Evaluation of Ultra Wideband Waveform Distortion with Trapezoidal Antenna

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ABSTRACT

In this paper, the distortion of ultra wideband (UWB) waveforms with trapezoidal antenna is evaluated. The rectangular passband, modulated rectangular and modulated Gaussian waveforms, which satisfied the Federal Communications Commission (FCC) definition of UWB signal and FCC spectral masks for the indoor and outdoor limits, are considered. The frequency transfer function of trapezoidal antenna is obtained by using measurement scheme. The distortion is evaluated by using the correlation coefficient. The correlation coefficients of the radiated and transmitted waveforms compared with the transmitted waveform at the specific angles are illustrated. From the results, we can see the distortion effect of each waveform caused by trapezoidal antenna along the specific angle.

Keywords: Ultra wideband (UWB) communications, trapezoidal antenna, distortion analysis.

1. INTRODUCTION

Recently, ultra wideband (UWB) radio technology has become an important topic for microwave communication because its potential is low cost and low power consumption properties [1]-[5]. UWB is different from other radio frequency (RF) technologies. Instead of using a narrow carrier frequency, UWB transmits pulses of power spectral density (PSD) in the range of the ultra wide frequency spectrum. The Federal Communications Commission (FCC) [6] in US specified that UWB signals have a frequency spectrum ranging from 3.1 to 10.6 GHz. The FCC defined the UWB signal as those, which have a fractional bandwidth greater than or equal to 500 MHz. The fractional and occupied bandwidth are defined as

\[
\text{Fractional bandwidth} = \frac{f_H + f_L}{f_H - f_L},
\]

\[
\text{Occupied bandwidth} = f_H - f_L,
\]

where \( f_L \) and \( f_H \) are the lower and upper frequencies, respectively.

The power spectral density (PSD) of the UWB signal is considered to be noise for other communication systems because its power spectrum is below the part 15 noise limit. The modulation design is used to get the maximum signal power to the UWB receiver, while satisfying the FCC mask on the PSD of UWB signal. The UWB receiver collects the power of the received signal to rebuild the pulse. Therefore, UWB radio technology can coexist with other RF technologies without interference [7]. Moreover, UWB radio technology is an ideal candidate that can be utilized for commercial, short-range, low power, low cost indoor communication systems such as wireless personal area networks (WPANs) [8].

Antenna is an important part of the UWB radio technology, for the reason that the conventional antennas are designed at only single frequency for using in general narrow band systems. If the impulse is excited do these antennas, the pulse will strongly distort and has time dispersion. For the UWB communication, the distortion between two waveforms is considered in the time domain by using the correlation coefficient. The correlation coefficient is equal to 1 when the waveforms are identical and is decreased when the waveform is more distorted from another. The trapezoidal antenna is developed for the UWB antenna [9]-[11]. Although this antenna has low voltage standing wave ratio (VSWR) in frequency range from 3.1 to 10.6 GHz, it dose not necessarily appropriate for UWB communication. The antenna can cause the strong distortion of UWB waveform. The effects of distortion caused by trapezoidal antenna are analyzed [12]. The modulated Gaussian waveform is used to study the distortion. But this waveform is not satisfied the FCC definition of UWB signal and FCC spectral masks for the indoor and outdoor limits and only modulated Gaussian waveform is considered.

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Gaussian waveforms, which satisfied FCC definition of UWB signal and FCC spectral masks for the indoor and outdoor limits [13], are considered. The frequency transfer function of trapezoidal antenna at the specific angles is obtained by using measurement scheme that proposed in [14]-[17]. The distortion is evaluated by using the correlation coefficient. The correlation coefficients of the radiated and transmitted waveforms compared with the transmitted waveform at the specific angles are illustrated. From the results, we can see the distortion effect of each waveform caused by trapezoidal antenna along the specific angle.

The rest of this paper is organized as follows. Section 2 and 3, the UWB waveforms and measurement scheme are briefly explained. Next, the distortion evaluation results are discussed in Sec. 4. The distortion evaluation results are illustrated in Sec. 5. Finally, conclusions are discussed in Sec. 6.

