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Evaluation of Distortion Due to the Antennas in Ultra Wideband Impulse Radio

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***Abstract*—In free space propagation loss is usually evaluated by using the Friis' transmission formula. However, it is not directly applicable to ultra wideband impulse radio (UWB-IR) transmission systems. This paper presents the link budget evaluation formula for UWB-IR systems that takes into account the transmission signal waveform, its distortion due to the antenna, and the receiver. Since the antennas are significant pulse-shaping filters in UWB-IR, various kinds of antennas are experimentally examined, especially focusing on the effect of template waveform.**

I. Introduction

In UWB communication systems, any frequency selectivity causes distortion of the transmitting pulse shape. Therefore, antennas usually act as significant pulse-shaping filters. Consequently this will increase the complexity of the detection mechanism at the receiver. Moreover, low cost, geometrically small and still efficient structures are required for typical wireless applications. Therefore the antenna design for UWB signal radiation is one of the main challenges.

For narrowband wireless systems, Friis' transmission formula is used for the line-of-sight (LOS) link budget evaluation [1]. However, it is not directly applicable to the UWB impulse radio (IR) system as the bandwidth of the pulse is extremely wide. Moreover, the effect of waveform distortion shall be quantitatively considered in the link budget evaluation.

Ref. [2] treats the special cases of constant gain and constant aperture antennas, but no general discussion had been made. McLean et.al. [3] considered the antenna and the receiver template waveform to evaluate the free space transmission property, but they only considered the relative performance.

In this paper, we discuss the free space transmission loss evaluation scheme for UWB-IR systems. This scheme is based on the Friis' transmission formula, adapted to UWB, in the sense that we derive the equivalent transmission gain of UWB systems. The transmission and the receiver template waveforms are the keys for the extension of the Friis' formula to UWB. Experimental investigations are done for different types of antennas.

II. Theory

A. UWB Impulse Radio Transmission System

Free space channel response including antennas is obtained by using Friis' formula as

$$H_{\mathrm{c}}(f,d) = H_{\mathrm{f}}(f,d)\mathbf{H}_{\mathrm{r}}(f,\boldsymbol{\Omega}_{\mathrm{r}})\cdot\mathbf{H}_{\mathrm{t}}(f,\boldsymbol{\Omega}_{\mathrm{t}}), \tag{1}$$

where $\mathbf{H}_a$ $(a = \mathrm{r}$ *or* $\mathrm{t})$ is a complex transfer function vector of the antenna relative to the isotropic antenna towards the $\boldsymbol{\Omega}_a = (\theta_a,\ \varphi_a)$ direction, i.e.

$$\begin{aligned}\mathbf{H}_a(f,\boldsymbol{\Omega}_{\mathrm{a}}) &= \mathbf{H}_a(f,\theta_a,\varphi_a)\\ &= \hat{\boldsymbol{\theta}}_a H_{a\theta}(f,\theta_a,\varphi_a) + \hat{\boldsymbol{\varphi}}_a H_{a\varphi}(f,\theta_a,\varphi_a),\end{aligned} \tag{2}$$

where $a = \mathrm{r}$ *or* t,

$$H_{\mathrm{f}}(f,d) = \frac{\lambda}{4\pi d}\exp(-\mathrm{j}kd) \tag{3}$$

is the free space transfer function where

$$k = \frac{2\pi}{\lambda} \tag{4}$$

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 the antennas. The following relations can be easily derived.

$$\hat{\boldsymbol{\theta}}_{\mathrm{r}} = \hat{\boldsymbol{\theta}}_{\mathrm{t}}, \tag{5}$$

$$\hat{\boldsymbol{\varphi}}_{\mathrm{r}} = -\hat{\boldsymbol{\varphi}}_{\mathrm{t}}. \tag{6}$$

The spectrum of the receiver input $V_{\mathrm{r}}(f)$ is given as

$$V_{\mathrm{r}}(f) = H_{\mathrm{c}}(f,d)V_{\mathrm{t}}(f), \tag{7}$$

where $V_{\mathrm{t}}(f)$ is the spectrum of the transmit waveform.

