Ultra Wide Band Technology: Performance of Physical Layer

Major Project Report

Submitted in partial fulfillment of the requirements

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In

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By

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Declaration

This is to certify that

i) The thesis comprises my original work towards the degree of Master of Technology in Communication Engineering at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgement has been made in the text to all other material used.

Patel Anand Vallabhbhai

Certificate

This is to certify that the Major Project entitled **"Ultra Wide Band Technology : Performance of Physical Layer"** submitted by **Patel Anand Vallabhbhai (08MECC12)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Electronics & Communication (Communication) of Nirma University, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of our knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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When I first started my M.Tech. journey,I was alone at some place without any map. I started learning,and making tracks on my own way. Today, the way to my destination is almost complete,and I hope it could be useful for others to reach their destination, who may already have started their trips or will be on the way to their M.Tech soon. There are frustrations during the journey, but the path finally led to some new and useful discoveries, which motivate me to keep the journey on. Many individuals have played important roles during my journey and have extended me a helping hand when I was about to fall. I cannot make it without the help and support from these people.

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- Patel Anand Vallabhbhai

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Abstract

Despite the fact ultra-wideband (UWB) technology has been around for over 30 years, there is a newfound excitement about its potential for communications. With the advantageous qualities of multipath immunity and low power spectral density, researchers are examining fundamental questions about UWB communication systems.

In this work, I analyze following features.IR-UWB is a potential physical layer for sensor networks and emerging pervasive wireless networks.Their average data-rate is low, on the order of a few megabits per second. IR-UWB physical layers are attractive for these networks because they potentially combine low-power consumption, robustness to multipath fading and to interference, and location/ranging capability.

• Detailed discussion of the fundamentals of UWB technology, short-pulse generation, UWB modulation and multiple-access techniques, as well as UWB applications.

• Comparative analysis of UWB, narrowband, and spread-spectrum wideband communication systems, emphasizing the strengths and weaknesses of UWB technology compared to traditional continuous-wave wireless communications techniques.

• In one part of this thesis, I am interested in IEEE 802.15.4a, a standard for low data-rate, low complexity networks that employs an IR-UWB physical layer.

• Comprehensive bibliographies at the end of the thesis to help readers delve further into the concepts discussed in the thesis.

In this report, I derive the performance graphs for UWB communication systems using different combining techniques in a RAKE Receiver. Comparisons have also been made between the techniques and conclusions have been drawn based on the requirements. I also incorporate the effect of number of fingers on the performance of the receivers. The results obtained give me way to evaluate the performance of Rake reception of UWB signals in dense multipath channels. I present simulation results using IEEE 802.15.3a UWB channel models. I evaluate the performances of Rake Receivers with different pulse-widths.

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Chapter 1

Introduction

1.1 Introduction

The recent rapid growth in technology and the successful commercial deployment of wireless communications are significantly affecting our daily lives. The transition from analog to digital cellular communications, the rise of third-and fourth-generation radio systems, and the replacement of wired connections with Wi-Fi and Bluetooth are enabling consumers to access a wide range of information from anywhere and at any time. Consumers will soon demand the same conveniences throughout their digital home, connecting their PCs, personal digital recorders, MP3 recorders and players, digital camcorders and digital cameras, High Definition TVs (HDTVs), Set Top Boxes (STBs), gaming systems, Personal Digital Assistants (PDAs), and cell phones, to connect to each other in a Wireless Personal Area Network (WPAN) in the home.

But todays wireless LAN and WPAN technologies cannot meet the needs of tomorrows connectivity of such a host of emerging consumer electronic devices that require high bandwidth. A new technology is needed to meet the needs of high-speed WPANs. 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 more and more strict with the introduction of new radio services.

Ultra Wide Band (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.[2]

1.2 Historical Background

Ultra Wide Band communications is fundamentally different from all other communication techniques because it employs extremely narrow RF pulses to communicate between transmitters and receivers. The main reason to use short-duration pulses for communications directly generates a very wide bandwidth and offers several advantages, such as large throughput, robustness to jamming, and coexistence with current radio services1.4.

Approximately fifty years after Marconi, modern pulse-based transmission gained momentum in military applications in the form of impulse radars. Some of the pioneers of modern UWB communications in the United States from the late 1960s are Henning Harmuth of Catholic University of America and Gerald Ross and K. W. Robins of Sperry Rand Corporation [3]. From the 1960s to the 1990s, this technology was restricted to military and Department Of Defense (DoD) applications under classified programs such as highly secure communications. However, the recent advancement in microprocessing and fast switching in semiconductor technology has made UWB ready for commercial applications. Therefore, it is more appropriate to consider UWB as a new name for a long-existing technology.

As interest in the commercialization of UWB has increased over the past several years, developers of UWB systems began pressuring the FCC to approve UWB for commercial use. In February 2002, the FCC approved the First Report and Order

(R&O) for commercial use of UWB technology under strict power emission limits for various devices. 1.9.1 and 1.10 present a detailed recent history of the standardization and worldwide regulation of UWB technology. Figure 1.1 summarizes the development timeline of UWB.

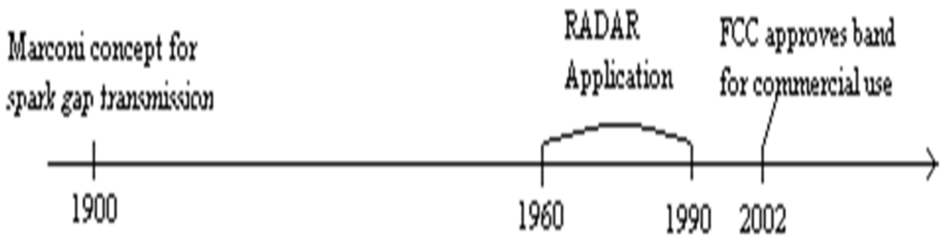

Figure 1.1: A brief history of UWB developments

1.3 UWB Concepts

The significant reason for existence of UWB technolgy is the traditional narrowband communication system which modulate Continuous Waveform (CW) RF signals with a specific carrier frequency to transmit and receive information. In that continuous waveform has a well-defined signal energy in a narrow frequency band that makes it very vulnerable to detection and interception. Figure 1.2 represents a narrowband signal in the time and frequency domains.

As mentioned in Section 1.2, UWB systems use carrierless, short duration (picosecond to nanosecond) pulses with a low duty cycle (less than 0.5 percent) for transmission and reception of the information. A simple definition for **duty cycle** is the ratio of the time that a pulse is present to the total transmission time. Figure 1.3 and Equation1.1 represent the definition of duty cycle.

$$DutyCycle = \frac{T_{on}}{T_{off} + T_{on}} \tag{1.1}$$

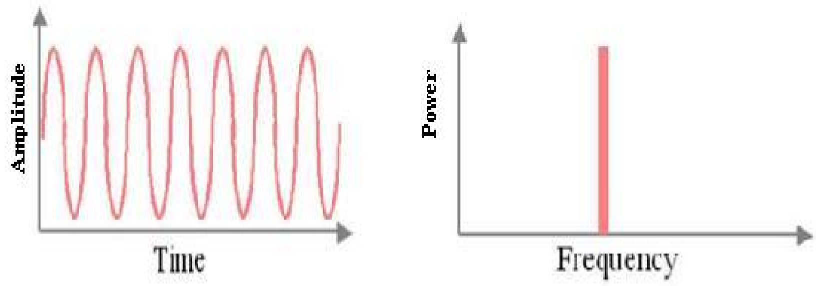

Figure 1.2: A narrowband signal in (a) the time domain and (b) the frequency domain

However, the peak or instantaneous power of individual UWB pulses can be relatively large**??**, but because they are transmitted for only a very short time ($Ton < 1$ nanosecond), the average power becomes considerably lower. Consequently, UWB devices require low transmit power due to this control over the duty cycle, which directly translates to longer battery life for handheld equipment.

As frequency is inversely related to time, the short-duration UWB pulses spread

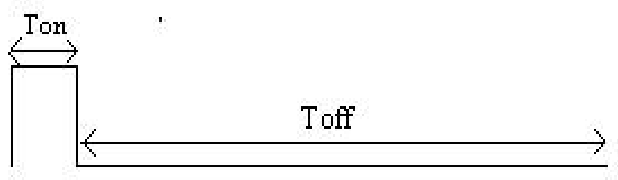

Figure 1.3: A low-duty-cycle pulse. Ton represents the time that the pulse exists and Toff represents the time that the pulse is absent.

their energy across a wide range of frequencies from near DC to several Gigahertz (GHz)with very low Power Spectral Density (PSD)[4]. The peak power of UWB pulses is reported to be about 1 watt for 1 Mbps at 1 MHz.Power spectral density is the signals' power in the frequency domain. Figure 1.4 illustrates UWB pulses in time and frequency domains.

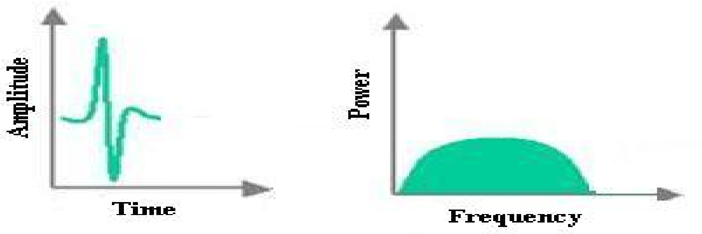

Figure 1.4: A UWB pulse in (a) the time domain and (b) the frequency domain

Definition of fourier transform (time scaling) results wide bandwidth as per following equation said:

$$x(at) = \frac{1}{\mid a \mid} X(\frac{f}{a}) \tag{1.2}$$

1.4 UWB Signals

As defined by the FCC's First Report and Order, UWB signals must have bandwidths of greater than 500 MHz or a fractional bandwidth larger than 20 percent at all times of transmission **??**.

Fractional bandwidth is a factor used to classify signals as narrowband, wideband, or ultra-wideband and is defined by the ratio of bandwidth at 10 dB points[5] to center frequency. The equation1.3 shows this relationship.[5] The 10 dB point represents the spectral power of a signal at 10 dB lower than its peak power.

$$B_f = \frac{BW}{f_c} \times 100\% = \frac{(f_h - f_l)}{\frac{(f_h + f_l)}{2}} \times 100\% \tag{1.3}$$

where f_h and f_l are the highest and lowest cutoff frequencies (at the 10 dB point) of a UWB pulse spectrum, respectively.

A UWB signal can be any one of a variety of wideband signals, such as Gaussian, chirp, wavelet, or Hermite-based short-duration pulses. For this thesis I am using only Gaussian pulses. The Gaussian monocycle is the first derivative of a Gaussian pulse and is given by,

$$P(t) = \frac{t}{\tau}e^{-}(\frac{t}{\tau})^2 \tag{1.4}$$

where t represents time and τ is a time decay constant that determines the temporal width of the pulse.

In following ways signals can be classified based on their fractional bandwidth:

Narrowband	Bf < 1%
Wideband	1% < Bf < 20%
Ultra-Wideband	Bf > 20%

For example, 802.11 and Bluetooth have fractional bandwidths of 0.8 percent and 0.04 percent, respectively.

1.5 Benefits

[6] Here are some of the benefits that put UWB technology into a row of wireless communication. Here some of the significant benefits have discussed.

1.5.1 Ability To Share The Spectrum

The FCC's power requirement of -41.3 dBm/MHz[7], equal to 75 nanowatts/MHz for UWB systems, puts them in the category of unintentional radiators, such as TVs and computer monitors. Such power restriction allows UWB systems to reside below the noise level of a typical narrowband receiver and enables UWB signals to coexist with current radio services with minimal or no interference. However, this all depends on the type of modulation used for data transfer in a UWB system[7].

The abbreviation dBm stands for decibels per milliwatt. Hence, -41.3 dBm/MHz is equal to 75 nW/MHz. As discussed in section 2.3, some modulation schemes generate undesirable discrete spectral lines in their PSD, which can both increase the chance of interference to other systems and increase the vulnerability of the UWB system to interference from other radio services.

In section 1.6.4, the detailed discussion on interference from UWB on narrowband and wideband radio systems is given. Figure 1.5 illustrates the general idea of UWB's coexistence with narrowband and wideband technologies.

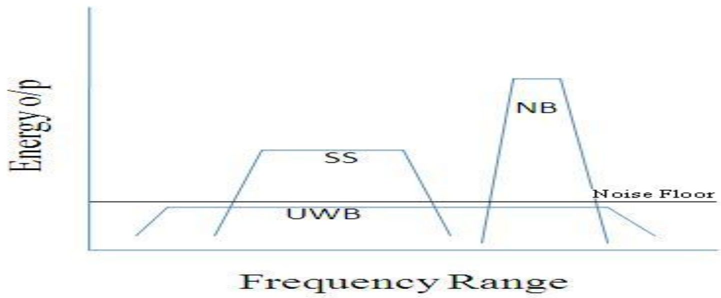

Figure 1.5: Coexistence of UWB signals with narrowband and wideband signals in the RF spectrum

1.5.2 Maximum Channel Capacity

Channel capacity, or data rate, is defined as the maximum amount of data that can be transmitted per second over a communications channel. The large channel capacity of UWB communications systems is evident from Hartley-Shannon's capacity formula:

$$C = Blog_2(1 + SNR)[8] \tag{1.5}$$

where C represents the maximum channel capacity, B is the bandwidth, and SNR is the signal-to-noise power ratio.

As shown in above Equation1.5, channel capacity C linearly increases with bandwidth B. Therefore, having several gigahertz of bandwidth available for UWB signals, a data rate of gigabits per second (Gbps) can be expected.

This makes UWB systems perfect candidates for short-range, high-data-rate wireless applications such as Wireless Personal Area Networks (WPANs). The **trade-off** between the range and the data rate makes UWB technology ideal for a wide array of applications in military, civil, and commercial sectors.

1.5.3 Ability To Work With Low Signal-to-Noise Ratios

The Hartley-Shannon formula for maximum capacity 1.5 also indicates that the channel capacity is only logarithmically dependent on Signal to Noise Ratio (SNR). Therefore, UWB communications systems are capable of working in harsh communication channels with low SNRs and still offer a large channel capacity as a result of their large bandwidth.

1.5.4 Low Probability Of Intercept And Detection

Because of their low average transmission power, as discussed in 1.3, UWB communications systems have an inherent immunity to detection and intercept. With such low transmission power, the eavesdropper has to be very close to the transmitter (about 1 meter) to be able to detect the transmitted information. In addition, UWB pulses are time modulated with codes unique to each transmitter/receiver pair. The time modulation of extremely narrow pulses adds more security to UWB transmission, because detecting nanosecond pulses without knowing when they will arrive is next to impossible. Therefore, UWB systems hold significant promise of achieving highly secure, low probability of intercept and detection **(LPI/D)** communications that is a critical need for military operations.

1.5.5 Resistance To Jamming

The UWB spectrum covers a wide range of frequencies up to several gigahertz and offers high processing gain for UWB signals. **Processing Gain** (PG) is a measure of a radio system's resistance to jamming and is defined as the ratio of the RF bandwidth to the information bandwidth of a signal:

$$PG = \frac{RFBandwidth}{InformationBandwidth} \tag{1.6}$$

The frequency diversity caused by high processing gain makes UWB signals relatively resistant to intentional and unintentional jamming, because no jammer can jam every frequency in the UWB spectrum at once.

1.5.6 High Performance In Multipath Channels

The term **multipath** is very much significant as far as wireless scenario concern. It is caused by multiple reflections of the transmitted signal from various surfaces such as buildings, objects, trees, and people. The straight line between a transmitter and a receiver is the Line Of Sight (LOS); the reflected signals from surfaces are Non Line Of Sight (NLOS). Figure 1.6 represents the multipath phenomenon in narrowband and UWB signals. As shown in 1.6, the effect of multipath is rather severe for narrowband

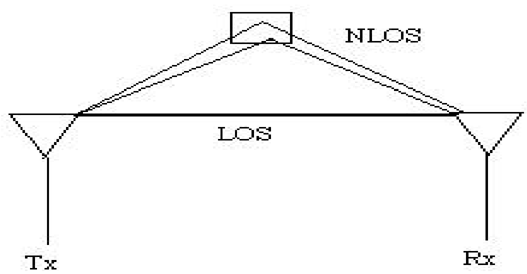

Figure 1.6: The multipath phenomenon in wireless links

signals; it can cause signal degradation up to few tens of dB due to the out-of-phase addition of LOS and NLOS continuous waveforms. On the other hand, the very short duration of UWB pulses makes them less sensitive to the multipath effect.

Research on UWB channel modeling3 has shown that depending on the UWB modulation scheme used, low-powered UWB pulses can become significantly distorted in indoor channels where a large number of objects and scatterers are closely spaced. For a comprehensive discussion on various UWB modulation techniques and their performance in multipath channels, refer to section 2.3.

1.5.7 Superior Penetration Properties

Unlike narrowband technology, UWB systems can penetrate effectively through different materials. The low frequencies included in the broad range of the UWB frequency spectrum have long wavelengths, which allows UWB signals to penetrate a variety of materials, including walls. This property makes UWB technology viable for through-the-wall communications and Ground Penetrating Radars(GPR). However, the material penetration capability of UWB signals is useful only when they are allowed to occupy the low-frequency portion of the radio spectrum.

1.6 Challenges

[6] There are many challenges involved in using nanosecond-duration pulses for communications inspite of many advantages. Some of the difficulties of UWB communications are discussed in the following subsections.

