EVALUATION OF WAVEFORM DISTORTION DUE TO ANTENNAS ON FREE SPACE TRANSMISSION IN ULTRA WIDEBAND IMPULSE RADIO

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ABSTRACT

The waveform of an ultra wideband impulse radio (UWB-IR) system can be extremely distorted through a channel even for free-space transmission because of antenna dispersion. Therefore, the understand of antenna characteristics, which effects on waveform distortion, is necessary. This paper we evaluate the waveform distortion due to antenna on free space transmission in UWB-IR system. The link budget is usually evaluated by using the Friis’ transmission formula. However, it is not directly applicable to the UWB-IR transmission system. The link budget evaluation formula attended from conventional Friis’ transmission formula that takes into account the transmitted waveform, its distortion due to the antennas, the channel and the correlation receiver is proposed. Since the antennas are significant pulse-shaping filters in UWB-IR system, the biconical antennas are experimentally examined, especially focused on the effect of the received signal and the isotropic template waveforms.

I INTRODUCTION

The effect of the waveform distortion shall be quantitatively considered in the link budget evaluation. Therefore, Friis’ transmission formula is necessary to extend for UWB-IR system. The link budget model composed with input admittance of transmitter, transmission impedance and frequency transfer function of receiver is proposed in [1]. The other models are factorized in the term of the frequency transfer function of each factor. The model composed with frequency transfer functions of Tx antenna and Rx antenna based on radar-range equation is proposed in [2]. The model composed with frequency transfer functions of Tx antenna/channel and Rx antenna is proposed in [3]. Next, the models in the terms of the antenna frequency transfer functions in transmission with reciprocity theorem are developed in [4]-[7]. Although the correlation receiver is included in the model of [4], it does not consider the optimum correlation receiver, which can be considered as the upper boundary of best performance. The purpose of this paper is to propose a new link budget model for studying the waveform distortion due to antenna on free space transmission in UWB-IR system. We develop the free space link budget evaluation scheme in the term of frequency transfer function for UWB-IR system that takes into account the transmitted waveform, its distortion due to the antennas, the channel and the correlation receiver. This model is based on the Friis’ transmission formula, adapted to the UWB-IR transmission system, in the sense that we derive the equivalent frequency transfer function of UWB-IR system [7]. Rectangular passband and root raised cosine passband waveforms are comparably used as the UWB-IR transmitted waveforms. Experimental investigations are done for different types of the antennas. The distortion quantities in the terms of magnitude, phase and waveform distortions, and transmission gain are defined and shown. This scheme provides some useful physical insights and optimized design procedure with clear and accessible description of the UWB-IR system.

II THEORY OF FREE SPACE LINK BUDGET EVALUATION

The Friis’ transmission formula [6] has been widely used to evaluate a link budget for the narrowband LOS channels. The Friis’ transmission gain $G_{\text{Friis}}(f)$ is defined as

$$ G_{\text{Friis}}(f) = \frac{P_t(f)}{P_r(f)} = G_t(f, d)G_r(f, \Omega_r)G_{\text{\eta}}(f, \Omega_r), $$

(1)

where $f$ is the operating frequency, $d$ is the separation between Tx and Rx antennas, $P_t(f)$ and $P_r(f)$ respectively are the input power to the Tx antenna and the output power from the Rx antenna, $G_t(f, \Omega_r)$ and $G_r(f, \Omega_r)$ respectively are effective gain of Tx and Rx antennas, $G_{\text{\eta}}(f, \Omega_r)$ is the free space propagation gain and $\eta_p(f)$ is the polarization matching efficiency. The free space propagation gain can be written as

$$ G_t(f, d) = \left( \frac{c}{4\pi df} \right)^2, $$

(2)

where $c$ is the velocity of light.

It is noted, however, that Eq. (1) is satisfied only at some frequency, and is not directly applicable to the UWB-IR transmission system. The formula shall be extended to take into account the transmitted waveform, its distortion due to the antennas, the channel and the correlation receiver [7].