B. Correlation Receiver

Let us consider a correlation receiver shown in Fig. 1. The output SNR is dependent on the choice of the template waveform. The correlator output $v_{\mathrm{o}}(\tau)$ is therefore expressed as

$$v_{\mathrm{o}}(\tau) = \int_{-\infty}^{\infty} v_{\mathrm{r}}(t)h_{\mathrm{w}}(t-\tau)\mathrm{d}t, \tag{8}$$

where $v_{\mathrm{r}}(t)$ is the receiver input waveform which is the inverse Fourier transform of Eq. (7), and $h_{\mathrm{w}}(t)$ is the template waveform. τ corresponds to the timing of the template waveform, and the optimum timing τ_{o} is chosen as

$$\tau_{\mathrm{o}} = \arg\max_{\tau} v_{\mathrm{o}}(\tau). \tag{9}$$

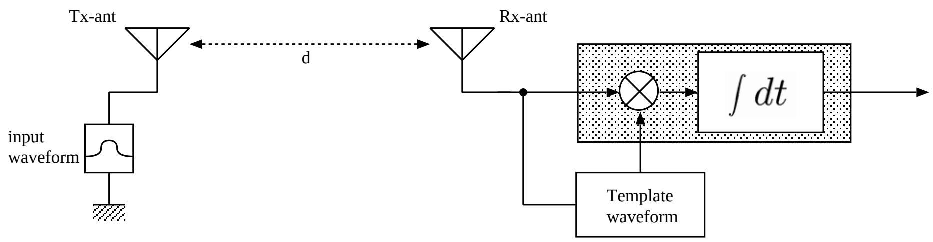

Fig. 1. Block diagram of transmission system Model for UWB signal.

Hereafter $h_{\mathrm{w}}(t)$ is normalized as

$$\int_{-\infty}^{\infty} |h_{\mathrm{w}}(t)|^2 \mathrm{d}t = 2B, \tag{10}$$

where B is the signal bandwidth, so that the output noise power is a constant as $N_0 B$, where $\frac{N_{\mathrm{o}}}{2}$ is the power spectral density of AWGN.

Under the constraint of Eq. (10), $h_{\mathrm{wm}}(t)$ maximizes $v_{\mathrm{o}}(\tau_{\mathrm{o}})$ when $h_{\mathrm{wm}}(t)$ is a time-reversed and scaled version of $v_{\mathrm{r}}(t)$, i.e.

$$h_{\mathrm{wm}}(t) = \frac{\sqrt{2B} v_{\mathrm{r}}(\tau_{\mathrm{o}} - t)}{\sqrt{\int_{-\infty}^{\infty} |v_{\mathrm{r}}(t)|^2 \mathrm{d}t}}, \tag{11}$$

where τ_{o} is usually chosen so that $h_{\mathrm{wm}}(t) = 0$ for $t < 0$ to satisfy the causality. $h_{\mathrm{wm}}(t)$ is called the optimum template waveform hereafter. It is noted that the link budget evaluation is identical to that in Ref. [4] when $h_{\mathrm{wm}}(t)$ is used as the receiver template.

C. Feasibility of the Optimum Correlation Receiver

It is obvious from Eq. (11) that the optimum template waveform is not the simple time-reversed version of the transmitter waveform, but the channel characteristics including the antennas and the free space propagation. Therefore, it is not always feasible to adapt the template waveform to the angular-dependent antenna characteristics, since the waveform shall be generated at the clock rate of tens of gigahertz. Therefore, we consider a canonical template waveform $h_{\mathrm{wc}}(t)$. In this paper we have chosen $h_{\mathrm{wc}}(t)$ that is optimum for the isotropic and the constant gain antennas, i.e.

$$h_{\mathrm{wc}}(t) = \frac{\sqrt{2B} v_{\text{r-iso}}(\tau_{\mathrm{o}} - t)}{\sqrt{\int_{-\infty}^{\infty} |v_{\text{r-iso}}(t)|^2 \mathrm{d}t}}, \tag{12}$$

where

$$v_{\text{r-iso}}(t) = \int_{-\infty}^{\infty} H_{\mathrm{f}}(f) V_{\mathrm{t}}(f) \exp(\mathrm{j} 2\pi f t) \mathrm{d}f \tag{13}$$

is the receiver input voltage for the case of isotropic antennas used in both sides. The difference between the optimum and the isotropic templates indicates quantitatively the distortion of the waveform.

