UWB Multipath Simulator based on TEM Horn Antenna

A. H. Muqaibel
Electrical Engineering Department, King Fahd University of Petroleum & Minerals, P.O. Box 1734, Dhahran 31261, KSA
muqaibel@kfupm.edu.sa

U. M. Johar
Electrical Engineering Department, King Fahd University of Petroleum & Minerals, P.O. Box 834, Dhahran 31261, KSA
umjohar@kfupm.edu.sa

Abstract

Most of the existing UWB models are extensions of narrowband models. These models suffer from limitations because UWB multipath propagation is frequency and antenna dependent. In this paper, a directional simulator based on TEM horn antenna is developed. This simulator illustrates the spatial impact on the received multipath profiles. Several deterministic scenarios are simulated to examine the antenna impact on receiver design and positioning accuracy.

1. Introduction

Ultra-wideband (UWB) technology is very promising because of its merits including very high multipath immunity and bandwidth reuse. To obtain a thorough and comprehensive understanding of the potentials of UWB communication in multipath channels, the antenna impact cannot be underestimated. Different proposed UWB multipath models are extended from narrowband studies. The issue is more complicated because UWB multipath rays are frequency and space dependent.

One of the very important, yet frequently overlooked, concepts about UWB antennas is that the commonly accepted principle of antenna transmit-receive reciprocity does not always hold true for their time domain performance [1]. For a TEM horn antenna, Kanda [2] has shown that the transmitting transient response of an antenna is proportional to the time derivative of the receiving transient response of the same antenna. In the derivation, he showed that an extra "jω" factor exists in the antenna reciprocity relationship. For most researchers working in the frequency domain at a single frequency, or a narrow band of frequencies, this "jω" term simply means a 90-degree phase shift (i.e. converts the sine wave into a cosine wave). Consequently, it has been ignored in the classical frequency domain antenna design and it has been assumed that an antenna's gain is identical when operating as a transmitter or as a receiver. On the other hand, this "jω" factor has a dramatically different effect in the time domain, namely differentiating or integrating, depending upon the usage of the antenna.

From our literature survey and research, not many directional UWB models were proposed. A directional model should include the angle of transmission and angle of arrival. Multipath components received at different angles have different shapes. Because existing statistical models do not incorporate the effect of the antenna, we have developed a deterministic directional simulator, which allows for the study of the multipath performance at different angles.

The next section of this paper reviews the existing UWB multipath models. Due to their importance, the third section is dedicated for UWB antennas and their role in multipath behavior. A simulator, based on the TEM horn antenna, is presented next. The paper concludes with some observations about the multipath performance of UWB communication under different scenarios.

2. Existing multipath models

When a communication channel is exited with a pulse, the pulse travels from the transmitter to the receiver through different paths having real positive gains, a_k, and propagation delays, τ_k, where k is the path index. The received waveform is referred to as multipath profile and the individual pulses are referred to as multipath components because they arrive to the receiver through different paths. For narrowband systems no dispersion within individual pulses may be assumed and hence the channel impulse response is real and can be represented as a superposition of these paths as in

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$$h(t) = \sum_k a_k \delta(t - \tau_k), \quad (1)$$

where $\delta(.)$ is the Dirac delta function. The assumption of no-dispersion is not acceptable for UWB signals due to the frequency selective nature of the transfer function of the overall communication channel. There have been many attempts to characterize the UWB multipath channels by modifying the existing narrowband models to make them suitable for UWB applications. Some research works on both deterministic [3] and statistical modeling [4,5] have been reported.

Kunisch and Pamp [6] observed that the channel gain tends to decrease with frequency, but details of their measurement system are not revealed. Yet the authors report that all results account for frequency dependent antenna characteristics. Prettie *et al.* [7] have presented spatial correlation of their UWB measurements. Lee [8] presented a deterministic multipath analysis using a two-ray model.

The model developed by the IEEE 802.15 working group is temporal and does not incorporate the spatial and frequency nature of the problem. Cassioli *et al.* [9] have presented simulation results for UWB indoor communications, while Chalillou *et al.* [10] have discussed the main structure of a general simulator for UWB communication systems. However, many unresolved issues remain and hence the need for more UWB propagation investigations. Multipath performance is among the priority issues that demand accurate investigation in order to formulate comprehensive and robust models before counting on simulation.

