SIGNAL PROCESSING FOR TRANSMITTED-REFERENCE ULTRA WIDEBAND SYSTEM

by

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Abstract

Signal Processing for Transmitted-Reference Ultra Wideband System

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This thesis focuses on transmitted-reference ultra wideband (TR-UWB) systems coexistence with IEEE802.11a WLAN systems. TR-UWB systems can relax the difficult synchronization requirements and can provide a simple receiver architecture that gathers the energy from many resolvable multipath components. However, UWB TR systems are susceptible to interference which comes from other wireless systems. In this thesis, TR-UWB system performance is studied in the presence of strong IEEE 802.11a WLAN interference in both AWGN and IEEE channel model. In order to reduce both the effects of interference by and into UWB signals, we propose a new method in conjunction with a multi-carrier type transmission pulse using wavelet analysis and notch filtering. Using wavelet analysis, spectral density of the transmitted UWB signal around the interfering band is reduced by 60 dB lower than the peak. With the modified TR-UWB receiver, the TR-UWB system shows performance improvement in the presence of strong IEEE 802.11a interference in both AWGN and IEEE channel models. The proposed method can be used for the coexistence of different wireless systems with UWB system.

Keywords: Wireless Communication, UWB, WLAN, Transmitted-Reference, Interference, Coexistence.

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Table of Abbreviations

ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GSM	Global System for Mobile communications
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter Symbol Interference
MAC	Media Access Control
LOS	Line Of Sight
OFDM	Orthogonal Frequency Division Modulation
OOK	On-Off Keying
PAM	Pulse Amplitude Modulation
PHY	Physical Layer
PLL	Phase Lock Loop
PPM	Pulse Position Modulation
PSD	Power Spectral Density
RF	Radio Frequency
RFID	Radio Frequency Identification
SNR	Signal to Noise Ratio
TR	Transmitted Reference
UWB	Ultra Wideband
WLAN	Wireless Local Area Networks
WPAN	Wireless Personal Area Networks

Chapter 1

Introduction

The need for high speed, mobility and flexibility in electronic media products has increased the interest to look for new wireless technologies which can fulfill these expectations. Marconi developed the first transceiver in the late nineteenth century before the carrier wave was invented. Today it is called ultra uideband radio. UWB has for many years been used in radar and military communication but has not been allowed on the open market until 2002. In April 2002, the federal communication commission (FCC) [1] lifted the restriction on the use of UWB technology for non-military applications. Lots of research works are going on internationally in both industry and academic circles [2] whose aim is to further explore the potential benefits and future challenges associated with extending UWB technology into the high-rate communications arena for short range indoor communication [3]. However, developments in high-speed switching technology are making UWB technology more attractive for low-cost consumer communications applications.

World famous electronic media production companies have divided into two major groups: UWB Forum led by Motorola (that supports DS-CDMA[4]) and Wimedia Alliance led by Intel (that supports Multi-Band OFDM (MB-OFDM) apporoach[5]), are working on two different physical (PHY) layer standards, pulsed based and multiband approach, for the upcoming IEEE 802.15.3a standard [6]. Choosing the standard has been the subject of intense debate because of their merits and demerits. The FCC has not made a final ruling on the future of UWB technology and standard, but it is currently working on setting emissions limits that would allow deployment of UWB communications systems on an unlicensed basis (more details on FCC standard are given in chapter 2).

1.1 What is Ultra Wideband?

Unlike traditional narrowband systems, UWB generates high frequency microwave pulses and uses these pulses for transmitting digital data over a wide spectrum of frequency bands with very low power intensity. Therefore, UWB is alternatively referred to as impulsive, carrierless or baseband transmission. However, it has now been realized that UWB does not have to be impulsive or carrierless [7]. This is because the FCC report only defines UWB as a signal that occupies more than 500 MHz in the 3.1-10.6 GHz spectral mask (see Fig. 2.4 and Fig. 2.5 for frequency mask for UWB signals).

Instead of transmitting traditional sine wave signals, UWB radio broadcasts digital pulses timed very precisely on a signal across a very wide spectrum. The transmitter and receiver must be coordinated to send and receive pulses with an accuracy of trillionths of a second. Very high-resolution radars and precision radio location systems can also use UWB technology.

The effect of transmitting high speed pulses instead of sine waves gives UWB transmissions a degree of immunity to multipath fading [8]. Multipath fading is the constructive and destructive interference created by multiple reflections of the same signal being received simultaneously. This favorable multipath fading capability makes UWB technology well suited for applications in environments that would otherwise suffer from multipath fading with sine wave transmissions.

UWB devices work inside the same increasingly crowded radio frequencies that many other systems use. They send out short electromagnetic pulses that last half a billionth of a second, followed by pauses that are perhaps 200 times that length. By spreading the pulses over a wide area of the spectrum (roughly 1 GHz), the devices use extremely low power. Many supporters of UWB technology envision applications such as home security and personal-area networks that activate home appliances when the user nears them. Police and fire departments are already trying out devices that can detect people behind walls using UWB technology.

1.2 Why Ultra Wideband?

The key advantage with UWB is its potential to send high data rates, more than 300 Mbps [7], over short distances making it favorable in applications like wireless local area network (WLAN) and also it can transmit data at very low rates for high distance at very low power. Also it has the ability to penetrate the obstacles. At higher power levels, UWB signals can travel significantly greater ranges.

The government and commercial industry are expressing great interest in UWB technology. For example, two main UWB applications of interest are the transmission of large amount of voice and data at very high speeds using very little power, and radars capable of penetrating walls and providing detailed views from "behind" the wall. In addition, the ability to define the precise location of hidden objects within 1 inch is of interest to military, law enforcement, and rescue agencies. In response, the FCC approved limited productions of UWB radars for police and rescue workers.

With these new applications, the wireless industry is interested in UWB technology to:

- **End spectrum congestion:**

  The wireless industry is currently experiencing limited spectrum availability. To compound this problem, the wireless industry is seeking room in the already congested spectrum to introduce next-generation services. Competition is high for the limited available spectrum, as is the cost for licensing. Users of UWB devices operating in a single channel do not need a license.

- **Eliminate interference from signals reflecting off buildings or walls and congested cell sites:**

  UWB devices would be virtually immuned to interference because UWB signals can penetrate walls and other obstructions, eliminating a major source of multipath interference.

- **Provide secure transmissions:**

  UWB devices transmit millions of coded pulses per second at emissions below the noise floor and across an ultra wide bandwidth using receiver/transmitter pairs communicating with a unique timing code. These transmissions have a very low radio frequency signature, providing intrinsically secure transmissions with low probability of detection and low probability of interception.

- **Reduce power consumption dramatically:**

  It is possible to develop a chip that consumes only 0.05 milliwatts of power compared with the hundreds of milliwatts used by current cell phones. This reduced power consumption leads to longer battery life.

1.3 Application Developments

Wireless systems being developed by UWB manufacturers around the world fit broadly into three categories:

1. **Communication systems:** This category includes short-range communication systems including wireless personal area networks and measurement systems. This category is expected to have the largest proliferation due to potential high-density use of UWB devices in office buildings, meeting and conference rooms, and public places (e.g. airports, shopping malls, etc.).

2. **Radar imaging systems:** This category includes ground penetrating radar, through-wall imaging, medical imaging, construction and home repair imaging, mining imaging, and surveillance systems. The UWB signal can penetrate the ground or a wall to sense what's inside or behind it, as well as measure distances precisely. The same principle could apply to the human body. Therefore, the principal users of this category would

be law enforcement, search and rescue, construction, mining, geological and medical professionals. Radar imaging systems operate at infrequent intervals and are expected to have low proliferation due to their nature of use. Such devices would have a niche market with limited distribution.

3. **Vehicular radar systems:** This category includes collision warning radars, improved airbag activation, and field disturbance sensors, etc. Vehicular radar systems can detect the distance between objects and a vehicle, or can be integrated into the navigation system of the vehicle. Some vehicular radar devices started appearing at car exhibits in luxury cars. Should it become mandatory to install such devices on all vehicles, then a proliferation of vehicular radar systems is expected. Users of this category are mostly mobile and outdoor which could increase the potential of interference to other services.

1.4 The Relevance of Signal Processing

The use of signal processing is important in nearly all communications systems today [9]. Future communication systems will increasingly rely on signal processing in order to push performance closer to fundamental bounds such as the channel capacity. This gradual increase in performance is necessary to fulfill the users expectations and market expectations. Efficient signal processing is thus one of the key factors determining the success of a communication system.

In case of the UWB systems this is also true. Signal processing for UWB systems is still being actively researched, making it an interesting and a hot topic [10],[11], [12], [13]. One of the interesting facts of the UWB system is that it uses no carrier frequency, and the signal is therefore purely baseband in nature. This makes it possible to eliminate traditional components such as radio frequency (RF) Oscillator, phase lock loop (PLL), mixer which is used to down-convert the signal before sampling. In turn, the signal processing methods become even more critical to system performance.

1.5 Problem Statement and Objective

From a technical standpoint, the extremely wide bandwidth offers high capacity communication but in a real scenario it is not possible because the channel estimation becomes very difficult as the number of resolvable signal paths that need to be estimated grows to infinity. In particular, the short pulse makes the synchronization extremely difficult, and such synchronization can limit the overall system performance. Practical channel estimation can indeed be difficult even with accurate channel estimation; the standard UWB system requires a Rake receiver with a large number of fingers and thus of prohibitive complexity. One method of addressing the synchronization and channel estimation problems is through the use of the TR-UWB system which offers a low complexity alternative to Rake reception (more details on TR-UWB system are given on chapter 4)[14].

There are still challenges in getting full potential of UWB technology. The FCC identify emission limits to allow the UWB system to be compatible with other wireless systems, but still it causing an unacceptable level of interference for other wireless services sharing the same frequency band and vice versa as shown in Fig. 1.1 .

Therefore, there is a need for improvement in TR-UWB systems, especially the mitigation of narrowband interferers. Although TR systems are susceptible to narrowband interference because of the interference multiplication that can occur in the receiver end. The motivation of this work is to develop improved TR-UWB system so that it will be possible to combat the interference **by** and **to** the UWB signals.

The objective of this work is:

- To develop a transmission signal waveform for TR-UWB such that interference from UWB to narrowband communication systems are minimized.
- To modify the TR-UWB receiver such that interference from other wireless systems to UWB system is minimized.
- To perform BER performance evaluation of an UWB system in the presence of IEEE 802.11a system.

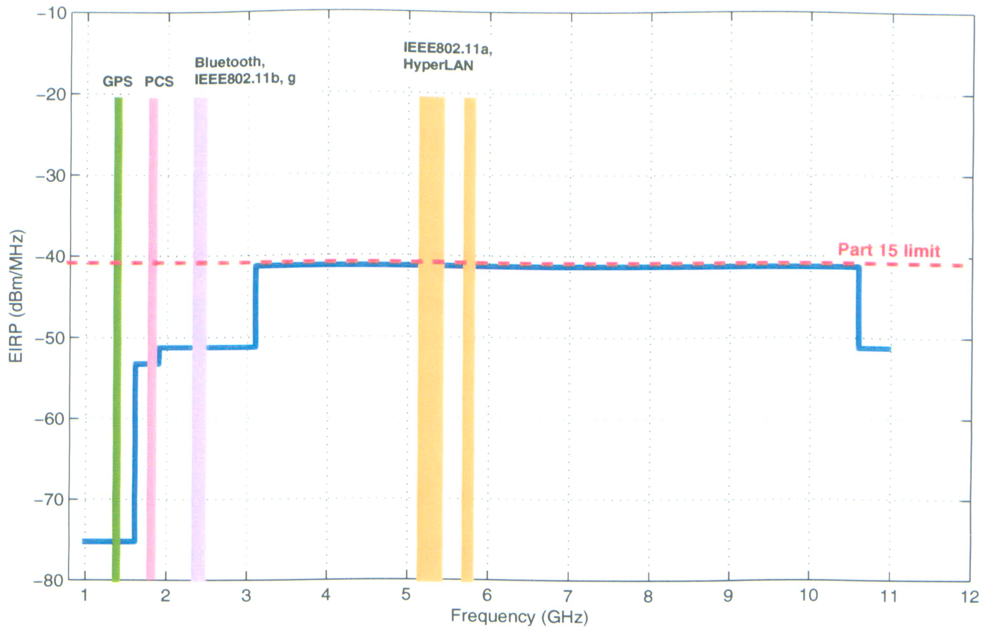

Figure 1.1: Spectrum allocation for different wireless schemes.

1.6 Outline of the Thesis

The focus discussed in this thesis is UWB coexistence with IEEE802.11a WLAN systems. Chapter 2 presents basics of UWB communication; definition, channel capacity, comparison with other communication systems and spectral regulations are discussed. A summary of a literature survey about TR UWB systems and some enhancement techniques applied to it are also given.

Chapter 3 presents UWB signal analysis; pulse shapes, multi-carrier pulse and different modulation schemes are discussed. A brief discussion about performance of these modulation schemes is also discussed. Chapter 4 investigates simple correlation receiver and TR correlation receiver. Analytical performance of TR receiver is presented. Chapter 5 investigates solution to the interference issues and proposed techniques is discussed. Chapter 6 focuses on evaluating the performance of different receiver schemes via simulation based approach. This chapter presents performance in ISI scenario.

Finally, Chapter 7 presents conclusions on the performance of different systems discussed earlier. Appendix A presents the power calculation. Appendix B contains the analytical analysis of the BPSK modulation scheme discussed in Chapter 3. Appendix C briefly introduces the IEEE channel model IEEE P802.15.3a. Listing of the Matlab code is given in Appendix D.

Chapter 2

Basics of UWB Communication

Since UWB communication makes use of very large bandwidth, the first question would be how fast it could communicate and how it is different from other wireless schemes. These issues (capacity and comparison), FCC regulation and UWB IEEE standards will be discussed in the following sections,

2.1 Definition of a UWB signal

Ultra Wideband refers to a system or signal with an extremely large bandwidth. UWB technology is at present defined by the FCC as a wireless transmission scheme that occupies a fractional bandwidth of at least 0.20, or more than 500MHz of absolute bandwidth [16]. The fractional bandwidth η is defined as:

$$\eta = \frac{f_{H\_10dB} - f_{L\_10dB}}{f_C} = 2 \bullet \frac{f_{H\_10dB} - f_{L\_10dB}}{f_{H\_10dB} + f_{L\_10dB}}, \tag{2.1}$$

where;

f_{H_10dB}	represents the highest -10dB bandwidth frequencies of the signal spectrum
f_{L_10dB}	represents the lowest -10dB bandwidth frequencies of the signal spectrum
f_C	is the center frequency.