1.6.1 Pulse Shape Distortion

The transmission characteristics of UWB pulses are more complicated than those of continuous narrowband sinusoids. A narrowband signal remains sinusoidal throughout the transmission channel. However, the weak and low-powered UWB pulses can be distorted significantly by the transmission link. This distortion can be mathematically shown with the widely used Friis transmission formula1.7:

$$P_r = P_t G_t G_r (\frac{C}{4\pi df})^2 \tag{1.7}$$

where P_r and P_t are the received and transmitted signal power, respectively; G_t and G_r are the transmitter and receiver antenna gains respectively; c is the speed of light; d is the distance between the transmitter and the receiver; and f is the signal frequency[9].

In a vacuum, all electromagnetic waveforms travel at the speed of light, $c = 3 \times 10^8$ meters per second. This 1.7 shows that the received signal power will decrease quadratically with the increase in frequency. In UWB due to the wide range of frequencies the received power drastically changes and thus distorts the pulse shape.

This will limit the performance of UWB receivers that correlate the received pulses with a predefined template such as classical matched filters.

1.6.2 Channel Estimation

Channel estimation is a core issue for receiver design in wireless communications systems. Because it is not possible to measure every wireless channel in the field, it is important to use training sequences to estimate channel parameters, such as attenuations and delays of the propagation path.

Given that most UWB receivers correlate the received signal with a predefined template signal, prior knowledge of the wireless channel parameters is necessary to predict the shape of the template signal that matches the received signal. However, as a result of the wide bandwidth and reduced signal energy, UWB pulses undergo severe pulse distortion; thus, channel estimation in UWB communications systems becomes very complicated [9].

1.6.3 High-Frequency Synchronization

As with any other wireless communications system, synchronization between the receiver and the transmitter is a must for UWB transmitter/receiver pairs. Synchronization is a major challenge and a rich area of study in UWB communications systems. However, sampling and synchronizing nanosecond pulses place a major limitation on the design of UWB systems. Very fast ADCs are required for sampling such kind of narrow pulses. Moreover, the strict power limitations and short pulse duration make the performance of UWB systems highly sensitive to timing errors such as jitter and drift. This can become a major issue in the success of Pulse Position Modulation (PPM) receivers, which rely on detecting the exact position of the received signal. For a thorough discussion on UWB PPM receivers, refer 2.3.

1.6.4 Multiple Access Interference

In a multiuser or a multiple-access communications system, different users or devices send information independently and concurrently over a shared transmission medium (such as the air interface in wireless communications). At the receiving end, one or more receivers should be able to separate users and detect information from the user of interest. Interference from other users with the user of interest is called **Multiple Access Interference** (MAI), which is a limiting factor to channel capacity and the performance of such receivers. The addition of MAI to the unavoidable channel noise can significantly degrade the low-powered UWB pulses and make the detection process very difficult. Figure 1.7 represents a UWB multiple-access channel. As shown

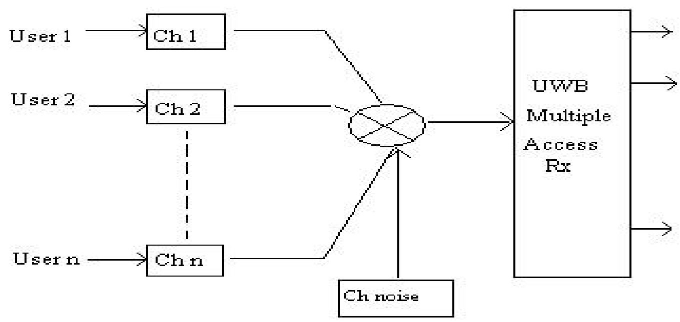

Figure 1.7: A UWB multiple-access channel

in figure 1.7, separating each user's information from the combination of heavily distorted and low powered UWB signals from all users is a very challenging task.

Challenge	Problem
Pulse-shape distortion	Low performance using classical matched filter receivers.
Channel estimation	Difficulty predicting the template signals.
High-frequency synchronization	Very fast ADCs required.
Multiple-access interference	Detecting the desired user's information is more challenging than in narrowband communication.
Low transmission power	Information can travel only short distances.

Table 1.1: Some challenges and problems associated with UWB systems

A comprehensive study of multiple-access techniques in UWB systems appears in Chapter 2. Table 1.1 summarizes the challenges and problems that narrow pulses can bring to UWB communications systems. This table provides basic idea for challenges which may be faced by us while using UWB technology.

1.7 Differences Between UWB and Spread Spectrum

1.7.1 Direct-Sequence Spread Spectrum

In Direct Sequence Spread Spectrum (DSSS), a pseudorandom code is used to spread each data bit with a large number of chips, where a chip interval is much smaller than a bit interval, as shown in figure 1.8. These code words spread the data to a larger bandwidth than required to transmit information. In figure 1.8[6], the data bit 1 is represented by a four bit code (1010) and the data bit 0 is represented by another four bit code (1100).

Spreading the data to shorter duration chips in time results in a spread of energy in the frequency domain to slightly above a typical narrowband receiver's noise floor. In order to transmit data, each of the chips is modulated with conventional narrowband techniques.

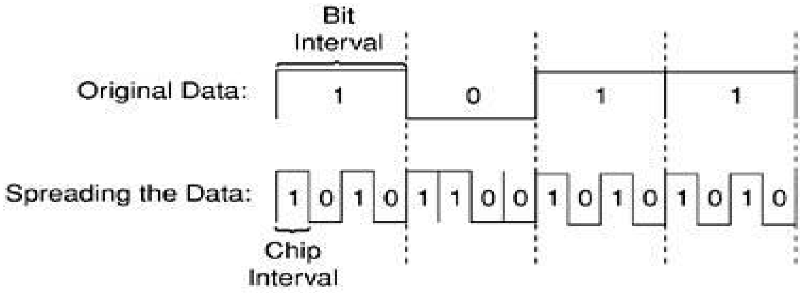

Figure 1.8: A data sequence and a spreading code using DSSS

1.7.2 Frequency Hopping Spread Spectrum

The Frequency Hopping Spread-Spectrum (FHSS) technique was invented by actress **Hedy Lamarr** and patented in 1942 as **Secret Communication System** [10]. FHSS in concept is exactly like DSSS in terms of spreading the signal energy in the frequency domain and offering the advantages of wideband communications.

However, the wide bandwidth does not result from spreading the data, as in the DSSS technique. Instead of, FHSS hops the frequencies used for transmission and reception according to a pseudorandom code, and the combination of those frequencies generates a wide bandwidth.

The change in frequencies that represent the data bits happens so fast that detection becomes very difficult for unauthorized parties. As shown in Figure 1.9, the signal hops from one frequency to another at each instance in time.

1.8 Single Band Vs. Multiband

The ability of UWB technology to provide very high data rates for short ranges (less than 10 meters) has made it an excellent candidate for the physical layer of the IEEE 802.15.3a standard for Wireless Personal Area Networks (WPANs). However, two opposing groups of UWB developers are battling over the IEEE standard. The two

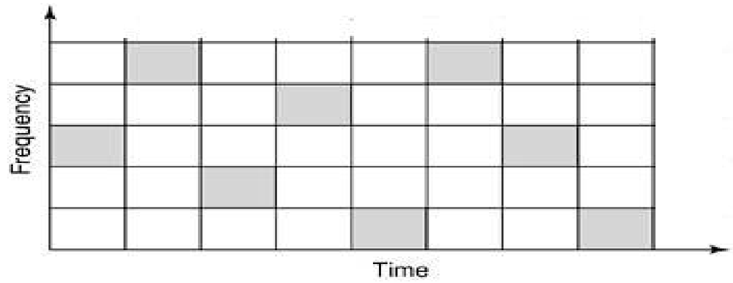

Figure 1.9: Frequency hopping in the FHSS technique

competing technologies are single band and multiband. The single-band technique, backed by Motorola/XtremeSpectrum, supports the idea of impulse radio that is the original approach to UWB by using narrow pulses that occupy a large portion of the spectrum. The multiband approach as shown in figure 1.10[6] divides the available

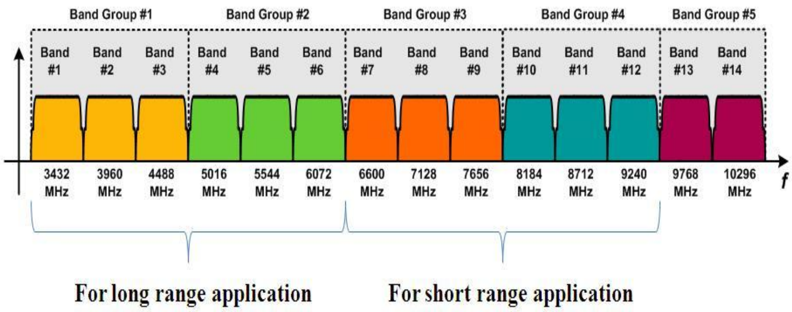

Figure 1.10: Multiband approach

UWB frequency spectrum (3.1 GHz to 10.6 GHz) into multiple smaller and nonoverlapping bands with bandwidths greater than 500 MHz to obey the FCC's definition of UWB signals. The multiband approach is supported by several companies, including Staccato Communications, Intel, Texas Instruments, General Atomics, and Time Domain Corporation.

To date, several proposals from both groups have been submitted to the IEEE 802.15.3a working group, and the decision is yet to be made because both technologies are impressive and have technical credibility. The two leading candidates for the 802.15.3a standard: Direct Sequence UWB (DS UWB) and multiband Orthogonal Frequency Division Multiplexing (OFDM) are discussed in 2.4.

1.9 The Regulatory Situation

1.9.1 Current FCC Regulations

On February 14, 2002, the FCC ruled to open up an unprecedented amount of bandwidth for commercial development of UWB technology. After much lobbying on both sides to either reduce or tighten the FCC restrictions, the FCC agreed to the requests of a wide range of supporters. Thus, a year later in February 2003, the FCC's release of a Memorandum Opinion and Order (*MO&O*) assured developers that UWB is here to stay.

These supporters run the gamut from leading companies in the home networking arena; to consumer electronics giants such as Philips Electronics and Samsung Electronics; to personal computing heavyweights such as Intel, Texas Instruments, and Microsoft; and to a growing number of UWB developers such as Multi spectral Solutions, Pulse LINK, Staccato Communications, Time Domain Corporation, and Xtreme Spectrum, as well as several U.S. organizations such as the Ground Penetrating Radar Industry Coalition (GPRIC).

While the FCC has set precedents in terms of changing the rules according to newly defined IEEE standards (for example, 802.11), few rules were as strongly debated as those for UWB.

1.10 FCC Emission Limits

As explained in Section 1.9.1, in order to protect existing radio services from UWB interference, the FCC has assigned conservative emission masks between 3.1 GHz and 10.6 GHz for commercial UWB devices. The maximum allowed power spectral density for these devices that is, -41.3 dBm/MHz, or 75 nW/MHz places them at the same level as unintentional radiators (FCC Part 15 class) such as televisions and computer monitors. Based on the FCC regulations, UWB devices are classified into three major categories: communications, imaging, and vehicular radar.

1.10.1 Communications Devices

For communications devices, the FCC has assigned different emission limits for indoor and outdoor UWB devices. The spectral mask for outdoor devices is 10 dB lower than that for indoor devices, between 1.61 GHz and 3.1 GHz, as shown in Figures 1.11. According to FCC regulations, indoor UWB devices must consist of handheld

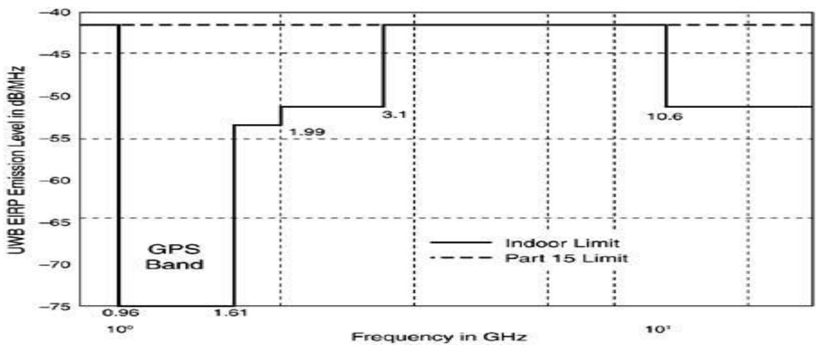

Figure 1.11: UWB emission limits for indoor communications systems

equipment, and their activities should be restricted to peer-to-peer operations inside buildings.

The FCC's rule dictates that no fixed infrastructure can be used for UWB communications in outdoor environments. Therefore, outdoor UWB communications are restricted to handheld devices that can send information only to their associated receivers.

In general, the FCC ruling per application with Part 15 classification of -41.3 dBm for both outdoor and indoor operations can be summarized as shown in Table 1.2.

		Operation band(GHz)
	Application	3.1 to 10.6
EIRP(dBm)	Communication	41.3
	Imaging	41.3
	Vehicular Radar	63.3

Table 1.2: Emission limits for various UWB applications in each operational band

1.11 UWB Applications

The trade-off between data rate and range in UWB systems holds great promise for a wide variety of applications in military, civilian, and commercial sectors. This section contains a detailed discussion of UWB's present and future applications. Now following a brief summary of UWB applications to complete our introductory discussion is given.

1.11.1 Initial Mass Market Opportunities

The unique characteristics of UWB communications make it suitable for multiple large mass markets, including several consumer electronics products, Personal Computers (PCs), peripherals, Wireless Local Area Networks (WLANs), Wireless Personal Area Networks (WPANs), and smart phone applications. The marketing research firm **ON World** predicts that by 2010, the number of UWB chip sets shipped will surpass that for Bluetooth and Wi-Fi chip sets combined.

Initially, most of the excitement over UWB is that it enables very high data rates potentially higher than those made possible with FireWire (IEEE 1394)without wires, with low power consumption, and with minimal to no interference to other wireless technologies. Today, devices such as PCs, laptops, printers, digital cameras, video camcorders, DVD drives, digital audio players, and many other devices are tethered through cable interfaces based on the USB 2.0 or FireWire (IEEE 1394) standards. (See Figure 1.12.)

Figure 1.12: Initial target UWB applications

1.11.2 Driving CE, PC, and Mobile Industry Convergence

Consumers typically have three or more display devices in their home that will need to receive at a minimum the MPEG-2 video format. With digital TV, flat panel displays (plasma and LCD), DVD, DVR, and digital camera sales at an all-time high, it is clear that consumers' move to a multimedia home environment and wireless connectivity within those devices is a natural next step. Today, consumers must deal with multiple wired interfaces such as 1394 (FireWire) or USB (1.1 or 2.0), which complicates the interoperability among the PC-oriented products and consumer electronics devices. Although USB 2.0 is being incorporated in a greater number of consumer electronics devices, there is still a significant "barrier of interfaces" that prevents true interoperability between the PC and CE industries. Figure 1.13 illustrates this division.

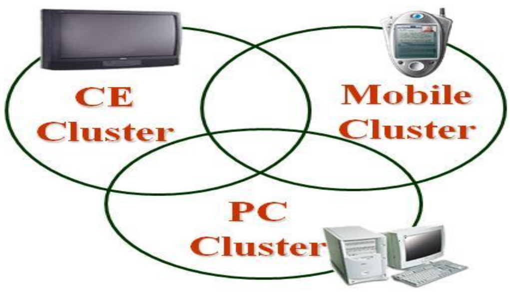

Figure 1.13: Bridging the divide among PC, CE and Mobile

1.11.3 Existing Potential Markets

It is clear that the digital revolution is here, as more consumers are buying an increasing array of digital devices for creating their own multimedia content, such as audio, video, and still photos. At an increasing rate, consumers are creating digital art of all types and using their PCs with their consumer electronics devices, from digital cameras to stereos to digital TVs. Analysts, such as Allied Business Intelligence, predict that more than 50 percent of all TVs shipped in 2008 will be networked [11].

1.11.4 UWB for PC Oriented Applications

UWB has much more to offer PC networking as a complement to Wi-Fi (802.11a/b/g) because of its ad hoc and quality-of-service qualities needed for media and peripherals. While UWB will appear first in the home for wireless PAN applications, it will find its way into corporate networks as well as home networks over the next few years in notebooks, desktops, and printers.

- **Wireless Personal Area Networks** UWB will start out as a wireless PAN multimedia-focused solution and penetrate the home networking market first. The trade-offs between power consumption, data rate, and range have also kept most UWB developers focused on shorter ranges in order to comply with current FCC rules while providing very high bit rates.

- **Wireless Local Area Networks** While most of the initial market focus will be on wireless PAN applications, there is no reason why UWB cannot or will not be used for longer-range applications as well. It is important to remember that UWB is a physical layer technology, which makes it a likely PHY for future Wi-Fi standards such as 802.11n, which will support a data rate up to 108 Mbps. UWB's unique advantages for wireless LANs include the following:

  a. Greater data rates and payload capacities for WLAN applications than existing Wi-Fi or alternate UWB WPAN-only solutions

b. Enhanced security

c. Positioning capabilities

d. Signal coexistence with other RF technologies

1.11.5 Future Mass Products

- **Wireless Sensor Networks** Wireless sensor networking is another prime target area for UWB, due to its covert communications, relative immunity to intentional jamming, accurate positioning capabilities, high data capacity, and low power consumption. Ad hoc wireless sensor networks have been gaining attention lately as a low-cost solution for home, building, and industrial automation, as well as for military applications.

- **Smart Phones** ON World predicts that by 2010, UWB-enabled devices, such as cell phones and handhelds, will allow users to wirelessly download large files and exchange data much the way they do with laptops today. UWB is likely to appear in smart phones in the near future, when silicon has been shipped in volume for several years, prices reach under $5 per unit, and regulations are relaxed enough to permit this.

