

Characterization of Ultra-Wideband Antenna with Human Body

Sathaporn Promwong^{1,2}, Wataru Hachitani¹, Gilbert S. Ching¹, and Jun-ichi Takada¹

¹Graduate School of Science and Engineering, Tokyo Institute of Technology

O-okayama Minami 6 Bldg., 2-12-1, O-okayama, Meguro-ku, 152-8550, Tokyo, Japan.

²Department of Information Engineering, Faculty of Engineering,

King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand.

E-mail: ken@ap.ide.titech.ac.jp

Abstract—This paper presents the characterization of ultra wideband antenna with human body. An experiment of the antenna transfer function needs the three-antenna method for calibrating the reference antenna. The results are used to evaluate the transmission gain based on the extended Friis' transmission formula. The matched filter is considered at the receiver side to maximize the SNR for evaluation. This technique gives very accurate results and is very useful for the design and evaluation of UWB impulse radio transmission systems, especially for the evaluation of waveform distortion effects.

I. INTRODUCTION

The ultra wideband (UWB) technology have attracted a great deal of attention because of its potentiality for application to short-range high-speed mobile communications, ultra low-power communications, and so on. In order to minimize the interference with existent systems, the UWB is expected to be mainly used in indoor environments such as wireless personal area networks.

Even if the channel is in line of sight (LOS), Friis' transmission formula cannot be directly applied to the UWB radio as the bandwidth of the pulse is extremely wide. Furthermore, simple comparison between waveforms of the transmitter and the receiver is not significant because of the distortion of the waveform caused by the frequency response of the antenna.

In this paper, we investigate the effects of human body on UWB antenna propagation. This scheme is based on the Friis' transmission formula, adapted for UWB, in the sense that we would like to derive the equivalent antenna gain for UWB systems. The transmission waveform and the matched filter reception are key for the extension of the Friis' formula to UWB. To know the actual antenna transfer function, we need the three-antenna method for calibration of the reference antenna. An experiment is carried out using biconical antennas for UWB operation in an anechoic chamber.

II. ULTRA-WIDEBAND EXPERIMENT SYSTEMS

A. Experiment scheme

By using the vector network analyzer (VNA), complex transfer functions can be measured [1]. However, this transfer function is a product of transfer functions of Tx and Rx antennas as well as the free space channel. Among them, the

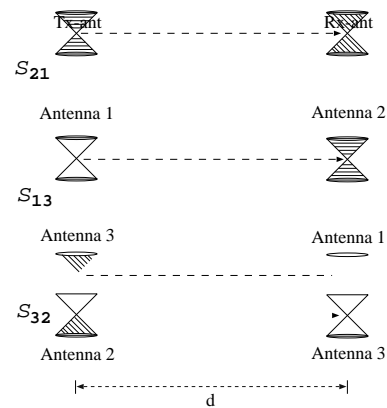


Fig. 1. Three antenna model.

free space transfer function is calculated from the distance between the antennas. To know the transfer function of the antenna under test (AUT) at the Rx side, the transfer function of the Tx antenna, which is usually a standard antenna, shall be known in advance as the calibration data. The overall measurement scheme is summarized as follows:

Step 1) Calibration of the standard antenna.

The standard antenna is calibrated using the three-antenna method. The three-antenna method has originally been proposed for the measurements of the complex antenna factor [2]. In this method, three linearly-polarized antennas are required, but they do not have to be identical to one another. Three sets of measurements are performed using all combinations of the three antennas pointing toward the same directions as shown in Fig. 1. The result is a set of three simultaneous equations of the form

$$S_{21}(f) = H_1(f)H_f(f, d)H_2(f), \quad (1)$$

$$S_{13}(f) = H_3(f)H_f(f, d)H_1(f), \quad (2)$$

$$S_{32}(f) = H_2(f)H_f(f, d)H_3(f), \quad (3)$$

where $H_i(f)$ is the complex frequency transfer function of antenna i , S_{ji} is the measurement result by using Tx antenna i and Rx antenna j , d is

