Ultra-wideband Systems: Review

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***Abstract* – Nowadays, the demand for higher capacity, faster service, and more secure wireless connections increases, new enhanced technologies have to find their place in the overcrowded and scarce radio frequency (RF) spectrum. This is because every radio technology allocates a specific part of the spectrum; for example, the signals for TVs, radios, cell phones, and so on are sent on different frequencies to avoid interference to each other. As a result, the constraints on the availability of the RF spectrum become stricter with the introduction of new radio services. Ultra-wideband (UWB) technology offers a promising solution to the RF spectrum drought by allowing new services to coexist with current radio systems with minimal or no interference. This coexistence brings the advantage of avoiding the expensive spectrum licensing fees that providers of all other radio services must pay. This article reviews the some basic knowledge of UWB systems including definition, transmitter, channel model and receiver of UWB systems. Moreover, we discuss the literature of three interesting topics, including pulse shape design, timing jitter and localization of UWB systems.**

***Keywords* – Impulse-radio, Ultra-wideband, Transmitter, Receiver, Channel model**

1. INTRODUCTION

Since the Ultra-wideband (UWB) technology has been approved by the Federal Communications Commission (FCC) in 2002 [1], it becomes one of the fast growing research topics. At the current stage, UWB technology is the promising candidate for the physical layer of the upcoming short range wireless network. The UWB radio is conventionally based on a very short pulse, which occupies a very broad bandwidth. Unlike conventional wireless communications systems that are carrier based, UWB systems transmit the information without translating it to a higher carrier frequency. This carrierless technique will greatly reduce the complexity and cost of the transceiver. Therefore, the some basic knowledge of UWB is important to known for using to study and design the UWB research fields.

In this article, we introduce the some basic knowledge of UWB systems. UWB systems can be classified into three important parts. The first part is UWB transmitter. This part describes the UWB modulation techniques and the multiple access methods. Furthermore, the advantage and disadvantage of each modulation technique are compared. The second part is UWB channel model. The channel model based on IEEE802.15 that derived from the Saleh-Valenzuela model is considered. The final part is UWB receiver. In this paper, we are summary two well-known UWB receivers that are the RAKE and the transmitted-reference (TR) receiver. Additionally, we are summary the three interesting UWB research fields, namely, the pulse shape design, the timing jitter problem and the localization techniques.

We organize the rest of this paper as follows. In section 2, history of UWB systems is presented. We show the UWB regulations and definition of UWB systems in section 3 and 4, respectively. In section 5, UWB transmitters are described. The UWB modulation techniques and the multiple access schemes are presented in section 6 and 7, respectively. Section 8 shows the UWB channel model. In section 9, the UWB receiver including the RAKE receiver and TR receiver are also reviewed. Moreover, we are summary the interesting UWB research fields in section 10. Concluding remarks are in section 11.

2. HISTORY OF UWB SYSTEMS

In fact, UWB technology is not a new; it was originally discovered by Guglielmo Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters. However, the benefit of a large bandwidth and the capability of implementing multi-user systems were never considered at that time. Approximately fifty years after Marconi, Harmuth at Catholic University of America, Ross and Robbins at Sperry Rand Corporation, and Van Etten at the United States Air Force or USAF, Rome Air Development Center were some of the pioneers [2-3] who started the modern UWB communications from time domain electromagnetic systems in the early 1960s. They all referred to the systems as baseband radio. During the same period, Los Alamos, an engineer at Lawrence Livermore National Laboratories (LLNL and LANL), and other engineers elsewhere performed some of the original researches on pulse transmitters, receivers, and antennas.

However, a major breakthrough in the UWB communications occurred as a result of the development of the sampling oscilloscope by both Tektronix and Hewlett-Packard in the 1960s. These sampling circuits provided a method to display and integrate UWB signals. Moreover, this research provided the simple circuits necessary for subnanosecond on baseband pulse generation. Cook and Bernfeld summarized Sperry Rand Corporation's developments in pulse compression, matched filtering, and correlation techniques in their book published in 1967. In 1972, Robbins invented a sensitive baseband pulse receiver as a replacement for the sampling oscilloscope. This invention led to the first patented design of the UWB communication systems by Ross at the Sperry Rand Corporation.

By the early 1970s, the basic designs for UWB radar and communication systems were developed with advances in electronic component technology. In 1974, Morey at the Geophysical Survey Systems Corporation commercialized the first ground-penetrating radar based on UWB. McEwan at LLNL developed the Micropower Impulse Radar (MIR) that provided compact, inexpensive and low power UWB systems for the first time in 1994. Around 1989, the United States Department of Defense (DOD or DoD) created the term *ultra wideband* to describe communication via the transmission and reception of impulses. The U.S. government has been and continues to be a major supporter of UWB research. The Federal Communications Commission (FCC) effort to authorize the use of UWB systems [3] spurred a great amount of interest and fear of UWB technology. In response to the uncertainty of how UWB systems and existing services could operate together, the U.S. government has sponsored several UWB interference studies

In 1993, Robert Scholtz at the University of Southern California presented a multiple access technique for UWB systems [4]. This technique allocates each user a unique spreading code that determines specific instances in time when the user is allowed to transmit. With a viable multiple access scheme, UWB systems become capable of supporting many fields like radar, point-to-point communications and wireless networks. For about the wireless network fields, a number of researchers in the late 1990s and early 2000s began investigations on UWB propagation in details. These propagation studies and the channel models developed from the measurement results were culminated in a number of notable publications (Cassioli, Win, Scholtz, Molisch [5-7] and Foerster [8]).

3. UWB Regulations

In February 2002, the FCC amended the Part 15 rules to allow operation of devices incorporating UWB technology in the frequency band of 3.1 - 10.6 GHz [3]. Devices must operate within this 7.5 GHz of unlicensed spectrum and be designed to coexist with other allocated radio systems in an uncontrolled environment. The FCC rules ensure that UWB emission levels are exceedingly small, with very low power spectrum density (PSD). The Equivalent Isotropically Radiated Power (EIRP) limit is -41 dBm/MHz. The total emitted power over several gigahertz of bandwidth is a fraction of a milliwatt. The spectrum mask of the UWB signal is shown in Figure 1.

4. Definition of UWB systems

UWB is used to refer to signal occupy fractional bandwidth greater than 20 % of the center frequency or more than 500 MHz of bandwidth in the 7.5 GHz band of spectrum between 3.1 GHz and 10.6 GHz. On the contrary, narrowband signals have fractional bandwidth less than 1% of the center frequency.

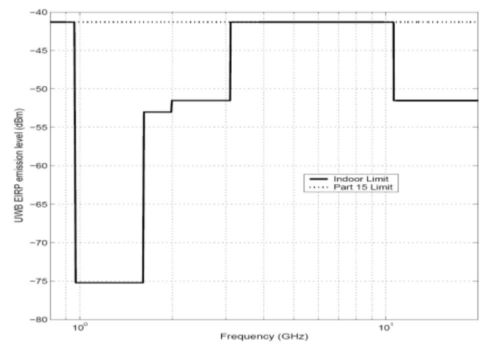

Figure 1 FCC spectral masks for indoor communications.

