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Overview and Trends of UWB (Ultra Wideband) Propagation Studies

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Abstract　Ultra wideband (UWB) radio has recently been investigated for wireless communications, as a candidate for multimedia personal area communications. UWB wireless system can share the frequency spectrum with the conventional narrowband wireless systems, and provide high data rates and high capacity with promising quality even in multipath fading environment. In this paper, we focus on the analysis of UWB propagation characteristics, and provide some overviews and trend analyses of recent research activities on UWB propagation around the world.

Keywords　Ultra Wideband, UWB, propagation, channel modeling, impulse radio

UWB（Ultra Wideband）伝搬の研究動向

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あらまし　近年，極めて広い帯域を占める信号によって伝送する Ultra wideband(UWB)無線の研究，特に近距離無線通信に関する研究が国内外において進められている．UWB 無線システムは，既存の無線システムとスペクトルを共用し，近距離のマルチパス環境において高速・大容量の通信が可能と考えられる．本稿では，UWB 信号の伝搬特性を検討し，国内外の UWB 伝搬の研究動向を説明する。

キーワード　Ultra Wideband，UWB，電波伝搬，チャネルモデリング，インパルスラジオ

I. Introduction

Ultra wideband (UWB) wireless technology has been investigated since the 1960s, but it was mainly used for radar-based applications until now, because of the wideband feature of impulse signal that results in very accurate timing-positioning information. However, due to recent developments in digital consumer electronics technology, UWB is becoming more and more attractive for low-cost personal area communication applications. Many researchers around the world are currently working in various projects with missions to further explore the potential benefits of UWB for utilizing this promising technology in the high-rate, multimedia personal communication area [1].

According to the definition of UWB, there are two main differences between UWB and other "narrowband" or "wideband" systems. First, the bandwidth of UWB systems, as defined by the Federal Communications Commission (FCC) of the United States is more than 20% of its center-frequency or more than 500 MHz [2]. Clearly, this bandwidth is much greater than the bandwidth used by any conventional wireless technology. Second, UWB system is typically implemented in a carrierless mode. Conventional "narrowband" and "wideband" systems use radio frequency (RF) carriers to convert the baseband signal to the working carrier frequency where the system is allowed to operate. In contrary, UWB systems can directly modulate an narrow "impulse" that has a very sharp rise and fall, which results in a waveform that occupies bandwidth of several GHz [3]-[5].

Since UWB pulses are spread over very large bandwidths, they will unavoidably overlap with existing narrowband radio systems, such as global position system (GPS), cellular mobile communications, terrestrial microwave relay systems, and wireless LAN (e.g. IEEE 802.11 a/b). Then, coexistence and compatibility is a severe subject need be paid some special attentions. That is why the UWB propagation characteristics should be investigated and grasped thoroughly, as prerequisite for any following UWB system implementations. Recently, FCC released the UWB radio emission mask (FCC 02-48, UWB Report & Order) [2], and opened the way for the realization of coexistence with conventional and existing radio services. Under strategic spectrum planning and appropriate regulation, such as UWB power density being controlled and limited to suitable levels corresponding to feasible UWB propagation model, the UWB wireless system will surely bring some revolutionary changes in wireless communications.

In this paper, we focus on the analysis of UWB propagation characteristics, and provide some overviews and trend analyses of recent research activities and results on UWB propagation around the world.

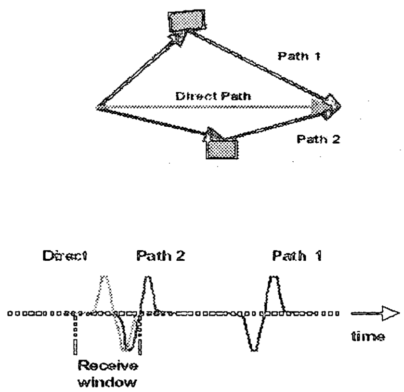

Fig. 1. UWB signal propagation based on multipath characteristics.