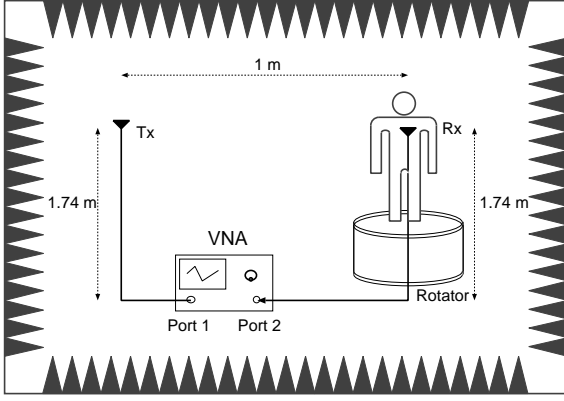


Fig. 2. The instrument setup.

the distance between antennas, and $H_f(f, d)$ is the complex transfer function of free space. Then, we can estimate the complex frequency transfer function of the antennas by using these equations

$$H_1(f) = \sqrt{\frac{S_{21}(f)S_{32}(f)}{S_{13}(f)H_f(f, d)}}, \quad (4)$$

$$H_2(f) = \sqrt{\frac{S_{21}(f)S_{13}(f)}{S_{32}(f)H_f(f, d)}}, \quad (5)$$

$$H_3(f) = \sqrt{\frac{S_{32}(f)S_{13}(f)}{S_{21}(f)H_f(f, d)}}. \quad (6)$$

Step 2) The transfer function of the antenna under test (AUT) is measured.

By using the standard antenna and the AUT as Tx and Rx antennas respectively, the transfer function between Tx and Rx antenna ports is expressed as

$$S_{21}(f) = H_{\text{AUT}}(\theta, \varphi, f)H_f(f, d)H_{\text{Std}}(f), \quad (7)$$

and the transfer function of AUT is obtained by

$$H_{\text{AUT}}(\theta, \varphi, f) = \frac{S_{21}(f)}{H_f(f, d)H_{\text{Std}}(f)}. \quad (8)$$

B. Instrument setup

The VNA was operated in the response measurement mode, where Port-1 was the transmitter port (Tx), and Port-2 was the receiver port (Rx), respectively. The measurement was done in an anechoic chamber. Both Tx and Rx antennas were fixed at the height of 1.74 m and separated by a distance of 1 m. The setup is sketched in Fig. 2.

In this study, we considered a broadband antenna that was suitable for the operation with pulsed waveforms. The structure of the UWB antennas is shown in Fig. 3 the Tx antenna is a biconical antenna with maximum diameter of 65.3 mm and length of 37 mm used as the standard antenna [3] and the Rx antenna is a commercial, small-size, low profile antenna developed by Skycross Lnc.,(USA) [4] used as the AUT.

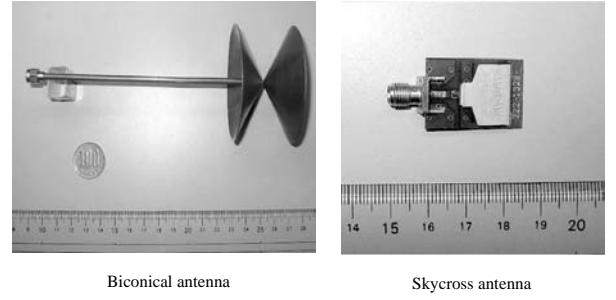


Fig. 3. Ultra Wideband antennas.

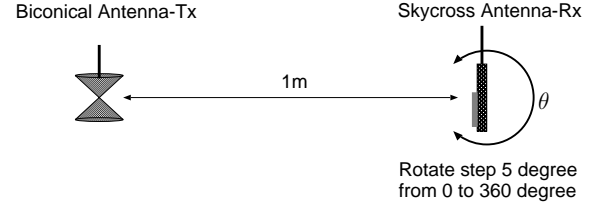


Fig. 4. Top view antenna setting.

S_{21} , measures the transfer function between Tx and Rx antennas. The Tx antenna is fixed at pointing angle 0° and the Rx antenna is rotated from pointing angle 0° to 360° with each step at 5° as shown in Fig. 4.

C. Parameters of experiments

The important parameters for the experiments are listed in Table I. It is noted that calibration is done at the connectors of the cables to be connected to the antennas. Therefore, all impairments of the antenna characteristics are included in the measured results.