3. UWB antennas

Designing and analyzing antennas for efficient UWB communication are hot research areas [11-14]. Some researchers studied the impulse and frequency responses of these antennas and others examined their usefulness in UWB technology based on duration, type, and amplitude of the radiated transient waveform. In addition, a number of researchers tried to propose modifications to the existing structures in order to achieve a better performance in the UWB environment. The UWB antennas need to fulfill a number of requirements. Some of the desired characteristics for most of the UWB applications are utra wideband operation with little pulse distortion, directionality, high radiation efficiency, matched feeding, and small size. [15]

The most widely available classical antenna types include: the element antennas, the frequency independent antennas and the horn antennas. Of these three types, the element antennas are widely used. Examples of element antennas are the monopole, dipole, bowtie ...etc. Element antennas are characterized by linear polarization, low directivity, relatively limited bandwidth and being non-dispersive. Due to their low directivity and relatively limited bandwidth these antennas are not good candidates for UWB communication. Frequency independent antennas, such as log-periodic antennas, are dispersive antennas, which make them unsuitable for short pulses; as a result, they are not appropriate for ultra wideband applications either. Classical horn antennas have a 3dB bandwidth of one octave and are very directive. The disadvantage of this antenna is its size. Except for its large size, TEM horn is one of the very promising antennas, which can meet the design considerations for UWB static communication applications. For transient reception measurement purposes, the antenna recommended by NIST (National Institute of Standards & Technology) is the TEM horn.

4. Simulated TEM horn antenna

TEM horn antenna guides a spherical TEM-like mode between its two conductors. Figure 1 illustrates a basic TEM horn antenna, which is essentially an open-ended parallel plate transmission line. A TEM horn is completely characterized by three parameters: the length of each plate, l_o, the apex angle (angular width of each plate), $2A$, and the elevation angle (angular separation between plates), $2B$.

These antennas may also take other forms, such as a pair of pie slices or "V" shaped plates. The height-to-width ratio of the parallel plate is maintained constant along the length of the antenna to maintain uniform characteristic impedance. Practical UWB TEM horn antennas are usually designed with resistive loading near the mouth of the antenna to help suppress multiple reflections. The upper bandwidth of a TEM antenna is mainly determined by the size of its aperture and secondarily by the parallel plate to coax connector transition. If a TEM antenna is used as a transmit antenna, the radiated electrical field is the first derivative of the input driving point voltage.

Although the TEM horn antenna has been used for several decades, a full theoretical analysis of this type of antennas has not been reported [12]. In the literature, this type of antennas has been analyzed in different ways [11,13-14,16-17]. In the remaining part of this section, we explain how the TEM antenna behaves when used as a transmitter or as a receiver.

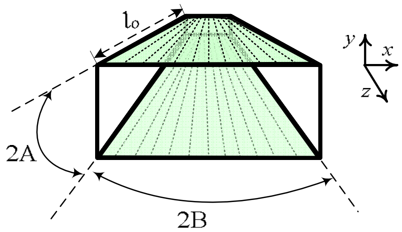

Figure 1. A TEM horn antenna geometry

Let us assume that a voltage signal, $v(t)$, is the input to a TEM Horn transmitting antenna located at an arbitrary point (x_s, y_s, z_s). The input signal depicted in Figure 2 is Gaussian with sigma = 0.1ns and peak = 2V. Our objective is to calculate the radiated electromagnetic fields in free space for all directions as a function of the input signal and antenna characteristics of the TEM transmitting horn antenna. Using the traveling-wave antenna approximation as given in [13,17-18], the TEM horn antenna is approximated by an array of Vee-dipoles. Then, the total radiated electric field at any observation point (x_0, y_0, z_0) due to such array is calculated.

A program was developed to calculate the radiated field in any observation point in space for an arbitrary excitation voltage. The simulated parameters are: $A = 7.9^o$, $B = 16.5^o$, $l_0 = 36.4$cm, and the distance between the antennas = 3m. The antenna was approximated by an array of 20 Vee-dipoles. The propagation speed within the antenna is 0.9667 c, where $c = 3\times10^8$ m/s.

In order to simulate the TEM horn antenna as a receiving antenna, it is assumed that the incident electric field on the antenna is known. Then, using a method similar to the one given by Smith [19] the received voltage at the terminals of the antenna can be calculated analytically. The TEM horn is terminated into a matched load, consequently the current entering the load is completely absorbed without reflection. The received voltage at the TEM horn output terminals is proportional to its current which will be approximated as the sum of the Vee-dipole currents [11]. Using such method, the current distribution as a function of the antenna parameters is calculated.

A program was developed to implement the equations in [11] in order to calculate the received voltage at the output terminals of a TEM horn antenna due to an arbitrary incident electric field. Figure 3 depicts the selected positions to illustrate the spatial impact of the multipath arrival on the received pulse shape. In the first case, the receiver is moved in the horizontal x-z plane and the associated received waveforms are shown in Figure 4a. Next, the antenna is moved vertically in the y-z plane and the associated received waveforms are illustrated in Figure 4b. The spatial impact on the amplitude and pulse shape is evident in both cases.