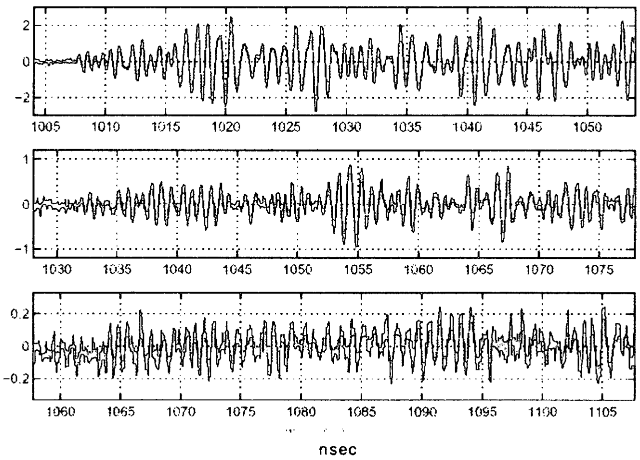

Fig. 2. Typical received UWB signals in multipath propagation environment.

II. UWB Propagation Characteristics

Referring to some former investigations [4]-[9], UWB wireless systems posses some special advantages based on the ultra wideband propagation features, as described in Fig. 1, such as: (1) immune to multipath fading and interferences – due to transmission of data in short pulses rather than continuous waves, the various multipaths are resolvable down to path differential delays in the order of nanosecond or less, and the fading and interference effects can be significantly reduced; (2) time and frequency diversity – UWB pulses are sent out from a transmitter discretely, and they arrive at a receiver at different times depending on the traveling paths. The receiver can be designed to take advantage of this effect by pre- and post-Rake combining the UWB pulses of different paths, thereby increasing the received signal in time and frequency domain.

With respect to the above-mentioned UWB propagation features, any fundamental propagation model for UWB propagation analysis should consider the following characteristics, such as: (1) path loss due to the propagation environment (e.g. indoor, outdoor, and between rooms, etc.), signal type and frequency band (e.g.

baseband and passband); (2) multipath features – number of multipath components, multipath amplitude distribution, multipath delay profile, and spatial variation (fading); (3) spectral features – impact of central frequency and bandwidth; and (4) material penetration/attenuation measurements (e.g. drywall, windows, and office partitions, etc.).

Generally, we should first consider a UWB system propagation model that is required to establish UWB system "link budgets" and to determine the amount of interference caused by nearby systems. It is well-known that conventional link budget is determined by exponential path loss factors (e.g. signal power falls off with square of distance in free-space line-of-sight conditions). However, with respect to UWB channel, we may need to modify the traditional link budget model, for instance, how does path loss change with frequency when the UWB fractional bandwidth is so large? Then, it is necessary to develop a UWB link budget analysis, which provides not only the description of transmitter peak power, average power, and pulse energy, but also the UWB equivalent of the Friis transmission formula for estimating received power/energy.

Meanwhile, receiving multipath channel model is also necessary, which provides basic information for UWB receiver design, such as pulse shape, statistical characterization of multipath distortion. For UWB propagation channel, one of the important issues is about the pulse waveform "distortion", as illustrated in Fig. 2. Some initial experimental results show that the first arriving pulse is similar to traditional Gaussian doublet pulse; however, later arriving paths deviate from that shape considerably. Then it is necessary to characterize the pulse shapes that are seen at the receiver and determine the amount of variance caused by the multipath components, which will have large impact on receiving correlator and Rake combining design.

III. UWB Propagation Modeling

Since some special characteristics have been reported for UWB propagation channel, it is important to develop an appropriate UWB channel model. Recently, many researchers around the world have taken part in the UWB channel modeling. Among them, the channel modeling sub-committee of IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) has initiated this kind of investigations in May 2002, and published its final UWB channel modeling report [10]-[20]. In this Section, the IEEE 802.15 UWB channel model will be discussed mainly.

