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Time-domain UWB transmission model for three-dimensional environments with low-loss obstacles

Bajrang Bansal*, Sanjay Soni [1]

Department of Electronics and Communication Engineering, Delhi Technological University, Delhi 110042, India

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ABSTRACT

In this work, time-domain (TD) solution is presented for ultra wideband (UWB) transmission through three dimensional (3-D) scenarios made up of low-loss dielectric materials. Considering soft and hard polarizations, propagation through different structures like building and wedge is analyzed with arbitrary position of the receiver (Rx). Further the presented TD solution for transmission has been compared with TD UWB diffraction; single diffraction, double diffraction and diffraction followed by reflection when both transmitter (Tx) and Rx are in a plane normal to the edge. A detailed analysis of attenuation and distortion of transmitted and diffracted pulse waveforms through lossy obstacles is presented. It is observed that transmitted pulse waveform suffers comparatively lesser attenuation and distortion in shape as compared to diffracted pulse for low-loss obstacles. The TD results have been validated with the inverse fast Fourier transform (IFFT) of the corresponding exact frequency-domain (FD) results.

1. Introduction

In recent years, research in ultra wideband (UWB) propagation through indoor scenario has received great attention because of unique features of UWB communication like resilient to multipath phenomena, good resolution, high bit rates, accurate positioning and ranging, low power density, low complexity and low cost [1,2]. In radio propagation of UWB signals, especially in non-line-of-sight (NLOS) communication in deep shadow regions, transmitted field component proves to be very significant [3,4]. Considering the huge bandwidth (3.1–10.6 GHz) of UWB signals [5], it is more efficient to study UWB propagation directly in time-domain (TD) than applying numerical inverse fast Fourier transform (IFFT) to frequency-domain (FD) solutions to convert them into TD. Also TD solutions appear to be more efficient as all the frequencies are treated simultaneously [1].

In the TD, diffraction and reflection have been well studied [6,7]. Considering the importance of transmission in the deep shadow regions, the TD solution of transmitted field through a dielectric slab was presented in Ref. [8]. The measurements characterizing the different materials within UWB range along with the discussion about dispersion suffered by UWB signals due to penetration through the walls were presented in Refs. [9,10]. A simplified TD model for UWB signals transmitting through a dielectric slab was presented in Refs. [11,12]. The TD solutions for the reflection and transmission through a dielectric slab were presented in Ref. [13]. The TD solutions for transmission through a multilayer wall structure were presented in Ref. [14]. The TD solutions for transmission of UWB signals in microcellular and indoor scenario were presented in Ref. [15].

To design the receiver (Rx) for wireless communication system optimally, the accurate channel characterization is an important aspect. The Knowledge of the significant multipath components and pulse distortion helps in optimal design of the UWB Rx [16]. An analysis of attenuation and distortion of UWB transmission through lossy obstacles has not been well studied before. This work gives a comprehensive TD analysis of attenuation and distortion of UWB transmission. The motivation behind this analysis is that the pulse distortion significantly affects the performance of UWB Rx and thus it needs to be analyzed properly [16]. In Ref. [16], it is explained how pulse distortion would affect the system performance if no compensation for this kind of distortion is included. It is known that a matched filter Rx yields maximum signal to noise ratio (SNR) if it is matched to the transmitted pulse. For the narrow band case, it is not the problem as the transmitted pulse suffers no distortion or negligible distortion. In UWB communication, due to the channel being frequency-selective, UWB pulse suffers significant distortion

* Corresponding author. Tel.: +91 8826435527.
E-mail addresses: bajrangbnsl@gmail.com (B. Bansal), sanjoo.ksoni@gmail.com (S. Soni).

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[1] Tel.: +91 9540390146.

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and hence after convolved with matched filer yields lower SNR output. Thus, the accurate knowledge of pulse distortion at the Rx helps in optimal design of the Rx.

Propagation is considered through low-loss obstacles because most of the building materials used in construction work are of low-loss types like glass, wood, brick, dry concrete, etc [9]. The propagation environments considered in our work are of great significance in various scenarios such as offices, residential structures and outdoor scenarios. A detailed list of these environments with the corresponding range is given in Ref. [17, Table 1]. In Ref. [18], UWB Propagation measurements in typical indoor scenarios, including line-of-sight (LOS), NLOS, room-to-room, within-the-room and hallways have been considered. In Ref. [16], UWB propagation in renowned Bertoni's urban environment consisting of high rise buildings is investigated. In other available literature, UWB propagation modeling has been considered inside the room [19,20] and inside the home [21] that includes transmitter (Tx) and Rx positioned on different floors also. In Refs. [1,8,11–15,22,23], scattering objects have been modeled as slabs, buildings, half-planes and wedges.

The goal of this work is to present TD solution for UWB transmission through three-dimensional (3-D) scenarios and carry out the comparison with UWB diffraction when both Tx and Rx are in a plane normal to the edge. In-depth analysis of physics behind the distortion in UWB pulse waveform has been presented which helps to understand the nature of distortion.

The paper is organized as follows: In Section 2, the 3-D propagation environments and TD formulations for transmitted and diffracted field are presented. Diffraction covers single diffraction, double diffraction, and diffraction followed by reflection. Next in the result section, a detailed TD analysis of UWB propagation is presented. The TD results are validated against the IFFT [24,25] of the corresponding exact FD results. Further the comparison of computational efficiency of the two approaches (IFFT-FD and TD) is performed to emphasize the significance of the TD solutions presented. Finally the comparative analysis of normalized mean and mean square error between TD and IFFT-FD solutions is performed for transmission through all considered scenarios for different loss-tangent values to show the accuracy of low-loss assumption.

