Phase Distortion Due to the Antennas in UWB-IR

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1 Introduction

This paper is studying the phase 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. Root raised cosine passband waveform is used as the UWB-IR transmitted waveform. Experimental investigations are done for different types of the antennas. The distortion quantities in the terms of phase are defined and shown. This scheme provides some useful physical insights and optimized design procedure with clear and accessible description of the UWB-IR link budget comprised of practical antennas.

2 Theory of UWB-IR

The Friis' transmission formula [1] has been widely used to evaluate a link budget for the narrowband LOS channels.

The Friis' transmission gain $G_{\mathrm{Friis}}(f)$ is defined as

$$\begin{aligned} G_{\mathrm{Friis}}(f) &= \frac{P_{\mathrm{r}}(f)}{P_{\mathrm{t}}(f)}, \\ &= G_{\mathrm{f}}(f,d)G_{\mathrm{r}}(f,\mathbf{\Omega}_{\mathrm{r}})G_{\mathrm{t}}(f,\mathbf{\Omega}_{\mathrm{t}})\eta_{\mathrm{p}}(f), \end{aligned} \tag{1}$$

where f is the operating frequency, d is the separation between Tx and Rx antennas, $P_{\mathrm{t}}(f)$ and $P_{\mathrm{r}}(f)$ respectively are the input power to the Tx antenna and the output power from the Rx antenna, $G_{\mathrm{t}}(f,\mathbf{\Omega}_{\mathrm{t}})$ and $G_{\mathrm{r}}(f,\mathbf{\Omega}_{\mathrm{r}})$ respectively are effective gain of Tx and Rx antennas, $G_{\mathrm{f}}(f,d)$ is the free space propagation gain and $\eta_{\mathrm{p}}(f)$ is the polarization matching efficiency. The free space propagation gain can be written as

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

where c is the velocity of light.

The free space transfer function $H_{\mathrm{f}}(f,d)$ can be written as

$$H_{\mathrm{f}}(f,d) = \frac{c}{4\pi fd}e^{-\mathrm{j}2\pi fd/c}. \tag{3}$$

Free space channel transfer function $H_{\mathrm{c}}(f)$ including the antennas is obtained by using the extension of Friis' transmission formula as

$$H_{\mathrm{c}}(f) = H_{\mathrm{f}}(f,d)\ \mathbf{H}_{\mathrm{t}}(f,\mathbf{\Omega}_{\mathrm{t}})\cdot\mathbf{H}_{\mathrm{r}}(f,\mathbf{\Omega}_{\mathrm{r}}), \tag{4}$$

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

$$\begin{aligned} \mathbf{H}_a(f,\mathbf{\Omega}_{\mathrm{a}}) &= \mathbf{H}_a(f,\theta_a,\varphi_a) \\ &= \hat{\boldsymbol{\theta}}_a H_{a\theta}(f,\theta_a,\varphi_a) + \hat{\boldsymbol{\varphi}}_a H_{a\varphi}(f,\theta_a,\varphi_a), \end{aligned} \tag{5}$$

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 receiver input waveform $v_{\mathrm{r}}(t)$ is given by

$$v_{\mathrm{r}}(t) = \int_{-\infty}^{\infty} H_{\mathrm{c}}(f) V_{\mathrm{t}}(f) e^{j2\pi f t} \mathrm{d}f, \tag{6}$$

where $V_{\mathrm{t}}(f)$ is the spectral density of the transmitted waveform.

2.1 Phase Distortion

The waveform distortion can be caused by the phase of channel transfer function. The channel transfer function can be written in the terms of magnitude and phase of channel transfer function as

$$H_{\mathrm{c}}(f) = M(f) e^{j\Theta(f)}, \tag{7}$$

where $M(f)$ and $\Theta(f)$ are the magnitude and phase of channel transfer function, respectively.

The quantity of phase distortion depends on the linearity of its phase. In this paper, the new quantity of phase distortion is proposed. The phase of channel transfer function is modeled as the linear regression as

$$\Theta(f) = -2\pi f \tau + \hat{\Theta}(f), \tag{8}$$

where τ is the absolute delay, which is derived using least square method as

$$\tau = -\frac{3}{2\pi(f_{\mathrm{H}}^3 - f_{\mathrm{L}}^3)} \int_{f_{\mathrm{L}}}^{f\mathrm{H}} f\Theta(f) \mathrm{d}f, \tag{9}$$

where f_{L} and f_{H} are the lowest and highest frequencies, respectively.

The phase fluctuation $\hat{\Theta}(f)$, which is influential to distortion. From this definition, the linearity of phase corresponds to the flatness of phase fluctuation. Therefore, the quantity of phase distortion is considered in the term of standard deviation of phase fluctuation $\sigma_{\hat{\Theta}}$ and can be defined as

$$\sigma_{\hat{\Theta}} = \sqrt{\frac{1}{f_{\mathrm{H}} - f_{\mathrm{L}}} \int_{f_{\mathrm{L}}}^{f_{\mathrm{H}}} (\hat{\Theta} - \mu_{\hat{\Theta}})^2 \mathrm{d}f}, \tag{10}$$

where $\mu_{\hat{\Theta}}$ is the means of phase fluctuation and can be written as

$$\mu_{\hat{\Theta}} = \frac{1}{f_{\mathrm{H}} - f_{\mathrm{L}}} \int_{f_{\mathrm{L}}}^{f_{\mathrm{H}}} \hat{\Theta}(f) \mathrm{d}f. \tag{11}$$

In this paper, the phase distortion is investigated only when the transmission gain is above 10 dB threshold from its maximum.

