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Experimental Study on the Applicability of the Complex Form Friis' Transmission Formula in Fresnel Region for UWB Free Space Channel Model

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1 Introduction

We have studied the use of Friis' transmission formula in complex form to treat the UWB signals to take into account the waveform distortion due to the frequency characteristics of the antennas [1]. It is noted that Friis' transmission formula is applicable only in the far field region. In personal area network (PAN) environments, however, the distance may not satisfy the far field condition. In this paper, we report the experimental results of the transmission properties in Fresnel region.

2 Complex Form Friis' Transmission Formula for UWB System

The Friis' transmission formula is first expressed in terms of power [2]. Then it is extended in terms of the transmission signal waveform to consider the transfer function H_{Friis} [1]. Defining the transmitted and received voltage signals as V_{r} and V_{t}, respectively, and assuming the polarization of transmitter and receiver antennas match perfectly. We obtain

$$H_{\mathrm{Friis}}(f,d) = \frac{V_{\mathrm{r}}(f)}{V_{\mathrm{t}}(f,d)} = H_{\mathrm{f}}(f,d)H_{\mathrm{r}}(f)H_{\mathrm{t}}(f), \tag{1}$$

where H_{f} is the transfer function of free space, H_{r} and H_{t} are the transfer functions of the transmitting (Tx) and the receiving (Rx) antennas, which are implicit functions of directions, and d is the transmitter-receiver (TR) separation distance.

The transfer function of free space can be written as

$$H_{\mathrm{f}}(f,d) = \frac{c}{4\pi df} e^{-j2\pi df/c}. \tag{2}$$

The received waveform $v_{\mathrm{r}}(t,d)$ can be found by using

$$v_{\mathrm{r}}(t,d) = v_{\mathrm{t}}(t) \otimes h_{\mathrm{Friis}}(t,d), \tag{3}$$

where $v_{\mathrm{t}}(t)$ is the transmitted signal waveform, $\otimes$ is the convolution operator, $h_{\mathrm{Friis}}(t,d)$ is the impulse response of the extension of Friis' formula defined as:

$$h_{\mathrm{Friis}}(t,d) = \mathcal{F}^{-1}\{H_{\mathrm{Friis}}(f,d)\}, \tag{4}$$

where $\mathcal{F}^{-1}\{\cdot\}$ is the inverse Fourier transform.

It is know that the Friis' transmission formula is satsfied only in the far field region, i.e. $d > 2D^2/\lambda$, where D is the largest dimension of the antenna.

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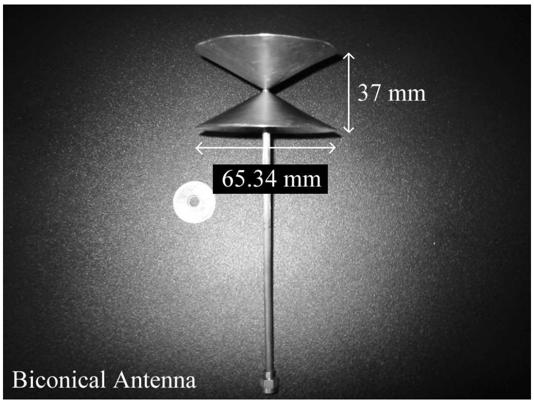

Figure 1: Geometry and dimensions of the biconical antenna.

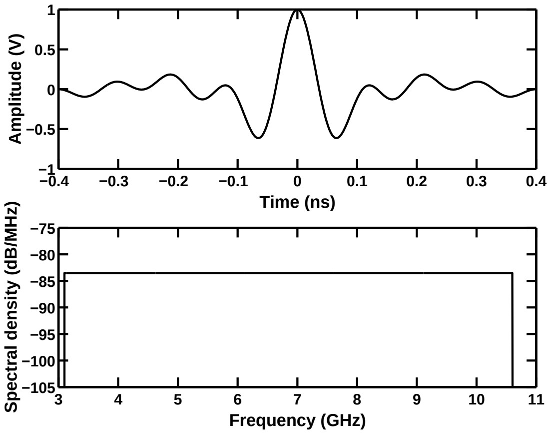

Figure 2: UWB signal waveform in time domain and magnitude of its spectral density function.