1.11.6 Radar and Imaging Applications

UWB's pulse-based properties give transceivers additional abilities, such as object sensing and range location. Also, because UWB uses a wide band of spectrum, the signal can more easily penetrate walls than can a narrowband frequency transmitter, at lower data rates and it suffers less interference and detection than other RF technologies. The various types of radar and imaging applications include the following.

- **Ground Penetrating Radar Systems** Ground-penetrating radar systems operate only when in contact with or within close proximity to the ground for the purpose of detecting or obtaining the images of buried objects. The energy from the GPR is intentionally directed down into the ground for this purpose.

FCC Restrictions: Operation is restricted to law enforcement, fire and rescue organizations, scientific research institutions, commercial mining companies, and construction companies.

- **Surveillance and Through-Wall Imaging Systems** Through-wall imaging systems detect the location or movement of persons or objects that are located on the other side of a structure such as a wall. Motorola, for example, is exploring see-through-the-wall systems for police, firefighters, and other public-safety agencies. UWB imaging devices also could be used to improve the safety of the construction and home repair industries by locating steel Reinforcement Bars (that is, REBAR) in concrete or electrical wiring, and pipes hidden inside walls.

  FCC Restrictions: Operation is limited to law enforcement and fire and rescue organizations.

As explained in Sections 1.9.1 and 1.10, the FCC categorizes UWB applications as either radar, imaging, or communications devices. Radar is considered one of the most powerful applications of UWB technology. The fine positioning characteristics of narrow UWB pulses enables them to offer high-resolution radar (within centimeters) for military and civilian applications. This property makes UWB based Ground Penetrating Radar (GPR) a useful asset for rescue and disaster recovery teams for detecting survivors buried under rubble in disaster situations.

The high datarate capability of UWB systems for short distances has numerous applications for home networking and multimedia-rich communications in the form of WPAN applications.

Chapter 2, *UWB Model With Physical layer Aspects*, provides an overview of UWB communications, such as UWB signal models,modulation schemes,multiple ac-

System	**Data rate(Mbps)**	**Transmission Dist.(m)**
	480	2
UWB	200	4
	110	10
Fast Ethernet	90	LAN
IEEE 802.11a	54	50
IEEE 802.11b	11	100
IEEE 802.11c	20	-
BLUETOOTH	1	10

Table 1.3: compares UWB technology and other currently available data communications standards

cess techniques and sampling issues. In this chapter, description of the physical layer model is given in detail.

Chapter 3, *UWB Channel Model*, gives an algorithm for UWB channel response and gives detail of UWB channel model.

Chapter 4, *Performance of RAKE Receiver in UWB Technology*, presents performance evaluation through simulations for the proposed UWB acquisition.

Chapter 5, *Implementation And Performance Evaluation*, concludes the research and provides directions for the future exploration.

Chapter 6, *Conclusion* concluding remarks and scope for future work is presented.

Chapter 2

UWB Model With Physical layer Aspects

This chapter presents an overview of UWB communications to provide several important concepts related to acquisition. Section 2.1 describes a signal model. Section 2.2 gives some of the idea about the basic model of the physical layer and the frame structure. In section 2.3, 2.4, possible modulation techniques and multiple access techniques will be defined. Section 2.5 explains the reason for choosing sampling rate at the symbol frequency. And finally basic idea of transmitter and receiver architecture is given2.6.

2.1 UWB Signal Model

A UWB transmitter works by means of sending extremely short duration pulses with a wide range in frequency spectrum, several GHz in bandwidth. UWB signals carry data using a low signal level below the thermal noise floor through a dense multi path channel. There were activities in designing suitable signal waveforms to satisfy the requirements of FCC [12][13].

UWB makes full use of impulse radio benefits to span the energy of a radio signal from near DC to a few GHz. The emission power of spectral density can be lower than the noise floor which makes UWB co-exist with other narrow band or wide band communication systems without interfering with other communication systems [13]. It is necessary to have a standard for UWB signal in order to protect the existing wireless communication systems [13].

2.1.1 Signal Waveform Format

In the view of system design, UWB pulse shape can be chosen for the purpose of simplifying a design. A pulse shape is an important factor affecting overall system performance and design challenge. An applicable pulse shape should be easy to implement and be convenient for theoretical analysis.

Generally there are three main waveforms in UWB systems: the Gaussian like pulse, the monocycle pulse, and the polycycle pulse [14]. The Gaussian monocycle pulse is chosen in this thesis due to its simplicity. The pulse has a waveform described by the Gaussian distribution. The amplitude of the waveform is given by,

$$f(t) = Ae^{(}\frac{-t}{\tau})^2 \tag{2.1}$$

where A is the maximum amplitude and τ is the pulse half duration.

A Gaussian monocycle is a wide-bandwidth signal. Its center frequency and bandwidth depends on the monocycle width. In time domain, the Gaussian monocycle pulse is mathematically similar to the first derivative of the Gaussian function.

This research uses an ideally modeled pulse shape propagating in free space, i.e., the first derivative of Gaussian monocycles. A mathematical expression for the monocycles in time domain is given as [15]:

$$f(t) = \frac{t}{\tau}e^{(} - \frac{t}{\tau})^2 \tag{2.2}$$

where τ is a parameter which determines the template width of the pulse. In frequency domain, the pulse is transformed into

$$F(\omega) = -j\pi\sqrt{\pi}\omega\tau^2 e^(- \pi^2\omega^2\tau^2) \tag{2.3}$$

To normalize 2.2, the normalized pulse shape function g(t) is defined as

$$g(t) = \frac{1}{\sqrt{\frac{3\tau}{4}}}\frac{t}{\tau}e^(- \frac{t}{\tau})^2 \tag{2.4}$$

The coefficient $\sqrt{\frac{3\tau}{4}}$ ensures the signal shape is normalized as unit energy,in another word

$$\int_{\infty}^{\infty} g^2(t)dt = 1 \tag{2.5}$$

Normalized waveform is a simple way to state the signal energy since the received energy in $\sqrt{E_g}g(t)$ is E_g. Figure 2.1 shows a typical waveform of the Gaussian monocycle pulse and its spectrum.

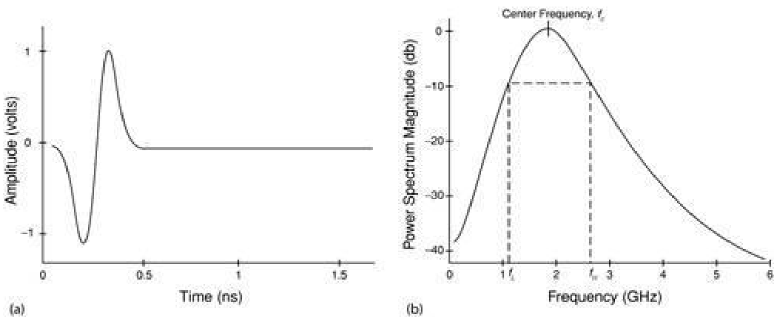

Figure 2.1: Gaussian monocycle pulse and its spectrum

2.2 Physical Layer model

The ability of UWB technology to provide very high data rates for short ranges (less than 10 meters) has made it an excellent candidate for the physical layer of the IEEE 802.15.3a standard for Wireless Personal Area Networks (WPANs). The IEEE

802.15.4a amendment [16] specifies an IR-UWB physical layer for the IEEE 802.15.4 standard [17][18] that can operate over several bands of 500 MHz (or 1.5 GHz) from approximately 3 GHz to 10 GHz.

2.2.1 Physical layer's Practical Aspects

An IEEE 802.15.4a packet consists of a preamble followed by a data part. The main difference with respect to the classic IR-UWB physical layer lies in the signal format of the data part. Instead of sending a single pulse per frame, a short, continuous burst of pulses with pseudo random polarity is sent. As per figure 2.2, for a payload

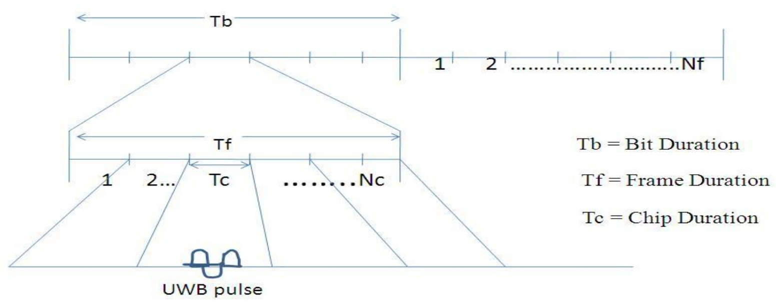

Figure 2.2: Frame structure of IEEE UWB Channel models

of N_c bits, the transmitted signal is made of N_f frames of duration T_f. A frame is further divided into N_c chips of T_c seconds. In each frame, a single burst of T_p pulses is transmitted. A burst of pulses is the concatenation of T_p pulses, whose amplitudes are modulated by a binary scrambling sequence.

A pulse has duration T_p. The location of the burst inside the ith frame depends on the ith data bit d_i and on the time-hopping sequence: it is a sequence $(c_0, c_1, ..., c_{N_c}-1)$ of integers chosen in $0, 1, ..., N_{hop} - 1$ where $N_{hop} = \frac{T_f}{4T_pT_c}$.

Note that half of the duration of the frame is not used to make sure that there is a sufficient guard time to avoid inter-symbol interference (ISI). The burst inside the lth frame is then time-shifted by $c_iT_pT_c + d_i\frac{T_f}{2}$ with respect to the beginning of the frame.

The binary scrambling sequences and the time-hopping sequences are generated by a Linear Feedback Shift Register (LFSR). Note that the LFSR is initialized to the same state for the transmission of each packet. Hence, all transmitters have the same scrambling sequence and time-hopping sequence. The transmitted signal of an IEEE 802.15.4a data part can be modeled as,

$$s(t) = \sum_{i=0}^{N_f-1} \sum_{j=0}^{N_c-1} b_{i,j} p(t - iT_f - c_i N_c T_c - d_i \frac{T_f}{2} - jT_c) \tag{2.6}$$

where $b_{i,j} \epsilon \underline{+} 1$ is the pseudo-random polarity of the j-th pulse of the i-th symbol specified by the scrambling sequence. The received signal for the data part, after filtering with a bandpass filter of bandwidth B, is then given by,

$$s(t) = \sum_{i=0}^{N_f-1} \sum_{j=0}^{N_c-1} b_{i,j} h(t - iT_f - c_i N_c T_c - d_i \frac{T_f}{2} - jT_c) + n(t) \tag{2.7}$$

where h(t) is the unknown channel response (including the convolution of the transmitted waveform with the impulse response of the channel and the bandpass filter), n(t) accounts for thermal noise and MUI. It is assumed that the duration of h(t) is shorter than $\frac{T_f}{4}$ to prevent ISI. Both c_i and $b_{i,j}$ are known to the receiver.

Basic Modeling of the Physical Layer

The IR-UWB physical layer with time-hopping allows several users to share the medium concurrently. This multiple-access capability of IR-UWB physical layers stems from time hopping. Unlike narrow-band systems, the collision of packets from different transmitters do not fully destroy the underlying radio signals.

In fact, if several users transmit concurrently with distinctive THSs, only occasional signal collisions will occur between the concurrent signals because the pulses from the different users are not transmitted at the same time.

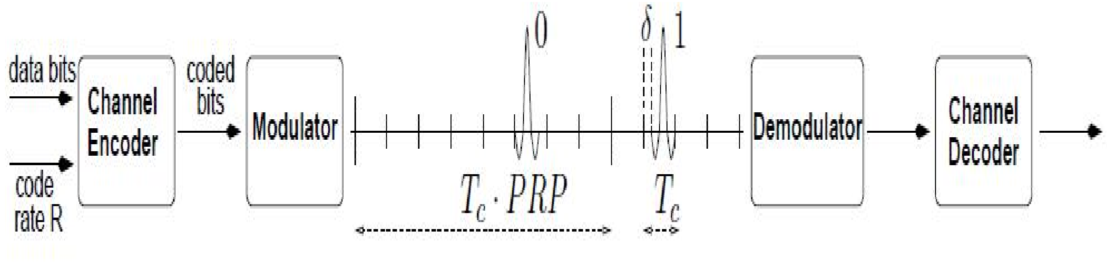

Figure 2.3: UWB physical layer model, L_b=8, TH_s=(6,2)

2.3 UWB Signal Modulation Techniques

Modulation is the process of facilitating the transfer of information over a medium. There are three main ways of modulating classified by the variation of the pulse amplitude, phase, or frequency in accordance with the information being transmitted. Data rate, transceiver complexity, Bit Error Rate (BER) performance,spectral characteristics of the transmitted signal, and robustness against impairments and interference are related to modulation types.

Although numerous modulation techniques are used with impulse-radio UWB. UWB signals can be modulated in different ways such as orthogonal Pulse Position Modulation (PPM),Binary Phase-Shift Keying (BPSK), Pulse Amplitude Modulation (PAM), and On-Off Keying (OOK) for binary schemes. Among those, BPSK is the best modulation for AWGN channels and Rayleigh fading channels [19].

Three common schemes are often found in research papers and journals. On-Off Keying (OOK), Biphase Modulation, and Binary Pulse Position Modulation (Binary PPM) are popular UWB modulation techniques due to their simplicity and flexibility towards low duty cycle pulsed communication systems.

2.3.1 OOK

On Off Keying or otherwise known as unipolar signaling in the analog baseband world, is a simple pulse modulation technique where a pulse is transmitted to represent a binary 1, while no pulse is transmitted for a binary 0. The baseband representation, which is illustrated in figure 2.4, of the transmitted signal is [20]:

$$w(t) = \sum_{j=-\infty}^{\infty} b_j s(t - jT_f) \tag{2.8}$$

where:w(t) is the transmitted UWB signal,
$b_j \quad \epsilon\{0, 1\}$ data bits,
s(t) is the pulse shape,
T_f is the frame period (seconds).

One Obvious advantage to using OOK is the simplicity of the physical implementation, as one pulse generator is necessary, as opposed to two, as is the case with bi phase modulation. A single RF switch can control the transmitted pulses by switching on for a 1 data bit and off for a 0 data bit. This effortless transmitter configuration makes OOK popular for less complex UWB systems.

Although OOK has a very straightforward implementation, there are numerous

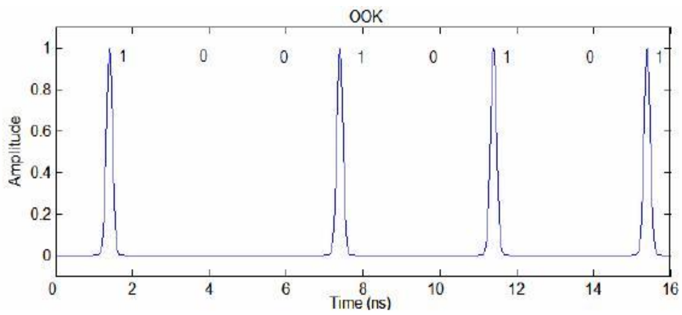

Figure 2.4: On-Off Keying

system drawbacks. In either a hardware or software based receiver design, synchronization can be easily lost if the data contains a steady stream of 0s. Also, the BER performance of OOK is worse than bi phase modulation due to the smaller symbol separation for equal symbol energy.

Bit errors occur less often when the amplitude difference is greater because more distortion is necessary in the channel to affect a bit decision. This effect is demonstrated in the probability of bit error for baseband OOK using a matched filter receiver, which is compared in figure 2.7 with biphase modulation and binary PPM [21]:

$$P_e = Q(\sqrt{(}\frac{E_b}{N_0})) \tag{2.9}$$

where:Q is the Q-function, E_b is the average energy per bit (Joules), N_o is the noise power spectral density at the detector (Joules) The Q-function is defined by [21]:

$$Q(z) \underline{\underline{\triangle}} \frac{1}{\sqrt{(}2\pi)} \int_z^\infty e^(- \frac{\lambda^2}{2d_\lambda}) \tag{2.10}$$

2.3.2 Biphase Modulation

In generic pulse modulation terms, Pulse Amplitude Modulation (PAM) transmits data by varying the amplitude of each pulse based on binary data. The most common form of PAM in UWB communications is 2-PAM, or bi phase modulation, where the polarity of a pulse is modulated.

In this situation, a positive pulse is transmitted for a 1 and a negative pulse is transmitted for a 0. The signaling waveform for the bi phase modulation technique is shown in Figure 2.5 and mathematically described as [20]:

$$w(t) = \sum_{j=-\infty}^{\infty} b_j s(t - jT_f) \tag{2.11}$$

where:$b_j \quad \epsilon\{-1, 1\}$ data bits.

One advantage of bi-phase modulation is its improvement over OOK in BER performance, as the Eb/No is 3 dB less than OOK for the same probability of bit error, as

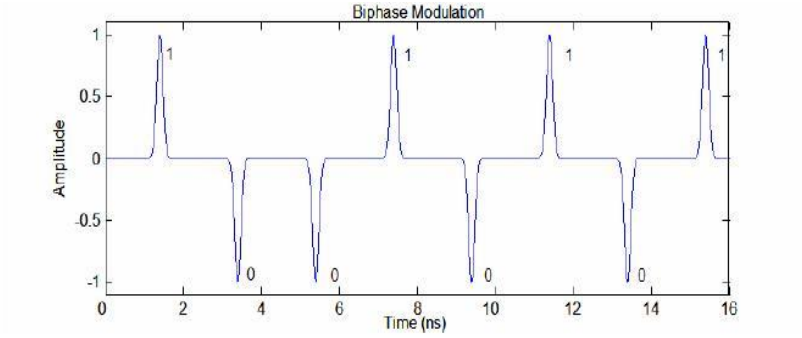

Figure 2.5: Biphase Modulation

shown in Figure 2.7. The probability of bit error for bi phase modulation assuming matched filter reception is [20]:

$$P_e = Q(\sqrt{(}\frac{2E_b}{N_0})) \tag{2.12}$$

Another benefit of bi phase modulation is its ability to eliminate spectral lines due to the change in pulse polarity. This aspect minimizes the amount of interference with conventional radio systems. A decrease in the overall transmitted power could also be attained, making bi phase modulation a popular technique in UWB systems when energy efficiency is a priority.

