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Sub-optimal Ultra-wide Band Receivers

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SUB-OPTIMAL ULTRA-WIDE BAND RECEIVERS

By

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ABSTRACT

Ultra-wide Band (UWB) has sparked a lot of interest lately from the industry and academia. The growing capacity of the wireless industry is requires a new communication system that satisfies the high data rate which does not interfere with existing RF systems. UWB promises to be this new technology. UWB also promises low power, low cost and flexibility. The UWB Channel opens up a huge new wireless channel with Giga Hertz Capacities as well as the highest spatial capacities measured in bits per hertz per square meter. When properly implemented UWB channel can share spectrum with traditional radio systems without causing harmful interference. In this thesis we studied and compared several reduced complexity sub-optimal Ultra-Wide Band receivers. These receivers include auto correlation receiver, the square value detector and the absolute value detector are studied. We consider OOK and PPM modulation schemes. We examine these schemes and the receivers on Gaussian and UWB indoor channels. We compare the performance with

optimal receivers.

A transmitter receiver system using 0.1us pulses implemented using existing hardware. A packet consisting of 24 bits were transmitted and the received signal could be verified in real time using a vector signal analyzer. The results show sub-optimal receivers provide a better trade off between robust, complexity and performance.

ACKNOWLEDGEMENTS

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INTRODUCTION

1.1 UWB History

Ultra-wide Band(UWB) has sparked a lot of interest lately from the industry and academia. The growing capacity of the wireless industry is requires a new communication system that satisfies the high data rate which does not interfere with existing RF systems. UWB promises to be this new technology. UWB also promises low power, low cost and flexibility. Although the idea has been around for quite some time it is only now that the timing is right for enabling this technology to reach its full potential. The UWB Channel opens up a huge new wireless channel with Giga Hertz Capacities as well as the highest spatial capacities measured in bits per hertz per square meter. When properly implemented UWB channel can share spectrum with traditional radio systems without causing harmful interference. Modern advances in microelectronics are enabling cost effective fabrication of UWB systems. The main obstacle for the growth of UWB were lack of spectral allocation and the creation of an industry standard. In a landmark ruling on Feb 14 2002, the Federal Communications Committee allocated the use of 7500Mhz of unlicensed spectrum for UWB devices for communication application in the 3.1Ghz to 10.6Ghz band.This ruling has generated considerable interest in developing UWB communication systems, primarily through standards efforts such as IEEE's 802.15.3a, and has created several new opportunities for innovation and technical advancement. There is an ongoing debate as to how best to use the allocated spectrum.

UWB promises data rates of 110Mbps for a distance of 10 meters and about 480Mbps for a distance of up to 2 meters. The main market as a result for UWB products is the home networking industry.

This chapter gives a general overview of ultrawideband systems. The concerns of the FCC with regard to the use of UWB is discussed. Also the current guidelines under which UWB must operate is presented.

Ultra wide band signals employs short duration RF pulses to convert information rather than modulating a sinusiodal carrier with information symbols. These pulses are typically of a few nanosecond to pico second duration.

As bandwidth is inversely proportional yields a spectrum ranges from 0 to a few Ghz. This results in very low energy densities and hence UWB signals appear as noise to existing RF systems.

The origin of ultra wideband (UWB) technology stems from work in time-domain electromagnetics begun in 1962 to fully describe the transient behavior of a certain class of microwave networks through their characteristic impulse response (Ross 1963, 1966). It was not until the advent of the sampling oscilloscope(Hewlett Packard c.1962) and the development of techniques for subnanosecond pulse generation, to provide suitable approximations to an impulse excitation, that the impulse response of microwave networks could be directly observed and measured.

The Harmuth books and published papers, 1969,1984, placed in the public domain the basic design for UWB transmitters and receivers. At approximately the same time, the Ross and Robbins R&R patents, 1972,1987, pioneered the use of UWB signals in a number of application areas, including communications and radar, and also using coding schemes. Ross' US Patent 3,728,632, dated 17th April, 1973, is a landmark patent in UWB communications. Both Harmuth and R&R applied the 50 year-old concept of matched filtering to UWB systems.

By early 1970s, the basic design for UWB signals systems were available. By 1975 a UWB system could be constructed from components purchased from Tektronix. Once impulse measurement techniques were applied to the design of wideband, radiating antenna elements (Ross 1968), it quickly became obvious that short pulse radar and communications systems could be developed with the same set of tools. While at the Sperry Research Center, then part of the Sperry Rand Corporation, Ross applied these techniques to various applications in radar and communications (Bennett & Ross 1978).

Through the late 1980's this technology was alternately referred to as baseband, carrier-free, or impulse. From 1977 to 1989, there was a UASF program in UWB system development.The name "Ultra-Wideband" was used by the US Department of Defense by 1989. Within the United States much of the early work in the field of UWB was carried out by the US government.Since 1994, the development of UWB has greatly increased within the private sector.

The interference issue is one of the primary concerns of the FCC. In February 2002, the FCC issued a Report & Order giving users permission to deploy low powered UWB systems within the 3.1 to 10.6GHz spectrum. UWB products are found to have lot of use in public saftey, business and consumer industry. One of the most important features of UWB is its security. Detection on random low power pulses is extremely difficult. As a result UWB can accommodate a large number of users in a multi path environment. Some of the applications of UWB include ground and wall penetration, position allocation, collision warning avoidance, vehicle radar measurements etc. Newer applications are more focussed on indoor wireless, like small local area networks, wireless broadcast of High Definition Television(HDTV), and through wall imaging systems to detect people behind walls.The FCC guidelines make UWB suitable for use in relatively short range applications such as wireless personal area networks (WPANs), where UWB has a lot of potential and a huge market. Applications also include replacing IEEE1394 between portable multimedia CE devices, and portable [38] MP3 players with wireless connectivity. Enabling high speed connectivity for PC and PC peripherals, including printers, scanners and external storage devices. INTEL has set its sights on wireless PC connectivity through USB and is now called WUSB(Wireless Universal Serial BUS)

1.2 Why Ultra Wide Band?

Many communication systems are available for short-range wireless communications applications. Some of these technologies include Blue- Tooth, Zigbee, Carrier Sense Multiple Access(CSMA) are some examples. Some of these wireless standards are discussed here.

IEEE 802.1b operates at a speed of up to 11Mbps in the 2.4Ghz Band. This technology offers high speed data for a range of up tp 300 feet from the base station. There are 14 channels available of which only 11 can be used in the United States due to FCC regulations.In a circle with a radius of 100 meters, three 22MHz IEEE 802.11b systems can operate on a non-interfering basis, each offering a peak over-the-air speed of 11Mbps. This yields a spatial capacity of about 1000bits/sec/square-meter.

Bluetooth is a radio technology that uses radio frequency the 2.5Ghz ISM band. It uses short range radio links intended to replace cable connecting portable and fixed electronic devices.Key features are low power, low complexity and low cost. The technology offers wireless access to LANs PSTN . In its low power mode it has a speed of 54Mbps for a 10 meter range. According to [27] the spatial capacity of bluetooth is 30,000 bits/per/sec/square meter.

IEEE 802.11a is projected to have an operating range of 50 meters and a peak speed of 54Mbps. Given the 200MHz of available spectrum within the lower part of the 5GHz U-NII band, 12 such systems can operate simultaneously within a 50-meter circle with minimal degradation, for an aggregate speed of 648Mbps. The projected spatial capacity of this system is therefore approximately 83,000 bits/sec/square-meter.

It is important to notice that while UWB may provide dramatic channel capacity, it can do so only at limited range. This is due mainly to the low power levels allowed by the FCC for legal UWB operation. UWB technology, when used for high-rate applications, is most useful at short-ranges (less than 10 meters). Longer-range flexibility is better served by WLAN (wireless local area network) technologies like 802.11a. Figure 1.1 shows the throughput UWB promises and a comparison with IEEE 802.11a, IEEE802.11g.

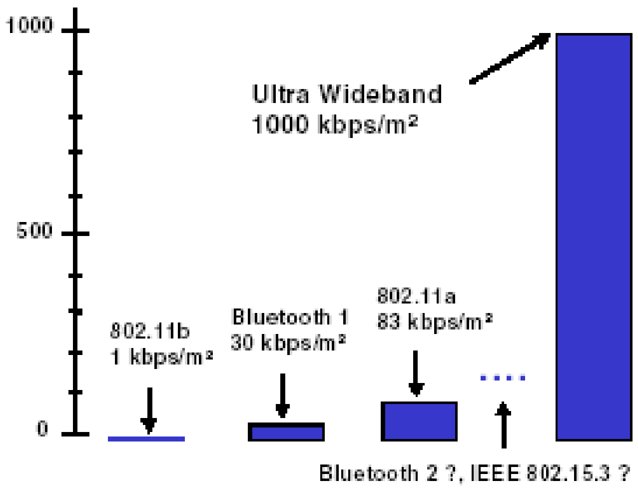

Figure 1.1: Spatial Capacity of different wireless standards. [27]

Ultra-Wide Band is preferred to the above techniques for a number of reasons. The main reasons include the high data rate that UWB promises(about 480Mbps) as well as the low power required for the UWB transmission. As a result of this low power there is also a very low probability of intercept. The spatial capacity calculated by [27] is over 1,000,000 bits/sec/square-meter. As shown in figure 1.1the UWB system offers considerable performance improvement over the other existing systems.

1.3 Ultra-Wide Band Versus Narrow Band.

UWB has many advantages over the conventional narrow band systems.. A narrow Band signal can be defined as EM waves with instantaneous Bandwidth of less than 1% of the center frequency. An Ultra-Wide Band signal as defined by DARPA is an EM wave with about 25% of the center frequency. A recent FCC ruling now defines a UWB signal as any signal which has a bandwidth of greater than 500Mhz in the 3.1 to 10.6 Ghz range. A narrow Band communication signal is obtained by modulating a sinusoidal carrier on the information to be transmitted. This resultant signal possesses a sinusoidal nature and occupies a narrow Band with. For a UWB communication system any signal that satisfies the definition of a UWB signal can be used. There is considerable research going on the shape of the pulse to be used. Thus the need for a carrier is avoided. This gives a system with reduced complexity.The UWB signal is much more robust to interference than the narrow band signal. This is because most of the interference covers only a portion of the UWB spectrum. However in the case of narrow band interferences at the right frequencies will distort the narrow band signal. Hence the UWB signal is also susceptible to jamming.

In the time domain UWB signals are discontinuous and appear to have characteristics similar to noise, in the frequency domain UWB signals register a low yet broad PSD making it almost impossible to detect.

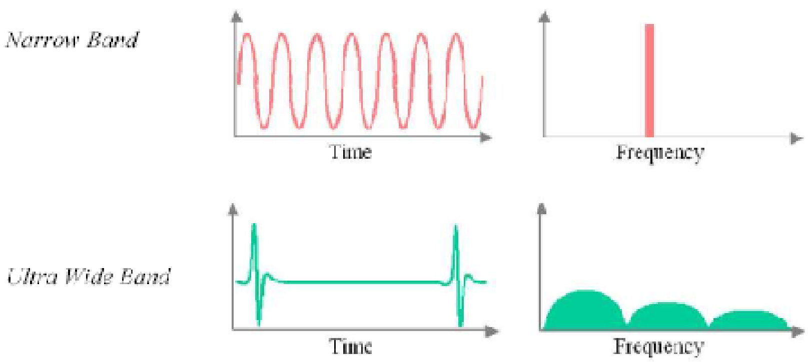

Figure 1.2: A comparison of a narrow band signal and a UWB Signal

A pictorial representation of a narrow band signal and a UWB signal is shown in figure 1.2. Another difference of the between narrow band and

Ultra wide band is the multiple access techniques used. Narrow-band signals use time, frequency and code division techniques for multiple access. The multiple access techniques for UWB was proposed by R.A.Scholtz in '93 [1] based on time hopping codes. In a typical hopping format for impulse radio with pulse position modulation, the time access is divided into t_f frames and every frame is sub divided into T_c time slots. The transmitted signal for the k^th user is given by the equation

$$S_t^{(k)}(t^k) = \sum_{j=-\infty}^{\infty} W_{tr}(t^{(k)} - jT_f - c_j^{(k)}T_c) \tag{1.1}$$

where W_{tr} is the transmitted pulse. K indicates the number of user. T_f is the pulse repetition period. Each user is assigned a time hopping sequence c_j. This hopping sequence provides an additional time shift of c_jT_c. This equation forms the basics of the time hopping using pulse position modulation for UWB communication systems.

1.4 The UWB Technology

A UWB signal as defined by the FCC is any signal that occupies more than 500Mhz in the 3.1 to 10.6 GHz frequency band. For this range the UWB pulse width is generally between 0.3 to 0.5 ns. The pulses are generally known as subnanosecond. These short monopulses are inherently ultra wideband. UWB used Low power RF techniques which allows previously designated RF bands to be used without interference. As the power spectral density is very low, it is difficult to detect and appears like noise to other systems. So UWB signals are effectively hiding beneath the noise floor. A typical UWB transmission along with the conventional radio service is shown in 1.3

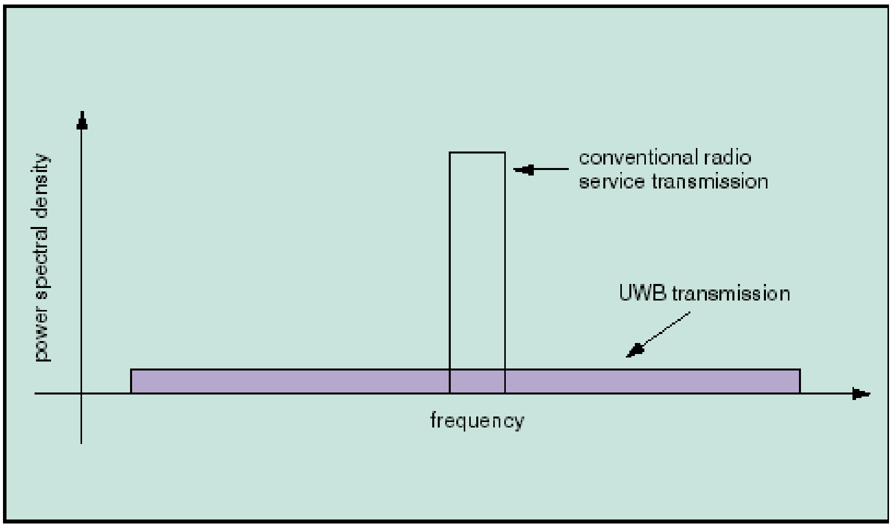

Figure 1.3: The Spectrum of UWB transmission and conventional transmission

The basic element in UWB radio technology is the use of Gaussian monocycle. The pulse is shown in both time and frequency domains. The monocycle width determines the center frequency and the bandwidth.

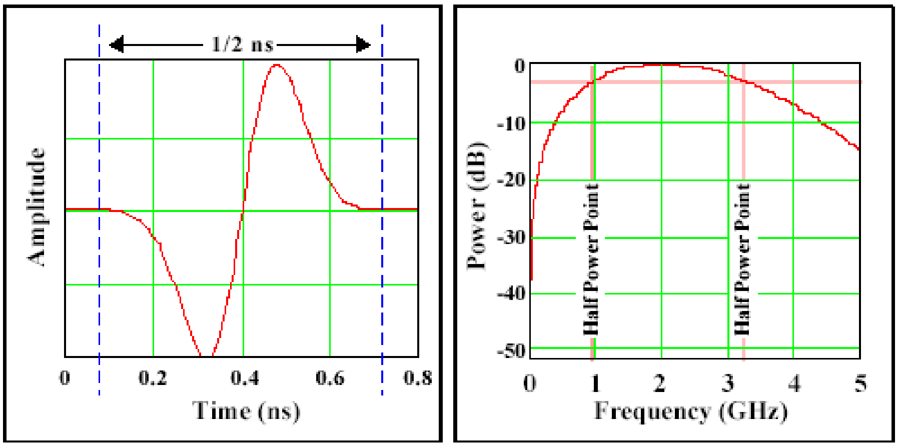

Figure 1.4: Gaussian Monocycle in Time and Frequency Domain [26]

In the time domain the Gaussian monocycle is mathematically similar to the first derivative of the Gaussian function. It has the form

$$V(t) = \frac{t}{\tau} e^{-(\frac{t}{\tau})^2} \tag{1.2}$$

where τ is the time decay that determines the monocycle duration and t is the time. In the frequency domain, a Gaussian monocycle has the form

$$V(f) = -jf\tau^2 e^{f^2\tau^2} \tag{1.3}$$

The center frequency is proportional to the inverse of the pulse duration, ie

$$f_c \alpha \frac{1}{\tau} \tag{1.4}$$

For the Gaussian Monocycle shown in figure 1.4 the pulse duration is 0.5ns and the center frequency, which is the reciprocal of the pulse width, is 2 GHz.As can be seen the signal spreads over a few GHz. In the past the development of UWB system has been restricted by the design difficulties of the traditional transceiver architecture.However, this problem has now been overcome by a new technology called time-modulated Ultra Wide Band. Work on UWB has been done by a number of organizations and individuals. For, communication applications a pulse train of monocycles is transmitted, with the pulse-to-pulse interval varied in accordance with the information signal and a channel code. A typical pulse train for a UWB signal is shown in figure 1.5.

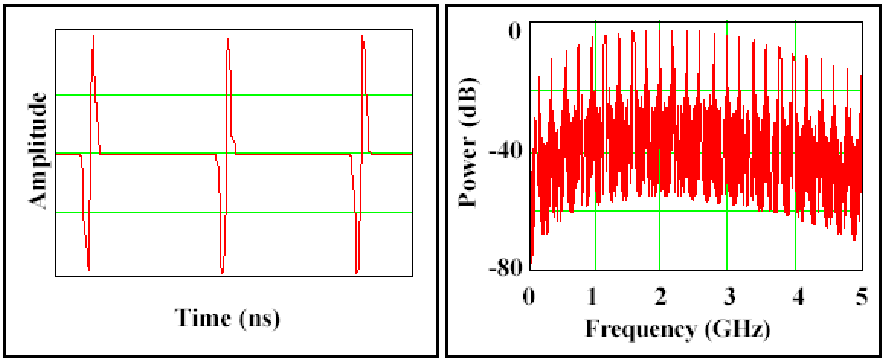

Figure 1.5: A monocycle pulse train in time and frequency domains. [26]

As can be seen from figure there are a number of spikes in the frequency domain. This could interfere with the existing radio systems. The modulation scheme used is pulse position modulation(PPM).

The link quality of the UWB signal is near constant over the entire indoor space [5] due to good ground penetrating capability of low frequency and diversity over the few gigahertz bandwidth. This can effectively provide a reliable service to any place in the indoor environment, while the conventional approach may not assure reliable communication. The low power spectral density ensures the coexistence with other devices. UWB promises high data rates, in excess of 100 Mbps. The main targeted application for high data rate are the wireless home applications segment. UWB systems are particularly promising for short range wireless communications as they combine reduced complexity with low power consumption, low-probability of intercept (LPI) and immunity to multipath fading. The successful deployment of UWB systems depends strongly on the development of efficient multi-access techniques. The idea behind UWB stems from the channel capacity equation for Gaussian channel.

$$C = B\ log_2(1 + \frac{S}{N}) \tag{1.5}$$

where: C is the maximum channel capacity B is the Bandwidth S is the signal power and N is the Noise power. It can be seen from equation 1.4 that increasing the bandwidth increases the channel capacity. An ultra wide band signal is defined as that signal which occupies a bandwidth of greater than 500MHz in the 3.1-10.6GHz range. This increased bandwidth means that the signal is robust to multipath fading, which is suitable for high speed mobile wireless communications. The fact that the maximum emission levels of UWB must be -41.25dB/MHz in the 3.1 to 10.6 GHz band, makes UWB undetectable(or has minimal impact) to narrowband receivers. UWB systems use Low power RF pulses transmitted at about a million pulses per second.Note that the center frequency is the reciprocal of the pulse width. An additional feature of UWB is that it provides for precise ranging, or distance measurement. This feature can be used for location identification in,for example, public safety applications.

1.5 Role of the Federal Communications Committee

The role of the Federal Communications Committee is to revise the commissions rules so as to pave way for new types of technology. The FCC initiated an investigation into the possibility of UWB systems on an unlicensed spectrum through the publication of a Notice of Inquiry (NOI) in 1998.