The fractional bandwidth (FB) is defined as

$$FB = \frac{2\left(f_H - f_L\right)}{\left(f_H + f_L\right)} \qquad (1)$$

where f_H and f_L are the upper and lower frequencies, respectively, measured at -10 dB below the peak emission point as shown in Figure 2.

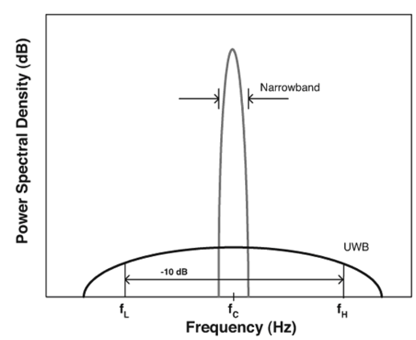

Figure 2 Narrowband versus UWB systems.

The UWB signals can be categorized into two main groups: single band or impulse radio UWB (IRUWB) [5-8] and multi-band or multicarrier UWB (MC-UWB) [9]. The IR-UWB systems are based on a very short pulse, which occupies a very broad bandwidth. Unlike conventional wireless communications systems, those are carrier based; UWB systems transmit information without translating it to a higher carrier frequency. This carrierless technique will greatly reduce the complexity and cost of the transceiver. On the other hand, the MC-UWB systems were based on multicarrier communications. The multicarrier techniques were firstly used in the late 1950s and the early 1960s for higher data rate High frequency (HF) military communications. Since that time,

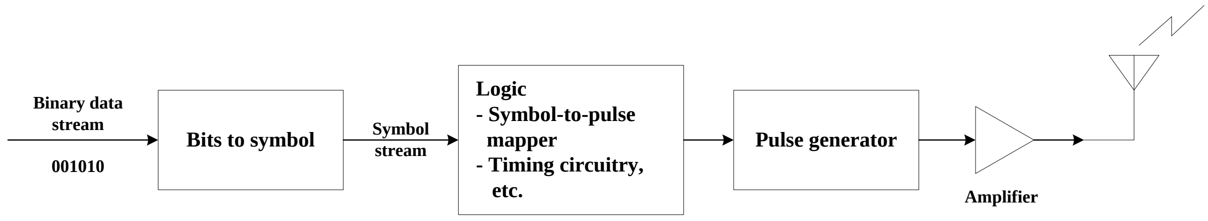

Figure 3 A general UWB transmitter block diagram.

orthogonal frequency division multiplexing (OFDM) has emerged as a special case of multicarrier modulation. OFDM is a multicarrier modulation with the minimum carrier spacing [10-11]. OFDM subcarriers are separated apart by the reciprocal of the symbol duration. Spectra of each subcarrier are mutually overlapping. Therefore, higher spectral efficiency, compared with the conventional single carrier transmission, can be obtained from OFDM. Even though, OFDM techniques of multicarrier modulation can also satisfy the wide bandwidth requirement, the impulse based UWB systems remain the strong competence due to its simplicity. Therefore, this article primarily focuses on impulse modulation.

5. UWB TRANSMITTERS

Figure 3 shows a block diagram of general UWB transmitters. The UWB transmitter part can be divided into three important blocks [12]. The first block is bits to symbols. This block maps bits received from the binary data stream to symbols by using modulation and multiple access techniques. The second block includes many parts such as symbol-to-pulse mapper, timing circuitry, etc. The symbols from the first block are then mapped to an analog pulse shape. Pulse shapes are generated by a pulse generator that is the last block. Precise timing circuitry which is crucially requires sending pulses out at intervals. If PPM is employed the timing must be even more precise, usually less than on pulse width. Pulses can then be optionally amplified before being passed to the transmitter. However, in general, a large gain is typically not needed to meet power spectral requirements and many are omitted.

6. UWB MODULATION SCHEMES

In this section, we review the conventional UWB modulation methods and discuss the advantages or disadvantages of each technique. For UWB systems, the data modulation is typically done using pulse-modulation techniques in the time domain. The choice of modulation method can affect a number of design parameters in UWB system's development such as data rate, robustness to interference and noise and transceiver complexity that directly impacts the overall size and cost of the systems.

6.1 On-Off Keying

The on-off keying (OOK) is the simplest technique of the UWB modulation. The transmission of a pulse represents a data bit "1" and its absence represents a data bit "0". Figure 4 shows an example of the OOK modulation technique in the UWB communication systems.

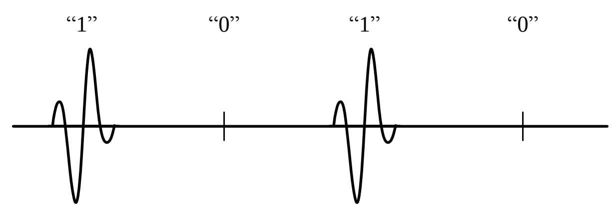

Figure 4 On-off keying modulation.

The general signal model, *s(t)*, for an OOK modulated signal can be represented by

$$s(t) = \sum_{n=1}^{N} b_n \cdot P(t - nT) \quad (2)$$

where N is the maximum number of transmitted bits, $b_n \in [0,1]$ represents the n^{th} data bit, $P(t)$ is the UWB pulse and T is the pulse repetition period.

The main advantages of the OOK modulation are simplicity and low implementation cost. The OOK transmitter is quite uncomplicated. This technique can use a simple RF switch that turns on and off to represent data. This way, the OOK modulation allows the transmitter to idle while transmitting a bit "0" and thus save power. However, this modulation scheme has several disadvantages in UWB systems. The OOK modulation is highly sensitive to noise and interference: an unwanted signal can be detected as a false data bit "1". Moreover, the difficult task of UWB synchronization becomes even more challenging for the OOK modulation if a stream of zeros is transmitted. Therefore, the OOK technique is not a popular modulation technique for UWB systems.

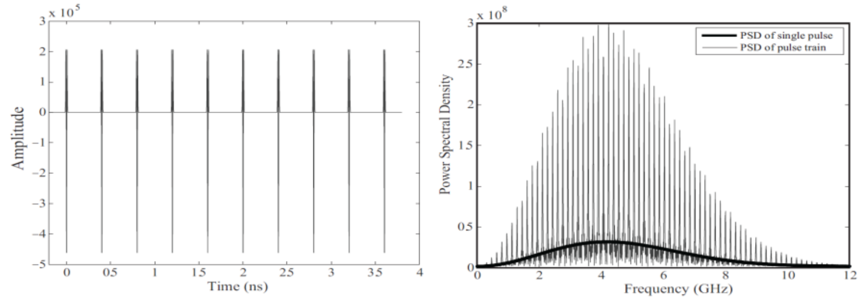

Figure 6 Discrete spectral lines of periodic pulses.

6.2 Pulse-Amplitude Modulation

The pulse-amplitude modulation (PAM) encodes the data bits based on different levels of power (amplitude) in short-duration pulses. In this modulation technique, a pulse with higher amplitude represents a data bit "1" and a pulse with lower amplitude represents a data bit "0". Figure 5 shows an example of the PAM for the UWB communications.

