Review on Antenna Design and Channel Characterization of Ultra-Wideband Technologies

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ABSTRACT

This paper describes the antennas and the channel characterization of the ultra-wideband (UWB) radio, focusing on the wireless personal area network (WPAN) application. At first, the impacts of antennas and propagation channels on different UWB transmission systems, namely MB-OFDM and DS-CDMA, are described. Next, Friis' transmission formula, which is used for the link budget estimation, is extended to consider UWB radio transmission. Next, various kinds of UWB antennas as well as the required properties are briefly mentioned. Finally, two different aspects of the channel characterization, namely for the transmission technology, and for the antenna technology, are described.

Keywords: ultra-wideband radio, antennas, propagation, link budget, waveform distortion, channel sounding

1. INTRODUCTION

Recently, ultra-wideband (UWB) radio technologies draw big attentions considering the applications to the short range wireless communication, ultra-low power communication, ultra-high resolution radar etc.

Among them, the standardization of the UWB radio is ongoing under IEEE 802.15 WPAN High Rate Alternative PHY Task Group 3a (IEEE802.15.3a) [1, 2]. A wireless personal area network (WPAN) is originated by the Bluetooth (IEEE802.15.1). IEEE802.15.3a is trying to establish the new standard of WPAN to drastically increase the data rate, which is a weak point of Bluetooth. Now IEEE802.15.3a considers the use of UWB, following the tentative ragulation of FCC (Federal Communications Commision, USA), to achieve the bit rate of 110 Mb/s at 10 m and 200 Mb/s at 4 m [3]. Although the standardization has been at the final voting stage for more than half a year, the first candidate Multi-Band OFDM [4] has not been able to gain the required 75 % approval, and has been in competition with the second candidate DS-UWB [5]. The study of the UWB radio had started from the impulse radio which is advantageous in the hardware simplicity [6], but more complicated systems such as MB-OFDM and DS-UWB are considered now. In MB-OFDM system, a sub-band with 128 OFDM carriers occupies 528 MHz band, and different sub-bands are selected from time to time to achieve the frequency hopping (FH). Contrary, DS-UWB uses only two sub-bands to avoid IEEE802.11a band, i.e. the mandatory low band with 2.05 GHz bandwidth and the optional high band with 4.775 GHz bandwidth, which is more like the impulse radio. Recently, another task group IEEE802.15.4a has formed to standardize the low rate PHY using UWB [7]. It focuses on the high precision ranging, as well as the communications, with ultra low power, longer range, and lower cost.

This paper reviews recent advances on the UWB antennas and propagation, focusing on the WPAN applications. The impulse radio is more emphasized in the paper, but the differences of the impact of antennas and propagation to MB-OFDM and DS-UWB. The requirements and the implementation examples of the antennas are presented. Then the propagation characteristics shall be described in two different contexts, i.e. the transmission properties and the antenna-related issues. The effect of the distortion due to the antennas is another important issue, and it will be discussed in a separate paper [8]

2. IMPACT OF ANTENNAS AND PROPAGATION TO DIFFERENT UWB SYSTEMS

In this section, the impacts of antennas and propagation to previously mentioned MB-OFDM and DS-UWB are summarized. The detail of the communication systems shall be described in Refs. [4, 5].

The biggest difference between them is the bandwidth per carrier. In MB-OFDM, one OFDM subcarrier only occupies 4.125 MHz, but DS-UWB carriers occupy 2.05 GHz (Low Band) or 4.775 GHz (High Band) after spreading.

In MB-OFDM, the channel can be regarded as the flat fading channel as far as the delay spread is within the guard interval (9.5 ns). As the channel estimation is executed per channel basis, the frequency characteristics of the antennas and the multipath delay spread within the guard interval have no influence to the transmission. Therefore, the discussion considering the impulse transmission is not applicable.

In DS-UWB system, on the other hand, the multipath signals arrival with more than one chip delay

(0.73 and 0.31 ns) can be distinguished at the correlator output, and the rake reception can be deployed to achieve the path diversity. However, the influence of the waveform distortion due to the antennas is more obvious as the mismatch loss at the matched filter is increased.