A disadvantage of bi-phase modulation is the physical implementation is more complex, as two pulse generators, one of them with the opposite polarity, are necessary instead of one, as is the case with OOK. This presents a problem when attempting to transmit a stream of pulses, as the time between pulses can become non-periodic if the pulse generators are not triggered in a timely fashion. Despite these issues, bi phase modulation is a very efficient way to transmit UWB pulses.

2.3.3 Binary PPM

The last popular UWB modulation scheme to be discussed is PPM, which is a technique where the timing of each pulse is altered to transmit data instead of varying the amplitude. The simplest form of PPM is binary PPM, where a pulse in a uniformly spaced pulse train represents a 0 and a pulse offset in time from the pulse train represents a 1. Conceptually, the binary PPM technique is shown in figure 2.6 and stated in equation form as [20]:

$$w(t) = \sum_{j=1}^{\infty} s(t - jT_f - \delta b_j) \tag{2.13}$$

where:$b_j \ \epsilon \{0, 1\}$ data bits, δ is the modulation index.

The most advantageous feature of PPM is the orthogonal signaling present in its

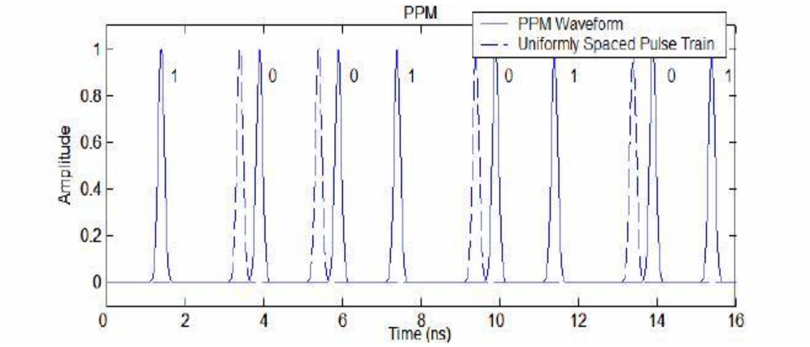

Figure 2.6: Pulse Position Modulation with Binary 0 Offset from the Regularly Spaced Pulse Train (Binary PPM)

data. Each of the pulses in time is independent of one another, meaning the time during the symbol period can be broken up to look for each pulse within a specified time slot. In the case of M-ary modulation schemes, PPM provides better error performance than PAM and also has the advantage of permitting non-coherent reception.

One of the disadvantages of PPM is its BER performance. As per constellation diagram, the distance between symbols is the same as in OOK. This lack of signal energy causes binary PPM to have the same probability of bit error as OOK, or 3 dB worse than bi phase modulation. This similarity between binary PPM and OOK is displayed in Figure 2.7 and the probability of bit error equation for binary PPM can

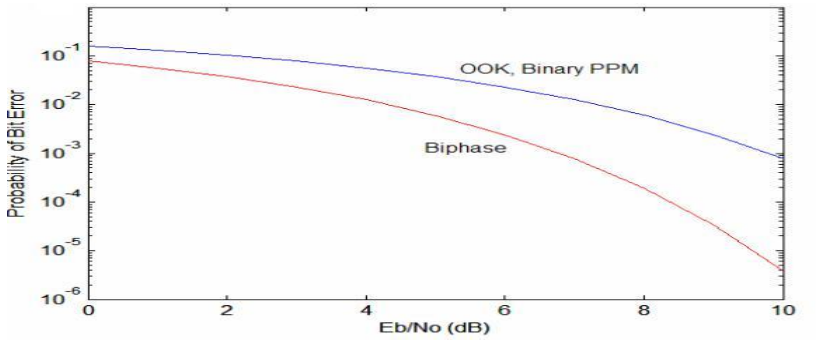

Figure 2.7: Theoretical Probability of Bit Error Rates for OOK, Binary PPM, and Biphase Modulation

be described by Equation 2.9[20].

Another apparent drawback to PPM is its susceptibility to inter symbol interference, as multiple positions are required to transmit at a higher data rate. PPM must lower the transmitted pulse rate to account for this effect. Therefore, there is a data rate limitation when using PPM in impulse-radio UWB applications. Even when the inter symbol interference is reduced at the transmitter by decreasing the pulse rate, multi path are more likely to overlap with the next data pulse, causing bit errors at the receiver if the reflections are strong. These types of problems lead to a more complex receiver design, which hampers the use of PPM.

2.4 Multiple Access Techniques

Using impulse-radio UWB,following two common multiple access (MA) techniques are typically applied to the modulation schemes previously discussed.

2.4.1 Time Hopping(TH)

Time-hopping (TH) can be applied to all of the modulation schemes, where each user is assigned a time hopping sequence. figure 2.2 shows the how time hopping based UWB signal is transmitted for one data bit by UWB device. An IEEE 802.15.4a packet consists of a preamble followed by a data part. The main difference with respect to the classic UWB physical layer lies in the signal format of the data part. Instead of sending a single pulse per frame, a short, continuous burst of pulses with pseudo random polarity is sent.Basic flow of algorithm for TH-UWB method is given in fig.2.8.

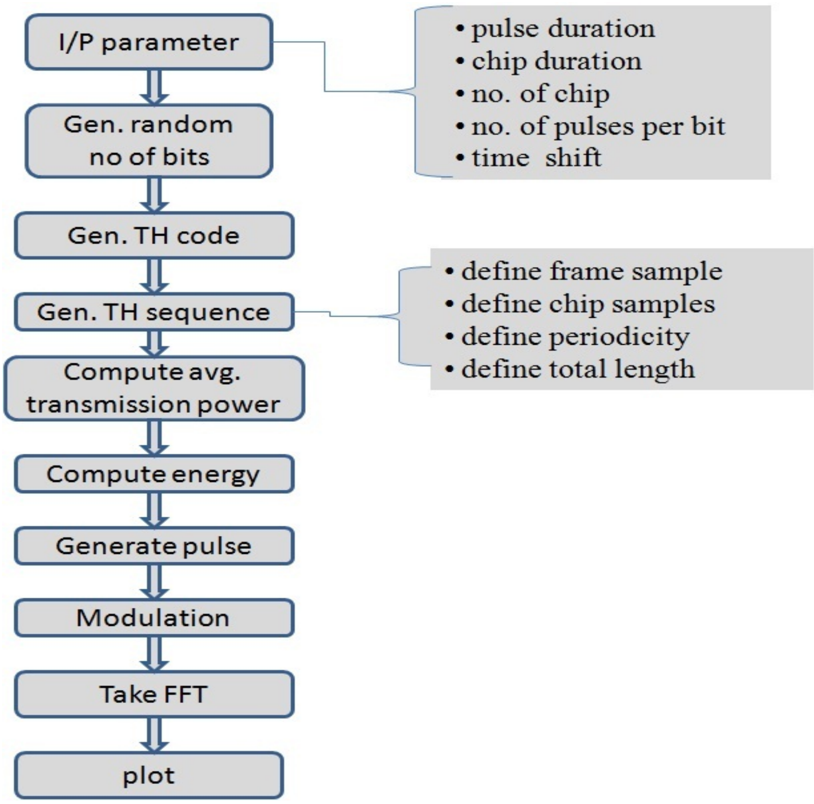

Figure 2.8: Flow of algorithm for TH-UWB

- **TH PAM:**

  In [22] TH-PAM UWB system is considered for Ultra Wide Band communication. In TH-PAM UWB single bit duration (T_b) is divided into N_f number of frames each with equal duration T_f , so $T_b = N_f T_f$. Further each frame is divided into N_c chips with chip duration of T_c such that $N_c T_c \leq T_f$. During each frame UWB pulse is transmitted which is Gaussian monocycle or Scholtz

Monocycle. UWB pulse occupy one chip slot depending on time hopping code c_j which take value such that $0 \leq c_j \leq N_c - 1$. During each bit duration N_f UWB pulses are transmitted by TH-PAM transmitter.

For modulation antipodal pulses are used. 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 kth users transmit signal for TH PAM is given as [13]:

$$s^{(k)} = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} d_i^{(k)} w(t - jT_f - c_j^{(k)} T_c) \tag{2.14}$$

Where $S^{(k)}$ is kth user signal, $d_{(i)}^{(k)}$ is kth user bipolar data, N_f is number of frames per bit and w() is UWB pulse.

- **TH PPM:**

  In literature [23],[24],[25] TH-PPM UWB system is proposed for Ultra wideband communication. In which single bit duration Tb is divided into Nf frames each with equal duration T_f so $Tb = N_f T_f$. Further each frame is divided in to N_c chips with chip duration of T_c such that $N_c T_c \leq T_f$. During each frame UWB pulse is transmitted which is Gaussian monocycle or Scholtz Monocycle. This UWB pulse is transmitted during chip duration depending up on time hopping code c_j which has value such that $0 \leq c_j \leq Nc - 1$. During each bit duration N_f UWB pulses are transmitted by TH-PPM transmitter. Additional delay of δ is provided to UWB pulse at the beginning of chip duration when data bit '1 is transmitted. Here TH-PPM signal is represented as

$$s^{(k)} = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_f-1} d_i^{(k)} w(t - jT_f - c_j^{(k)} T_c - d_i^{(k)} \delta) \tag{2.15}$$

Where S(k) is kth user signal, $d_{(i)}^{(k)}$ is kth user bipolar data, N_f is number of frames per bit and w(t) is UWB pulse.

2.4.2 DS(Direct Sequence)

Direct-sequence UWB is a single-band approach that uses narrow UWB pulses and time-domain signal processing combined with well-understood DSSS techniques to transmit and receive information. Figure 2.9 shows this approach.

Direct Sequence (DS) is the other form of MA commonly used with impulse-radio

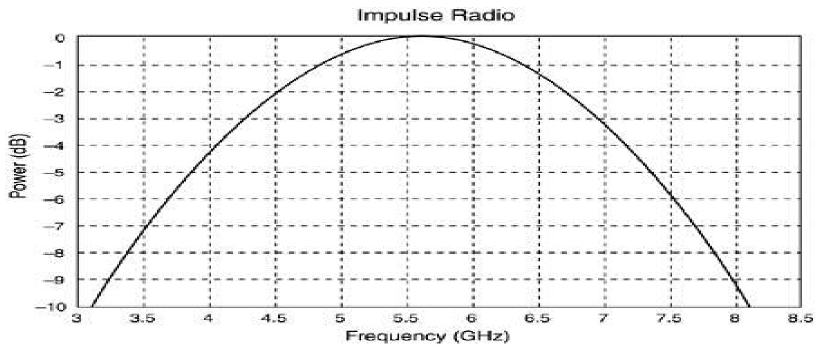

Figure 2.9: DS-UWB transmits a single pulse over a huge swath of spectrum to represent data

UWB, although it is typically limited to OOK and biphase modulation schemes. The idea is to modulate an antipodal PN sequence with a continuous string of pulses. At the receiver, the waveform is demodulated using the same PN sequence, which is unique at the time of communication. Therefore, a minimal amount of interference occurs with other users as they are assigned different PN codes with good auto-correlation and cross-correlation properties. The transmitted DS-UWB waveform is defined as [26]:

$$w^{(k)}(t) = \sum_{i=-\infty}^{\infty} \sum_{n=0}^{N_r-1} b_i^{(k)} a_n^{(k)} s(t - iT_r - nT_c) \tag{2.16}$$

where: N_r is the spread spectrum processing gain, $b_i^{(k)}$ is the modulated data symbols for the kth user, $a_n^{(k)}$ is the k^{th} user spreading chips, w is the transmitted baseband pulse waveform, T_r is the bit period (seconds), T_c is the chip period (seconds).

According to the proposals sent to the IEEE 802.15.3a standardization committee by the proponents of this technology, the DS-UWB technique is scalable and can achieve data rates in excess of 1 Gbps. The technical reason behind using DS-UWB is the propagation benefits of ultra wide band pulses, which experience no Rayleigh fading. In contrast, narrow band transmissions degrade significantly due to fading.

2.4.3 MultiBand OFDM

The multiband UWB approach uses the 7500 MHz of the RF spectrum available to UWB communications in a way that differs from traditional UWB techniques. The UWB frequency band is divided into multiple smaller bands with bandwidths greater than 500 MHz. Figure 2.10 depicts the result. This approach is similar to

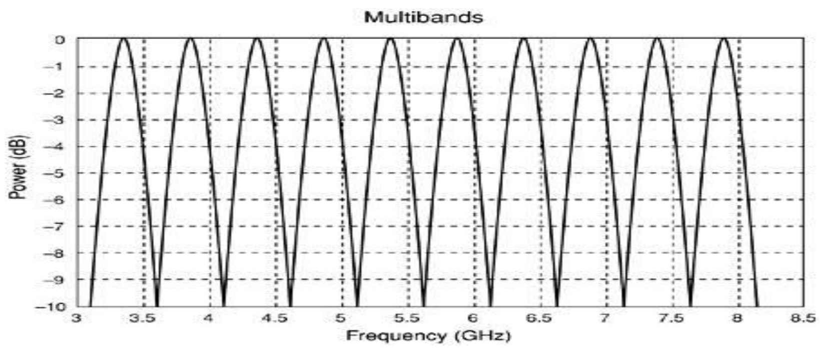

Figure 2.10: The multiband approach divides the available UWB spectrum into several nonoverlapping smaller bands

the narrow band frequency-hopping technique. Dividing the UWB spectrum into multiple frequency bands offers the advantage of avoiding transmission over certain bands, such as 802.11a at 5 GHz, to prevent potential interference. In the multi band approach, UWB pulses are not as narrow as in traditional UWB techniques; therefore, synchronization requirements are more relaxed. A variety of modulation techniques have been proposed by industry leaders for the multi band approach; however, OFDM, which was initially proposed by Texas Instruments, offers improved performance for high-data-rate applications.

As explained briefly, both technologies are technically valid and impressive. Supporters of DS-UWB criticize the multi band OFDM systems for their complexity, which results from using complex Fast Fourier Transforms (FFTs). On the other side, advocates of multi band OFDM believe that their technique offers better coexistence with other radio services, and they disapprove of DS-UWB because of possible interference concerns. The debate will likely continue until the IEEE 802.15.3a standardization committee reaches a decision.

2.5 Sampling Issue

Sampling rate plays a crucial role in signal processing and communications. As time passes, more and more analog techniques are being replaced by their digital counterparts. The choice of sampling rate is decided by the symbol rate and performance of the system.

2.5.1 Sampling Rate for UWB

It is well known from Nyquist-Shannon sampling theorem that unambiguous reconstruction is possible if the signal is bandlimited and the sampling frequency is greater than twice of the signal bandwidth. The error which corresponds to the failure of band limitation is referred to as aliasing. The condition for alias-free sampling at rate F_s called Nyquist sampling frequency is

$$2B \leq F_s$$

where B is the bandwidth of the signal. From signal processing perspective, the theorem includes two parts: a **sampling process**, in which a continuous time signal is converted into a discrete time signal, and a **reconstruction process** in which the continuous signal is recovered from the discrete signal.

UWB signal processing requires much higher sampling rate than general narrow band signal if the Nyquist sampling frequency is observed. The reason is that the UWB signal occupies a much wider bandwidth.

2.5.2 UWB Sampling Strategy

It is a clear trend to design UWB system with digital implementation.Digital-oriented systems have well-known advantages, including less expensive technology, easy integration, and high stability. As discussed, the sampling rate for signals should be higher than the spectrum of signals. Otherwise,the message can not be recovered if spectrum aliasing of the modulated signal occurs during under-sampling. In fact, spectrum aliasing does not necessarily lead to spectrum aliasing of the message signal. Even though the modulated signal cannot be recovered, it is still possible to reconstruct the message using the received signal energy and phase.

In fact, spectrum aliasing of the modulated signal is not exactly equal to spectrum alias of the message signals. The modulated signal is Gaussian monocycle pulse and the message data are digitalized as -1, or 1 for BPSK . It is an obvious observation that the modulated signal is an ultra-wide bandwidth signals and the message data are narrow band signals which use a single frequency. This observation gives some clues to recover message signals without concerning spectrum alias of modulated signals. Under-sampling is achievable from such principle. This means that there is a symbol at every symbol time.

2.6 Transceiver Architecture

As mentioned earlier in this chapter, UWB transmission is carrierless, meaning that data is not modulated on a continuous waveform with a specific carrier frequency, as in narrowband and wideband technologies. Carrierless transmission requires fewer RF components than carrier-based transmission. For this reason UWB transceiver architecture is significantly simpler and thus cheaper to build. Figure 2.11 shows the block diagrams of typical UWB transceivers. As shown in Figure2.11, the UWB

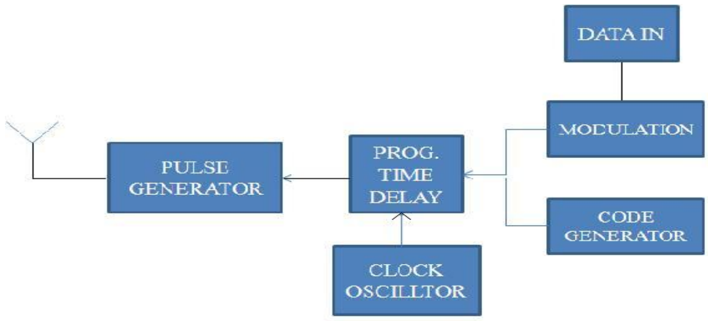

Figure 2.11: An example of a UWB transmitter architecture

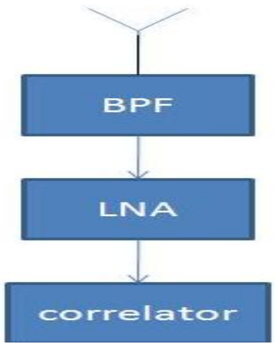

Figure 2.12: An example of a UWB receiver architecture

transceiver architecture is considerably less complicated than that of the narrowband transceiver.Here there is no need of Power Amplifier(PA) due to transmission of low powered pulses. Also, because UWB transmission is carrierless, there is no need for mixers and local oscillators to translate the carrier frequency to the required frequency band; consequently there is no need for a carrier recovery stage at the receiver end.