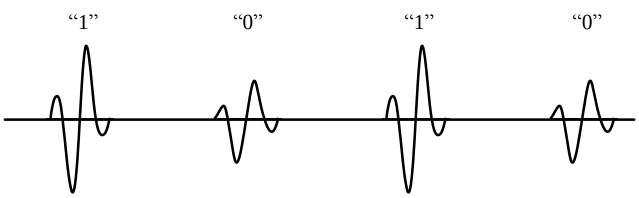

Figure 5 Pulse amplitude modulation.

The general signal model for the PAM signals is given by

$$s(t)=\sum_{n=1}^{N} A_{b_n} \cdot P(t-nT) \quad (3)$$

where A_{b_n} is the specific power level for each user's data bits, N is the maximum number of transmitted bits, $P(t)$ is the UWB pulse, $b_n \in [0,1]$ represents the n^{th} data bit, and T is the pulse repetition period. As shown in (3), the PAM and the OOK signal models are very similar, except for the existence of the amplitude parameter, A_{b_n} , in the PAM model, which represents the different amplitudes considered for a UWB pulse data transmission.

The advantage of the PAM modulation is also simplicity. It is simple because the PAM generation requires pulses with only one polarity to represent data. On the contrary, the first disadvantage of the PAM modulation is noise immunity. Although PAM pulses are less sensitive to noise than the OOK modulated pulses when OOK has long zero sequences, attenuation in wireless channels can convert them to the OOK case.
Furthermore, because of the periodicity of transmitted pulses, some discrete lines will be presented on the PSD of the PAM pulses. These discrete lines can cause harmful interference to other narrowband and wideband signals sharing the frequency spectrum with UWB systems. Figure 6 illustrates such discrete spectral lines on the PSD of periodic pulses.

The discrete power spectral lines can interfere with the conventional radio services and the UWB signals. Therefore, it's quite important to avoid the discrete spectral lines. One method to overcome these spectral lines is to "dither" the transmitted signal by adding a random offset to each pulse and removing the common spectral components [12]. However, the random offset of this technique is unknown at the receiver, making it extremely difficult to acquire and track the transmitted the UWB signal. Another method with similar random properties, but using a known sequence, is to use *pseudo-random noise* (PN) codes. For more information on this technique, we will describe it at the end of the next subsection.

6.3 Pulse-Position Modulation

The pulse-position modulation (PPM) is pseudo-randomly encoded based on the position of the transmitted pulse trains by shifting the pulses in a predefined window in time. Compared to the OOK and the PAM pulses, the PPM signals are more immune to false detection due to channel noise. This is because the pulses that represent the data bits in the PPM have the same amplitude, so the probability of detecting a false data bit is reduced. A version of the PPM represents a data bit "0" by not shifting with respect to a specific reference point in time; it represents a data bit "1" by a pulse advancing the same reference point as shown in Figure 7.

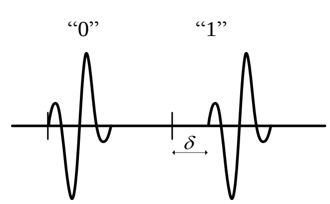

Figure 7 Pulse-position modulation.

The general signal model for the PPM signals is given by

$$s(t)=\sum_{n=1}^{N} P(t-nT-b_n\delta) \quad (4)$$

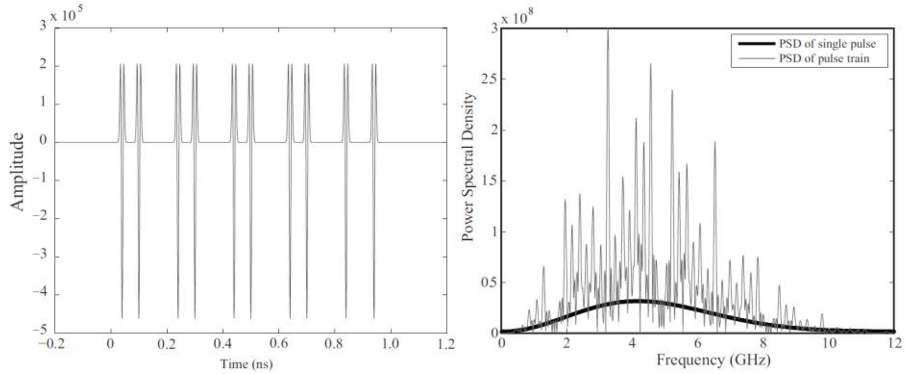

Figure 8 Smooth spectrum of PN time offsets.

where δ is the modulation index that provides a time shift to represent digital bit, N is the maximum number of transmitted bits, $P(t)$ is the UWB pulse, $b_n \in [0,1]$ represents the n^{th} data bit, and T is the pulse repetition period.

The disadvantage of the PPM scheme is its sensitivity to timing synchronization. Because data bits are recovered exclusively based on their exact position in time, timing uncertainties, such as jitter and drift, can degrade their performance significantly. For instance, timing uncertainties can cause synchronization errors that result in increased MAI in multiple-access channels. Further, the strict timing synchronization of narrow UWB pulses prior to the correlation process in the PPM receivers requires very fast (on the order of gigahertz) analog-to-digital converters (ADCs). Moreover, multipath distortions can stretch the pulses and cause them to overlap; thus detection becomes challenging of the pulse positions in the PPM systems.

For the discrete spectral lines problem, another method to overcome this problem is to use PN codes to add an offset to the PPM signal [12]. Since these codes are known and easily reproducible at the receiver, the problem for the receiver becomes mostly acquisition of the signal, but tracking makes it much easier. Moreover, the use of a PN time shift has other benefits besides just reducing the spectral lines. Since the PN code is a channel code, it can be used as a multiple access method to separate users in a similar manner to the code division multiple access (CDMA) scheme. By shifting each pulse at a pseudo-random time interval the pulses appear to be white background noise to users with a different PN code. Furthermore, the use of the PN code makes data transmission more secure in a hostile environment. The impact of the PN time offsets on energy distribution in the frequency domain is illustrated in Figure 8.

6.4 Biphase Modulation

The biphase modulation (BPM) employs the polarity of the pulse changes to represent digital data bits. Figure 9 demonstrates the biphase modulation for the UWB pulses.

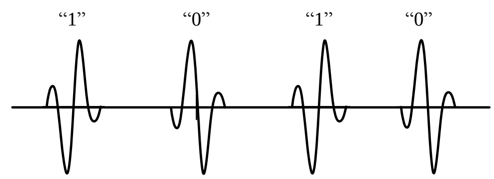

Figure 9 Biphase modulation.

The general signal model for the biphase modulation is given by

$$s(t) = \sum_{n=1}^{N} b_n P(t - nT) \qquad (5)$$

where N is the maximum number of transmitted bits, $P(t)$ is the UWB pulse, $b_n \in [0,1]$ represents the *nth* data bit, and T is the pulse repetition period.

The first advantage of the biphase modulation is less susceptible to distortion because the difference between the two pulse levels is twice the pulse amplitude. Another advantage of biphase modulation is that the change in polarity can remove the discrete spectral lines in the pulse's PSD, because changing the polarity of pulses produces a zero mean [13]. However, for a stream of data, accurate timing between the two transmitters is of great importance.