2. UWB WAVEFORMS

For the UWB waveforms, the rectangular passband, modulated rectangular and modulated Gaussian waveforms are considered as the transmitted waveform $v_t$ in time domain and its spectral density $V_t$ in frequency domain. These waveforms can satisfy the FCC definition of UWB signal and FCC spectral masks for the indoor and outdoor limits. The parameters obtained from maximum bandwidth, amplitude and average power optimizations, which proposed in [13], are used.

2.1 Rectangular Passband Waveform

The rectangular passband transmitted waveform in time domain and its spectral density function are given by

$$v_t(t) = \frac{A}{f_b} [f_H \text{sinc}(2f_H t) - f_L \text{sinc}(2f_L t)], \quad (3)$$

$$V_t(f) = \begin{cases} \frac{A}{2\pi f_b} & |f| - f_c \leq \frac{f_b}{2} \\\n 0 & |f| - f_c > \frac{f_b}{2} \end{cases}, \quad (4)$$

where $A$ is the maximum amplitude, $f_b$ is the occupied bandwidth, $f_c$ is the center frequency, $f_L = f_c - f_b/2$ and $f_H = f_c + f_b/2$ are the minimum and maximum frequencies.

This waveform has the $A/2f_b$ constant magnitude of spectral density in the $-f_H$ to $-f_L$ and $f_L$ to $f_H$ frequency ranges. The area of its spectral density is $\int_{-\infty}^{\infty} V_t(f) df = A$, then this waveform has $A$ maximum amplitude at $t = 0$. This is the ideal case of the UWB waveform then it used to consider the upper limit of the maximum bandwidth, amplitude and power for the UWB waveform.

2.2 Modulated Rectangular Waveform

The modulated rectangular transmitted waveform in time domain and its spectral density function are given by

$$v_t(t) = \begin{cases} A \sin(2\pi f_c t)/|t| \leq \frac{f_b}{2} \\
 0 & |t| > \frac{f_b}{2} \end{cases}, \quad (5)$$

$$V_t(f) = \frac{A f_b}{\sqrt{2}} \left\{ \text{sinc} [t_b (f - f_c)] - \text{sinc} [t_b (f + f_c)] \right\}, \quad (6)$$

where $A$ is the maximum amplitude, $f_c$ is the carrier frequency and $t_b$ is the pulse width of the waveform.

This waveform is modulated between the $A$ constant amplitude and $t_b$ width rectangular pulse and $f_c$ carrier frequency sine function. The sine function is used for reducing the direct current (DC) component of the modulated waveform to zero.

2.3 Modulated Gaussian Waveform

The modulated Gaussian transmitted waveform in time domain and its spectral density function are given by

$$v_t(t) = Ae^{-(t/d)^2} \sin(2\pi f_c t), \quad (7)$$

$$V_t(f) = \frac{Ad\sqrt{\pi}}{f_b} \left[ e^{-\pi d^2 (f-f_c)^2} - e^{-\pi d^2 (f+f_c)^2} \right], \quad (8)$$

where $A$ is the maximum amplitude of the envelope waveform, $f_c$ is the carrier frequency and $d$ is the $1/e$ characteristic decay time.

This waveform is modulated between the $A$ maximum amplitude and $d$ $1/e$ characteristic decay time Gaussian pulse and $f_c$ carrier frequency sine function. The sine function is used for reducing the direct current (DC) component of the modulated waveform to zero same the modulated rectangular waveform.

3. MEASUREMENT SCHEME

A trapezoidal antenna with a L-shaped ground plane is developed for the UWB antenna [9]-[11]. The structure and dimensions of the antenna is shown in Fig. 1. The element shape is similar to that of a bow tie antenna, but the L-shaped ground plane is parallel to the trapezoidal element to achieve directional characteristics.