The NOI requested comments on potential applications for UWB devices and their technical characteristics, such as frequency ranges of operation, bandwidths, power levels and operating distances. In addition, the NOI requested comments concerning what regulatory treatment would be most appropriate for UWB devices, including whether they should be regulated under Part 15 or some other rule part. The NOI asked for the appropriate definition of UWB devices. Further, the NOI sought comments on whether UWB devices should be prohibited from operating in restricted frequency bands and TV/radio broadcast frequency bands or if there are certain restricted frequency bands where the Commission should permit UWB operation. Comments were also sought on what emission limits and measurement procedures would be appropriate for UWB devices. The NOI invited comments on any other matters or issues that may be pertinent to the operation of UWB systems. In response to the NOI, 42 parties filed comments and 37 parties filed reply comments. In response to the NOI three reports were produces by NTIA. The second of these reports deals with the compatibility of UWB with respect to selected federal systems.

The third NTIA report addresses the compatibility with respect to GPS receivers. Since the spectrum encroaches that of other communication systems concerns were raised about the comparability of UWB, impulse like signals, with other users of the radio spectrum. The agrement raised by the proponents of UWB were that with appropriate modulation techniques and low levels they appear like noise to other systems. The bandwidth of a narrow impulse is very wide and they will occupy the frequencies allocated to specific radio uses like for example TV broadcast, passive sensing, safety services etc. Part 15 defines regulations under which an intentional, unintentional, or incidental radiator may be operated without an individual license where the emission may occur in a part of the spectrum assigned for use by particular services. Limits are defined in the form of the maximum allowable signal transmit levels. [36]

The FCC Report and order issued in Feb 2002 allotted, 7500MHz of spectrum for unlicensed use of UWB devices in the 3.1 to 10.6 GHz band. This allocation opens up new possibilities to develop UWB technologies different from older approaches. More spectral allocation is likely to follow in the next few years. This is by far the largest use to unlicensed spectrum the FCC has ever allocated. The definition of a UWB signal, as declared by the FCC was, any signal that occupies a bandwidth of greater than 500 MHz in the 3.1 to 10.6 GHz range.

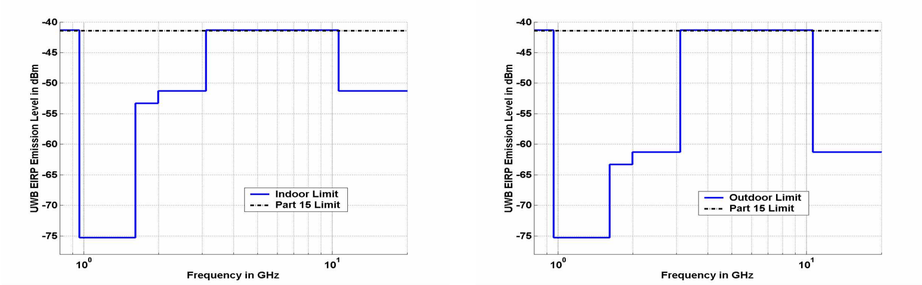

Figure 1.6: UWB spectrum for indoor and outdoor communications

This definition replaces the previous one which expressed a UWB signal in terms of its fractional bandwidth. Also stringent emission levels were outlined in the ruling. As can be seen in figure 1.6 the spectral emissions the spectral emissions for UWB and other services are shown. A comparison with other unlicensed bands currently available in the United States is shows in Table1.1.

Table 1.1: US spectrum allocation for unlicensed use

Unlicensed Bands	**Frequency of Operation**	**Bandwidth**
ISM at 2.4 Ghz	2.4000-2.4835	83.5 MHz
U-NII at 5 Ghz	5.15-5.35 Ghz 5.75 -5.85 Ghz	300 Mhz
UWB	3.1-10.6 GHz	7500Mhz

As stated earlier, the FCC spectral mask specifies 7.5 GHz of usable spectrum (between 3.1 GHz and 10.6 GHz), which is shared with existing radio solutions. When the FCC adopted new Part 15 rules permitting the marketing and operation of products incorporating UWB, it was felt that initial restrictions were quite conservative and that some relaxing may be possible once UWB was better understood by the industry.

However, personal computing and consumer entertainment applications may require closer device proximity for use models. The most obvious technology that will need to coexist at close proximity to UWB is WLAN, since the allocated spectrum for UWB completely overlaps the 5 GHz U-NII bands. Personal computers and possibly consumer electronic equipment may employ both Wireless LAN and UWB peripheral connectivity. This implies the possibility of UWB-connected peripherals in very close proximity to networked systems (within 1 meter, for example) using 802.11a in the 5 GHz spectrum.

Studies performed by Intel and the IEEE (Institute of Electrical and Electronics Engineers) have determined that some form of interference mitigation will be required for these types of scenarios to succeed. UWB technology is expected to share the approved spectrum with existing technologies. It will be the responsibility of the industry (through the establishment of responsible standards) to avoid interference with existing spectrum users if UWB is to be successful. The multi-band modulation scheme shown below, which is currently part of a focused research project within the Intel research and development network, is an example of a UWB waveform design that can coexist with IEEE 802.11a at very close ranges[27].

Due to numerous inputs and comments, and objections especially from the remote sensing and astronomy users of the 24 Ghz band the ruling is complex and limits emissions in several ways. The most stringent if these is thus in the 23.6 Ghz- 24Ghz band which is used for astronomical study. As can be seen from the figure the maximum power can be used in the 3.1-10.6 Ghz range.

CHAPTER 2

BACKGROUND

2.1 Conventional Spread-Spectrum Systems

Digital communications systems have been designed to communicate from one place to another as efficiently as possible in a stationary Additive White Gaussian noise (AWGN)environment. Many of the real world communication channels are accurately modelled as AWGN channels but there are other important channels which do not fit this model. Examples of such channels are the military communication system which might be jammed by a continuous tone near the modems center frequency, or by a distorted retransmission of the modems own signal. Such an interference cannot be modelled as stationary AWGN in either of these cases. Another kind of interference which does not fit stationary AWGN model, is multi-path reception and is a problem in line of sight microwave digital radios. [28]

To help minimize the kind of interference discussed above a modulation scheme called *spread spectrum* was introduced. Here the transmission bandwidth employed is much greater than the minimum required bandwidth required to transmit the digital information. For a system to be classified as a spread-spectrum system the transmitted signal energy must occupy a bandwidth which is larger than the information bit rate, and should be independent of the information bit rate. Also demodulation must be accomplished in part by correlation of the received signal with a replica of the signal which is used in the transmitter to spread the information signal.

The formal definition of Spread spectrum is an RF communications system in which the baseband signal bandwidth is intentionally spread over a larger bandwidth by injecting a higher frequency signal. As a direct consequence, energy used in transmitting the signal is spread over a wider bandwidth, and appears as noise. The ratio (in dB) between the spread baseband and the original signal is called processing gain. Typical SS processing gains run from 10dB to 60dB.

Different SS techniques are available, but all have one idea in common: the key (also called code or sequence) attached to the communication channel.

The manner of inserting this code defines precisely the SS technique in question. To achieve spread, the code is inserted somewhere in the transmitting chain before the transmitting antenna. In the receiver side the de-spreading operation takes place by using the same code in the receiver side.

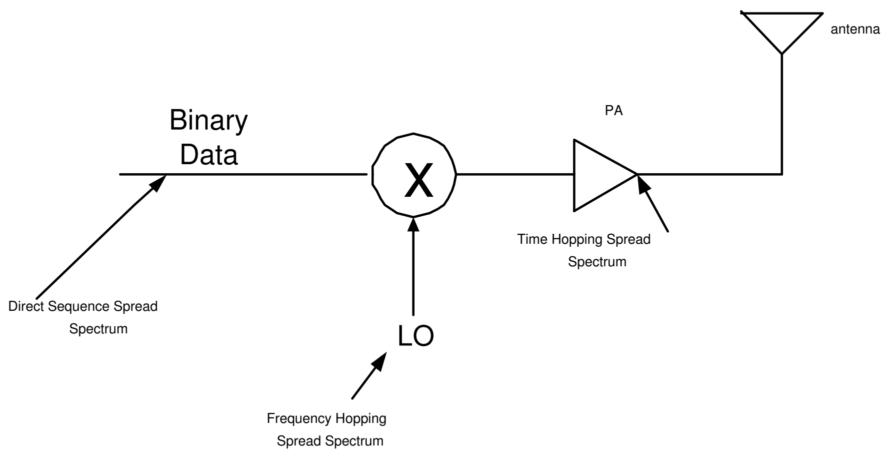

Figure 2.1: Modulation Spreading Techniques

Different modulation shchemes are distinguished according to the point in the system at which the pseudo random code is inserted in the communication channel. The most common modulation techniques employed are

- Direct Sequence(DS)
- Frequency Hopping(FH)
- Hybrid Direct-Sequence/Frequency Hop Spread Spectrum (DS/FH)

2.1.1 Direct Sequence Spread Spectrum

A data modulated signal is can be spread by modulating the signal a second time with a very wide-band spreading signal. The spreading signal is chosen to have properties which facilitate the demodulation of an unintended receiver as difficult as possible. These same properties will also make it possible for the intended receiver to distinguish between the communication signal and the jammer. Bandwidth modulation by direct modulation of data-modulated carrier is called *Direct Sequence (DS) Spread Spectrum.*The modulator sees a much larger bit rate as a result of the data modulation.

The result of modulating an RF carrier with such a code sequence is to produce a direct-sequence-modulated spread spectrum with ((sin x)/x)2 frequency spectrum, centered at the carrier frequency. The main lobe of this spectrum (null to null) has a bandwidth twice the clock rate of the modulating code, and the side-lobes have null-to-null bandwidths equal to the code"s clock rate. Illustrated below is the most common type of direct-sequence-modulated spread spectrum signal. Direct-sequence spectra vary somewhat in spectral shape, depending on the actual carrier and data modulation used.

The simplest form of DS Spread Spectrum uses BPSK as the spreading modulation. Figure 2.2 shows the block diagram of a BPSK Direct sequence

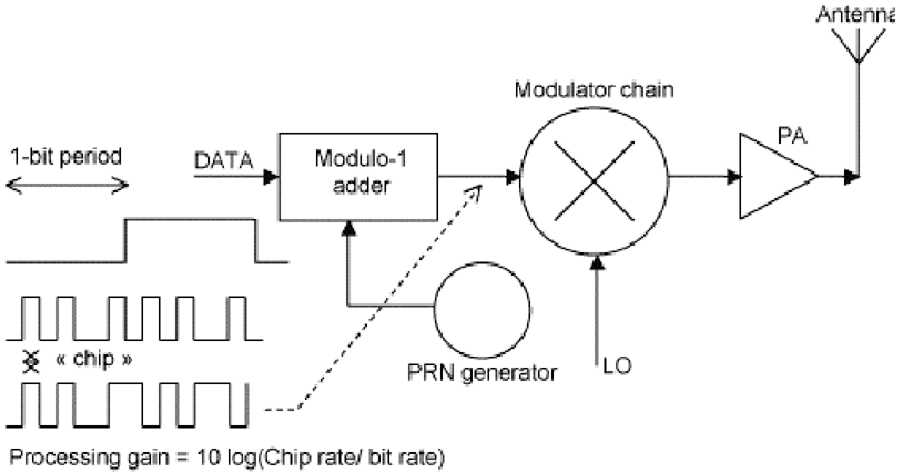

Figure 2.2: Direct Sequence Spread Spectrum Communications

spread spectrum system. Here the phase of the signal is depends on c(t) which is either ±1. The signal occupies a bandwidth typically between one-half and twice that of the data rate prior to DS spreading. The data modulated signal is spread using a suitable spreading code. This signal is then multiplied by the carrier and transmitted through the transmitting antenna.

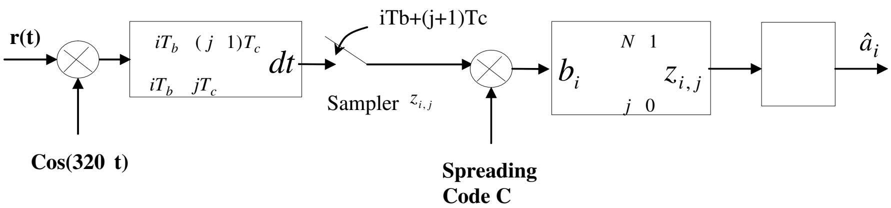

Figure 2.3: Receiver for DSSS

At the receiving side the signal along with some kind of interference and Gaussian Noise and the receiver. The receiver consists of two parts matched filter and de-spreader. The matched filter is matched to the carrier and then passed through and integrator and a sampler.Demodulation is accomplished by remodulating the with the spreading code. This remodulating or correlation or correlation of the received signal is called *de-spreading.* The block diagram for a receiver is shown in figure 2.3.

2.1.2 Frequency Hopping Spread Spectrum

This method does exactly what its name implies, it causes the carrier to hop from frequency to frequency over a wide band according to a sequence defined by the PRN. The speed at which the hops are executed depends on the data rate of the original information, but one can distinguish between Fast Frequency Hopping (FFHSS) and Low Frequency Hopping (LFHSS). The latter method (the most common) allows several consecutive data bits to modulate the same frequency. FFHSS, on the other hand, is characterized by several hops within each data bit. The transmitted spectrum of a frequency hopping signal is quite different from that of a direct sequence system. Instead of a ((sin x)/x)2-shaped envelope, the frequency hopper's output is flat over the band of frequencies used (see below). The bandwidth of a frequency-hopping signal is simply N times the number of frequency slots available, where N is the bandwidth of each hop channel. Typically each carrier frequency is chosen from a set of 2^k frequencies which are spaced approximately the width of the data modulation bandwidth. The spreading code in this case does not directly modulate the data modulated carrier but is instead used to control the sequence of carrier frequencies. In the receiver the frequency hopping is removed by mixing with a local oscillator signal which is hopping synchronously with the received signal.

Frequency hopping is used much more in the military than the DS spread spectrum. The reason for this is that the signals hop outside the band of conventional systems which results in less interference. The problem with this system is that the signals hop around very fast and within a short period of time the carrier frequency which makes it difficult for the receiver to synchronize. The original signal is then spread across the available spectrum by hopping the transmitted signals to the center frequency of various frequency slots.

FHSS techniques can be implemented with slow or fast hopping. With slow hopping, one or more symbols are transmitted at each hopping frequency. The most common modulation scheme used in FH systems is M-ary frequency shift keying. If the data modulator outputs one of 2^L tones each LT seconds, where T is the duration of one information bit. Each T_c seconds the data modulator output is translated to a new frequency by the frequency hop modulator. When T_c is less $\leq$ LT the FH system is called slow-frequency-hop-system. This is shown in figure 2.4

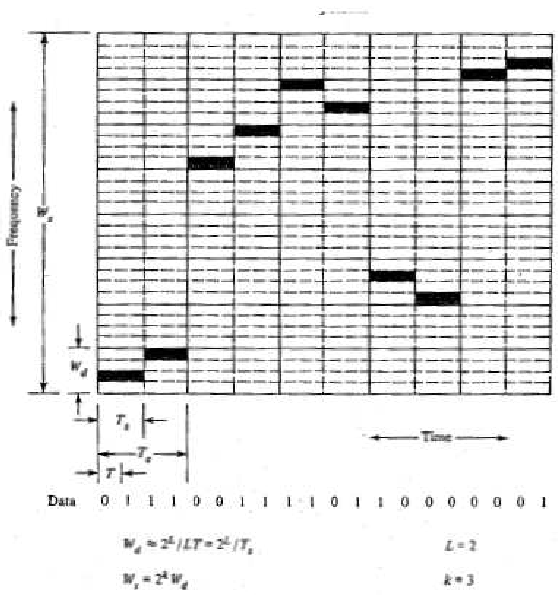

Figure 2.4: Slow frequency hop system [30]

With fast hopping, only fractions of an individual symbol are transmitted at a given hopping frequency. A significant benefit achieved when fast frequency hopping is used is that frequency diversity gain is seen on each transmitted symbol. This is particularly beneficial in partial band jamming or when transmission channel causes rapid fading as in microwave mobile telephony applications. This is shown in figure 2.5.

The output of the MFSK is one of 2^L tones as before but now this tone is subdivided into K chips. After each chip, the MFSK modulator output is hopped to a different frequency. Since the chip duration T_c is shorter than the data modulator output symbol duration T_s, the minimum tone spacing for orthogonal signals is now $1/tc = K/LT$.

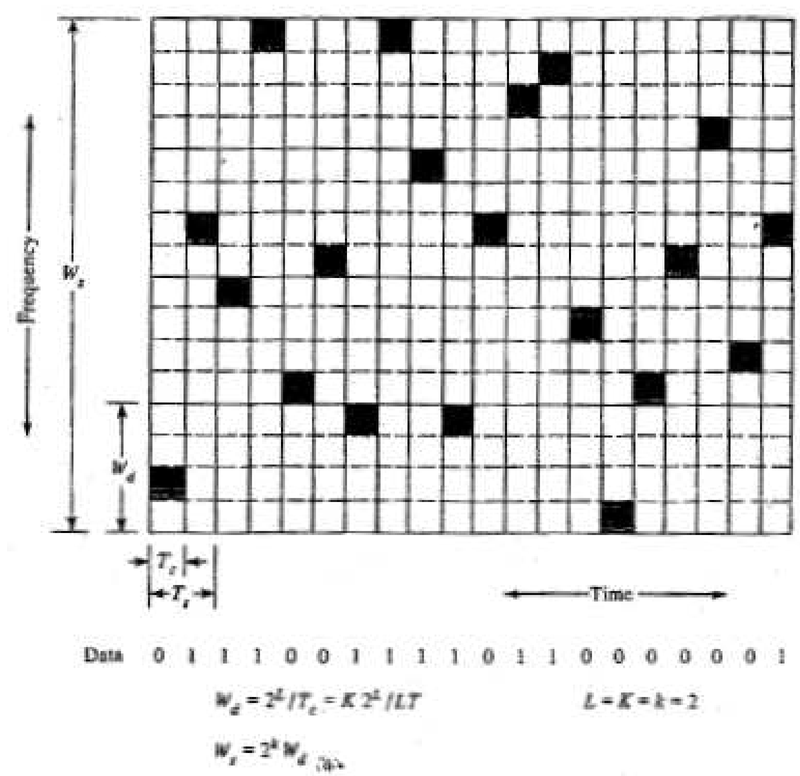

Figure 2.5: Fast frequency hop system[30]

2.1.3 Hybrid Direct-Sequence/Frequency Hop Spread Spectrum

The third method for spread spectrum is to employ both direct sequence and frequency hop spread spectrum techniques. The main reason for using a hybrid spread spectrum is that some of the advantageous of both systems are combined into a single system. Such a system will possess a very high degree of information security as well as a high ability to reject interference. The block diagram of a hybrid system is shown in figure 2.6.

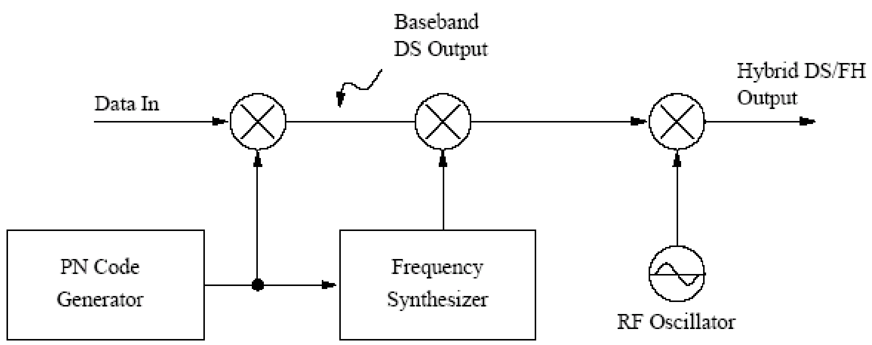

Figure 2.6: Hybrid Spread Spectrum System

The disadvantage of this type of system is the overall increase in complexity and operation. A hybrid system can be thought of as a direct sequence system in which the carrier frequency is changed periodically. The information to be transmitted is spread by mixing with a PN sequence, but the band of frequencies over which the data is spread is changed at a rapid rate. It is very difficult for a narrow band listener to intercept and gather information from a direct sequence transmission, but when the entire spread bandwidth is hopping around the spectrum, this task becomes almost impossible. Figure 2.7 shows the spectrum one can expect from a hybrid SS system.