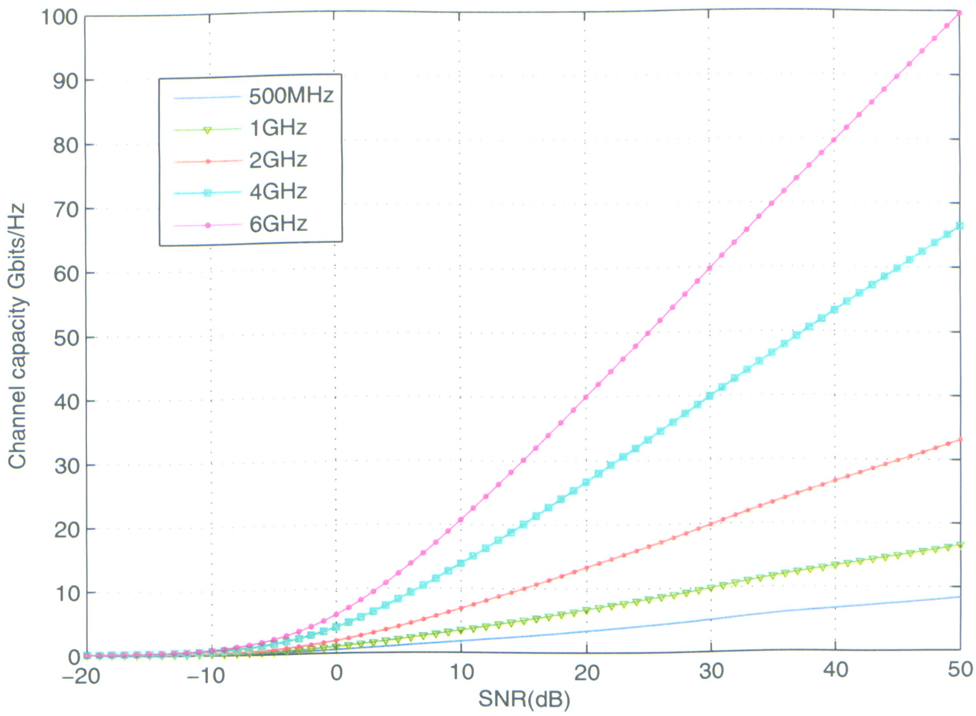

Figure 2.1: Shannon's channel capacity for different bandwidths.

2.2.2 Capacity vs Distance

In traditional narrowband communications (where the fractional bandwidth is of the order of 1 percent or less), the received power spectral density (PSD) can be related to the transmit PSD by the Friis formula that accounts for two loss components [3]:

1. a distance dependant loss component governed by the average path loss exponent

2. a frequency dependant loss component that is assumed constant over the band

Due to the very large UWB signal bandwidth, the second component can no longer be strictly approximated as a constant over the entire bandwidth. Thus, the received SNR in additive white Gaussian noise (AWGN) is given by [3]:

$$SNR(f)(dB) = -41.3 - (-114 + 6) - L - 20\log_{10}(\frac{4\pi f}{c}) - \gamma 10\log_{10}(d). \qquad (2.4)$$

where:

c	is the speed of light
γ	is the exponent of path loss
d	is the distance to the receiver from the source
L	is all additional system implementation losses

-41.3 dBm/MHz is the allowed emitted PSD per FCC Part 15 rules. A 6 dB noise figure was applied to the N_0 =-114 dBm/MHz standard thermal noise PSD in the above computation as representing a more realistic assessment of the SNR at the receiver input. An average received SNR is obtained from Eq.(2.4) using the center frequency 6.85 GHz. The results of computation of Eq.(2.4) are shown in Fig. 2.2 where the path loss exponent is assumed equal to 3.5 .

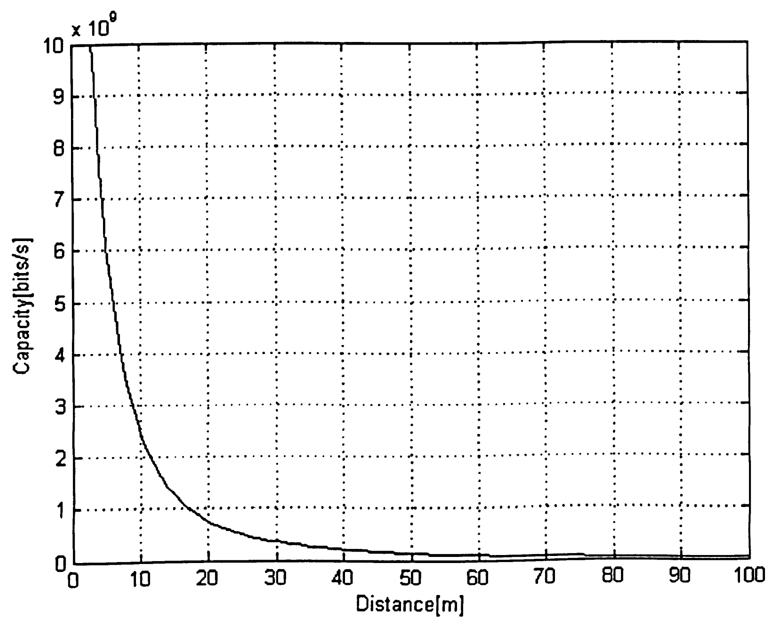

Figure 2.2: Capacity of UWB channel.

Based on these results as shown in Fig. 2.2 , we can observe that a UWB system with short distance (less than 5 m) may still maintain a very high data rate (greater than 6 Gbps).

2.3 Comparison with Other Communication Systems

As the basic idea behind the UWB is now known, let us compare the UWB with other communication systems. The main advantage of using a narrowband system is that it is a well-known technology that has been used for many years and that emission levels are not as strict as in the UWB case, as a dedicated spectrum is available. When is an UWB system preferred over a narrowband system?.

In order to answer this question, it is interesting to examine the theoretical AWGN channel capacity of realistic systems that could be used to provide a given service, such as WLAN or Wireless Personal Area Networks (WPAN) services. In Fig. 2.3, the channel capacity of four different systems are compared: UWB system, IEEE802.11a WLAN, IEE802.11g WLAN and finally Bluetooth WPAN system (the relevant MATLAB script is given in Appendix C). The UWB system is operating in the 6-7 GHz band (bandwidth of 3 GHz) and is compliant with the FCC rules and the IEE802.11a WLAN operates in the 5 GHz Industrial Scientific Medical (ISM) band with a channel bandwidth of 100 MHZ emitting 100 mW. The IEEE 802.11g , which is the most common WLAN system today, operates in the 2.4 GHz ISM band with a bandwidth of 83.5MHz and transmitting a maximum of 100 mW. Finally, the Bluetooth system also operates in the 2.4 GHz ISM band with a channel bandwidth of 1 MHz emitting 1 mW. The channel model includes free-space propagation loss and thermal noise.

As it can be seen from Fig. 2.3, the UWB system has a large advantage in capacity compared with the narrowband systems, as long as the distance is less than 20 meters, but it rapidly decreases as the distance increases. This shows the potential of UWB when very high speed short range communication is the goal.

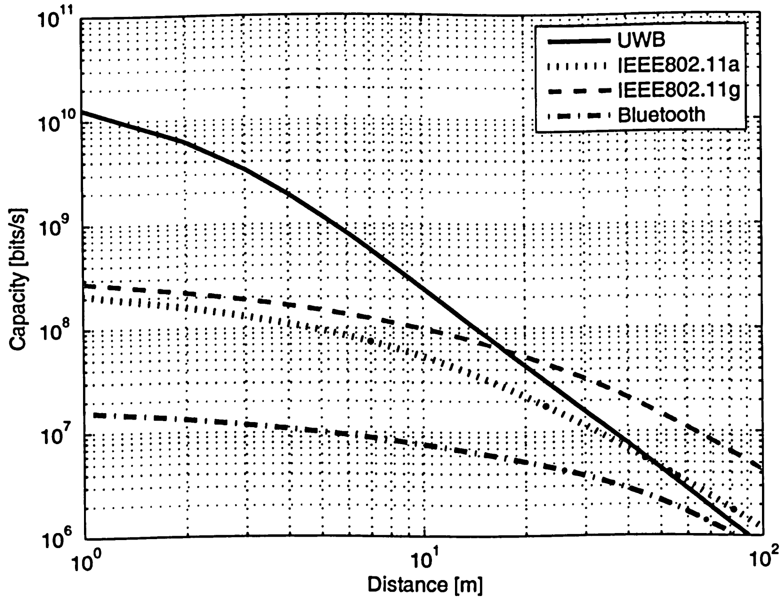

Figure 2.3: Channel capacity of UWB, IEEE802.11a,IEEE802.11g and Bluetooth .

2.4 Application of UWB technology on Other Wireless schemes

2.4.1 UWB Radio Frequency Identification (RFID)

Radio Frequency Identification(RFID) is an automatic identification technology, similar to barcode, but with the distinct advantage that it does not require line of sight (LOS) operation. It uses radio waves to communicate with the target tags. The key challenges in RFID technology are to assure connectivity to the tags, to determine accurate position, and to reliably communicate sensor status while reducing the costs of the infrastructure and tags. It is demonstrated that UWB systems measure distances precisely as well as UWB systems work well indoors because the short bursts of radio pulses emitted from UWB tags are easier to filter from multipath reflections than conventional RF signals [15]. Therefore, the UWB-RFID becomes a hot topic in RFID area. FCC has approved UWB-RFID tags made by Ubisense in 2004 and by Multispectral Solutions in 2005. They are mostly deployed in hospital environments.

2.4.2 UWB Bluetooth Wireless Technology

Bluetooth wireless technology is moving towards voice and data applications and operates in the unlicensed 2.4 GHz spectrum. It can operate over a distance of 10 meters or 100 meters depending on the Bluetooth device class and the peak data rate is 3 Mbps. Bluetooth wireless technology is able to penetrate solid objects. It does not require LOS positioning of connected devices. The Bluetooth SIG (Special Interest Group) announced in May 2005 its intentions to work with both UWB groups (Motorolas group and Multi-Band OFDM (MB-OFDM) Alliance) behind UWB to develop a high rate Bluetooth specification on the UWB radio certified wireless.

2.5 FCC Regulatory, Issues and IEEE Standards

For the legal use of UWB products, FCC released its initial rules on February 14, 2002 [16]. It contained the policy for UWB and states restrictions and regulations on the different types of UWB products. Some important restrictions and regulations for indoor and outdoor (handheld) systems were presented here.

There is 7.5 GHz available spectrum to use between 3.1 GHz and 10.6 GHz. The bandwidth must be larger than 500 MHz or the fractional bandwidth must be larger than 20% at 10 dB. The transmitter must also be in contact with a receiver in 10 second intervals. The main concern is about the interference with existing radio systems. The spectrum that the FCC has proposed for UWB devices now is also being used by 5GHz WLAN, GPS and ground penetrating radar (GPR). Therefore, the allowed transmission power for UWB equipment is restricted to a very low level to avoid interference to those systems, as shown in Fig. 2.4 and Fig. 2.5. As one might expect, when the FCC announced that it was considering the rules for UWB to operate within a spectrum that had already been licensed. UWB promoters believed that UWB pulses will only cause negligible interference with narrowband applications, because the pulses operate at low power level.

2.5.1 FCC Mask

Table 1 represents the emission limits for indoor and outdoor (handheld) systems measured in Effective Isotropic Radiated Power (EIRP).

Emission limits for UWB	Outdoor	Indoor
Frequency[MHz]	EIRP[dBm]	EIRP[dBm]
960-1610	-75.3	-75.3
1610-1900	-63.3	-53.3
1900-3100	-61.3	-51.3
3100-10600	-41.3	-41.3
Above 10600	-61.3	-51.3

Table 2.1: Emission limits for Outdoor and Indoor systems in EIRP

Spectral masks are in place to protect the existing users who are operating within the spectrum. UWB signals may be transmitted at PSD levels up to -41.3 dBm/MHz, which complies with general FCC Part 15 emission limits to control radio interference. Fig. 2.4 and Fig. 2.5 show spectral masks for indoor and outdoor operations. Outdoor operation has a higher degree of attenuation than the indoor operation at the out-of-band region to protect the GPS receivers, centered at 1.6 GHz.

2.5.2 IEEE 802.15.3 standard: WPAN Alternative High Rate PHY

The IEEE 802.15 Task Group 3 (TG3a) for Wireless Personal Area Networks (WPANs) is defining a standard to provide a higher speed UWB PHY enhancement amendment to 802.15.3 for applications, which involve imaging and multimedia. Based on the FCC regulation, various proposals of UWB PHY layer solution to this new standard were made by different UWB companies [18].

2.5.3 IEEE802.15.4 standard: WPAN Alternative Low Rate PHY

The IEEE 802.15 Task Group 4 (TG4a) for Wireless Personal Area Networks (WPANs) is defining a standard to provide a lower speed UWB PHY enhancement amendment to 802.15.4

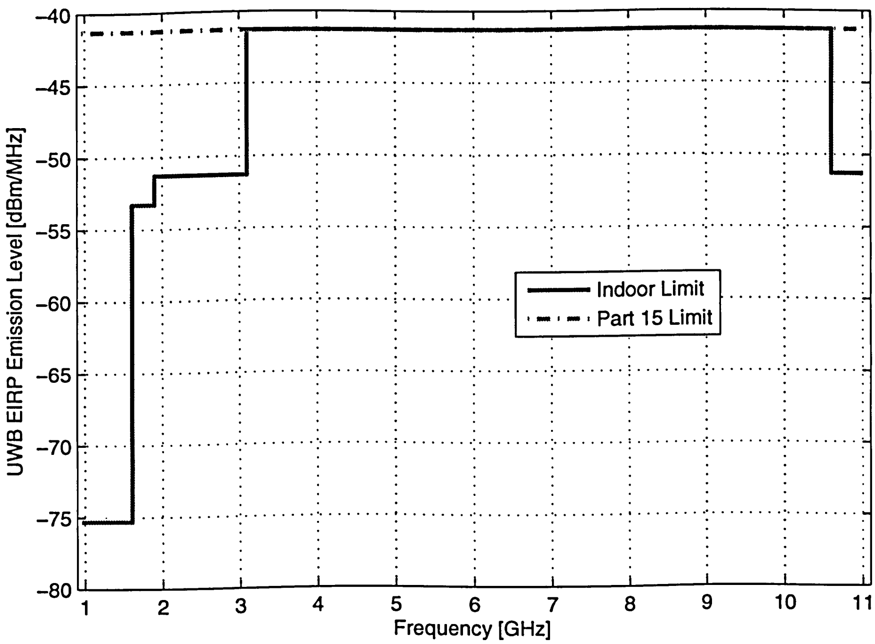

Figure 2.4: Spectral Mask for Indoor Applications.

for applications, that could increase the recent data rates or the positioning accuracy in the future [18].

2.6 Related work

UWB coexistence and interference issues are very important. Up to now, most investigations of coexistence issues concern the interference of UWB devices on existing services such as UMTS, GPS and GSM. Recent research progress shows mitigation of interference by UWB signals is possible using different pulse shapes, modulation techniques and whitening and shaping of the power spectral density (PSD) [19], [11], [20]. There also exist some publications considering the impact of existing systems interference on UWB systems [21], [13]. But only in few publications, e.g., in [22], [12], interference mitigation techniques are considered. The authors in [22] have presented the use of multi-carrier type transmission pulse and template waveforms to mitigate narrow band interference. However, the use of simple correlator at receiver will not perform well in the multipath condition.

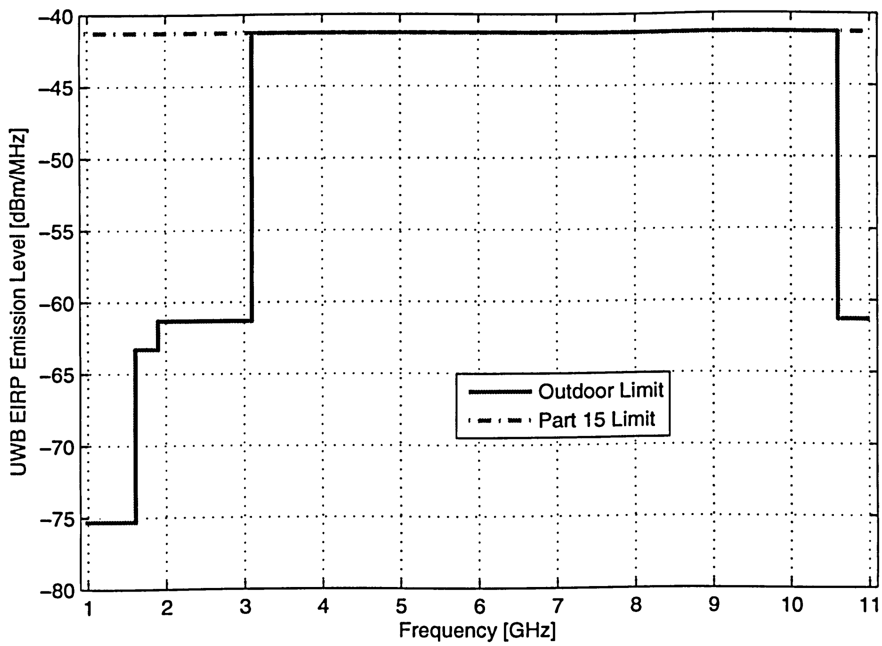

Figure 2.5: Spectral Mask for Outdoor Applications.