2. Propagation through 3-D scenarios

2.1. Propagation environments

Figs. 1 and 2 show 3-D and 2-D (side view) view for different propagation mechanisms through the building (with low-loss materials) scenario with Tx height h_t greater and lower than the building height h_b respectively. The plane along which the ray propagates from Tx to Rx through the building, changes with the movement of Rx along the y direction (can be seen in Figs. 1 and 2). Thus the 3-D scenario gets converted to 2-D for a particular Rx position.

The intersection points of ray path at roof-top and side-walls of the building (e.g. points P and S in Fig. 1) are found out using the parametric form of equation of line [26]. For $h_t > h_b$, transmission is through the corner of the building comprising roof-top and side-wall transmission. Side-wall width d_2 changes with the change in plane containing Tx and Rx. While for $h_t < h_b$, transmission is through the side-walls of the building and both d_1 and d_2 changes with Rx movement along the y direction.

Fig. 3 shows 3-D and 2-D (front view) propagation through the wedge structure. Similarly to building scenario, Rx is fixed along x and z direction while moving along the y direction. Parameters d_1, d_2 and internal wedge angle a_i change with Rx movement along the y direction.

2.2. Formulations

For a signal transmitting through the building or wedge structure in a particular plane, the FD transmitted field at Rx is given as [4,27]

$$E_{RX,s,h}(\omega) = (E_{inc}(\omega)/r_{total}(\omega))\left(\prod_{i=1}^{N} T_{i,s,h}(\omega)\right)L_{total,s,h}(\omega) \quad (1)$$

where E_{inc} is the relative amplitude of the spherical source [22], $r_{total}(\omega) = \sum_{i=1}^{J} r_i$ represents the total distance traversed by the transmitted field from Tx to Rx (J is equal to 5 for the building and 3 for the wedge structures). $T_{total,s,h}(\omega) = \prod_{i=1}^{N} T_{i,s,h}(\omega)$ represents the total FD transmission coefficient [27], 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 N corresponds to 4 and 2 for the building and wedge structures respectively. $L_{total,s,h}(\omega)$ [11,12] represents the total propagation path-loss suffered by the transmitted field during transmission between Tx to Rx.

The corresponding TD transmitted field through the building or wedge structure is given as

$$e_{RX,s,h}(t) \approx \left(\frac{e_{inc}(t)}{r_{total}}\right) * \Gamma_{total,s,h}(t) * l_{total,s,h}(t) \quad (2)$$

with '*' representing the convolution operator. $\Gamma_{total,s,h}(t)$ and $l_{total,s,h}(t)$ [11,12] are TD counterparts of $T_{total,s,h}(\omega)$ and $L_{total,s,h}(\omega)$

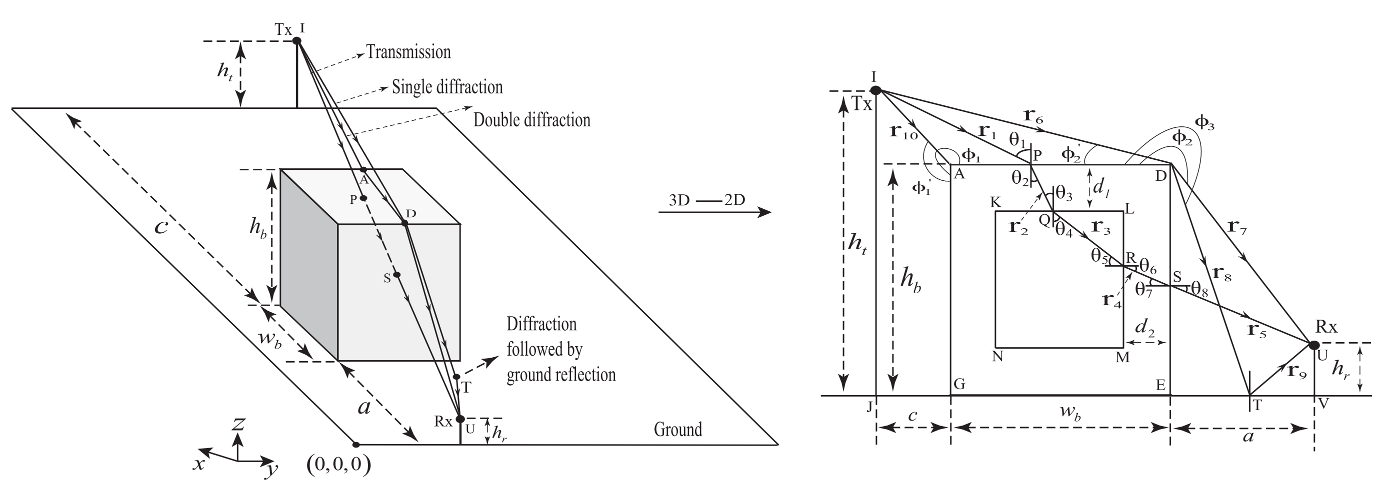

Fig. 1. Propagation through the building scenario with $h_t > h_b$.