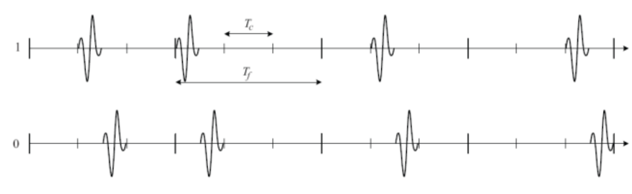

Figure 10 TH-PPM Modulation Examples.

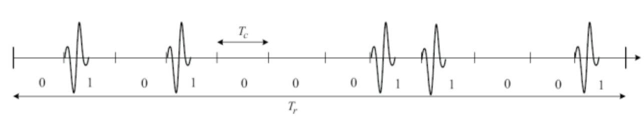

Figure 11 DS-BPAM Modulation Example.

6.5 Summary of UWB Modulation Methods

In this subsection, we conclude the discussion of the modulation methods for the UWB communications with Table I which summarizes the advantages and disadvantages of each of the modulation methods [12].

Table I. Advantages and disadvantages of the various modulation methods.

Modulation methods	Advantages	Disadvantages
OOK	Simplicity	Binary only, noise immunity
PAM	Simplicity	Noise immunity
PPM	Simplicity	Fine time resolution needed
BPM	Simplicity, efficiency	Binary only

7. UWB MULTIPLE ACCESS TECHNIQUES

In this section, we describe the typical multiple-access methods for the UWB communications systems. The multiple-access techniques are needed to perform the channelization for multiple users because several users transmit information simultaneously and independently over a shared channel. For the impulse-radio UWB, two common multiple access (MA) techniques are employed such as time-hopping (TH) technique and direct-sequence (DS) technique. Both of the methods are typically applied to the modulation schemes previously discussed.

First of all, the TH technique can be applied to all of the modulation schemes, where each user is assigned a time- hopping sequence. This sequence reduces collisions in the communication system by assigning each user a unique time shift pattern. Each receiver can detect a signal during its own unique hopping pattern, mitigating interference. The mathematical representation for the k^{th} user's transmit signal is given as [14]:

$$y_{(k)}(t) = \sum_{j=-\infty}^{\infty} s\left(t - jT_f - c_j^{(k)}T_c - \delta b_{[j/N_s]}^{(k)}\right) \qquad (6)$$

where $s(t)$ is the transmitted baseband pulse waveform, T_f is the pulse repetition time, $c_j^{(k)}$ is the time-hopping sequence, T_c is the duration of the time delay bins, $b_j^{(k)}$ is the data sequence, N_s is the number of pulses in any given binary symbol and δ is the modulation index.

An example of pulse trains for binary data bit "1" and "0" is demonstrated in Figure 10, in which the first pulse train is transmitting binary bit "1", and the second pulse train is sending binary bit "0". The only difference between the two is that all pulses in pulse train "0" are delayed a little bit comparing to the pulse in pulse train "1".

The direct sequence (DS) is the other form of MA commonly used with the impulse-radio UWB, although it is typically limited to OOK, Binary PAM and biphase modulation schemes. The idea is to modulate an antipodal pseudo-random noise (PN) sequence, which is unique at the time of communication. Therefore, a minimal amount of interference occurs with other users as they are assigned with different PN codes that have good autocorrelation and cross- correlation properties. The transmitted DS-UWB waveform is defined as [15]:

$$y_{(k)}(t) = \sum_{i=-\infty}^{\infty}\sum_{n=0}^{N_r-1} b_i^{(k)} a_n^{(k)} s\left(t - iT_r - nT_c\right) \qquad (7)$$

where $s(t)$ is the transmitted baseband pulse waveform, N_r is the spread spectrum processing gain, $b_j^{(k)}$ is the modulated data symbols for the k^{th} user, $b_n^{(k)}$ is the k^{th} user spreading chips, T_r is the bit period and T_c is the chip period.

An example of the direct sequence binary amplitude modulation (DS-BPAM) is demonstrated in Figure 11, where data bit "1" is spread into a binary sequence of 010100011001.

8. UWB CHANNEL MODELS

Based on the clustering phenomenon observed in several channel measurements, the IEEE 802.15 [16] task group adopted an UWB channel model derived from the Saleh- Valenzuela model [17] with a couple of slight modifications. Specifically, the multipath model is described by the discrete time impulse response below:

$$h(t) = X\sum_{l=0}^{L}\sum_{k=0}^{K} \alpha_{k,l}\,\delta\left(t - T_l - \tau_{k,l}\right) \qquad (8)$$

where $\alpha_{k,l}$ is the path gain coefficient of the k^{th} path within the l^{th} cluster, T_l is the arrival time of the first path of the l^{th} cluster, $\tau_{k,l}$ is the delay of the k^{th} path within the l^{th} cluster relative to the first path arrive time T_l and X is the log-normal shadowing coefficient.

Clearly, we have $\tau_{0,l} = 0$ by definition. To proceed, we further define the following two arrival rates: Λ is cluster arrival rate and λ is ray arrival rate, i.e., the arrival rate of path within a cluster

Now, the distribution of the T_l and $\tau_{k,l}$ can be characterized by

$$p\left(T_l \mid T_{l-1}\right) = \Lambda e^{-\Lambda\left(T_l - T_{l-1}\right)}, \quad l > 0 \qquad (9)$$

$$p\left(\tau_{k,l} \mid \tau_{k-1,l}\right) = \lambda e^{-\lambda\left(\tau_{k,l} - \tau_{k-1,l}\right)}, \quad k > 0 \qquad (10)$$

i,e., the inter-cluster arrival time is exponentially distributed with rate Λ and the inter-ray arrival time is exponentially distributed with rate λ.

The channel gain coefficient $\{\alpha_{k,l}\}$ is defined as follows:

$$\alpha_{k,l} = p_{k,l}\,\xi_l\,\beta_{k,l} \qquad (11)$$

where $p_{k,l}$ is equally probable of ± 1 to account for the signal inversion due to reflections, ζ_l reflects the fading associated with the l^{th} cluster and $\beta_{k,l}$ corresponds to the fading associated with the k^{th} ray of the l^{th} cluster. With the mean energy of the first path of the first cluster being denoted by Ω_0, the mean energy of $\alpha_{k,l}$ is given by [16]:

$$\mathrm{E}\left[\left|\alpha_{k,l}\right|^2\right] = \mathrm{E}\left[\left|\xi_l \beta_{k,l}\right|^2\right] = \Omega_0 e^{-(T_l/\Gamma)} e^{-(\tau_{k,l}/\gamma)} \quad (12)$$

where Γ is the cluster decay factor and γ is the ray decay factor. The distribution of the path gain magnitude $|\alpha_{k,l}|$ is assumed to be log-normally distributed:

$$20\log_{10}\left(\xi_l \beta_{k,l}\right) \sim N\left(\mu_{k,l}, \sigma_1^2 + \sigma_2^2\right), \quad (13)$$

where σ_1 is the standard deviation of the cluster log-normal fading (in dB) and σ_2 is the standard deviation of the ray log-normal fading (in dB). From (12) and (13), we obtain:

$$\mu_{k,l} = \frac{10\ln\Omega_0 - 10T_l/\Gamma - 10\tau_{k,l}/\gamma}{\ln 10} - \frac{\ln 10\left(\sigma_1^2 + \sigma_2^2\right)}{10} \quad (14)$$

Finally, with a standard deviation of σ_x in dB, the log-normal shadowing term X is characterized by

$$20\log_{10} X \sim N\left(0, \sigma_x^2\right) \quad (13)$$

Since we can capture the total multipath energy in term X, the total energy contained in the terms $\{\alpha_{k,l}\}$ is normalized to unity for each realization.