As the following discussion mainly focus on the impulse radio, DS-UWB is applicable more than MB-OFDM.

3. ANTENNAS FOR UWB SYSTEMS

Antennas suitable for the UWB transmission is considered in this section.

3.1 Requirements

The following properties are required for the UWB antennas:

Linear phase and constant group delay in directivity: If the group delay is not constant, the pulse waveform is spread out in the time domain.

Low return loss over ultra wide bandwidth: If there are mismatches both at the antenna end and the circuitry end, the overall dispersion characteristic is much degraded due to the multipath within the feeding cable.

Constant directivity over ultra wide bandwidth: The variation of the directivity according to the frequency results in the ripples of the frequency transfer function in some cirtation direction. The dispersion characteristic is then degraded.

3.2 Principle of Broadband Antennas

Different from the multimode terminals deploying multiple frequency bands, the multiple-resonance structure is not an apropariate technique for UWB terminal to enhanse the bandwidth. The reason is that the multiple resonances cause the frequency dependence of the group delay. Therefore, it is not suitable for the UWB waveform transmission although it is usually used for the wideband impedance matching.

There are two fundamental principles to achieve the broadband or UWB property of the antennas [9]:

Self similarity antenna: A self similarity antenna is with the constant electric shape over the wide frequency bandwidth. Here, the electric shape means the shape described in the dimension of the wavelength. A biconical antenna, a bow-tie antenna, a discone antenna, an equi-angular spiral antenna are the examples of this class.

Self complementary antenna: A self complementary antenna is usually conposed of planar conductor(s), and its complementary structure is identical to the original structure. Here, complementary structure is obtained by replacing the conductor and the non-conductor parts in the plane. Among the self complementary antennas, the log-periodic antenna is well known.

Note that both structures require the infinite size of the conductor. The shape is therefore truncated in reality, and it limits the lower bound of the bandwidth.

3.3 Antennas

3.3.1 Practical Antennas

For the WPAN applications, the miniaturization of the antenna is essential.

It is theoretically known that the bandwidth and the efficiency are in the trade-off [10]. However, recently proposed small UWB antennas claim to achieve the high efficiency and the broad bandwidth simultaneously.

Two small antenna modules are commercialy available, one from SkyCross and the other from TY. The SkyCross antenna [11] operates at VSWR below 2.5 in the range of3.1–10 GHz. It exhibits the highest efficiency of 82 % at 5.25 GHz. The radiation pattern is horizontally omnidirectional. The physical dimensions are as small as $16 \times 13.6 \times 3$ mm. It is claimed that the meander line technology is applied, but the detail of the structure is not disclosed. The TY antenna [12] operates at VSWR below 2.2 in the range of 3.1–11 GHz. The "total average gain" that approximates the mean effective gain [13] for the uniform angular distribution is -3.4 dBi at maximum, and the directivity is like isotropic. The physical dimensions are as small as $10 \times 8 \times 1$ mm. It is claimed that it consists of dielectric chip, but the detail of the structure is not disclosed, neither. Unfortunately, how these antennas are operating physically can not be known as the structures are not disclosed.

In the test board of the Trinity chip set of Xtreme Spectrum [14], a printed antenna with the size of 2.5 cm has been used.

Other types of the small antennas have been proposed for the integration into the terminals, such as a small Vivaldi antenna [15], a combination of a microstrip and a monopole [16], a printed bow-tie antenna [17], and so on.

In the above proposals, however, the connection with the circuitry or the integration into the terminal are not well considered in the evaluation. The characteristic impedance, the balanced or imbalanced feeding, the type of the feed line, the interactions with circuit board and the chacis shall be taken into account, by considering the RF implementation of UWB transceivers [18].

