A TTE-LAN Communication Scheme for Tunnel Rescuing

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Abstract. In this paper, a communication scheme for tunnel rescuing is proposed, in which a moving base station (BS) is used for communication -devices in an isolated space and the ones in the outer space after tunnel collapse. Local area network (LAN) links are used for the direct communication between the base station and the inner terminals while an electrode based through-the-earth (TTE) communication link is used for the direct communication between the BS and the outer terminals. It enables the portability of the terminal devices for construction workers and ensures the communication reliability after tunnel collapse. The performance advantage of the proposed rescue communication system is demonstrated by simulation results.

1. Introduction
Tunnel construction is a key part of transportation facility construction in a nation’s infrastructure constructions. For the tunnel construction beneath earth surface, collapse may happen due to the pressure of earth, which would result in an isolated space with constructing workers in. The communication between the inner workers and the outer would be very helpful for rescuing.

Wireless communication systems working in UHF-SHF, such as 3GPP LTE \cite{1}, 5G \cite{2} and IEEE WiFi \cite{3}, are widely used in local area network (LAN) and wide area network (WAN). High frequencies enable small antennas and thus the corresponding terminal devices are portable. However, such wireless communication systems perform badly in blockage penetration \cite{4}, \cite{5}.

Through-the-earth (TTE) communication in VLF-LF performs good for signal propagation in earth \cite{6}–\cite{12}. However, due to the antenna size and the working mechanism, carrying the device for TTE communication is not convenient for constructing workers.

In this paper, a rescue communication scheme in tunnel construction is proposed: a moving base station (BS) is used for communication between the inner workers and the outer workers. Local area network (LAN) links are used for the direct communication between the base station and the inner workers while an electrode based through-the-earth (TTE) communication link is used for the direct communication between the BS and the outer workers.

The remaining part of this paper is organized as follows. In Section 2, the TTE-LAN communication scheme for tunnel rescuing is described and the path loss expressions for electrode based TTE communication and LAN are provided and analysed. In Section 3, simulation results are provided. In Section 4, the simulation results are discussed and the performance advantage of the rescue communication system for tunnel construction is demonstrated.
2. Method

Fig. 1 illustrates the TTE-LAN communication scheme for tunnel construction introduced in this paper, where an inner terminal and an outer terminal are connected via a BS. A TTE communication link is established for the communication between the BS and the outer terminal while a LAN communication link is established for the communication between the BS and the inner terminal. In-earth electrodes are used for the TTE link while antennas in air are used for the LAN link. The outer terminal is equipped with electrodes for TTE communication and the inner terminal is equipped with antennas for LAN communication while the BS is equipped with both the electrodes and the antennas for TTE communication and LAN communication respectively. The TTE communication link is supposed to adopt frequencies in VLF or LF bands while the LAN communication link is supposed to adopt frequencies in UHF or SHF bands.

For simplicity, as in [9], we assume the electrode pairs installed at the outer terminal and at the BS are perfectly aligned as Fig. 2 shows, where $l_{o}$ is the distance between the two electrodes of the outer terminal, $l_{b}$ is the distance between the two electrodes of the BS, and $d_{e}$ is the distance between the outer terminal and the BS. According to [8], when the outer terminal is receiving the signal from the BS, the electric field for the electrode based TTE communication is

$$E = \frac{I_{b}}{4\pi \sigma d_{e}^{2}} (1 + \gamma d_{e} + \gamma^{2} d_{e}^{2}) e^{-\gamma d_{e}},$$

(1)

where $I$ is the current between the electrodes of the BS, $\sigma$ is the earth conductivity, and

$$\gamma^{2} \equiv \frac{j \omega_{\text{tte}} \mu \sigma},$$

(2)

with the $\omega_{\text{tte}}$ the angular frequency, $\omega_{\text{tte}} = 2\pi f_{\text{tte}}$, and $\mu$ the permeability of free space, $\mu = 4\pi \times 10^{-7} \text{ H/m}$.

Similar to [9] but with some correction, the induced voltage $V_{o}$ can be calculated by integrating Eq. (1) over $l_{o}$ as follows
\[ V_0 = \frac{V_{b}l_{b}}{4\pi d_{e}^{2}\sigma z_c} (1 + \gamma d_e + \gamma^2 d_e^2)e^{-\gamma d_e}, \quad (3) \]

and \( V_b \) is the driving voltage at the BS and \( Z_c \) is the electrode contact impedance.

