NOTE ON ANTENNA DESIGN IN UWB WIRELESS COMMUNICATION SYSTEMS

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Abstract

Requirements for the antennas in wireless communication systems are presented, from a systems point of view. Differences between narrowband and ultra-wideband systems in assessing system performance are discussed. Several parameters are introduced for the antennas in ultra-wideband wireless communication systems, to evaluate the performance of antennas based on the system requirements. As an example, a transmitting/receiving antenna system comprising two identical planar bow-tie antennas is analyzed numerically and experimentally in both time and frequency domains. By the introduced parameters, the effects of source and template pulses on the performance of the antenna system are also investigated.

1 INTRODUCTION

Ultra-wideband (UWB) radio has a long history from the 1960s, in radar and communication applications [1], but mostly for military purpose. To permit the marketing and operation of new products that incorporate UWB technology, Federal Communications Commission (FCC), USA amended the Part 15 of its rules [2] on February 14, 2002. The revised order specifies different technical standards and operation restrictions for three types of UWB products, namely imaging systems, vehicular radar systems, and communication & measurement systems. Among them only wireless communication systems are of concern in this paper. UWB antenna shares the same history with UWB radio since it is an indispensable component in UWB systems.

Traditional antenna parameters are suitable for narrowband applications, but inconvenient for ultra-wideband systems. In 1993, Allen proposed many time-domain antenna parameters to describe the antennas transmitting or receiving short pulses [3]. However, because of some special considerations for the design of antennas in UWB wireless communication systems, some of those parameters cannot be used directly.

In this paper, requirements for antennas are presented from a communication systems point of view, and several useful parameters are introduced to assess the performance of antennas for UWB wireless communication systems. Focusing on these requirements, a transmitting/receiving antenna system comprising two identical bow-tie antennas, which feature broad impedance bandwidths [4][5], is studied experimentally and numerically in both time domain (TD) and frequency domain (FD). Particularly, the effects of source and template pulses on the performance of the whole system are explored.

2 SYSTEM REQUIREMENTS & ANTENNA PARAMETERS

From a systems point of view, there are at least four typical requirements anticipated for antennas in wireless communication systems, regardless of narrowband or ultra-wideband.

1. High efficiency
2. Acceptable emission levels in free space to comply with regulator's limits
3. Detectable signals at a receiver
4. Specified radiation pattern depending on applications

In narrowband systems, traditional antenna parameters such as gain, impedance matching, and polarization are enough to assess the performance of an antenna. Therefore, antenna engineers are ready to start their design with the specification of these parameters. But, in the world of UWB radio, the situation is complicated and these antenna parameters are inadequate to fully describe an antenna. Therefore, additional parameters should be introduced to guide antenna engineers engaging in UWB wireless communication systems.

First, efficiency is a vital parameter, especially for mobile devices whose power supply is limited. Taking the transmitting mode as an example, the radiation efficiency of an antenna in narrowband systems is obtained by Eq. 1, where $|\mathrm{S}_{11}|$ is the return loss at a carrier frequency. This equation assumes a constant $|\mathrm{S}_{11}|$ over the band of signal, which is obviously not valid for UWB systems. If the exciting power $P_{inc}(f)$ and $|\mathrm{S}_{11}(f)|$ are frequency dependent, the formula ought to be rewritten as Eq. 2, where the efficiency depends on not only the antenna parameter $|\mathrm{S}_{11}(f)|$ but also the spectrum of a source pulse. To raise the system efficiency, good impedance matching over the band of a source pulse is expected. In the receiving mode, Eq. 2 can also be used to evaluate the antenna efficiency because of the reciprocity theorem.

$$\eta_{nb\_trans} = (1 - |\mathrm{S}_{11}|^2) \tag{1}$$

$$\eta_{uwb\_trans} = \frac{\int_0^\infty P_{inc}(f)(1 - |\mathrm{S}_{11}(f)|^2)df}{\int_0^\infty P_{inc}(f)df} \tag{2}$$

