社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE.
A・P2003-42,SAT2003-34
MW2003-48,OPE2003-35(2003-07)

UWBアンテナの自由空間伝送特性の評価実験

サターポンプロムウォン[†,††]　蜂谷　渉[†]　高田　潤一[†]　プラキットタンティサノン[††]

† 東京工業大学 大学院理工学研究科　〒152–8552 東京都目黒区大岡山 2–12–1
†† モンクット王ラカバン工科大学　タイ国バンコク市
E-mail: †{ken,hachi,takada}@ap.ide.titech.ac.jp, ††ktprakit@kmitl.ac.th

あらまし　ウルトラワイドバンド (UWB) 無線，中でも特にシングルバンドのインパルスラジオにおいては，パルス信号の帯域が極めて広く，通常の自由空間無線回線設計に用いられる Friis の伝送公式は周波数の関数として表されているためにそのまま使用することは不可能である．さらに，アンテナ自体の周波数特性により伝送波形には歪みが生じるため，単純な送受信波形の比較も困難である．著者らはこれまで，Friis の伝送公式を UWB 信号に適用できるよう拡張し，UWB アンテナにおける利得を整合フィルタ受信により定義する方法を提案してきた．本報告では，標準的な広帯域アンテナとして広く用いられているバイコニカルアンテナを例に，実験を行った結果を示す．

キーワード　ウルトラワイドバンド, UWB, インパルスラジオ, フリスの伝送公式, 波形伝送，バイコニカルアンテナ

Experimental Evaluation of the Free Space Transmission Characteristics of Ultra-Wideband Antenna

Sathaporn PROMWONG[†,††], Wataru HACHITANI[†], Jun-ichi TAKADA[†], and Prakit TANGTISANON[††]

† Graduate School of Science and Engineering, Tokyo Institute of Technology　2–12–1, O-okayama, Meguro-ku, Tokyo 152–8552, Japan
†† King Mongkut's Institute of Technology Ladkrabang　Bangkok, Thailand
E-mail: †{ken,hachi,takada}@ap.ide.titech.ac.jp, ††ktprakit@kmitl.ac.th

Abstract　The link budget of the free space propagation loss is usually estimated by using Friis' transmission formula. However, it is not directly applicable to the ultra-wideband (UWB) radio transmission systems, in particular the single band impulse radio, 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, and the comparison between Tx and Rx waveforms is not straightforward. The authors have proposed the use of the matched filter for the definition of the wideband gain of the antenna. This paper is presented an experimental evaluation of the free space transmission characteristics of ultra-wideband antenna by using proposed technique. The authors have utilized the biconical antenna which is often used as the standard antenna. The effect of the directivity is considered.

Key words　ultra-wideband, UWB, UWB antennas, impulse radio, Friis' transmission formula, waveform transmission, biconical antenna.

1. Introduction

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

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

In this paper, we discuss the experimental evaluation of the free space transmission characteristics of ultra-wideband antenna. This technique is based on the Friis' transmission formula, 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 keys for the extension of the Friis' formula to UWB. We carried out an experiment using the biconical antenna for UWB operation.

We show theoretical formulation first. Then we explain an illustration with the biconical antennas after.

2. Extension of Friis' Transmission Formula for UWB Systems

In this study, we focus on the link budget evaluation in the free space. For the narrowband systems, Friis' transmission formula [1] have been widely used.

$$G_{\mathrm{Friis}} = \frac{P_{\mathrm{r}}}{P_{\mathrm{t}}} = G_{\mathrm{f}} G_{\mathrm{r}} G_{\mathrm{t}}, \tag{1}$$

where G_{r} and G_{t} are Rx and Tx antenna gain,

$$G_{\mathrm{f}} = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2}$$

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, and f is the frequency.

It is noted, however, that Eq. (1) is satisfied only at some certain frequency, and is not directly applicable to UWB systems. We have recently proposed a new extension of the Friis' transmission formula to take into account the transmission signal waveform and its distortion as well [2]. The results are summarized as followed. The detailed derivation is presented in Ref. [2].