3 Experimental Evaluation of UWB-IR Antenna Links

3.1 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 [2] and common frequency band available among 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 [3]. In this paper, the root raised cosine passband waveforms is used as the transmitted waveform.

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

$$V_{\mathrm{t,ro}}(f) \quad = \quad \begin{cases} 1 & ||f| - f_c| \leq \frac{(1-\beta)}{2T} \\ A & \frac{(1-\beta)}{2T} < ||f| - f_c| \leq \frac{1+\beta}{2T} \\ 0 & \text{otherwise} \end{cases} , \tag{12}$$

where

$$A \quad = \quad \sqrt{\frac{1}{2}\left[\ 1 + \cos\left(\tfrac{\pi T}{\beta}\left[||f| - f_{\mathrm{c}}| - \tfrac{1-\beta}{2T}\right]\right)\ \right]},$$

$T = 1/f_{\mathrm{b}}$ is the reciprocal of the symbol-rate and f_{b} is the spectral bandwidth, f_{c} is the center frequency, $\beta = 0.3$ 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 GHz. For satisfying the common frequency band spectral mask, f_{c} and f_{b} are set to 7.877 and 0.975 GHz, respectively.

3.2 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 3 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.

4 Results and Discussion

4.1 Biconical Antenna

First, the same biconical antennas were used both at Tx and Rx sides. The channel transfer function of biconical–biconical link was measured and evaluated as function of the antenna pointing angle in the E-plane with rotation of both antennas. Figure 1 shows the phase distortions in FCC frequency band compared with that in common frequency band. The biconical antenna has low phase distortion. The phase distortion in common frequency band is clearly less than that in FCC frequency band. The phase of the waveforms satisfying each spectral mask is considered.

4.2 Log-Periodic Dipole Antenna

A log-periodic dipole antenna (LPDA) is also used at broadband. It also has a frequency-independent gain. Different from the biconical antennas, however, the dispersion characteristic of the LPDA is rather big, since the phase center changes with frequency due to the resonance of the dipole elements [4]. The antenna has been designed to operate in the range of 1 to 12.4 GHz.

The channel transfer function of LPDA–LPDA link was measured and evaluated as function of the antenna pointing angle in the E-plane with rotation of both antennas. Figure 2 shows the phase distortions in FCC frequency band compared with that in common frequency band. Similarly, the phase distortion in common frequency band is less than that in FCC frequency band. The phase distortion of LPDA is higher than that of biconical antenna. As is known, an LPDA is uni-directional and its gain is higher than that of a biconical antenna. As the phase distortion in FCC frequency band is higher than that in common frequency band.

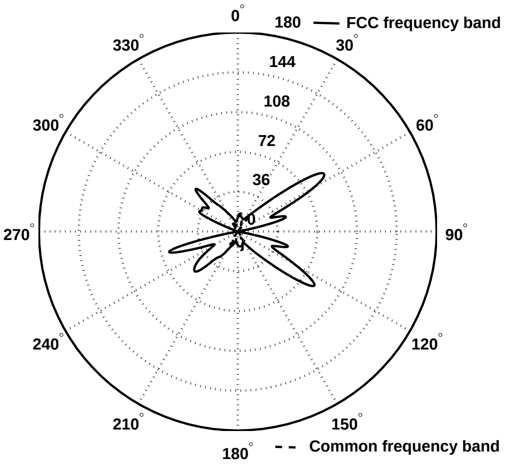

Figure 1: Phase distortion in FCC frequency band compared with that in common frequency band for biconical–biconical link.

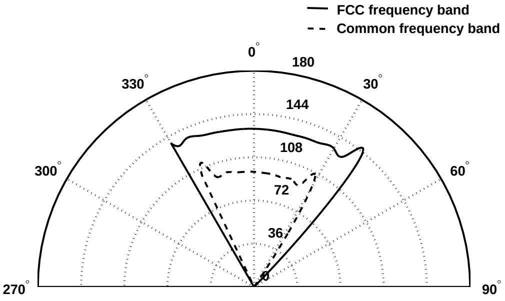

Figure 2: Phase distortion in FCC frequency band compared with that in common frequency band for LPDA–LPDA link.

From these results, the phase distortion in UWB-IR, using both the received signal and the isotropic template waveforms, gives us the quantitative measurement of the link budget. Another issue is the distortion due to the antennas. It is obvious that although LPDA antenna has higher phase, the distortion due to the LPDA antenna is more than that due to the biconical antenna. Due to the higher spectral bandwidth, the phase distortion satisfying FCC spectral mask are more than that satisfying common frequency band spectral mask.

5 Conclusion

This paper has presented how to evaluate the phase distortion of UWB-IR transmission, which includes the transmit waveform, the antennas, the free space propagation, and the correlation receiver. By using the proposed definition, we have evaluated two types of the broadband antennas. This approach can be easily extended to the multipath environment as well. There are two key issues: One is the focus of this paper, i.e. the antenna transfer function is angular-dependent. The other one is that the propagation channel is also angular dependent at both Tx and Rx. By considering the rectangular frequency spectrum, the frequency independent isotropic antenna and the received signal template.

References

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