Transmitted reference is not a new technique. Decades ago it was proposed as a technique for communicating in random and unknown channels [23],[24],[25]. In year 2002, Hoctor and Tomlison proposed and experimented a simple UWB delay-hopper TR (DHTR) system [26],[27] that captures all the received signal energy without requiring channel estimation and provides multi-user capability. In this scheme each code divison multiple access (CDMA) code chip is represented by multiple pulse pairs (data pulse and reference pulse). For each code chip the time interval between pulse pairs is unique. The major drawback of this system is the use of noisy template for demodulation. In [28], an autocorrelation receiver that averages previously received reference pulses to suppress noise was presented. This TR systems performance was evaluated using pulse position modulation (PPM). But the implementation of the averaging operation as described in this approach is a complicated process. Chao and Scholtz in [29] described optimal and suboptimal receivers for UWB TR systems. The suboptimal receiver based on differential coding was described in that paper and the system was named differential transmitted reference (DTR). This system is a modification of the TR system since in this, instead of transmitting a separate pulse the data are differentially modulated using previously sent pulses. A 3 dB gain in performance was obtained with the modification. A drawback in this system is that its performance is not good because of noisy template problem. Some enhancement techniques were defined in [30] that improve the quality of reference and thereby improving the performance of the receivers.

Feedback loop mechanism has also been proposed to enhance the signal-to-noise ratio of reference pulses in a conventional TR receiver [12], however the mechanism was tested with *sinusoidal* interference model.

Chapter 3

UWB Signal Analysis

3.1 Transmission Signal Model

Gaussian waveforms are often used in UWB systems. Impulse radio type UWB signals have been widely studied [31]; often with second and third derivatives of Gaussian function. A short Gaussian waveforms with typically less than 1 ns pulse width is used to obtain large bandwidth. These waveforms are termed as Gaussian waveforms because of their similarity to the Gaussian function. A Gaussian waveform as shown in Fig. 3.1 can be described by

$$p(t) = A\exp(-\frac{t^2}{\tau^2}); \quad t \geq 0 \tag{3.1}$$

where:

$p(t)$	is the UWB pulse
A	is the pulse amplitude (Volts)
t	is the time (seconds)
τ	is the parameter that determines the pulse width (seconds)

3.1.1 Single Pulse Representation

Sending data with pulses based on the same center frequency works well and requires only one frequency source. Impulse radio type UWB signals and its PSDs are presented in Fig. 3.1 and Fig. 3.2 respectively.

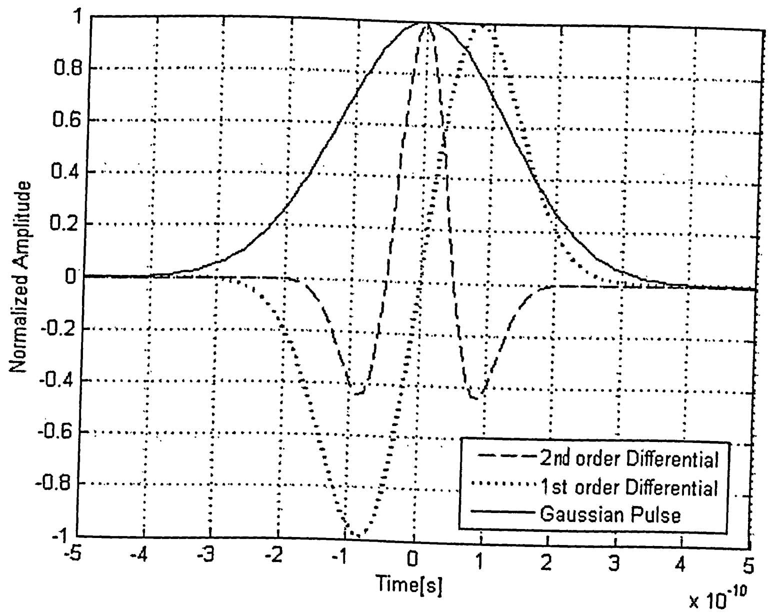

Figure 3.1: Shape of a Pulses in Time Domain

In this study, the original pulse waveform adopted for UWB was the Gaussian pulse. In the frequency domain, this pulse occupies the band from near direct current (dc) to the GHz range, the upper frequency depending on the pulse width. The current FCC UWB regulations [16] limit the use of frequencies below 3.1 GHz for communication applications as stated in Fig. 2.4 and Fig. 2.5, which also means that *the higher order derivatives of the Gaussian pulse are required to fulfil the spectral requirements* or *we have to shift frequency spectrum by sinusoidal modulation.* In this thesis, the pulse waveform used in the further studies is Gaussian weighted sinusoidal pulse. It is fitting the FCC mask as in Fig. 3.9 and it is given by the following equation;

$$S(t) = A\exp(-\frac{t^2}{\tau^2})\sin(2\pi f_c t), \tag{3.2}$$

where $\tau = 0.2ns$ and $f_c = 6.85GHz$. The pulse amplitude A is set to adhere to the FCC limit.

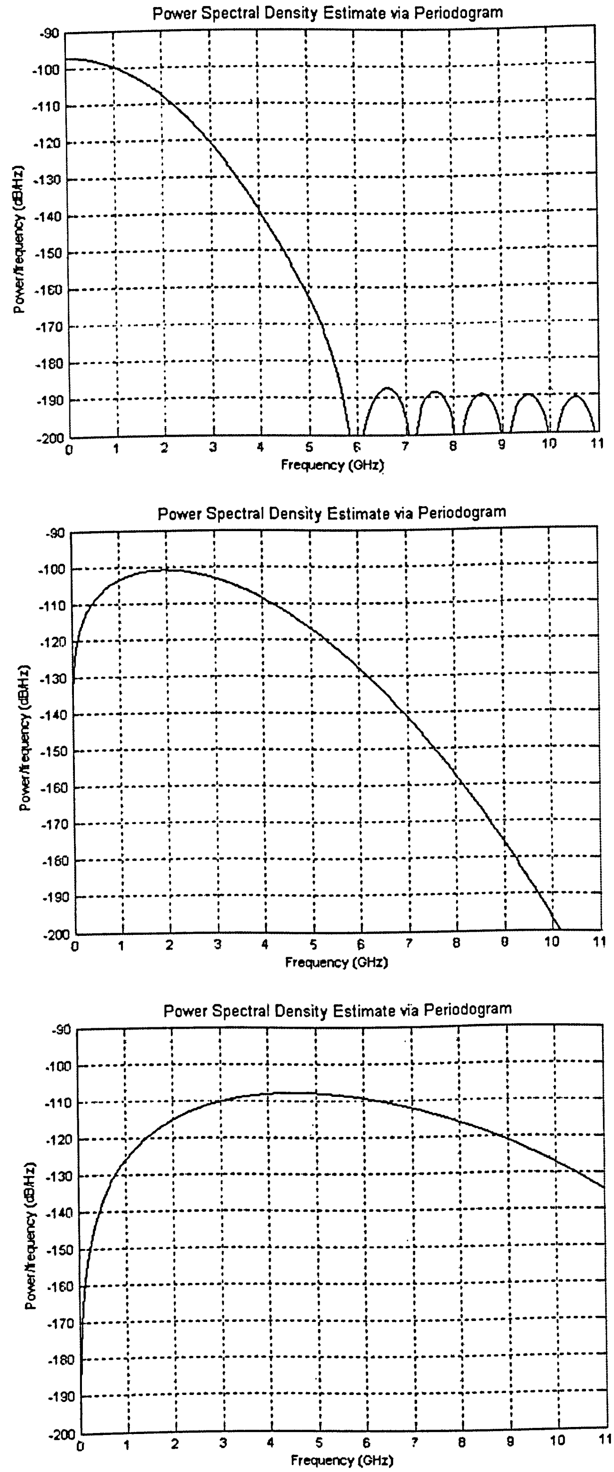

Figure 3.2: Shape of a Pulses in Frequency Domain: Gaussian, 1st order differential and 2nd order differential

3.1.2 Multi-carrier pulse

An alternative way to increase the flexibility and reduce the sensitivity to interferers is to split the frequency spectrum into bands. The pulses have different center frequencies but have the same pulse widths. This type of pulse is called multi-carrier pulse. In environments with high RF interferers, it is also possible to temporarily close a band containing an interferer to reduce the bit error rate (BER), Fig. 3.5. Multi carrier technique is used with wavelet analysis in Chapter 5 to suppress the interference.

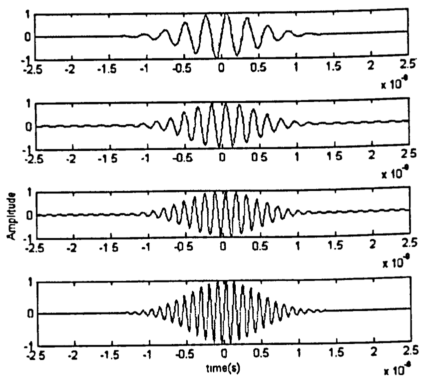

Figure 3.3: Four Gaussian pulses with different center frequencies.

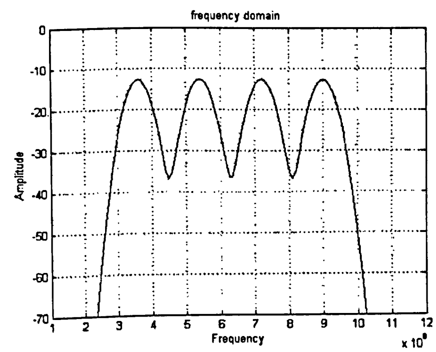

Figure 3.4: Spectrum of the pulses in the Fig. 3.3

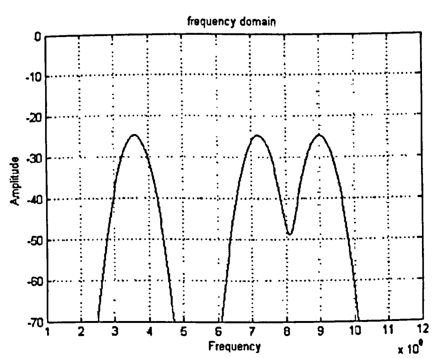

Figure 3.5: The spectrum when a band is unused to avoid an interferer.

3.2 Modulation techniques

In order to transmit information, additional processing is needed to modulate the Gaussian pulse sequence. The desired modulation technique needs to provide the best error performance for a given energy per bit. As we compare different modulation schemes, we examine its robustness against the interference of wireless links. Some modulation approaches produce spectral lines in frequency domain, thus further limiting total transmit power to stay within FCC limits on signal PSD, leading to a lower average power solution. Several modulation techniques can be used to create UWB signals, some are more efficient than others. The most popular methods to create UWB pulse streams used mono-phase techniques are PAM, PPM, OOK or BPSK. In these techniques, a '1' is differentiated from a '0' either by the amplitude of the signal or its time of arrival but all the pulses have the same shape.

The following modulation methods, OOK, BPSK and PAM, are investigated in the following paragraphs.

3.2.1 On Off Keying (OOK)

In OOK , a '1' is a pulse and an absence of a pulse is a '0'. Actually, it is a special case of PAM where the amplitude of zero represents an '0'. Following equation represents a OOK modulated UWB transmitted signal and the waveform is as shown in Fig. 3.6:

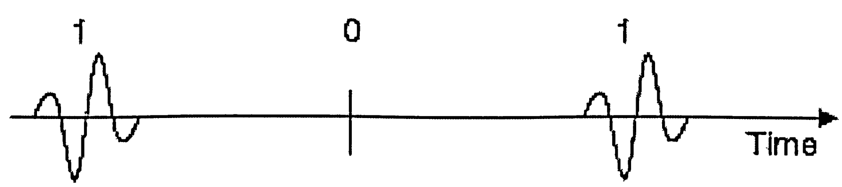

Figure 3.6: OOK modulation.

$$s(t) = \sum_{n=-\infty}^{\infty} b_n p(t - nT_f) \tag{3.3}$$

where:

$s(t)$	is the UWB signal
b_n	$\epsilon\{0,1\}$ data bits
$p(t)$	is the UWB pulse
T_f	is the frame time

The main advantage of OOK scheme over other shape-based modulation techniques is its ease of physical implementation. Only one pulse generator is required for OOK modulated system so that this pulse generator is switched on or off using an RF switch depending on whether '1' or '0' is transmitted.

The main drawback for OOK over other shape-based modulation systems like Bi-phase modulation is its bit error rate performance shown in Eq.(3.4). This is because for an equal symbol energy in both the cases, OOK has smaller symbol separation and thus has worse performance based on the fact that BER performance is directly proportional to the separation between symbols. BER performance of an OOK system under the correlation receiver is given by:

$$P_e = Q(\sqrt{\frac{E_b}{N_0}}) \tag{3.4}$$

where:

P_e	is the probability of error
Q	is the Q-function
E_b	is the average energy per bit (Joules)
N_0	is the noise energy spectral density at the detector (Joules/Hz)

The Q-function is the tail integral of the standard Gaussian density function (mean= 0 and variance = 1)

3.2.2 Binary Phase Shift Keying (BPSK)

Antipodal modulation is that a binary '1' is represented by a positive pulse and binary '0' is represented by a negative pulse as shown in Figure 2.5. There is a 180 degrees polarity shift between pulses of '0' and '1'. From the constellation diagrams, we can see a significant property of BPSK. A BPSK is an antipodal signaling technique and has the greatest distance for equal bit energy. This difference leads to a 3 dB benefit in efficiency: to achieve the same bit error rate, OOK must use a double bit energy, or a 3 dB higher E_b. Mathematically bi-phase is given by:

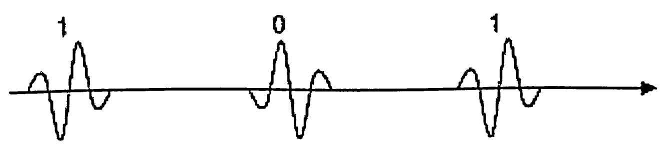

Figure 3.7: BPSK modulation.

$$s(t) = \sum_{n=-\infty}^{\infty} b_n p(t - nT_f) \tag{3.5}$$

where:

b_n $\quad \epsilon\{1, -1\}$ data bits

Analytical performance of correlation receiver for BPSK modulation is given in Appendix B. The BER performance is given by,

$$P_e = Q(\sqrt{\frac{2E_b}{N_0}}) \tag{3.6}$$

Although it has many advantages, its main disadvantage is the physical implementation part. A bi-phase modulated system requires two pulse generators with opposite polarities as compared to one in an OOK system. Although the implementation is a bit complex, still bi-phase modulation is a very efficient and popular technique for transmitting UWB pulses.

3.2.3 Pulse Amplitude Modulation (PAM)

PAM works by separating the large and the small amplitude pulses. By varying the amplitude the receiver can tell the difference between 1 and 0, and thereby decode the data from the received signal.

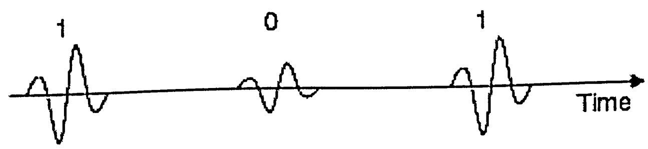

Figure 3.8: PAM modulation.