In general, the analog front end of a UWB transceiver is noticeably less complicated than that of a narrowband transceiver. This simplicity makes an all Complementary Metal-Oxide Semiconductors(CMOS) implementation of UWB transceivers possible, which translates to smaller form factors and lower production costs.

$$w^{(k)}(t^{(k)}) = \sum_{j=-\infty}^{\infty} s(t^{(k)} - jT_f - c_j^{(k)} T_c - \delta b_{(\frac{j}{N_s})}^{(k)}) \tag{2.17}$$

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

2.7 Summary

In this chapter, all the possible modulation and multiple access techniques are discussed and basic overview of physical layer model is given. And basic idea of signal model and its sampling rate and also transceiver block diagram is given.

Chapter 3

UWB Channel Model

This section describes channel models for UWB communications and responses of an impulse passing through a channel. An accurate model is a prerequisite for designing an efficient communication system which includes maximum achievable data rate, suitable modulation scheme, and algorithm for signal processing.

In general, the received signal is made up of several components: first, the direct component is commensurate with the portion of the wave travel along a Line Of Sight (LOS) between the transmit and receive antennae and; second, the components arrive after having been reflected or diffracted on scattering objects that are part of the propagation environment. The latter is the result of a well known effect: **multi path propagation**. As a consequence, the received signal is made up of multiple replicas of the transmitted signal, all of which exhibit different attenuations, delays and polarizations. Multi path propagation gives rise to two important phenomena: time and location dependent on the received signal strength. Multipath components that arrive at different time instants, which causes a frequency selective transmission channel.

UWB channel model is a dense multi path channel. A great deal of proposals and measurements support this conclusion [27][28]. Different from the narrow band,which used Rayleigh fading channel, UWB channel model is presented by a log normal fading model. A modified Saleh-Valenzuela (SV) model is used for power and delay profile as shown in figure 3. To unify the evaluation of UWB design,the IEEE 802.15.3a group developed channel models for UWB communication system [29], which was accepted by a full standardization group. UWB channels are quite different from narrow band wireless channels, especially in fading statistics and multi path clusters which cause a high challenge in acquisition design[30][31]. The SV model thus distinguishes between

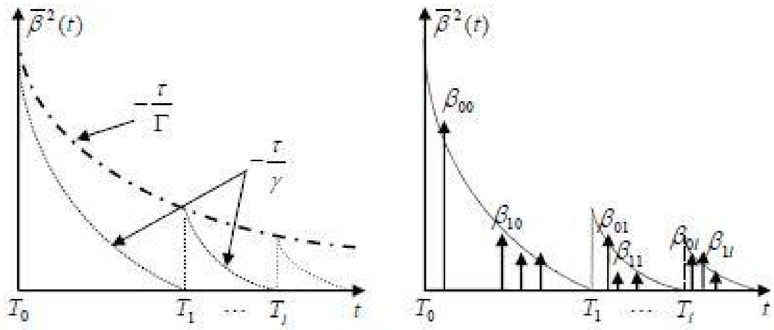

Figure 3.1: (a) Exponentially decaying ray and cluster average powers.(b) A realization of the impulse response.

cluster arrival rates and **ray arrival rates**. The first cluster starts by definition at time t=0, and the following rays are a arriving with a rate given by a Poisson process with rate λ. The power of those rays decays exponentially with increasing delay from the first ray. The cluster arrival rate, which is smaller than the ray arrival rate, in turn determines when the next cluster has its origin. The rays within that cluster are again a Poisson process with rate λ.Before going for channel characteristic first take a closer look at channel model as follows.

3.1 Generic Channel Model

[32] In this chapter, the description of the generic channel model that is used for the 2-10 GHz model is given. Before going into details,I summarize the key features of the model:

- model treats only channel, while antenna effects are to be modeled separately

- d^-n law for the pathloss
- frequency dependence of the pathloss
- modified Saleh-Valenzuela model:
  a. arrival of paths in clusters
  b. mixed Poisson distribution for ray arrival times
  c. possible delay dependence of cluster decay times
  d. some NLOS environments have first increase, then decrease of power delay profile
- Nakagami-distribution of small-scale fading, with different m-factors for different components
- block fading: channel stays constant over data burst duration

3.1.1 Pathloss And Shadowing

Shadowing, or large-scale fading, is defined as the variation of the local mean around the pathloss. Also this process is fairly similar to the narrowband fading. The pathloss (averaged over the small-scale fading) in dB can be written as

$$PL(d) = PL_0 + 10nlog_(10)(\frac{d}{d_0}) + S \tag{3.1}$$

where S is a Gaussian-distributed random variable with zero mean and standard deviation σ_S. Remark: While the shadowing shows a finite coherence time (distance), this is not considered in the model. The simulation procedure in 802.15 4a prescribes that each data packet is transmitted in a different channel realization, so that correlations of the shadowing from one packet to the next are not required/allowed in the simulations. Finally, since the log-normal shadowing of the total multipath energy is captured by the term, i X , the total energy contained in the terms $\{\alpha^i_{k,l}\}$ is normalized to unity for each realization. This shadowing term is characterized by the following[32]:

$$20log_{10}(\chi_i) \propto Normal(0, \sigma_x^2) \quad (3.2)$$

3.1.2 Impulse Response and Power Delay Profile

The impulse response (in complex baseband) of the SV (Saleh-Valenzuela) model is given in general as [11]

$$h(t) = \chi_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l} exp(j\phi_{k,l)})\delta(t - T_l - \tau_{k,l}) \quad (3.3)$$

where $a_{k,l}$ is the tap weight of the kth component in the lth cluster, T_l is the delay of the lth cluster, $\tau_{k,l}$ is the delay of the kth MPC relative to the l-th cluster arrival time T_l, χ_i represents the log-normal shadowing, and i refers to the ith realization. The phases $\phi_{k,l}$ are uniformly distributed, i.e., for a bandpass system, the phase is taken as a uniformly distributed random variable from the range $[0, 2\pi]$.The number of clusters L is an important parameter of the model. It is assumed to be Poisson-distributed.

$$pdf_L(L) = \frac{(\overline{L})^L exp(-\overline{L})}{L!} \quad (3.4)$$

so that the mean $\overline{L}$ completely characterizes the distribution. By definition, it would be $\tau_{0,l} = 0$. The distributions of the cluster arrival times are given by a Poisson processes[32]

$$p(\frac{T_l}{T_{l-1}}) = \Lambda_l exp[-\Lambda_l(T_l - T_{l-1})] \quad (3.5)$$

where l>0 and Λ_l is the cluster arrival rate (assumed to be independent of l). The classical SV model also uses a Poisson process for the ray arrival times.Due to the discrepancy in the fitting for the indoor residential, and indoor and outdoor office environments, the proposal to model ray arrival times with mixtures of two Poisson processes as follows,

$$p(\frac{\tau_{(k,l)}}{\tau_{(k-1,l)}}) = \beta\lambda_1 exp[-\lambda_1(\tau_{k,l} - \tau_{(k-1,l)})] + \beta\lambda_2 exp[-\lambda_2(\tau_{k,l} - \tau_{(k-1,l)})] \tag{3.6}$$

where β is the mixture probability, while λ_1 and λ_2 are the ray arrival rates. Remark: while a delay dependence of these parameters has been conjectured, no measurements results have been found up to now to support this. For some environments, most notably the industrial environment, a "dense" arrival of multipath components was observed, i.e., each resolvable delay bin contains significant energy. In that case, the concept of ray arrival rates loses its meaning, and a realization of the impulse response based on a tapped delay line model with regular tap spacings is to be used. The next step is the determination of the cluster powers and cluster shapes. The power delay profile (mean power of the different paths) is exponential within each cluster[32].

$$E\{|\alpha_{k,l}|^2\} = \Omega_l \frac{1}{\gamma_l[(1-\beta)\lambda_1 + \beta\lambda_2 + 1]} exp[\frac{-\tau_{k,l}}{\gamma_l}] \tag{3.7}$$

where Ω_l is the integrated energy of the lth cluster, and γ_l is the intra-cluster decay time constant. Note that the normalization is an approximate one, but works for typical values of λ and γ. Remark: Some measurements, especially in industrial environments, indicate that the first path of each cluster carries a larger mean energy than what I expect from an exponential profile. However, due to a lack of measurements, this has not been taken into account in the final model. The cluster decay rates are found to depend linearly on the arrival time of the cluster,

$$\gamma_l \propto k_\gamma T_l + \gamma_0 \tag{3.8}$$

where k_γ describes the increase of the decay constant with delay. The mean (over the cluster shadowing), mean (over the small-scale fading) energy (normalized to γ_l), of

Target Channel characteristic	CM1	CM2	CM3	CM4
Distance(m)	0-4	0-4	4-10	
(Non) Line of sight	Yes	No	No	No
Mean excess delay $r_{rms}(ns)$	5.05	10.38	14.18	
RMS delay spread $r_{rms}(ns)$	5.28	8.03	14.28	25
NP_{10dB}			35	
$NP_{85\%}$	24	36.1	61.54	

Table 3.1: Channel parameter as per model

the lth cluster follows in general an exponential decay,

$$10log(\Omega_l) = 10log(exp(\frac{-T_l}{\Gamma})) + M_{cluster} \tag{3.9}$$

where $M_{cluster}$ is a normally distributed variable with standard deviation $\sigma_{cluster}$ around it.

Four types of UWB channels are defined by the IEEE 802.15.3a group to meet measurement results, namely CM1, CM2, CM3, and CM4, for different channel characteristics.

- CM1: LOS scenario with a separation between transmitter and receiver of less than 4m.
- CM2: the same range as CM1, but no LOS.
- CM3: a N-LOS scenario for distance between 4-10m.
- CM4: a situation with strong delay dispersion, resulting in a delay spread of at least 25ns.

Note: NP_{10dB} is the number of paths within 10dB of the strongest path and $NP_{85\%}$ gives the number of paths containing 85% of the energy.Root Mean Square (RMS) of spread delay, r_{rms}, is also measured for all models.

3.2 The Algorithm With flow Chart

Following is the algorithm which generate impulse response of UWB channel that will be useful in physical layer design. Performance of this algorithm is discussed in 5.3.2 and flowchart shows the way of algorithm works.

Algorithm 3.1 Flow of the algorithm for the Impulse Response

1 Input the channel model parameter as per 3.1.
Generate the random variable for the no. of clusters L.
Determine arrival time of the first component of the cluster.
Generate cluster decay time and total power of for each cluster.3.83.9
Determine the no. of arrival component(Rays) for each cluster.
plot response.

2 Convert continuous time to discrete samples.
Compute total no. of paths in each channel.
Normalize Impulse function.

3 Compute channel energy.
Compute excess delay and RMS delay.
Determine number of significant paths (paths within 10 dB from peak and >85%).
Determine number of sig. paths (captures x % of energy in channel).
For each component, compute the mean power.3.7

4 Plot PDP, No. of significant path as per channel,rms delay.

Now we will see the flow chart of these algorithm.

3.3 Simulink Model

In this section, one complete simulink model of physical layer in matlab is discussed. Lets start with source and encoding procedure.

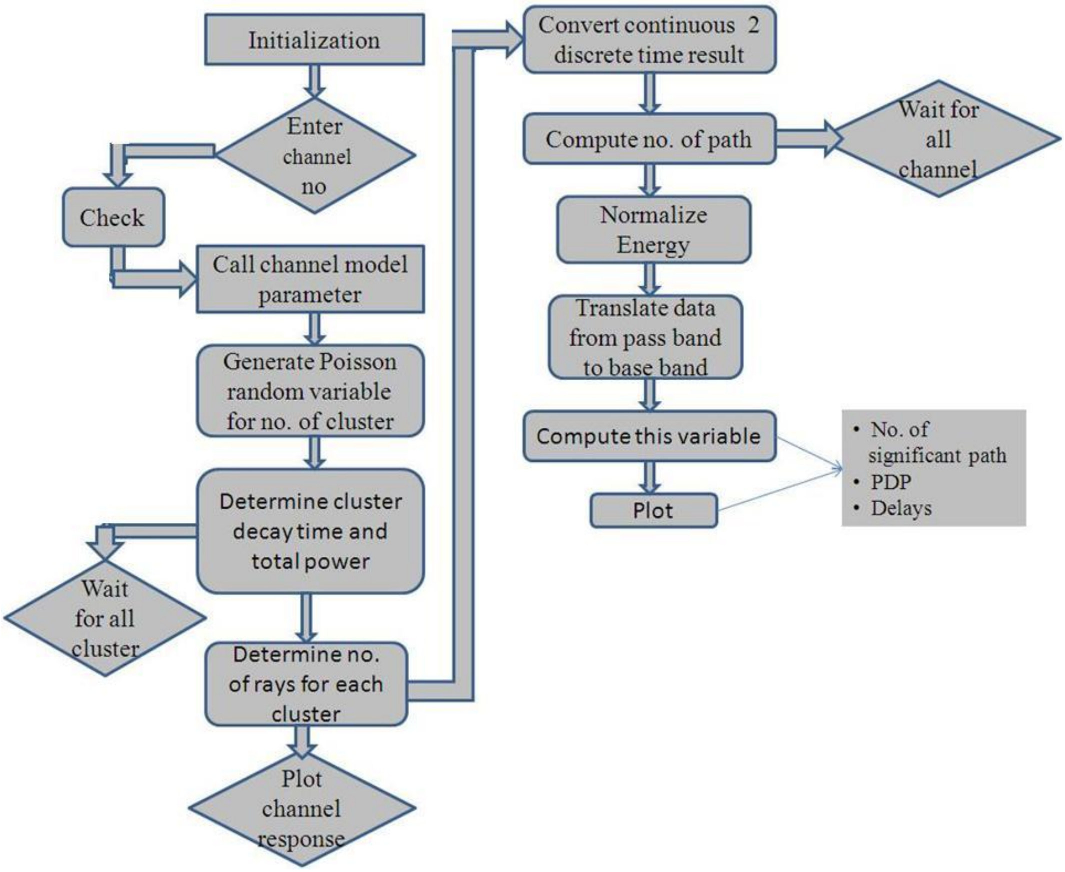

Figure 3.2: Flowchart for UWB channel

3.3.1 Source

The information bits must be randomized before the transmission. The randomization process is used to minimize the possibility of transmissions of non-modulated subcarriers. The process of randomization is performed on each burst of data on the downlink and uplink, and on each allocation of a data block (subchannels on the frequency domain and OFDM symbols on the time domain). In our case, instead of performing a randomization process, a binary source that produces random sequences of bits is used. The number of bits that are generated is specified to be frame-based and is calculated from the packet size required in each situation. The packet size depends on the number of transmitted OFDM symbols and the overall coding rate of

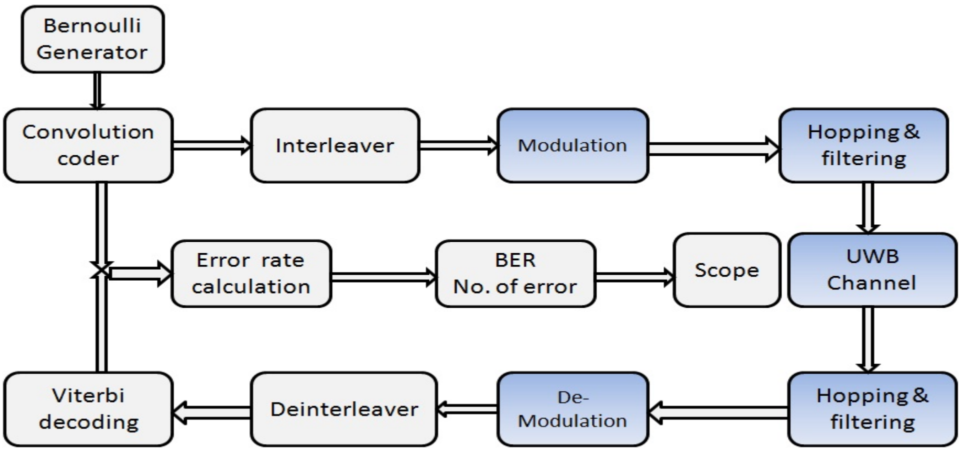

Figure 3.3: Simulink model of physical layer

the system, as well as the modulation alphabet.

3.3.2 Encoder

The encoding process as shown in Figure 3.3 consists of a convolutional code (CC) as a FEC scheme. That means that first data passes across the convolutional encoder. It is a flexible coding process due to the puncturing of the signal, and allows different coding rates. The last part of the encoder is a process of interleaving to avoid long error bursts.

A variable-rate coding scheme that depends on the channel conditions is designed to offer optimal error protection levels to the users. The FEC options are paired with several modulation schemes to form burst profiles of varying robustness and efficiency.