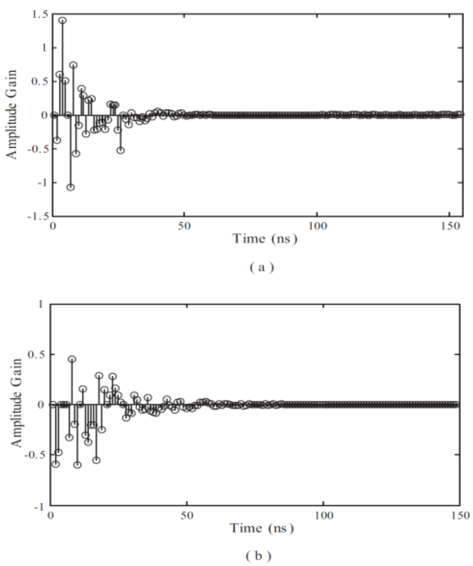

Figure 12 Impulse response of (a) CM1 (b) CM2.

In IEEE 802.15 working group, the UWB channel is further classified into four models. Channel model 1 (CM1) represents Line-Of-Sight (LOS) and distance from 0 to 4 m UWB channel, while channel model 2 (CM2) represents Non-Line-Of-Sight (NLOS) and distance from 0 to 4 m UWB channel. Distance from 4 m to 10 m and NLOS UWB channel is modeled as CM3 and distance over 10 m NLOS UWB channels are all classified into the extreme model CM4. The simulation parameters setting for all the four channel models are listed in Table II [16].

With the exact channel parameters listed in Table II, the UWB channels for all the four channel scenarios are simulated using the Saleh-Velenzuela model. The simulated channel impulse responses for CM1, CM2, CM3 and CM4 are shown in Figures 12(a), 12(b), 13(a) and 13(b), respectively.

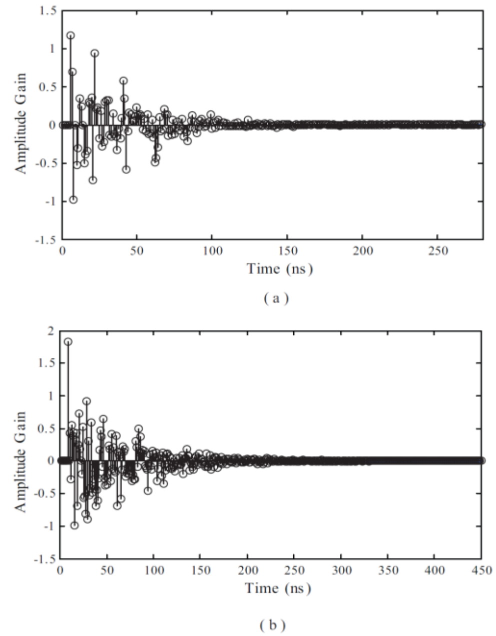

Figure 13 Impulse response of (a) CM3 (b) CM4.

9. UWB RECEIVERS

A general UWB receiver block diagram is shown in Figure 14. The receiver performs the inverse operation of the transmitter to recover the data. As shown in the Figure 14, the first block of the receiver includes many parts such as acquisition, tracking, demapping pulse shapes-to-symbols, etc. This block performs the functions of detection or acquisition to locate the required pulses amongst the other signals and then to continue tracking these pulses to compensate for any mismatch between the clocks of the transmitter and the receiver. The second block is pulse generation that generates the template pulse for the use of detecting the received signals of a first block. The last block is a symbol to bits. This block converses an analog pulse shape to the binary data stream.

The most common UWB receiver design includes threshold/energy detectors, correlation detectors, RAKE and transmit-reference (TR) receivers. The threshold/energy detectors are simple to implement. However, this receiver is a trade-off between the simplicity and the performance. The correlation receiver is a matched filter system and it can provide the optimum detection SNR if the template wave- form exactly matches the time and shape of the incoming waveform. However, this receiver has high complexity from the match filter structure. RAKE receivers are a bank of correlators. Each finger of the RAKE is synchronized to a

Table II. Parameter Settings for IEEE UWB Channel Models.

Scenario	Λ (1/ns)	λ (1/ns)	Γ (ns)	γ (ns)	σ_1 (dB)	σ_2 (dB)	σ_3 (dB)
CM1 LOS (0-4 m)	0.0233	2.5	7.1	4.3	3.3941	3.3941	3
CM2 NLOS (0-4 m)	0.4	0.5	5.5	6.7	3.3941	3.3941	3
CM3 NLOS (4-10 m)	0.0667	2.1	14	7.9	3.3941	3.3941	3
CM4 Extreme NLOS	0.0667	2.1	24	12	3.3941	3.3941	3

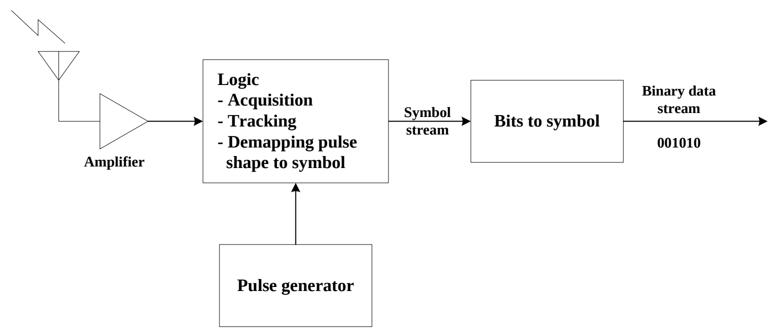

Figure 14 A general UWB receiver block diagram.

multipath component. Most of early receiver researches focused on RAKE type of receivers. Recently due to the difficulty and complexity from stringent timing synchronization requirement and energy capture of multipaths, suboptimal TR (also called autocorrelation) receivers attract significant attentions. Next we will look into the ideas of the RAKE and the TR receiver structures, and compare their advantages and disadvantages.

9.1. RAKE Receivers

For AWGN channels, the typically optimum receiver is a correlator (i.e. match filter) receiver. The local receiver generated template waveform is perfectly synchronized and correlated with the incoming pulse train, which is only distorted by AWGN noise.

For impulse-radio UWB systems, the UWB transmissions can resolve many paths and are thus rich in multipath diversity. RAKE receivers can be used to exploit the diversity by constructively combining the separable received multipath components. It consists sub-receivers each of which delays to tune into the individual multipath components. Each branch of the RAKE receivers is a correlator (match filter) that collects coherent received signal energy independently. The output of each finger is combined in order to make the most use of the different transmission characteristics of each transmission path. This can be very well result in higher signal- to-noise ratio (SNR, also known as Eb/N0) in a multipath environment.