D. Signal model

The effect of the waveform distortion is more obvious when the bandwidth is wider. We considered the impulse radio signal that fully covers the FCC band [5], i.e., 3.1 ~ 10.6 GHz. The center frequency and the bandwidth were therefore set to be $f_0 = 6.85$ GHz and $f_b = 7.5$ GHz, respectively. The transmit waveform assumed in the simulation was a single ASK pulse with the carrier frequency f_0 . To satisfy the bandwidth requirement of f_b , the pulse length

TABLE I
EXPERIMENTAL SETUP PARAMETERS.

Parameter	Value
Frequency range	3 GHz to 11 GHz
Number of frequency points	1601
Dynamic power range	80 dB
Tx antenna height	1.74 m
Rx antenna height	1.74 m
Distance between Tx and Rx	1 m
Rx rotate range	0° to 360°
Rx rotate step	5°

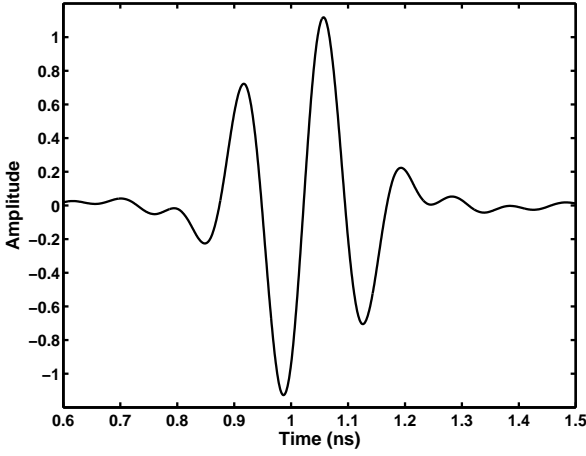


Fig. 5. The transmission waveform of UWB signal.

was set to be $\frac{2}{f_b}$. Then the signal was band-limited by a Nyquist roll-off filter with roll-off factor $\alpha = 0$ (rectangular window) and passband $\left(f_0 - \frac{f_b}{2}, f_0 + \frac{f_b}{2}\right)$. Figure 5 shows the transmit pulse waveform. The transmission process of the pulse waveform is simulated based on the measured transfer function of the antennas.

III. EXTENSION OF FRIIS' TRANSMISSION FORMULA FOR ULTRA-WIDEBAND SYSTEM

In this study, we focus on the link budget evaluation of UWB-IR system in free space.

In narrowband systems, the link budget of the free space propagation loss is usually estimated by using Friis' transmission formula [6]. However, it is not directly applicable to the UWB-IR transmission system, as the formula is expressed as a function of the frequency. Moreover, the waveform may be distorted due to the frequency characteristics of the antenna. Ref. [7] treats the special cases of the constant gain and the constant aperture, but no general discussion had been made although it suggested the use of the time-domain antenna effective length.

The Friis' transmission formula has been widely used, and can be applied to the calculation of these LOS channels.

$$G_{\text{Friis}}(f) = \frac{P_r(f)}{P_t(f)} = G_r(f)G_r(f)G_t(f), \quad (9)$$

where G_r and G_t are Rx and Tx antenna gain,

$$G_f(f) = \left(\frac{\lambda}{4\pi d}\right)^2 \quad (10)$$

is the free space propagation gain (less than unity in practice), $\lambda = \frac{c}{f}$ is the wavelength, c is the velocity of the light, f is the operating frequency, and d is the separation between transmitter and receiver antennas.

It is noted, however, that Eq. (9) is satisfied only at some certain frequency, and is not directly applicable to UWB

systems. The Friis' transmission formula shall be extended to take into account the transmission signal waveform and its distortion as well [?].