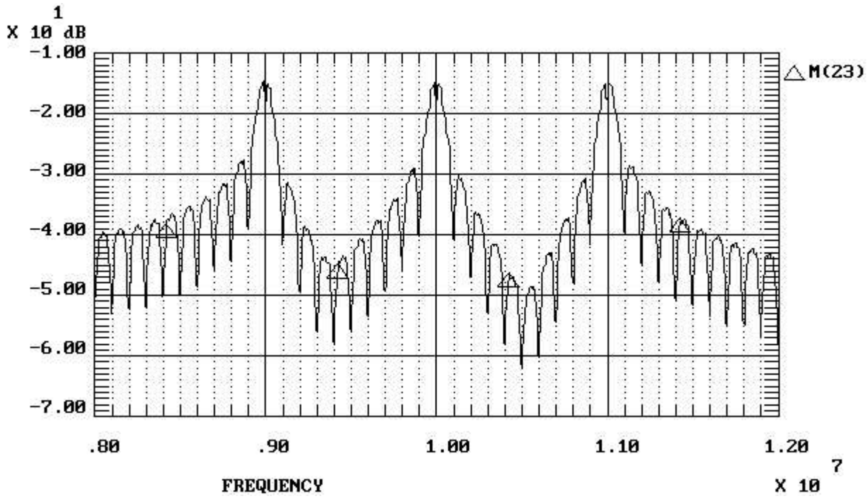

Figure 2.7: Spectrum of hybrid system [29]

2.2 Time Modulated Ultra Wide-Band

The Time Modulated Ultra-Wideband (TM-UWB) spread spectrum technique is commonly used in UWB. This proprietary technique utilizes pulses transmitted at specified times to convey user information. In the TM-UWB technique, time is divided into very small slots (Tf) and pulses are transmitted within these slots, relative to a pseudo random time (ti) within the time slot, to denote the transmitted bit. Thus, a pulse received immediately after the pseudo random time would denote a "0" or a pulse received somewhat after the pseudo random time would denote a "1". Individual bits are also transmitted in multiple time slots in order to realize a processing gain. The pulses spread RF energy across an ultra-wideband spectrum. The TM-UWB architecture is characterized by

- Ultra short pulse widths(typically in nanoseconds) which yields ultra-wideband pulses
- Extremely low power spectral densities
- Center frequencies typically between 650 MHz and 5 GHz, with potential to go higher as technology advances
- Multi-mile ranges with sub-milliWatt average power levels (even with

low gain antennas)

- Excellent immunity to interference from other radio systems.

The pulses used are typically Gaussian monopulse [26] with pulse widths in nano seconds. Thus the spectrum is ultra wide band. The system uses pulse position modulation. Thus the spreading is provided by transmission of these pulses. The amount of spreading can be controlled by the manipulation of the pulse characteristics.

Code sequences are used by the transmitter and receiver to determine the appropriate time slot and random offsets within the time slot. TM-UWB also exhibits resistance to narrowband and wideband interference as well as multipath fading. In TM-UWB systems, these interfering sources mentioned above will likely be poorly correlated with the user signal in the time domain, thus they have little impact on signal reception. Just as with CDMA, TM-UWB can also utilize multipath signals to increase the overall received signal power. In a fashion similar to that done with CDMA, a time-staggered RAKE receiver can be used to lock onto the resolvable multipath components, which can then be combined with the main component and others to form the received signal input into the demodulator.

Tm-UWB uses a relatively simple receiver design. The most important aspect of the TM-UWB receiver is the clock synchronization.The optimal receive technique, and the technique used in TM-UWB, is a correlation receiver (correlator). A correlator multiplies the received RF signal with a template waveform and then integrates the output of that process to yield a single DC voltage. This multiply-and-integrate process occurs over the duration of the pulse and is performed in less than a nanosecond. The block diagram for a TM-UWB architecture is shown in figure2.8

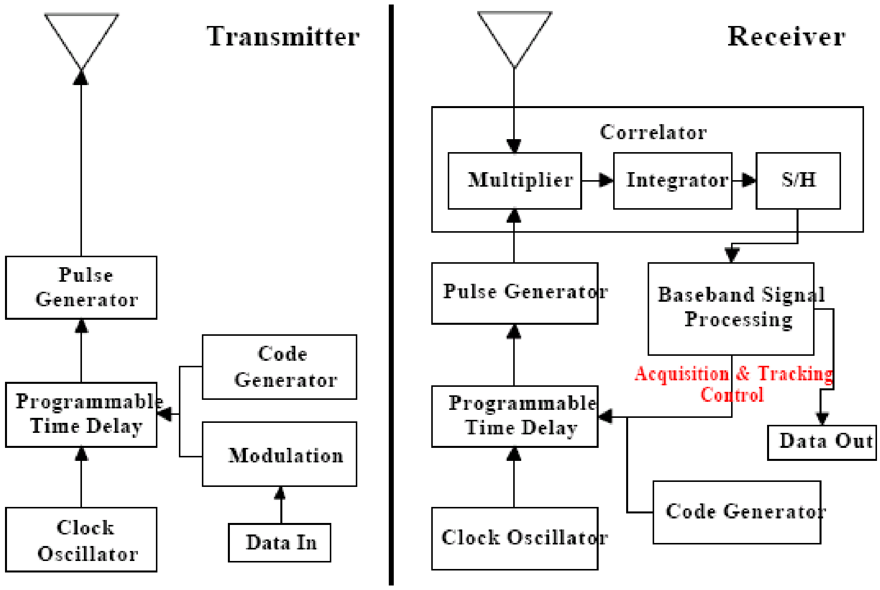

Figure 2.8: TM-UWB Receiver[26]

2.3 On-OFF Keying (OOK) and Pulse Position Modulation(PPM)

Two types of modulation schemes commonly used in UWB are On-OFF keying and pulse position modulation. As the name suggests for On-Off keying when we have a 1 we transmit a pulse, ON, and when the bit is zero no pulse is transmitted.

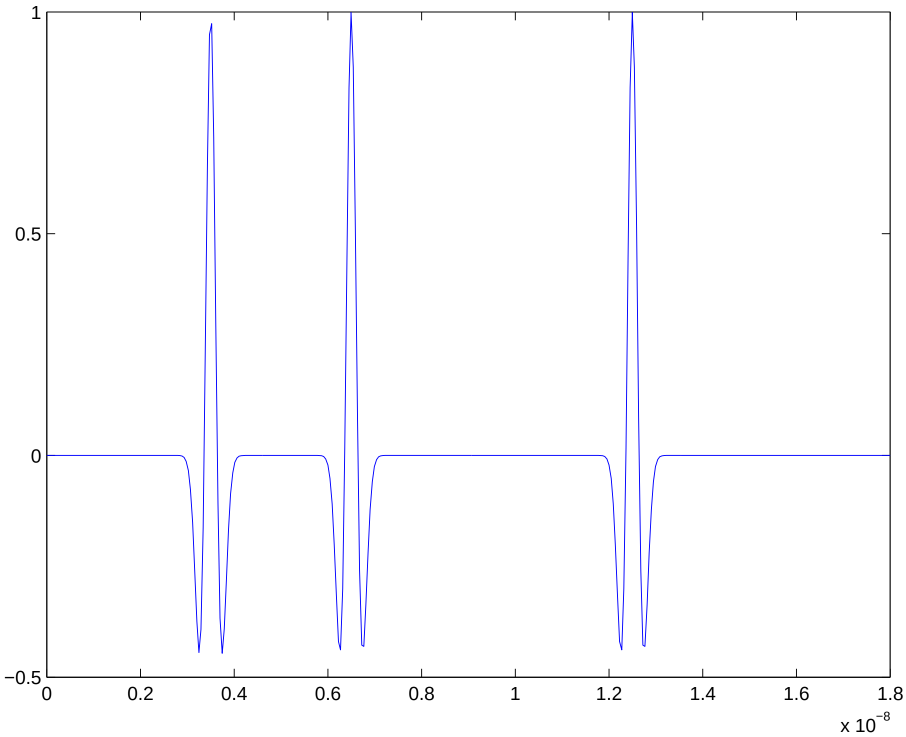

Figure 2.9: Example of OOK

For a data sequence of 11010 the corresponding signal will look like as shown in figure 2.9. When the data bits are equally likely then and a matched filter receiver is used the optimum threshold value is $E_b/2$. The probability of error for such a scheme is

$$P_b = Q(\sqrt{\frac{E_p}{2N}}) \tag{2.1}$$

A comparison with other polar signalling schemes shows that on-off signalling requires twice as much energy per bit to achieve the same performance.

A PPM signal consists of pulses in which the pulse displacement from a specified time reference is proportional to the sample values of the information bearing signal. Pulse position modulation is based on the principle of encoding information with two or more positions in time, referred to as nominal pulse position as shown in figure 3.9

The figure shows a two position modulation, where one bit is encoded in one impulse. Additional positions can be used to provide more bits per symbol. The time between positions is typically a fraction of a nanosecond, while there time between nominal positions is typically much longer to avoid interference between impulses. This data modulation helps smooth the spectral spikes with the unmodulated pulse train.Multiple users can use the same bandwidth by each user having a distinct periodic pulse shift pattern derived from their PN sequence channel code. This will reduce the Power Spectral Density.

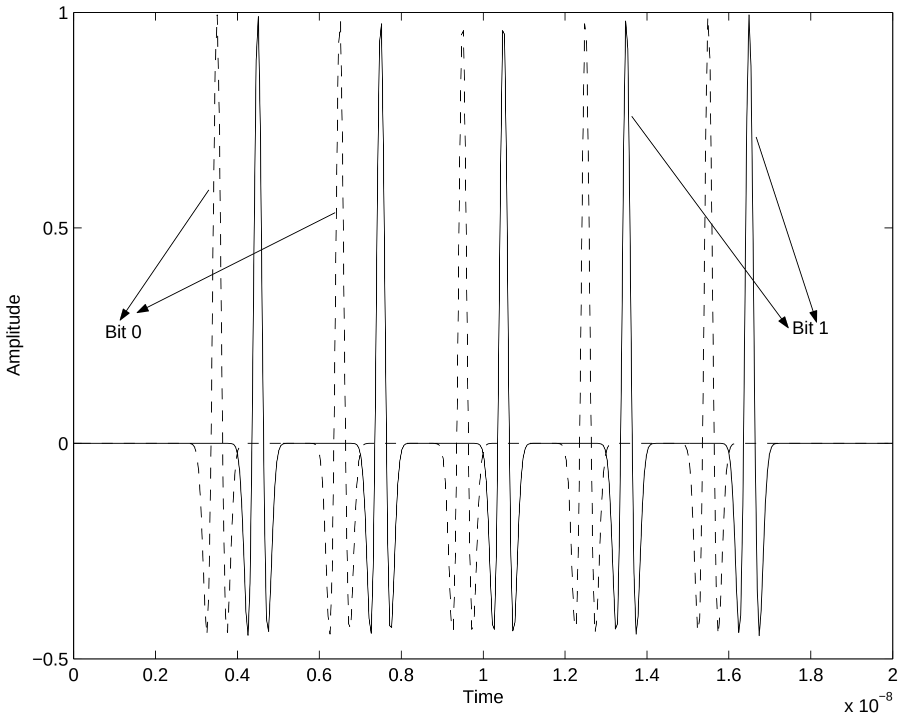

Figure 2.10: Pulse Position Modulation

2.4 Multiple Access for Ultra Wide Band

We shall now discuss the multiple access techniques that UWB communication systems uses to accommodate a number of users. The modulation scheme used to obtain this is Pulse Position modulation with time hopping as shown by R.A. Scholtz. [1]

$$s_t^{(k)}(t^k) = \sum_j AW_{tr}(t - jT_f - c_j^{(k)}T_c - \delta d_(j/Ns)^k) \tag{2.2}$$

- "A" represents the amplitude of the received signal which is $\sqrt{E_p}$ where

E_p is the energy per pulse.

- Ns is the number of pulses used to represent one data symbol, which is the pulse repetition number.

- $W_t r$ is the received pulse

- Ns is the number of pulses used to represent one data symbol, ie the pulse repetition number.

- T_f is the frame repetition time.

- c_j^k is the time hopping sequence

- δ is the PPM time delay parameter.

The transmitted pulse $W_t r$ can be represented by the equation

$$W_{Tr} = [1 - 4\pi(t - 0.35)^2/\tau m]exp[-2\pi(t - 0.35)^2\tau m] \qquad (2.3)$$

The original Monocycle will have a time interval of T_f between them. Thus a pulse train of the form $W_j = w(t - jT_f)$ consists of monocycle pulses spaced T_f seconds apart. The value of T_f will typically be hundred to a thousand times the monocycle width.

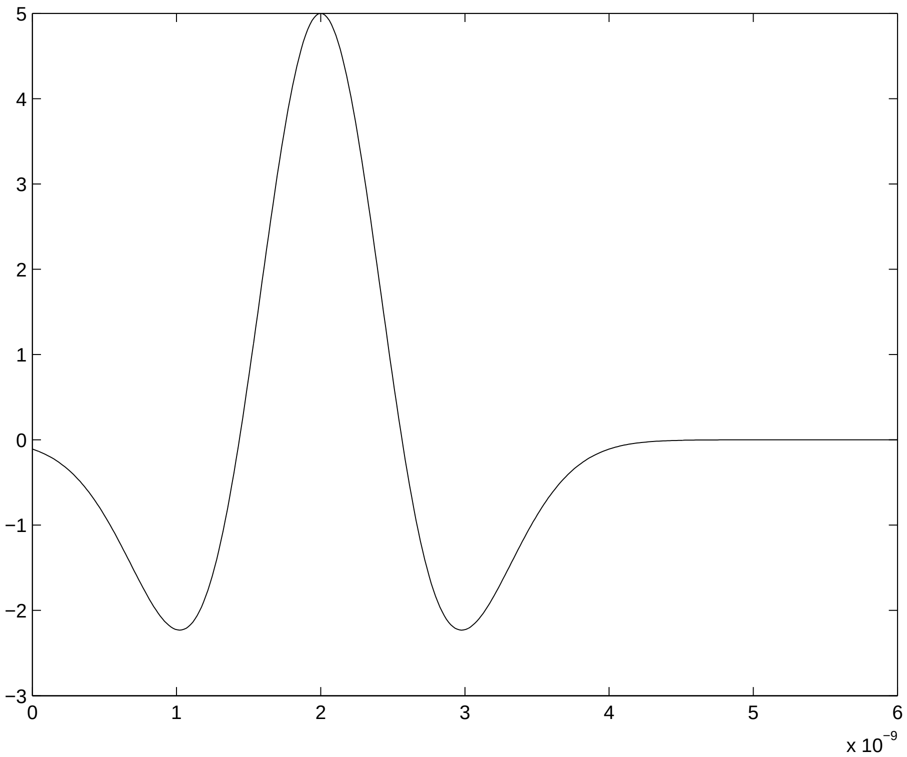

Figure 2.11: A sub nanosecond Monopulse for UWB Transmission

For multiple access systems of uniformly spaces pulses are vulnerable to catastrophic collisions.These collision can be avoided to a certain extent by incorporating a unique spreading code for each user $C_j^{(k)}$. This code is called as time hopping code. A two user case is shown in figure 2.13. These spreading codes are periodic with period Np.

The last term will is for data modulation. An additional time shift of δ is added to the pulse train if the data is 1 and no shift if the data is a 0. Figure 2.14 shows this additional data shift.

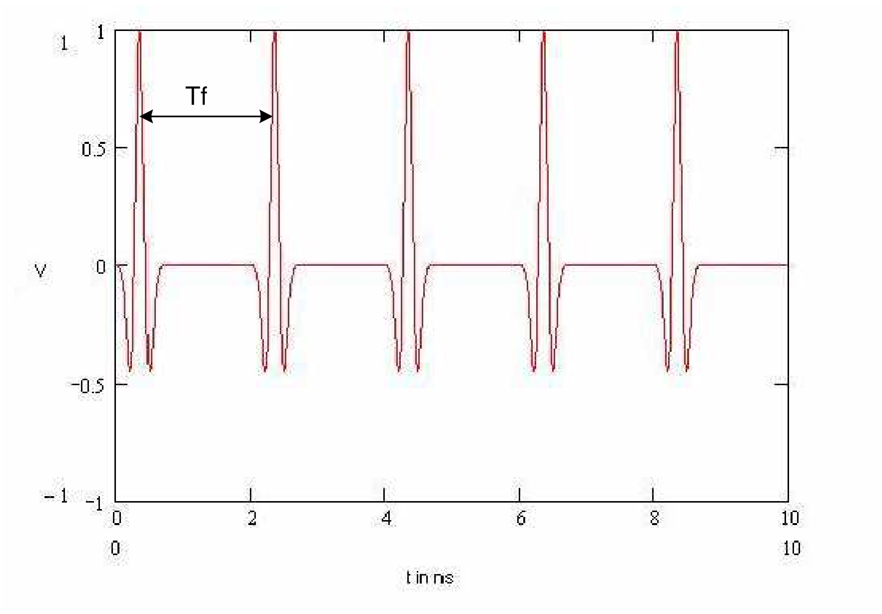

Figure 2.12: A Monocycle pulse Train with Tf pulse seperation

In the receiver side a matched filter receiver is used. The receiver can be modelled as

$$r(t) = \sum_{k=1}^{Nu} A_k.s^{(k)}(t - \tau(k)) + n(t) \tag{2.4}$$

where A_k is the attenuation of transmitter K's signal over propagation path to the receiver.$\tau(k)$ represents the asynchronism between the transmitter and the receiver. The matched filter receiver can be modelled as a single branched receiver with the template signal being the difference of the transmitted signal and a transmitted signal shifted by δ. This can be represented by the equation

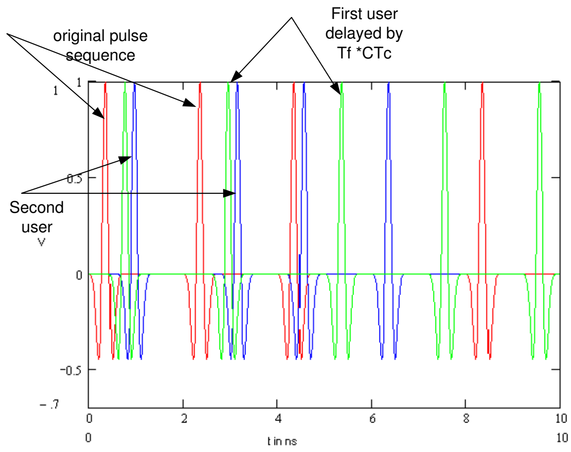

Figure 2.13: Pulse train for a two user case

$$v(t) = w(t) - w(t - \delta) \tag{2.5}$$

The decision statistic is based, on the sum of the product the template signal and the received signal over a period. The transmitted bit is one if r¿0 or else the bit was 0. Time frame of T_f of 100 nanoseconds.

2.5 Current UWB Standards

UWB has been chosen as a possible candidate for the IEEE 802.15.3a wireless networking standard for use in the indoor home environment. Many companies are participating in the standards process. There are two main

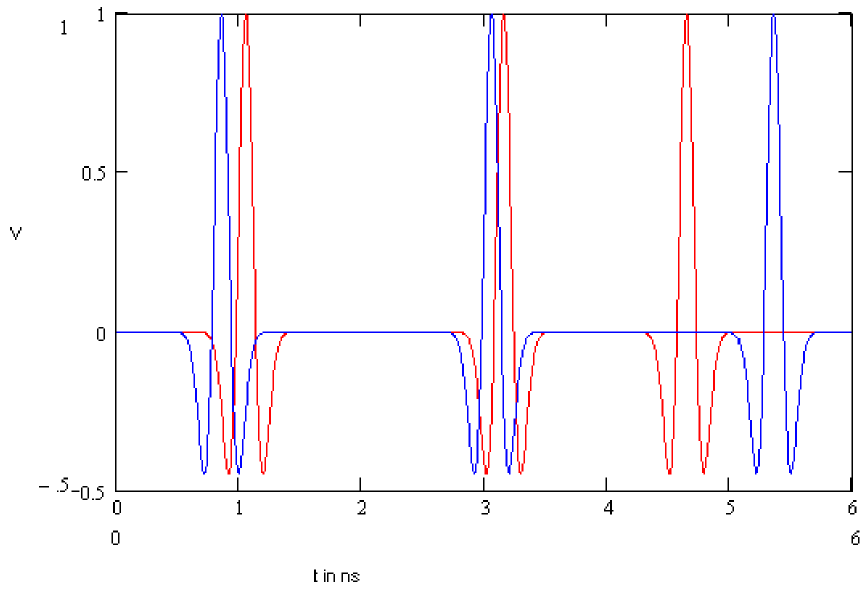

Figure 2.14: Data Modulation for the two user case

groups that have been formed. The Texas Instruments(TI) and Intel led Multi-band OFDM alliance and the motorola.