Figure 15 shows the receiver block diagram, which con- sists of L_p correlators/fingers to collect the received signal energy from the L_p strongest paths having excess delays $\{\tau_l\}\big|_{l=0}^{L_p-1}$. The l^{th} correlator, $l = 0,1,2,\ldots,L_p - 1,$, is to correlate the received signal with the receiver locally generated reference signal delayed by τ_l . The output of the correlators can be linearly combined in different ways to form the decision variable. The maximal ratio combining (MRC) approach provides optimal performance, with the prerequisite of accurate channel information at the receiver. As accurate channel information are not available, equal gains combining (EGC) and some other methods could be selected.

9.2. Transmit-reference Receivers

From the previous subsection, we know that the coherent RAKE receivers offer optimal performance that rely on enough fingers to accurately capture all or a significant part of resolvable multipath components (MPCs) [18-19]. In a pulse based UWB systems, the number of resolvable paths could reach tens to over a hundred in typical indoor propagation environments [20], which impose technical hurdles as well as implementation difficulties. In order to capture a

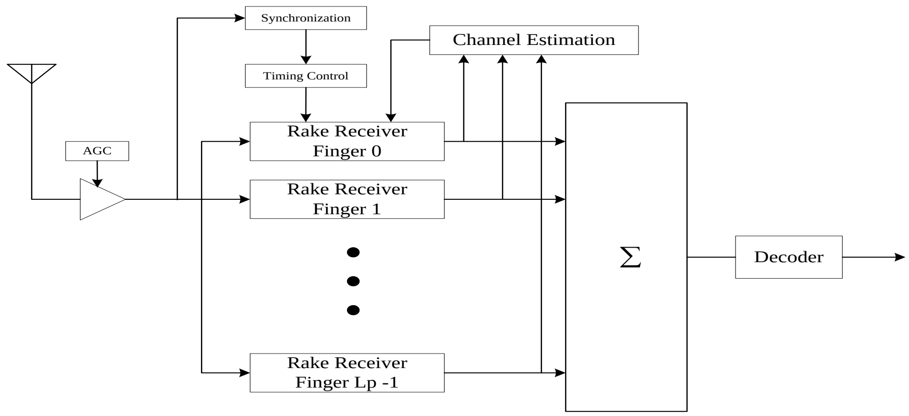

Figure 15 Block diagram of a typical RAKE receiver structure.

considerable portion of the signal energy scattered in multipath components, a conventional RAKE-based digital receiver not only has to sample and operate at a minimum of hundreds of MHz to even multi-GHz clock rates, but also requires an impractically large number of RAKE fingers. In addition, realizing optimal RAKE reception performance requires accurate channel and timing knowledge, which is quite challenging to obtain as the number of resolvable paths grows. The received pulse shapes of resolvable multipath are distorted differently due to diffraction, which make it suboptimal to use line-of-sight signal waveform as the correlation template in RAKE reception. Since these issues are unique to the UWB pulsed radios, an optimal RAKE receiver design becomes either ineffective or very complicated.

For these reasons, TR receivers (also called autocorre lation receivers) have drawn significant attention in recent years [21-22]. As a suboptimal, low-complexity alternative, TR receivers offer a better multipath capture capability at much lower hardware complexity than RAKE receivers. TR encodes the data in the phase difference of the two pulses of a pulse pair. The first pulse in that pair does not carry information, but serves as a reference pulse; the second pulse is modulated by the data and is referred to as the data pulse. The two pulses are separated by a fixed delay. It can be easily shown that the receiver can demodulate this signal by simply multiplying the received signal with a delayed version of itself. The simple TR transceiver structure is shown by the block diagram in Figure 16.

In a slow fading environment, TR collects multipath energy efficiently without requiring multipath tracking or channel estimation. Analog autocorrelation also alleviates the burden on A/D converters, thus lowering the power consumption by interface circuits in the UWB regime. However, TR autocorrelators entail several drawbacks and usually show worse performance than coherent RAKE receivers: the use of reference pulses increases transmission overhead and reduces data rate, which results in reduced transmission power efficiency; the bit error rate (BER) performance is limited by the noise term in the reference signal [22]. Finally, the performance of TR receivers relies on the implementation of accurate analog delay lines which can save and delay the reference waveforms for up to tens of nanoseconds. This is still a big challenge to current circuit technology.

10. Challenges for Ultra-Wideband

While UWB has many reasons to make it an exciting and useful technology for future wireless communications and many other applications, it also has some challenges which must be overcome for it to become a popular and ubiquitous technology.

Perhaps the most obvious one to date has been regulatory problem. Wireless communications have always been regulated to avoid interference between different users whose spectrum. Since UWB occupies such a wide bandwidth, there are many users whose spectrum will be affected and need to be convinced that UWB will not cause undue interference to their existing services. In many cases these users have paid to have exclusive use of the spectrum. One solution for solving this problem is pulse design techniques.

Apart from the pulse design problem, UWB systems are also very sensitive to a timing jitter. Timing jitter results from the presence of non-ideal sampling clocks in practical receivers. This distortion affects the correlation of signals at the receiver and thus the signal detection ability of UWB systems. Since UWB pulse duration is very short (in the range of a nanosecond), only small timing misalignment can severely affect the performance of a correlation detector.

Finally, how to apply the other application combine with UWB systems especially the wireless networks. The IR-UWB system which is characterized by the transmission of extremely short duration pulses (very low duty-cycle) can enable very accurate ranging and location applications. The UWB applications are popular in the wireless network application. UWB based wireless networks ranging and positioning techniques can achieve centimeter-level precision as well as high data rate, low power and complexity. Therefore, we review many researches about the wireless location network.

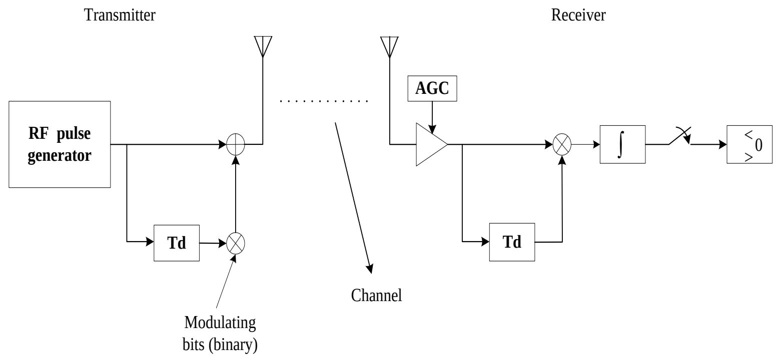

Figure 16 Block diagram of a transmit-reference system.

10.1. Pulse Shap Design

The conventional pulse, Gaussian 2^{nd} derivative pulse, is widely adopted in the investigation of UWB applications due to mathematical convenience and ease of generation [14, 23]. Unfortunately, this pulse is not flexible enough to conform the FCC spectral masks. Thus, the Gaussian mono- cycle pulse must be modified and filtered to meet the FCC requirements [24-27]. One of the techniques to modified Gaussian monocycle is the method based on the linear combination of a number of Gaussian derivative pulses to form on single pulse that are introduced in [28-29]. In [29], W. Gao, R. Venkatesan and C. Li generated pulse using the combination of Gaussian derivative pulses from the 1^{st} to 15^{th} ones. The power spectral density (PSD) of this technique conforms the FCC spectral masks. However, this combination makes the implementation of the pulses very complicated.