But in the wireless channel, attenuation is a significant problem. Due to that, the receiver will need the attenuation gain control. Therefore, this modulation is not very popular for implementation. BER performance of PAM is also worse than that of OOK and BPSK.

3.2.4 Other modulation schemes

Pulse position modulation (PPM) is an orthogonal signaling technique in time. The information is modulated on the position of pulses. Because the signal set is orthogonal, the Euclidean distance between any two signals is less than BPSK. Therefore, the processing gain required for PPM should be larger than BPSK in order to keep the same performance level. However, PPM is more difficult to get acquired and has a more stringent constraint on timing since the information is carried by the timing offset. PPM performance is not considered in this study because of the complex nature of modulator and demodulator implementation. Chirp Modulation is also proposed by some researchers [32], but the design and realization of relevant surface acoustic wave (SAW) devices is difficult. Therefore, this modulation technique is also not covered by this thesis.

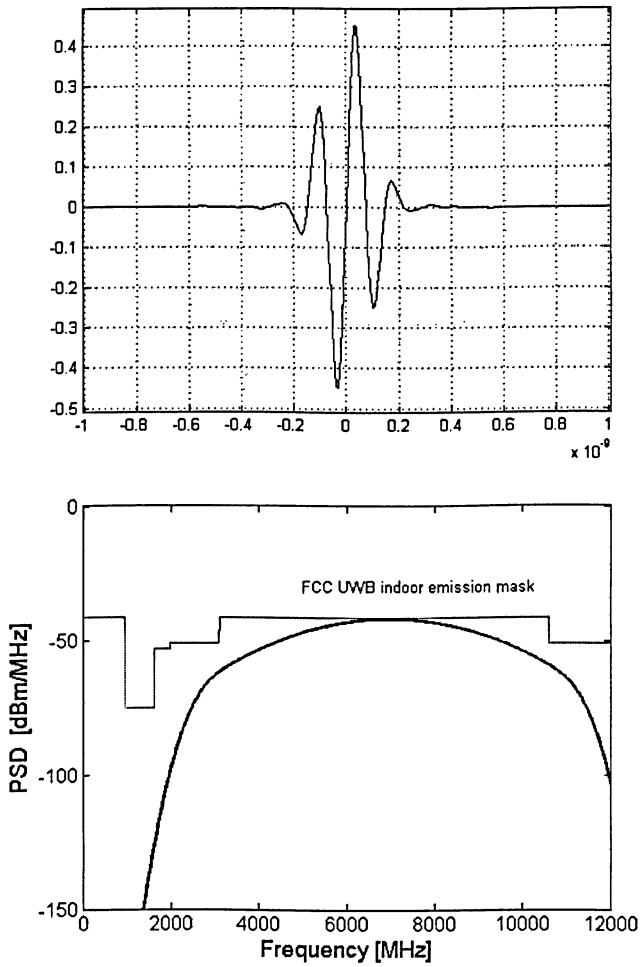

Figure 3.9: The Gaussian weighted sinusoidal pulse and its PSD.

Chapter 4

UWB Receivers

In this chapter, correlation receivers are studied. Two receiver structures, simple correlation receivers and transmitted reference (TR) receivers, are discussed. Analytical performance of TR receiver is also evaluated.

4.1 Correlation Receiver

The general structure of the correlation receiver is introduced here. The correlation receiver might be realized by correlating the input signal with the desired received signal and the output signal is given by:

$$r_o(t) = \int_0^{T_f} r(t) s_{template}(t) dt \tag{4.1}$$

where:

$s_{template}(t)$	is the known template pulse (or reference signal)
$r_o(t)$	is the output signal at the integrator
T_f	is the frame time
$r(t)$	is the input signal power at the receiver.

The correlation receiver for UWB signaling is illustrated in Fig. 4.1, where a correlation processor using an integrate-and-dump filter is shown. Analytical performance of correlation receiver for BPSK modulation is given in Appendix B.

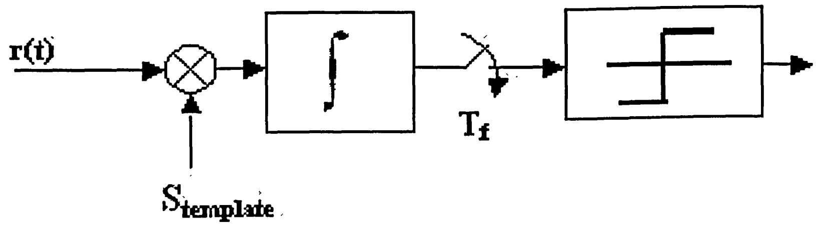

Figure 4.1: Block diagram of a correlator receiver.

4.2 Transmitted Reference (TR)

Channels encountered by UWB communication systems are highly dispersive in nature and so the channel estimation is a very challenging task. Designing a receiver that generates reference locally at the receiver, estimates the channel, and captures enough energy for data detection is a difficult and costly process. But instead of locally generating the reference signal, it can be transmitted along with the information data. Such a system is known as transmitted reference (TR) system. TR scheme is not a new technique but had been proposed around 1964 for spread spectrum communication [23, 24, 25]. TR has regained popularity with UWB communication systems after Hoctor and Tomlinson [26, 27] proposed a UWB TR system with a simple receiver structure which captures all of the energy available in a UWB multipath channel for demodulation at the receiver. TR is a correlation receiver system; thus a TR system does not require channel estimation and has weak dependence on distortion.

4.2.1 Attractive Properties of TR-UWB Architecture

1. Multipath gathering is achieved, since the first pulse (i.e. "reference pulse") in each of the possible transmitted- reference signals goes through the same channel as the second pulse (i.e. "data pulse"). Thus, the reference arm of the receiver provides a perfect (but, unfortunately, noisy) template to which to match the data pulse without explicit channel estimation or the need for a Rake receiver with many branches.

2. Simple timing acquisition can be achieved by repeating reference pulse.

3. Since the reference pulse and the data pulse are transmitted within one frame, the channel need to be constant only over the frame time. This can be significant for systems operating in a highly mobile environment.

4.2.2 System Structure

The most basic form a TR communication system is one in which a pair of pulses are transmitted in each frame. Of these two pulses first one is the unmodulated reference pulse, which provides the multipath channel's pulse response at the receiver end. Second pulse is the data modulated pulse. Since the two pulses are transmitted within a very short time period, it is assumed that the channel response is the same for both pulses in a TR frame [29]. Placement of the two pulses in a TR frame is as shown in Fig. 4.2.

The block diagram of a TR transmitter system is shown in Fig. 4.3. As shown in the figure, transmitter of a TR system comprises of a pulse generator, a delay line, and an antenna unit.

Pulse generator produces pulses after some fixed frame time and a replica of this pulse is delayed with the help of a delay line. This delayed pulse is modulated according to the information bit and added to the pulse generated earlier. This is how a TR frame is produced having a structure as shown in Fig. 4.2. The biggest advantage of this system as shown in Fig. 4.4 is its simple receiver structure.

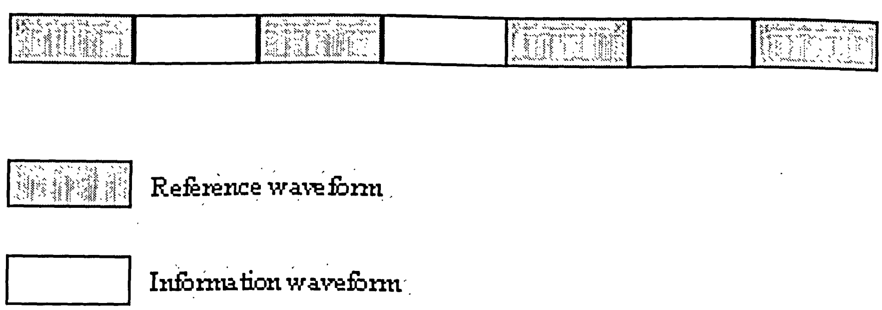

Figure 4.2: TR Frame Structure

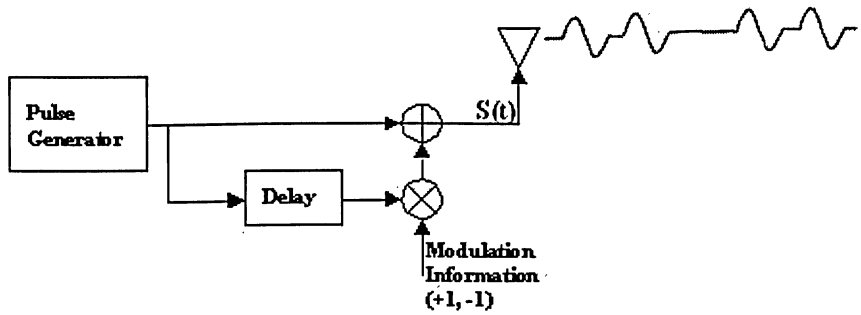

Figure 4.3: Block Diagram of TR Transmitter

The receiver comprises of a delay line and a correlator to demodulate the signal. Assuming a single user UWB system with antipodal modulation (binary pulse amplitude modulation), a typical transmitted reference frame is given by [29, 33]

$$s_{tr}(t) = \sum_k p(t - kT_f) + b_k p(t - kT_f - T_d) \tag{4.2}$$

where:

$p(t)$	is the Gaussian pulse with pulse width T_w
k	is the frame index
T_d	is the delay between reference and modulated pulse
b_l	is the l^{th} binary data bit $\epsilon\{1, -1\}$

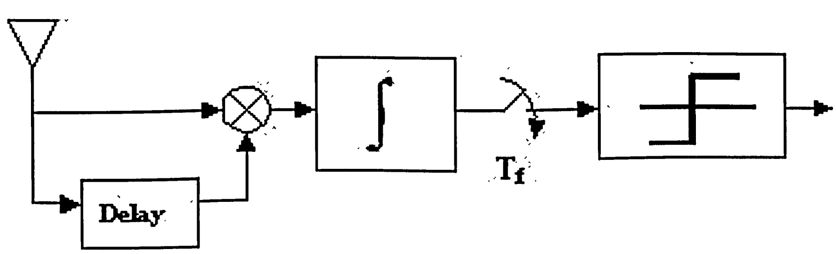

Figure 4.4: Block Diagram of TR Receiver

Fig. 4.5 is an example transmitted TR frame. For a single user case when operating in a multipath channel with multipath delay spread time T_{mds}, a TR frame is designed such that

$T_f \geq 2T_d \geq 2T_{mds}$ to avoid inter symbol interference (ISI) problem

4.2.3 Performance Analysis of TR Receiver

The received signal is given by

$$r(t) = s_{tr}(t) \otimes h(t) + n(t) \tag{4.3}$$

where:

- $\otimes$ represents convolution operation
- $h(t)$ is the channel impulse response
- $n(t)$ is the additive white gaussian noise (AWGN) with two sided power spectral density $N_0/2$ and zero-mean.

For a multipath channel, $h(t)$ is spread over time T_{mds}. The received signal $r(t)$ corresponding to a transmitted signal s_{tr} is as shown in Fig. 4.6. As it can be seen in Fig. 4.6 the two pulse responses corresponding to the reference pulse and the modulated pulse are not overlapping with each other. This case is referred to as a non-ISI case and is possible because of the careful placement of the two pulses in a TR frame.

To evaluate the performance of the structure the received signal is passed through a filter to limit the out-of-band noise. The bandwidth W of the filter is wide enough so that the signal spectrum is not distorted when the signal passes through it. The filtered received signal is expressed as

$$\hat{r}(t) = s_{tr}(t) \otimes \hat{h}(t) + \hat{n}(t) \tag{4.4}$$

where $\hat{r}(t)$, $\hat{h}(t)$ and $\hat{n}(t)$ represent the terms defined earlier at the output of the filter.

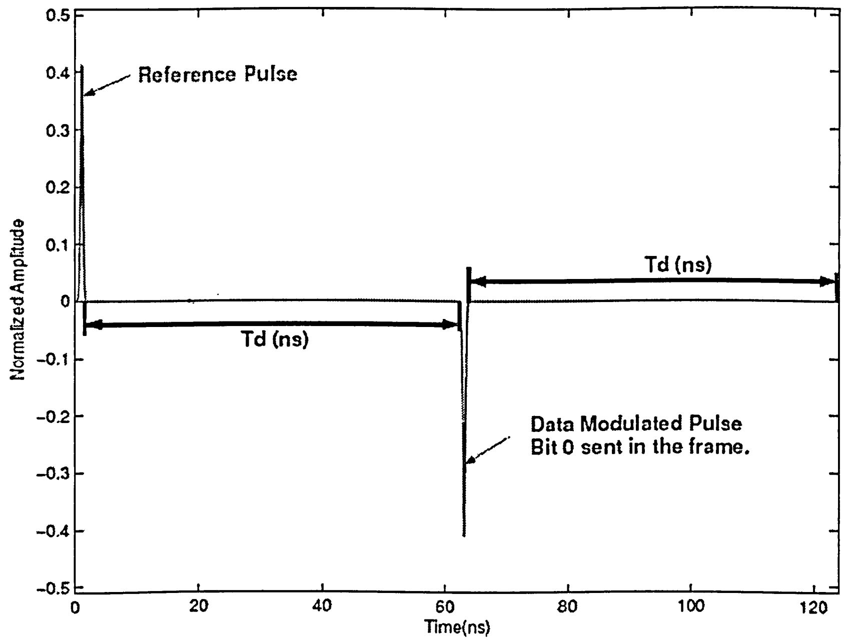

Figure 4.5: Transmission TR frame

The receiver exploits the diversity inherent to the multipath channel by using the auto-correlation demodulation technique [28]. For any transmitted symbol, the receiver correlates the channel response of the corresponding reference pulse and the channel response of the information carrying pulse. Assuming perfect synchronization and one pulse transmission for one bit information so that enough energy is captured to estimate the information bit, the correlated value is used as the decision statistic to detect the transmitted data symbol b_n, the decision statistic (y) is given by [29, 33]:

$$y = \int_{T_d}^{T_d+T_{mds}} \hat{r}(t - T_d)\hat{r}(t)dt \tag{4.5}$$

From Equations (4.5) and (4.3), the correlator output y can be rewritten as:

$$\begin{aligned} y &= \int_{T_d}^{T_d+T_{mds}} [s_{tr}(t - T_d) * \hat{h}(t - T_d) + \hat{n}(t - T_d)][s_{tr}(t) * \hat{h}(t) + \hat{n}(t)]dt \\ &= \int_{T_d}^{T_d+T_{mds}} [s_{tr}(t - T_d) * \hat{h}(t - T_d)][s_{tr}(t) * \hat{h}(t)]dt \end{aligned}$$

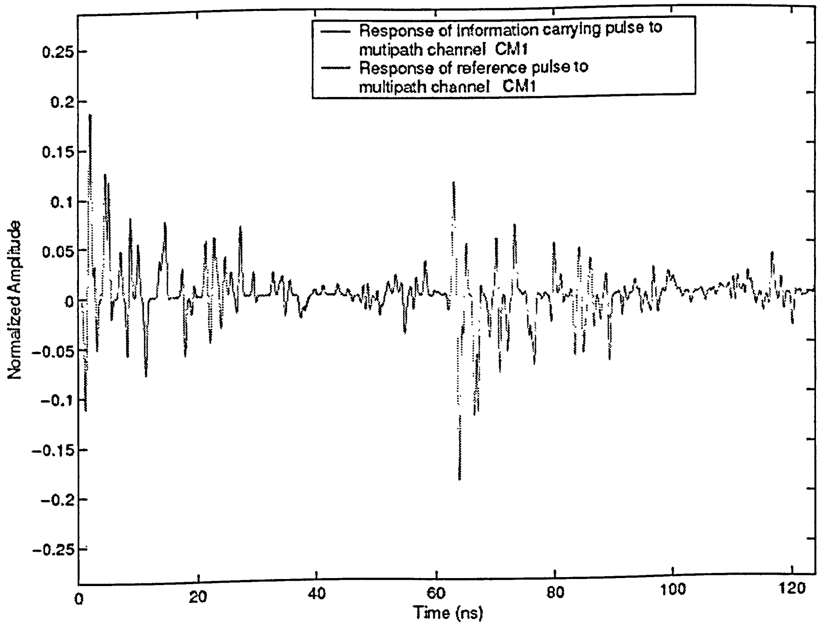

Figure 4.6: Received TR frame in IEEE UWB channel model

$$
\begin{aligned}
& + \int_{T_d}^{T_d+T_{mds}} [s_{tr}(t-T_d) * \hat{h}(t-T_d)]\hat{n}(t)dt \\
& + \int_{T_d}^{T_d+T_{mds}} [s_{tr}(t) * \hat{h}(t)]\hat{n}(t-T_d)dt \\
& + \int_{T_d}^{T_d+T_{mds}} \hat{n}(t-T_d)\hat{n}(t)dt \\
= \; & Y + N_1 + N_2 + N_3 \qquad (4.6)
\end{aligned}
$$

The decision at the decision unit is based on y. As shown in Equation (4.6), Y is the desired correlator output. Y is the mean of the random variable y and the three terms N_1, N_2, and N_3 are the noise terms. N_3 is the noise cross noise term which mainly degrades the performance of the TR system where as N_1 and N_2 terms are produced by the product of noise term in the reference part of frame and desired signal in data part or vice versa. Also the three terms N_1, N_2, and N_3 are uncorrelated random variables. Thus the detection SNR as defined at the output of the correlator is given by [33]:

$$SNR_{tr} \cong \frac{Y^2}{var(N_1) + var(N_2) + var(N_3)} \tag{4.7}$$

where $var(N_i)$ is the variance of the noise terms.

