UWB Channel Sounding and Channel Characteristics in Rectangular Metal Cavity

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Abstract

This paper first describes channel sounding for Ultra-wideband (UWB) channel in rectangular metal cavity. According to the measurement results, different UWB channel characteristics in such an environment are analyzed and compared with the channel characteristics of other environments such as hallway and office environments. This paper will be helpful in better understanding of UWB channel inside confined metal environment that is related to many commercial and military applications and guide us to design high performance system for wireless communication in such an environment.

1. Introduction

UWB communication has emerged as one of the most promising area in the field of wireless communication recently [1]. The large bandwidth in the unlicensed spectrum is the main advantage of UWB communication. This makes communication immune to frequency selective fading, which means more reliable and efficient communication, since multipath can be resolvable even in the RF harsh environments like a metal cavity.

A large number of UWB channel sounding have been reported for indoor environment [2]-[4], but no reference has systematically reported results for channel sounding in rectangular metal cavity. This paper presents the results of UWB channel sounding in rectangular metal cavity. Communication inside rectangular metal cavity holds a huge importance because it is an emulation of different confined metal environments like intra-ship, intra-vehicle, intra-engine, manufacturing plants, assembly lines, nuclear plants, body area network sensors surrounded by vehicles and tanks, etc. Effective communication has always been a problem in these environments. Narrowband communications cannot be used for these environments because of resonance caused by metal walls. However, UWB with high bandwidth in frequency domain and high resolution in time domain is a competitive communication technology suitable for these environments.

Vector Network Analyzer (VNA), the type of which is two-port Agilent N5230A (300 kHz - 13.5 GHz), is used for channel sounding in rectangular metal cavity. It is highly precise equipment for frequency domain channel sounding. It can be calibrated before measurement to compensate the cable and probe losses. Different channel characteristics are analyzed in this paper such as channel transfer function, channel impulse response, channel energy, spatial focusing, channel reciprocity and channel capacity.

This paper is organized as follows. Section 2 describes the setup and procedure for channel sounding. Section 3 introduces the channel characteristics to be analyzed in rectangular metal cavity. On the basis of channel sounding results channel characteristics are analyzed in Section 4. Finally conclusions are drawn in Section 5.

2. Channel Sounding

The channel sounding is performed using frequency domain technique in rectangular metal cavity. In this technique, a set of narrowband sinusoid signals (tones) are swept through a wide frequency band and each tone has the same power. VNA is operated in transfer function mode where one of its ports serves as transmitting port and the other as receiving port. S-parameters are measured and recorded as the channel transfer function used in this paper. Two-port VNA can measure four individual S-parameters such as $S_{11}$, $S_{12}$, $S_{21}$ and $S_{22}$. The rectangular metal cavity is shown in Figure 1.

![Rectangular metal cavity used for channel sounding.](image)

The size of rectangular metal cavity is 16 feet by 8 feet by 8 feet and the material of it is aluminum. The setup for channel sounding in rectangular metal cavity is shown in Figure 2. The small and compact antennas with wide
bandwidth used in our measurement are omnidirectional.

Figure 2 Setup for channel sounding in rectangular metal cavity.

The channel sounding is performed for single input single output (SISO) in rectangular metal cavity. Table 1 lists the main parameters for channel sounding.

Table 1 Parameters for channel sounding.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Band</td>
<td>3 GHz - 10 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>7 GHz</td>
</tr>
<tr>
<td>Number of Tones</td>
<td>7001</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>10 dBm</td>
</tr>
<tr>
<td>Frequency Step</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Antenna Polarization</td>
<td>vertical</td>
</tr>
<tr>
<td>Averaging Number</td>
<td>128</td>
</tr>
<tr>
<td>Antenna Height</td>
<td>1.35 m</td>
</tr>
</tbody>
</table>

Line of Sight (LOS) case is considered here. The transmitter antenna is fixed, and the receiver antenna is moved along the middle line of rectangular metal cavity. The distance between two antennas is varied from 0.5 m to 4 m in step of 0.5 m.