In the literature, the pulse design techniques are categorized according to two criteria for a pulse design. Most of those works [30-50] consider a s the methods of obtaining pulse that meets the power spectral constraint of FCC masks. The other portion [51-53] devotes to the design of pulse that provides timing jitter tolerance. However, the later group spans only small number of works concerning with the optimal pulse design.

The pulse generation algorithms fitting the FCC masks can be grouped into three different techniques. Firstly, the most straight-forward method probably is the digital generation from sampled frequency response [30-31]. The implementation of this technique is prohibitively limited

by the need of extremely high sampling rate digital to an analog (D/A) converter. Secondly, the method is based on linear combination of orthogonal pulse sets. The orthogonal pulse families are ranged from Prolate Spheroidal, Wavelet to Modified Hermite Pulse [32-45]. For the Prolate Spheroidal schemes, A. B. Parr, B. L. Cho and Z. Ding presented a pulse design algorithm for acquiring a set of orthogonal UWB impulse with limited time duration subject to a pre-selected frequency mask [32] in 2003. In addition, L. Yin and Z. Hongbo [33] proposed an optimized pulse design by using the Approximate Prolate Spheroidal Wave Functions (APSWF) in 2005. Their pulses meet the power spectral constrain and simple mathematical expression. Unfortunately, the mutual orthogonality of the pulses, which are generated using the prolate spheroidal function, are not preserved with the distortion of channel and the characteristics of antennas. Thus, this pulse design algorithm does not provide the orthogonality for received pulses which have notable impact on the performance of the correlation receiver [32]. Therefore, the new orthogonal pulse based on wavelet technique is proposed in [34-35] for a UWB pulse design that can maintain orthogonality at a receiver. Moreover, other linear combination pulse techniques such as Nyquist criteria or term of B-splines are proposed in [44-45]. These works offer a design of pulses that meet the FCC spectral masks and have time-limit signals for no intersymbol interference (ISI).

A popular technique of the linear combination pulse is based on the modified Hermite polynomials (HP) that are proposed in [36-43]. Hermite pulses are orthogonal to one another; this orthogonality suggests that variety of designs making use of simultaneous pulse transmission can be considered. Furthermore, these waveforms are well confined in both time and frequency, ensuring that all pulses have the same duration, which relates to achievable data rate, while maximizing frequency efficiency. Therefore, many works investigate the orthogonal UWB pulse using this method. In 2003, G. T. F. de Abreu, C. J. Mitchell and R. Kohno [36] presented orthogonal pulse of transmit waveform that are constructed as the combination of elementary Hermites with weighting coefficients derived by employing the Gram-Schmidt factorization. They originally established orthogonal pulse in UWB systems, but their pulses did not consider the condition of power spectral density limitation. In 2005, W. Hu and G. Zheng [37] proposed M-ary biorthogonal modulation based on orthogonal Hermite Pulse Shapes whose frequency response met the FCC standard. For the TH-PPM UWB system, J. G. Xing, Z. H. Bo and C. Wei [38] presented the design of a class of pulses that were based on Hermite functions. However, the high order of these pulses would be more susceptible to timing jitter. In 2007, X. L. Wu, X. J. Sha and N. T. Zhang [42] suggested a modified Hermite function based pulse shaping algorithm on the TH-PPM UWB system. The pulse duration presented in this study is shorter than orthogonal Hermite pulse in [38]. Unfortunately, frequency shifting and bandpass filters are required for the HP of order 0 or 1 and higher order HP, to satisfy the FCC spectral masks. High order HP pulses are susceptible to timing jitter and noise, and they also need bandpass filters to fit their PSD into the FCC mask [54].

The pulse design techniques, based on famous orthogonal pulse sets, gain from the rich knowledge of those pulse sets. However, these techniques are also difficult to implement due to the need of hundreds of pulse generators. This problem can even more severe if the pulse generator creates drifts or offsets during the generation process. Some authors suggested the digital implementation of such orthogonal pulse transformation [55]. However, the digital implementation of low duty cycle signals leads to the expensive hardware as in the case of D/A technique.

The last technique, the digital FIR filter solution, differs from the previous two methods because it does not aim to directly generate the desired pulse. On the other hand, it synthesizes the desired pulse by filtering the conventional input pulse, such as monocycle which was proposed in [46-50]. In 2003, X. Luo, L. Yang and G. B. Giannakis [48] proposed digital FIR filter design based on the Parks-McClellan (PM) algorithm for shaping UWB pulses under mask-fitting requirements [3]. The PM design utilizes the bandwidth (BW) and power allowed by the FCC spectral masks, and it can dynamically avoid narrow-band interference. However, trial-and-error may be required to find suitable values for the implicit parameters in a PM design including the edge tolerances of the pass- and stop-bands, and the frequency weighting of the approximation error. In 2006, X. Wu, Z. Tian, T. N. Davidson and G. B. Giannakis [49] introduced a globally optimal pulse design method based on semidefinite programming (SDP) to maximize the power utilization efficiency while complying with the spectral mask. The digital FIR filter technique was proposed to avoid the extremely high sampling rate implementation of the direct impulse optimization method. In addition, the direct pulse optimization also suffers from numerical instability because of the complicated optimization of very large number of variables. The optimization of FIR filter involves much smaller number of variables thus it is more attractive in the implementation perspective.

10.2. Timing Jitter Problem

For the prior research on the performance of timing jitter, it can be separated into two forms - as uncorrelated (white timing jitter) and correlated (colored timing jitter). The performance of UWB systems under white timing jitter has been extensively studied by many works [56-63]. In 2002, W. M. Lovelace and J. K. Townsend [56] considered the effects of timing jitter performance of binary and orthogonal 4-ary PPM UWB communications. Moreover, they also investigated the tracking error performance on UWB systems. I. Guvenc and H. Arslan [57] presented UWB systems performance by evaluating the degradation of the signal-to-noise ratio due to timing jitter. They present the BER performance of various modulation options for UWB systems such as PAM, PPM, OOK and BPSK. Moreover, they consider another practical condition, including multipath, multiple access interference (MAI) and narrowband interference (NBI). In 2004, L. Mucchi, D. Marabissi, M. Ranaldi, E. Del Re, and R. Fantacci [58] compared the sensitivity to synchronization errors of the different multiple access techniques between the TH-PPM and the DS. Their results show that the TH technique overcomes DS when timing jitter occurs. In 2005, C. S. Sum, M. A. Rahman, S. Sasaki and J. Zhou [60] presented the impact of timing jitter on a DS-UWB system in AWGN and multipath channel. Investigation is performed in different Rake receivers (all-Rake and selective-Rake) and two types of timing jitter (uniformly and Gaussian distributed). In 2005, Z. Tian and G. B. Giannakis [61], [62] presented the BER sensitivity to epoch timing offset under different operating conditions, including frequency-flat fading channels, dense multipath fading channels, multiple access with and without time hopping, and various receiver types including sliding correlators and RAKE combiners. In 2006, N. V. Kokkalis, P. T. Mathiopoulos, G. K. Karagiannidis, and C. S. Koukourlis [63] also studied the performance of UWB under timing jitter. They consider the BER performance of M-ary PPM which is not the same as that reported in [56] in the presence of MUI. In addition, our work [64] investigated the effect of pulse shapes to timing jitter tolerance. The simulation results confirm that different pulses are the result of different level of immunity to timing jitter. The pulses having relatively flat autocorrelation function tend to be less sensitive to timing jitter.