2.5.1 The Multiband OFDM Approach

Multi-carrier, multi-band systems use orthogonal frequency division multiplexing (OFDM) techniques to transmit the information on each of the sub-bands. OFDM has several nice properties, including high spectral efficiency, inherent resilience to RF interference, robustness to multi-path, and the ability to efficiently capture multi-path energy. It is also well understood

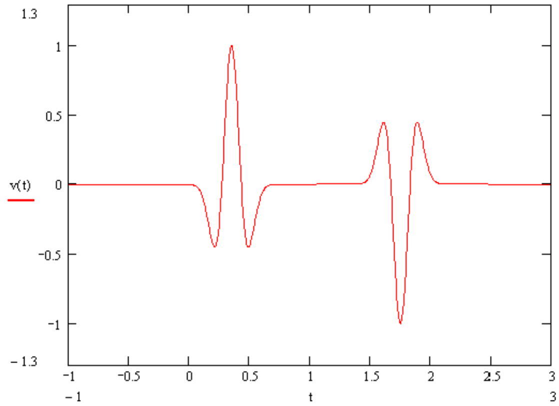

Figure 2.15: Template Signal

and has been proven in other commercial technologies (ex. IEEE 802.11a/g). The main advantages are that it is easier to collect multi-path energy using a single RF chain, relaxed switching times, insensitivity to group delay variations, and ability to deal with narrowband interference at the receiver without having to sacrifice sub-bands or data rate. The only drawback of this type of system is that the transmitter is slightly more complex because it requires an IFFT and the peak-to-average ratio may be slightly higher than that of the pulse-based multi-band approaches. The multiband OFDM divides the The multiband OFDM system divides the UWB spectrum (3.1 to 10.6 GHz) into 528-MHz-wide sub-bands and uses OFDM modulation to transmit the information in each subband. The OFDM symbols are then interleaved over three contiguous subbands across both time and frequency to provide a robust link and maximum range to support multiple access between piconets. [34] Figure 2.16 shows an example of how to divide the allocated frequency into sub-bands for OFDM. As can be seen from the figure the there is sufficient guard band

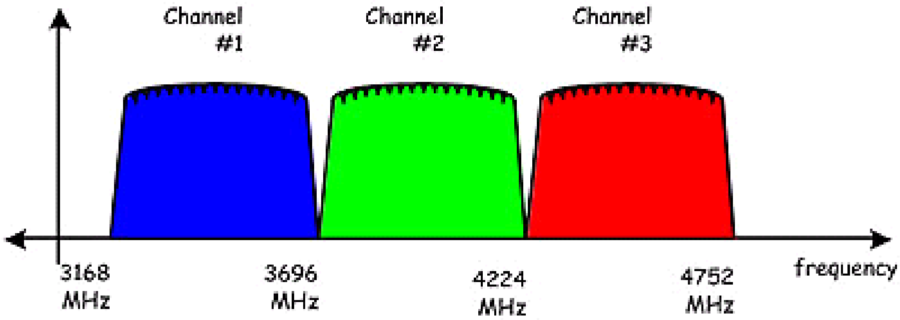

Figure 2.16: Frequency allocation for multi band OFDM [34]

on the lower side of of channel number 1 and upper side of channel 3 to simplify the pre-select filter design. It also allows the transmitter and receiver to switch to the next center frequency within the specified nanoseconds time frame. An example of how the symbols are transmitted are shown in figure 2.17 The three symbols are dispersed among the three channels respectively. The guard interval has been inserted to ensure that only a single RF transmit and RF receiver chain are needed for all channel environments and all data rates and that there is sufficient time for the transmitter and receiver to switch to the next channel. This proposal defines rates from 55 to 480Mbps and uses

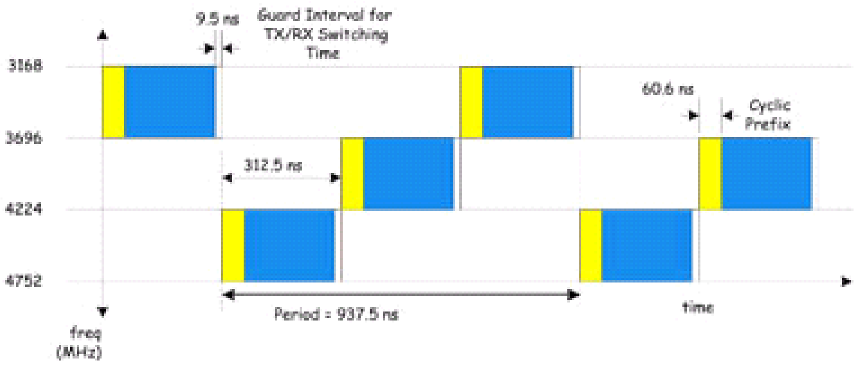

Figure 2.17: Time Frequency Interleaving for multi band OFDM
[34]

quadrature phase shift keying. An example of the block diagram of an OFDM structure is shown in figure and is similar to that of wireless OFDM physical layer except that the carrier frequency is changed on the time frequency interleaving pattern.

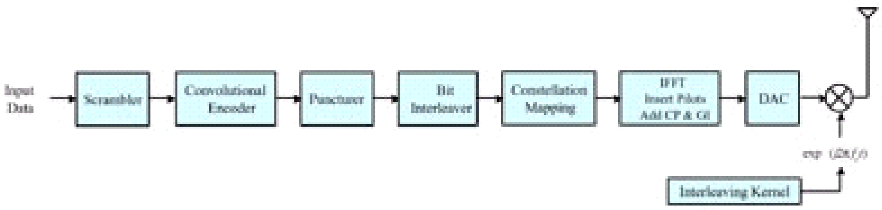

Figure 2.18: Block diagram for multiband OFDM system
[34]

2.5.2 DS-CDMA UWB Approach

The second group of companies proposed a standard based on DS-CDMA. It combines the traditional spread spectrum techniques with that of UWB. The DS CDMA group is headed by Motorola and has companies such as PulseL̃ink, Fuxura et al as its members.The group calls itself UWBFORUM.

Among the proposed approaches before the IEEE 802.15.3a standards committee, the DS-CDMA transmitted waveform is capable of serving the broadest of spectral applications.[45]. It can allow very low-cost low power transmit-only devices (even at Gbps rates) because it requires no FFT or DAC or DSP as the MBOA approach. DS-CDMA offers the highest aggregate Mbps/m2 data rates because its CDMA codes are designed from the ground up to support multi-user which in this case, means multiple overlapping un-coordinated networks like two wireless home theater systems in neighboring rooms or apartments.

The proponents of DS-CDMA claim that the a simple 2 finger RAKE DS-CDMA receiver radio performs as well as the more complex OFDM radio proposed by Texas Instruments.

The DS-CDMA transmitter consists of a simple high chip rate pulse generator and modulator. There are no FFTs, no complex window multiplies, no DACs, and no multiplicity of frequency generators or fast hopping synthesizers. It is efficient, small, low cost, easy to make with low spurious emissions and FCC compliant, and yet flexible in terms of the variety of codes it can broadcast. It can just as easily send 2-BOK as 32-BOK. It delivers the most payload-bits per consumed-watt of any transmitter by a large margin. Finally, XtremeSpectrum has implemented, tested, and proven a low complexity DS-CDMA UWB solution in working silicon.**??**

The OFDM transmitter proposed by Texas Instruments (TI) is vastly more complex by comparison. It requires an FFT engine capable of a 128 point IFFT every 312.5 ns, plus a pair of 528 Ms/s transmit DACs, plus filters for the DACs since they are operating near Nyquist, plus a fast switching frequency hopper to shift the spectrum to the hopped subband. TI requires the frequency hopper to shift and be settled to an accurate and low phase-noise state in 9.5 ns.

As the argument between the two groups goes on it looks increasingly likely that the the market will have two different standards.

CHAPTER 3

SYSTEM FORMULATION AND PERFORMANCE ANALYSIS

3.1 The UWB System

In 3.1 we present the block diagram of a UWB system over indoor channels with cross-channel interference.

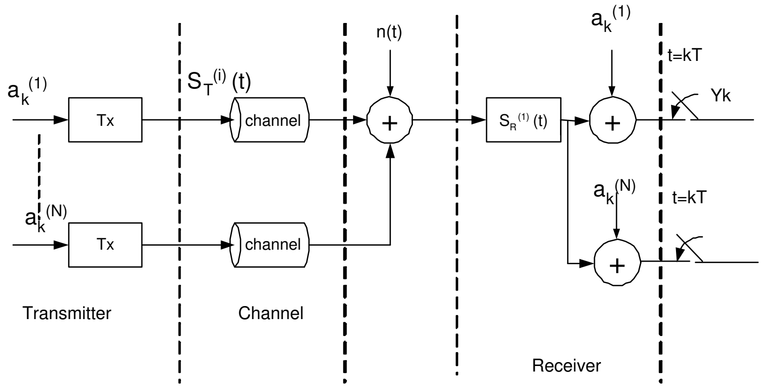

Figure 3.1: A simple Transmitter and Receiver

Let $a_k^{(i)}$ denote the message signal for the i-th user at the k-th time slot. The message signal can be binary, ie $a_k^{(i)} \varepsilon$ {0,1} or M-ary, i.e,$a_k^{(i)} \varepsilon$ {0,1. . . M-1}

. The Transmitter will select a waveform $p_{a_k^{(i)}}$(t)to transmit for a given message signal $a_k^{(i)}$. $p_{a_k^{(i)}}$(t)includes the format of signalling (either Pulse- Position Modulation(PPM) or ON-OFF keying(OOK)and the spreading code(time shift patterns for each individual user). We have the transmitted signal for user i as

$$S_T^{(i)}(t) = \sum_{k=\infty}^{-\infty} p_{a_k^{(i)}}(t - kT - \tau^{(i)}) \tag{3.1}$$

where T is the symbol duration and $\tau^{(i)}$ is the time delay. Without loss of generality we assume 0$\leq \tau^{(1)} \leq \tau^{(2)} \ldots \leq \tau^{(N)}$

Let the UWB Channel for the i^{th} user be $h^{(i)}(t)$. We then have a signal at the receiver input for the first user as

$$\gamma^{(i)}(t) = \sum_{i=1}^{N} S_T^{(i)}(t) * h^{(i)}(t) + n(t) \tag{3.2}$$

where $*$ denotes the convolution operation, n(t)denotes the Additive White Gaussian Noise (AWGN) with zero mean and double side variance of σ^2.

Let $S_R^{(t)}$(t)denote the impulse response of the first receiver. We then obtain the decision statistics of the first user at the k^{th} time interval as

$$Y_k^{(1)} = \gamma^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.3}$$

Substituting (2) into (3) we have

$$Y_k^{(1)} = A_k^{(1)} + B_k^{(1)} + N_k^{(1)} \tag{3.4}$$

where

$$A_k^{(1)} = S_T^{(1)}(t) * h^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.5}$$

$$B_k^{(1)} = \sum_{i=2}^{N} S_T^{(i)}(t) * h^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.6}$$

$$N_R^{(1)} = n(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.7}$$

Substituting (1) into 5-7 we obtain

$$A_k^{(1)} = C_k^{(1)} + D_k^{(1)} \tag{3.8}$$

where $C_k^{(1)}$is the desired signal.

$$C_k^{(1)} = p_{a_k^{(1)}}(t - kT) * h^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.9}$$

$D_R^{(1)}$ is the inter-symbol interference signal and

$$D_k^{(1)} = \sum_{j=-\infty}^{\infty} p_{a_j^{(1)}}(t - jT) * h^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.10}$$

$B_k^{(1)}$ is the multiuser interference and

$$B_k^{(1)} = \sum_{i=2}^{N} \sum_{j=-\infty}^{\infty} p_{a_j^{(i)}}(t - jT - \tau^{(i)}) * h^{(1)}(t) * S_R^{(1)}(t) \mid_{t=kT} \tag{3.11}$$

$N_R^{(1)}$ is the noise term with zero mean and variance

$$V_{N_R^{(1)}} = E[N_R^{(1)}.(N_R^{(1)})^*] = \sigma^2. \int_{-\infty}^{\infty} |S_R^{(1)}|^2 dt \tag{3.12}$$

where E[.] denotes average, the superscript $*$ denotes complex conjugate.

Thus the lait energy to noise power ratio is

$$E_b/N_o = \frac{E[|p_{a_k}^{(1)}|^2]}{V_{N_R^{(1)}}} \tag{3.13}$$

and

$$E[|p_{a_k}^{(1)}|^2] = \frac{1}{M} \sum_{j=0}^{M-1} \int_{-\infty}^{\infty} |p_j(t)|^2 dt \tag{3.14}$$

Now let us study a few simple cases,namely single transmitter/reciever with OOK and single transmitter/reciever with PPM.

3.2 A Single Transmitter/Reciever with OOK

This is the simplest case. The block diagram of the UWB system is reduced to that in 3.2

$a_k^{(1)}$ is binary i.e. $a_k^{(1)} \varepsilon$ {0,1}. If $a_k^{(1)} = 1$, then the transmitter sends $p_1(t)$. The waveform $p_1(t)$can be selected to optimize the system performance. In this section we consider 3 types of waveforms illustrated in fig 3.

The impulse response of the channel is modelled by the equation

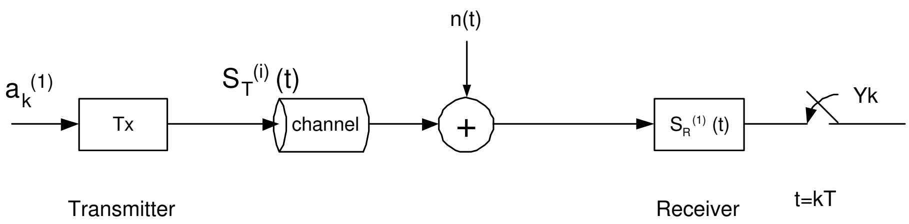

Figure 3.2: Single Transmitter UWB system

$$h(t) = 0.9.p(t).e^{i\theta} + .23.p(t - 3.33.10^{-8}).e^{i\theta} + .3.p(t - 4.58.10^{-8}).e^{i\theta} + .2.p(t - 1.67.10^{-8}).e^{i\theta} \quad (3.15)$$

where p(t)is the monopulse that is transmitted.

The pulse is the convolution of the input signal with the impulse response of the channel.

$$p_{1b}(t) = 2\sqrt{e}A(t - t_s)f_c\pi e^{-2[\pi(t-t_s)]^2} \quad (3.16)$$

The next pulse can be expressed as

$$p_{1c}(t) = [1 - 4\pi(\frac{t - .35}{\tau_m})^2]e^{2\pi[\frac{(t-.35)}{\tau_m})^2]} \quad (3.17)$$

Using $p_{1b}(t)$ as example for a given sequence of the message signal 0100010 we have the transmitted signal illustrated in Fig 3.

This transmitted signal $S_T^{(1)}(t)$is then added with a Gaussian noise n(t)and then fed into the receiver. Fig 4 illustrates the noise corrupted OOK signal.

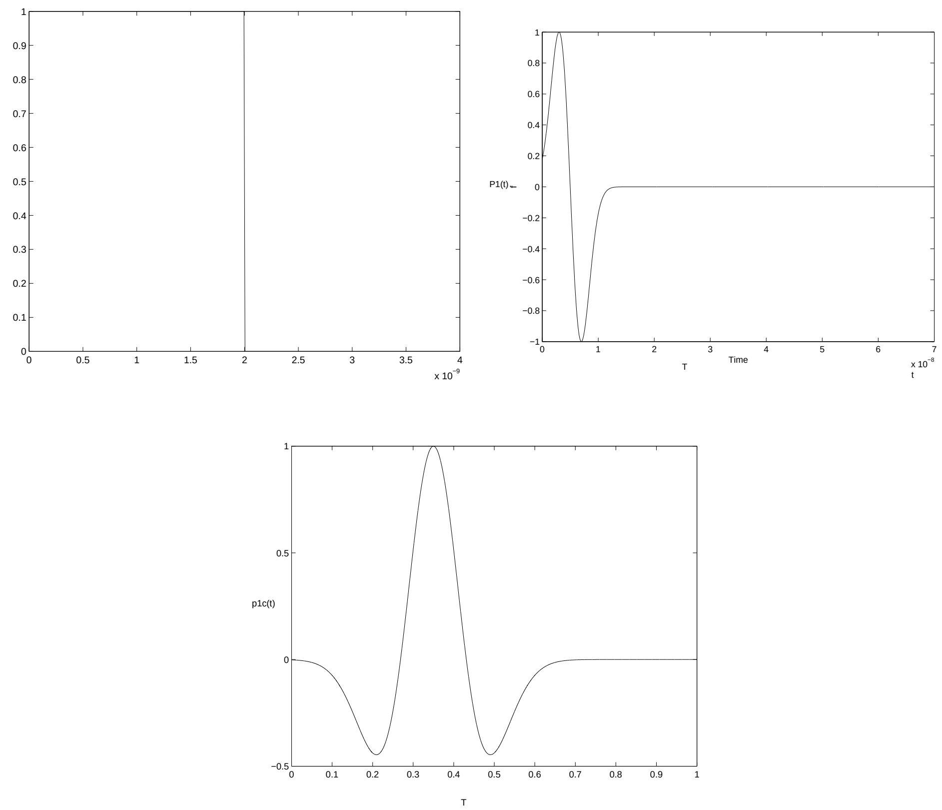

Figure 3.3: Different pulse waveform for studying OOK signals

The impulse response of the receiver is p(T-t). Thus, for an input signal p(t) without noise we have the output signal as

$$p(t) * p(T - t) = \int_{-\infty}^{\infty} p(\tau) \cdot p(t - T + \tau) d\tau \tag{3.18}$$

At t=T the matched filter reaches maximum output. That is we sample at t=T to get the maximum signal to noise ratio. If the impulse response is

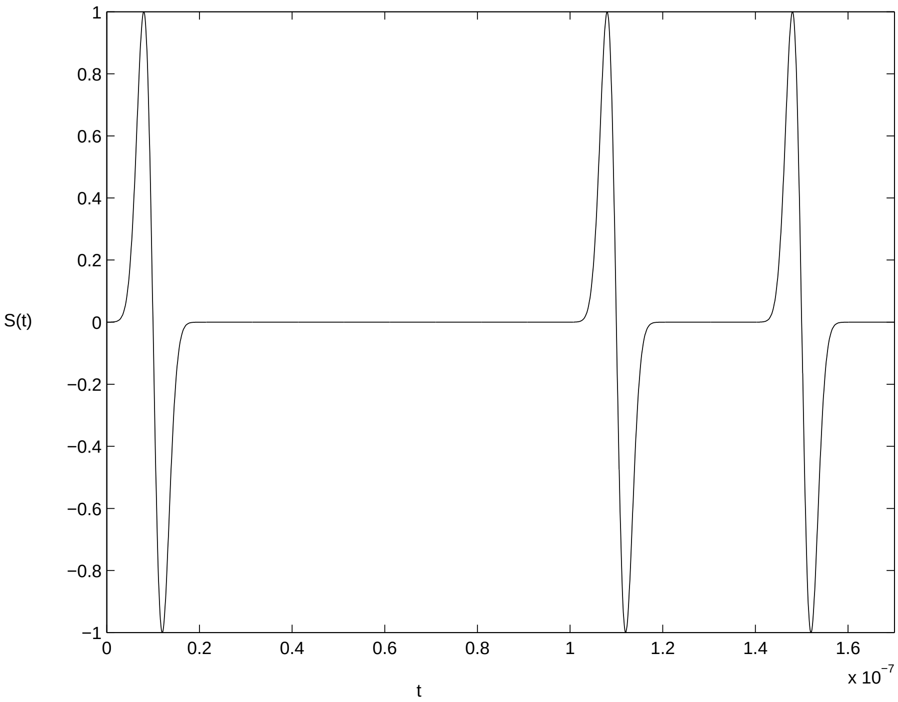

Figure 3.4: A Transmitted signal sample for OOK Signalling

p(-t)then the output signal in (17) becomes

$$p(t) * p(-t) = \int_{-\infty}^{\infty} p(\tau) \cdot p(t + \tau) d\tau \qquad (3.19)$$

At t=0, the matched filter receiver reaches the maximum output. In the following section, we will take p(-t) as the impulse response of the receiver. Thus, the decision statistics of the first user at time slot k can be obtained by sampling $\gamma(t) * S_R(t)$, ie in equation (3).