Input signal $v_{\mathrm{t}}(t)$ at the transmitter port is expressed as the convolution of an impulse and the pulse shaping filter as

$$v_{\mathrm{t}}(t) = E_{\mathrm{t}}\delta(t) * h_{\mathrm{t}}(t), \tag{3}$$

where

$$\int_{-\infty}^{\infty} h_{\mathrm{t}}^2(t)\mathrm{d}t = \int_{-\infty}^{\infty} |H_{\mathrm{t}}(f)|^2 \,\mathrm{d}f = 1. \tag{4}$$

Friis' formula is extended to take into account the transmission waveform as

$$H_{\text{e-Friis}}(f) = \frac{V_{\mathrm{r}}(f)}{E_{\mathrm{t}}} = H_{\mathrm{f}} H_{\mathrm{t}} \mathbf{H}_{\mathrm{r}} \cdot \mathbf{H}_{\mathrm{t}}, \tag{5}$$

where

$$\begin{aligned} \mathbf{H}_a &= \mathbf{H}_a(\theta_a,\ \varphi_a,\ f) \\ &= \hat{\boldsymbol{\theta}}_a \mathbf{H}_{a\theta}(\theta_a,\ \varphi_a,\ f) + \hat{\boldsymbol{\varphi}}_a \mathbf{H}_{a\varphi}(\theta_a,\ \varphi_a,\ f) \\ a &= \mathrm{r}\ \mathit{or}\ \mathrm{t} \end{aligned} \tag{6}$$

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

$$H_{\mathrm{f}} = \frac{\lambda}{4\pi d}\exp(-\mathrm{j}kd) \tag{7}$$

is the free space transfer function where

$$k = \frac{2\pi}{\lambda} \tag{8}$$

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

$$\hat{\boldsymbol{\theta}}_{\mathrm{r}} = \hat{\boldsymbol{\theta}}_{\mathrm{t}}, \tag{9}$$

$$\hat{\boldsymbol{\varphi}}_{\mathrm{r}} = -\hat{\boldsymbol{\varphi}}_{\mathrm{t}}. \tag{10}$$

At the receiver, the matched filter $H_{\mathrm{MF}(f)}$ is introduced to maximize the signal-to-noise ratio (SNR) of the receiver output, as shown in Figure 1.

$$H_{\mathrm{MF}}(f) = \frac{H^*_{\text{e-Friis}}(f)}{\sqrt{\displaystyle\int_{-\infty}^{\infty} |H_{\text{e-Friis}}(f)|^2 \,\mathrm{d}f}}, \tag{11}$$

which satisfies the following constant noise output power condition

$$\int_{-\infty}^{\infty} |H_{\mathrm{MF}}(f)|^2 \,\mathrm{d}f = 1. \tag{12}$$

In case, the output waveform when $E_{\mathrm{t}} = 1$

$$v_{\mathrm{MF}}(t) = h_{\text{e-Friis}}(t) * h_{\mathrm{MF}}(t) \tag{13}$$

takes its maximum at $t = 0$ as

$$\begin{aligned} \max_t v_{\mathrm{MF}}(t) &= v_{\mathrm{MF}}(0) = \int_{-\infty}^{\infty} V_{\mathrm{MF}}(f)\mathrm{d}f \\ &= \sqrt{\int_{-\infty}^{\infty} |H_{\text{e-Friis}}(f)|^2 \,\mathrm{d}f}. \end{aligned} \tag{14}$$

Equation (14) is the UWB extension of Friis' transmission formula. Equation (14) includes three elements, i.e., the frequency characteristics of the antennas, the frequency characteristics of free space propagation, and the spectrum of the transmit signal.

3. Preparation for the Experiments

3.1 UWB 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 [3], i.e., 3.1 ~ 10.6 GHz. The center frequency and the bandwidth were therefore set to be $f_0 = 6.85$ GHz and $f_{\mathrm{b}} = 7.5$ 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 was set to be $\frac{2}{f_{\mathrm{b}}}$.