3.3.2 Measurements of UWB Antennas

The following items shall be measured to know the performance of the UWB antennas:

- Input impedance
- Directivity (complex transfer function)
- Radiation efficiency

Although the time domain measurement is not impossible, it is suggested to use a vector network analyzer

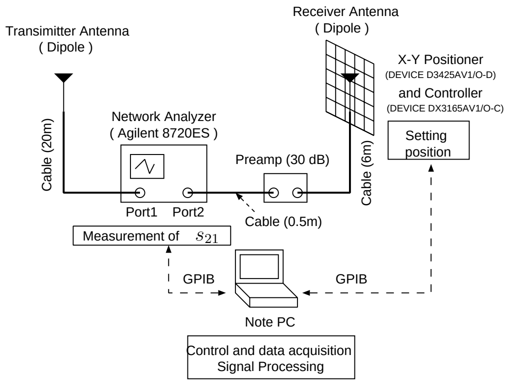

Fig. 1: *UWB channel sounding system.*

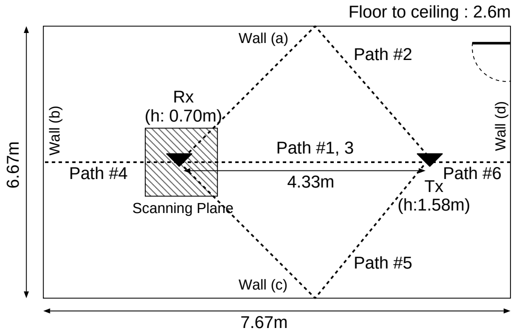

Fig. 2: *Experimental result of ray paths estimation.*

(VNA) in the frequency domain since the time domain calibration of the instruments is not well established.

The input impedance can be measured directly by VNA.

The complex transfer function of the antenna can not be measured directly even by using VNA, as the frequency characteristics of the testing antenna and the antenna under test (AUT) can not be distinguished. Therefore, the calibration of the testing antenna is necessary. A complex three-antenna method [19] shall be deployed for this purpose. In the three-antenna method, three testing antennas are needed for the calibration, but the none transfer functions shall be known in advance. After the measurements of three combinations, all the transfer functions can be derived. Ref. [19] is described by using an antenna factor, but it can be easily rewritten by using Friis' transmission formula in the form of the transfer function [8]. After the calibration of the testing antenna, the transfer function of AUT can be measured by the transmission measurement using VNA.

The antenna radiation efficiency can be obtained by integrating the radiation pattern over the sphere, although it is time consuming and need spherical antenna measuments. Alternatively, a Wheeler cap method can be deployed as far as the antenna is smaller than the wavelength at the highest frequency [20].

4. PROPAGATION

The UWB propagation has been investigated in many different approaches and the readers are suggested to refer the review papers [21–23]. In this paper, we focus on the approach of the double-directional channel modeling which can consider the influence of the antenna [24, 25].

4.1 Double directional channel model

It is usual that the channel impulse response model ignores the antenna directivity since some omnidirectional antennas are implicitly deployed. However, the influence of the antenna transfer function that is a function of the frequency and the direction shall not be discussed by using such a model.

To establish the antenna-free channel model, the double directional channel model taking into account the direction of departure (DOD) and the direction of arrival (DOA) of each propagation path, as well as its delay time (DT) is necessary. When the path directions are known, the antenna transfer functions are multiplied in the frequency domain, and the total transfer function including the antennas and propagation can be known. It has originally been proposed for the wideband (not UWB) multipath propagation modeling [26, 27]. Each ray path has a DOD, a DOA, a DT, and a path magnitude in the model. However, it is impossible to consider the constant magnitude within the ultra wide bandwidth. Therefore, the authors have proposed the extension of this ray path model to express the magnitude as a function of the frequency [24]. In the implementation, the different magnitude values are assigined for each of the subbands, while DOD, DOA and TD valued are kept constant over the bandwidth. SAGE algorithm [28] which is a class of the maximum likelihood estimation has been deployed to estimate all the parameters.

An indoor measurement has been done in the office environment by using a VNA and a synthetic array driven by the X-Y positioner as shown in Fig. 1. The detail can be found in Ref. [24]. Figure 2 shows the result for the empty room without any furnitures. Due to the limitation of the facility, only the single directional measurement could be done. Instead, the ray paths were determined by considering the delay time. All the paths were regarded as the specular rays in geometrical optics.

This system can be extended to double directional, by introducing another scanner on the other side.

5. CONCLUSION

The antennas and the propagation in UWB radio are reviewed by focusing the WPAN applications.

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