For UWB-IR system, we develop the free space link budget in the term of frequency transfer function that takes into account the transmitted waveform, its distortion due to the antennas, the channel and the correlation receiver. The free space transfer function $H_t(f, d)$ can be written as

$$ H_t(f, d) = \frac{c}{4\pi fd} \cdot \Omega(t \cdot 2\pi fd/c). $$

(3)

Free space channel transfer function $H_t(f)$ including the antennas is obtained by using the extension of Friis’ transmission
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formula as

\[ H_c(f) = H_t(f, d) H_r(f, \Omega_t) \cdot H_a(f, \Omega_a), \]

where \( H_a(f, \Omega_a) \) \((a = r \text{ or } t)\) is a complex transfer function vector of the antenna relative to the isotropic antenna towards the \( \Omega_a = (\theta_a, \varphi_a) \) direction, i.e.

\[ H_a(f, \Omega_a) = H_a(f, \theta_a, \varphi_a) + \varphi_a H_{a\varphi}(f, \theta_a, \varphi_a), \]

and which has the relation as

\[ \frac{1}{4\pi} \int_{-\infty}^{\infty} \int_{0}^{2\pi} |H_a(f, \theta_a, \varphi_a)|^2 \sin \theta d\theta d\varphi = \eta_a, \]

where \( \eta_a \) is the antenna efficiency, so that the value is normalized by that for isotropic antenna. Unit vectors \( \hat{\theta}_a, \hat{\varphi}_a \) express the polarization and are defined with respect to the local polar coordinates of the antennas. The following relations can be easily derived as

\[ \hat{\theta}_t = \hat{\theta}_i, \]
\[ \hat{\varphi}_t = -\hat{\varphi}_i. \]

For the identical Tx and Rx antennas satisfying Eqs. (7) and (8), the complex transfer functions of Tx and Rx antennas can be written as [5]

\[ H_t(f) = \sqrt{\frac{j e H_c(f)}{f H_t(f, d)}}, \]
\[ H_r(f) = \sqrt{\frac{f H_c(f)}{j e H_r(f, d)}}, \]

with the relation between complex transfer functions of Tx and Rx antenna satisfying reciprocity theorem as

\[ H_r(f) = \frac{1}{j} H_t(f). \]

The receiver input waveform \( v_r(t) \) is given by

\[ v_r(t) = \int_{-\infty}^{\infty} H_r(f)V_i(f)e^{j2\pi f t} df, \]

where \( V_i(f) \) is the spectral density of the transmitted waveform.

Note that the angular and distance dependence is not shown in Eqs. (2), (4) and (9) to (12) to reduce notational complexity.

**II.A Correlation Receiver**

Let us consider a correlation receiver shown in Fig. 1. The output signal-to-noise ratio (SNR) is dependent on the choice of the template waveform. The correlator output \( v_o(\tau) \) is therefore expressed as

\[ v_o(\tau) = \int_{-\infty}^{\infty} v_r(t) h_w(t - \tau) dt, \]

where \( h_w(t) \) is the template waveform and \( \tau \) corresponds to the timing of the template waveform. The optimum timing \( \tau_o \) is chosen as

\[ \tau_o = \arg \max_{\tau} v_o(\tau). \]

Hereafter \( h_w(t) \) is normalized as

\[ \int_{-\infty}^{\infty} |h_w(t)|^2 dt = 2B, \]

where \( B \) is the signal bandwidth, so that the output noise power is a constant as \( N_0B \), where \( N_0/2 \) is the power spectral density of additive white Gaussian noise (AWGN).

Under the constraint of Eq. (15), \( h_{wm}(t) \) maximizes \( v_o(\tau_o) \) when \( h_{wm}(t) \) is a time-reversed and scaled version of \( v_r(t) \), i.e.

\[ h_{wm}(t) = \frac{\sqrt{2B} v_r(t - \tau_o)}{\sqrt{\int_{-\infty}^{\infty} |v_r(t)|^2 dt}}, \]

where \( \tau_o \) is usually chosen so that \( h_{wm}(t) = 0 \) for \( t < 0 \) to satisfy the causality. \( h_{wm}(t) \) is called the received signal template waveform hereafter. It is noted that the link budget evaluation \( h_{wm}(t) \) is used as the receiver template.

**II.B Feasibility of the Optimum Correlation Receiver**

It is obvious from Eq. (16) that the received signal template waveform is not the simple time-reversed version of the transmitted waveform, but including the frequency characteristics of 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 \( h_{tc}(t) \). In this paper we have chosen \( h_{tc}(t) \) that is optimum for the isotropic and the constant gain antennas, i.e.

\[ h_{tc}(t) = \frac{\sqrt{2B} v_{r\text{iso}}(t - \tau_o)}{\sqrt{\int_{-\infty}^{\infty} |v_{r\text{iso}}(t)|^2 dt}}, \]

where the receiver input voltage for the case of isotropic antennas used in both sides \( v_{r\text{iso}}(t) \) can be written as

\[ v_{r\text{iso}}(t) = \int_{-\infty}^{\infty} H_{ld}(f)V_i(f)e^{j2\pi f t} df. \]
II.C Waveform distortion