III. Experimental Evaluation of Channels with Various UWB Antennas

In this section, LOS links with different kinds of UWB antennas are evaluated based on the previous section.

A. Transmission Waveform

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 [6], 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 $\frac{2}{f_{\mathrm{b}}}$. Then the signal was band-limited by a Nyquist roll-off filter with roll-off factor $\alpha = 0$ (rectangular window) and passband $\left(f_0 - \frac{f_{\mathrm{b}}}{2},\ f_0 + \frac{f_{\mathrm{b}}}{2}\right)$. Figure 2 shows the transmit pulse waveform.

B. Experimental Setup and Measurement Model

An UWB radio channel transfer function was measured as S_{21} in frequency domain by using a vector network analyzer (VNA) in an anechoic chamber. The VNA was operated in the response measurement mode, where Port-1 was the transmitter (Tx) port and Port-2 was the receiver (Rx) port, respectively. Both Tx and Rx antennas were fixed at the height of 1.75 m and separated by 1 m.

We used a biconical antenna as the Tx antenna. We have chosen this antenna for ease of fabrication, as well as its low distortion property. The geometry of the antenna is shown in Fig. 3. The upper cone is connected to the center conductor of a coaxial line while the lower cone is connected to the shield conductor. The maximum diameter is 65.3 mm and length is 37 mm. We changed only the Rx antennas to compare the transmission properties. The experimental parameters are listed in Table I. It is noted that the calibration of VNA 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.

IV. Results

In this section, standard broadband antennas and deployable antennas are used in the measurement for the link budget evaluation.

USA suggested the use of a biconical antenna, a log-periodic antenna, and a double-ridged guide horn for the frequency ranges of $30 - 200$ MHz, $200 - 960$ MHz, and $0.96 - 18$ GHz, respectively, for the compliance test of UWB

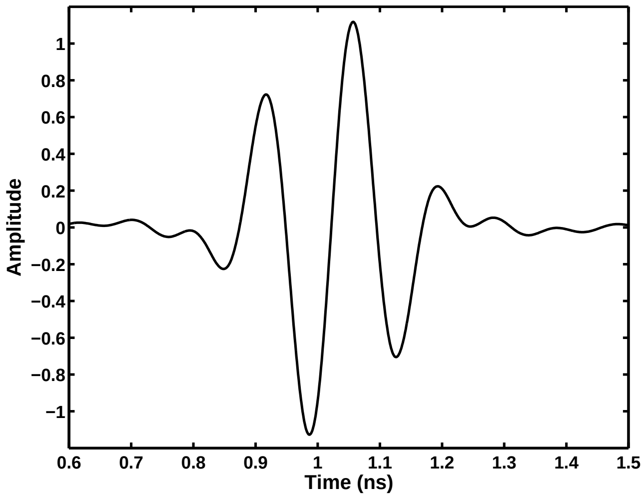

Fig. 2. The transmission waveform of UWB signal.

TABLE I
EXPERIMENTAL SETUP PARAMETERS.

Parameter	Value
Frequency range	3 GHz to 11 GHz
Number of frequency points	1601
Dynamic range	80 dB
Tx antenna height	1.75 m
Rx antenna height	1.75 m
Distance between Tx and Rx	1 m
Rx rotation range	0° to 360°
Rx rotation step	5°
Rx rotation cut	E- or H-plane

transmitters [7]. We chose these three kinds of antennas, operating in the same frequency range.

Recently, many UWB antennas have been proposed for the short range communications and radars. Among them, we have used a miniature antenna that is commercially available, and a trapezoidal antenna with an L-shaped ground plane that is easily fabricated.