The frequency transfer function of UWB channel was measurement as $S_{21}$ in frequency domain by using 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. The calibration of VNA was done at the connector of the cables to be connected to the antennas. Therefore, all the impairments of the antenna characteristics are included in the measurement results. The frequency transfer function of trapezoidal antenna at
each specific directions is obtained by using measurement scheme that proposed in [14]-[17]. The orientation of the trapezoidal antenna is shown in Fig. 2.

For the received signal, the extension of Friis’ transmission formula in the complex form is applied to considered the free space channel [14]. The Tx and Rx antennas are assumed to be identical. Therefore, the spectral density of the received waveform \( V_{rc} \) can be written as

\[
V_{rc}(f) = V_{rd}(f) \cdot H_f(f) \cdot H_a(f),
\]

where \( H_f \) is the frequency transfer function of free space channel which defined as

\[
H_f(f) = \frac{c}{4\pi fd} e^{-j2\pi fd/c}.
\]

The received waveform \( v_{rc} \) is calculated by using the inverse Fourier transform of its spectral density, which is

\[
v_{rc}(t) = \int_{-\infty}^{\infty} V_{rc}(f) e^{j2\pi ft} df.
\]

The distortion of UWB waveforms is evaluated by using the correlation coefficient. The correlation coefficients of the radiated and received waveforms compared with the transmitted waveform, \( c_{rd,t} \) and \( c_{rc,t} \), are respectively defined as

\[
c_{rd,t} = \frac{\max|\int_{-\infty}^{\infty} V_{rd}^*(t) \cdot v_t(t + \tau) dt|}{\sqrt{\int_{-\infty}^{\infty} |v_{rd}(t)|^2 dt \cdot \int_{-\infty}^{\infty} |v_t(t)|^2 dt}},
\]

\[
c_{rc,t} = \frac{\max|\int_{-\infty}^{\infty} V_{rc}^*(t) \cdot v_t(t + \tau) dt|}{\sqrt{\int_{-\infty}^{\infty} |v_{rc}(t)|^2 dt \cdot \int_{-\infty}^{\infty} |v_t(t)|^2 dt}}.
\]

The correlation coefficient is equal to 1 when the waveforms are identical and is decreased when the waveform is more distorted from another.

5. EVALUATION RESULTS

In this paper, the distortion of UWB waveforms with trapezoidal antenna is evaluated by using the correlation coefficient. The correlation coefficients of the radiated and received waveforms compared with the transmitted waveforms, which are the rectangular passband, modulated rectangular and modulated Gaussian waveforms, are evaluated along the specific angles. The parameters of each waveform, which obtained from the maximum bandwidth, amplitude and average power optimizations satisfied the FCC spectral masks for indoor and outdoor limits [13], are used. The distortion of the waveform dose not depends on the waveform amplitude. Therefore, the amplitude of each waveform is set to be 1 V. The parameters of rectangular passband waveform obtained from maximum bandwidth, amplitude and average power are the same for both indoor and outdoor limits. The results are \( f_L = 3.1\,GHz \), \( f_H = 10.6\,GHz \), \( f_b \) and \( f_c = 6.85\,GHz \). The parameters of modulated rectangular and modulated Gaussian waveforms are listed in Table 1 and 2, respectively.
Table 1: Parameters of modulated rectangular waveform.

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Indoor limit</th>
<th>Parameter</th>
</tr>
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<tbody>
<tr>
<td>Maximum bandwidth</td>
<td>( t_b = 0.21 \text{ ns}, f_c = 6.62 \text{ GHz} )</td>
<td></td>
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<tr>
<td>Maximum amplitude</td>
<td>( t_b = 0.22 \text{ ns}, f_c = 6.58 \text{ GHz} )</td>
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<tr>
<td>Average power</td>
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<td>Outdoor limit</td>
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<tr>
<td>Maximum bandwidth</td>
<td>( t_b = 0.21 \text{ ns}, f_c = 6.62 \text{ GHz} )</td>
<td></td>
</tr>
<tr>
<td>Maximum amplitude</td>
<td>( t_b = 0.22 \text{ ns}, f_c = 6.46 \text{ GHz} )</td>
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<tr>
<td>Average power</td>
<td>( t_b = 0.96 \text{ ns}, f_c = 6.72 \text{ GHz} )</td>
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Table 2: Parameters of modulated Gaussian waveform.