A. IEEE 802.15 UWB Path Loss Model

The main purpose of IEEE 802.15 UWB path loss modeling is to fairly compare different physical layer characteristics at the target IEEE 802.15 system operating distances, and to ensure adequate performance of the final IEEE 802.15 standard. According to their report, in general, the IEEE 802.15 path loss model has been investigated by modifying the traditional free space path loss model while providing the needed link margin that will be available to make up for additional channel losses, implementation losses, UWB waveform distortion, imperfect multipath energy capture, etc. Table I below describes the link budget analysis for the IEEE 802.15 UWB path loss model and how to calculate the final link margin. This path loss model is based on the narrowband path loss calculations (known as the Friis transmission formula), and some revisions have been carried out. Table I lists the parameters and equations that should be used by the users to demonstrate their PHY ability to close the link at the throughputs and target operating ranges desired for the IEEE 802.15 WPANs standard. The highlighted parameters below are up to the users to define, while all other parameters will be common so easy comparisons can be made.

In the next Section, UWB multipath channel model will be described, corresponding to additional path loss, additional implementation losses, additional waveform distortion, imperfect multipath energy capture, amplitude fading, etc.

B. IEEE 802.15 UWB Multipath Model

Based on observed "clustering" phenomenon in several UWB channel measurements, a modified S-V (Saleh-Valenzuela) multipath channel model has been proposed and testified in IEEE 802.15 Working Group [21]-[22]. It has been shown that the modified S-V model was able to best fit the measured channel characteristics. Additionally, the Rayleigh and lognormal amplitude distribution was compared with the measured data, and the results there showed that the lognormal distribution best fit the statistical characteristics of the measured data. The proposed IEEE 802.15 S-V multipath model has been given as the following, in discrete time impulse response:

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \qquad (1)$$

where $\alpha_{k,l}^i$ are the multipath gain coefficients, T_l^i is the delay of the l^{th} cluster, $\tau_{k,l}^i$ is the delay of the k^{th} multipath component relative to the l^{th} cluster arrival time T_l^i, X_i represents the log-normal shadowing, and i refers to the *i-th* multipath channel realization.

In addition, this model uses the following key parameters:

Λ = cluster arrival rate;

λ = ray arrival rate, i.e., the arrival rate of path within each cluster;

Γ = cluster decay factor;

γ = ray decay factor;

σ_1 = standard deviation of cluster lognormal fading term (dB).

σ_2 = standard deviation of ray lognormal fading term (dB).

σ_x = standard deviation of lognormal shadowing term for total multipath realization (dB).

The main multipath characteristics of the UWB channel that are used to derive the above model parameters have been chosen to be the following:

- Mean excess delay
- RMS delay spread
- Number of multipath components (defined as the number of multipath arrivals that are within 10 dB of the peak multipath arrival)
- Power decay profile

One of such typical impulse response realizations generalized by the IEEE 802.15 S-V channel model is given in Fig. 3 in the case of NLOS multipath fading.

It should be noted that the general complex tap model was not adopted in the IEEE 802.15 Working Group and a real-valued simulation at RF was considered to be more suitable.

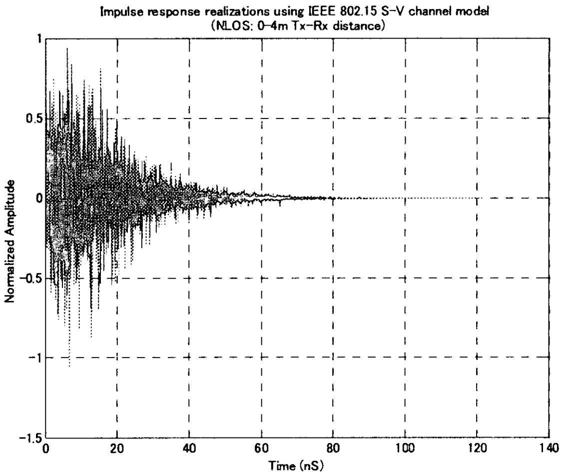

Fig. 3. Impulse response realization based on IEEE 802.15 S-V channel model in multipath fading environment (none-line-of-sight case).

C. UWB MIMO Propagation Modeling

Since the actual transmitted and received UWB pulse waveforms also depend on the transmitting and receiving antenna and the antenna would re-shape and "distort" the pulse waveforms accordingly, it is believed that any UWB propagation model should divide the propagation channel from the antenna pairs, namely, the UWB channel model should focus on the antenna-independent air-interface propagation procedure between the transmitter and receiver antenna. Based on this basic consideration, a ray-oriented modeling of spatio-temporal and MIMO (multi-input-multi-output) channel has been proposed recently, which may be applied to the UWB MIMO channel modeling [23].