Secondly, as a compulsory requirement, the emission level in free space must meet emission limits, to coexist with other radio systems. In narrowband systems, this requirement can easily be obtained by controlling the transmitted power. But in UWB systems, the emitted power spreads over a wide spectrum. Therefore, not only the transmitted power but also the shape of radiated spectrum have to be controlled. Antenna engineers must make sure that the resultant emission levels meet regulator's limits at every frequency, but not only the central frequency. From the theory of linear, time-invariant (LTI) system, which all passive antennas comply with, the spectrum of a radiated pulse can be obtained by multiplying the spectrum of a source pulse by a system function in frequency domain in Eq. 3, where $H(f, \theta, \phi)$ is a system function independent of source pulse. Herein, the source pulse plays an equally important role, if not more important, to a transmit antenna in shaping emission spectra.

$$P_{radia}(f, \theta, \phi) = H(f, \theta, \phi)P_{inc}(f) \tag{3}$$

Thirdly, the scheme of pulse detection in UWB systems is different from that in narrowband systems. In an additive white Gaussian noise (AWGN) channel, the detection of received pulses is not a problem for narrowband systems if the signal noise ratio (SNR) is large enough. With the help of a local oscillator (LO) in a coherent detection scheme or an envelope detector in a non-coherent detection scheme, modulated signals can easily be detected in narrowband systems because there is a carrier. In contrast, the absence of carrier in UWB single-band systems makes the pulse detection operate in a different way. As UWB systems operate at noise level, they experience serious interference and therefore non-coherent detection is not appropriate. Furthermore, since there is no carrier, an alternate template pulse should be adopted rather than a continuous sinusoidal waveform. A parameter called fidelity is defined in Eq. 4 to assess the capability of a coherent receiver to detect modulated signals, where $a(t, \theta, \phi)$ and $b(t)$ are the waveforms of received pulses and template pulses, respectively. Actually, for the signals without DC portion as discussed here, the fidelity varies in the range of 0 to 1. A large fidelity results in easy detection at a receiver, if the symbols are synchronized.

$$F(\theta, \phi) = \left| \frac{\int_0^\infty a(t, \theta, \phi)b(t)dt}{\sqrt{\int_0^\infty a^2(t, \theta, \phi)dt}\sqrt{\int_0^\infty b^2(t)dt}} \right| \tag{4}$$

Lastly, radiation pattern is another important specification for the antenna design. In narrowband systems, the pattern is simply for power. With enough radiated power along desired directions, the modulated signals can be successfully detected by an appropriately designed receiver. However in UWB systems, satisfactory power patterns alone are not enough to describe an antenna. A high radiated power along a specific direction does not always result in successful detection, for example, in the cases where fidelities are low. In UWB systems, an antenna works as a spatial filter such that the system function $H(f, \theta, \phi)$ in Eq. 3 varies with the radiation angle, in both magnitude and phase, leading to different waveforms of both radiated and received pulses. With a fixed template at a receiver, the fidelity may vary greatly along different directions. Therefore, there is a need to introduce a pattern for the fidelity to assess the detection of received pulses along different directions. Only if both the radiated power and the fidelity are large enough, the received pulse could be detected. By calculating the fidelities in Eq. 4 along all directions, the fidelity pattern can be obtained. The power pattern can be obtained by calculating the average power of received pulse along all directions from Eq. 5, where T is the time duration of received pulses.

$$P_{receiv}(\theta, \phi) = \frac{1}{T}\int_0^T a^2(t, \theta, \phi)dt \tag{5}$$

3 EVALUATION OF ANTENNA SYSTEM

As an example, a wideband planar antenna system is analyzed by calculating the parameters defined above, to evaluate its performance in UWB wireless communication systems.

3.1 Antenna system

Consider two identical bow-tie antennas forming a transmitting/receiving antenna system as shown in Fig. 1. The antennas are isosceles triangle planars with a 9-mm height and a 8-mm-long top side. They are vertically and face-to-face installed above a 300 × 200-mm ground plane, 196mm away from each other, and connected to two probes of 1.2-mm diameter. The transmit antenna at point A is driven by a monocycle pulse in the form of Eq. 6, whose duration is approximately 5σ. The output pulse at the receive antenna located at point B ($\theta = 90°$, $\phi = 90°$, $r = 196$mm) is $p_o(t)$.