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Indoor limit</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum bandwidth</td>
<td>( d = 0.10 \text{ ns}, f_c = 6.85 \text{ GHz} )</td>
<td></td>
</tr>
<tr>
<td>Maximum amplitude</td>
<td>( d = 0.11 \text{ ns}, f_c = 7.34 \text{ GHz} )</td>
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<tr>
<td>Average power</td>
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<tr>
<td>Outdoor limit</td>
<td></td>
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<tr>
<td>Maximum bandwidth</td>
<td>( d = 0.10 \text{ ns}, f_c = 6.85 \text{ GHz} )</td>
<td></td>
</tr>
<tr>
<td>Maximum amplitude</td>
<td>( d = 0.13 \text{ ns}, f_c = 6.85 \text{ GHz} )</td>
<td></td>
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<tr>
<td>Average power</td>
<td></td>
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</table>

5.1 Distortion of Radiated Waveform

The correlation coefficients of the radiated waveforms with the Tx trapezoidal antenna compared with the transmitted waveforms are evaluated. The rectangular passband, modulated rectangular and modulated Gaussian waveforms are considered as the transmitted waveform.

5.1.1 Rectangular Passband Waveform

For the indoor and outdoor limits, the parameters obtained from the maximum bandwidth, amplitude and average power optimizations are the same. Figure 3 shows the correlation coefficients of radiated waveform, which is the rectangular passband waveform, along the specific angles for the indoor and outdoor FCC spectral masks. The maximum and minimum correlation coefficients are 0.88 and 0.47 at 51.3° and 166.5° angles, respectively. The mean of correlation coefficient is 0.71.

5.1.2 Modulated Rectangular Waveform

For the indoor limit, the parameters obtained from the maximum amplitude and average power optimizations are the same. The correlation coefficients of radiated waveform, which is the modulated rectangular waveform, along the specific angles are shown in Fig. 4. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.90 and 0.47 at 335.2° and 296.4° angles, respectively. The mean of correlation coefficient is 0.71. For the maximum amplitude and average power optimizations, the maximum and minimum correlation coefficients are 0.91 and 0.48 at 328.8° and 205.7° angles, respectively. The mean of correlation coefficient is 0.72.

For the outdoor limit, the correlation coefficients of the radiated waveform, which is the modulated rectangular waveform, along the specific angles are shown in Fig. 5. The correlation coefficients obtained from maximum bandwidth and amplitude optimizations are almost the same and less than that obtained from maximum average power optimization at almost all specific angle. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.90 and 0.47 at 335.2° and 296.4° angles, respectively. The mean of correlation coefficient is 0.71. For the maximum amplitude optimization, the maximum and minimum correlation coefficients are 0.91 and 0.49 at 328.8° and 205.8° angles, respectively. The mean of correlation coefficient is 0.72. For the maximum average power optimization, the maximum and minimum correlation coefficients are 0.98
and 0.47 at 328.2° and 190.6° angles, respectively. The mean of correlation coefficient is 0.84.

5.1.3 Modulated Gaussian Waveform

For the indoor limit, the parameters obtained from the maximum amplitude and average power optimizations are the same. The correlation coefficients of the radiated waveform, which is the modulated Gaussian waveform along the specific angles, are shown in Fig. 6. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.94 and 0.51 at 328.8° and 205.3° angles, respectively. The mean of correlation coefficient is 0.74. For the maximum amplitude and average power optimizations, the maximum and minimum correlation coefficients are 0.95 and 0.47 at 15.0° and 205.5° angles, respectively. The mean of correlation coefficient is 0.75.

For the outdoor limit, the parameters obtained from the maximum amplitude and average power optimizations are the same. The correlation coefficients of the radiated waveform, which is the modulated rectangular waveform along the specific angles are shown in Fig. 7. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.94 and 0.51 at 328.8° and 205.3° angles, respectively. The mean of correlation coefficient is 0.74. For the maximum amplitude and average power optimizations, the maximum and minimum correlation coefficients are 0.97 and 0.52 at 328.5° and 205.1° angles, respectively. The mean of correlation coefficient is 0.78.