1) Biconical Antenna: First, the same biconical antennas were used both at Tx and Rx sides. Figure 4 shows the normalized UWB transmission gain as a function of antenna pointing angle in the E-plane. Well-known 8-shaped patterns were obtained. Two template waveforms were used for comparison, and the difference was rather small. The phase center of the biconical antenna is the feed point and it has theoretically the frequency independent gain at broadside direction, and that is why the waveform distortion effect is small compared with the isotropic template.

2) Log-Periodic Dipole Antenna: A log-periodic dipole antenna (LPDA) is also used at broadband. It also has a frequency-independent gain. Different from biconical antennas, however, the dispersion characteristic of LPDA is rather big, since the phase center changes with frequency due to the resonance of the dipole elements [8].

We used a commercial LPDA, Watkins–Johnson's AR7-15A, shown in Fig. 5. The antenna has been designed to operate in the range of 1 to 12.4 GHz. Figure 6 shows the normalized UWB transmission gain pattern for biconical–LPDA link in E-plane. As is known, an LPDA is uni-directional and its gain is higher than that of a biconical antenna. The degradation of the transmission gain is observed when the canonical isotropic template is used, since the waveform dispersion is obvious [8].

3) Double Ridge Guide Horn: A double ridge guide horn (DRGH) is often used as a standard antenna for broadband measurement above 1 GHz. Different from the standard pyramidal horn, DRGH operates in TEM mode and is similar to the vivaldi antenna. It has relatively low dispersion and is suitable for the waveform detection.

We used a commercial DRGH, Microwave Factory's MDR0218, shown in Fig. 7. The frequency range is from 2 to 18 GHz. Figure 8 shows the normalized UWB transmission gain pattern for biconical–DRGH link in E-plane. As the graph is drawn in linear power pattern, the shift of main beam is observed although it is negligibly small in dB scale. It seems to be due to the asymmetrical feed structure. The transmission gain is much higher than other antennas, and thethe frequency independent isotropic antenna, and the optimum receiver template.

isotropic template case shows that the distortion of the waveform is not significant.

V. CONCLUSION

This paper we presented how to evaluate the transmission loss of UWB impulse radio, which includes the transmit waveform, antennas, free space propagation, and receiver correlator template. By using the definition, we have evaluated three types of broadband antennas. The formulation presented in the preceding paper [4] is a special case for the optimum template waveform in this paper. Therefore, as is also presented in [4], IEEE 802.15.3a path loss model [5] is also a special case of the formulation presented in this paper, by considering the single ASK pulse, the frequency independent isotropic antenna, and the optimum receiver template.

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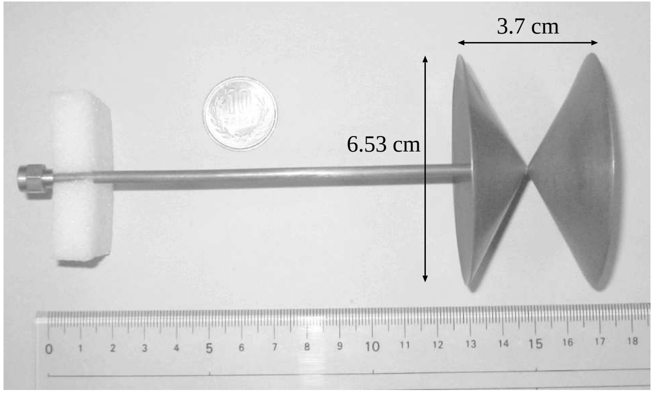

Fig. 3. Biconical antenna structure.