Input signal $v_i(t)$ at the transmitter port is expressed as the convolution of an impulse input and the pulse shaping filter $h_i(t)$ as

$$v_i(t) = \delta(t) * h_i(t), \quad (11)$$

where

$$\int_{-\infty}^{\infty} h_i^2(t)dt = \int_{-\infty}^{\infty} |H_i(f)|^2 df = 1. \quad (12)$$

Friis' formula is extended taking into account the transmission waveform as

$$H_{\text{Friis}}(f) = H_f \mathbf{H}_r \cdot \mathbf{H}_t, \quad (13)$$

$$H_{e\text{-Friis}}(f) = H_f H_i \mathbf{H}_r \cdot \mathbf{H}_t, \quad (14)$$

and for the isotropic case

$$H_{e\text{-Friis,Iso}}(f) = H_f H_i \quad (15)$$

where

$$\begin{aligned} \mathbf{H}_a &= \mathbf{H}_a(\theta_a, \varphi_a, f) \\ &= \hat{\boldsymbol{\theta}}_a H_{a\theta}(\theta_a, \varphi_a, f) + \hat{\boldsymbol{\varphi}}_a H_{a\varphi}(\theta_a, \varphi_a, f), \\ a &= r \text{ or } t, \end{aligned} \quad (16)$$

is a complex transfer function vector of the antenna relative to the isotropic antenna,

$$H_f = \frac{\lambda}{4\pi d} \exp(-jkd), \quad (17)$$

is the free space transfer function where

$$k = \frac{2\pi}{\lambda}, \quad (18)$$

is the propagation constant. Unit vectors $\hat{\boldsymbol{\theta}}_a$, $\hat{\boldsymbol{\varphi}}_a$ express the polarization and are defined with respect to the local polar coordinates of each of the antennas. The following relations can be easily derived.

$$\hat{\boldsymbol{\theta}}_r = \hat{\boldsymbol{\theta}}_t, \quad (19)$$

$$\hat{\boldsymbol{\varphi}}_r = -\hat{\boldsymbol{\varphi}}_t. \quad (20)$$

At the receiver, the matched filter $H_{\text{MF}}(f)$ is introduced to maximize the signal-to-noise ratio (SNR) of the receiver output, as shown in Fig. 6.

$$H_{\text{MF}}(f) = \frac{H_{e\text{-Friis}}^*(f)}{\sqrt{\int_{-\infty}^{\infty} |H_{e\text{-Friis}}(f)|^2 df}}, \quad (21)$$

and for the isotropic case

$$H_{\text{MF,Iso}}(f) = \frac{H_{e\text{-Friis,Iso}}^*(f)}{\sqrt{\int_{-\infty}^{\infty} |H_{e\text{-Friis,Iso}}(f)|^2 df}}, \quad (22)$$

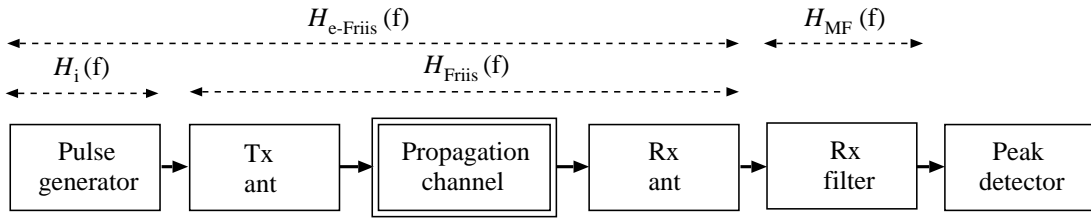


Fig. 6. Block diagram of transmission system for the extension of Friis' transmission formula to treat UWB signal.

which satisfies the following constant noise output power condition

$$\int_{-\infty}^{\infty} |H_{MF}(f)|^2 df = 1. \quad (23)$$

In this case, $E_i = 1$ the output waveform, and the spectrum of the receiver output are $h_{e-Friis}(t)$ and $H_{e-Friis}(f)$, respectively. The waveform of the output from the matched filter $v_{MF}(t)$ is

$$\begin{aligned} v_{MF}(t) &= h_{e-Friis}(t) * h_{MF}(t) \\ &= \frac{h_{e-Friis}(t) * h_{e-Friis}(-t)}{\sqrt{\int_{-\infty}^{\infty} h_{e-Friis}^2(t) dt}}, \end{aligned} \quad (24)$$

and for the isotropic case

$$\begin{aligned} v_{MF,Iso}(t) &= h_{e-Friis,Iso}(t) * h_{MF,Iso}(t) \\ &= \frac{h_{e-Friis,Iso}(t) * h_{e-Friis,Iso}(-t)}{\sqrt{\int_{-\infty}^{\infty} h_{e-Friis,Iso}^2(t) dt}}, \end{aligned} \quad (25)$$