5.2 Distortion of Received Waveform

The correlation coefficients of the received waveforms with the Tx and Rx trapezoidal antennas compared with the transmitted waveforms are evaluated. The rectangular passband, modulated rectangular and modulated Gaussian waveforms are considered as the transmitted waveform in the same way as Sec. 5.1.

5.2.1 Rectangular Passband Waveform

Figure 8 shows the correlation coefficients of the received waveform, which is the rectangular passband waveform, along the specific angles for the indoor and outdoor FCC spectral masks. The maximum and
minimum correlation coefficients are 0.82 and 0.32 at 346.0° and 151.9° angles, respectively. The mean of correlation coefficient is 0.56.

Fig. 8: Correlation coefficients of the received waveform, which is the rectangular passband waveform, along the specific angles for the indoor and outdoor FCC spectral masks.

5.2.2 Modulated Rectangular Waveform

For the indoor limit, the correlation coefficients of the received waveform, which is the modulated rectangular waveform, along the specific angles are shown in Fig. 9. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.83 and 0.28 at 25.2° and 150.7° angles, respectively. The mean of correlation coefficient is 0.55. For the maximum amplitude and average power optimizations, the maximum and minimum correlation coefficients are 0.84 and 0.29 at 25.2° and 150.6° angles, respectively. The mean of correlation coefficient is 0.56.

For the outdoor limit, the correlation coefficients of the received waveform, which is the modulated rectangular waveform, along the specific angles are shown in Fig. 10. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.83 and 0.28 at 25.2° and 150.7° angles, respectively. The mean of correlation coefficient is 0.55. For the maximum amplitude optimization, the maximum and minimum correlation coefficients are 0.84 and 0.29 at 25.2° and 150.6° angles, respectively. The mean of correlation coefficient is 0.56.

Fig. 9: Correlation coefficients of the received waveform, which is the modulated rectangular waveform, along the specific angles for the indoor FCC spectral mask.

5.2.3 Modulated Gaussian Waveform

For the indoor limit, the correlation coefficients of the received waveform, which is the modulated Gaussian waveform, along the specific angles are shown in Fig. 11. For the maximum bandwidth optimization, the maximum and minimum correlation coefficients are 0.87 and 0.28 at 25.2° and 150.6° angles, respectively. The mean of correlation coefficient is 0.59. For the maximum amplitude optimization, the maximum and minimum correlation coefficients are 0.89 and 0.31 at 24.9° and 291.4° angles, respectively. The mean of correlation coefficient is 0.57.

For the outdoor limit, the correlation coefficients of the received waveform, which is the modulated rectangular waveform, along the specific angles are shown in Fig. 12. For the maximum bandwidth optimization, the maximum and minimum correlation coeffi-
Fig. 11: Correlation coefficients of the received waveform, which is the modulated Gaussian waveform, along the specific angles for the indoor FCC spectral mask.

Fig. 12: Correlation coefficients of the received waveform, which is the modulated Gaussian waveform, along the specific angles for the outdoor FCC spectral mask.

6. CONCLUSIONS

In this paper, the distortion of UWB waveforms with trapezoidal antenna is evaluated. The rectangular passband, modulated rectangular and modulated Gaussian waveforms, which satisfied the FCC definition of UWB signal and FCC spectral masks for the indoor and outdoor limits, are considered. From the results, we can see the distortion characteristic of each UWB waveform along the specific angle of trapezoidal antenna. Averagely, the wide bandwidth waveform trends to have more distortion. Therefore, the waveform obtain from the maximum bandwidth optimization has the distortion more than that obtained from the maximum amplitude and average power optimizations. The modulated Gaussian waveform has lowest distortion and the modulated rectangular waveform has the distortion less than the rectangular passband waveform. The correlation coefficient of the radiated waveform is about 0.74, while that of the received waveform is about 0.58.

References

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