Hence, the path loss of the electrode based TTE communication \( \rho_{tte} \) in dB is

\[ \rho_{tte} = -20 \log_{10} \left| \frac{\frac{l_{b}}{4\pi d_{e}^{2}\sigma z_c} (1 + \gamma d_e + \gamma^2 d_e^2)e^{-\gamma d_e}}{1} \right|. \quad (4) \]

For LAN communications in UHF-SHF, according to [4], with typo correction on the expression (2) in [5], the penetration loss \( \alpha_{lan} \) in dB is

\[ \alpha_{lan} = \frac{20\pi}{\ln 10} \frac{\sqrt{\pi \tan \delta}}{\lambda_{lan}} d_e \quad (5) \]

where \( \epsilon_r \) is the relative dielectric constant, \( \lambda_{lan} \) is the wavelength, \( d_e \) is the penetration length, and \( \tan \delta \) is the loss tangent with

\[ \tan \delta = \frac{\omega_{lan}\epsilon''}{\omega_{lan}\epsilon'} + \sigma \quad (6) \]

where \( \epsilon' \) and \( -\epsilon'' \) are the real part and the imaginary part of the complex permittivity \( \epsilon \) respectively, \( \omega_{lan} \) is the angular frequency \( \omega_{lan} = 2\pi f_{lan} \), and \( \sigma \) is the earth conductivity as in Eq. (1).

Moreover, for LAN communications in UHF-SHF, the path loss in the air \( \beta_{lan} \) in dB can be calculated as

\[ \beta_{lan} = 20 \log_{10} \left( \frac{4\pi d_o}{\lambda_{lan}} \right) \quad (7) \]

with \( d_o \) the propagation distance in the air.

Consequently, the path loss for LAN communication with earth penetration \( \rho_{lan} \) in dB is

\[ \rho_{lan} = \alpha_{lan} + \beta_{lan}. \quad (8) \]

As \( d_e \) increases, it can be derived that both \( \rho_{tte} \) and \( \rho_{lan} \) become linear to \( d_e \), and the proportion between \( \rho_{tte} \) and \( \rho_{lan} \) is

\[ \frac{\rho_{tte}}{\rho_{lan}} \rightarrow \frac{l_{b}}{\pi \sqrt{\pi \tan \delta}} \quad (9) \]

Substituting the parameters obtained by the measurements in literature, e.g. in [4], [6]–[10], [13], to the Eq. (9), it is obtained that when the distance \( d_e \) is greater than a certain value, the path loss of electrode based TTE communication is less than the path loss of LAN communication, and the gap in dB becomes proportional to the distance \( d_e \) as it increases.

3. Results

(a) TTE only

(b) xxLAN only
Figure 3. Three rescue communication schemes.

In our simulation, we suppose that a tunnel collapsed as Fig. 3 shows, when the collapse length is \( d_e \) and the length of the isolated space is \( d_0 \). In a TTE-only scheme as Fig. 3a shows, the distance between the two TTE devices is \( d_e + d_0 \). In a LAN-only scheme as Fig. 3b shows, the distance between the LAN devices is also \( d_e + d_0 \). In the preferred TTE-LAN scheme as Fig. 3c shows, the distance between the BS and the LAN device in the same isolated space is \( d_0 \) and the distance between the BS and TTE device is \( d_b \).
We assume that the frequency used for TTE links is 100 Hz, the earth conductivity for 100 Hz is 0.01 S/m [14], and the steel rods are used with the contact impedance \((1760 - j60.3) \Omega\) as given in [9]. Eq. (4) is used to calculate path loss of TTE links.

We assume that the frequency used for LAN links is 2.4 GHz, the relative permittivity for 2.4 GHz is about 10.8 \(- j\) and the earth conductivity for 2.4 GHz is 0.15 as given in [13] from the measured data at Site 3 on 21 Oct 2002. Eq. (5), Eq. (7) and Eq. (8) are used to calculate path loss of LAN links.

In our simulations, \(d_e\) varies from 1 meter to 50 meters and \(d_0\) is 5 meters.

The simulation results for performance are plotted as shown in Fig. 4, Fig. 5 and Fig. 6.

4. Discussion

In Fig. 4, the preferred TTE-LAN scheme is compared with the TTE-only scheme. In the TTE-LAN scheme, since the BS receives the LAN signal and then converts it to the TTE signal, only the collapse length dB affects the path loss factor. From Fig. 4, we see that, as the propagation length of the TTE-LAN scheme is shorter than the TTE-only scheme, the path loss of the TTE-LAN scheme always performs better than the TTE-only scheme.

In Fig. 5, the preferred TTE-LAN scheme is compared with the LAN-only scheme. As the penetration loss for 2.4GHz is far worse than the path loss for electrode based TTE communication, we see that the pass loss of the LAN scheme become unacceptable when the collapse length is greater than 1 meter, i.e. the LAN communication is blocked when the collapse length is greater than 1 meter.

In Fig. 6, the three schemes are compared with respect to path loss per meter. We see that in terms of path loss per meter, the TTE-LAN is the best scheme among the three and the gap with respect to path loss per meter approaches a constant which proves the expression.

5. Conclusions

A TTE-LAN rescue communication scheme for tunnel construction is presented in this paper, in which a BS equipped with a TTE communication module and a LAN communication module is used to connect the inner devices and the outer devices. LAN links working in UHF-SHF are used for communication between portable inner devices and BS while an electrode based TTE link working in VLF-LF is used for communication between the BS and the outer devices. Path loss models and the performance gap are derived. It is demonstrated by simulation results that the performance of the TTE-LAN is the best among three candidate schemes and the performance gap with respect to path loss per meter approaches a constant when the collapse length increases.

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