 and 5, respectively. The periodic variations of these impedances are the results of the frequency variations of the

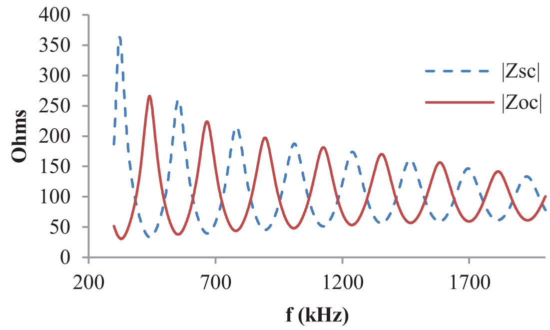


Fig. 4. $Z_{oc}/Z_{sc}$ measurements of the two-conductor TL.

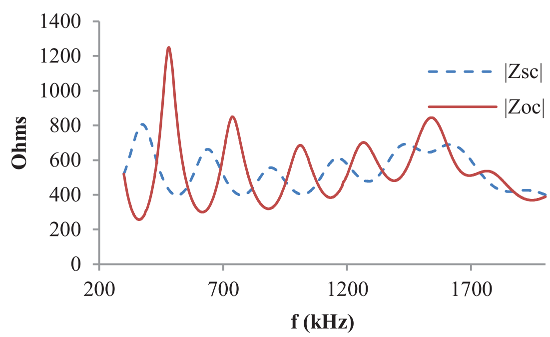


Fig. 5. $Z_{oc}/Z_{sc}$ measurements of the single-conductor TL.

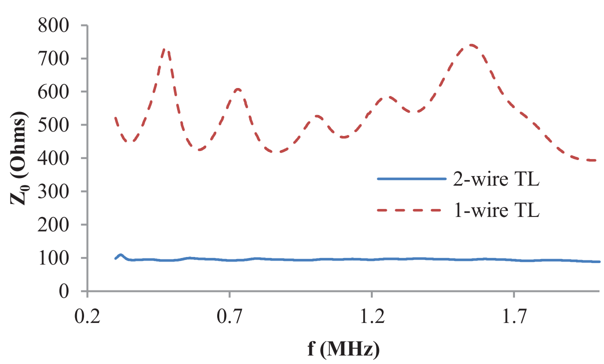


Fig. 6. Characteristic impedance of both the two- and single-conductor TLs.

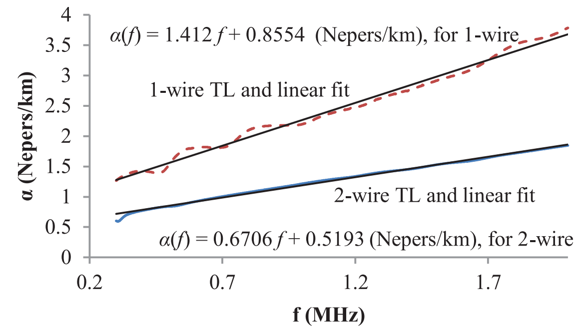


Fig. 7. Attenuation constant of both the two-and single-conductor TLs.

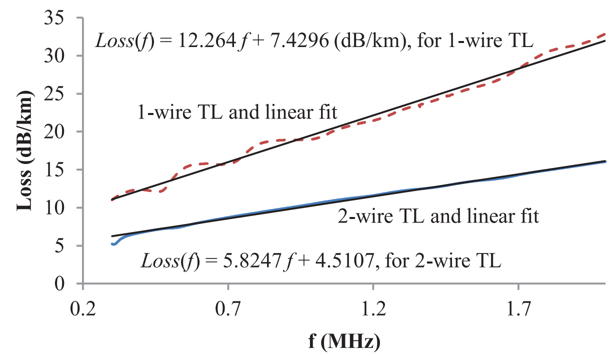


Fig. 8. Power loss rates of both the two- and single-conductor TLs.