For the spectrum of the output from the matched filter $V_{MF}(f)$

$$\begin{aligned} V_{MF}(f) &= H_{e-Friis}(f) H_{MF}(f) \\ &= \frac{|H_{e-Friis}(f)|^2}{\sqrt{\int_{-\infty}^{\infty} |H_{e-Friis}(f)|^2 df}}, \end{aligned} \quad (26)$$

taking its maximum as

$$\begin{aligned} \max_t v_{MF}(t) &= \int_{-\infty}^{\infty} V_{MF}(f) df \\ &= \sqrt{\int_{-\infty}^{\infty} |H_{e-Friis}(f)|^2 df}. \end{aligned} \quad (27)$$

Equation (27) is the UWB extension of Friis' transmission formula. It includes three elements, namely the frequency characteristics of the antennas, the frequency characteristics of free space propagation, and the spectrum of the transmit signal. It is clear from Eq. (27) that the transmission gain of the UWB signal can not be defined as the product of gains of antennas and a free space channel as Friis' formula (9). Instead, the total transmission gain including the effect of the waveform can be obtained as Eq. (27). For the normalization, the reference isotropic antenna with $H_{Iso}(f) = 1$ is considered. The UWB transmission gain can be defined as

$$G_{UWB} = \max_t v_{MF}(t) / \max_t v_{MF,Iso}(t). \quad (28)$$

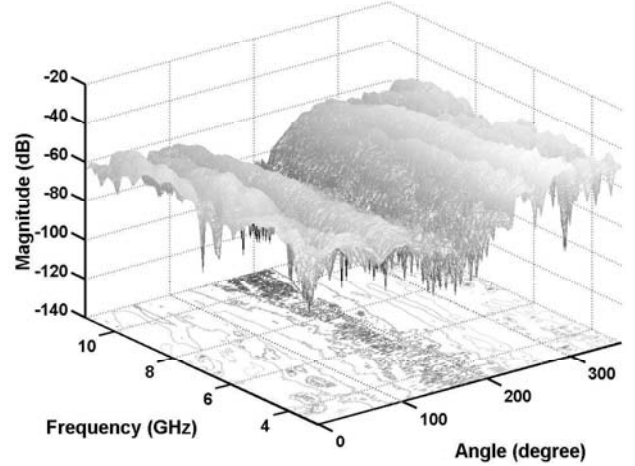


Fig. 7. Antenna transfer function: magnitude.

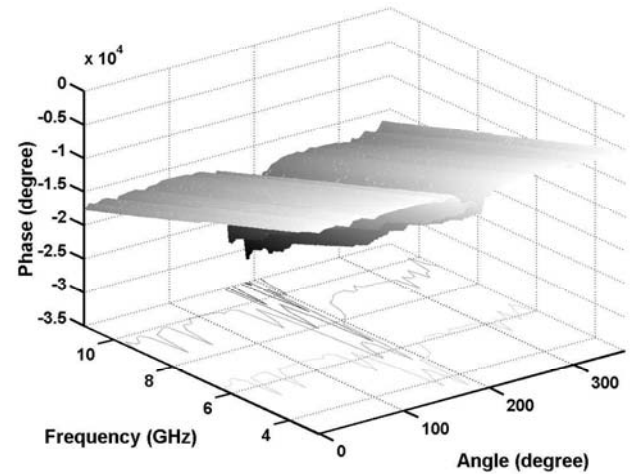


Fig. 8. Antenna transfer function: phase.

IV. EXAMPLE RESULTS AND DISCUSSION

This section, describes the graphical compilation of the experiment results.

