Accurate Measurement of the Transfer Function of UWB Antennas

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Abstract Antennas which are used to transmit and receive UWB signals must be able to accomodate its large bandwidth. Moreover, the signals should not be distorted too much when they pass through the antennas. Therefore, the transfer function of antennas should be known for the performance evaluation. Conventionally, the authors measure the transfer function of the antenna by measuring the transmission coefficient between the transmit and the receive antenna, assuming that the transmit and receive antennas are identical. In this presentation, a more accurate three-antenna method is introduced so that the transfer function of each individual antenna can be measured. By using this method, three hand-made biconical antennas are tested. The results show that these three transfer functions are close to each other and that the antenna can be used for UWB.

Key words UWB, antenna, three antenna method, transfer function

1. Introduction

Ultra-wideband (UWB) impulse radio transmission systems have attracted a great deal of attention because of its potential applications on short-range high-speed mobile communications, ultra low-power communications, ultra high-resolution radar, and so on. In order to minimize the interference with existing systems, the UWB is expected to be mainly used in indoor environments such as Wireless Personal Area Network (WPAN) [1], [2].

In UWB communication, the antennas are significantly pulse-shaping filters. Any distortion of the signal in the frequency domain causes the distortion of the transmitting pulse. Consequently this will increase the complexity of the detection mechanism at the receiver [3]. The antenna design for UWB signal radiation is one of the main challenges [4], [5].

Even if the channel is in line of sight (LOS), Friis’ transmission formula cannot be directly applied to the UWB radio as the bandwidth of the pulse is extremely wide. Furthermore, simple comparison between waveforms of transmitter and receiver is not significant because of the distortion of the waveform caused by the frequency response of the antenna.

In the previous reports [6], [7], we simply used two identical antennas to obtain the transfer function of a single antenna. However, this method can not eliminate the individual errors due to the repeatability of the fabrication. In this report, we introduced the three antenna method [8] to eliminate these effects and to get the individual transfer function of each of the antennas accurately. We carried out an experiment using the biconical antenna in the anechoic chamber.
We first show the theoretical formulation, and then show experimental results using the biconical antennas.

2. Model of Antenna in Free Space

Figure 1 is the transmission model when the transmitter and receiver are in the line of sight (LOS). The Friis’ transmission formula can be applied to the calculation of these LOS channels. To investigate the characteristics of an UWB antenna, the free space propagation is considered. The complex form of the Friis’ transmission formula for the frequency transfer function [9], \( H_{\text{Friis}} \), between transmitter and receiver antennas is expressed by using the input voltage \( V_t \) and the output voltage \( V_r \) as

\[
H_{\text{Friis}}(\theta_t, \varphi_t, \theta_r, \varphi_r, f, d) = \frac{V_r(f)}{V_t(f)} = H_t(f, d)H_r(\theta_t, \varphi_t, f)H_s(\theta_r, \varphi_r) \quad (1)
\]

where \( H_t \) is complex frequency transfer function in free space given as

\[
H_t(f, d) = \frac{\lambda}{4\pi d} e^{-jkd} \quad (2)
\]

where \( \lambda \) is the wavelength and \( k \) is the wavenumber, \( H_r \) and \( H_s \) are the complex frequency transfer functions of transmitter and receiver antennas, respectively. \( \theta_t \) and \( \varphi_t \) are elevation and azimuth angles of transmitter antenna in spherical coordinate system, \( \theta_r \) and \( \varphi_r \) are those of receiver antenna, and \( d \) is the separation between transmitter and receiver antennas.

3. Conventional Antenna Measurement

The authors have used two identical antennas to measure the antenna transfer function [6], [7].

Suppose the complex frequency transfer functions of the transmitter and receiver antennas are identical as \( H_s \). By making \( \theta_t = \theta_r = \theta \) and \( \varphi_t = \varphi_r = \varphi \) meter, Eq. (1) can be rewritten as

\[
H_{\text{Friis}}(\theta, \varphi, f, d) = H_t(f, d)H_s^2(\theta, \varphi, f). \quad (3)
\]

The complex frequency transfer function of an antenna at any angle \( H_s(\theta, \varphi, f) \) can be obtained by

\[
H_s(\theta, \varphi, f) = \sqrt{\frac{H_{\text{Friis}}(\theta, \varphi, f, d)}{H_t(f, d)}} \quad (4)
\]

where \( H_{\text{Friis}} \) can be extracted from the measurement of \( S_{21} \) by using vector network analyzer.

The drawbacks of this method are as follows:
- Two identical antennas are needed.
- Error due to the repeatability of the fabrication can not be eliminated.