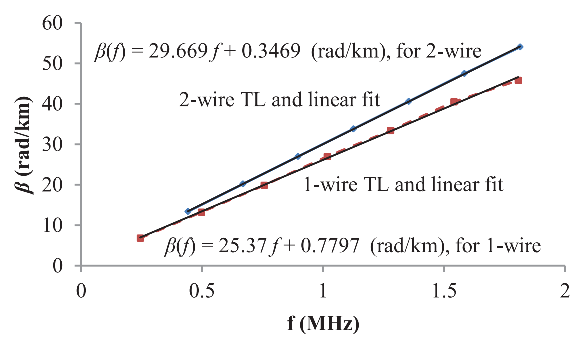


Fig. 9. Phase constant of both the two- and single-conductor TLs.

voltage and current standing waves measured at the input end of the TLs. Fig. 6 shows the plot of the derived characteristic impedance $Z_0(f)$ from the measurements of $Z_{oc}(f)$ and $Z_{sc}(f)$ for both the two- and single-conductor configurations of the TLs. The legend "2-wire" in the figure stands for the "two-conductor" and "1-wire" the "single-conductor." The average characteristic impedance over the frequency band for the two-conductor TL is $95\,\Omega$ with the standard deviation of $2.6\,\Omega$. The average characteristic impedance for the single-conductor TL is $528\,\Omega$ with the standard deviation of $92\,\Omega$. The higher standard deviation of the single-conductor TL suggests that the single-conductor TL has a greater variation in its characteristic impedance, relative to frequency, than the two-conductor TL.

The plots of the attenuation constants $\alpha(f)$ versus frequency for the TLs in both configurations are given in Fig. 7. The equation of a linear fit of the data for each configuration is also given in the figure to serve as an empirical model of the attenuation constant as a function of frequency. Likewise, Fig. 8 shows the power loss rates Loss($f$) of the TLs in both configurations. As shown in Fig. 8, the power loss rate of the TL in the single-conductor configuration is substantially higher than that of the TL in the two-conductor configuration.

Fig. 9 shows the plots of the phase constants $\beta(f)$ in both configurations with the linear fit equation, for each configuration, present. As shown in Fig. 9, the two-conductor TL has a higher phase constant than the single-conductor counterpart.

Fig. 10 shows the plots of the velocity factors VF($f$) for these two configurations. The average VF is 0.6972 for the two-conductor configuration TL, and 0.7927 for the single-conductor configuration TL.

### *B. Discussion and Analysis*

The MF propagation parameters obtained from the LL TLs in this study manifest some basic propagation characteristics of the LL TL in an underground coal mine environment.

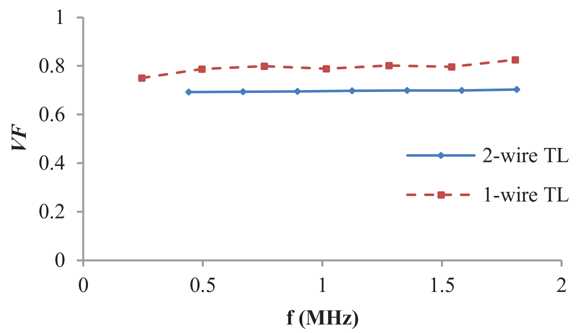


Fig. 10. VF of both the two- and single-conductor TLs.

Understanding these parameters would be beneficial for the design and development of a high-performance communication system using an LL as a signal path.

As shown in [20], the electromagnetic field of the two closely parallel conductors with currents in opposite directions has a cancellation effect in the space outside of those two conductors and a strengthening effect in the space between the two conductors. This suggests that a limited amount of electromagnetic energy radiates out from a two-conductor LL TL, and the electromagnetic energy mostly concentrates in and propagates along the space between the two conductors of the two-conductor LL TL. Thus, the LL TL in the two-conductor configuration is more suitable for wired communication. On the other hand, the electromagnetic energy travels in the space between the LL and the entry walls for the LL TL in the single-conductor configuration, and an MF receiver inside the entry is able to pick up the signal wirelessly. As such, the single-conductor LL TL is more suitable to wireless communication within a mine entry. For these reasons, the single-conductor LL TL can be more highly dependent on the mine conditions, and may vary substantially from installation to installation and even from place to place along the mine entry, while the two-conductor LL TL will be more stable with its characteristic impedance at approximately 95 Ω, not only along the length of one installation but in almost every mine.