Convolutional Encoder

The data bits are encoded by a binary convolutional encoder, which has a native rate of 5/8 and a constraint length of 7. The generator polynomials used to derive its output code bits are specified in the following expressions:

$$G_1 = 175_{oct} \tag{3.10}$$

$$G_2 = 145_{oct} \tag{3.11}$$

$$G_2 = 133_{oct} \tag{3.12}$$

A convolutional encoder accepts messages of length k bits and generates codewords of n bits. Generally, it is made up of a shift register of L segments, where L denotes the constraint length. The binary convolutional encoder that implements the described code is shown in Figure 3.4.

A connection line from the shift register feeding into the adder means a "one" in the octal representation of the polynomials, and no connection is represented by a "zero".

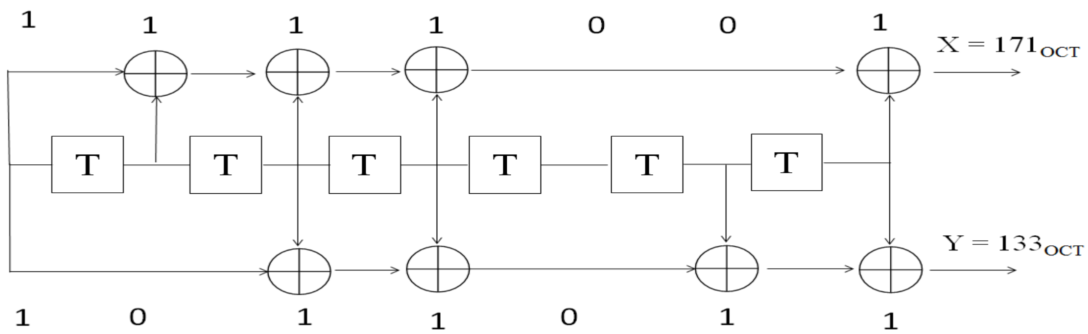

Figure 3.4: Convolutional encoder of binary rate 1/2.

Puncturing Process

Puncturing is the process of systematically deleting bits from the output stream of a low-rate encoder in order to reduce the amount of data to be transmitted, thus forming a high-rate code. The bits are deleted according to a perforation matrix, where a "zero" means a discarded bit.

The process of puncturing is used to create the variable coding rates needed to provide various error protection levels to the users of the system. The different rates that can be used are rate 1/2, rate 2/3, rate 3/4, and rate 5/8. Among that here used is rate 5/8.

3.3.3 Interleaver

Data interleaving is generally used to scatter error bursts and thus, reduce the error concentration to be corrected with the purpose of increasing the efficiency of FEC by spreading burst errors introduced by the transmission channel over a longer time.

Interleaving is normally implemented by using a two-dimensional array buffer, such that the data enters the buffer in rows, which specify the number of interleaving levels, and then, it is read out in columns. The result is that a burst of errors in the channel after interleaving becomes in few scarcely spaced single symbol errors, which are more easily correctable.

The effect of this process can be understood as a spreading of the bits of the different symbols, which are combined to get new symbols, with the same size but with rearranged bits.

The interleaver of the simulator has been implemented in two steps. First, data passes through a matrix interleaver which performs block interleaving by filling a matrix with the input symbols row by row, and then sending this matrix content column by column. The parameters used for this block are the number of rows and columns that compose the matrix:

$$N_{columns} = 12, N_{rows} = \frac{NSD * spreadFactor}{codedBitsPerQPSKSymbol} \tag{3.13}$$

where NSD is data subscriber.

3.3.4 Modulation

Once the signal has been coded, it enters the modulation block. All wireless communication systems use a modulation scheme to map coded bits to a form that can be effectively transmitted over the communication channel. Thus, the bits are mapped to a subcarrier amplitude and phase, which is represented by a complex in-phase and quadrature-phase (IQ) vector.

The IQ plot for a modulation scheme shows the transmitted vector for all data word combinations. Gray coding is a method for this allocation so that adjacent points in the constellation only differ by a single bit.

This coding helps to minimize the overall bit error rate as it reduces the chance of multiple bit errors ocurring from a single symbol error. The different modulation techniques used for UWB has already been discussed in2.3.

3.3.5 OFDM

After modulation OFDM may be used in that following features are used.

The Guard Bands

The OFDM physical layer of the UWB standard specifies that transmission must be performed using 256 frequency subcarriers. The total amount of subcarriers to be used is determined by the number of points needed to perform the IFFT.

After the assembling process only 100 of the total 256 subcarriers are used. The remaining carriers, that are zero subcarriers appended at the end of the cited structure, act as guard bands with the purpose to enable the naturally decay of the signal. These guard bands are used to decrease emissions in adjacent frequency channels.

Figure 3.5 show the structure of the subcarriers before and after appending the guard bands.

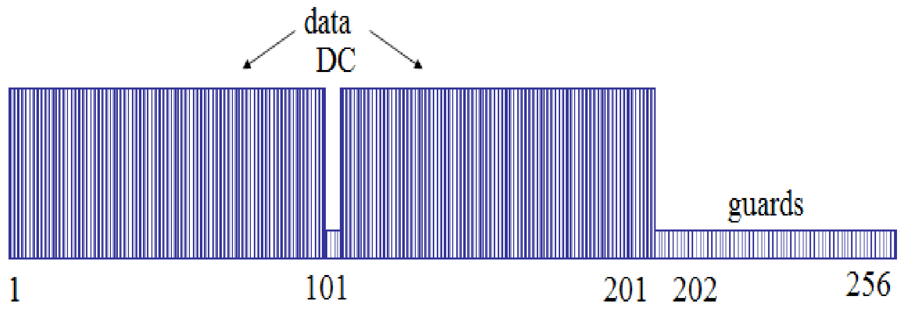

Figure 3.5: Structure after appending the guard bands

3.3.6 Inverse Fast Fourier Transform Algorithm

The IFFT is used to produce a time domain signal, as the symbols obtained after modulation can be considered the amplitudes of a certain range of sinusoids. This means that each of the discrete samples before applying the IFFT algorithm corresponds to an individual subcarrier. Besides ensuring the orthogonality of the OFDM subcarriers, the IFFT represents also a rapid way for modulating these subcarriers in parallel, and thus, the use of multiple modulators and demodulators, which spend a lot of time and resources to perform this operation, is avoided. Before doing the IFFT operation in the simulator, the subcarriers are rearranged. Figure 3.6 [33] shows the subcarrier structure that enters the IFFT block after performing the cited rearrangement. As seen in the following figure, zero subcarriers are kept in the center of the structure.

3.3.7 The Cyclic Prefix

The robustness of any OFDM transmission against multipath delay spread is achieved by having a long symbol period with the purpose of minimizing the inter-symbol interference. Figure 3.7[33] depicts one way to perform the cited long symbol period, creating a cyclically extended guard interval where each OFDM symbol is preceded by a periodic extension of the signal itself.This guard interval, that is actually a copy

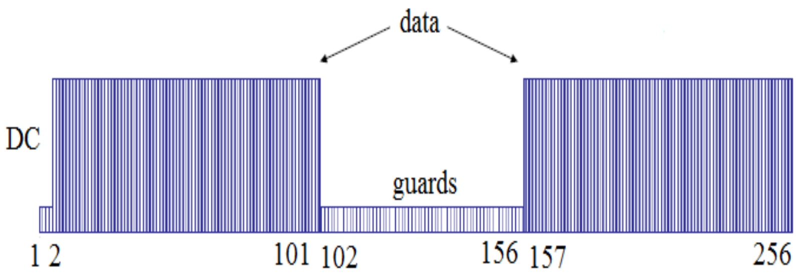

Figure 3.6: Rearrangement performed before realizing the IFFT operation.

of the last portion of the data symbol, is known as the cyclic prefix (CP). Copying

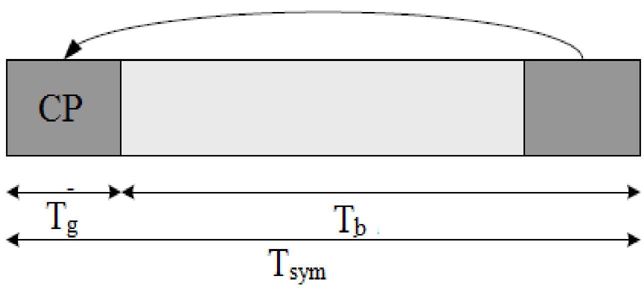

Figure 3.7: OFDM symbol with the cyclic prefix.

the end of a symbol and appending it to the start results in a longer symbol time. Thus, the total length of the symbol is

$$T_{sym} = T_b + T_g \tag{3.14}$$

where:

- T_{sym} is the OFDM symbol time,
- T_b is the useful symbol time, and
- T_g represents the CP time.

The parameter G defines the ratio of the CP length to the useful symbol time. When eliminating ISI, it has to be taken into account that the CP must be longer than the dispersion of the channel. Moreover, it should be as small as possible since it costs energy to the transmitter. For these reasons, G is usually less than 1/4:

$$G = \frac{T_g}{T_b} \tag{3.15}$$

3.4 UWB Channel

The complete IEEE model of UWB channel has discussed in the previous topic of the same chapter.

3.5 Decoder

The final stage of receive processing is the decoder. The decoder accepts the sequence of bits in accordance with the encoding method that was used, attempts to reproduce the information originally generated by the source. Like in the encoder block, the decoder is also composed of four steps, which perform diverse operations with the aim of reversing the process done by the encoder.

Deinterleaving The deinterleaver rearranges the bits from each burst in the correct way by ordering them consecutively as before the interleaving process. It consists of two blocks, a general block deinterleaver and a matrix deinterleaver. These blocks work similarly as the ones used in the interleaver. The general block deinterleaver rearranges the elements of its input according to an index vector. The matrix deinterleaver performs block deinterleaving by filling a matrix with the input symbols column by column, and then, sending its contents to the output row by row. The parameters used in both blocks are the same as those ones used in the interleaving process.

Inserting Zeros The block named "Insert Zeros" deals with the task of reversing the process performed by the "Puncture" block. As previously explained in Section 3.3.2, the puncturing process consists of deleting bits from a stream. The receiver does not know the value of the deleted bits but it can know their position from the puncturing vectors. Thus, zeros are used to fill the corresponding hollows of the stream in order to get the same code rate as before performing the puncturing process. The inserted zeros can also be seen as erasures from the channel. They have no influence on the metric calculation of the succeeding Viterbi decoder described in the following section.

Viterbi Decoder The Viterbi algorithm reduces the computational load by taking advantage of the special structure of the trellis code. Another advantage is its complexity, which is not a function of the number of symbols that compose the codeword sequence. The Viterbi algorithm performs approximate maximum likelihood decoding. It involves calculating a measure of similarity or distance between the received signal at time t_i, and all the trellis paths entering each state at the same time.

The algorithm works by removing those trellis paths from consideration that could not possibly be candidates for the maximum likelihood choice. When two paths enter the same state, the one that has the best metric is chosen as the "surviving" path. The selection of the different "surviving" paths is performed for all the states. The decoder continues in this way to advance deeper into the trellis making decisions by eliminating the least likely paths. The early rejection of unlikely paths is the fact that reduces the complexity. The goal of selecting the optimum path can be expressed equivalently as choosing the codeword with the maximum likelihood metric, or as choosing the codeword with the minimum distance metric [34].

Furthermore, the delay introduced in the decoding process has to be taken into account. The rejection of possible paths does not really begin until the third step in the representation in the trellis diagram. This is due to the fact that until this time two branches can not have converged in one state, and thus, no decision can be done. This delay effect is considered in a parameter called traceback depth, which specifies how many symbols may preceed the beginning of the algorithm.

Another parameters of the Viterbi decoder block of Simulink are the trellis structure used in the convolutional encoder, the decision type of decoding, and the operation mode. They are defined as follows:

- The type of signals that can support the Viterbi decoder block are based on the decision type parameter. This parameter can have three values: unquantized, hard-decision, or soft-decision. As the decision process has been implemented in the demapper, the last kind of decision type, that is the "unquantized", is the one used in our simulator. It accepts real numbers as inputs for the decoder block. The positive numbers are interpreted as a logical zero, and the negative ones, as a logical one. However, when this parameter is set to "soft-decision", the entries of this block are integers between 0 (most confident decision for logical zero) and 2^b (most confident decision for logical one), being b the number of soft-decision bits.

- The *operation mode* parameter controls which method the block uses for transitioning between successive frames. The "truncated" mode, in which each frame is treated independently and the traceback depth parameter starts at the state with the best metric and ends in the all-zeros state, is the *operation mode* used in the simulator.Other values for this parameter are the "continuous" and "terminated" modes. For more details about these parameters consult the documentation help of MATLAB.

Chapter 4

Performance Of RAKE Receiver In UWB Technology

This chapter contains different diversity combining techniques, how RAKE receiver operate and its tupe.

4.1 Introduction

In wireless communication multipath is a common phenomenon,In this process the transmitted signal proceeds towards its receiver along multiple routes while reflecting, scattering and dispersing due to obstacles it encounters in its path. The receiver in return hears echoes having, different and randomly varying delays and amplitudes [35]. The two effects contributes in multipath fading are selective fading and inter symbol interference as discussed follows[35].

Selective Fading It majorly concerns with the relative phases of the signals received by the receiving antenna via various paths [36]. It is stated that the total received signal at any one frequency, is the vector sum of the individually delayed signals and their relative phase angles depends upon the frequency, amplitudes and delays [36]. As the amplitudes and the delays are time varying, we can observe difference or variations in the received signal strength at a single frequency as a function of time [36].

Inter Symbol Interference It comes into picture due to time delay between the first and the last significantly large reflected component. In the presence of the modulation, the echoes appearing in this modulation would result in smearing of information, regardless of the form of the signal used [36]. The intersymbol interference aspect of the multipath was long recognized to have placed a limit on the rate at which discrete or digital information can be communicated with time division schemes.

As a solution we can use multiple sub carriers, frequency division, each having long symbol waveforms to carry a fraction of the total information rate over multipath, has been standard for many years [37]. Another solution to overcome the problems created by the multipath, RAKE receivers concept was evolved.These days RAKE receivers are in widespread use, especially in CDMA systems employing spread spectrum techniques [38]. In these systems the link improvement is obtained through time diversity. Spread spectrum systems are not only resistant to multipath fading but they can also exploit the delayed multipath components to improve the performance of the system [38]. The RAKE receiver anticipates the multipath propagation delays of the transmitted spread spectrum signal and combines the information obtained from the various resolvable multipath components to form a stronger version of the signal [38]. A RAKE receiver consists of a bank of correlators,each of which correlate to a particular multipath component of the desired signal. The correlators outputs may be weighted according to their relative strengths and summed to obtain the final signal estimate [36].

Summarizing it all, It does this by using several sub receivers each delayed slightly in order to make it coherent to the individual multipath components. In this process, each component is decoded individually and at a later stage combined in order to make the most use of the different transmission characteristics of each transmission path. This could well result in higher signal to noise ratio Eb/No, in a multipath communication scenario.

The RAKE is so named because of its analogous function to a garden RAKE, each finger collects bit or symbol energy similarly like tines on a rake collects leaves.

4.2 Working Of RAKE Receiver

A Rake receiver's job to collect the the time-shifted versions of the original signal by providing a separate correlation receiver for each of the multipath signals. Each of the correlation receiver may be adjusted in time delay, so that a microprocessor controller can cause different correlation receivers to search in different time windows for significant multipath [38]. The range of time delays that a particular correlator can search is called a search window [38].

The RAKE receiver shown in Figure 4.1, is essentially a diversity receiver designed specifically for CDMA, where the diversity is provided by the fact that the multipath components are practically uncorrelated from one another when their relative propagation delays exceed a chip period. A RAKE receiver utilizes multiple correlators to separately detect the M strongest multipath components [38]. Each correlator's output are then weighted to provide a better estimate of the transmitted signal than is provided by a single component. Demodulation and bit decisions are then based on the weighted outputs of the M correlators [38].

To explore the performance of a RAKE receiver, assume M correlators are used in a receiver to capture the M strongest multipath components [38]. A weighting network is used to provide a linear combination of the correlator output for bit detection.

Correlator 1 is synchronized to the strongest multipath m_1 [38]. Multipath component m_2 arrives δ_1 later then the component m_1, where $\delta_2 - \delta_1$ is assumed to be the greater then a chip duration. The second correlator is synchronized to m_2. It strongly correlates to m_2, but has low correlation to m1[38]. The M decision statistics are weighted to form an overall decision statistic as shown in Figure 4.2. The outputs of the M correlators are denoted as Z_1, Z_2, and Z_M.

They are weighted by α_1, α_2, and α_m respectively. The weighting coefficients are

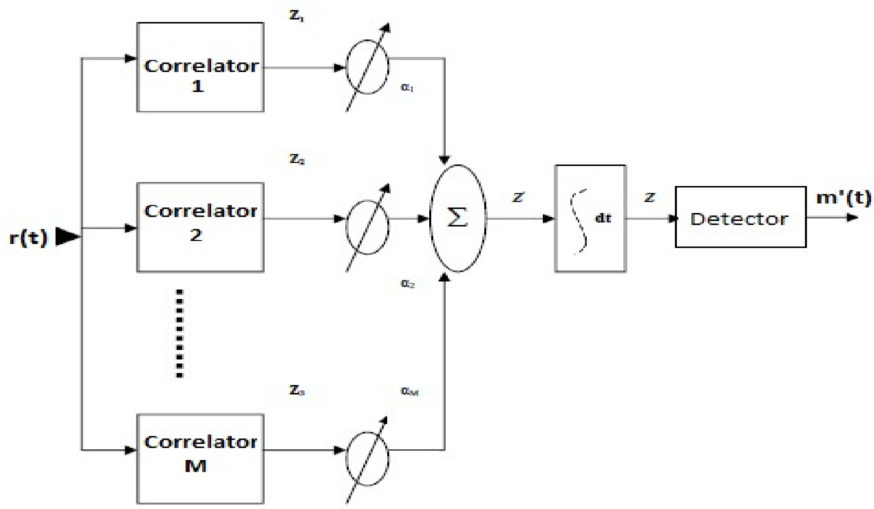

Figure 4.1: M finger rake receiver

based on the power or the SNR from each correlator output [38]. If the power or SNR is small out of a particular correlator, it will be assigned a small weighting factor. The over all signal Z is given by,

$$Z' = \sum_{m=1}^{m} \alpha_m Z_m \tag{4.1}$$

The weighting coefficients, α_m, are normalized to the output signal power of the correlators in such a way that the coefficients sum to unity, as shown in Equation 4.2.

$$\alpha_m = \frac{Z_m^2}{\sum_{m=1}^{m} Z_m^2} \tag{4.2}$$

In case of multiple access interference, RAKE fingers with strong multipath amplitudes will not necessarily provide strong output after correlation. Choosing weighting coefficients based on the actual outputs of the correlators gives better RAKE performance[38].