By following the steps shown in [33], Equation (4.7) reduces to

$$SNR_{tr} = [(\frac{N_0}{E_p}) + (\frac{N_0}{E_p})^2 \frac{T_{mds}W}{2}]^{-1} \tag{4.8}$$

where:

W	is the one sided noise bandwidth of the receiver
E_p	is the pulse energy

Thus probability of bit error (P_e) of the TR system is given by

$$P_e = Q([(\frac{N_0}{E_p}) + (\frac{N_0}{E_p})^2 \frac{T_{mds}W}{2}]^{-\frac{1}{2}}) \tag{4.9}$$

Here E_b ,defined as energy per bit transmitted, is given as $E_b = 2E_p$. The bit error performance (BEP) of TR receiver reduces to

$$P_e = Q([2(\frac{N_0}{E_b}) + 2(\frac{N_0}{E_b})^2 T_{mds} W]^{-\frac{1}{2}}) \tag{4.10}$$

Chapter 5

Coexistence with IEEE802.11a WLAN system

Initially, the main concern about UWB was whether or not they would interfere with the existing RF systems that provide essential military, aviation, fire, police and rescue services. For such a reason, the FCC proposed UWB specifications and concluded that there should be no major interference from the UWB system to other systems. This conclusion is made mainly because of the extremely low emission power limitation on the UWB system. But on the other hand, low powered UWB equipments themselves are facing significant interference problem from other wireless systems. Among them, 802.11a WLAN system is the main concern, because it has a high emission power and its operating frequency band (5.15 - 5.35 GHz) is inside of the FCC approved operating band for UWB systems [17]. The interference scenarios outlined in this chapter will therefore focus on this problem, but generally applies to any narrowband technology used in the same environment as UWB systems and using overlapping frequency bands.

The coexistence can be divided into two parts:

- Interference from UWB systems to other narrowband systems
- Interference from other narrowband systems to UWB systems

In order to make estimates of the level of interference, it is important to know the propagation conditions under which the systems operate. As the interferers are uncorrelated with the desired signal, the statistical properties of the channel model of the interferers become less important. Instead the received interference power can be used to estimate the impact on the desired signal and it is therefore only necessary to know the Path Loss (PL) of the interferer. The path loss is calculated by [34]

$$PL = \frac{c^2}{16\pi^2 r^n f_c^2}, \tag{5.1}$$

with c being the speed of light, r being the range and f_c is the center frequency. The path loss exponent n is a function of the environment and is usually in the range 1.5-6. A special case is free space propagation where $n = 2$.

5.1 Solution to the Interference Problem

WLAN interference signal is the killer to UWB system and a solution needs to be found to allow UWB system operating with a nearby 5GHz WLAN interference source.

In order for the UWB receiver to operate, the interference level must be reduced. This can be done using two different strategies:

- Suppress interference by not using the frequency band in which the interferer operates
- Cancel interference in the receiver.

5.2 Suppression of interference from UWB systems to IEEE802.11a WLAN system

Multi-band solution can be used to solve this interference problem. In this work, 7.5 GHz of unlicensed UWB spectrum is divided into several overlapping frequency bands, and each band is between 300 and 400MHz wide. Data can be transmitted through all the sub-bands or several of them. In the case of coexistence with IEEE 802.11a, multiple UWB sub-bands centered around the interferer can be removed from the transmission to guarantee there is no interference of 802.11a system in UWB signal. The way this was achieved is explained in following subsection.

5.2.1 Multi Resolution Analysis

Wavelets can be used to perform a multi resolution analysis of a transmitted UWB waveform into multiple subband pulses centered on a set of different subcarriers [22]. First, the pulse in Equation.(3.2) is analyzed using the following equations based on wavelet transform,

$$W_f(a) = \int \psi(\frac{t}{a}) f(t) dt \tag{5.2}$$

$$f(t) = A \exp(-\frac{t^2}{\tau^2}) \sin(2\pi f_c t) \tag{5.3}$$

$$\psi(\frac{t}{a}) = \exp(-\frac{t^2}{\tau'^2}) \sin(2\pi a t) \tag{5.4}$$

where $f(t)$ is the pulse waveform, f_c is the frequency of the carrier and $\psi(\frac{t}{a})$ represents subcarriers with $\tau' = 1ns$. The amplitudes of carriers are decided from $W_f(a)$ and the pulse waveform is constructed from

$$f(t) = \sum W_f(a) \psi(\frac{t}{a}) \tag{5.5}$$

Assume $a = nf_s$, with n an integer and pulse repetition rate $f_s = 400MHz$. Then we approximated the transmission pulse with that of 20 subcarriers from 3.2 GHz to 10.2 GHz as in Equation. 5.6. The designed pulse and its PSD are shown in Fig. 5.2.

$$f(t) \simeq S(t) = \sum_{n=7}^{n=27} W_f(nf_s) \psi(\frac{t}{nf_s}) \tag{5.6}$$

To reduce interference from the UWB system to the IEEE 802.11a WLAN systems, we eliminated 5 interfering subcarriers around 5.25 GHz. The resultant pulse and its corresponding PSD are shown in Fig. 5.3. This avoids transmission signal in IEEE 802.11a band. Spectral density after elimination around the interfering band tends to reduce by **60dB** from the spectral peaks, hence the potential interference to the IEEE 802.11a WLAN system is greatly reduced.

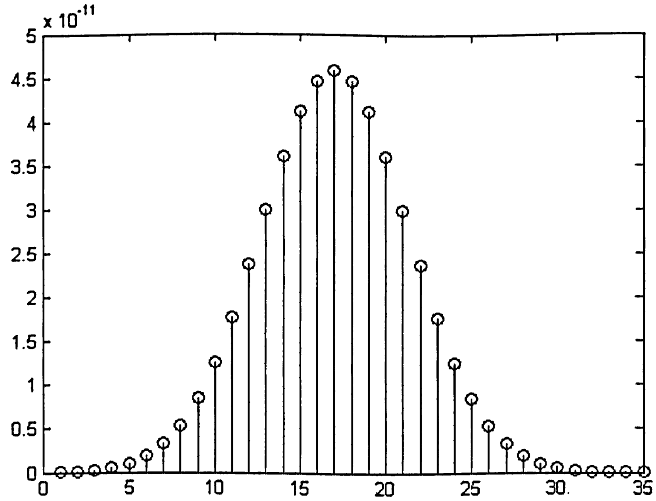

Figure 5.1: Wavelet coefficients

5.3 Suppression of interference from IEEE802.11a WLAN system to UWB systems

Severe interference saturates an unprotected UWB receiver front-end. In this section we introduce a simple method to suppress interference in TR receivers while preserving the desired UWB signal. Interference suppression in the TR receiver is achieved by eliminating the interfering band by a notch filter. Gaussian pulse has the advantage again because notch filter bandwidth can be relatively narrow compared to the full-band of Gaussian pulse. Notch filter effectively causes the interfering band to be "turned off", and it is implemented with filter order of 400 and operates around 5.25GHz. It reduces interference to the UWB system from the IEEE 802.11a WLAN system. The block diagram of the modified TR receiver is shown in Fig. 5.4.

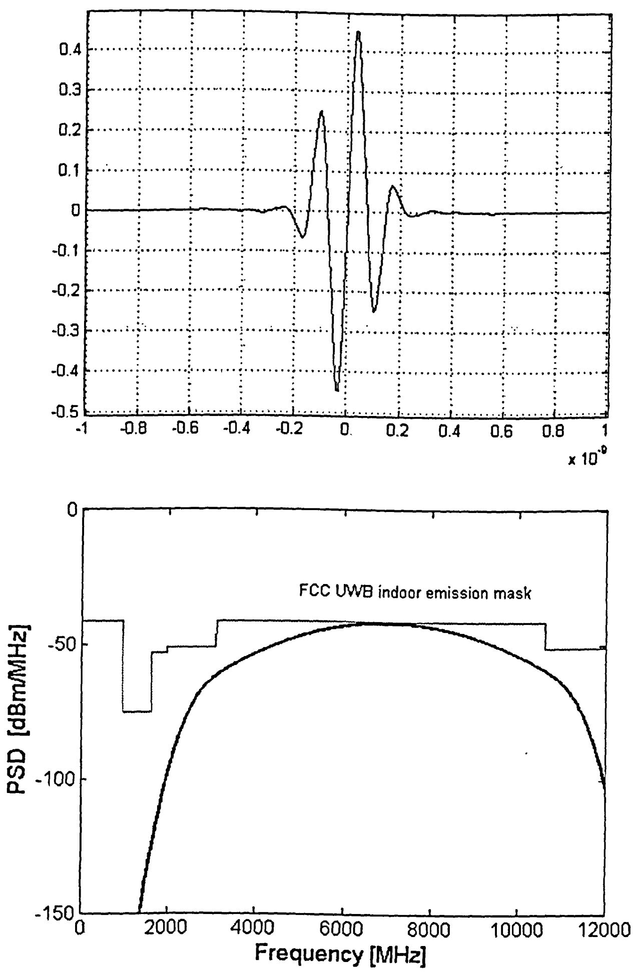

Figure 5.2: The approximated Gaussian pulse and its PSD.

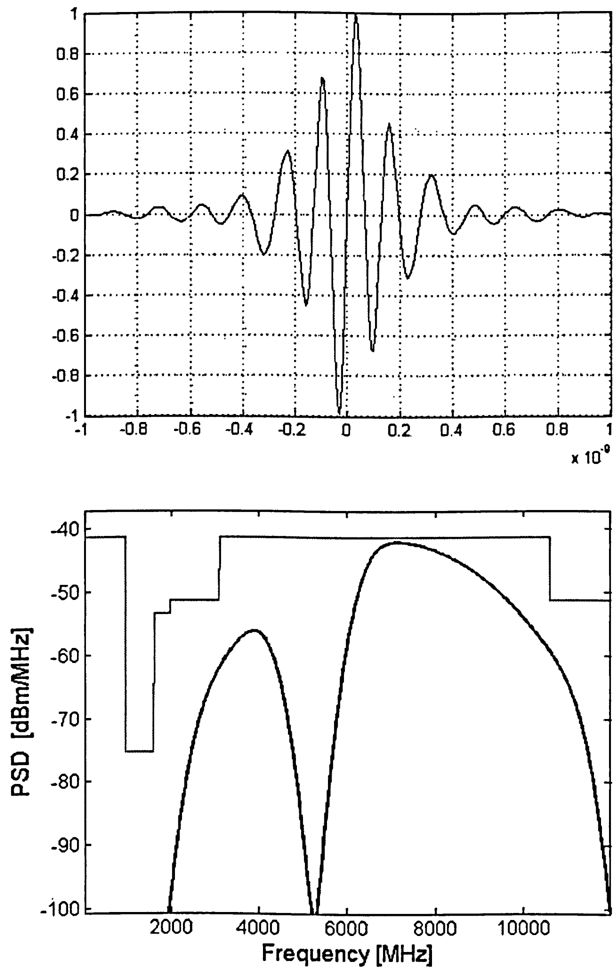

Figure 5.3: Multi-carrier type pulse for an IEEE 802.11a interferer and its PSD.

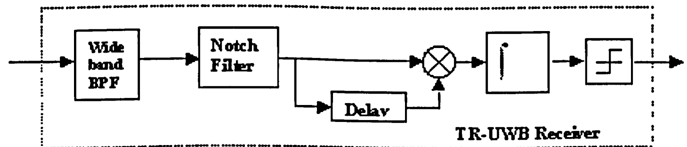

Figure 5.4: Block diagram of a modified TR receiver with a notch filter [14]

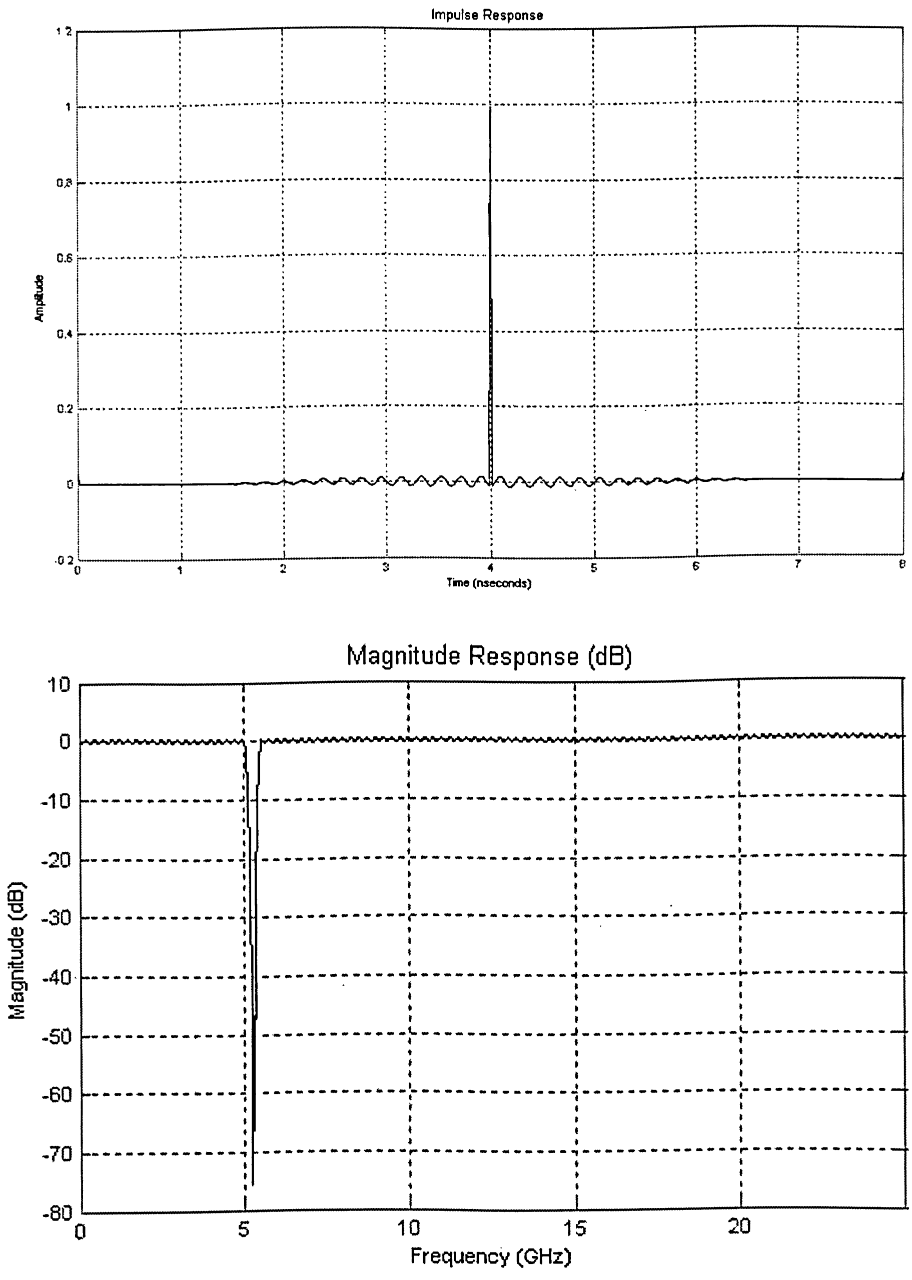

Figure 5.5: The Notch characteristics

Chapter 6

Evaluation by Simulation

The goal of the system simulation is to study the system performance. This work is done based on knowledge of the UWB system and related modulation technology.