$$p_s(t) = te^{-(\frac{t}{\sigma})^2} \tag{6}$$

With an EM software package (XFDTD) and a network analyzer (HP8510), the antenna system is investigated experimentally and numerically in both FD and TD. In FD, the simulated and measured S-parameters are plotted in Fig. 2, where the $|S_{11}|$ shows good impedance matching from 5 to 8.5GHz. The $|S_{21}|$ varies from -40 to -30dB over the range of 4 to 16GHz and reaches the peak at 6GHz. In TD, the measured and simulated output pulses of the receive antenna are compared in Fig. 3, where the σ of the source monocycle is 50ps. The measured pulse is not obtained directly from time domain measurements, but calculated numerically from the measurement results of FD by IFFT (Inverse Fast Fourier Transform). The noticeable ringing appearing at the end of the measured pulse is due to the reflections at the edges of the finite ground plane used in the measurement set-up. However, there is no such ringing in the simulated results because two equivalent dipoles are chosen in the simulation model. The good agreement between the measured and simulated results in both TD and FD verifies the validity of the model in the simulation.

3.2 Radiation efficiency

Fig. 4 plots the radiation efficiency using Eq. 2, with respect to the different source pulses in the form of Eq. 6 where σ increases from 30 to 70ps. With increasing σ, more energy in the source pulse concentrates in the low frequency band, where the impedance matching is poor, resulting in low radiation efficiency. However, this does not mean that smaller σ leads to better system performance because only is radiation efficiency discussed here. If other performances are considered, trade-off between the efficiency and other parameters ought to be made.

3.3 Emission spectra

Besides radiation efficiency, emission limits pose another restriction to the UWB antenna design. Fig. 5 plots the simulated emission spectra along $\theta = 90°$, $\phi = 90°$ direction for three different source pulses with σ=30, 50 and 70ps. The results are obtained by Eq. 3. In the band of 3.1-10.6GHz, only the case of σ=50ps meets FCC's indoor mask. To suppress the undesired radiation in the band of 0.96-1.61GHz in Fig. 5, a high-pass filter may be used, or an alternate source pulse with low energy in the band of 0.96-1.61GHz could be adopted instead of the monocycle used here.

3.4 Pulse detection

Two different waveforms, truncated sinusoidal signal and higher order Gaussian series, are chosen as template candidates to capture the energy of received pulses. Fig. 6 illustrates the waveform of a received pulse synchronized by two template pulses. The σ of the source pulse is 50ps. The template of Gaussian series $b(t)$ has the form of Eq. 7, where σ=82.38ps. The template of truncated sinusoidal signal has the frequency of 6.09GHz. For the transmit and receive antennas face-to-face installed as in Fig. 1, the resultant fidelities defined in Eq. 4 are 0.9717 for the template of Gaussian series, and 0.8780 for the template of truncated sinusoidal signal. While the former leads to a higher fidelity, the latter is easier to implement and its fidelity is also acceptable.

$$b(t) = \frac{d^5}{dt^5} e^{-(\frac{t}{\sigma})^2} \tag{7}$$

3.5 Radiation pattern

With a monocycle of σ=50ps exciting the transmit antenna, the patterns of both power and fidelity are calculated numerically. Fig. 7 plots the power pattern that is normalized to 0dBm. In the plane of $\phi = 90°$, the received power increases from -120 to 0dBm when θ increases from 0° to 90°, while in the plane of $\theta = 90°$, the received power remains nearly constant. If the template pulses mentioned above are adopted, the patterns of fidelity are illustrated in Fig. 8 for $\phi = 90°$, and Fig. 9 for $\theta = 90°$. It can be seen that along any direction of the two planes, the fidelity is greater than 0.86. The antenna system is approximately omnidirectional, since the patterns of both power and fidelity change little along different directions in the plane of $\theta = 90°$.

4 CONCLUSION

This paper has presented the special requirements for the antennas in UWB wireless communication systems. Based on these requirements, several parameters such as the radiation efficiency, emission level, fidelity, power pattern, and fidelity pattern have been introduced to evaluate the performance of antenna systems. As an example, a planar bow-tie antenna system has been analyzed in terms of these parameters. Since these parameters depend on not only transmitting/receiving antennas, but also the source pulse at a transmitter and the template pulse at a receiver, it is necessary to combine the antenna design with the designs of pulse generator and pulse detector.