In a RAKE receiver, if any correlator's output is corrupted by fading, the others may not be, and the corrupted signal may be discounted through the weighting process. Decisions will be based on the combination of the M separate decision statistics offered by the RAKE provide a form of diversity which can overcome fading and thereby improve signal reception[38].

4.3 Types Of RAKE Receiver

The three common types of RAKE receivers are as follows:

1. All RAKE receiver $A - RAKE$

2. Selective combining RAKE receiver $S - RAKE$

3. Partial combining RAKE receiver $P - RAKE$

4.3.1 All RAKE Receiver

The term All RAKE means combine all of the resolved multipath components [1]. From the energy capture view, these type of receivers are very efficient and captures most of the energy carried by a very large number of different multipath signals[39]. In fact, the number of detectable multipath components, defined as those exceeding threshold above the noise floor, can be up to one hundred.

To achieve this, it requires $L_r = T_d/T_c$ taps, where T_d is the maximum excess delay counted from the instant at which the first path arrives. Since the number of resolvable multipath components increases with the spreading bandwidth, the number of correlators required for the A-RAKE receiver may be quite large for UWB channels. However, the number of multipath components that can be utilized in a typical Rake combiner is limited by power consumption, design complexity and channel estimation. Thus, it is considered that the A-RAKE receiver only provides an upper limit of achievable performance [1].

4.3.2 Selective Combining RAKE Receiver

The S-Rake selects the L_b best paths (a subset of the L_r available resolved multipath components) and then combines the selected subset using MRC [35][36]. This receiver makes the best use of its L_b available fingers while keeping track of all multipath components. Due to the propagation characteristics of UWB signals, a good trade off of performance degradation Vs. receiver complexity is provided by the simpler P-Rake [1]. Figure 4.2 gives basic idea for this technique. As each element is an independent

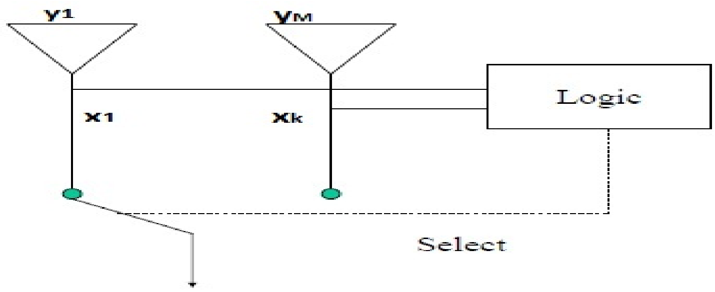

Figure 4.2: Selective Combiner

sample of the fading process, the element with the greatest SNR is chosen for further processing. In selection combining therefore,

$$x_k = \begin{cases} 1 & \text{if } \gamma_k = \max \{ \gamma_M \} \\ 0 & \text{otherwise} \end{cases} \tag{4.3}$$

Since the element chosen is the one with the maximum SNR, the output SNR of the selection diversity scheme is $\gamma = max\{\gamma_M\}$. Such a scheme would need only a measurement of signal power,phase shifters or variable gains are not required. To analyze such a system first take a look on the probability of outage, BER, and resulting improvement in SNR. The probability of outage can be stated as probability that the output SNR falls below a threshold γ_s, i.e., the SNR of all elements is below the threshold. Therefore,

$$\gamma = max\{\gamma_M\} \tag{4.4}$$

$$P_{out} = P[\gamma < \gamma_s] \tag{4.5}$$

where the final product expression is valid because the fading at each element is assumed independent. This would not be true if I had only assumed the fading to be uncorrelated from one element to the next. Using the pdf of γ_M[40],

$$P[\gamma_M < \gamma_s] = \int_0^{\gamma_s} \frac{1}{\Gamma} e^{\frac{-\gamma_M}{\Gamma}} d\gamma_M \tag{4.6}$$

$$P[\gamma_M < \gamma_s] = 1 - e^{-\frac{\gamma_M}{\Gamma}} \tag{4.7}$$

$$P_{out}(\gamma_s) = [1 - e^{\frac{-\gamma_M}{\Gamma}}]^N \tag{4.8}$$

The outage probability therefore decreases exponentially with the number of elements. Figure 5.10 illustrates the improvement in outage probability as a function of the number of elements in the array.

As it is clearly seen, selecting between just two elements results in significant performance improvements.output SNR can, at best, double. Note also the linear relationship in Fig. 5.10 expected given the exponential relationship between P_{out} and γ_s/Γ.The slope of the plot increases with increasing N.

P_{out} also represents the cdf of the output SNR as a function of the threshold γ_s. The pdf of the output SNR,γ, is therefore[40],

$$f_\Gamma(\gamma) = \frac{dP_{out}(\gamma)}{d\gamma} = \frac{N}{\Gamma} e^{-\frac{\gamma}{\Gamma}} [1 - e^{-\frac{\gamma}{\Gamma}}]^{N-1} \tag{4.9}$$

At this point, The probability of outage and the pdf of the output SNR have been derived.The other possible figures of merit is the improvement in BER. The overall error rate is obtained by integrating the conditional error rate at a given SNR. For BPSK modulation, the conditional Bit Error Rate (BER) is $erfc(\sqrt{2\gamma})$ and the overall error rate[40] is

$$P_e = \int_0^\infty (\frac{BER}{\gamma}) f_\Gamma(\gamma) d_\gamma = \int_0^\infty erfc(\sqrt{2\gamma}) \frac{N}{\Gamma} e^{-\frac{\gamma}{\Gamma}} [1 - e^{-\frac{\gamma}{\Gamma}}]^{N-1} d\gamma \qquad (4.10)$$

4.3.3 Partial Combining RAKE Receiver

The P-Rake uses L_p paths out of L_r available diversity paths, but it combines the first L_p arriving paths, which are not necessarily the best. There is a reduction in complexity compare to the S-Rake is due to the absence of the selection mechanism. Thus it alleviates the need to sort the multipath components by the magnitude of their instantaneous path gains, which would require instantaneous and highly accurate channel estimation. The P-Rake only needs to find the position of the first arriving path, leading to a substantial complexity reduction [1].

4.4 Diversity Techniques Used In RAKE Receivers

For the combination of different shifted, delayed and attenuated received signals at the RAKEs fingers and for the determination of the desired signal, different diversity techniques are used. The most commonly used of them are:
1. Maximal Ratio Combining (MRC)
2. Equal Gain Combining (EGC)
Let us have a look at each of these techniques and their application in RAKE receivers.

4.4.1 Maximum Ratio Combining

This method describes that signals from all of the M branches are weighted according to their individual signal voltage to noise power ratios and then summed. Consider figure 4.3 and observe that the individual signals must be co-phased before being summed.This generally requires an individual receiver and phasing circuit for each antenna element. Maximal ratio combining produces an output SNR equal to the sum of the individual SNRs. Maximal-ratio diversity has sometimes been called ratio

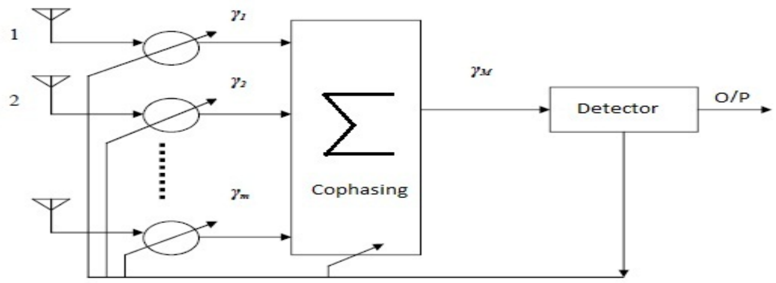

Figure 4.3: Maximal Ratio Combiner

squarer diversity, optimum diversity, and combiner diversity [36]. Let me have a close look at the maximal ratio combining improvement. In maximal ratio combining, the voltage signals (signals) r_i from each of the M diversity branches are co-phased to provide optimal SNR. If each branch has gain G_i, then the resulting signal envelope applied to the detector is,

$$r_M = \sum_{i=1}^{M} G_i r_i \tag{4.11}$$

Assuming that each branch has the same average noise power N, the total noise power N_T applied to the detector is simply the weighted sum of the noise in each branch.Thus,

$$N_T = N \sum_{i=1}^{M} G_i^2 \tag{4.12}$$

which results in an SNR applied to the detector γ_M, is given by[40],

$$\gamma_M = \frac{r_m^2}{2N_T} \tag{4.13}$$

Using Chebychevs inequality [39], γ_M is maximized when $G_i = \frac{r_i}{N}$, which leads to

$$\gamma_M = \frac{\frac{1}{2}\sum(\frac{r_i^2}{N})^2}{N\sum(\frac{r_i^2}{N^2})} = \frac{1}{2}\sum_{i=1}^{M}\frac{r_i^2}{N} = \sum_{i=1}^{M}\gamma_i \tag{4.14}$$

Thus, the SNR out of the diversity combiner is simply the sum of the SNRs in each branch. The received signal envelope for a fading mobile radio signal can be modeled from two independent Gaussian random variables T_c and T_s, each having zero mean and equal variance σ^2. That is[40],

$$\gamma_i = (\frac{1}{2N})r_i^2 = (\frac{1}{2N})(T_c^2 + T_s^2) \tag{4.15}$$

Hence γ_M is a Chi-square distribution of 2M Gaussian random variables with variance.

$$\frac{\sigma^2}{(2N)} = \frac{\Gamma}{2} \tag{4.16}$$

where Γ is SNR and is defined as[40],

$$SNR = \Gamma = (\frac{E_b}{N_o})\overline{\alpha^2} \tag{4.17}$$

Where I assume $\alpha^2 = 1$. The resulting pdf for γ_M can be shown to be

$$p(\gamma_M) = \gamma_M^{M-1} e^{-\frac{\gamma_M}{\Gamma}} for \gamma_M \geq 0 \tag{4.18}$$

The probability that γ_M is less than some SNR threshold γ is

$$P_r\{\gamma_m \leq \gamma\} = 1 - e^{-\frac{\gamma}{\Gamma}} \sum (\frac{(\frac{\gamma}{\Gamma})^{k-1}}{(k-1)!}) \tag{4.19}$$

This equation is the probability distribution for the maximal ratio combining [16]. It follows directly from Equation 4.14 that the average SNR, γ_M, is simply the sum of the individual $\gamma' i$ from each branch. In other words[40],

$$\gamma_M' = \sum_{i=1}^{M} \gamma_i' = \sum_{i=1}^{M} \Gamma = M\Gamma \tag{4.20}$$

The control algorithms for setting the gains and phases for maximal ratio combining receivers are similar to those required in equalizers and RAKE receivers.

The MRC has the advantage of producing an output with an acceptable SNR even when none of the individual signals are themselves acceptable. This technique gives the best statistical reduction of fading of any known linear diversity combiner [41].

4.4.2 Equal Gain Combining

Another important diversity technique is EGC used when the variable weighting capability for the MRC is not convenient to provide. In this condition all the branch weights are set to 1 or unity but, the signals from each branch are co-phased to provide equal gain combining diversity.

The benefit of using this type of diversity is that it allows the receiver to exploit the signals that are received simultaneously on each branch. This dictates that the possibility of producing an acceptable signal from a number of unacceptable input signals is still retained and the performance is marginally inferior to maximal ratio combining [41]. While utilizing EGC, the channel gains can be made to vary in such

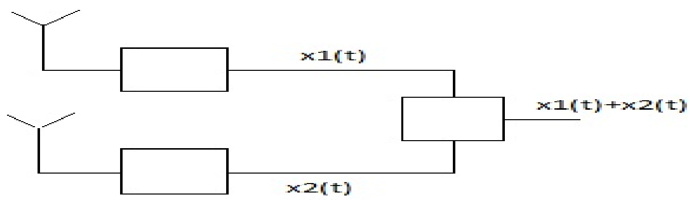

Figure 4.4: Basic equal-gain diversity [14].

a way that the output is almost constant. While noticing that it is irrelevant to the performance of the system.The important feature is that the gain of all channels is equal.

A basic two-channel equal-gain system is illustrated in figure 4.4. Figure 4.4

shows the blank boxes representing receivers must have the same gains, including conversion and detection gains, which therefore must be fixed; they could not include separate,independent AGC systems.

Also, they could not be conventional FM receivers, as the detection gain of an FM receiver depends on the signal level. However,it is possible to instrument unconventional FM detectors for post-detection equal gain combining [42].

An arrangement suitable for use with AGC is shown in Figure 4.5. The application of an equal gain combiner before detection would require the addition of phase control provisions to figures4.5.[1] It will be appropriate to illustrate the output of

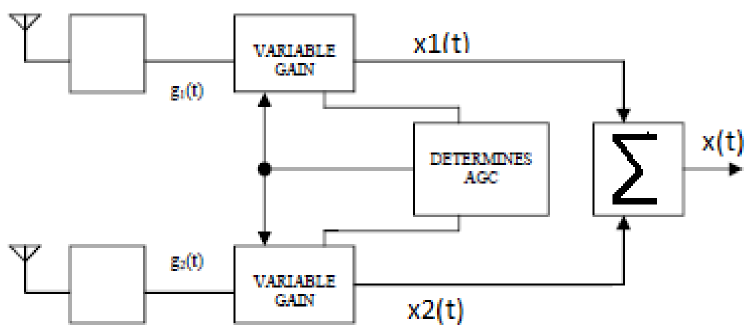

Figure 4.5: Equal-gain diversity. The boxes variable gain must have the same gain, which may include conversion and detection gain [1].

the combiner in the EGC diversity receivers.The combiner output is given by

$$r(t) = \sum_{i=1} Me^{-j\theta_i} r_i(t) \tag{4.21}$$

where r(t) is the output of the sum,

$e^{-j\theta_i}$ is the phase angle,

M is the number of diversity branches,

$r_i(t)$ the outputs of the variable gains, which must be same. Having combiner output available, SNR can be given by

$$\Gamma = (\sum_{i=1} A_i)^2 (\frac{E_b}{MN_o}) \tag{4.22}$$

where A_i is the gain factor and its estimation is not required[43].

4.5 Basic flow of Algorithm

This gives basic idea of how the receiver process in physical layer.

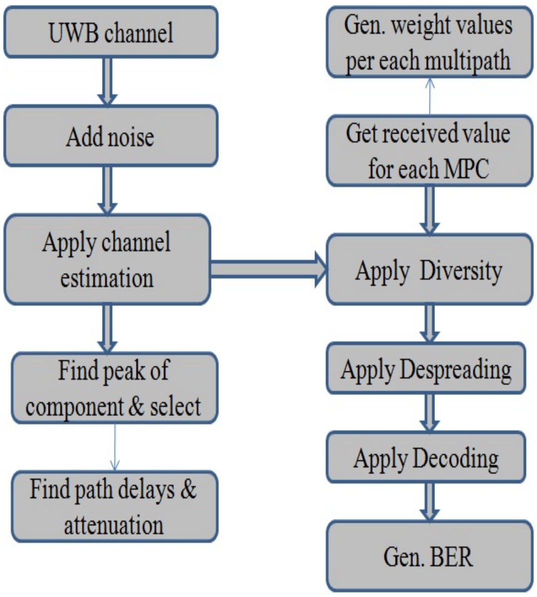

Figure 4.6: Basic flow of algorithm for receiver

4.6 Summary

In this discussion of diversity, it is investigated that Selection Combining required no phase shifters or gain elements, only the measurement of SNR at each element while MRC required both.

Chapter 5

Implementation And Performance Evaluation

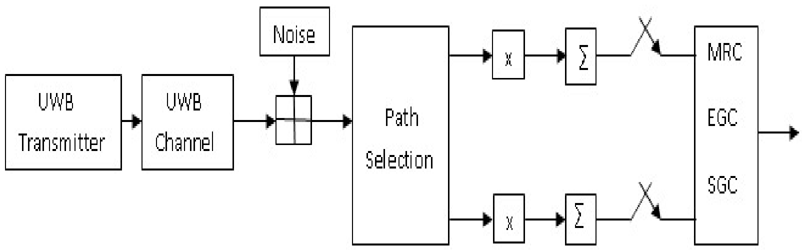

Figure 5.1: System model

Figure 5.1 shows the UWB system used during our simulations. In that there is a one block of UWB transmitter which gets the input signal which is transmitted over the UWB indoor wireless channel. The system may be includes a Narrow Band Interference(NBI) transmitter also which passes through the NBI channel and is added to the signal. Noise is also added to the signal. This signal then reaches the receiver.