Therefore, for the optimal receiver (i.e, the matched filter receiver) we

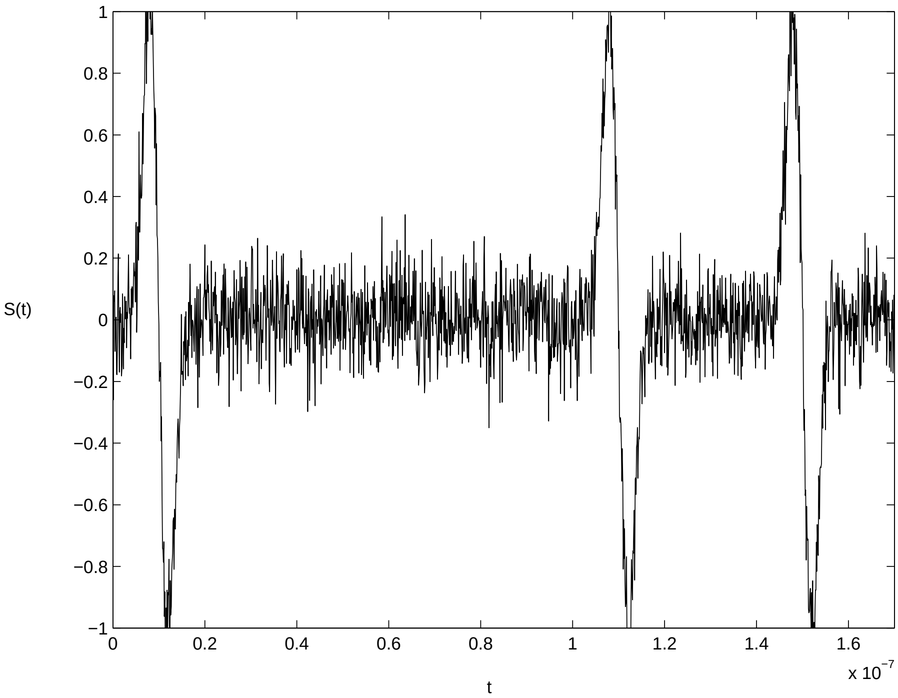

Figure 3.5: A noise corrupted OOK signal

have $S_R^{(1)}(t) = p_1(-t)$. The decision statistics

$$Y_k^{(1)} = \sum_{j=-\infty}^{\infty} p_{a_j^{(i)}}(t - jT) * p_1(-t + kT) + n(t) * p_1(-t + kT) \mid_{t=kT} \quad (3.20)$$

If the pulse waveforms are time limited to T then we have

$$Y_k^{(1)} = p_{a_j^{(i)}}(t - kT) * p_1(-t + kT) + n(t) * p_1(-t + kT) \mid_{t=kT} \quad (3.21)$$

which results in no intersymbol interference. Furthermore if $a_k^{(1)}$=0, we have

$$Y_k^{(1)} = n(t) * p_1(t - kT) \quad (3.22)$$

which contains only the noise term.

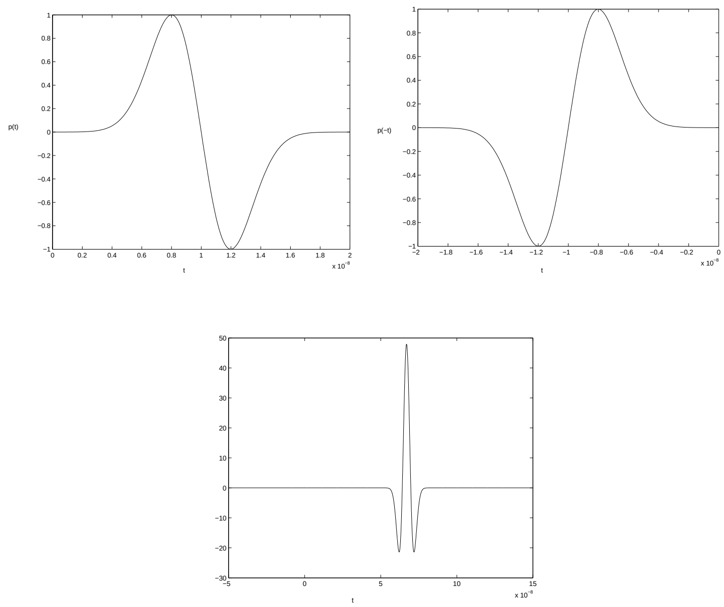

Figure 3.6: Convolution operation for p(t)∗ p(T-t)

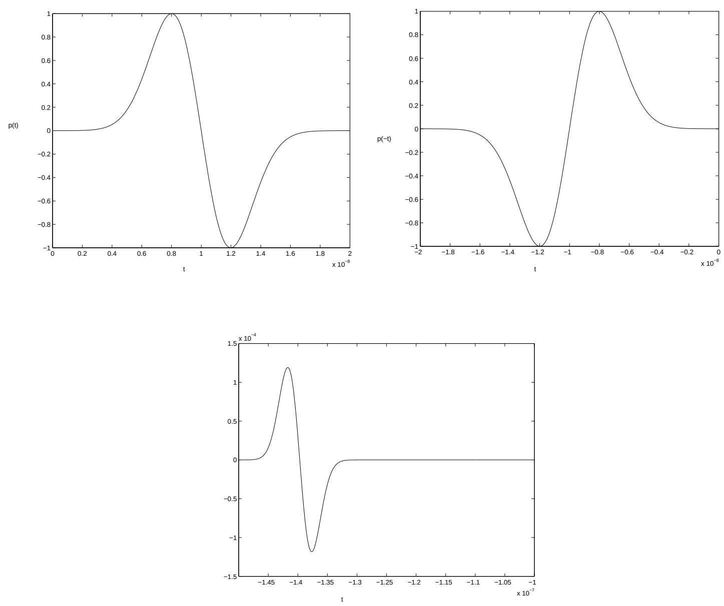

Figure 3.7: Convolution operation for p(t)∗ p(-t)

If $a_k^{(1)} = 1$ we have

$$Y_k^{(1)} = p_1(t - kT) * p_1(-\gamma t + kT) + n(t) * p_1(-t + kT) \mid_{t=kT} \quad (3.23)$$

The optimal decision rule is

$$Y_k^{(1)} >_{a_k^{(1)}=0}^{a_k^{=1}} \frac{1}{2} p_1(t - kT) * p_1(\gamma t + kT) \mid_{t=kT} \quad (3.24)$$

That is if $Y_k^{(1)} > \frac{1}{2} p_1(t - kT) * p_1(\gamma t + kT) \mid_{t=kT}$, then we make the decision $a_k^{(1)} = 1$, else we make the decision $a_k^{(1)} = 0$.

The average energy per bit for equi probable input is

$$E_b = \frac{1}{2} \int_0^T p_1^2(t)dt = \frac{1}{2} p_1(t - kT) * p_1(-t + kT) \quad (3.25)$$

The noise variance in (21) and (22) is

$$Var = \sigma^2 \int_0^T p_1^2(t)dt = 2\sigma^2 E_b \quad (3.26)$$

In Fig 7 we plot the PDF of the decision statistics for $a_k^{(1)} = 0$ and $a_k^{(1)} = 1$ (i.e equation (21) and (22))

The PDF can be expressed as

$$f_y^{(x)} = \frac{1}{\sqrt{2\pi}\sigma_x} exp(-\frac{X^2}{2\sigma_x^2}) \quad (3.27)$$

where $\sigma_x^2 = 2\sigma^2 E_b = N_0 E_b$

The error probability is then

$$P(e|input\ 0) = \int_{E_b}^{\infty} f_y(x)dx = Q(\frac{E_b}{\sigma_x}) = Q(\frac{E_b}{\sqrt{2\sigma_0^2 E_b}}) = Q(\sqrt{\frac{E_b}{N_0}}) \qquad (3.28)$$

The overall error probability is then

$$P(e) = Q(\sqrt{\frac{E_b}{N_0}}) \qquad (3.29)$$

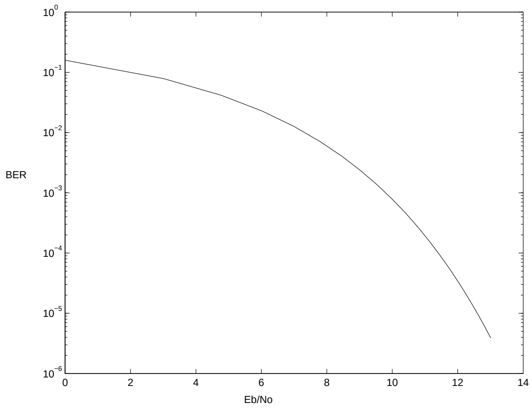

Figure 3.8: BER Versus E_b/N_0

3.3 A Single Transmitter Receiver with PPM

While in the previous section we used On- OFF Keying in this section we use Pulse Position Modulation(PPM).

Figure 3.9 shows a simple PPM Transmitter/Reciever for a single user. $a_k^{(1)}$ is binary i.e $a_k^1 \epsilon = \{0, 1\}$. If $a_k = 0$ then the transmitter sends $p_1(t)$. The waveform $p_1(t)$ has been described in the previous section. If $a_k = 1$ then the

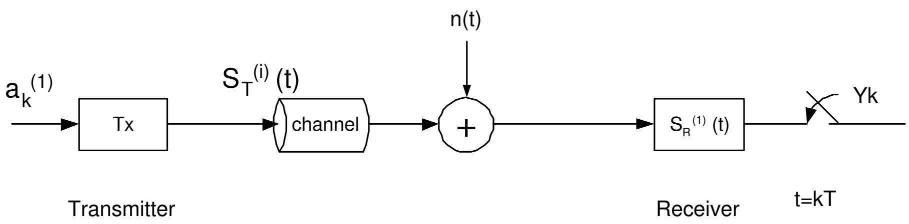

Figure 3.9: A simple Transmitter and Receiver with PPM

transmitter send $p_1(t-\delta)$. This signal is then passed through the channel and the impulse response of the channel is given by equation 3.15 where p(t) is the monopulse that is transmitted. The channel output is the convolution of the impulse response and the monopulse. The trasnmitted signal $S_T^{(1)}$ is then added with AWGN Noise.

The receiver signal is $p(-t) - p(-t + kT - \delta)$ For an input signal p(t) without noise the decision criterion as

$$r_0 = \int_0^T p(t)[p(t) - p(t-\delta)] = \int_0^T p^2(t) + \int_0^T R(\delta)r_1 = \tag{3.30}$$

$$r_1 = \int_0^T p(t-\delta)[p(t) - p(t-\delta)] = \int_0^T -p^2(t) - \int_0^T R(\delta) \tag{3.31}$$

where $r(\tau)$ is the autocorrelation function of w(t)

$$R(\tau) = \int_{-\infty}^{\infty} p(t)p(t-\delta) \tag{3.32}$$

The average bit energy for PPM signals is

$$E_b = \int_0^T w^2(t)dt \tag{3.33}$$

In the presence of noise we can express the decision criteria $r_0 and r_1$ as

$$r_0 = E_b - \Gamma + N \tag{3.34}$$

$$r_1 = -E_b - \Gamma + N \tag{3.35}$$

where N is the AWGN with variance $N_0/2$ and γ is expressed as

$$\Gamma = \frac{\int_0^T R(\delta)dt}{E_b} \tag{3.36}$$

The decision is "0" if r¡0 and if r¿1 then the decision is "1". With the threshold being zero we can express the error probability as

$$P(e) = \frac{1}{2}P(r = 1|0) + \frac{1}{2}P(r = 0|1) \tag{3.37}$$

$$P(e) = \frac{1}{2}\int_{-\infty}^{0} \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{\frac{(-x-E_b+\Gamma)^2}{2\sigma_n^2}} dx + \frac{1}{2}\int_{0}^{\infty} \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{\frac{(-x-E_b+\Gamma)^2}{2\sigma_n^2}} dx \frac{1}{2}P(r = 0|1) \tag{3.38}$$

$$P(e) = \frac{1}{2}Q(\sqrt{\frac{(1-\Gamma)E_b}{N_0}}) + \frac{1}{2}Q(\sqrt{\frac{(1-\Gamma)E_b}{N_0}}) \tag{3.39}$$

which gives the probability of error for a UWB system using PPM as

$$Q(\sqrt{\frac{(1-\Gamma)E_b}{N_0}}) \tag{3.40}$$

CHAPTER 4

SUB-OPTIMAL RECEIVER ANALYSIS

4.1 Various Sub-optimal Receivers

A UWB system is primarily used in the indoor environment. Hence the signal encounters a dense multi-path. Typically a received sub-nanosecond pulse is different from the transmitted one. The received pulse has a long tail4.1.

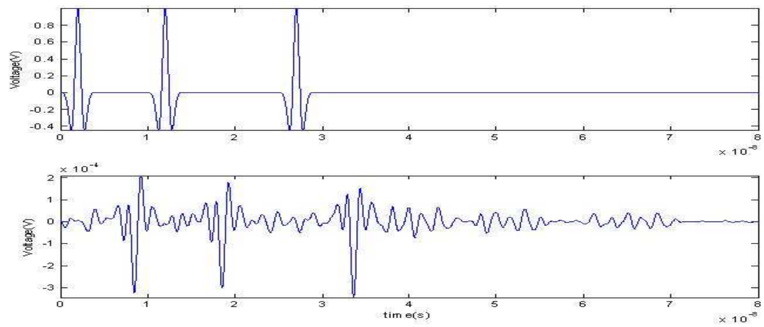

Figure 4.1: A transmitted and received UWB pulse

This can be explained from the channel impulse response $h_r(t)$. Ideally

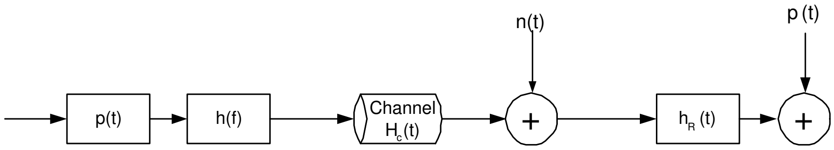

Figure 4.2: A typical matched filter System

we would want a flat response over the entire bandwidth but this virtually impossible for the Giga Hertz range. The impulse response of the channel is typically flat over a few Khz. For a 1Mhz bandwidth the impulse response will generally have 3 peaks which results in a 3 finger receiver. When this is expanded to the Giga Hertz range there will be around 100 such peaks. A suitable receiver for the system will then have around 60 to 80 fingers for the optimal RAKE receiver.

Also in the transmitter side the amplifier that is designed is not perfect. The antenna required to transmit ideally would require a flat antenna over the Giga hertz range. Lot of research is concentrated in this area. At the receiver too there is an imperfect antenna and an imperfect amplifier. The optimal receiver then boils down to the design of the pulse $p_r(t)$. For a matched filter

$$h_r(t) * p_r(t) = p(t) * h_T(t) * h_c(t) \tag{4.1}$$

The optimal receiver will not work as a result. If we do not know the channel impulse response we use the sub-optimal receiver. Current real systems using UWB use sub optimal receivers. This chapter discusses various simple sub-optimal UWB receivers to be used in UWB. Bit Error Rate curves are plotted for each case and a comparison is done.

4.1.1 The Auto correlation Receiver

For this system the transmitter sends the pulse out twice. The receiver uses the first pulse as a reference and the second pulse for the actual data. If a "0" is transmitted only the reference pulse is transmitted and if a "1" is transmitted both pulses are transmitted.

Such a receiver is called an auto correlation receiver. Let $s_1(t)$ and $s_2(t)$ denote the first and second transmitted pulses. Then

$$s_1(t) = ((t)*h_T(t)*h_c(t)+n1(t)ands_2(t) = a_0(p(t)*h_T(t)*h_c(t)+n1(t)) \quad (4.2)$$

The received signal can be expressed as

$$r_1(t) = s_1(t) * h_r(T)r_2(t) = s_2(t) * h_r(T) \quad (4.3)$$

In the simple case where $h_T(t) = h_c(t) = h_R(t) = \delta(t)$ we then get

$$r_1(t) = p(t) + n_1(t)andr_2(t) = a_0p(t) + n_2(t) \quad (4.4)$$

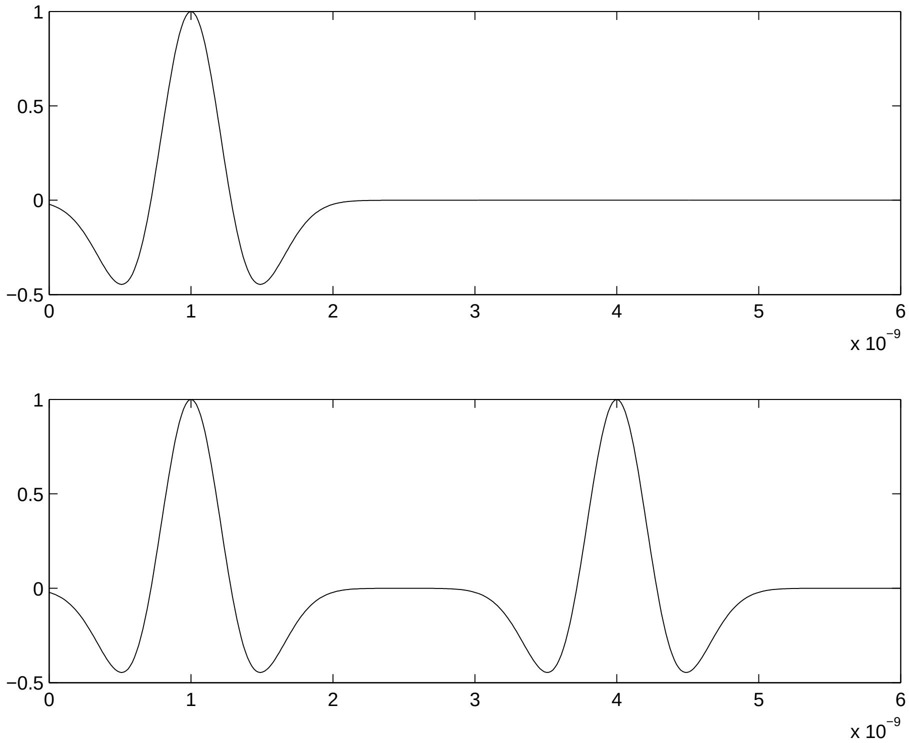

Figure 4.3: Transmitted pulses for Auto Correlation Receiver

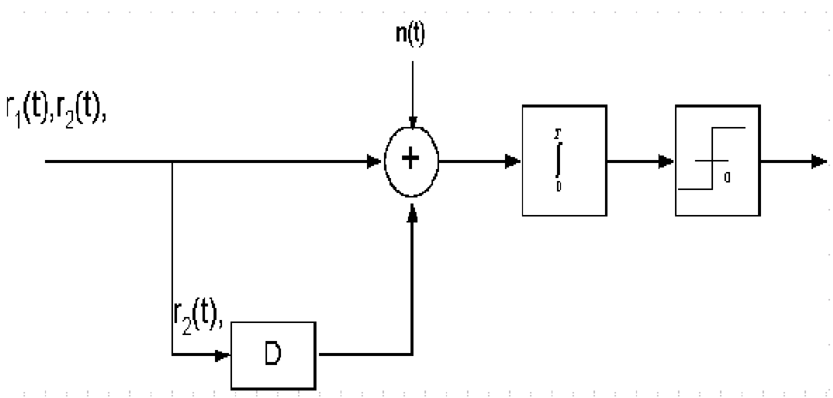

Figure 4.4: Auto Correlation receiver Implementation

The decision statistics is then

$$Y = \int_0^T r_1(t)r_2(t) = \int_0^T a_0 p(t)^2 dt + \int_0^T n_1(t)p(t)dt + \int_0^T n_2(t)p(t)dt + n1(t)n2(t) \tag{4.5}$$

The energy of the pulse is the sum of the energies of the first two pulses, ie

$$E_b = E_{firstpulse} + E_{secondpulse} \tag{4.6}$$

From 4.5 we can see that the noise power doubles with the same amount of signal power. This results in an SNR loss of 3dB. If we use a_0 as ± 1, then the signal power doubles. This is $E_b = 2\int_0^T p^2(t)dt$. The bit error rate in this case is then

$$BER_{highSNR} = Q(\sqrt{\frac{E_b}{2N_o}}) \tag{4.7}$$

which results in a 6dB loss. In the case of OOK we have

$$E_b = E_{pulse} + 0.5E_{pulse} = 1.5E_{pulse} = 1.5\int_0^T p^2(t)dt = 3E_{book} \tag{4.8}$$

This gives a probability of error as

$$p(e) = Q(\sqrt{\frac{Eb}{3N_0}})) \tag{4.9}$$

In the case of PPM we have

$$E_b = E_{pulse1} + E_{pulse} = 2E_{bPPM} \tag{4.10}$$

For the non overlapping case the probability of error can b expressed as

$$p(e) = Q(\sqrt{\frac{Eb}{2N0}}) \tag{4.11}$$

The OOK system will result in a 7.7dB loss. The OOK system is suitable for high power communications like in radar communications where a 7.7dB loss can be tolerated, where as conventional communication systems cannot sustain this high loss.