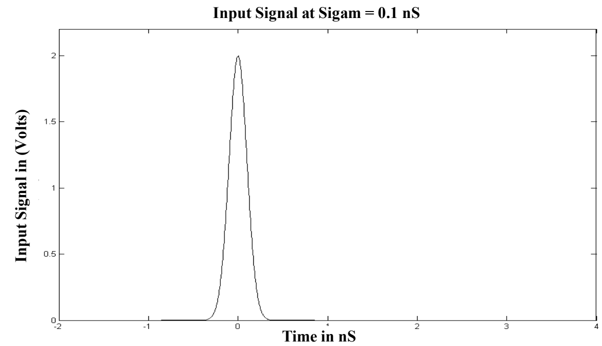

Figure 2. Gaussian input signal

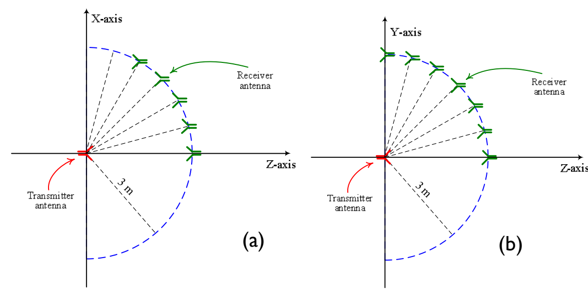

Figure 3. Positions of the transmitter & receiver

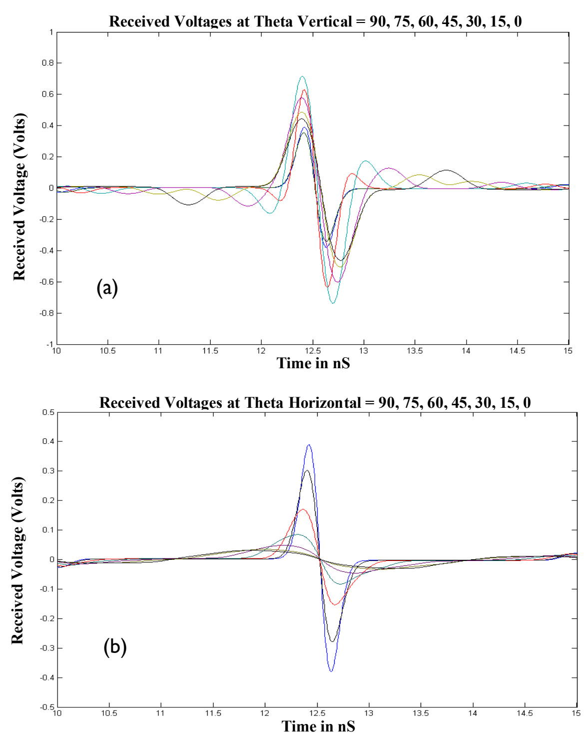

Figure 4. TEM horn as a receiving antenna

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5. Simulated typical indoor scenarios

In order to examine the capability of the simulator, we considered a basic scenario where two TEM horn antennas are installed in a narrow corridor/room. The transmit antenna receives an electrical signal similar to that given in Figure 2 on its input terminals. When the second antenna receives the radiated electric field, it will be composed of five different components. The first component is due to the direct path signal and the others are due to those signals resulting from reflections from the two walls, the floor, and the ceiling. The resulting received signal will be mainly dependent on the following dimensions: corridor width, w, height, h, distance between the two antennas, d, and their heights, h_a, and the positions of the two antennas from the wall, d_w. Four scenarios were simulated. Table 1 summarizes the parameters for the simulated scenarios. Their resulting received voltages are depicted in Figures 5-8.

Table 1. Parameters for the simulated cases

#	Scenarios	w	h	d	h_a	d_w
1	Vertical Symmetry only	2	3	3	1.5	1.5
2	No Symmetry	3	4	3	1.5	1
3	Full Symmetry	3	3	3	1.5	1.5
4	Narrow and High Corridor	2	5	3	2	1.5

Due to the partial symmetry of the first scenario, the two reflections from the sidewalls will interfere with the line-of-sight component resulting in modified pulse shape with less maximum value. The other two components from the ceiling and floor will add coherently as illustrated in Figure 5.

There is no symmetry in the second case. However, not all the five different multipath components are easily distinguishable. Two components constructively interfere with each other producing a signal with maximum amplitude greater than the line-of-sight component as depicted in Figure 6.