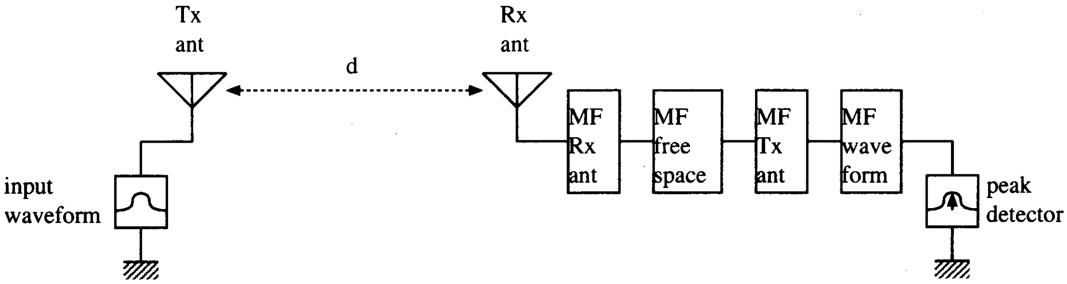

Figure 1 Block diagram of transmission system for the extension of Friis' transmission formula to treat UWB signal.

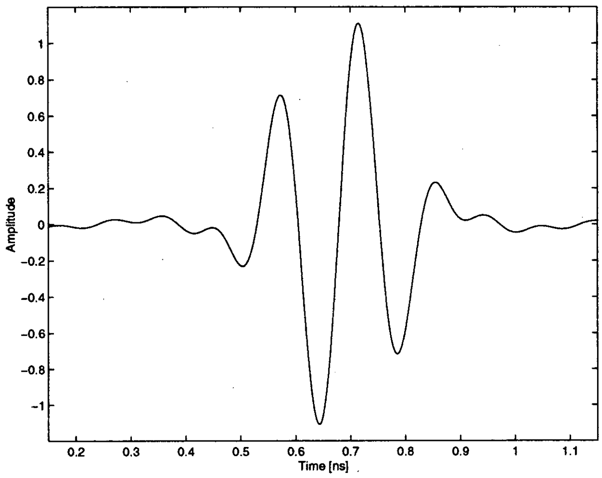

Figure 2 The transmission waveform of UWB signal.

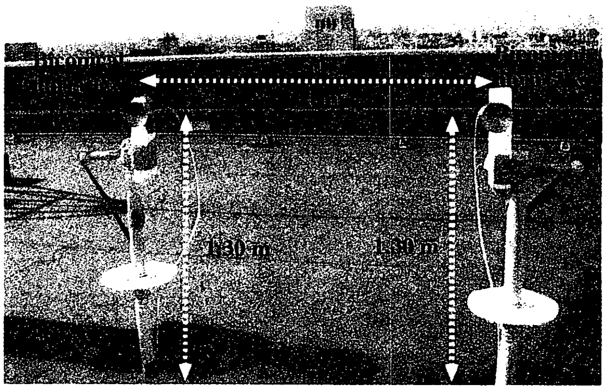

Figure 3 The experiments setup.

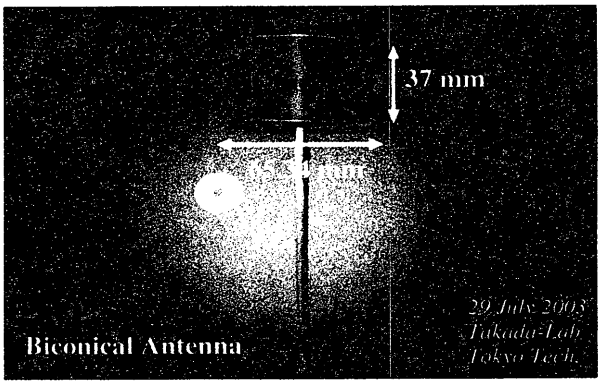

Figure 4 Geometry and dimensions of the biconical antenna.

