Wireless Channel and Electromagnetic Environments for Through-the-earth (TTE) Communications in an Underground Coal Mine

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Chenming Zhou
Pittsburgh Mining Resesarch Division
National Institute for Occupational Safety and Health
Pittsburgh, USA
czhou@cdc.gov

Nicholas Damiano
Pittsburgh Mining Resesarch Division
National Institute for Occupational Safety and Health
Pittsburgh, USA
ndamiano@cdc.gov

Abstract*—Through-the-earth (TTE) communication systems are useful for post-disaster emergency communications due to their likelihood of surviving a mine disaster. The wireless channel and electromagnetic environment (EME) are two primary factors that affect the performance of a TTE system and have not been well understood. This paper reports measurements made in an active coal mine to characterize the wireless channel and EME of a TTE system operating at frequencies up to 25 KHz. TTE transmissions were successfully demonstrated in a mine location with a depth of 567m (1860 ft) by using ground rods installed on the surface and existing roof bolts in the underground mine as electrodes. The results show that the EME in the mine is dominated by the 60-Hz signal and its harmonics for both the surface and the underground environments. The signal attenuation caused by the channel increases for frequencies greater than 90 Hz. This paper provides a measured data set pertaining to realistic EMEs and channels that an E-field TTE system operator or system designer can reference when implementing similar technologies in a mining environment.

Keywords—EMI, Electromagnetic noise, Through-the-earth communications, electromagnetic environments

I. INTRODUCTION

Through-the-earth (TTE) communications use extremely low frequency (ELF) or low-frequency (LF) waves to communicate directly through the earth overburden which is generally opaque to higher-frequency conventional radio signals [1]. TTE communication systems provide less infrastructure that can be exposed to damage in the case of fire, explosion or large ground-fall. As a result, TTE systems are more survivable and particularly useful in underground mines for emergency communications following a mine disaster during which conventional communication systems might be impaired [2].

A TTE system can be categorized as either a magnetic-field system, or an electric-field system, based on the fields that the system generates. As shown in Fig. 1, an electric-field TTE system uses one set of electrodes to inject electric currents into the earth and another set of electrodes on the other end of the overburden to receive the signals. While communication channels have been well understood at conventional frequency bands, there has been limited research concerning the wireless channels in the ELF and LF band, particularly in an underground mining environment. In addition to the channel, TTE system performance is also greatly impacted by the electromagnetic environments (EMEs) where the system is operated [3].

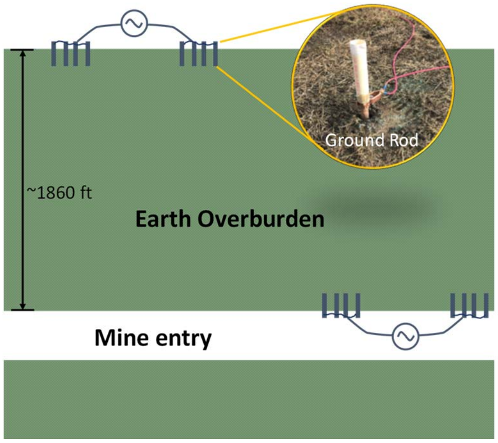

Fig. 1 An electrod-based TTE communicaiton system used in a coal mine. The inset shows an examplel of the installed ground rods on the surface.

In this paper, we report our recent measurement results on characterizing the communication channel and EMEs of an electric-field-based TTE system in an active coal mine. We demonstrated that TTE signals can penetrate 567 m (1860 ft) of earth overburden and still be detectable in the underground. It should be noted that the depth of the mine where we made the TTE transmission demonstration in this paper is about twice the depth of the mine (~900 ft) reported in [4].

II. MEASURING WIRELESS CHANNEL AND ELECTROMAGNETIC NOISE IN MINING ENVIRONMENTS

A. Experimental Setup

To characterize TTE communication channels and EMEs in a mining environment, four researchers from the National Institute for Occupational Safety and Health (NIOSH) made TTE measurements in an active coal mine located in the southern U.S. in November 2019. To prepare for the tests, two ground beds were installed on the surface in a relatively flat and open area covered by grass. The two constructed ground beds were separated by 73.8 m (242 ft) with each consisting of an array of 24 four-foot-long copper-clad ground rods. The inset in Fig. 1 shows an example of the ground rods installed on the surface. In the underground, no ground rods were installed. Instead, existing roof bolts were used to demonstrate that roof bolts may be used as the required electrodes for a TTE transmission. Fig. 2 shows a picture of the mine entry and an example of the roof bolts that were used in the underground. The separation distance between the two roof bolt arrays in the underground is about 12.1 m (40 ft). The overburden of the mine is about 567 m (1860 ft) and there is a horizontal offset of 152.4 m (500 ft) between the surface ground beds and the underground TTE electrodes.

Fig. 2 TTE measurements in an underground coal mine. (a) shows a picture of the mine entry in the underground, and (b) shows one of the roof bolts used as the electrode for TTE signaling.