6.1 UWB system simulation setup

Using computer simulation, TR-UWB physical layer model is developed with multi-carrier type transmission pulses and pulse width of 1 ns. The spectra of the multi-carrier transmission pulse waveform is presented in Fig. 5.3 with FCC mask and the design methodology is explained in Chapter 5. The system of interest is a single user UWB link operating at a data rate of 100 Mbps without error correction coding. These pulses are transmitted every 10 ns. Fig. 6.1 shows the system model where UWB signals are received with a TR receiver in the presence of AWGN and interference from IEEE 802.11a WLAN systems. Out of band noise was removed using wideband bandpass filter(BPF). It should be noted that in all computer simulations, the BER performance is based on assuming perfect synchronization and prior knowledge of the exact integration period.

6.1.1 System simulation overview

The UWB system simulation is implemented in *Matlab*©*Simulink* and designed in a flexible manner, which enables quick modifications. Fig. 6.2 illustrates the general structure of UWB system simulation which consist of UWB transmitter, channel and receiver.

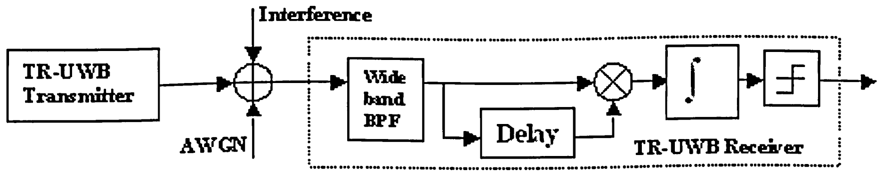

Figure 6.1: A simple model of the TR-UWB transceiver with a transmission channel consisting of AWGN and WLAN interference.

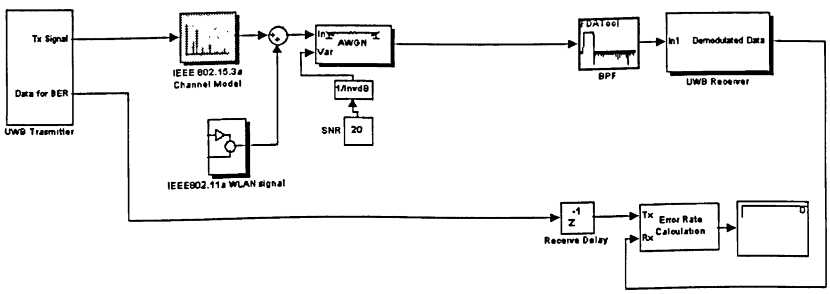

Figure 6.2: Simulation model of the whole UWB System

6.1.2 UWB pulse generator

The UWB pulse generator is one of the major components in the UWB communication system. The UWB pulse generator block supports generating UWB pulses according to different modulation schemes. Fig. 6.3 shows the train of pulse which was generated by the model and its PSD

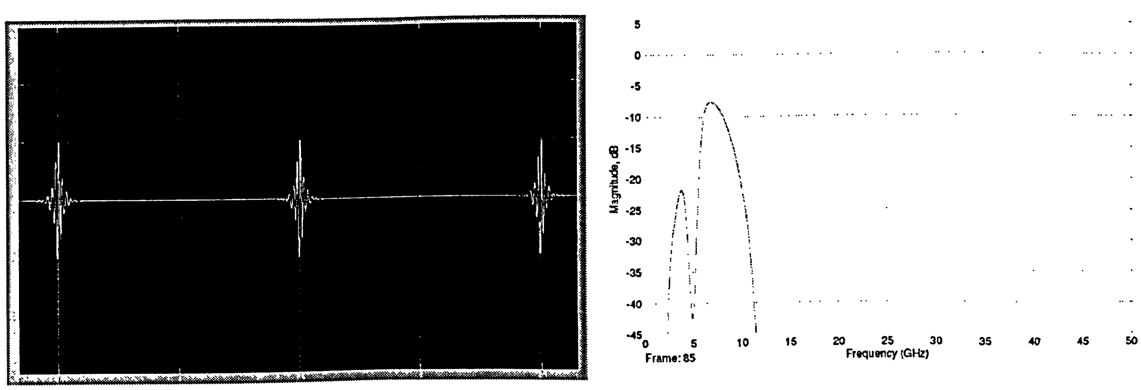

Figure 6.3: (a) Generated UWB pulses and (b) Its PSD

6.1.3 UWB receiver and demodulation

UWB receiver module can retrieve the UWB baseband signal from the received signal. At the demodulation block, the UWB baseband signal is received and correlated. Then it is feed into a threshold device (a comparator). The threshold device produces the binary serial data waveform, which can be compared with the input binary serial data to evaluate the BER. Fig. 6.4 shows two different receiver architectures used in this simulation study.

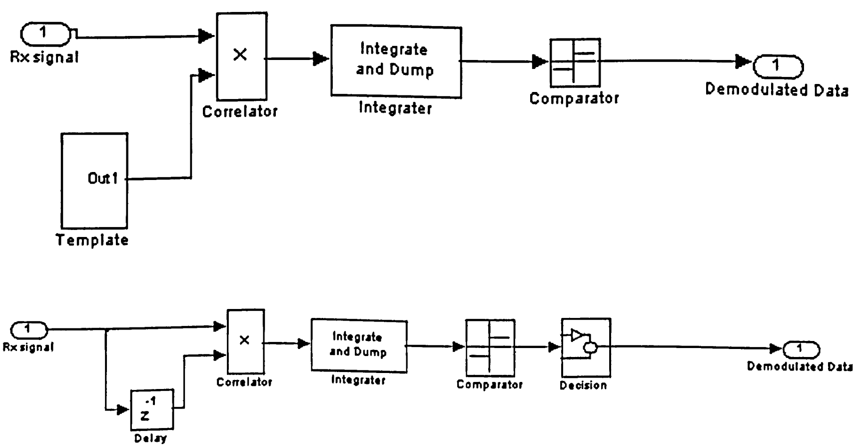

Figure 6.4: (a) Correlator receiver and (b) TR receiver simulation models.

6.1.4 IEEE 802.11a WLAN interference model

As shown in [35], this signal can be approximated with a Gaussian narrowband process. Using the colored Gaussian noise (CGN) interference approach, the spectral allocation and the power level for the interference could independently be selected. Based on the central limit theorem, the sum of statistically independent and identically distributed variables that have zero mean and variance has a Gaussian cumulative distribution function [9]. This is why a band-limited CGN model was selected as the general interference model. For the spectrum allocation, both the center frequency and bandwidth can be defined. In this case, the white Gaussian noise signal is passed through a raised cosine filter. The output, after the filtering, has colored PSD.

In our simulator, the interfering signal is added to the desired signal in the channel, so the interference is also passing through the blocks modelling the front-end of the UWB receiver.

The central frequency and the bandwidth of the interferer will then be set to 5.25 GHz and 200 MHz respectively. The UWB system, which has a 10 dB bandwidth of approximately 7.5 GHz, operates at FCC part 15 limits of -41 dBm per MHz. The IEEE 802.11a transmitted power is 100 mW. When the two transmitters experience the same attenuation, we obtain a signal to interference ratio of -20 dB. The Fig. 6.5 shows simulated 802.11a WLAN interference signal and its spectrum.

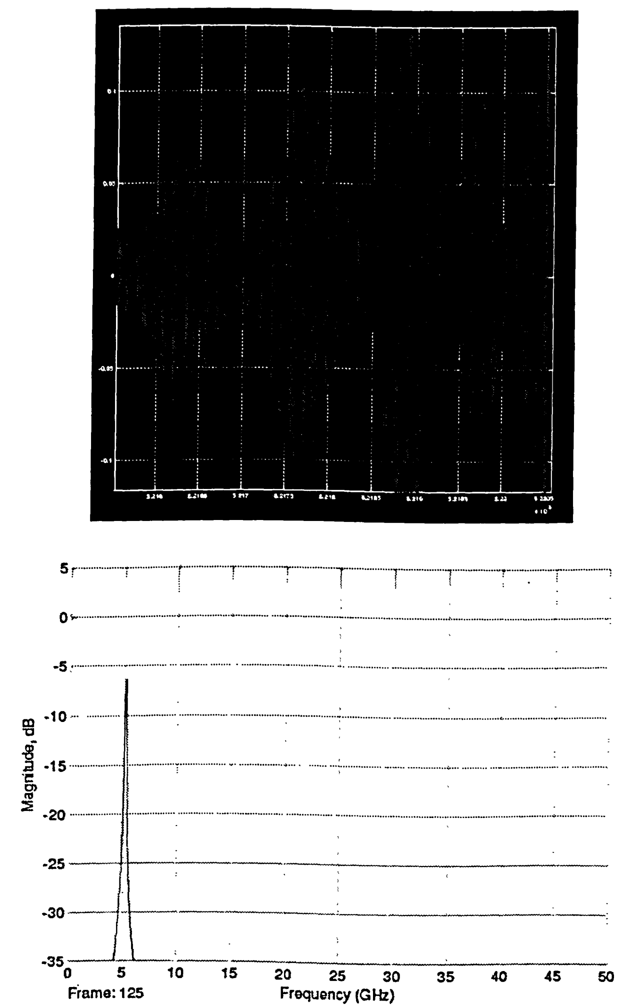

Figure 6.5: (a) Simulated 802.11a WLAN signal and (b) Its spectrum

6.1.5 IEEE Channel model

An adequate indoor UWB channel, rather than AWGN channel, should be introduced in order get the real performance of the Transmitted Reference modulation scheme. In this research we employed the model proposed by the IEEE 802.15.3a channel modelling group [6], based on a modification of the Saleh-Valenzuela [36]. This model takes into account the clustering phenomenon observed in several UWB channel measurements. According to [37], the channel impulse response can be modelled as

$$h(t) = X\sum_{l=0}^{L}\sum_{k=0}^{K}\alpha_{k,l}\delta(t - T_l - \tau_{k,l}). \tag{6.1}$$

where:

$\alpha_{k,l}$ are the multipath gain coefficients

T_l is the delay of the l^{th} cluster

$\tau_{k,l}$ is the delay of the k^{th} multipath ray relative to the l^{th} cluster arrival time T_l

X represents the log-normal shadowing

By definition, we have $\tau_{0,l} = 0$. The distribution of clusters and rays inter-arrival time is exponential. The distribution of cluster arrival time and the ray arrival time are given by:

$$p(T_l \mid T_{l-1}) = \Lambda exp[-\Lambda(T_l - T_{l-1})], l > 0 \tag{6.2}$$

$$p(\tau_{k,l} \mid \tau_{k-1,l}) = \lambda exp[-\lambda(\tau_{k,l} - \tau_{k-1,l})], k > 0 \tag{6.3}$$

where:

Λ cluster arrival rate

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

Finally, The average power delay profile shows a double exponential decay and the fading statistics is log-normal. The total multipath energy is captured by the term, X. This shadowing term is characterized by the following:

$$20log10(X) \propto Normal(0, \sigma_x^2) \tag{6.4}$$

Finally the sign of each multipath replica is either positive or negative, each with the same probability. In [37] four sets of parameters are given, to characterize the statistical properties of different channels. In particular, the following propagation conditions are considered:

1. CM1: LOS channel with a TX-RX distance between 0 and 4 m.

2. CM2: NLOS channel with a TX-RX distance between 0 and 4 m.

3. CM3: NLOS channel with a TX-RX distance between 4 and 10 m.

4. CM4: Extreme NLOS channel (RMS delay spread of 25 ns).

In simulations, channels were sampled with a sampling period of 0.05ns. (T_{mds}) for different channel models are listed in Table 6.1.

Channel	CM1	CM2	CM3	CM4
$T_{mds}(ns)$	40	60	122	200

Table 6.1: Multipath delay spread time for the channels

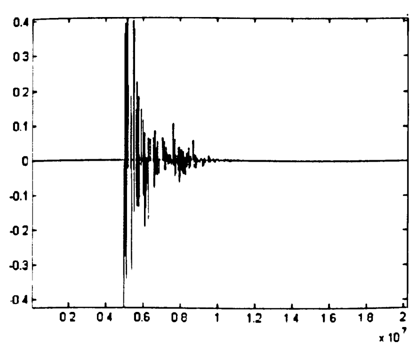

Figure 6.6: Impulse response of CM1:LOS(0-4 m)

IEEE channel models are discussed in detail in Appendix C. CM 1 has a response as shown in Fig. 6.6

6.2 Results

6.2.1 Case 1: Correlator receiver in AWGN Channel

During a simulation, a data sequence (UWB signal) is sent through the AWGN building block. The interference signal is added to the propagating UWB signal. Simulation is done in this section to study the OOK, PAM and BPSK performance in AWGN channel with and without 802.11a WLAN interference . Figs 6.7, 6.8 and 6.9 shows OOK, PAM and BPSK performances respectively.