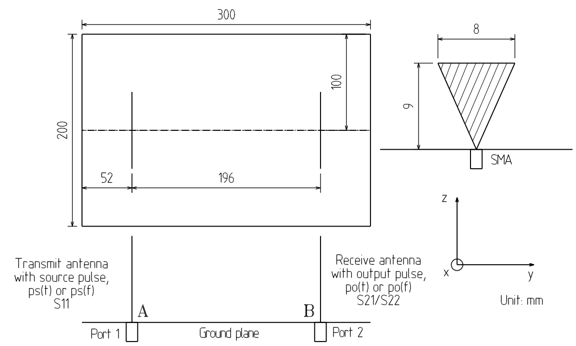

Figure 1: Geometry of UWB antenna system under test

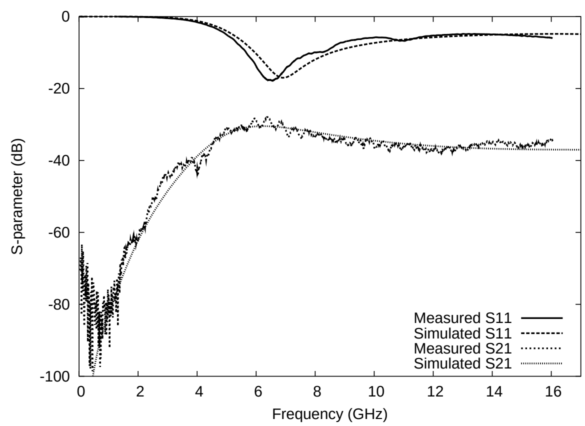

Figure 2: Measured and Simulated S-parameters

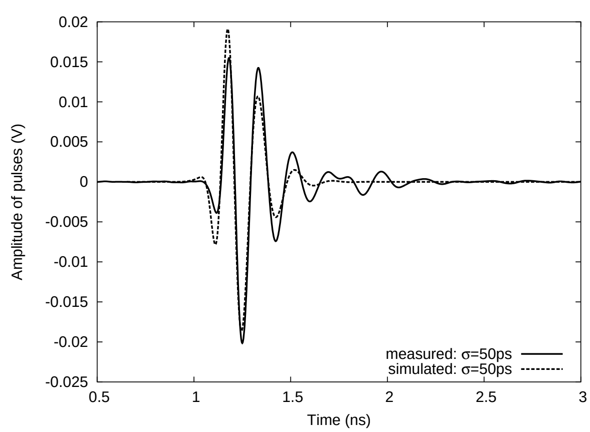

Figure 3: Comparison of measurement and simulation in time domain

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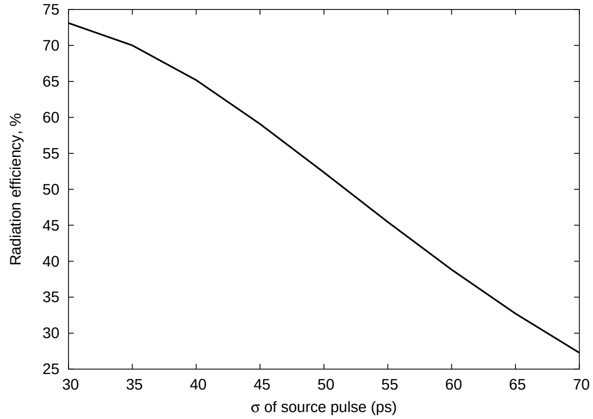