IV. UWB Propagation Measurements

In order to properly understand and characterize the fundamental propagation behaviour of UWB signals in various environments, it is very important to take a large number of indoor and outdoor UWB propagation measurements (both baseband and passband). Based on these measurements, we can create some suitable propagation models to predict specific interactions, link budget analysis, interference prediction, and receiver development for a variety of UWB application scenarios.

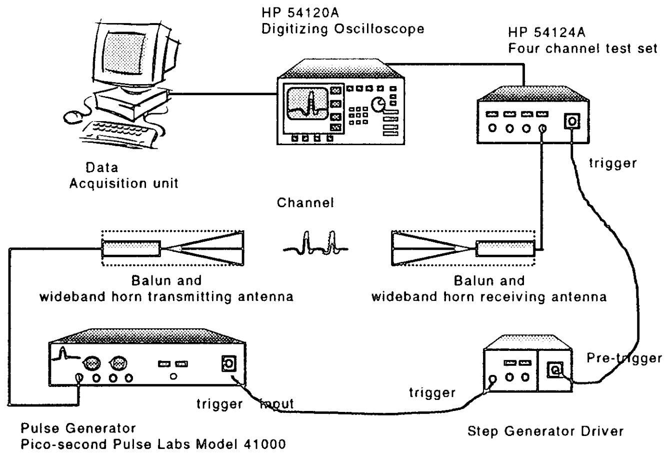

Fig. 4. Typical time domain UWB measurement set-up.

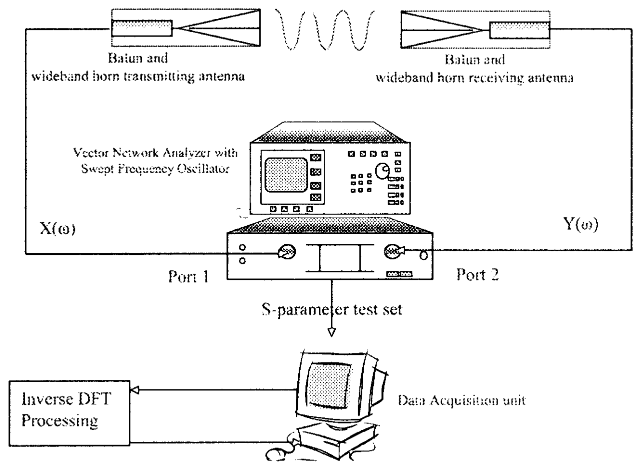

Fig. 5. Typical frequency domain UWB measurement set-up.

There are two measurement methods for UWB measurements, namely time domain and frequency domain UWB measurements. With respect to time domain measurements, a baseband or bandpass UWB channel sounder is employed, which uses pico-second pulse generator along with a digital sampling oscilloscope and a passband filter. Time domain measurement method has been widely chosen by UWB-related companies and universities in USA, such as Time Domain Corporation, University of South California, and Virginia Pylotechnic Institute and State University. One typical baseband UWB channel sounder of time domain is illustrated in Fig. 4.

As for frequency domain measurements, vector network analyser is usually employed. Frequency domain measurement method is very suitable for limited-range and indoor material characterization, such as dry walls (with and without white boards), block walls, glass doors, glass windows, and office partitions. It is also suitable for human body shadowing measurements. One typical UWB channel sounder of frequency domain is shown in Fig. 5. Since the majority of today's personal wireless communications devices have the capability of being carried and attached to human body, the close proximity of the portable device to the human body suggests that the body itself will become a critical part of the UWB propagation channel. Considering the possible influence of human body on UWB propagation, especially in office or home environment, human body shadowing should be investigated. Since December 2002, a series of human body shadowing measurements have been conducted in anechoic-chamber, in Communications Research Laboratory (CRL), which have been described in [27] in detail.

V. UWB Propagation Research Projects in Europe and Japan

In Europe, several UWB-related research projects have been set up within the IST (Information Society Technologies) program supported by Europe an Commission. These research projects within IST are mainly listed as following.

