TD Analysis of Transmission through a Building with Multilayer Wall Structure for UWB Signals

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Abstract

In this work the time-domain (TD) solution for transmission through a building with multilayer wall structure has been presented. The layers of the walls are considered with different thickness and dielectric materials. The exact frequency-domain (FD) formulation for transmitted field at the receiver (Rx) has been simplified under the condition of low-loss assumption and converted to TD formulation using inverse Laplace transform. The TD results have been validated with the inverse fast Fourier transform (IFFT) of the corresponding exact FD results. Further the computational efficiency of both the methods has been compared.

1. Introduction

In radio propagation of ultra wideband (UWB) signals, the main physical mechanisms considered are reflections, diffraction and transmission through the obstacles \cite{1,2}. In urban microcellular scenario and indoor scenario especially in non-line of sight (NLOS) communication in deep shadow regions, where the reflected and diffracted field components are weak, transmitted field component proves to be very significant \cite{2,3,4}. So it becomes important to analyze the effect of transmitted field for UWB communication in microcellular and indoor scenario.

Considering the large range of frequency of UWB signals, it is more efficient to study UWB propagation directly in time-domain (TD) where all the frequencies are treated simultaneously \cite{1,5}. The TD solution of transmitted field through a dielectric slab was presented in \cite{6}. A simplified TD model for UWB signals

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transmitting through a dielectric slab was presented in [7-8]. The TD solutions for the reflection and transmission through a dielectric slab were presented in [9]. In [10], TD solution for transmission through structures like single wedge and single building scenarios has been analyzed. In [11], the TD solution for received field calculation after penetration through multilayer wall structure having multiple layers with different dielectric materials has been presented.

In this work, we present an approximate TD solution for the field transmitted through a building with multilayer wall structure, under the condition of low-loss assumption. The analysis presented in this paper is an extension of work in [11]. Different layers of the walls are considered to be of different dielectric materials and also the effect of changing the layers thickness is presented. The presented TD solution is based on the established FD transmission model of [4,12,13], upon which suitable approximations are applied to obtain a simpler, accurate and more computationally efficient TD solution. The TD results are validated against the inverse fast Fourier transform (IFFT) [14-15] of the corresponding exact FD solution results. At last, the computational efficiency of the two approaches is compared to emphasize the significance of the TD solutions presented.

2. Propagation Environment

Fig. 1 shows transmission through a single building with multilayer wall structure, where the front and back walls of the building are assumed to be made up of three layers, each with different dielectric materials. The parameters \( r_i \) are the distances traversed by the transmitted field through the structure from the transmitter (Tx) up to the receiver (Rx). Angles \( \theta_i \) (for \( n = 0 \) to \( 7 \)) are the incidence angles with \( \theta_i(i = 2n + 1) \) (for \( n = 1 \) to \( 8 \)) as the angles of refraction at different points. The parameters \( h_x, h_y \) and \( h_b \) are the heights of the Tx, Rx and the building respectively. Tx and Rx are at distances \( d_1 \) and \( d_2 \) from the building respectively with \( d \) as the thickness of different layers of the walls.

3. Transmission Model

The FD expression for the transmitted field at Rx for Fig. 1 is given as [4,12,13]

\[
E_{Rx}(\omega) = \left( \frac{E_{inc}(\omega)}{r_{total}(\omega)} \right) \left( \prod_{i=1}^{8} T_{i,s,h}(\omega) \right) \left( \prod_{j=2}^{9} \exp \left( -\alpha_j(\omega) \exp(-jk\rho_j) \right) \right)
\]

where \( E_{inc} \) is the relative amplitude of the incident spherical source [16], \( r_{total}(\omega) = \sum_{i=1}^{8} r_i \) with \( T_{total,s,h}(\omega) = \prod_{i=1}^{8} T_{i,s,h}(\omega) \) representing the total FD transmission coefficient [13], which is equal to the product of all the FD transmission coefficients occurring along the transmission path between Tx and Rx with \( s \) and \( h \) subscripts referring to the soft and hard polarizations respectively. The parameter \( \alpha_b \) is the specific attenuation constant of the interior of the building [3]. \( \alpha_s(\omega), \beta_s(\omega) \) are total effective attenuation constants and phase shift constants respectively for different regions of the building [10-11]. The FD path-loss expression from (1) is given as

\[
L_{total,s,h}(\omega) = \left( \prod_{j=2}^{9} \exp \left( -\alpha_j(\omega) \exp(-jk\rho_j) \right) \right)
\]

Now the corresponding TD expression for the received field at Rx based on the FD expression is as follows
with \(*\) representing the convolution operator. \(\Gamma_{total,s,h}(t)\) and \(l_{total,s,h}(t)\) [7-8] are TD counterparts of \(\Gamma_{total,s,h}(\omega)\) and \(l_{total,s,h}(\omega)\) respectively. The TD expressions for \(\Gamma_{i,s,h}(t = 1 to 8)\) can be obtained using [10-11] for different polarizations.