3. Channel Characteristics

3.1 Frequency and Time Domain Response

The channel transfer function $H(f)$ can be measured by using the setup and procedure described in Section 2. After channel transfer function is recorded, channel impulse response $h(t)$ can be obtained from it according to the following steps. The first step is zero padding between 0 Hz and 3 GHz; the second step is conjugate reflection between $-10$ GHz and 0 Hz and the last step is to do Inverse Fast Fourier Transform (IFFT).

3.2 Channel Energy

Channel energy is an important channel characteristic. Channel energy can represent the signal attenuation between transmitter antenna and receiver antenna in the large scale. The energy of the channel can be calculated as

$$E_h = \int_0^{T_h} \hat{h}(t) \, dt$$

where $T_h$ is the time duration of the channel.

3.3 Spatial Focusing

Time reversal is used to focus energy in space and time domain on the intended user by utilizing a time-reversed complex conjugate of the channel impulse response as the prefilter in the transmitter side [5]. This leads to spatial focusing in which all users other than the intended user will receive signal with much degraded quality [6].

In order to get channel transfer function for analyzing spatial focusing, the distance between transmitter antenna and receiver antenna is fixed at 4 m and the receiver antenna is moved in horizontal line that is perpendicular with the middle line of rectangular metal cavity. There are 18 points for receiver antenna and the gap between each point is 3 cm. We have assumed that first point corresponds to intended user and is denoted as $r_0$ and all other points correspond to unintended users and are denoted as $r_i, i = 1, 2, \ldots, 17$.

Let $h(r_0, t)$ represents the channel impulse response between transmitter and intended user. The autocorrelation for intended user is defined as

$$R_{hh}(r_0, t) = h(r_0, -t) \ast h(r_0, t)$$

Similarly, let $h(r_i, t), i = 1, 2, \ldots, 17$ denotes the channel impulse response between transmitter and unintended user $i$. The crosscorrelation for the unintended user $i$ is defined as

$$R_{ih}(r_0, r_i) = h(r_0, -t) \ast h(r_i, t)$$

The spatial focusing can be characterized by the metric $D(r_0, r_i)$ called directivity, which is defined as

$$D(r_0, r_i) = \frac{\max | R_{ih}(r_i, t) |^2}{\max | R_{hh}(r_0, t) |^2}$$

The value of $D(r_0, r_i)$ determines how well the transmitted energy is focused on the intended user if time reversal is employed in the transmitter side.

3.4 Channel Reciprocity

Channel reciprocity is also analyzed in the rectangular metal cavity. It eliminates the need of continuous
feedback of channel to the transmitter to acquire Channel State Information (CSI) [7]. CSI at the transmitter provides the flexibility to shift the signal processing to wherever it is desired—for UWB systems, the receiver complexity is minimized for easy implementation in the current semiconductor industry.

For analyzing channel reciprocity in the non-line-of-sight situation, an aluminum sheet was placed in the middle of rectangular metal cavity that divides the cavity into two compartments with size of 8 feet by 8 feet by 8 feet. The transmitter antenna is placed in one compartment and receiver antenna in the other. The distance between transmitter antenna and receiver antenna is fixed at 4m. The setup is shown in Figure 3. $S_{21}$ serves as channel transfer function for the forward link and $S_{12}$ serves as channel transfer function for the reverse link.

![Figure 3 Setup for analyzing channel reciprocity](image)

### 3.5 Channel Capacity

Channel capacity is also an important channel characteristic and can be used as a metric to quantify and model the channel. If channel transfer function and transmitted power are given, channel capacity can be calculated when different spectrum-shaping schemes are employed [8]. Here, water filling, time reversal, channel inverse, and constant power spectrum density (PSD) are considered.

### 4. Results and Analysis

#### 4.1 Frequency and Time Domain Response

The channel transfer function and channel impulse response in rectangular metal cavity when the distance between transmitter antenna and receiver antenna is 4 m are shown in Figure 4 and Figure 5.

![Figure 4 Channel transfer function in rectangular metal cavity.](image)

![Figure 5 Channel impulse response in rectangular metal cavity.](image)

The channel transfer function and channel impulse response in office with the same distance between transmitter antenna and receiver antenna are shown in Figure 6 and Figure 7.