(1) Whyless project [24]:

The Whyless project objective is to provide an air interface definition and an advanced physical layer transceiver architecture, which is able to adapt to very different business service requirements instantaneously (on-the-fly) only by the exchange of parameters. In Whyless project, a number of UWB indoor radio channel measurements have been performed inside the premises of IMST GmbH, covering various visibility conditions as well as intra and inter office and corridor propagation.

(2) UCAN project [25]:

The major aim in UCAN (Ultra-wideband Concepts for Ad-hoc Networks) project is to develop a complete UWB system demonstrator. All aspects of a functioning UWB system will be investigated, including the air channel characterization, the coexistence issues, the communication systems, physical layer, medium access control (MAC) and network layer. Ad-hoc networking and positioning aspects will be investigated as well. Seven companies (e.g. Motorola) and 2 Universities (e.g. University di Rome "La Sapienza") have taken part in the UCAN project.

(3) ULTRAWAVES project [26]:

The aim of ULTRAWAVES (Ultra WideBand Audio Video Entertainment System) is to provide a high performance and low cost wireless home connectivity solution, supporting applications requiring home multi streaming of high quality video and broadband multimedia. A development platform will be developed to support project evaluation activities, such as UWB channel model, smart antenna, coexistence issues, performance/range tradeoffs, etc. Totally 7 companies and universities are involved in this project.

In Japan, UWB Technology Institute has been set up in CRL since August 2002. The Institute has co-operated with a number of companies and universities in various fields of micro- and milli-wave UWB researches, in which the UWB propagation working group is responsible for the UWB channel measurements and modeling. The other study programs mentioned above have intensively measured and modeled UWB propagation characteristics, most of which are, however, dependent on characteristics of antennas used for transmission and reception in the experiments. The CRL group intends to separate (i.e. deconvolute) the antenna-independent propagation characteristics from the measured data, using the amplitude and phase of antenna radiation patterns, and to construct the antenna-independent UWB propagation model applicable to any system. For more detailed information, refer to papers as following [27] [28].

VI. Conclusions

In this paper, we first provide the analysis of UWB propagation characteristics, corresponding to path loss, multipath fading and pulse waveform. Then, we give the summary of UWB channel modeling, including IEEE 802.15 S-V model. After that, UWB measurement methods of time and frequency domain are discussed. Finally, overviews UWB-related research activities and results in Europe and Japan are briefly described.

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Table I: Link Budget Analysis Table (IEEE 802.15 Path Loss Model)

Parameter	Value	Value
Throughput (Rb)	> 110 Mbps	> 200 Mbps
Average Tx power (P_T)	dBm	dBm
Tx antenna gain (G_T)	0 dBi	0 dBi
$f_c' = \sqrt{f_{\min} f_{\max}}$: geometric center frequency of waveform ($f_{\min}$ and $f_{\max}$ are the -10 dB edges of the waveform spectrum)	Hz	Hz
Path loss at 1 meter ($L_1 = 20\log_{10}(4\pi f_c'/c)$) $c = 3\times10^8$ m/s	dB	dB
Path loss at *d* m ($L_2 = 20\log_{10}(d)$)	20 dB at d=10 meters	12 dB at d=4 meters
Rx antenna gain (G_R)	0 dBi	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$ (dB))	dBm	dBm
Average noise power per bit ($N = -174 + 10\cdot\log_{10}(R_b)$)	dBm	dBm
Rx Noise Figure (N_F)	7 dB	7 dB
Average noise power per bit ($P_N = N + N_F$)	dBm	dBm
Minimum Eb/No (S)	dB	dB
Implementation Loss[1] (I)	dB	dB
Link Margin ($M = P_R - P_N - S - I$)	dB	dB
Proposed Min. Rx Sensitivity Level[2]	dBm	dBm

[1] Implementation loss is defined here for the AWGN channel only, and could include such impairments as filter distortion, phase noise, frequency errors, etc.

[2] The minimum Rx sensitivity level is defined as the minimum required average Rx power for a received symbol in AWGN, and should include effects of code rate and modulation.