Physics-based Ultra-Wideband Channel Modeling for Tunnel/Mining Environments

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Abstract—Understanding wireless channels in mining environments is critical for designing optimized wireless systems in these complex environments. In this paper, we propose a physics-based deterministic UWB channel model for characterizing wireless channels in mining/tunnel environments. Both the time domain Channel Impulse Response (CIR) and frequency domain channel transfer function for tunnel environments are derived in an analytical form. The derived CIR and transfer function are validated by RF measurements at different frequencies.

I. INTRODUCTION

As mandated by the Mine Improvement and New Emergency Response Act (MINER Act), wireless communication and tracking systems are now required in all U.S. underground coal mines. To design reliable, high-performance wireless systems that can be deployed in highly complex mining environments, it is essential to understand the wireless channels in these environments. Characterization of wireless channels in underground mines has been extensively investigated recently. Many prior studies focused on statistically characterizing channels [1]–[4]. While statistical characteristics of channels are useful, a deterministic channel model often provides more physical insight [5]. In this paper, we propose a physics-based deterministic UWB channel model for characterizing wireless channels in mining/tunnel environments. The Channel Impulse Response (CIR) and complex channel transfer function are derived explicitly and validated by RF measurements.

II. TIME DOMAIN UWB CHANNEL MODELING FOR TUNNEL ENVIRONMENTS

A. General time domain UWB channel model

A general Wide Sense Stationary (WSS) UWB channel is often modeled as a tapped delay line [5], [6]

\[ h(t) = \sum_{l=1}^{L} A_l \delta(t - \tau_l) \]  

where \( L \) is the number of multipath components. \( A_l \) and \( \tau_l \) are the amplitude and delay of the \( l^{th} \) multipath component, respectively.

In practice, estimation of \( h(t) \) is a challenging task, especially when there is per-path pulse distortion for wide band signals [5]. It would be desirable if an analytical model for \( h(t) \) were available. The analytical form of \( h(t) \) is useful for investigating system performance under different configurations (e.g., for time reversal [7] related studies).

B. Time domain UWB channel model for tunnel environments

The origin of the coordinate system is oriented at the center of the tunnel, with \( x \) horizontal, \( y \) vertical, and \( z \) down the tunnel. Let \( 2a \) and \( 2b \) denote the width and height of the tunnel, respectively. Without loss of generality, we also assume that the source is vertically polarized. For a communication system with a transmitter located at \( T(x_0, y_0, 0) \) and receiver at \( R(x, y, z) \), the CIR can be obtained based on the ray tracing method introduced in [8], [9] as

\[ h(t) = \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} A_{m,n} \delta(t - \tau_{m,n}) \]  

where

\[ A_{m,n} = \frac{(-1)^{m+n}}{r_{m,n}} \exp \left\{ -\frac{2}{r_{m,n}} \left( \frac{|x_m - x|}{\sqrt{\varepsilon_a - 1}} + \frac{|y_n - y|}{\sqrt{\varepsilon_b - 1}} \right) \right\}, \]

\[ \tau_{m,n} = \frac{r_{m,n}}{c}, \]

and where

\[ x_m = 2ma + (-1)^m x_0 \]
\[ y_n = 2nb + (-1)^n y_0 \]
\[ r_{m,n} = \sqrt{(x_m - x)^2 + (y_n - y)^2 + z^2} \]

In (3), \( c \) is the speed of light in a vacuum and \( \varepsilon_{a,b} = \varepsilon_{a,b}/\varepsilon_0 \) are the complex relative permittivities for the horizontal and vertical walls, normalized by the vacuum permittivity \( \varepsilon_0 \). \( \varepsilon_{a,b} \) can be expressed as

\[ \varepsilon_{a,b} = \varepsilon_{a,b} - j \frac{\sigma_{a,b}}{2\pi f \varepsilon_0} \]  

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where \( \varepsilon_{a,b} \) denotes the real part of the relative permittivity \( \varepsilon_{a,b} \). \( \sigma_{a,b} \) are the conductivity of the horizontal and vertical walls, respectively. If the frequency \( f \) is sufficiently high such that \( \sigma_{a,b}/(2\pi f \varepsilon_{a,b} \varepsilon_0) \ll 1 \) is satisfied, the tunnel walls generally act as a good dielectric where the displacement current density is much greater than the conduction current density [9]. As a result, the imaginary term in (5) can be ignored and thus \( \varepsilon_{a,b} \) becomes independent of frequency.