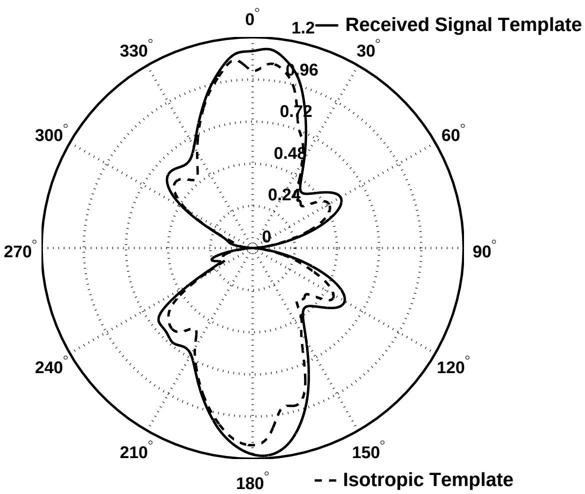

Fig. 4. Normalized UWB transmission gain for biconical–biconical link.

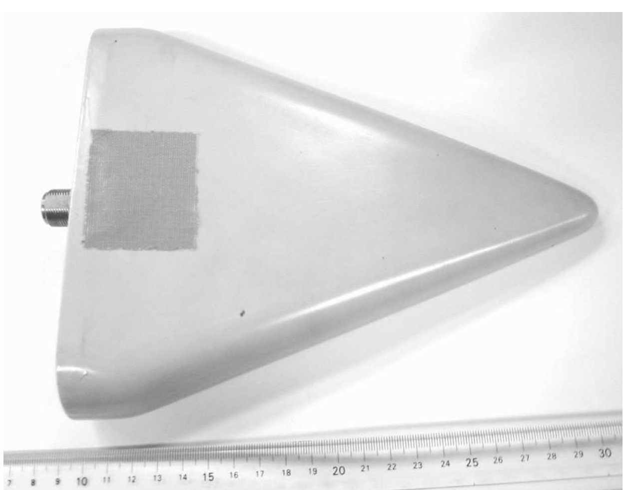

Fig. 5. Log-periodic dipole antenna (Watkins–Johnson AR7-15A).

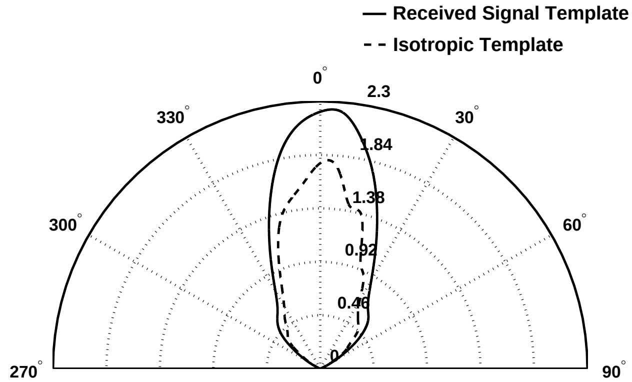

Fig. 6. Normalized UWB transmission gain for biconical–LPDA link.

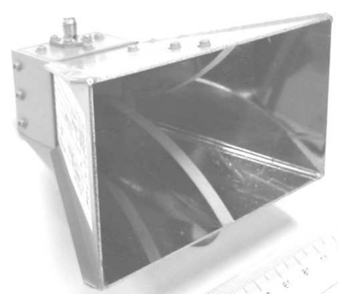

Fig. 7. Double ridge guide horn (Microwave Factory's MDR0218).

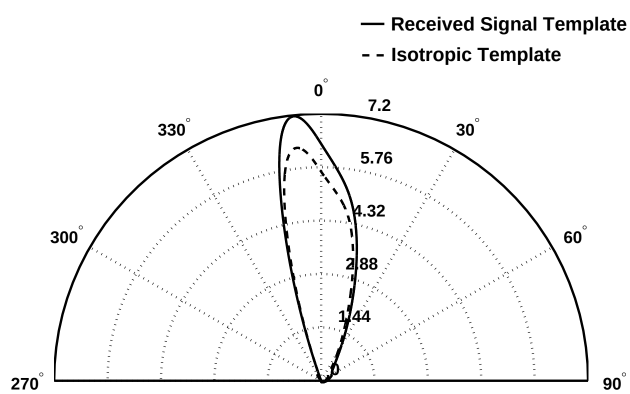

Fig. 8. Normalized UWB transmission gain for biconical–DRGH link.