3 Measurement Setup

The vector network analyzer was operated in the response measurement mode from 3 to 11 GHz, where port-1 was used as the transmitter port and port-2 was used as the receiver port, respectively. The measurement was done in an anechoic chamber to simulate free space. Both Tx and Rx antennas were fixed at the height of 1.72 m. We have chosen the biconical antenna for Tx and Rx antennas. The geometry and dimensions of the antenna are shown in Fig. 1.

From Fig. 1, the largest dimension of each Tx and Rx antennas are the inclined height $D_t = D_r = 75$ mm. The largest dimension of the antenna considering the field regions are $D = D_t + D_r = 150$ mm. For the whole UWB frequency spectrum, the inner boundary distance of the Fresnel region is 0.21 m while the outer boundary distance is 0.47 m. The inner boundary distance of the far field region for the whole UWB frequency spectrum is 1.59 m. Then, 0.3 and 0.4 m TR separation distances are chosen for the Fresnel region, while 1.6 and 2.0 m TR separation distances are chosen for the far field region. The practical maximum measured distance, 4 m, is chosen as reference distance to estimate the accuracy of the antenna transfer function. The Tx and Rx antennas are assumed to be identical.

The rectangular density spectral waveform covering the FCC band [3], that is 3.1 to 10.6 GHz is used to test the distortion of the received UWB waveform. This waveform is expressed by

$$v_{\mathrm{t}}(t) = \frac{1}{f_{\mathrm{max}} - f_{\mathrm{min}}}[f_{\mathrm{max}}\mathrm{sinc}(2f_{\mathrm{max}}t) - f_{\mathrm{min}}\mathrm{sinc}(2f_{\mathrm{min}}t)], \quad (5)$$

where $f_{\mathrm{min}} = 3.1$ GHz is the minimum frequency, $f_{\mathrm{max}} = 10.6$ GHz is the maxmimum frequency and $\mathrm{sinc}(x) = \sin(\pi x)/(\pi x)$. This signal waveform in time domain and magnitude of its spectral density function are shown in Fig. 2.

4 Results

The transfer function of Tx and Rx antennas are estimated by using the channel transfer function at 4 m, assuming that these antennas are with identical transfer function. The magnitude and phase of the antenna transfer function are shown in Fig. 3.

Figures 4 and 5 show the magnitude and the phase of the transfer functions measured at 0.3, 0.4, 1.6 and 2.0 m distances. In Figs. 4 and 5, the measured values are compared with the predicted values using the antenna transfer function (Fig. 3) and complex form Friis'

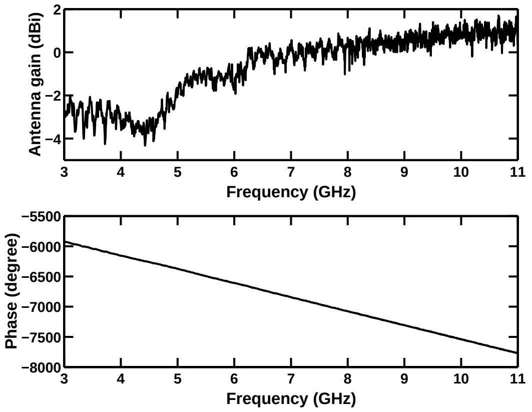

Figure 3: Magnitude (antenna gain) and phase of transfer function of each antenna.

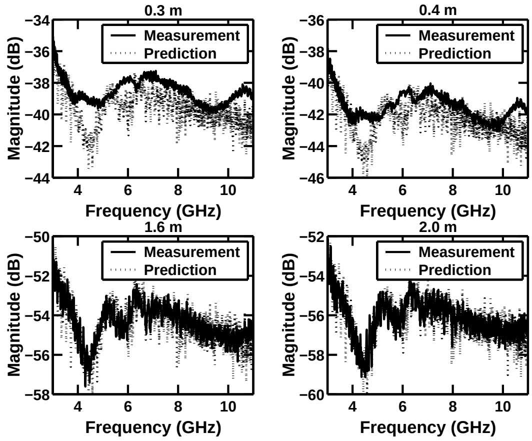

Figure 4: The magnitude of the transfer function of the UWB channel at 0.3, 0.4, 1.6 and 2.0 m distances.