Then the signal band was limited by the Nyquist roll-off filter with the roll-off factor $\alpha = 0$ (rectangular window) and the passband $\left(f_0 - \frac{f_b}{2},\ f_0 + \frac{f_b}{2}\right)$.

The transmission of the pulse waveform is simulated based on the measured transfer function of the antenna.

3.2 Experiments Setup

An UWB radio channel transfer function was measured as S_{21} in frequency domain by using a vector network analyzer (VNA). 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 on the top of the building to simulate as in the free space. Both Tx and Rx antennas were fixed at the height of 1.3 m and separated by 1 m. The setup equipment are shown in Figure 3.

The difference of the free space propagation distance d does not affect the waveform distortion. For this reason, It was set to be $d = 1$ m in this simulation.

In the S_{21} measurements, there are three different kinds of orientation as shown in Figure 6. They are facing toward the same directions to each other so that $G_t = G_r$ is satisfied. The main beam resides in xy-plane, i.e. omnidirectional pattern in Figure 4. The antenna is also tilted as much as 30° and 60° along θ directions, as well as the main beam direction.

In this study, we considered a broadband antenna that was suitable for the operation with pulsed waveforms [4]~[7]. We have chosen this biconical antenna for the ease of the fabrication, as well as it is often used as the standard antenna. The geometry and the dimension of antenna are shown in Figure 4. The upper cone is connected to the RF signal while the lower cone is connected to ground. Figure 5 shows the reflection coefficient $|S_{11}|$ of the antenna feed point. From the figure, we can see that the reflection coefficient was below -10 dB in the frequency range between 3.1 GHz and 10.6 GHz.

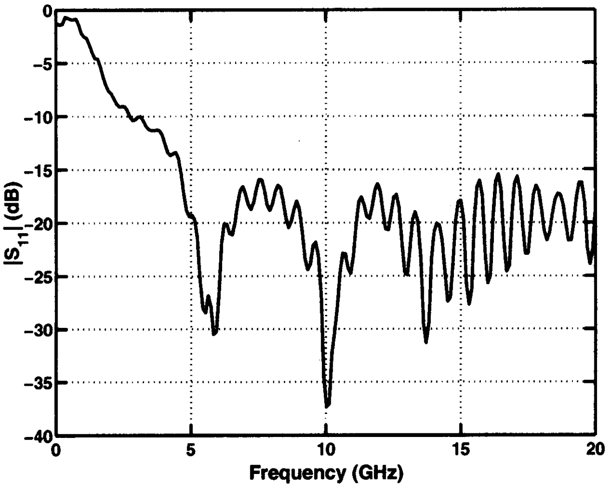

Figure 5 $|S_{11}|$ characteristics of biconical antenna.

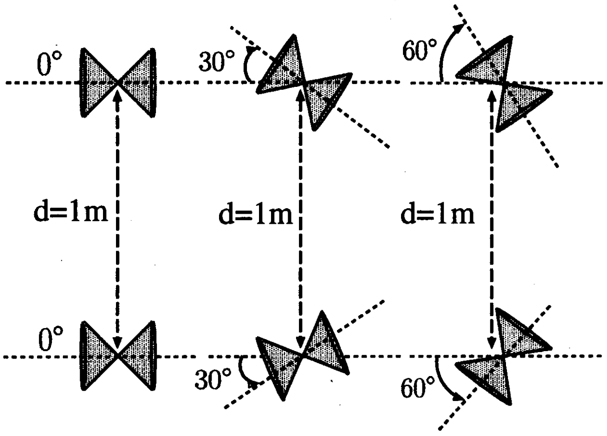

Figure 6 Orientations of two biconical antennas.

Table 1 Experimental setup parameters.

Parameter	**Value**
Frequency range	3 GHz to 11 GHz
Number of frequency points	1601
Dynamic power range	80 dB
IF bandwidth	3 MHz
Tx antenna height	1.3 m
Rx antenna height	1.3 m
Distance between Tx and Rx	1.0 m
Pointing angle	0 / 30 / 60 degrees

3.3 Parameters of Experiments

The important parameters for the experiments are listed in Table 1.