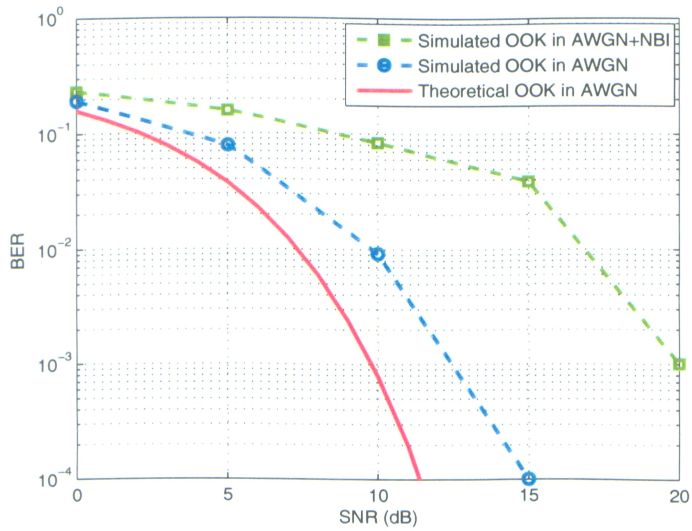

Figure 6.7: SNR vs. BER simulation with OOK modulation in correlator receiver

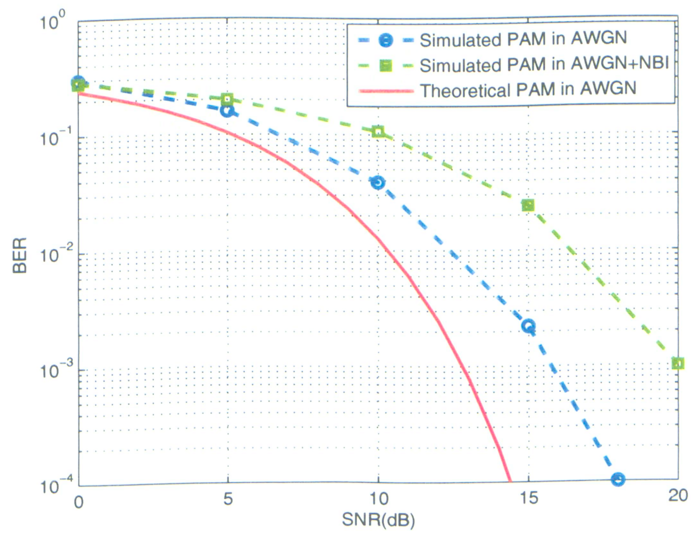

Figure 6.8: SNR vs. BER simulation with PAM modulation in correlator receiver

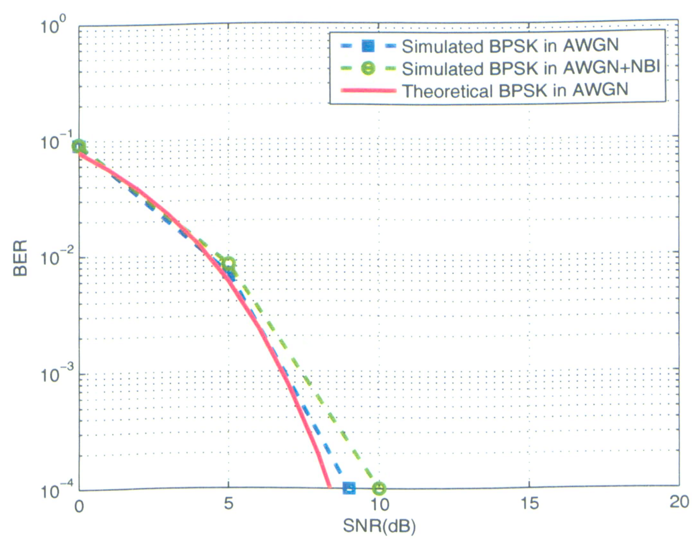

Figure 6.9: SNR vs. BER simulation with BPSK modulation in correlator receiver

6.2.2 Case 2: TR receiver in AWGN channel

This module is built to simulate the TR-UWB communication. Simulation is done in this section to study the TR performance with and without 802.11a WLAN interference . Fig. 6.10 compares the performance degradation of a conventional TR receiver in an AWGN only channel with a transmission channel consisting of AWGN, plus a strong interference from IEEE 802.11a WLAN interferer.

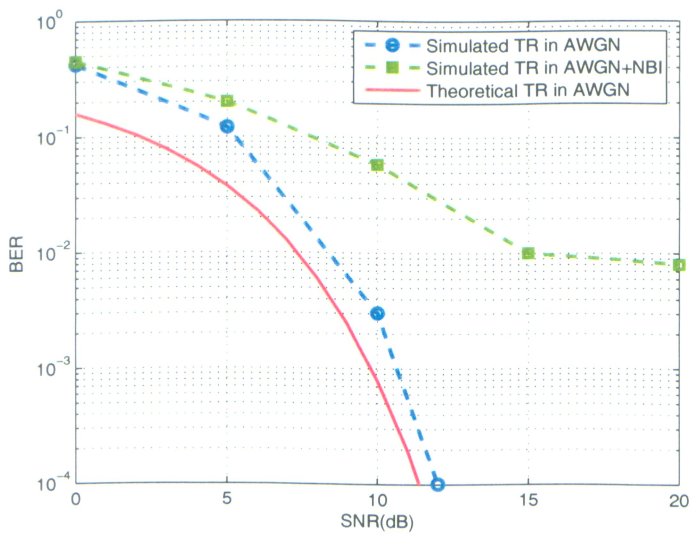

Figure 6.10: Performance degradation of a TR receiver due to AWGN and WLAN narrow band interference(NBI)

6.2.3 Case 3: Modified TR receiver in AWGN channel

This module is built to simulate the modified TR receiver in AWGN channel. Fig. 6.11 illustrates a comparison of BER performance improvement for the modified TR receiver and a conventional TR receiver in a transmission channel consisting a combined AWGN plus a strong interference from IEEE 802.11a WLAN interferer.

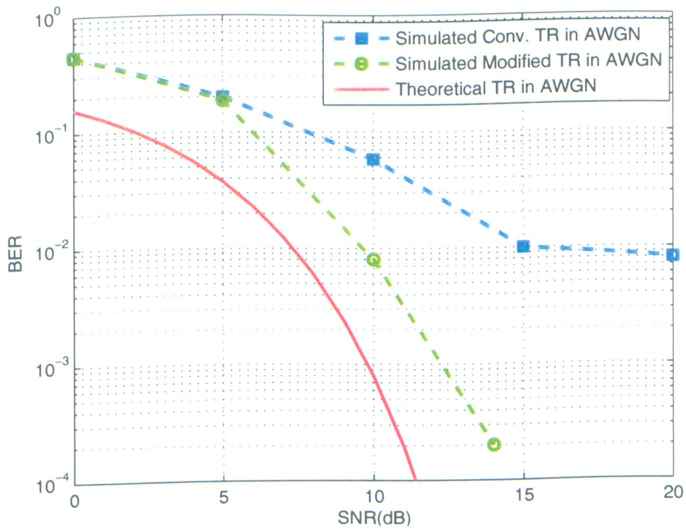

Figure 6.11: BER vs. SNR performance comparison of a conventional TR receiver and the modified TR receiver

6.2.4 Case 4: TR receiver in IEEE UWB channel

This module is built to simulate the TR receiver performance in IEEE UWB channel model. The system of interest is a single user UWB link operating at a data rate of 10 Mbps in IEEE UWB channel. Simulation is done in this section to study the TR performance with and without 802.11a WLAN interference. Fig. 6.12 shows the performance of a conventional TR receiver in an IEEE UWB channel and Fig. 6.13 shows the performance of a conventional TR receiver in an IEEE UWB channel plus a strong interference from IEEE 802.11a WLAN interferer. This BER performance is worse and not acceptable in communication systems.

6.2.5 Case 5: Modified TR receiver in IEEE UWB channel

This module is built to simulate the modified TR receiver in IEEE UWB channel. The system of interest is a single user UWB link operating at a data rate of 10 Mbps in IEEE UWB channel. Fig. 6.14 illustrates BER performance improvement of the modified TR receiver compared to conventional TR receiver in a IEEE UWB channel plus a strong interference from IEEE 802.11a WLAN interferer.

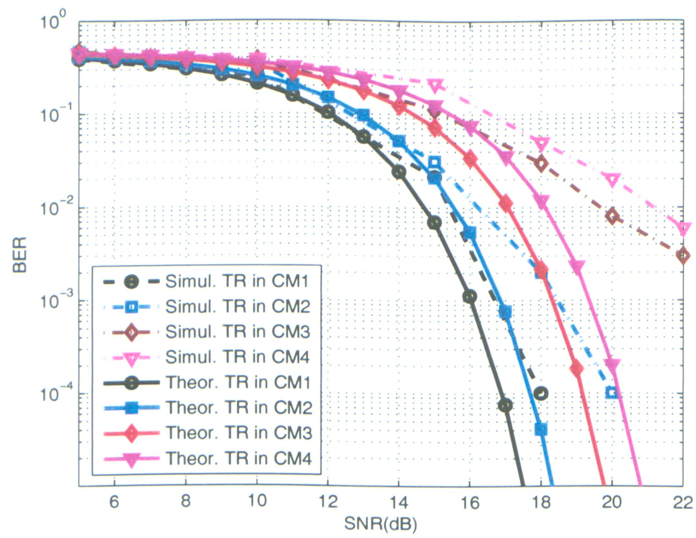

Figure 6.12: BER vs. SNR performance of a conventional TR receiver in different IEEE UWB channel models without any interference

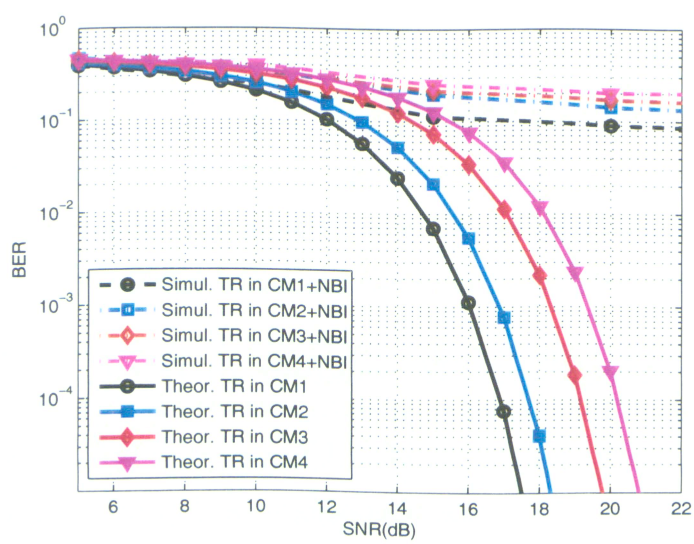

Figure 6.13: BER vs. SNR performance of a conventional TR receiver in different IEEE UWB channel models with WLAN narrow band interference(NBI)

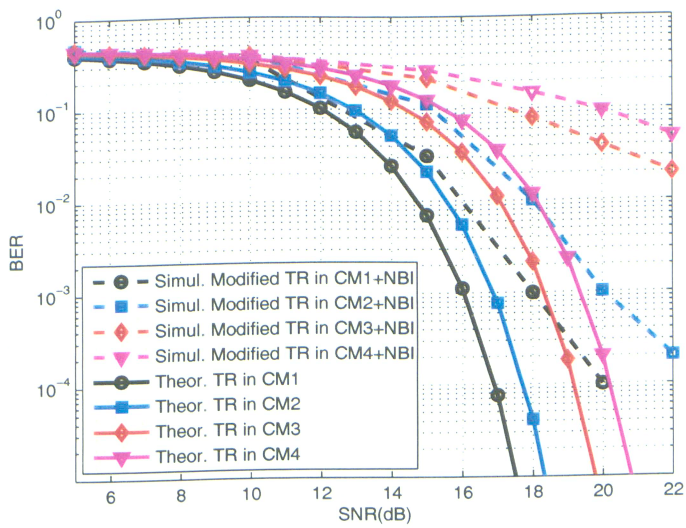

Figure 6.14: BER vs. SNR performance of the modified TR receiver in different IEEE UWB channel models with WLAN narrow band interference(NBI)

Chapter 7

Conclusions

In this thesis, we examine ultra wideband (UWB) communication systems paying particular attention to transmitter and receiver architecture such that it will overcome channel estimation and interference problem which are known to be difficult problems in UWB communications. To overcome dense multipath channel estimation problem we choose TR receivers for UWB communication.

The research presented in this thesis focuses on TR-UWB systems and TR-UWB system performance is studied in the presence of a strong IEEE 802.11a interference.

The main contributions are as follows:

- suppression of interference from WLAN to TR-UWB system
- suppression of interference from TR-UWB to WLAN system

The following conclusions can be drawn:

- By using wavelet techniques, interference from TR-UWB to IEEE 802.11a is reduced by alleviating the energy in overlapping bands.
- Using wavelet techniques, spectral density of the transmitted UWB signal around the interfering band is reduced by 60 dB lower than the peak.
- When UWB error performance is checked with OOK, PAM, BPSK and TR modulations in AWGN channel, the BER performance of UWB system is affected very much when the WLAN interference is introduced in the AWGN channel.

- When UWB error performance is checked with TR modulations in different UWB channel models, the BER performance of UWB system is severely affected when the WLAN interference is introduced in the UWB channel.

- By introducing the notch filter in the TR-UWB receiver, the interference from the WLAN systems could be removed successfully without affecting the required signals.

- With the modified TR receiver, we achieved better performance in the presence of WLAN interference in both AWGN and IEEE channel model for UWB .

Finally, our proposed scheme eliminates interference from the UWB system to the WLAN system and vice versa. The proposed method can be used for the coexistence of different wireless systems with UWB system.

Appendix A

Power Calculation

The maximum transmitted UWB signal power according to FCC specification is:

$$P_{Tx} = -41.25dBm/MHz * 7.5GHz = 0.56mW = -32.5181dB \tag{A.1}$$

Let's assume that the distance between the receiving antenna and transmitting antenna is 10 meters, according to the -1.7LOS model

$$PL = -45 - 10 * 1.7 * log(d) \tag{A.2}$$

We can have the received UWB signal power:

$$P_{Rx-dB} = -45 - 10 * 1.7 * log(10) - 32.5 = -62 - 32.518 = -94.518dB \tag{A.3}$$

Based on the assumption that circuit's noise is from thermal sources, the noise power is estimated by the following:

$$\begin{aligned} P_{Noise-dB} &= 10log(P_{Noise}) + NF \\ &= 10log(k.T.B) + NF && \text{(A.4)} \\ &= 10log(1.38 * e - 23.298.10 * e9) + 5 && \text{(A.5)} \\ &= -98.859dB && \text{(A.6)} \end{aligned}$$

Thus, SNR can be calculated based on the received UWB signal power and thermal noise power:

$$SNR = P_{Rx-dB} - P_{Noise-dB} = -94.518 + 98.859 = 4.34dB \tag{A.7}$$

Appendix B

Optimal UWB Single-user Receivers in AWGN

In this appendix the optimal receiver in an AWGN channel is given and the BER of selected UWB modulation schemes will be presented.

B.1 General AWGN Detector Design

When the transmitted signal $S_m(t)$ having m=1....M different waveforms and $0 < t < T$ is subjected to a memory-less AWGN channel, the received signal $r(t)$ can be modelled as

$$r(t) = S_m(t) + n(t) \tag{B.1}$$

where the noise term $n(t)$ is Gaussian with zero mean and variance σ^2. It is shown in [9] that a bank of N correlators yield sufficient statistics to perform optimal detection with N being the dimension of the signal. The output of these N correlators are then given by

$$\begin{aligned} r_k &= \int_0^T r(t) f_k(t) dt = \int_0^T (S_m(t) + n(t)) f_k(t) dt \\ r_k &= S_{mk} + n_k = \int_0^T S_m(t) f_k(t) dt + \int_0^T n(t) f_k(t) dt, k = 1..N \\ r &= [r_1, ..., r_N] \quad s_m = [r_1, ..., r_N] \quad n = [n_1, ..., n_N] \end{aligned} \tag{B.2}$$

with $f_k(t)$ being the N orthonormal basis functions that make it possible to represent $s_m(t)$ as a linear combination of $f_k(t)$, that is $s_m(t)$ can be represented as

$$s_m(t) = \sum_{k-1}^{N} a_{mk} f_k(t) \tag{B.3}$$

where a_{mk} are the k constants for the m^{th} waveform.

Given that the prior distribution of the transmitted signal is uniform, the optimal detector is the Maximum Likelihood(ML) detector and it can be implemented by selecting the value of m that minimizes the Euclidian distance metric

$$D(r, s_m) = \sum_{k-1}^{N} (r_k - s_{mk})^2 = |r - s_m|^2 \tag{B.4}$$

This means that the ML detector should choose the waveform $s_m(t)$ that gives rise to the smallest error in terms of B.4.