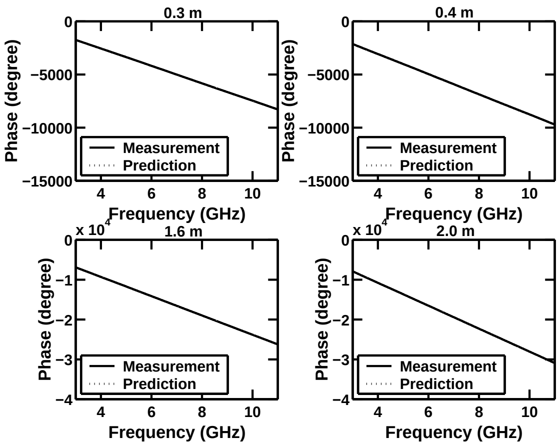

Figure 5: The phase of the transfer function of the UWB channel at 0.3, 0.4, 1.6 and 2.0 m distances.

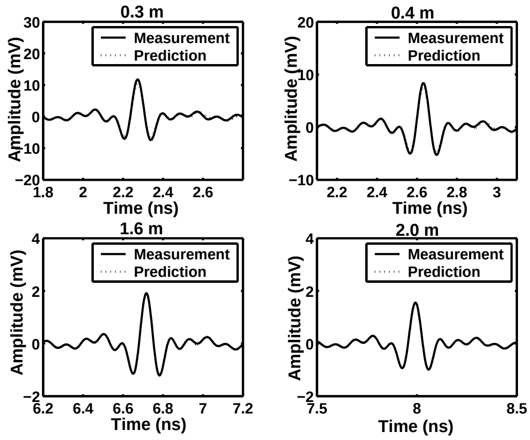

Figure 6: The received UWB waveforms at 0.3, 0.4, 1.6 and 2.0 m distances.

transmission formula. Both results are almost identical in the far field region, but the differences of magnitude are observed in the Fresnel region. We can clearly see that in the Fresnel region, the measured magnitude results are greater than the predicted magnitude results. This is due to the radial field in the Fresnel region. In the far field region, the radial field can be negligible.

Figure 6 compares the transmission of the received UWB waveform presented in Fig. 2, by using the measured transfer functions and those predicted by using the complex form Friis' transmission formula and the antenna transfer function. We can see a little difference between the measured and the predicted waveforms in the Fresnel region. In the far field region on the other hand, the received waveforms are almost the same.

Table 1 summarizes the results of Fig. 6 with respect to the path loss. As expected from Fig. 6, the difference of the path gain is more obvious in the Fresnel region. Table 2 shows the correlation between two waveforms corresponding to the measured and the predicted transfer functions. It has higher distortion in the Fresnel region. While in the far field region, the distortion is very small.

Table 1: Path loss of the received UWB waveform.

	Path loss			
	0.3 m (dB)	0.4 m (dB)	1.6 m (dB)	2.0 m (dB)
Measured	38.58	41.55	54.36	56.16
Prediction	39.63	42.32	54.42	53.20

Table 2: the percent of the correlation coefficient of the received UWB waveform.

	correlation coefficient			
	0.3 m (%)	0.4 m (%)	1.6 m (%)	2.0 m (%)
Prediction	99.45	99.46	99.89	99.94

5 Conclusion

The applicability of the complex form Friis' transmission formula in Fresnel region has been experimentally studied to consider the UWB free space channel model. The error of the path loss is observed in the Fresnel region caused by the radial field. More comprehensive studies are necessary to consider the type of antennas (size and current distribution) and to find how to compensate the error.

References

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