The receiver constitutes of different number of correlators depending on the number of multipath components. Here the gains and time instants of the channel are obtained as per our requirement depending upon the type of RAKE receiver. The input signal is reconstructed according to the time instants obtained from the channel and multiplied with the received signal. The signal is then added bit by bit. After addition the signal is multiplied with the weight vector.

The gain factors in the weight vector vary and depend on the type of combining scheme we are using. In MRC, the gains can be obtained from the channel. In EGC, gain must be kept to one and it is co-phased with the channel. After multiplication with the weight vector the signal is recovered.

5.1 Second Derivative Of Gaussian Pulse(Doublet)

The smallest component of our input signal is the second derivative of the Gaussian pulse also known as the Doublet. The reason for using Doublet being that it has two zero crossings which helps us in bit detection and improves our results. It can be seen in the figure 5.2 below. Our signal constitutes of 8 frames in each bit and each frame has space to accommodate 3 chips..

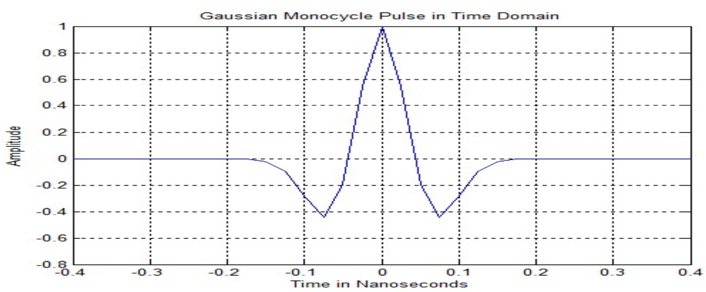

Figure 5.2: Second derivative of basic Gaussian pulse (Doublet)

5.2 Parameters used for simulation

Following parameters used for different constituents of the transmitted signal.

- The channel and transmitted bits are sampled
- Frame duration = Tf = 5nsec
- Chip duration = Tc = 1.6nsec
- Bit rate = Rb =$\frac{1}{Tb}$ = 25 Mbps
- Number of frame = 8
- Number of chip = 3
- Pulse duration = 0.15nsec
- shift = 0.5nsec
- 2 and 8 fingers used for SRAKE simulation and PRAKE simulation
- Multipath channel is stationary

5.3 Implementation Environment

In this chapter the simulation results are shown and discussed. In the following sections, first the modulation techniques and the structure of the implemented channel model simulator is presented. And how all channel models are performed that will be also discussed. In first phase it have been studied the possible modulation techniques and multiple access for UWB and also channel model which is proposed by IEEE802.15.3a work group.

5.3.1 Modulation Techniques and Multiple access

Here There are several modulations described in [44] like PPM, OOK, and BPSK are comparable in term of Power Spectral Density (PSD).The simulation results for all techniques are shown as follows. First simulation is for Time hopping PAM techniques, which clearly shows difference between unmodulated and modulated signal. Next simulation is for Time hopping PPM techniques, which clearly shows difference

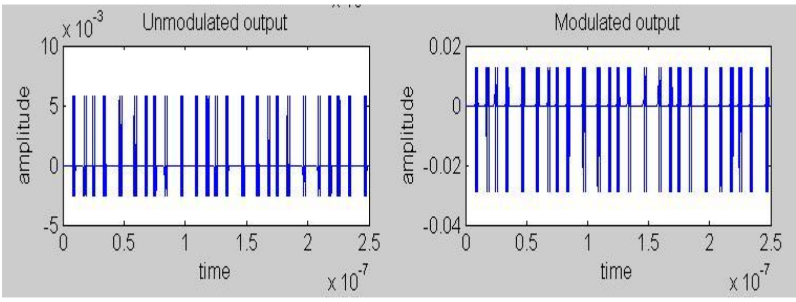

Figure 5.3: THPAM (a)Unmodulated signal (b)Modulated signal

between unmodulated and modulated signal. Next simulation is for Direct Sequence

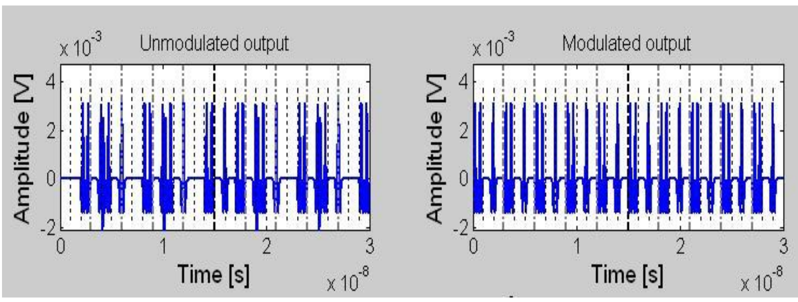

Figure 5.4: THPPM (a)Unmodulated signal (b)Modulated signal

PAM techniques, which clearly shows difference between unmodulated and modulated signal.

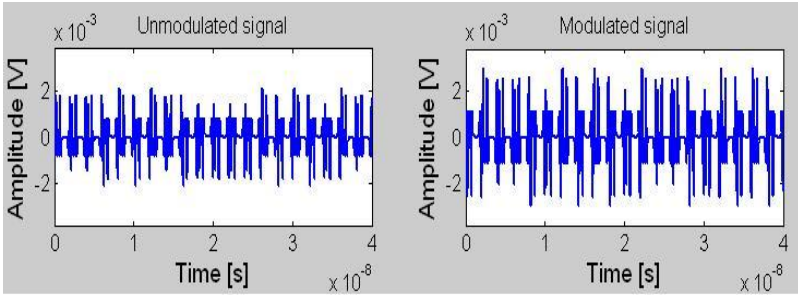

Figure 5.5: DS (a)Unmodulated signal (b)Modulated signal

5.3.2 Channel Model

As UWB is a rather recent topic, and the development time for the model was restricted by the necessity of having the model available for proposal evaluation, only a relatively small number of measurement results were available for the construction of the model. In this section it is pointed out some aspects which would be particularly responsive to improvement in the future. For comparison purposes, Figure 5.7 presents impulse responses of the four IEEE channel models. The original flowchart for this impulse response discussed in 3.2. Following simulations 5.65.7 along with the channel measurement characteristics listed in Table 3.1, highlight characteristics of the multi path channel that are important to discuss. First, the multipath spans

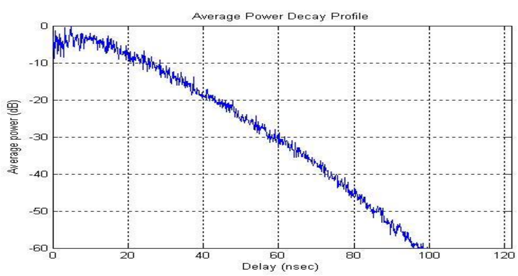

Figure 5.6: Power Delay Profile for CM

several nanoseconds in time, which results in Inter Symbol Interference (ISI) if UWB pulses are closely spaced in time. However, this interference can be mitigated in a number of ways through proper waveform design as well as signal processing and equalization algorithms. Second, the very wide bandwidth of a transmitted pulse re-

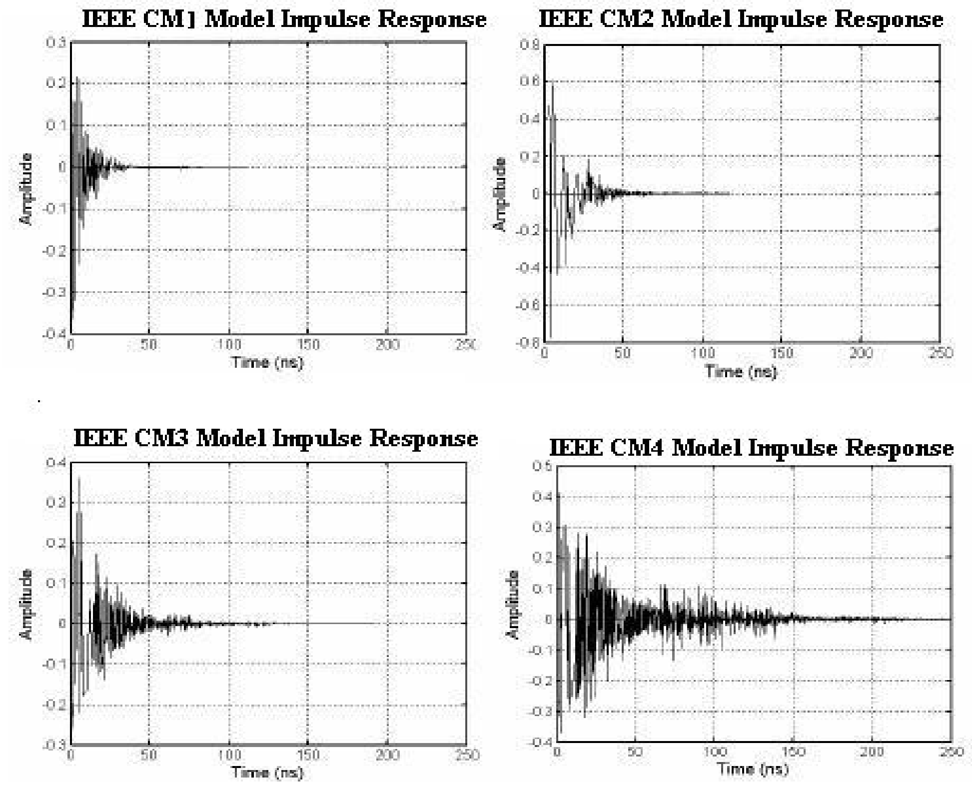

Figure 5.7: Impulse response of IEEE UWB Channel models

sults in the ability to individually resolve several multipath components. The positive and negative implications of this fact are discussed later. For the actual comparison of proposals within IEEE 802.15.3a, 100 impulse responses were generated for each of the four model environments, and stored as publicly available Excel tables.

The number of multipath components in this realization, spanning over a delay spread as per parameter defined for the different model. The defined channel parameters for these four models are listed in Table 3.1. These models assume the channel impulse response is constant during transmission of one packet if the transmission take longer time. Moreover, channel realizations are assumed to be independent between packets.

BER Performance of different Channel Models

This BER curve of simulink model3.3 As per figure5.8 it is concluded that CM1

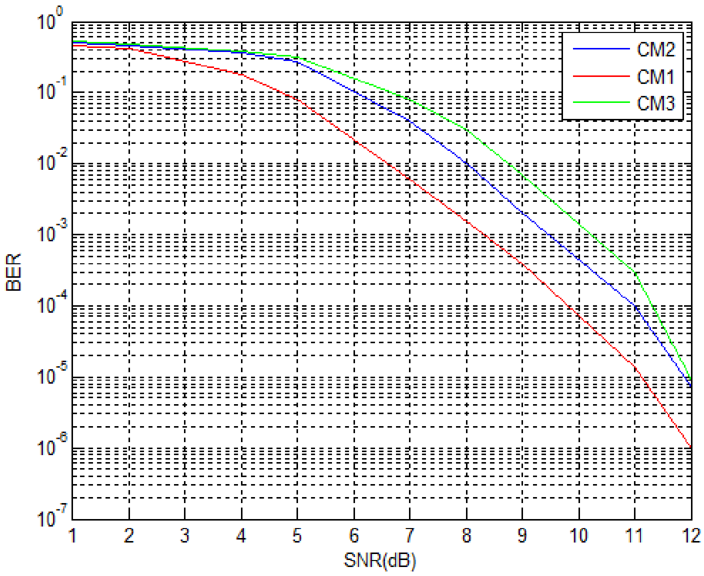

Figure 5.8: BER performance with diff. channel models

outperforms than other models because of its LOS property. And between CM2 and CM3, CM2 outperforms than CM3 because that model is used only for shorter range compare to CM3.

Analysis of Results

Various simulation runs were conducted for different set of parameters. The results were taken as above shown. Figures 5.6 and 5.7,show some important characteristics of characteristics of channels obtained from this model. The delay spread is at least several nanoseconds, leading to considerable Inter-Symbol Interference (ISI) if UWB pulses are closely spaced in time. This necessitates some form of countermeasure. On the other hand, this also implies a high degree of available diversity for the receiver.

5.3.3 Results Of Diversity Techniques Using RAKE Receiver

MRC Vs EGC BER with S-RAKE

A comparison between the performance of MRC and EGC combining schemes was done here. The system parameters were kept constant for both schemes. A S-RAKE receiver with 8 fingers was employed. Narrowband interference was ignored. We can see from the graph, Figure 5.9, that MRC out performs EGC and SLC also.

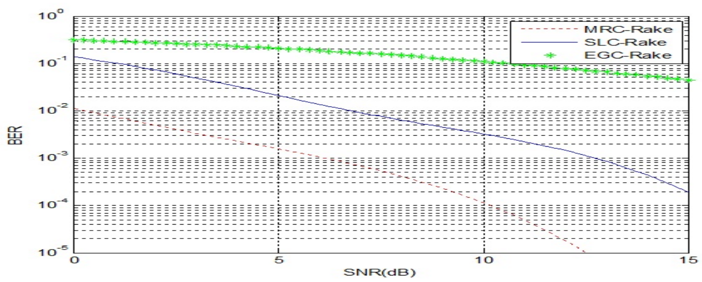

Figure 5.9: MRC vs EGC BER with S-RAKE

S-RAKE Vs P-RAKE BER Using MRC

Comparison between S-RAKE and P-RAKE receivers with 8 fingers was made using MRC combining scheme. Narrowband interference was ignored. It can be seen from the graph, Figure 5.10, that S-RAKE outperforms P-RAKE.

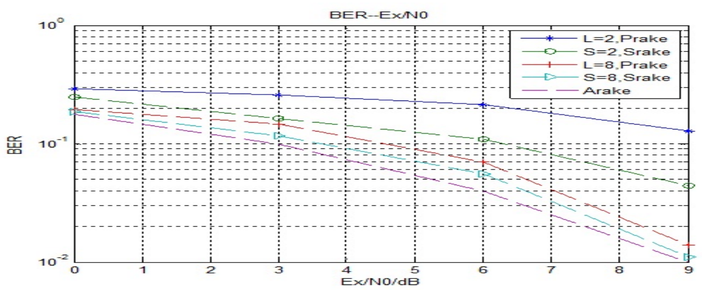

Figure 5.10: SRAKE VS PRAKE BER using MRC

MRC Employed In S-RAKE Using Different Fingers

The effect of number of fingers on the performance of system was observed. MRC combining scheme was employed in an S-RAKE and P-RAKE receiver for 2 and 8 fingers.From the graph we can see that the receiver with 8 fingers outperforms the receiver with 2 fingers. As the increase of fingers also increases the complexity of the system. Figure 5.10 depicts the performance graph.

Effect Of Increase In Pulse Width On MRC S-RAKE Receiver

The effect of the increase in pulse width on our results was also observed. It can be seen from the graph that when used the pulse width of 1nsec the results were much better as compared to the case when used pulse width of 3nsec. So 1ns pulse is better than 3nsec by 12dB. Figure 5.11 depicts this difference.

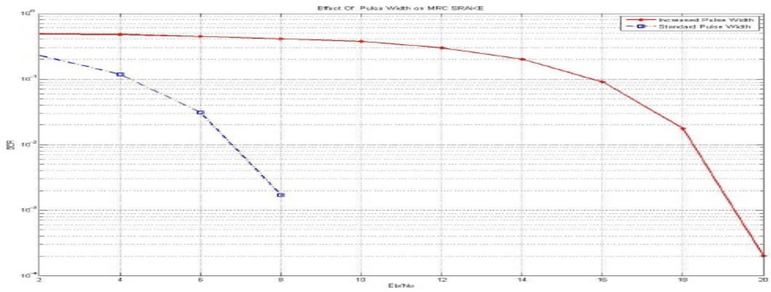

Figure 5.11: Effect of increase in pulse width on MRC SRAKE receiver

5.4 Summary

This chapter gives all kind of simulation results and its analysis for modulation techniques, multiple access techniques, UWB channel, diversity techniques.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

The results were obtained after thorough study of Ultra-wideband and the modulation techniques used in ultra-wideband and its applications. The UWB channels,fading and multipath propagation phenomenon was studied. Deep understanding of rake receivers and the combining techniques used in rake receivers was also required.

The structure of the channel model has a strong influence on the system performance assessment.The long delay spread (several nanoseconds) can have both positive and negative implications. It is good in the sense that the multi path arrivals will undergo less amplitude fluctuations (fading) since there will be fewer reflections that cause destructive/constructive interference within the resolution time of the received impulse.

On the other hand, the average total received energy is distributed between a number of multi path arrivals. In order to take advantage of that energy, unique systems and receivers need to be designed with multi path energy capture in mind.

Observing the graphs showing BER it has been concluded that MRC outperforms EGC. S-RAKE outperforms P-RAKE. The increase in number of fingers improves the results but we have to settle on an optimum value for the number of fingers which provides me the best results and also keeps our system simple.

The optimum value may vary depending upon the application in which it is used and the amount of precision required. A pulse with a narrow width gives better results as compared to a pulse with a wider width. Inter frame interference induces errors. Without inter frame interference, performance is slightly better.

6.2 Future Scope

The interference caused by UWB signals to existing NB users has been thought to be negligible due to the extremely low power spectral densities of UWB impulse radio. However, recent work in this area by Fontanna in [45] indicates that the noise power due to a UWB transmitter and seen by a NB receiver is dependent on the pulse repetition frequency of the UWB signal and the resolution bandwidth of the NB receiver. For pulse repetition frequencies less than the resolution bandwidth of the receiver, the noise power is proportional to the square of the resolution bandwidth but when the pulse repetition frequency is greater than the resolution bandwidth, the noise power is proportional to the square of the pulse repetition frequency. This is a very important attribute of NB receivers and may limit the combined multi-user data rate of UWB signals that overlap existing NB users.

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