On the other hand, the performances of UWB systems under colored timing jitter have been studied as follow. In 2004, P. B. Hor, C. C. Ko and W. Zhi [65-66] presented the BER performance of the pulse UWB system in the presence of colored timing jitter. They found that colored jitter degrades the BER performance more than white jitter and they are proposed a new jitter compensation scheme to improve the BER performance under colored jitter. In 2006, U. Onunkwo, Y. Li and A. Swami [67] investigated the impact of timing jitter on OFDM-based UWB systems and derived an exact expression for the ICI power due to timing jitter. For mathematical simplification, however, many works investigated timing jitter that has a normal distribution [56], [58], [63]. Thus, in this dissertation, we will use timing jitter modeled by the normal distributed random process.

Besides performance evaluation of timing jitter, the prior works in an attempt to alleviate the effect from timing jitter have been studied. These proposed methods can be categorized in two approaches: improve the timing synchronization accuracy and improve timing jitter involving the pulse shape. The first scheme which is techniques for improving the timing synchronization accuracy is proposed in [68-73]. In 2005, W. Zhang, Z. Bail, H. Shen, W. Liu and K. S. Kwak [68] proposed a virtual received waveform as integration of time-shifted version of conventional received waveform and the distribution of timing jitter. However, they neither clearly state the motivation of their virtual received waveform design nor show method in obtaining timing jitter distribution. The on- off keying modulation scheme is considered by Q. Li and W. S. Wong in [69]. A receiver is proposed to over-sampling the received waveform and the optimum threshold is determined by a version of Kiefer-Wolfowitz algorithm. The technique, proposed in [69], is difficult to apply to other popular modulation systems such as PPM or PAM. In 2006, S. Gezici, Z. Sahinoglu, H. Kobayashi and H. V. Poor proposed multi-user UWB systems that use multiple pulse waveforms [73]. For the conventional system that uses single pulse waveform, pulse with fast decaying autocorrelation function is desired in order to prevent interframe interference. However, such an autocorrelation function also results in a considerable de- crease in the desired signal part of the receiver output in the presence of timing jitter [74]. In 2007, R. Merz, C. Botteron and P. A. Farine [75] estimated the BER performance for a UWB impulse radio in an AWGN transmission channel and with Gaussian jitter. They investigated the influence of the jitter on the received signal by assuming that the received pulses are combined to increase the SNR. Though, the timing synchronization accuracy is limited by the advancement of both algorithms and equipments. It seems to be impossible to perfectly synchronize the timing in the near future.

The other approach that proposed by G. T. F. de Abreu and R. Kohno in 2005 to improve the robustness against timing jitter involves the pulse shape optimization [51]. In [51], the authors exploited the autocorrelation properties of the modified Hermite pulses to generate a pulse. Their works inherently lead to a relatively flat pulse. The pulse, obtained from the algorithm in [51], is a single polarized pulse with large time duration. Such pulse has narrow bandwidth, which does not efficiently utilize the allocated spectrum and violates the wide continuous bandwidth requirement. Moreover, Y. Chen and J. Chen and T. Lv [52] proposed a novel technique that couples High Order Monocycle (HOM) with biphase modulation (BPM) to achieve timing jitter-robust in UWB systems. However, the proposed technique finding high order monocycle pulse tends to lengthen the pulse duration, thereby reducing the data rate and system capacity as a result of [25]. In 2007, a new method for constructing UWB pulse based on Daubechies wavelets is proposed by L. Xin, A. B. Premkumar and A. S. Madhukumar [53]. The constructed pulse not only meets the FCC masks, but also provides good performance in the presence of timing jitter. However, the proposed pulse of this previous study has utilized low spectral mask and the high order tends to lengthen the pulse duration. This result of lengthening the pulse duration is the same as that yielded by using the technique in [52].

In 2008, W. Lee, S. Kunaruttanapruk and S. Jitapunkul [76] jointly consider two crucial problems such as pulse transmission power and timing jitter tolerance. They proposed a novel technique in designing the optimum pulse shape for UWB systems under the presence of timing jitter. The proposed pulse attains the adequate power to survive the noise floor and simultaneously provides good robustness to timing jitter. It also meets the power spectral mask restriction as prescribed by the FCC for the indoor UWB systems. Moreover, the implementation of the proposed pulse and the essential parameters of the proposed optimization algorithm are also investigated.

10.3. Localization Technique

The well-known localization techniques such as Angle of Arrival (AOA), Received Signal Strength Indication (RSSI) and Time of Arrival (TOA) are considered in many literatures
[77-81]. An AOA-based positioning technique involves measuring angles of the target node seen by reference nodes, which are done by means of antenna arrays. However, the AOA scheme is not suited to UWB positioning because this method use of antenna arrays that increase the system cost. Moreover, an AOA technique also difficult to find the accuracy angle estimation due to the number of scattering from objects in the environment may be very large owing to the large bandwidth of a UWB signal. For RSSI technique, different wireless technologies, like WiFi and ZigBee are normally use the RSSI for finding the indoor localization. However, the main problem of RSSI estimation is that position errors are nearly 1 meter, which is unacceptable for wireless network localization.

The IR-UWB system which is characterized by the transmission of extremely short duration pulses (very low duty-cycle) can enable very accurate ranging and location applications. This high time resolution nature of the UWB signal makes TOA estimation method a good candidate for positioning estimation in UWB communications. We selected TOA method because it can be shown that it achieves the best accuracy related with Cramer-Rao lower bound (CRLB) [77]. The different transceiver types such as the SR and ED are common used in TOA estimation techniques for IR-UWB systems. In [78-79], they consider the tradeoffs between SR- and ED-based transceiver architectures by using the raised cosine pulse. They found that when the system has a sufficient sampling rate and no time mismatch, the SR performance is better than the ED approach. If only lower sampling rates are possible, the SR performance will be quickly decreased because it can not be able to collect sufficient energy. On the other hand, if the symbol energy is spread over more pulses, the ED schemes suffer from degraded SNR than SR approach. [80] presents the performance of TOA estimation with different signal waveforms such as direct sequence impulse radio (DS-IR), transmitted reference impulse radio (TR-IR), time hopping impulse radio (TH-IR) and M-ary ternary orthogonal keying impulse radio (MTOK-IR) by using non-coherent receiver, the energy detection. In [81] considers the different Gaussian derivative pulses on ranging and positioning based on the estimation of TOA with IR-UWB signal. Their simulation results show that the higher order Gaussian pulse is advised to be exploited in order to improve the accuracy of range and position estimation.

11. CONCLUSION

In this paper, we review the some basic knowledge of UWB systems, namely, UWB transmitter, UWB channel model and UWB receiver. At UWB transmitter, we show the conventional modulation scheme and the multiple access techniques of UWB systems. We summarized the advantages and disadvantages of the various modulation methods. The UWB channel model in S-V model is also discuss. At UWB receiver, two well-known receiver types e.g., RAKE and Transmitted-reference are reviewed. Finally, we discuss three hot topics including pulse shape design, timing jitter problem and localization techniques in UWB systems.

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