B.2 BPSK Performance

When using BPSK to modulate the information onto the UWB pulses, only two waveforms are possible, namely $s_1(t) = s(t)$ when the information bit b is +1 and $s_2(t) = -s(t)$ when it is -1. This results in N=1 and only a signal correlator is needed to demodulate the signal optimally. In order to minimize, one simply has to choose the sign of $s_m(t)$ to be the same as r, because $s_1 = -s_2$. An optimal receiver for BPSK is therefore given by

$$\hat{b} = sgn(\int_0^T r(t)s(t)dt) = sgn(s_1 + n_1) \tag{B.5}$$

where $sgn(.)$ is the sign function. The BER of BPSK can now be found by observing the statistics of s_1 and n_1. It is shown that n_1 is a Gaussian variable with zero mean and variance σ^2 and given that the waveform is normalized so that $\int_0^T s^2(t)dt = 1$, the BER can be found as

$$BER = (1/2)p(s_1 + n_1 < 0 \mid s_1) + (1/2)p(s_2 + n_2 > 0 \mid s_2) \tag{B.6}$$

and because of the symmetry this can be written as

$$BER = p(s_1 + n_1 < 0 \mid s_1) = p(n_1 > 1) = \frac{1}{\sqrt{2\pi}\sigma}\int_1^\infty e^{\frac{-\alpha^2}{2\sigma^2}} d\alpha = (1/2)\text{erfc}(\sqrt{\frac{1}{2\sigma^2}}) \quad \text{(B.7)}$$

where $erfc(.)$ is the complementary error function defined by

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-z^2} dz \quad \text{(B.8)}$$

using the fact the SNR Ratio is given by $SNR = \frac{1}{\sigma^2}$, it gives

$$BER = (1/2)\text{erfc}\{\sqrt{\frac{SNR}{2}}\} \quad \text{(B.9)}$$

Appendix C

IEEE CHANNEL MODEL IEEE P802.15.3A

The proposed IEEE UWB model [37] uses the some definitions and parameters as presented in Table C.1. Channel characteristics that were used to derive the model parameters were chosen to be the following:

- Mean excess delay
- RMS delay spread
- Number of multipath components
- Power decay profile

Channel parameters were found using measurement data based on couple of channel characteristics for different channel models and are shown in Table C.2:

Parameter	Meaning
T_l	the delay of the l^{th} cluster
$\tau_{k,l}$	the delay of the k^{th} multipath ray relative to the l^{th} cluster arrival time T_l
Λ	cluster arrival rate
λ	ray arrival rate, i.e., the arrival rate of a path within each cluster
Γ	Cluster delay factor
γ	Ray decay factor
σ_1	Standard deviation of cluster log-normal fading term
σ_2	Standard deviation of ray log-normal fading term
σ_x	Standard deviation of log-normal shadowing term for total multipath realization

Table C.1: Channel model components and parameters

Target Channel Characteristics	**CM 1**	**CM 2**	**CM 3**	**CM 4**
Mean excess delay(nsec)	5.05	10.38	14.18	
RMS delay(nsec)	5.28	8.03	14.28	25
NP(85%)	24	36.1	61.54	
Model Parameters				
Λ(1/nsec)	0.0233	0.4	0.0667	0.0667
λ(1/nsec)	2.5	0.5	2.1	2.1
Γ	7.1	5.5	14.00	24.00
γ	4.3	6.7	7.9	12
σ_1(dB)	3.3941	3.3941	3.941	3.941
σ_2(dB)	3.3941	3.3941	3.941	3.941
σ_x(dB)	3	3	3	3
Model Characteristics				
Mean excess delay(nsec)	5.0	9.9	15.9	30.1
RMS delay(nsec)	5	8	15	25
NP(85%)	20.8	33.9	64.7	123.3
channel energy mean(dB)	-0.4	-0.5	0.0	0.3
channel energy std(dB)	2.9	3.1	3.1	2.7

Table C.2: Channel Model, Parameters and Comparison with Channel Characteristics from Measurements

Channel shown in Figure C.1 is one realization of channel CM1. This channel model is of a line of sight (LOS) case with the transmitter and the receiver antenna being separated by a distance in the range (0-4 m). Figure C.2 shows single realization of the channel model CM2. This channel is a model for a non line of sight (NLOS) case with antenna separation being in the range (0-4 m). Figure C.3 and C.4 represent channel models CM 3 and CM 4 for NLOS case with antenna separation being in the range (4-10 m) and an extreme case respectively.

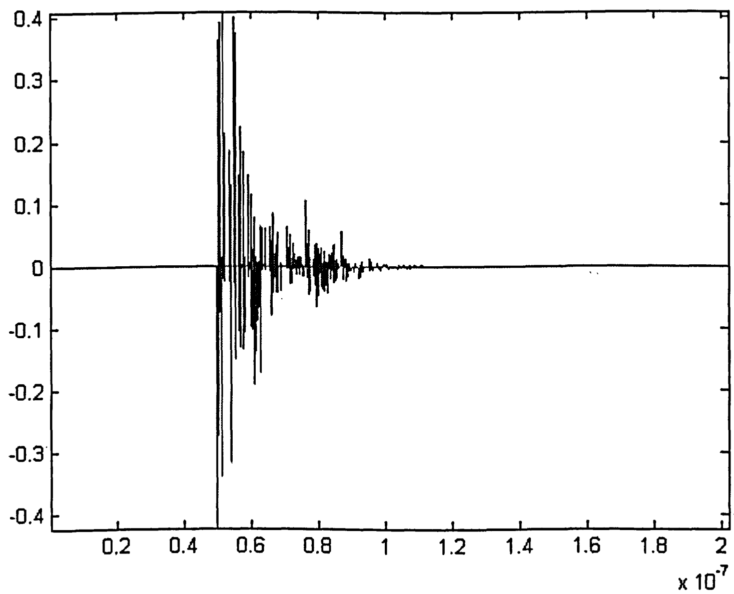

Figure C.1: Impulse response of CM1 : LOS(0-4m)

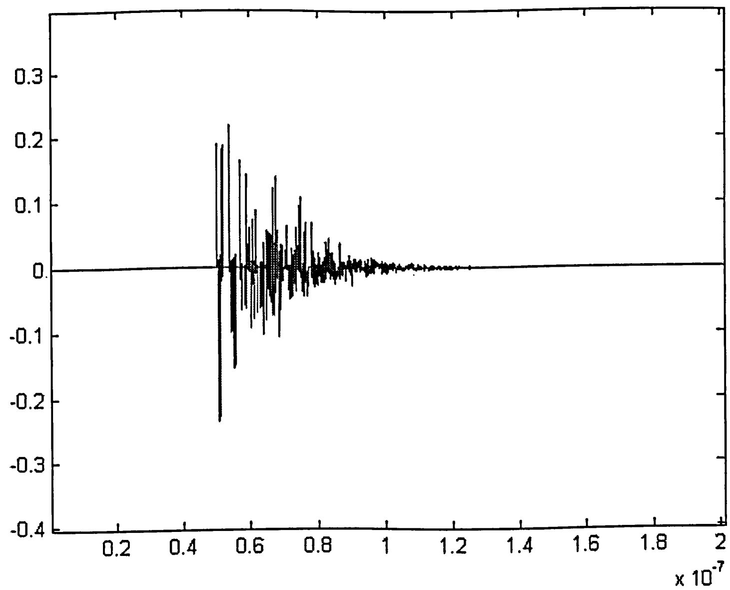

Figure C.2: Impulse response of CM2 : NLOS(0-4m)

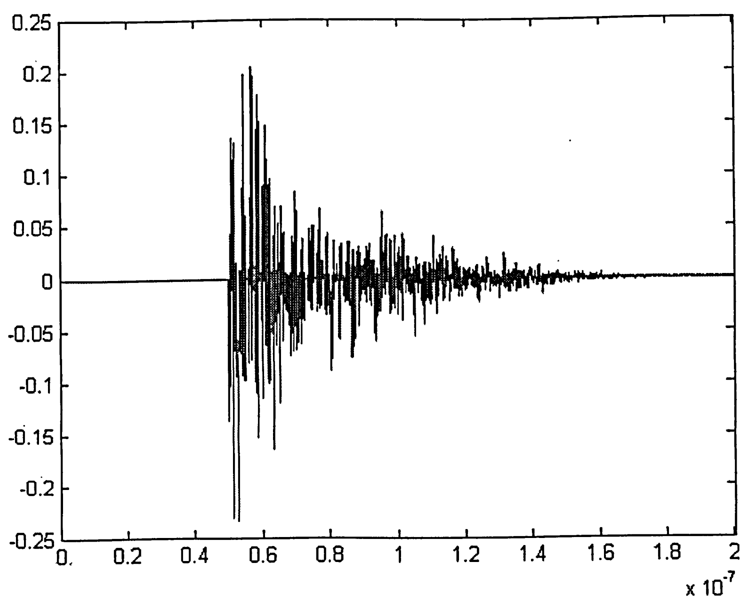

Figure C.3: Impulse response of CM3 : NLOS(4-10m)

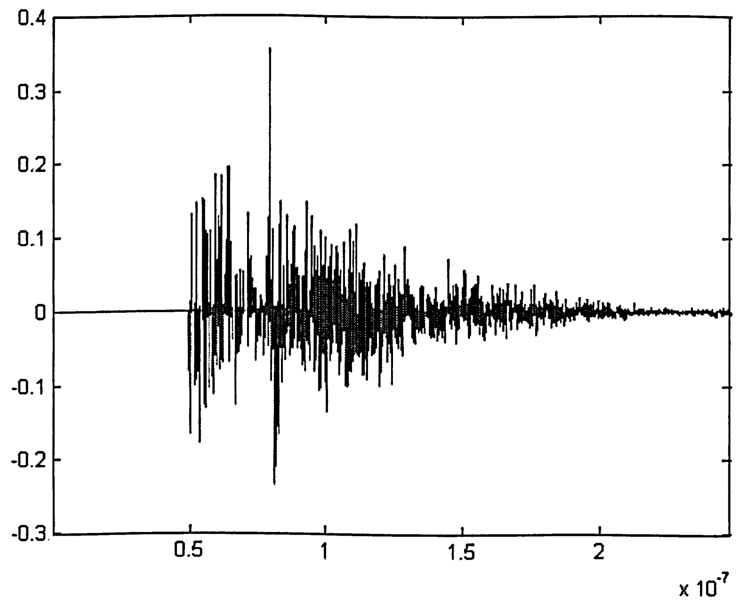

Figure C.4: Impulse response of CM4 : Extreme NLOS

Appendix D

Matlab Scripts used in this Study

The Matlab Simulink files were written by the author to run the system simulation can be found on the CD attached to this thesis. The following is a list of Matlab Scripts used in this Study.

D.1 Capacity Vs SNR

```
close all; clear all; snr=-20:1:50;
    y(1,:)=500e6*log2(1+10.^(0.1*snr));
    y(2,:)=1000e6*log2(1+10.^(0.1*snr));
    y(3,:)=2000e6*log2(1+10.^(0.1*snr));
    y(4,:)=4000e6*log2(1+10.^(0.1*snr));
    y(5,:)=6000e6*log2(1+10.^(0.1*snr));
    plot(snr,y/1e9);
```

D.2 Capacity Vs distance

```
d=1:1:100;
    gamma=3.5;
    snr1=-40+108-20*log10(4*pi*6.85e9/3e8)-gamma*10*log10(d);
    y1=3e9*log2(1+10.^(0.1*snr1));
    %WLAN 5GHz
```

```
snr2=-20+108-20*log10(4*pi*5e9/3e8)-gamma*10*log10(x);
y2=25e6*log2(1+10.^(0.1*snr2));
%WLAN 2.4GHz
snr3=-20+108-20*log10(4*pi*2.4e9/3e8)-gamma*10*log10(x);
y3=85e6*log2(1+10.^(0.1*snr3));
%bluetooth
snr4=-20+108-20*log10(4*pi*2.4e9/3e8)-gamma*10*log10(x);
y4=1e6*log2(1+10.^(0.1*snr4));
semilogy(d,y1,'',d,y2,'',d,y3,'',d,y4,'');
```

D.3 Signal Power Calculation

```
close all;
clear all;
fm=400e6;
f0=6.85e9;
taw1=1e-9;
taw=0.2e-9;
A=log(10);
x=-0.5e-9:1e-12:0.5e-9;
p=(.0004*exp(-log(10)*x.^2/(0.2e-9*0.2e-9)).
sin(2*pi*6.8e9*x)).^2;
plot(x,p);
q=inline('((0.0004*exp(-log(10)*x.^2/(0.2e-9*0.2e-9)).
sin(2*pi*6.8e9*x)).^2)');
power=(quad(q,-0.5e-9,0.5e-9)/25e-9);
```

D.4 Gaussian Waveforms

```
clear all; close all;
```

```
pw=.175e-9;
Fs=100e9;
Fn=Fs/2;
t=-0.5e-9:1/Fs:0.5e-9;
A=log(10);
y(1,:)=(1 - 4*pi.*((t)/pw).^2).* exp(-2*pi.*((t)/pw).^2);
y(2,:)=20e9*t.*exp(-A*((t)/pw).^2);
y(3,:)=exp(-((t)/pw).^2);
figure plot(t,y)grid on
figure periodogram(y(1,:),[],'onesided',8*512,Fs);
axis([0 11 -200 -90])
figure periodogram(y(2,:),[],'onesided',8*512,Fs);
axis([0 11 -200 -90])
figure periodogram(y(3,:),[],'onesided',8*512,Fs);
axis([0 11 -200 -90])
```

D.5 Wavelet Coefficients

```
close all;
fs=400e6;
f0=6.85e9;
taw1=1e-9;
taw=0.15e-9;
A=log(10); ans1=zeros(1,54);
for n=1:1:55,
q=@(x)(.4*exp(-A*x.^2/(taw*taw)).*sin(2*pi*f0*x).
(exp(-A*x.^2/(taw1*taw1))).*sin(2*pi*n*fs*x));
ans1(1,n)=quad(q,-.5e-9,.5e-9,1e-16);
end
```

```
figure plot(ans1);
```

D.6 Gaussian weighted sinusoidal pulse

```
close all;
clear all;
pw1=0.5e-9;
pw=pw1/1;
Fs=100e9; Fn=Fs/2;
t=-5e-9:1/Fs:5e-9;
td=0;
fm=400e6;
f0=6.8e9;
taw1=1e-9; taw=0.2e-9;
A=log(10);
ans1=zeros(1,27);
for n=1:1:35,
q=@(x)(.4*exp(-A*x.^2/(taw*taw)).*sin(2*pi*f0*x).
(exp(-A*x.^2/(taw1*taw1))).*sin(2*pi*n*fm*x));
ans1(1,n)=quad(q,-1e-9,1e-9,1e-16);
end
figure stem(ans1);
yy=zeros(1,1001);
for n=7:1:10
yp=1.8e9*ans1(1,n)*sin(2*pi*n*fm*t).*(exp(-A*t.^2/(taw1*taw1)));
yy=yp+yy; end for n=16:1:27
yp=1.8e9*ans1(1,n)*sin(2*pi*n*fm*t).*(exp(-A*t.^2/(taw1*taw1)));
yy=yp+yy; end
ma=max(yy);
```

```
yy=yy/ma;
for i=1:200,
if yy(i)¡=0.01
yy(i)=0;
end end for i=800:1001,
if yy(i)¡=0.01
yy(i)=0;
end
end
figure
plot(t,yy)
grid on
figure periodogram(.2*yy,[],'onesided',8*512,Fs);
```

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