It is noted that the calibration is done at the connectors of the cables to be connected to the antennas. Therefore, all the impairments of the antenna characteristics are included in the measured results.

Figures 7 and 8 show the amplitude and the phase of the transfer function measured for three different antenna setups. From Figure 7, the radiation pattern seems to change from frequency to frequency, which may result in the waveform distortion. Although the ground reflection caused the ripples, the matched filter receiver can eliminate the reflected wave component as well as the time domain resolution is sufficiently high.

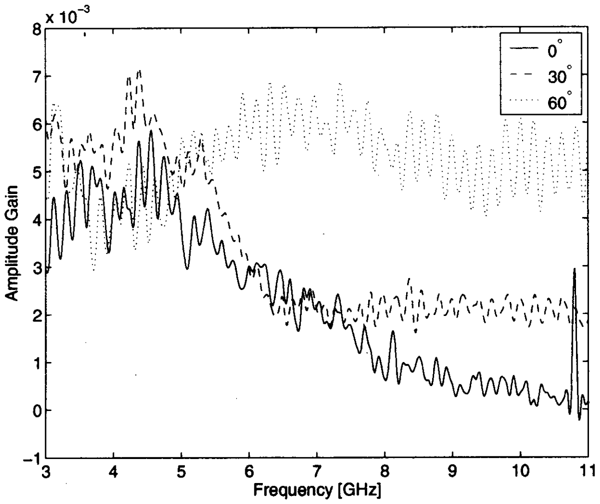

Figure 7 Measured transfer functions for different antenna pointing conditions: amplitude.

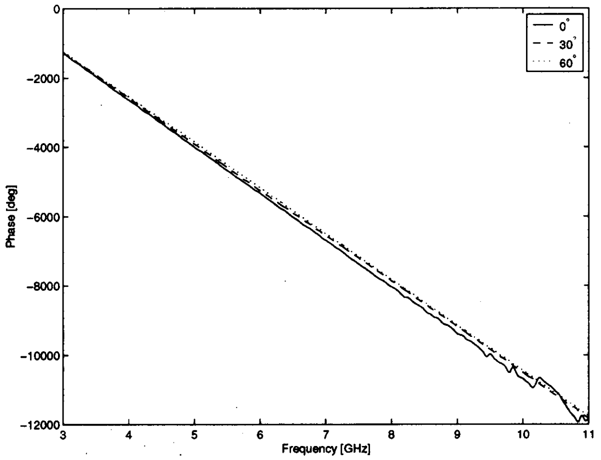

Figure 8 Measured transfer functions for different antenna pointing conditions: phase.

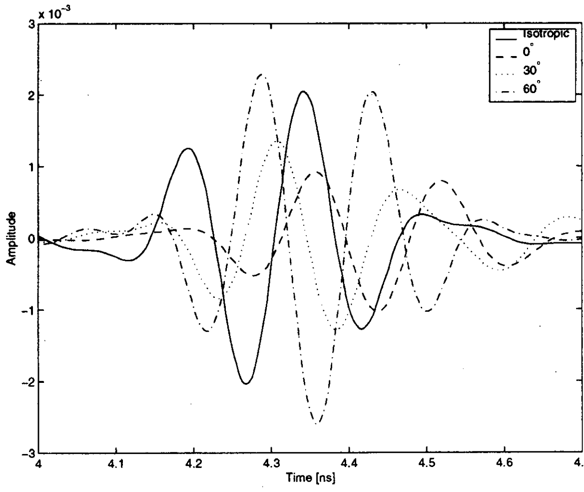

Figure 9 Received waveform at the antenna output.