The waveform distortion is considered in the term of distortion between received waveform and received waveform for the case of isotropic antennas used in both side. Therefore, the quantity of waveform distortion \( W \) is defined in the time domain by using the difference between one and correlation coefficient between these waveforms and it can be written as

\[
W = 1 - \frac{\max \left| \int_{-\infty}^{\infty} v_r(t) \cdot v_{t-\text{iso}}(t + \tau) dt \right|}{\sqrt{\int_{-\infty}^{\infty} |v_r(t)|^2 dt \cdot \int_{-\infty}^{\infty} |v_{t-\text{iso}}(t)|^2 dt}}, \tag{19}
\]

where \(*\) is the complex conjugate operator, \( v_r(t) \) is the transmitted waveform in time domain and can be evaluated by using inverse Fourier transform of its spectral density

\[
v_r(t) = \int_{-\infty}^{\infty} V_r(f) e^{j2\pi ft} df. \tag{20}
\]

This quantity is equal to 0 when two waveforms are identical and it is increased when the waveform is more differ from another.

II.D Transmission Gain

The transmission gain in this paper is defined as the peak amplitude of the correlator output with the considered antennas normalized by that with the isotropic antennas. Due to the normalization of template waveforms in Eqs. (13) and (14), this gain value represents the gain of SNR ratio. Therefore, the transmission gain of the received signal template case \( G_{\text{wm}} \) can be written as

\[
G_{\text{wm}} = \frac{\max \left| \int_{-\infty}^{\infty} v_{t}(t) h_{\text{wm}}(t - \tau) dt \right|}{\max \left| \int_{-\infty}^{\infty} v_{t-\text{iso}}(t) h_{\text{wm}}(t - \tau) dt \right|}. \tag{21}
\]

Similarly, the transmission gain of the isotropic template case \( G_{\text{wc}} \) can be written as

\[
G_{\text{wc}} = \frac{\max \left| \int_{-\infty}^{\infty} v_{t}(t) h_{\text{wc}}(t - \tau) dt \right|}{\max \left| \int_{-\infty}^{\infty} v_{t-\text{iso}}(t) h_{\text{wc}}(t - \tau) dt \right|}. \tag{22}
\]

The difference between the transmission gain of the received signal and the isotropic template cases also indicates the distortion quantity of the waveform. Different from the original Friis’ transmission formula, the optimum transmission gain of UWB-IR signal can not be simply expressed by the product of antenna indices.

III EXPERIMENT OF EXAMPLE UWB-IR ANTENNA

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

III.A Transmitted Waveforms

The effect of the waveform distortion is more obvious when the bandwidth is wider. We considered the transmitted waveforms that fully cover the Federal Communications Commission (FCC) frequency band, i.e., 3.1 – 10.6 GHz [8] and common frequency band available between the FCC of USA, European Conference of Postal and Telecommunications Administrations/Electronic Communications Committee (CEPT/ECC) of Europe and Ministry of Internal Affairs and Communications (MIC) of Japan, i.e., 7.25 – 8.5 GHz [9]. In this paper, the rectangular passband and root raised cosine passband waveforms are used as the transmitted waveforms.

III.A.1 Rectangular Passband Waveform

The rectangular passband waveform is the waveform with rectangular spectrum and its spectral density is defined as

\[
V_{t,\text{re}}(f) = \begin{cases} 
1 & \text{if } |f| - f_c | \leq \frac{f_b}{2} \\
0 & \text{otherwise}
\end{cases}, \tag{23}
\]

where \( f_c \) is the center frequency and \( f_b \) is the spectral bandwidth.

III.A.2 Root Raised Cosine Passband Waveform

The root raised cosine passband waveform is the waveform with root raised cosine spectrum and its spectral density is defined as

\[
V_{t,\text{ro}}(f) = \begin{cases} 
1 & \text{if } |f| - f_c | \leq \frac{1 + \beta T}{2T} \\
A \frac{(1-\beta)^2}{2T^2} < |f| - f_c | \leq \frac{1 + \beta T}{2T} & \text{otherwise}
\end{cases}, \tag{24}
\]

where

\[
A = \sqrt{\frac{1}{2} \left[ 1 + \cos \left( \frac{\pi T}{\beta} \left[ |f| - f_c \right] - \frac{1-\beta}{2T} \right) \right]},
\]

\( T = 1/f_b \) is the reciprocal of the symbol-rate and \( \beta = 0.3 \) is the roll-off factor. For satisfying the FCC spectral masks, \( f_c \) is set to 6.85 GHz. The spectral bandwidth \( f_b \) is set to 6.37 and 5.94 GHz for satisfying FCC spectral masks for indoor and outdoor limits, respectively. For satisfying the common frequency band spectral mask, \( f_c \) and \( f_b \) are set to 7.875 and 1.250 GHz, respectively.