The third scenario represents a full symmetry for the four reflected components. As depicted by Figure 7, the four components add up constructively and produce a dominant component. The precursor and the ringing before and after the main pulse are more pronounceable. This scenario clearly illustrates the importance of using RAKE receiver otherwise most of the received energy will not be utilized.

In the fourth scenario associated with Figure 8, the dimensions are changed to illustrate the possibility of getting a modified and extended pulse shape due to the overlapping of the different components.

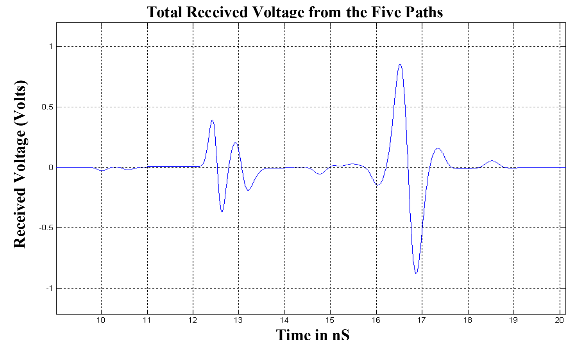

Figure 5. Received voltage for case study # 1

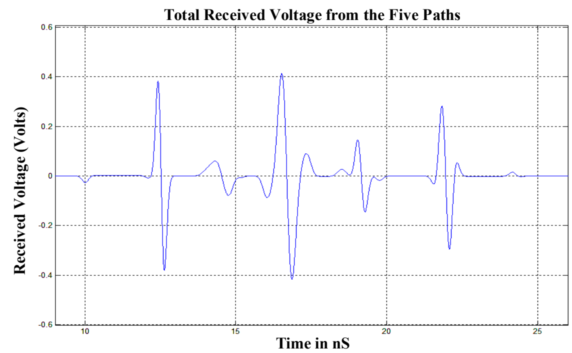

Figure 6. Received voltage for case study # 2

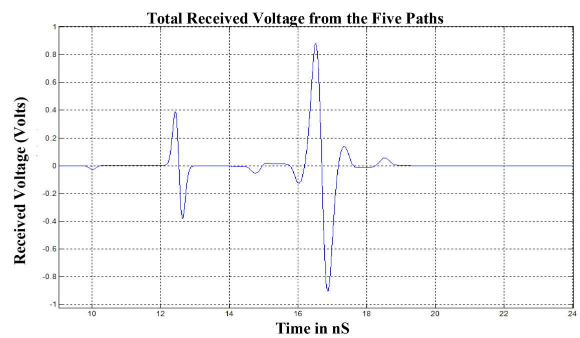

Figure 7. Received voltage for case study # 3

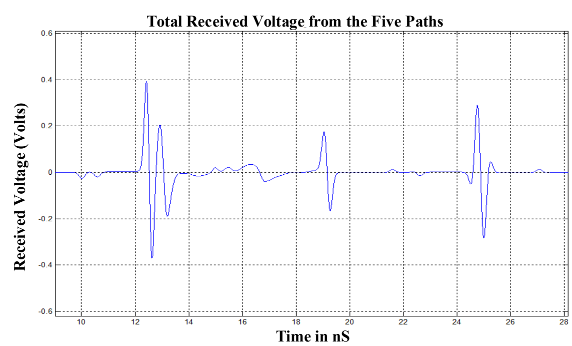

Figure 8. Received voltage for case study # 4

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From the previous presented cases, the following points are emphasized. Though UWB signals have high multipath resolution, in indoor scenarios later components may add up constructively resulting in dominant amplitude, which might be mistakenly confused with the line-of-sight component. This is very important in positioning and communication applications. The expected pulse shape is changing not only because of the directionality of the transmitter and receiver antennas, but also due to the overlap between multipath components. A correlator-based receiver has to consider the effect of this shape change to capture the maximum energy in the received signal. The simulated cases also demonstrated that RAKE receiver is vital to the optimization of the system. For example, in indoor scenarios, multipath components carry a significant percentage of the over all signal energy.

6. Conclusion

There has been some research in spatial characterization of narrowband systems but very few in the spatial modeling of UWB multipath profiles. To explain the directional nature of the multipath characteristics, an end-to-end simulator based on the TEM horn antenna was developed. This simulator was used to examine different indoor deterministic scenarios and some conclusions related to receiver design were drawn.

Due to the rapidly growing interest in UWB communications, the simulator will help in the assessment of UWB technology in different propagation environments. The developed simulator will be a tool in developing and testing future directional UWB models.

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