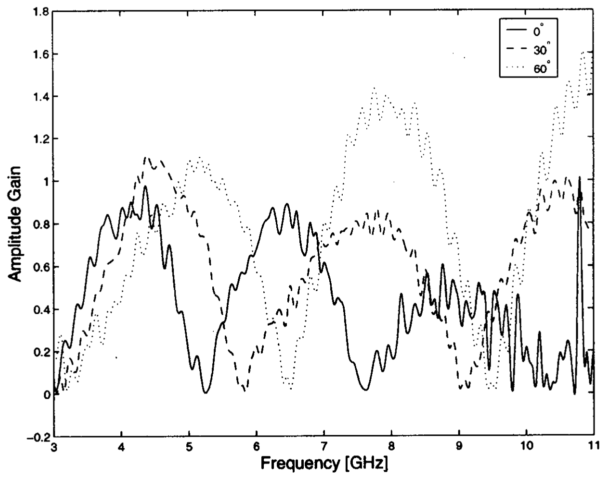

Figure 10 Antenna transfer function: amplitude.

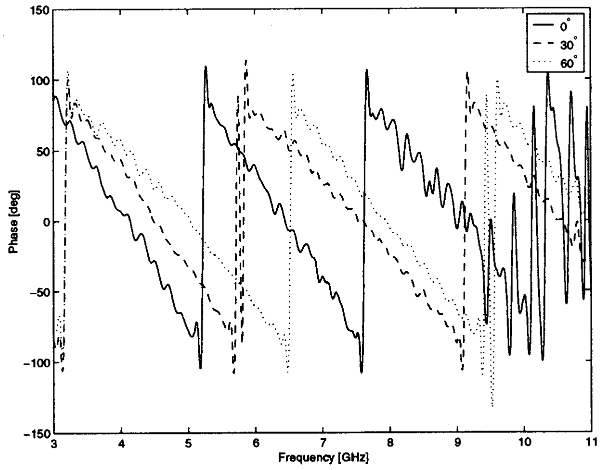

Figure 11 Antenna transfer function: phase.

Figure 9 shows the received pulse waveforms when the transmit waveform shown in Figure 2 is input. For comparison, the waveform for isotropic antennas are shown as 'isotropic'. Compared with the isotropic case, the pulse waveform is very much distorted and lengths become longer.

Although the accurate transfer function of each individual antenna shall be measured using three-antenna method, Figures 10 and 11 show the approximate antenna transfer function which are obtained by assuming that Tx and Rx antennas are identical. The vertical axis is normalized by the isotropic antenna.

Figures 12 and 13 show the output of matched filters. For Figures 12, a matched filter is optimized for the each individual scenario, and the results correspond to the maximum available gain. In contrast, for Figures 13, the matched filter is replaced by that for ideal isotropic antennas. This result is more realistic in practice, because the directions of the Tx and Rx antennas are not usually arbitrarily controllable, but set at the convenient positions.

Table 2 summarizes the overall gain with respect to the isotropic antennas case. Since the gain at the most of the frequencies was below unity, the dB value of the gain is negative. By using the isotropic matched filter, the gain has been degraded.

As the amount of the gain degradation depends on the setups, Table 3 lists the correlation coefficient of the impulse responses between the received signal and the approximate

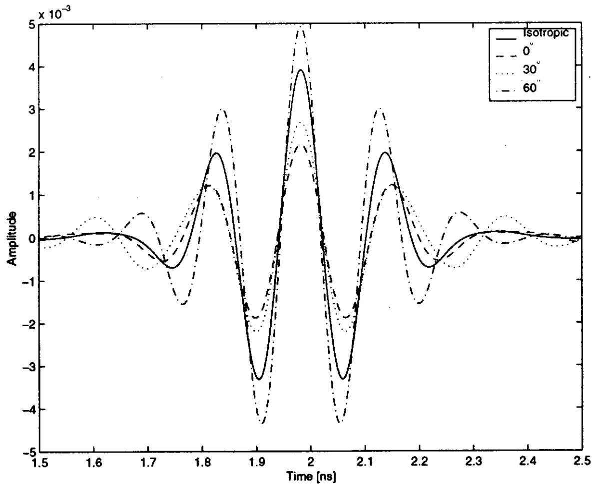

Figure 12 Output of matched filter: optimal.