III.B Experimental Setup and Measurement Model

The UWB-IR 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 Tx port and Port-2 was the Rx port, respectively. Both Tx and Rx antennas were fixed at the height of 1.75 m and separated by 4 m.

We used a biconical antenna as the Tx antenna. We have chosen this antenna for ease of the fabrication, as well as its low distortion property. 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 the length is 37 mm. We changed only the Rx antennas to compare the transmission gain properties. The experimental parameters are listed in Table 1. 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 measurement results.
Table 1: Experimental setup parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>3 GHz to 11 GHz</td>
</tr>
<tr>
<td>Number of frequency points</td>
<td>1601</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>80 dB</td>
</tr>
<tr>
<td>Tx antenna height</td>
<td>1.75 m</td>
</tr>
<tr>
<td>Rx antenna height</td>
<td>1.75 m</td>
</tr>
<tr>
<td>Distance between Tx and Rx</td>
<td>4 m</td>
</tr>
<tr>
<td>Rx rotation range</td>
<td>0° to 360°</td>
</tr>
<tr>
<td>Rx rotation step</td>
<td>5°</td>
</tr>
<tr>
<td>Rx rotation cut</td>
<td>E- or H-plane</td>
</tr>
</tbody>
</table>

The complex transfer function of Tx biconical antenna is obtained by measurement with identical Tx and Rx biconical antennas and then using Eq. (9). Therefore, the channel transfer function of desired antenna link can be calculated and reconstruction by using Eqs. (4), (10) and (11).

### III.C Results

The transmission gain of each waveform satisfying each spectral mask are considered. For FCC spectral masks, the transmission gains of the rectangular passband waveforms, the root raised cosine passband waveforms satisfying limits are shown in Figs. 2 and 3, respectively. Figures 4 and 5 show the transmission gains of the rectangular and root raised cosine passband waveforms satisfying common frequency band spectral mask, respectively. Well-known 8-shaped patterns are obtained. Two template waveforms are used to compare and investigate the difference. The differences of transmission used received signal and isotropic templates satisfying FCC spectral masks are clearly more than that satisfying common frequency band spectral mask. For FCC spectral masks, the average differences of the rectangular passband waveform, the root raised cosine passband waveforms satisfying limits are 1.22 and 1.28 dB, respectively. The average differences of the rectangular and root raised cosine passband waveforms satisfying common frequency band spectral mask are only 0.11 and 0.09 dB, respectively. The phase center of the biconical antenna is the feed point and it has theoretically the frequency independent gain at the broadside direction, and that is why the waveform distortion effect is small compared with the isotropic template.

From these results, the UWB-IR transmission gain, using both the received signal and the isotropic template waveforms, gives us the quantitative measurement of the link budget. Since we have chosen the broadband antennas, the trend of the narrowband gain is reflected in the UWB-IR transmission gain. Another issue is the distortion of the waveform. The difference between the optimum and the isotropic templates is the measurement of the waveform distortion. It is obvious that the type of waveform in the same frequency band has little distortion difference. The waveforms in FCC frequency band with wider bandwidth have more distortion than that in common frequency band.

### IV Conclusion

This paper has presented how to evaluate the UWB-IR transmission gain, which includes the transmit waveform, the antennas, the free space propagation, and the correlation receiver. By using the proposed definition, we have evaluated by using the biconical antennas. This scheme may be effective especially to evaluate the deployable antenna with non-ideal frequency characteristics of return loss and directivity, as the overall performance can be evaluated only by the term of the UWB-IR transmission gain.

Note that the formulation presented is a special case for the optimum template waveform in this paper. Therefore, the IEEE 802.15.3a path loss model presented is also a special case of the formulation presented in this paper, by considering the rectangular frequency spectrum, the frequency independent isotropic antenna and the received signal template.

### References


Figure 2: Transmission gain of rectangular passband waveform satisfying FCC spectral mask for biconical–biconical link.

Figure 3: Transmission gain of root raised cosine passband waveform satisfying FCC spectral mask for biconical–biconical link.

Figure 4: Transmission gain of rectangular passband waveform satisfying common frequency band spectral mask for biconical–biconical link.

Figure 5: Transmission gain of root raised cosine passband waveform satisfying common frequency band spectral mask for biconical–biconical link.