The transceiver used in the measurement (one on the surface and one in the underground) was a battery-powered prototype system developed by NIOSH. Transmitted signals were generated by a National Instruments Data Acquisition (NI-DAQ) module (NI-9269). An audio amplifier was used to boost the transmitted signal. To measure the transmitted current, a 0.1-ohm resistor was added into the wire connecting the amplifier and the ground bed. The voltage dropped over the 0.1-ohm resistor was recorded by the same NI-DAC which sampled at 50k samples/sec. For the receiver, signals from the wire connected to electrodes were directly fed into one of the analog input ports of the NI-DAC. More details about the measurement system can be found in [4].

B. Experiment Description

First, to characterize the EME in a mining environment, background E-fields were recorded for both the underground and the surface without transmitting a signal. Second, to characterize the TTE channel, signals were transmitted across a frequency range of 30–2010 Hz at 34 discrete frequencies with a frequency spacing of 60 Hz. For each frequency, the signal was transmitted for 3 seconds followed by a 0.1-second gap. These frequencies were chosen to avoid the 60-Hz signal and its harmonics. A 330-Hz CW pulse was transmitted immediately before and after each channel sounding for the purpose of synchronization. During the channel sounding process, transmitted currents were recorded at the transmitter and received voltages were recorded at the receiver.

III. RESULTS AND DISCUSSION

A. Electromagnetic Envirornments

Fig. 3 illustrates the power spectrum of the measured E-field noise on the surface, when there is no target signal transmitted from the underground. The power spectrum was obtained by dividing the measured time domain waveform into small segments and applying a Fourier transform to each segment. A windowing (Hanning window) function was applied to reduce spectrum leakage. In Fig. 3, the maximum and mean value of the power spectrum over different segments are labeled as “Max” and “Mean”, respectively. As expected, the strongest emission in the environment is the 60-Hz signal caused by the nearby power system. The harmonics of the 60-Hz signal were noticeable as well. There is about a 10-dB difference between the mean value and the max value of the noise floor. The difference between the max and mean value is less for frequency components (e.g., 60 Hz and its harmonics) with a higher power.

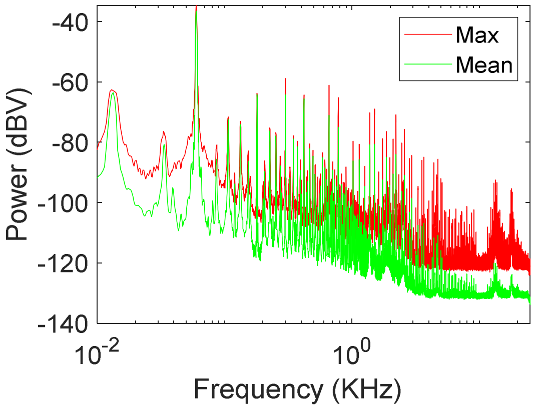

Fig. 3 Measured power spectrum on the surface when there is no signal transmitted from the underground .

Fig. 4 shows a comparison of the measured power spectrum for the underground and the surface. To simplify the plots, only mean values are compared. It is interesting to note that emissions from the 60-Hz signal and its harmonics in the underground seem to be stronger than those measured on the surface. However, the electromagnetic energy measured on the surface appears to be distributed in more frequency components. For example, in Fig. 4, more “spikes” are observed between 60 Hz and 180 Hz on the surface than in the underground. For TTE communications, target signals should be chosen to avoid 60-Hz and its harmonics that exist in the environments.

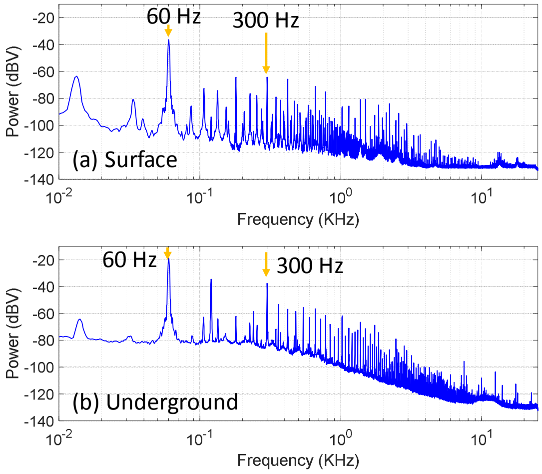

Fig. 4 A comparision of the measured electromagnetic noise for different environments: (a) on the surface and (b) in the underground.

B. *TTE Wireless Channel*

Fig. 5 shows a visual representation of the spectrum of the signal received in the underground, as it varies with time. It is clear in Fig. 5 that target signals at frequencies from 30 Hz to 690 Hz transmitted from the surface can be visually identified from the background noise (interference). The 60-Hz signal and its harmonics are also noticeable in Fig. 5. In contrast to target signals which were designed to last 3s, the 60-Hz signal and its harmonics are continuous over time. The synchronization CW pulse at 330-Hz is also clear (as labeled) in Fig. 5.