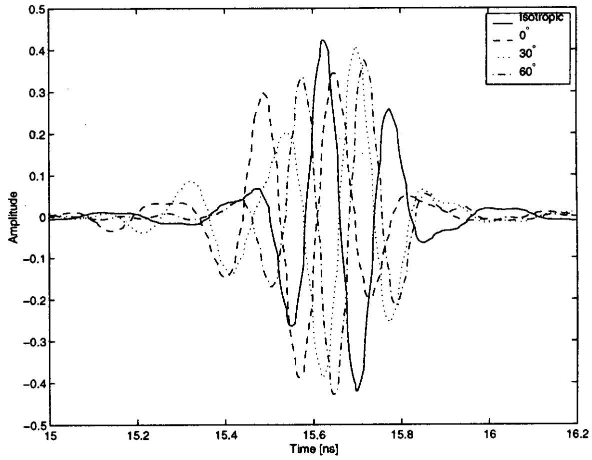

Figure 13 Output of the matched filter: free space approximation.

Table 2 Relative gain of (antennas + matched filter), with respect to the ideal isotropic antennas.

Filter	Gain [dBi]		
	0°	30°	60°
Optimum	−4.9728	−3.1940	1.9
Isotropic approximation	−6.2468	−4.9728	1.0478

Table 3 Correlation coefficient between the impulse responses of the received signal and the approximate matched filter by using isotropic antennas.

Orientation	0°	30°	60°
Correlation	0.8620	0.8215	0.8733

matched filter using the isotropic antennas. Since the correlation coefficient is approximately the same, the amount of degradation is also of the same magnitude.

4. Conclusion

In this paper, we discussed the experimental evaluation of the free space transmissoin charateristics of ultra wideband antenna. In the proposed scheme, Friis' transmission formula is extended in order to take into account the transmit waveform and the matched filter to the system. Experimental demonstration using the biconical antenna for UWB was shown, and the specific gain value could be obtained for Tx-Rx antenna pair.

In the present paper, we introduced the matched filter for the optimum receiver. However, if the distorted component should be regarded as the interference, the equalizer instead of the matched filter shall be introduced. Even in the case, similar discussion can be done on the definition of the gain. To know the individual antenna parameters, three-antenna measurement shall be introduced.

This scheme is applicable for the evaluation of various UWB antennas. Therefore, some typical UWB antennas shall be evaluated by using the proposed technique.

Acknowledgement

The authors would like to thank Dr. Ichirou Ida, Mr. Gilbert S. Ching, Mr. Chulgyun Park, Mr. Katsuyuki Haneda, and Ms. Navarat Lertsirisopon, all from Tokyo Institute of Technology, for their helps in the experiments and reviewing of this paper.

References

[1] H.T. Friis, "A Note on a Simple Transmission Formula," Proc. IRE, vol. 34, no. 5, pp. 254–256, May 1946.

[2] J. Takada, S. Promwong and W. Hachitani, "Extension of Friis' Transmission Formula for Ultra-Wideband Systems," IEICE Tech. Rep., WBS2003-8/MW2003-20, May 2003.

[3] Federal Communications Commission, "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," First Report and Order, FCC 02–48, Apr. 2002.

[4] H. Schantz, "Measurement of UWB Antenna Efficiency," Proc. IEEE Veh. Tech. Conf. (VTC), May 2001.

[5] H.F. Harmuth and S. Ding-Rong, "Antennas for Nonsinusiodal Wave — Part I: Radiators," IEEE Trans. Elec. Mag. Compat., vol. EMC-25, no. 1, pp. 13–24, Feb. 1983.

[6] H.F. Harmuth and S. Ding-Rong, "Antennas for Nonsinusiodal Wave — Part II: Sensors," IEEE Trans. on Elec. Mag. Compat., vol. EMC-25, no. 1, no. 2, pp. 107–115, May 1983.

[7] M.K.Y. Lai, A.L. Sinopoli and W.D. Burnside, "A Novel Antennas for Ultra-Wideband Applications," IEEE Trans. Antennas Propagat., vol. AP-40, no. 7, pp. 755–760, July 1992.