4. Three-Antenna Method

In this report, we introduce the three-antenna method which has originally been proposed for the measurements of the complex antenna factor [8]. In this methods, three antennas are required for the measurements, but they do not have to be identical to one another. In the three-antenna method, three sets of measurements are performed using all combinations of the three antennas as shown in Fig. 2. The result is a set of three simultaneous equations of the form.

\[
H_1(\theta, \varphi, f)H_t(f, d)H_3(\theta, \varphi, f) = S_{21}(f) \quad (5)
\]

\[
H_2(\theta, \varphi, f)H_t(f, d)H_1(\theta, \varphi, f) = S_{13}(f) \quad (6)
\]

\[
H_3(\theta, \varphi, f)H_t(f, d)H_2(\theta, \varphi, f) = S_{31}(f) \quad (7)
\]

where \( H_t(f) \) is the complex frequency transfer function of antenna \( i \), \( S_{ij} \) is the measurement result by using transmitted antenna \( i \) and received antenna \( j \), \( d \) is the distance between antennas, and \( H_t(f, d) \) is the complex transfer function of free space given in Eq. (2).

Then, we can estimate the complex frequency transfer function of the antennas by using these equations.

\[
H_1(f) = \sqrt{\frac{S_{21}(f)S_{22}(f)}{S_{13}(f)H_t(f, d)}} \quad (8)
\]

\[
H_2(f) = \sqrt{\frac{S_{21}(f)S_{13}(f)}{S_{32}(f)H_t(f, d)}} \quad (9)
\]

\[
H_3(f) = \sqrt{\frac{S_{23}(f)S_{13}(f)}{S_{21}(f)H_t(f, d)}} \quad (10)
\]

— 30 —
5. Experiments

5.1 Instruments Setup

The transfer functions were measured as $S_{21}$ in the frequency domain by using a vector network analyzer (VNA). The VNA was operated in the response measurement mode, where Port-1 was used as the transmitter port (Tx) and Port-2 was used as the receiver port (Rx), respectively. The measurement was done in an anechoic chamber to simulate free space. Both Tx and Rx antennas were fixed at the height of 1.4 m and separated by 1 m. The setup is illustrated in Fig. 3.

We used the three identical antennas for the comparison with the conventional method. Three different angle orientations are considered as shown in Fig. 4. In any case, the antennas are facing toward the same directions to each other so that $H_t = H_r$ is satisfied.

We have chosen the biconical antenna for ease of fabrication, as well as it is often used as the standard antenna for the wideband application. The geometry and dimensions of the antenna and its characteristics are in Ref.[7].

![Figure 3](image1.png) The instruments setup.

![Figure 4](image2.png) Antenna setting.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<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 power range</td>
<td>80 dB</td>
</tr>
<tr>
<td>Tx antenna height</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Rx antenna height</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Distance between Tx and Rx</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Pointing angle</td>
<td>0° / 30° / 60°</td>
</tr>
</tbody>
</table>

Table 1 Experimental setup parameters.

5.2 Parameters of Experiments

The important parameters for the experiments are listed in Table 1.

It is noted that the calibration 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.

5.3 Experiment Results

In this section, the measurement results of conventional two identical antennas are compared with those of the three-antenna method. In the conventional measurement method, antenna 1 is the transmitter antenna and antenna 2 is the receiver antenna. Figures 5, 7, and 9 are the magnitude of the transfer function at pointing angle are 0°, 30°, and 60°, respectively. The phase of the transfer function of each antenna at pointing angles are 0°, 30°, and 60°, are shown in Figs. 6, 8, and 10, respectively.  

![Figure 5](image3.png) Antenna transfer functions at pointing angle is 0°: magnitude.

5.4 Discussion

From these figures, we can see that the results obtained by using the conventional measurement method are the average of antennas 1 and 2 because it is assumed that the transmitter and receiver antennas have the same characteristics. As well, the use of three identical antennas with identical inclined angles, the transfer functions of three antennas look alike.
The magnitude of the antenna transfer function at pointing angle of 0° is large, and is not so much changing with the frequency. As well the phase is linear, and the waveform distortion may be small.

In case of 30°, antenna 3 showed some different results although the reason is unknown.

At the pointing angle of 60°, the deep dip is found in the frequency range from 8 to 11 GHz. In this frequency range, the error due to the noise is very significant for both magnitude and phase. This error may be reduced if we fix two antennas at 0° while only the last one is inclined to 60°. It is almost trivial, but two among three antennas are used as the references in the realistic measurement, and the main beam direction shall be chosen.

Additionally, all of the antenna transfer functions in this report include the phase delay due to the semi-rigid cables connected to the antennas.

6. Conclusion

In this report, we discussed the accurate measurement of the transfer function of UWB antenna. The complex three-antenna method has been deployed for accuracy. Experimen-
tal demonstration using the biconical antennas was shown as measurement examples.

In the three-antenna method, all the antennas are assumed to be purely polarized so that Eq. (1) is expressed by using scalar antenna transfer functions. It is left for the future study to extend this three-antenna method for the polarimetric measurement.

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