As shown in Fig. 6, the characteristic impedances between the LL TLs in the two- and single-conductor configurations are substantially different. The characteristic impedance in the two-conductor configuration is almost constant at 95 Ω while the characteristic impedance in the single-conductor configuration varies with frequency and averages approximately 528 Ω. This suggests that different terminal loads should be considered for different TL configurations to maximize efficiency of the power transfer for MF communication signals on LLs.

A TL system has maximum power transfer efficiency when its terminal load is equal to its characteristic impedance. A constant 95-Ω terminal load needs to be considered for a two-conductor LL TL system. Because the characteristic impedance varies with operating frequency as shown in Fig. 6, the terminal load for a single-conductor LL TL system needs to be selected according to system operating frequency, and validated with measurements taken *in situ* after LL installation. This also suggests that for an MF transceiver that uses a two-conductor configuration for an LL, its input and output impedances should be set to be 95 Ω for maximizing both power reception for its receiver and power output for its transmitter. As shown in Fig. 11, a single terminal network is sufficient to match the characteristic impedances of both signal- and two-conductor LL TLs. The termination given in Fig. 11 will present approximately 95 Ω to the two-conductor TL and 500 Ω to the single-conductor TL.

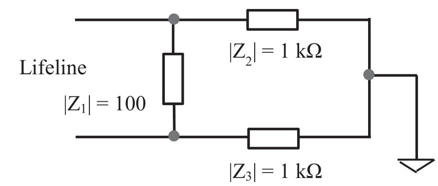


Fig. 11. Single terminal network matches the characteristic impedances of both single- and two-conductor LL TLs.

Another consideration for an MF communication system using an LL for its signal path is the difference of signal attenuations with a TL configuration. As shown in Fig. 7, the attenuation constant for the single-conductor LL TL at a given frequency is almost doubled over that for the two-conductor LL TL despite the fact that the attenuation constants in both configurations are all considered low. A similar finding applies to the power loss rate as shown in Fig. 8. This difference suggests that an MF communication system using a two-conductor TL can have a communication distance nearly doubled over that when using a single-conductor TL under an assumption that both have the same incident power and each of them has its own matched terminal load.

As shown in Fig. 10, the propagation velocities of the LL TLs in the single-conductor and two-conductor configurations are notably different. The velocity of the single-conductor TL is 13.7% higher than that of the two-conductor configuration counterpart. This suggests that for those MF communication systems able to take multiple signal paths with mixed LL TL configurations, the time delay on different routes with different configurations can be different due to the signal velocity difference of these two configurations. A large delay difference may cause a large phase difference for the same signal in different routes to the same destination. In this case, this delay difference may need to be taken into account for the system design in order to maintain the performance of an MF communication system.

## V. Summary

The measured MF propagation parameters of the two LL TL systems, one in a two-conductor configuration and the other in a single-conductor configuration in an underground coal mine entry, are presented to provide signal propagation data for underground MF communication systems, which use an LL as a signal path. Although both systems exhibit a low signal attenuation in the underground coal mine environment, the higher signal attenuation is found with the TL in the single-conductor configuration by comparison to that of the TL in the two-conductor configuration. The characteristic impedances, phase constants, and VFs are also noticeably different between these two configurations of the TLs.

These measurements can serve as technical data to conduct an MF communication system performance evaluation in the underground coal mine environment described in Section III. The values of the propagation parameters of a LL TL can yet vary, in some cases substantially, in different mine environments or with an LL in different structures. Still, the method used in the experiment can be applied to any of mines running with any LL to determine the actual MF propagation parameters of the LL. These parameters ultimately can be incorporated to design MF communication systems for underground coal mines and enhance their performance to enable miners to more readily have communications to the surface in the event of an emergency.

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