![Figure 6 Channel transfer function in office.](image)
It can be observed that the delay spread of channel impulse response is about 800 ns in rectangular metal cavity while in office it is less than 100 ns. The delay spread of channel impulse response in hallway is also less than 100 ns as shown in [9]. This shows that there are a large number of rich multipaths in rectangular metal cavity, which will cause severe inter-symbol interference (ISI) in the receiver side when data rate is high. How to take advantage of these rich multipaths and reduce ISI is the main concern to design the communication system that will give better performance in rectangular metal cavity. The system using time reversal technique and chirp waveform is proposed in [8].

4.2 Channel Energy

Figure 8 shows the energy of the channel impulse response in rectangular metal cavity in comparison with channel energies in office and hallway environments.

The channel energy in rectangular metal cavity is much higher than those in office and hallway environments. For example, when the distance between antennas is 3 m, the channel energy in rectangular metal cavity is nearly 20 dB larger than those in other environments. Meanwhile, the channel energy in rectangular metal cavity is almost the same as the distance between antennas increases. But the channel energy in office or hallway environment drops apparently when distance increases from 0.5 m to 3 m. This characteristic can save the transmitted power for the short-distance communication.

4.3 Spatial Focusing

The autocorrelation $R_{hh}(r_0, t)$ between transmitter and intended user is shown in Figure 9 and the crosscorrelation $R_{hh}(r_1, t)$ between transmitter and unintended user one is shown in Figure 10.
Figure 11 Directivity of spatial focusing in rectangular metal cavity.

Figure 11 show us that directivity drops by almost 20 dB when the unintended user is only 3 cm away from intended user. In hallway environment directivity drops by 10 dB when the unintended user is 1 m away from the intended user [6]. So the spatial focusing in rectangular metal cavity is more apparent than that in hallway environment. This characteristic can make the communication more secure.

4.4 Channel Reciprocity

The channel reciprocity is shown in Figure 12.

Figure 12 Channel reciprocity in rectangular metal cavity.

Figure 13 Zoom in version of channel reciprocity in rectangular metal cavity.

Figure 13 shows the zoom in version of channel reciprocity. The correlation between forward link and reverse link is almost 0.99. This shows that the forward and reverse links are nearly symmetrical in rectangular metal cavity. The channel reciprocity will be useful to design Time-Division Duplexing (TDD) communication system in rectangular metal cavity and more CSI can be exploited in the transmitter side. In this way, the complexity of the receiver side will be shifted to the transmitter side that is a highlight for our system design.

4.5 Channel Capacity

Figure 14 shows spectrum efficiencies in rectangular metal cavity when different spectrum-shaping schemes are employed. Water filling gives the maximum spectrum efficiency and channel inverse gives the minimum one amongst the four spectrum-shaping schemes. Time reversal performs better at low TX SNR than constant PSD, but the spectrum efficiency of constant PSD approaches that of water filling very well at high TX SNR.

Figure 14 Spectrum efficiency in rectangular metal cavity.

By using water filling scheme, the maximum spectrum efficiency is achieved and spectrum efficiency can be used to serve as a metric to quantify the channel. Figure 15 shows spectral efficiencies in rectangular metal cavity, office and hallway environment when water filling is used. The capacity in rectangular metal cavity is larger than those in other two environments. This results clearly illustrate that confined metal environment has the potential to support high data rate transmission.
4. Conclusion

This paper first presents the channel sounding of UWB channel in rectangular metal cavity. Then UWB channel characteristics such as channel transfer function, channel impulse response, channel energy, spatial focusing, channel reciprocity and channel capacity are analyzed. Meanwhile, some comparisons are made between the channel characteristics in rectangular metal cavity and those in traditional communication environments. By analysis and comparison, it is easily found that UWB channel in rectangular metal cavity has many characteristics such as long delay spread, a large number of rich multipaths, more channel energy, better spatial focusing, high channel capacity and so on. These characteristics will give us more opportunities and challenges to design new communication system [10] in rectangular metal cavity.

5. Acknowledgement

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6. References