### III. Frequency Domain Channel Modeling for Tunnel Environments

Based on the modal method given in [8], the complex channel transfer function can be expressed as

\[
H(f) = -\frac{j2\pi}{ab} \sum_{p=1}^{\infty} \sum_{q=1}^{\infty} e^{-|\alpha_{p,q}(f)+j\beta_{p,q}(f)|z} B_{p,q}(f)
\]

where

\[
B_{p,q}(f) = \sin \left( \frac{q\pi}{2a} x + \varphi_p \right) \sin \left( \frac{q\pi}{2b} y + \varphi_q \right) \times \sin \left( \frac{p\pi}{2a} x_0 + \varphi_p \right) \sin \left( \frac{p\pi}{2b} y_0 + \varphi_q \right),
\]

\[
\alpha_{p,q}(f) = i \left( \frac{q\pi}{2a} \right) \Re \left\{ \frac{x}{\sqrt{\varepsilon_{a,b}}} \right\} + \frac{1}{2} \left( \frac{p\pi}{2a} \right) \Re \left\{ \frac{y}{\sqrt{\varepsilon_{a,b}}} \right\}
\]

\[
\beta_{p,q}(f) = \sqrt{\left( \frac{2\pi f}{c} \right)^2 - \left( \frac{q\pi}{2a} \right)^2 - \left( \frac{p\pi}{2b} \right)^2},
\]

\[
\varphi_{p,q} = \begin{cases} 0 & \text{if } p(q) \text{ is even} \\ \pi/2 & \text{if } p(q) \text{ is odd} \end{cases}
\]

The received signal in the frequency domain can be obtained by multiplying the transmitted pulse (in the frequency domain) with the complex channel transfer function \( H(f) \)

\[
R(f) = P(f)H(f)
\]

### IV. Results and Discussion

Fig. 1 shows two typical examples (corresponding to two different separation distances, respectively) of the simulated CIR in a tunnel environment. Unless stated otherwise, the parameters used in the simulations reported in this paper are listed in Table I. It is apparent from Fig. 1 that the number of noticeable multipath components increases with the separation distance. The Root Mean Square (RMS) delay spread [6] computed based on the CIRs for different separation distances is shown in Fig. 2. It is interesting to note that the RMS delay spread of the channel remains relatively stable as the distance increases, despite the fact that the number of significant multipath components increases with the distance.

Theoretically, an infinite number of multipath components exist as radio waves propagate in a confined tunnel environment. Practically, however, a limited number of multipath components make a noticeable contribution to the received signal and need to be included in the model. As a result, we can limit the range of the index \( m, n \) in (2) to \([-M, M]\) and \([-N, N]\), respectively. Both numbers of

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>2a</td>
<td>1.83 m</td>
<td>2b</td>
<td>2.35 m</td>
</tr>
<tr>
<td>( x_0 )</td>
<td>0</td>
<td>( x )</td>
<td>0</td>
</tr>
<tr>
<td>( y_0 )</td>
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<td>( y )</td>
<td>0.0457 m</td>
</tr>
<tr>
<td>( \varepsilon_{a,b} )</td>
<td>8.9</td>
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\( M \) and \( N \) are closely related to the number of multipath components included in the CIR shown in (2), and the number of the multipath components can be calculated as \((2M + 1)(2N + 1)\). As a special case, for \( M = N = 0 \), only the Line of Sight (LOS) path is included in the model, so (2) reduces to the the free space case where the standard Friis transmission equation can be applied.

Fig. 3 shows a comparison between the simulated received power and the measured power at 915 MHz. The simulated power is calculated based on the derived CIRs shown in (2) with different values of \( M \) and \( N \). The simulation result for the free space case (where \( M = N = 0 \)) is also plotted as a reference. The measurement was taken in a straight tunnel with four smooth concrete walls. More details about the measurement can be found in [9]. It appears from Fig. 3 that there is a critical distance of about 265 m for this specific case where the free space LOS power loss crosses the derived CIR loss in the tunnel. At a separation distance smaller than the critical distance, the tunnel (which acts as a dielectric waveguide) confines more energy compared to the free space channel. For distances greater than the critical distance, more power attenuation is observed in the tunnel than in the free space. The exact value of the critical distance depends on many factors such as the tunnel dimensions, electrical properties, and the frequency. It is also observed that the simulated received power curve gradually approaches the measured power curve as \( M \) and \( N \) increase. Additionally, it is
found that larger values of $M$ and $N$ are needed for greater distances in order to include all the significant multipath components. For example, it is shown in Fig. 3 that $M = N = 20$ is sufficient for including all the major multipath components for any distances less than 345 m, but is not sufficient for distances greater than 345 m. Another interesting finding is that when the receiver is located in the vicinity of the transmitter, only the LOS path needs to be considered in the model as evidenced by the fact that the $M = N = 0$ curve shows a good agreement with the measurement curve for short separation distances.

Fig. 4 shows a comparison between the measured and simulated received signal power at 5.8 GHz. $M = N = 40$ is used in the time domain impulse response and $P = Q = 5$ is used for the frequency domain channel transfer function. It is shown that the time domain simulated result matches the frequency simulation result well and both of them reasonably agree with the measurement result.

V. CONCLUSION

The wideband CIR and channel transfer function were derived explicitly for characterizing wireless channels in tunnel/mining environments. The derived CIR is expressed in an analytical form similar to the classic tap delay line model. The models are validated by RF measurements in a concrete tunnel. The results in this paper help improve the understanding of radio channels in mining environments and are useful for designing better underground wireless communication and tracking systems.

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REFERENCES