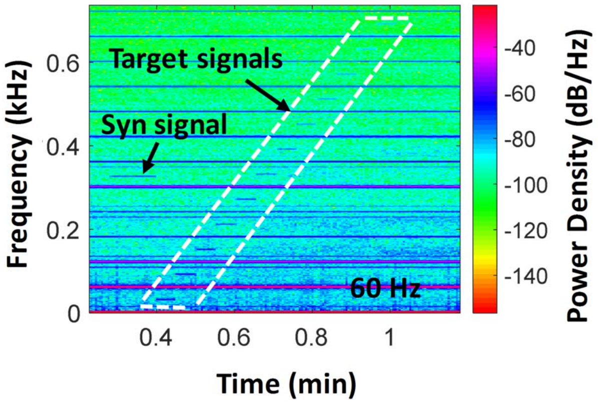

Fig. 5 A spectrogram plot of the received signal in the underground

To further quantify the channel loss, Fig. 6 shows the received signal power at different target frequencies, normalized to the associated transmitted current at each frequency. To determine the interference for each transmit frequency, the received power at each transmit frequency—when no signal at the target frequency was being sent—was analyzed and averaged over time. The result is plotted as “Interference (Mean)” in Fig. 6. Similarly, “Interference (Max)” shows the maximum interference power from the environment when there is no target signal transmitted from the surface. The difference between the signal and the interference power can be viewed as signal-to-interference ratio (SIR) which is a key factor determining the quality of wireless communications.

It is shown in Fig. 6 that the channel loss for the tested location ranges from -102 dB/Hz to -65 dB/Hz, depending on the frequency. The channel introduces more attenuation to higher frequency signals for frequencies greater than 90 Hz. It is interesting to note that there appears to be an optimum frequency around 90 Hz which shows the minimum attenuation caused by the channel. This finding is consistent with the finding reported in [4] which was based on the measurement results from a different coal mine. Similar to the received signal power, the interference power also decreases with frequency. As a result, selecting low frequencies does not necessarily guarantee higher SIR which also depends on the interference power in the environment at the selected frequency.

IV. CONCLUSION

In this study, TTE measurements were made in an active coal mine using a customized channel sounding prototype system. The results show that the channel loss generally increases with frequencies for frequencies greater than 90 Hz which corresponds to the lowest channel loss. In addition, the measured EME for both the surface and the underground environments were presented. The result shows that the EME in the mine is dominated by the 60-Hz signal and its harmonics from the nearby power system. Accordingly, TTE systems should operate at frequencies not close to 60-Hz and its harmonics to avoid possible strong interferences at those frequencies.

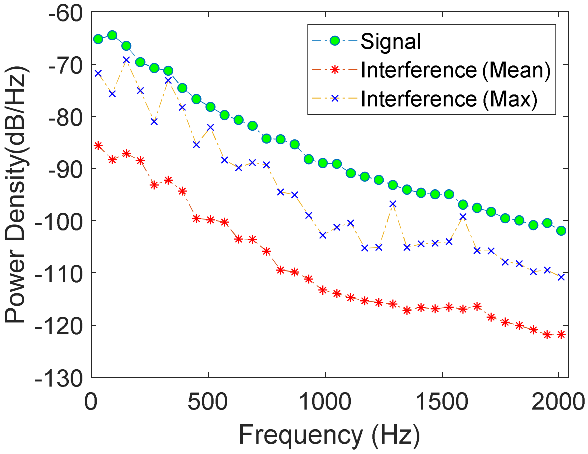

Fig. 6 Signal (normalized to transmitter current) and interference power received in the underground at different frequencis.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

REFERENCES

[1] N. Damiano, L. Yan, B. Whisner, and C. Zhou, “Simulation and Measurement of Through-the-Earth, Extremely Low-Frequency Signals Using Copper-Clad Steel Ground Rods,” *IEEE transactions on industry applications,* vol. 53, no. 5, pp. 5088-5095, 2017.

[2] M. Yenchek, G. Homce, N. Damiano, and J. Srednicki, “NIOSH-sponsored research in through-the-earth communications for mines: a status report,” *IEEE Transactions on Industry Applications,* vol. 48, no. 5, pp. 1700-1707, 2012.

[3] A. Muñoz, V. Bataller, N. Ayuso, P. Molina, A. Mediano, J. Cuchı, and J. Villarroel, “Noise Characterization in Through-The-Earth Communications with Electrodes,” in PIERS Proceedings, Marrakesh, MOROCCO, 2011.

[4] L. Yan, C. Zhou, M. Reyes, B. Whisner, and N. Damiano, “Mathematical modeling and measurement of electric fields of electrode-based through-the-earth (TTE) communication,” *Radio Science,* vol. 52, no. 6, pp. 731-742, 2017.