Figure 7 shows the magnitude of the measured antenna transfer function and its phase is also shown in Fig. 8. We can particularly see the frequency characteristic of the antenna transfer function at each pointing angle. As the AUT is the broadband biconical antenna, the ideal linear phase is almost realized, except for the null directions, which change with

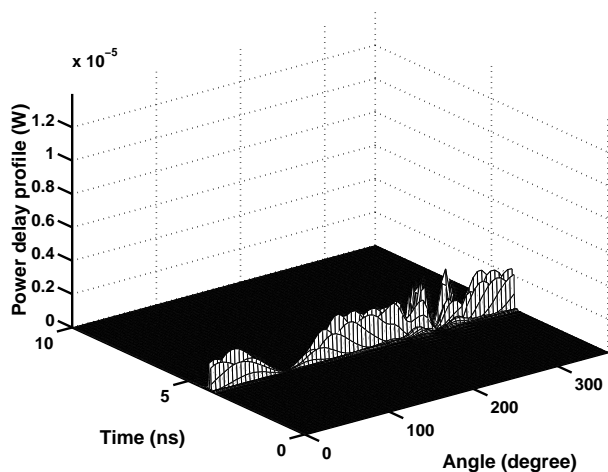


Fig. 9. Power delay profiles of the UWB channel without human body.

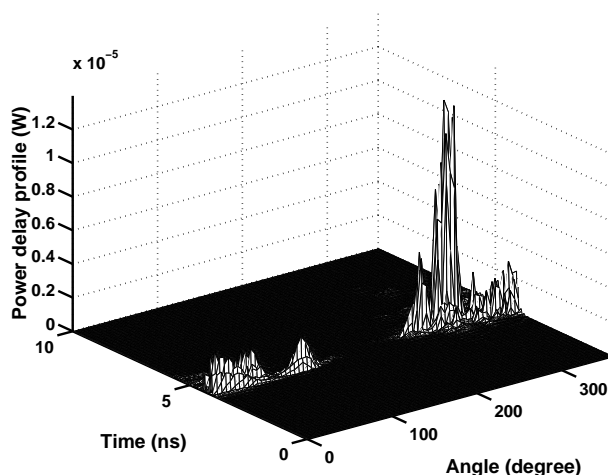


Fig. 10. Power delay profiles of the UWB channel with human body.

frequency.

The UWB signal shown in Fig. 5 is used as the transmission waveform. The received waveforms at the output of the matched filters is evaluated. The relative gain is defined as Eq. (28). In practice, it is quite complicated and is not feasible to implement the adaptive matched filter to adjust for the antennas. Therefore, the matched filter designed for an isotropic antenna is also considered and is compared with the ideal matched filter.

Figure 9 shows the without human body case (free space) of power delay profiles of the measured antenna transfer function and its with human body case is also shown in Fig. 10. We can particularly see the frequency characteristic of the antenna transfer function and delay spread at each pointing angle. The effects of human body shadowing on the UWB antenna propagation, the nulls are observed at 90° to 270° pointing angles.

Figure 11 shows the comparison of UWB transmission gain versus antenna pointing angle that uses the optimum matched filter compared with the matched filter for an isotropic antenna

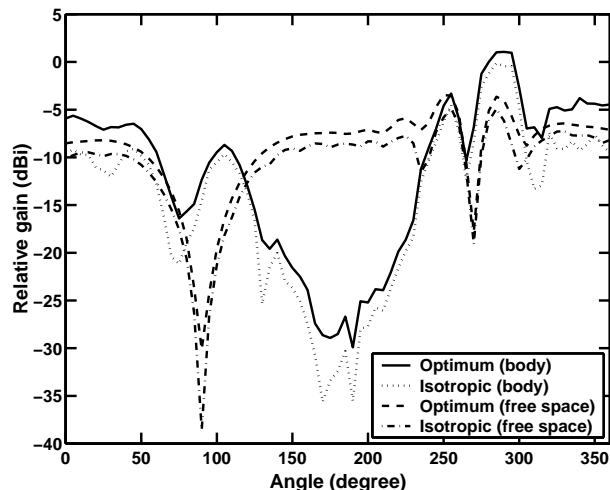


Fig. 11. UWB transmission gain.

for without human body (free space) and with human body. In the without human body case, the peaks are found at 0° to 180° , and 360° pointing angles which corresponds to the broadside of the antenna. The nulls are observed at 90° and 270° pointing angles. For with human body case, the peaks are found at 0° to 270° , and 360° pointing angles which corresponds to the broadside of the antenna. The nulls are observed at 180° pointing angles.

V. CONCLUSION

The characterization of ultra wideband antenna with human body using an extension of Friis' transmission formula in order to take into account the transmit waveform and the matched filter into the system. The experimental examples using the biconical antenna as the transmitter and the Skycross antenna as the receiver are presented.

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