For loss tangent much less than unity (\(\epsilon/\omega\epsilon \ll 1\)) [13], the FD path-loss expression (2) reduces to the following approximate form with constant values of angles of refraction and along a single effective path for transmission [10-11]

\[
L_{total,s,h}(\omega) \approx \exp \left[ -j\omega d \sum_{i=1}^{3} \sqrt{\mu_i} \varepsilon_i \left( 1 + \frac{\sigma_i}{2j\omega \epsilon_i} \right) \left( \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i-1)}} + \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i+1)}} \right) \right] \exp \left( -j k_0 (r_1 + r_5 + r_6) \right) \exp(-\alpha_0 r_5)
\]

where \(r_1 + r_5 + r_6\) is the total distance travelled by the field in free space. \(\varepsilon_i\) and \(\sigma_i\) are the electromagnetic properties of the \(i^{th}\) layer of the wall (assuming front and back walls to be identical). The term \(l_{total,s,h}(t)\) in (3) is then given by

\[
l_{total,s,h}(t) \approx \exp(-\alpha_0 r_5) \exp \left[ -d / 2 \sum_{i=1}^{3} \sqrt{\mu_i} \varepsilon_i \left( 1 + \frac{\sigma_i}{2j\omega \epsilon_i} \right) \left( \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i-1)}} + \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i+1)}} \right) \right] \exp \left( -j k_0 (r_1 + r_5 + r_6) \right) \exp(-\alpha_0 r_5)
\]

\[
\delta \left( t - d \sum_{i=1}^{3} \sqrt{\mu_i} \varepsilon_i \left( 1 + \frac{\sigma_i}{2j\omega \epsilon_i} \right) \left( \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i-1)}} + \frac{\varepsilon_{rl}}{\varepsilon_{rl} - \varepsilon_{rl(i-1)} \sin^2 \theta_{(2i+1)}} \right) \right) \exp \left( -j k_0 (r_1 + r_5 + r_6) \right) \exp(-\alpha_0 r_5)
\]
This approximated TD path-loss expression will be used in (3) to compute the TD transmitted field and the accuracy will be proved by the comparison of TD transmitted field with the IFFT of the exact FD results, as shown in next section.

4. Results and Discussion

In this Section, our goal is to compare the presented TD solution with conventional IFFT-FD method. The software tool MATLAB 7.1 is used and all the cases are run on an Intel Core-i5 2.5 GHz computer, with 8 GB of RAM. Considering propagation profile in Fig. 1, if conductivity becomes zero, then the transmitted field computed through IFFT approach is supposed to exactly match the transmitted field computed through TD approach. But in MATLAB simulation, it is observed that some offset value in time-axis still remains between TD and IFFT-FD results and that was noted due to MATLAB limitations. In all the following results, this offset has been compensated. Throughout our work, the Gaussian doublet pulse [16] is used as the excitation UWB signal. Table 1 shows the electromagnetic properties of the considered materials.

Table 1. Electromagnetic properties of different dielectric materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Permittivity ($\varepsilon_r$)</th>
<th>Conductivity ($\sigma$) (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick [9]</td>
<td>4.4</td>
<td>0.018</td>
</tr>
<tr>
<td>Dry Concrete [7]</td>
<td>5</td>
<td>0.016</td>
</tr>
<tr>
<td>Drywall [17]</td>
<td>2.4</td>
<td>0.004</td>
</tr>
<tr>
<td>Wood [7]</td>
<td>2</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 2 shows transmitted field at the Rx through the single building structure with front and back walls having multiple layers made up of different dielectric materials. Two different cases of three-layer wall structure of the building are analyzed: (i) drywall-wood-drywall (ii) dry concrete-brick-dry concrete. For both polarizations, the TD results are in excellent agreement with corresponding IFFT of exact FD results, thus providing validation to the proposed TD solution.

Fig. 2. Transmitted field through single building with multilayer wall structure, with drywall [17], wood [7], brick [9], dry concrete [7].
As it can be seen, the transmitted field at Rx suffers no distortion in shape in comparison to the shape of the excited UWB pulse. The transmitted field is undistorted due to very small magnitude of the loss tangent with respect to unity. However, the amplitude of the transmitted field is attenuated because of the transmission loss through the dielectric mediums. Also it can be seen that the transmitted field in second case is more attenuated than in the case of drywall and wood. This is because of comparatively larger value of dielectric constants for brick and dry concrete.

Considering soft polarization, Fig. 3 shows transmitted field at Rx for different values of the thickness of the layers. Dielectric materials considered in this result are drywall-wood-drywall. It is observed that with increase in layer thickness, the UWB received pulse gets delayed and more attenuated. This is because of the corresponding increase in the distance traversed through the dielectric mediums. Again the good agreement between TD and IFFT-FD results confirms the accuracy of presented TD solution.

A comparison between the computation times of the IFFT-FD method and the presented TD solution is presented in Table 2 which establishes that the TD analysis is computationally very efficient in comparison to the IFFT-FD solution.

Table 2. Average ratios of the computation time of the two methods

<table>
<thead>
<tr>
<th>Propagation profile</th>
<th>$T_{IFFT,FD}/T_{TD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single building with multilayer wall</td>
<td>~275</td>
</tr>
</tbody>
</table>

The two main reasons for such a significant reduction in the computational time in TD are: (i) the efficient convolution technique (Section 10.1, Fig. 10.1 and 10.2 in [14]) due to which few number of time samples suffice to provide accurate results. (ii) Approximation of the multiple transmission paths in FD by a single effective path for low-loss dielectric case [10-11].

Given the excellent agreement between presented TD solution and IFFT-FD solution, it can be concluded that the TD method is accurate for low loss tangent values in the UWB bandwidth. The presented work also establishes that the TD solution is computationally more efficient than the conventional IFFT-FD method.

![Fig. 3. Transmitted field for different values of layer thickness, with drywall [17], wood [7].](image-url)
5. Conclusion

An analytical TD solution has been presented for the transmitted field through a building with multilayer wall structure made up of low-loss dielectric materials. The results of the presented TD solution are validated against the corresponding IFFT-FD results and computational efficiency compared. The TD solution outperforms the IFFT-FD analysis in terms of the computational efficiency. The TD solution is vital in the analysis of UWB communication as it can provide a fast and accurate prediction of the total transmitted field in microcellular and indoor propagation scenarios.

References