4.1.2 The Energy Detector

The second type of sub-optimal detector is the energy detector. This is used in the second standard for UWB. In this case we a no pulse for a "0" and a pulse for a "1". At the receiver side the energy is measured inside the bit duration. The optimal detector for the energy detector can be based on the following equations. Let r(t) be the received signal and p(t) be the transmitted pulse. The decision statistic for a matched filter is

$$Y = \int_0^T r(t)p(t) = \int_0^T (p(t) + n(t))p(t)dt \tag{4.12}$$

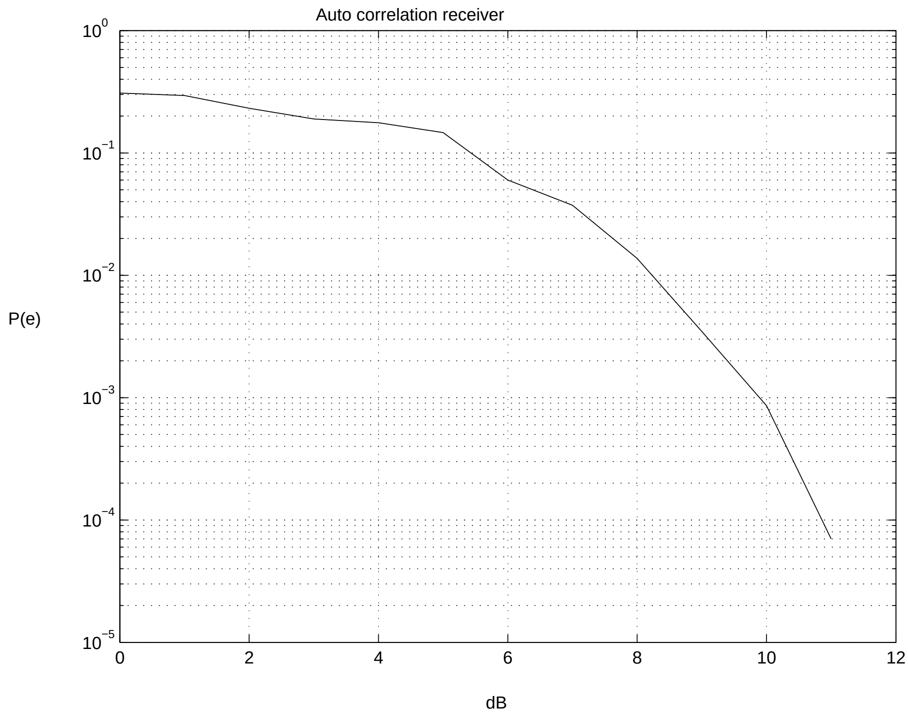

Figure 4.5: BER for an auto correlation reciever

For the energy detector we do not have a receiver waveform. The received pulsed is squared to get the decision statistics.

$$Y = \int_0^T r^2(t) = \int_0^T (p(t) + n(t))(p(t) + n(t))dt = \tag{4.13}$$

$$\int_0^T p^2(t)dt + \int_0^T p(t)n_1(t) + \int_0^T p(t)n_2(t) + \int_0^T n_1 n_2 \tag{4.14}$$

If T is long enough the sum of the product of n1 and n2 will be zero. Also it can be seen that the noise power is doubled. So the probability of error will be

$$P(e) = Q(sqrtE_b/N0) \tag{4.15}$$

The energy detector is better than the auto correlation receiver. For the UWB communication system energy detector is preferred.

4.1.3 Square Value Detector

The square value sub-optimal detector is obtained by using the received signal itself as the template signal.

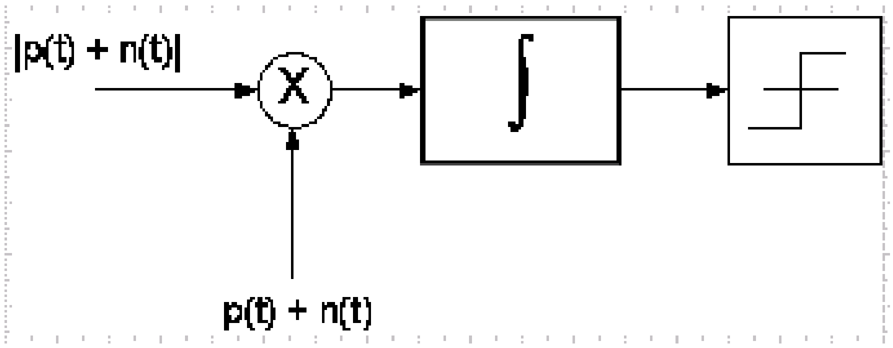

Figure 4.6: Square value sub-optimal detector

If p(t) is the transmitted pulse then the signal received at the matched filter receiver will be

$$r(t) = p(t) * h_c(t) + n(t) \tag{4.16}$$

If this received signal is used as the template signal then we get the decision statistic as

$$Y = \int_0^T (p(t) + n(t))^2 dt \tag{4.17}$$

$$= \int_0^T p^2(t)dt + 2\int_0^T p(t)n(t) + \int_0^T n^2(t)dt \tag{4.18}$$

The last term in equation 4.1.3causes a noise term to double which results in a 3dB loss. The bit error curve for such a detector using OOK is shown in figure 4.7

4.1.4 The Absolute Value Detector

Another sub optimal detector is the absolute value detector. Figure**??** shows the transmitter/ receiver for such a system. Here the decision statistics is based on the absolute value of the received signal.

If p(t) is the transmitted pulse then the signal received at the matched filter receiver will be

$$r(t) = p(t) * h_c(t) + n(t) \tag{4.19}$$

The template signal is then —r(t)—. Based on this the decision statistics

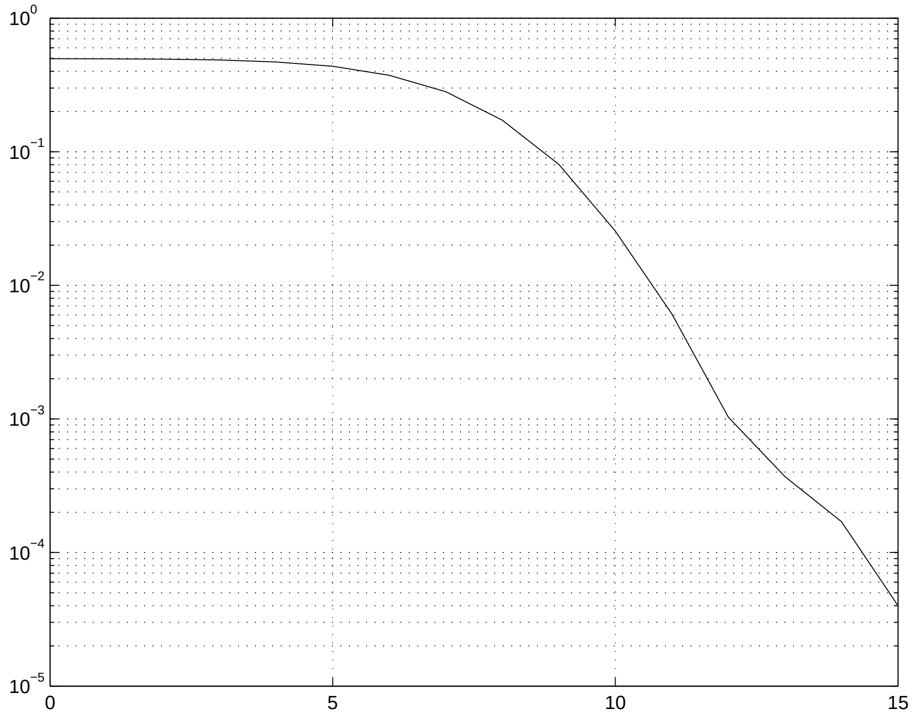

Figure 4.7: BER curve for square value detector

$$Y = \int_0^T |p(t)|dt + \int_0^T |n(t)|dt \tag{4.20}$$

Based on equation 4.1.4 we can see that the noise parameter is half of that of the square value detector. This results in considerable increase in performance. The BER curve is plotted for the absolute value detector.

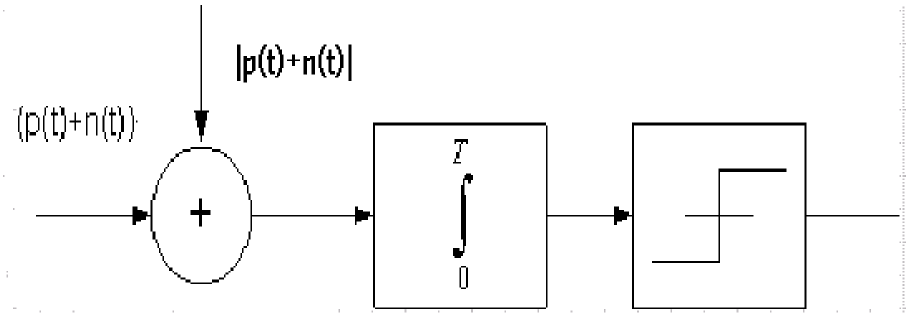

Figure 4.8: The absolute value detector system

4.2 Performance analysis with UWB channel

In this section performance analysis curves are plotted on a UWB channel. The channel is simulated based on [37]. The bandwidth of the channel is 1.25Ghz.

Figure4.10 shows a simulated UWB channel. It has 400 points of single sided spectrum. The bandwidth of the pulse was adjusted to match that of the channel. The single sided spectrum of the pulse before and after passing through the channel is shown in figure.

The full sided spectrum of the pulse and the channel is shown in

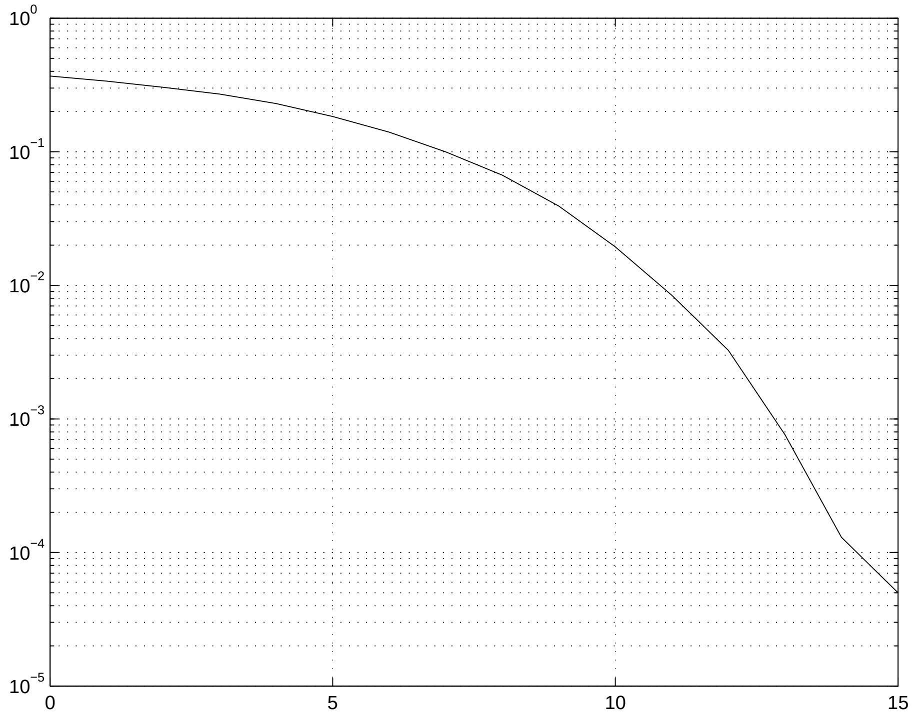

Figure 4.9: BER for absolute value detector

figure4.12 and the signal after passing through is shown in figure 4.13.For simulation purposes 20 samples of the channel were averaged.

4.3 The Optimal Pulse

Pulse waveform optimization techniques were discussed in [44]. The pulses were simulated for a PPM system on Gaussian and dense multi path channels which minimize the BER for a given modulation index.For the same modulation index the optimal pulses can improve performance by 0.4-0.7db. When the modulation index is large the shape of the pulse can be approximated

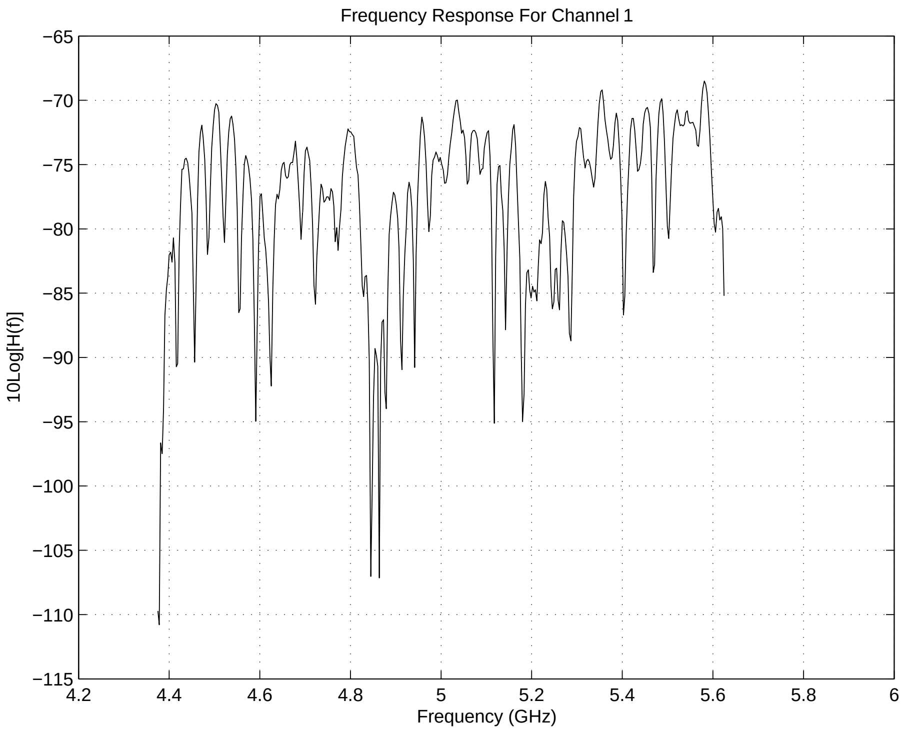

Figure 4.10: UWB Channel

to a Gaussian function. The Gaussian function is

$$g(t) = \frac{1}{\sqrt{2\pi\sigma}} exp \frac{-t^2}{2\sigma^2} - a \qquad (4.21)$$

The optimal pulse waveform is chosen as a half sine waveform.

We can approximate the optimal waveform by generating g(t) first, then multiplying g(t) by a sine function, as shown in Fig 4.15. Comparison of PSDs of the optimal and the approximated waveform are shown in figure4.16. The optimal pulse for a modulation index of $\frac{1}{20}$ is shown in figure 4.17.

This pulse is used for various receivers discussed above. The results are

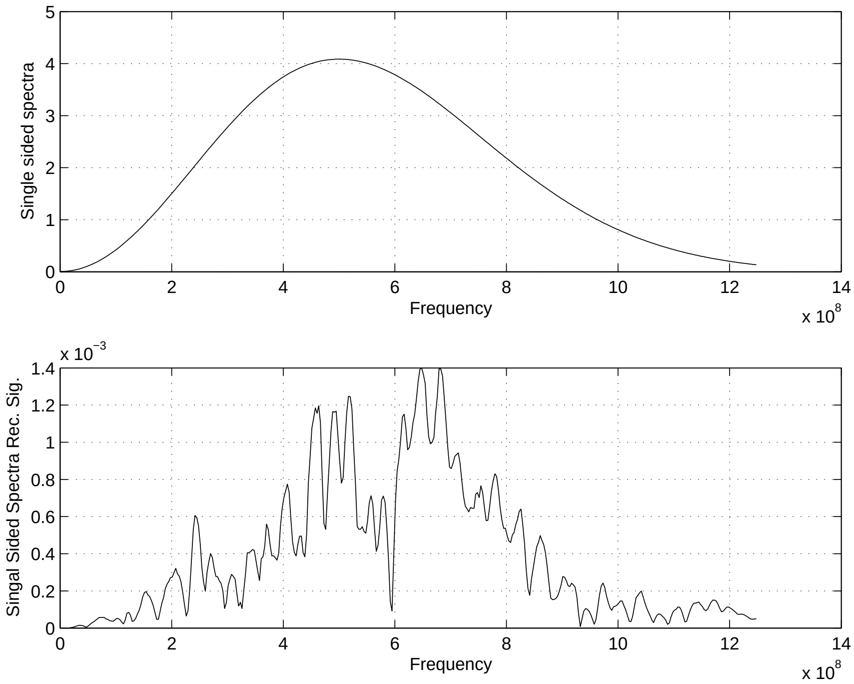

Figure 4.11: Spectrum of pulse before and after channel

discussed in the next section.

4.4 Comparison Of BER curves with various receivers

In this section a comparison is done study is done with all the receivers discussed above. All the curves plotted had a pulse width of 4nanoseconds. In the case where the channel was used width was 3.2nanoseconds to match the channel parameters. Figure 4.18 shows BER curves for the Square,Absolute, Optimal and the measured receiver. Here all the receivers use OOK except

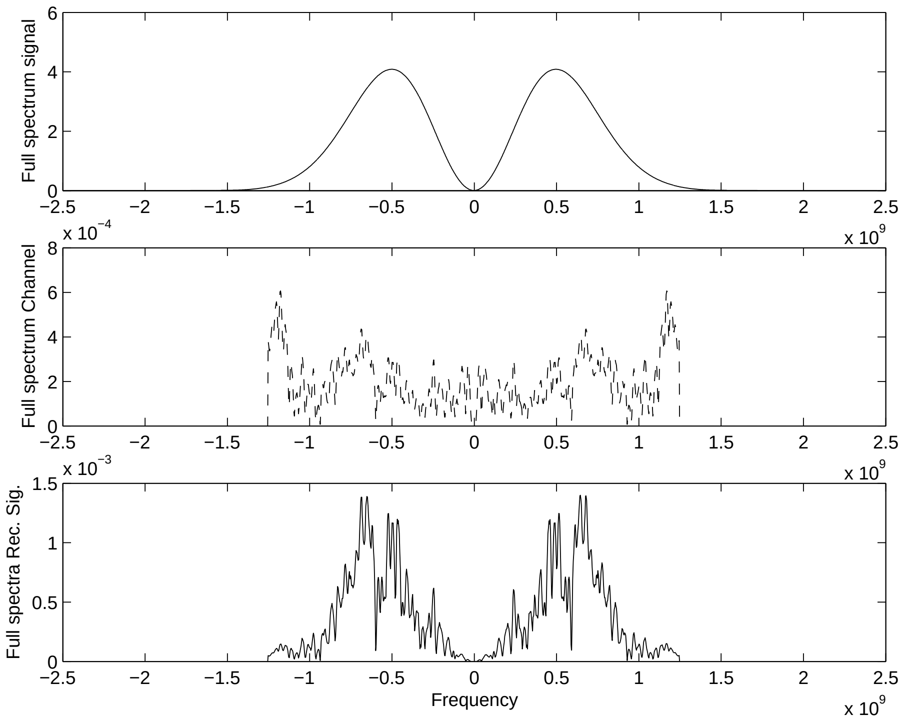

Figure 4.12: Full Spectrum of pulse before and after channel

the PPM. The measured and the absolute receiver have almost identical performance. The Square receiver is the worst at low SNR. At high SNR the it tends to have a slight advantage over the absolute receiver. This is due noise getting doubled.