Figure 4: Radiation efficiency with different source pulses

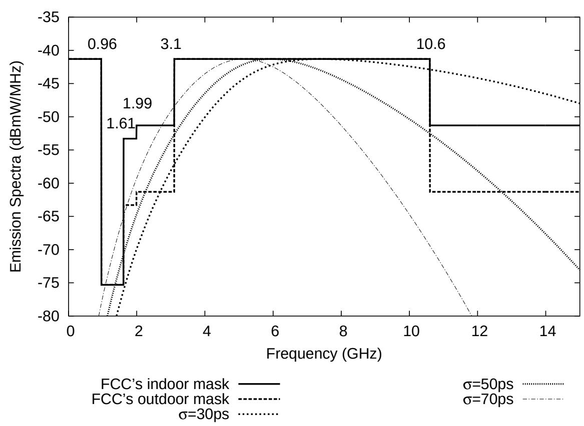

Figure 5: Emission levels in free space

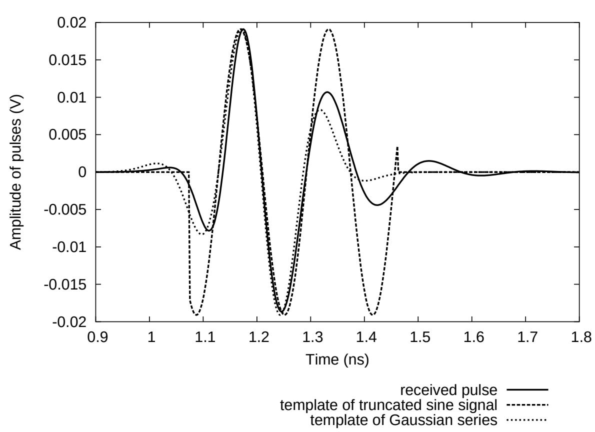

Figure 6: Received pulse with different templates

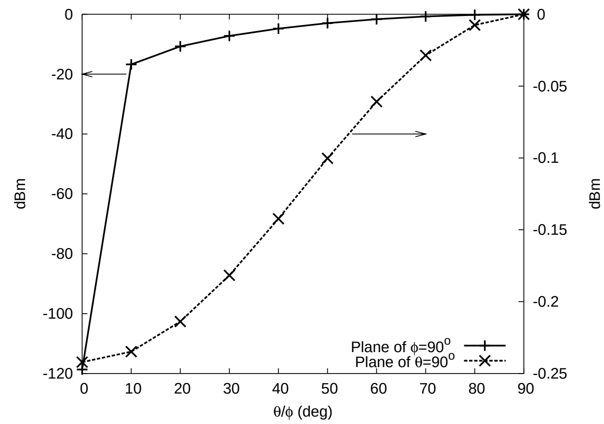

Figure 7: Power pattern

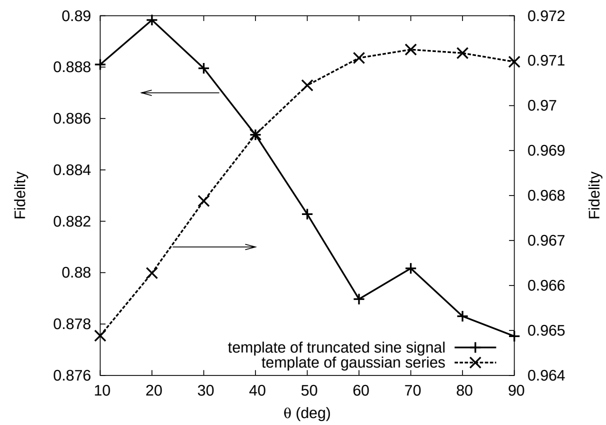

Figure 8: Fidelity pattern in the plane of $\phi = 90^\circ$

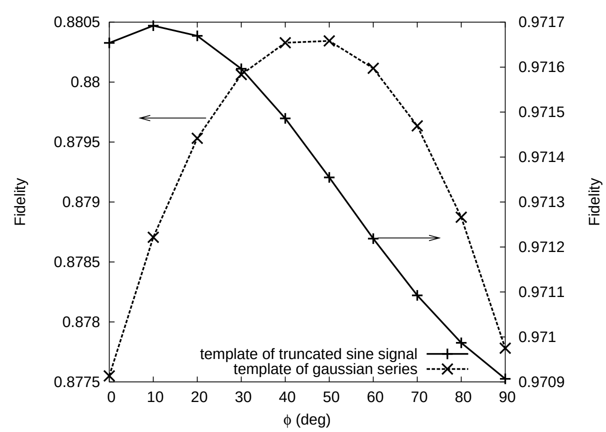

Figure 9: Fidelity pattern in the plane of $\theta = 90^\circ$