Figure 4.19 shows a comparison of all receivers with the UWB channel. Figure 4.20 refers to a comparison of BER curves for receivers using the optimal pulse. Here too the absolute value detector gives the best performance when compared to the other sub-optimal receivers.

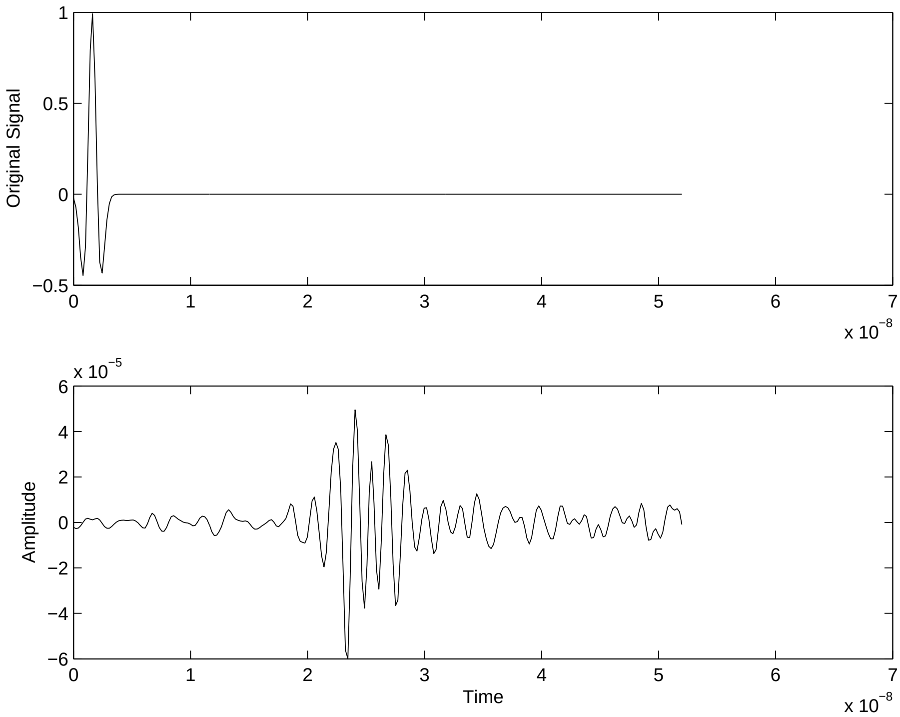

Figure 4.13: Signal in time

These simulations show that the absolute value detector gives the best performance of all the sub-optimal receivers.

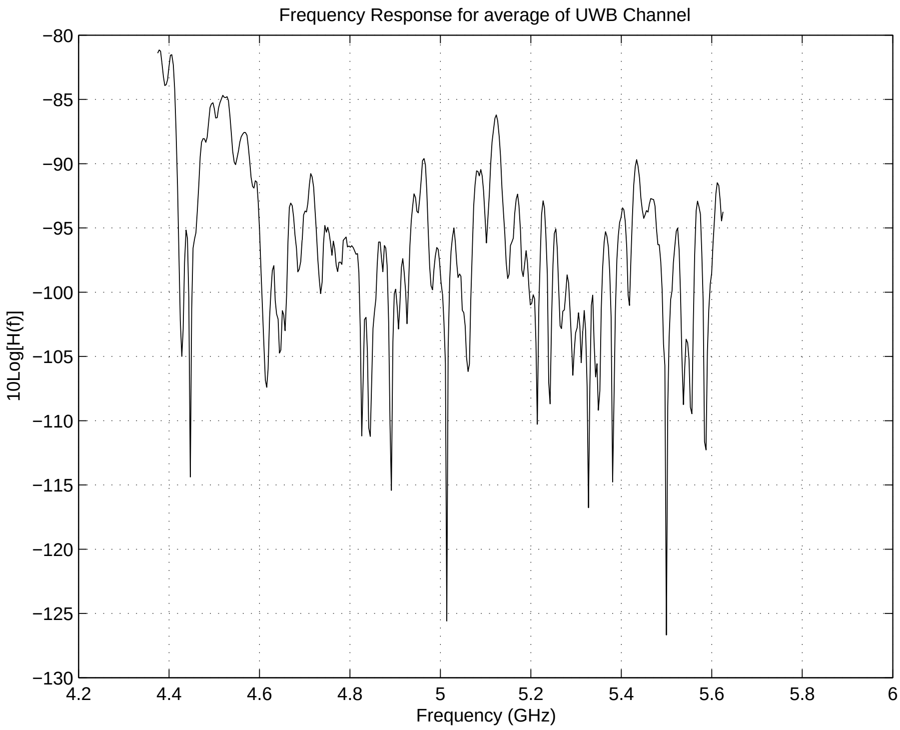

Figure 4.14: Average of channel

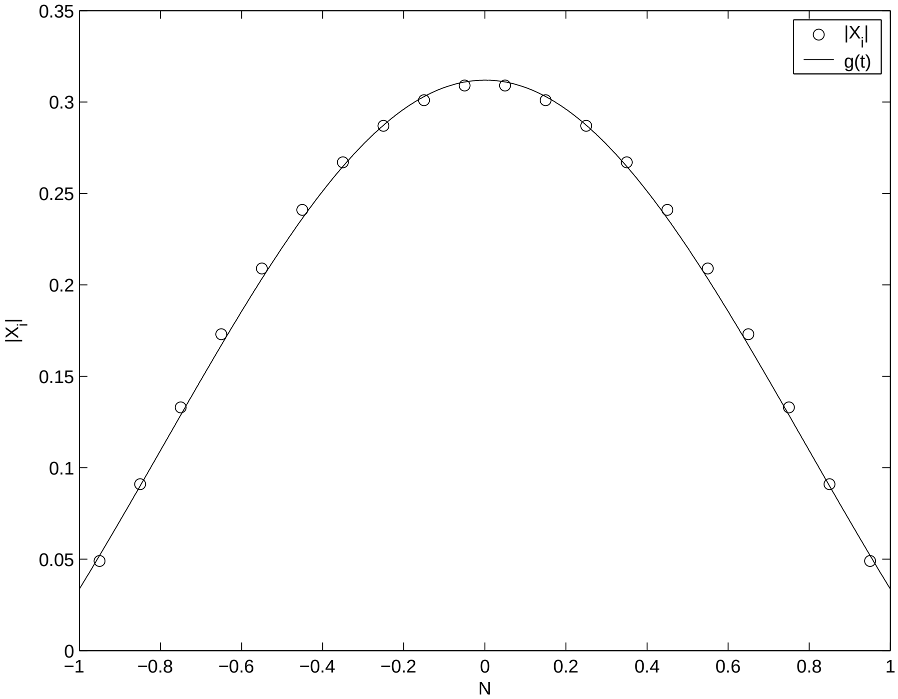

Figure 4.15: Comparison of approximated and gaussian curve

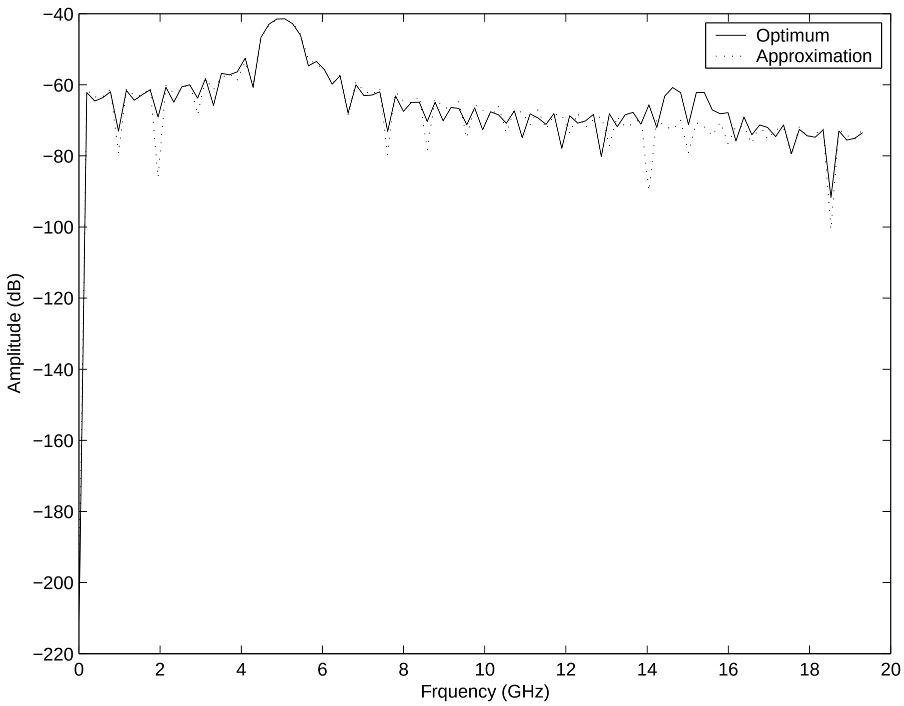

Figure 4.16: Comparison of power spectral densities of optimal and approximated waveform

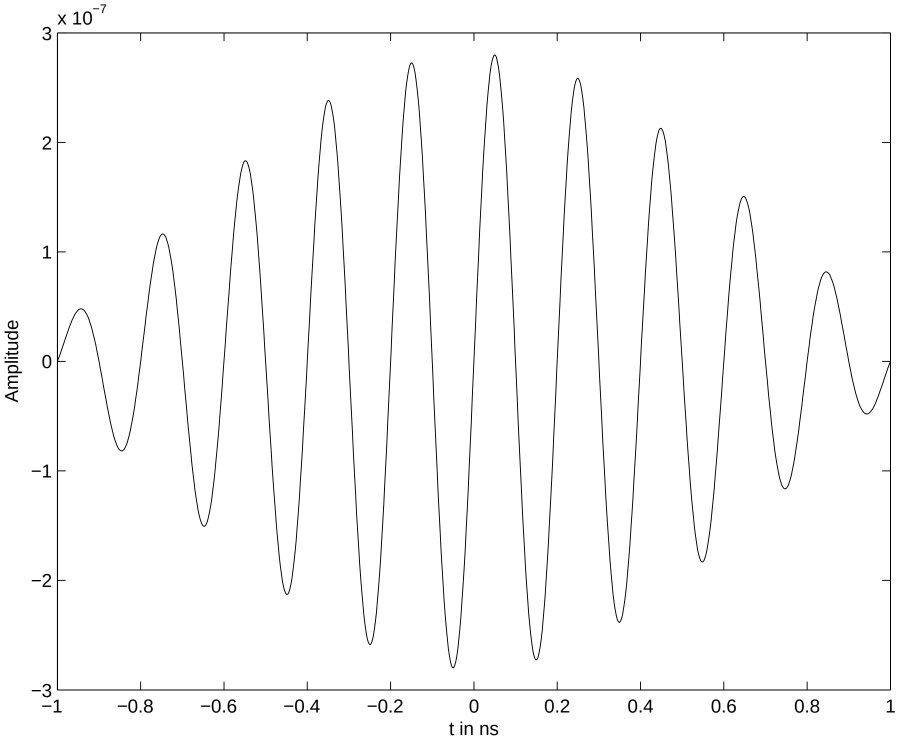

Figure 4.17: Optimal pulse for UWB on Gaussian channel

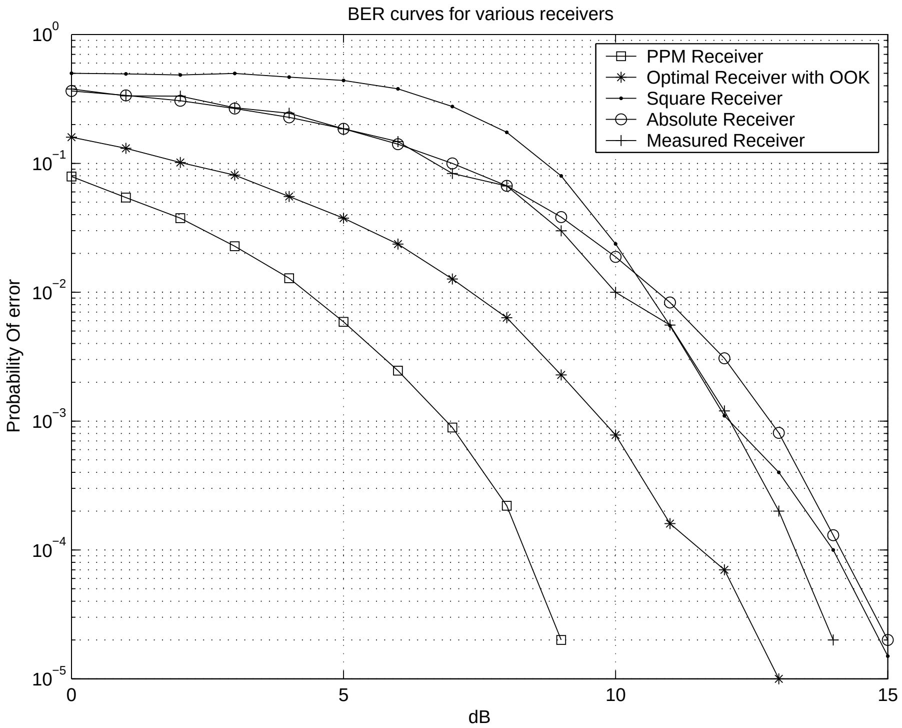

Figure 4.18: Ber curves for various UWB receivers

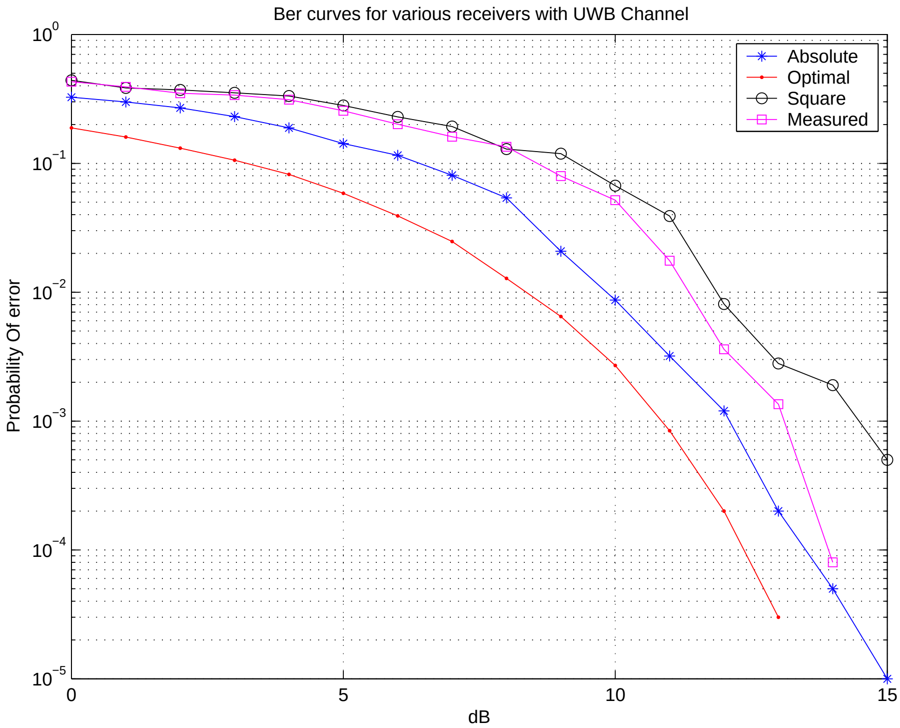

Figure 4.19: BER with optimal pulse

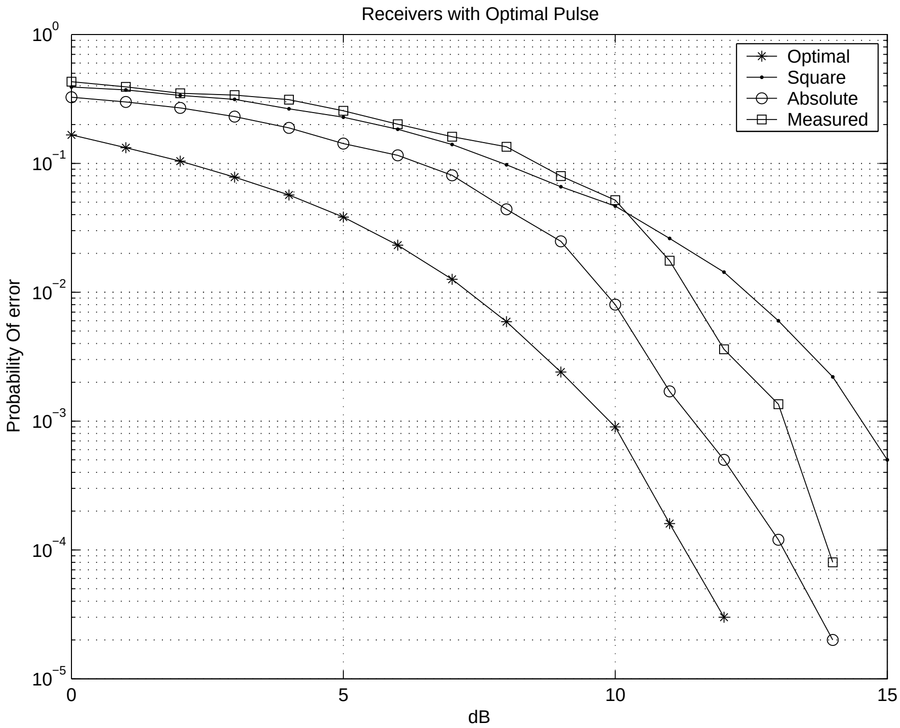

Figure 4.20: BER with optimal pulse

CHAPTER 5

UWB TRANSMITTER/RECEIVER SYSTEM DESIGN

5.1 Measurement Set up

The aim of the hardware experiment was to verify the reception of a 0.1us pulse in an indoor environment. The following equipment was used two Tektronics AWG2021 Signal Generators, Agilent VSA E8408A, transmission and receiving antenna.

For the receiver an Agilent Vector Signal Analyzer(VSA). Agilent's VSA has a maximum sampling rate of 96M samples/sec. The receiving antenna was connected to the input of the VSA. The VSA does the Analog to Digital conversion and can be programmed using c++. To ensure synchronization between the transmitter and receiver we use a second signal generator(AWG 2021) to provide trigger signals. The trigger frequency is set to 2Khz.

The VSA is linked to a computer via a IEEE 1394 cable and real time digital data is then available. To enable real time transmission and reception

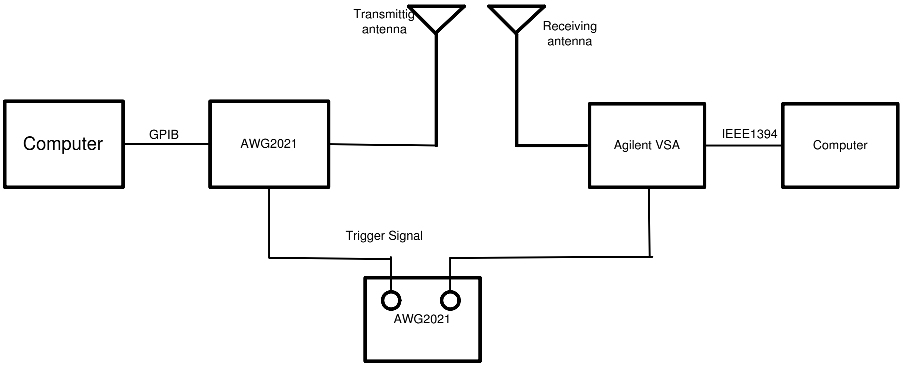

Figure 5.1: Block Diagram Of Transmitter and Receiver

the AWG2021 was programmed in C++ and connected via a GPIB cable. Depending on the data,the bits was encoded using the UWB waveform.

$$p(t) = [1 - 4\pi(\frac{t - ts}{\tau_m})^2]e^{2\pi[\frac{(t-ts)}{\tau_m})^2]} \tag{5.1}$$

5.2 Measurement Procedure

Here we choose ts to be $0.5 * 10^-6$ and τ_m to be 0.1us. Data is transmitted by packets of 24 bits. The duration of each packet is 24.56us. The output of the signal generator is connected to an antenna.

The block diagram for the set up is shown in figure5.1.

The channel response can be obtained by transmitting a single pulse and viewing the spectrum.

Figure 5.2 shows a transmitted pulse and the response of the channel to the pulse.

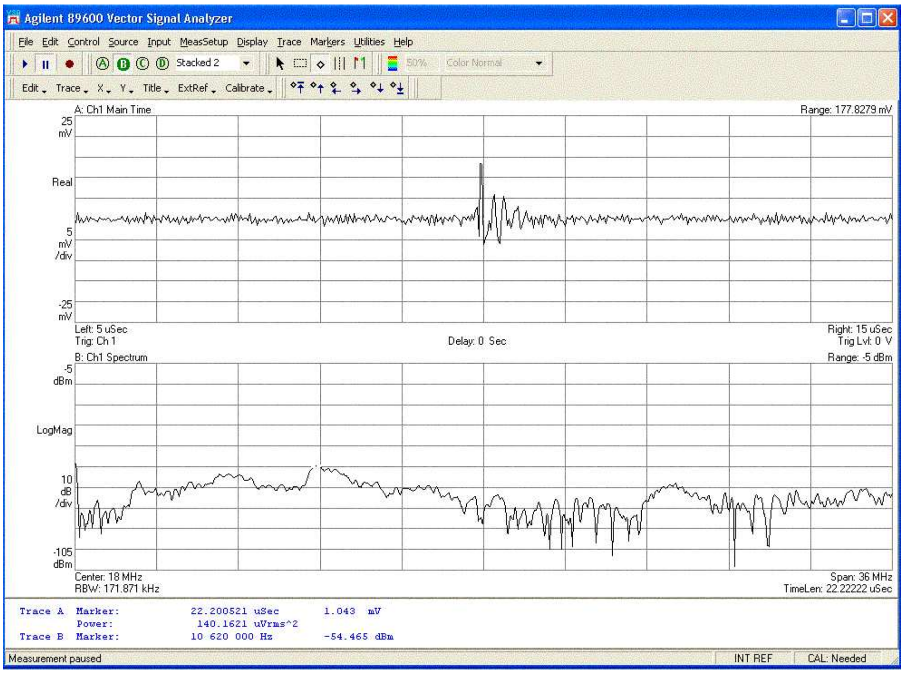

Figure 5.2: Channel response

5.3 Measurement Results

Bit 1 or 0 is transmitted in real time from the computer to the AWG 2021. The signal generator produces the pulse corresponding to the bit. This is then transmitted out using the transmitting antenna. The received signal is converted to a digital signal and can be viewed on the computer using the VSA. This data is stored and further processing can be done in MATLAB. A typical received signal sequence is shown in figure 5.3.Here the signal was transmitted at 3V. The signal was received at a distance of 2 feet. From the graph the pulses are clearly distinguishable. The transmitted bit can be easily

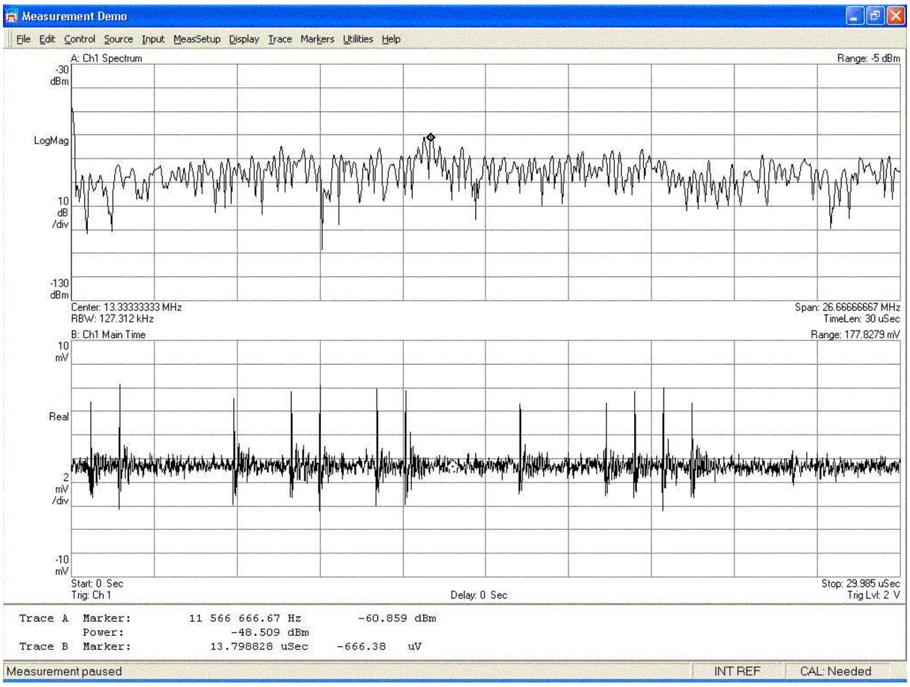

Figure 5.3: A Received Packet of 24 bits

verified. In the case where the transmitting voltage is very low we will need a bandpass filter. A sixth order low pass filter is used. The response of the filter is shown in figure5.4

We now transmit a signal of 0.5 volt and receive the signal at a distance of 5 feet. The signal is first squared as shown in fig5.5. This is then convolved with the original pulse p(t) as in the match filter. The resulting signal is shown in figure5.6.

Now the signal is passed through the 6th order butterworth filter to and the transmitted bits can be decoded. A comparison of the original signal

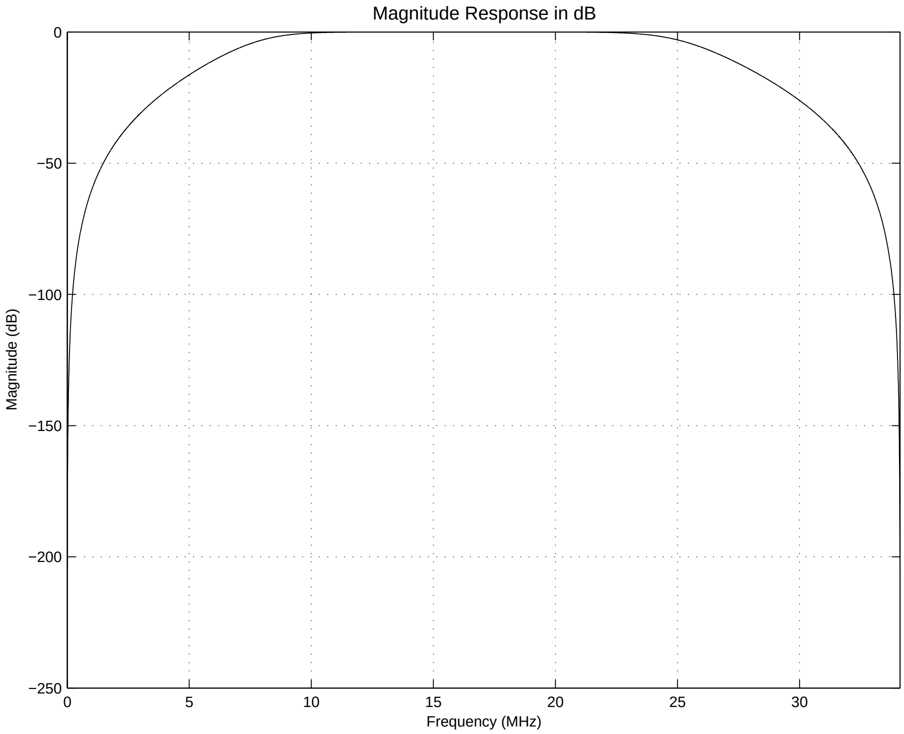

Figure 5.4: Frequency Response Of 6th order ButterWorth Filter

and after processing is shown in fig 5.7.

This shows that pulses can received and transmitted at very low power if the range is small. We can create a network of repeaters within a building and a low data rate communication system can be build with very low cost.

5.4 Conclusion

This Thesis set out to investigate the performance analysis of various reduced complexity sub-optimal receivers. Optimal receivers could not be used

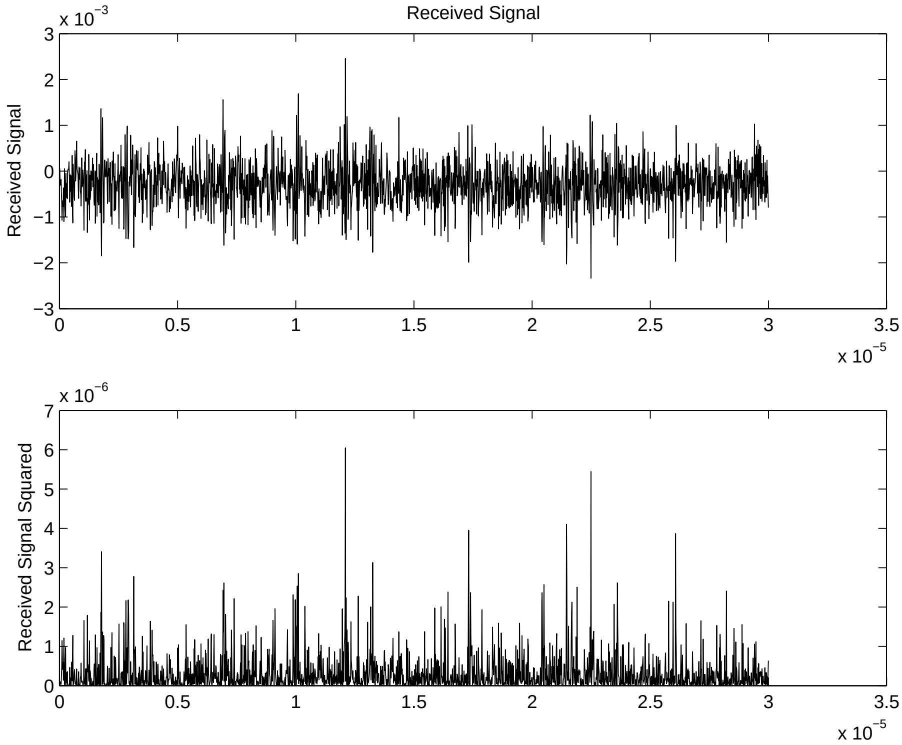

Figure 5.5: Recieved Signal

because in many cases the channel impulse response is not known. Sub-optimal receivers such as the square value detector, the absolute value detector and the measured detector were all analyzed.

Performance curves were examined on a UWB channel and on a Gaussian Channel. OOK and PPM modulation schemes were used. Also analysis was done using optimal pulses. It was found that the absolute value detector gives best performance.

Existing hardware was used to generate pulses of 0.1us and a simple

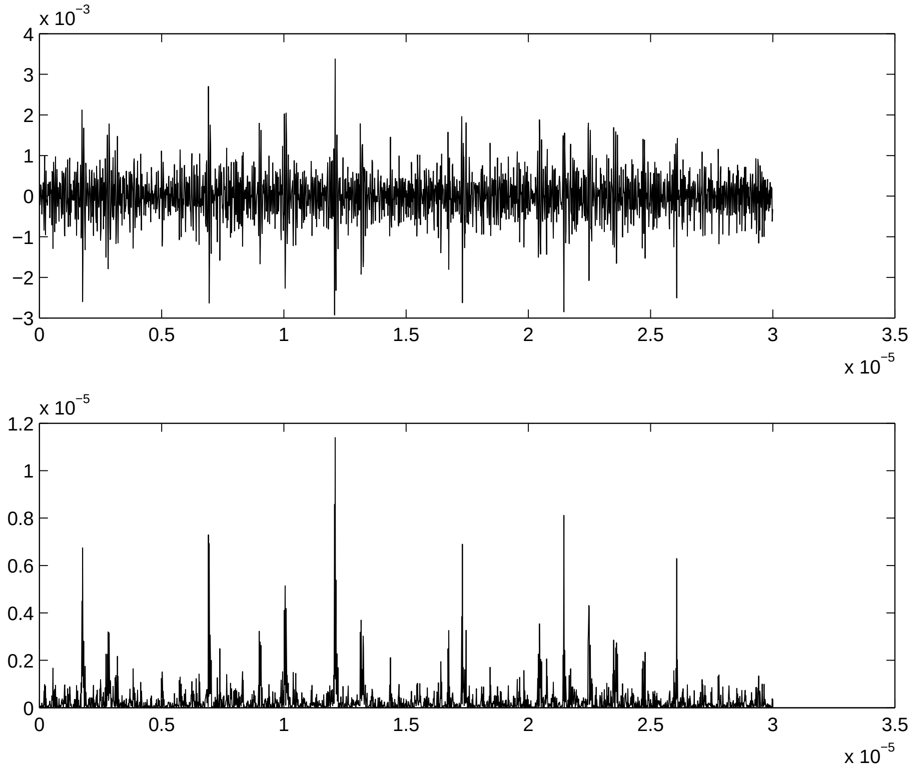

Figure 5.6: Received Signal convolved with original pulse

receiver transmitter system was implemented. Data was transmitted at low voltage and after some processing, was received successfully. This system with the help of periodic repeaters can be implemented for a low data rate communication system in the indoor environment.

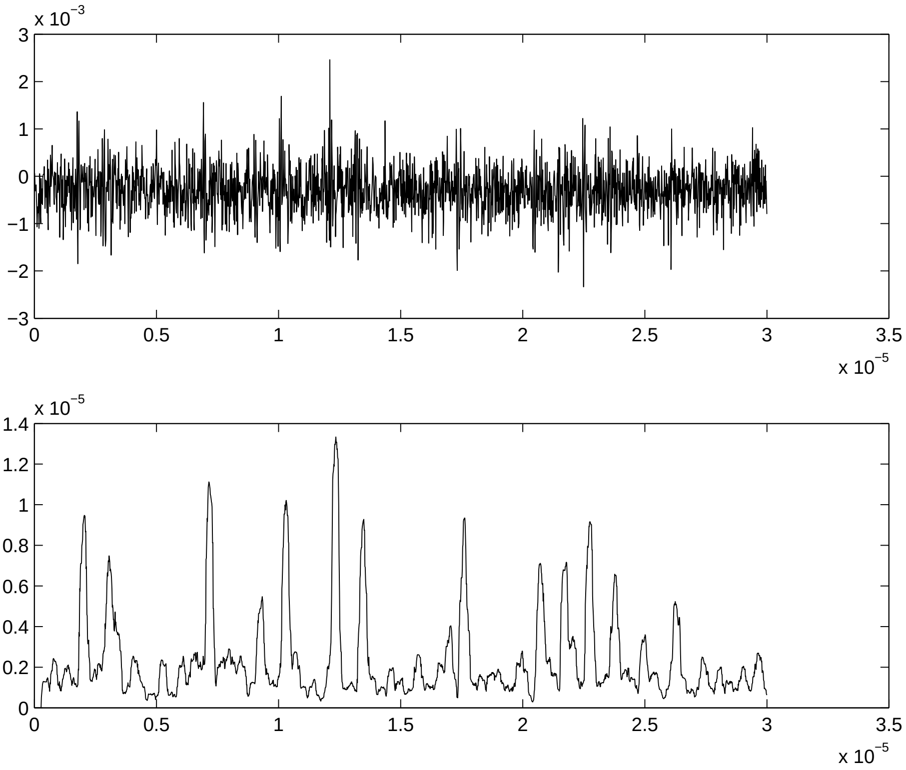

Figure 5.7: Received signal before and after processing.

LIST OF REFERENCES

[1] R. A. Scholtz, " Multiple Access with Time-Hopping Impulse Modulation" *IEEE Commun. Letters,* Vol.2, pp.447- 450, January 1993.

[2] M. Z. Win and R. A. Scholtz, " Impulse radio: How it works," *IEEE Commun. Letters,* Vol.2, pp.10-12, January 1998.

[3] R. A. Scholtz, R. Weaver, E. Homier, J. Lee, P. Hilmes, A. Taha and R. Wilson, "UWB radio deployment challenges," *Proceedings of IEEE PIRMIC,* 2000, pp.620-625.

[4] J. Foerster, E. Green, S. Somayazulu, and D. Leeper, "Ultra-Wideband Technology for Short- or Medium-Range Wireless Communications," Intel Technology Journal, 2001, 2nd Quarter.

[5] M. Z. Win and R. A. Scholtz, "Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication-Theoretic View," *IEEE JSAC,* Dec. 2002, pp.1613-1627.

[6] L. Micahle, M. Ghavami and R. Kohno, "Multiple Pulse Generator for Ultra-Wideband Communication using Hermite Polynomial Based Orthogonal Pulses," 2002 IEEE Conference on Ultra Wideband Systems and Technologies, pp.47-52.

[7] A. Taha and K.Chugg, "On Designing the Optimal Template Waveform for UWB Impulse Radio in the Presence of Multipath," 2002 IEEE Conference on Ultra Wideband Systems and Technologies, pp.41-46.

[8] G. Corral, S. Sibecas, S. Emami, and G. Stratis, "Pulse Spectrum Optimization for Ultra-Wideband Communication," 2002 IEEE Conference on Ultra Wideband Systems and Technologies, pp.31-36

[9] M. Hamalainen, V. Hovinen, R. Tesi, J. Iinatti and M. Latva-aho, "On the UWB system Coexistence with GSM900, UMTS/WCDMA, and GPS," IEEE JASC, Dec. 2002, pp.1712-1721.

[10] Z. Wu, F. Zhu, and C. Nassar, "High performance Ultra-Wideband Systems Via Novel Pulse Shaping and Frequency Domain Processing," 2002 IEEE Conference on Ultra Wideband Systems and Technologies, pp.53-58.

[11] Ramires-Mireles F., M. Z. Win, and R. A. Scholtz, "Signal Selection for

the Indoor Wireless Impulse Radio Channel," Proceedings IEEE VTC conference, May 1997.

[12] B. Berksoy and L. Wei "Pulse waveform optimization for UWB signal with PPM on Gaussian channels," in Proceeding of IEEE 58th Vehicular Technology Conference (VTC-2003/Fall), Oct, 2003.

[13] B. Berksoy and L. Wei "Aspects of Optimal Performance and Optimal Pulses for UWB/PPM," *submitted UWBST2003.*

[14] L. Wei, Z. Li, M. James and I. Petersen, "A Minimax Robust Decoding Algorithm," IEEE Trans. on Information Theory, May 2000, pp.1158-1167

[15] Jeff Foerster;Evan Green;Srinivasa Somayazulu,; David Leeper,"Ultra-Wideband Technology for Short- or Medium-Range Wireless Communications" Intel Technology Journal Q2, 2001.

[16] Laney, D.; Maggio, G.M.; Lehmann, F.; Larson, L., "BER for multi-access UWB radio using pseudo-chaotic time hopping," Radio and Wireless Conference, 2002. RAWCON 2002. IEEE , 11-14 Aug. 2002 Page(s): 91 -94

[17] FCC Document 00-163, "Revision of commision rules ET Docket No. 98-153 regarding UWB transmission systems", adopted 5-10-2000.

[18] FCC Document 02-48, "Revision of commision rules ET Docket No. 98-153 regarding UWB transmission systems", adopted 2-14-2002.

[19] Leon-Garcia, Alberto, "Probability and Random Processes for Electrical Engineering", 2nd ed.,Addison-Wesley Inc., 1994.

[20] Turin, W., Jana, R., Ghassemzadeh, S.S., Rice, C.W., Tarokh, T., "Autoregressive modeling of an indoor UWB channel," Ultra Wideband Systems and Technologies, 2002. Digest of Papers. 2002 IEEE Conference on , 21-23 May 2002 Page(s): 71 -74

[21] Cassioli, D., Win, M.Z., Molisch, A.F., A Statistical Model for the UWB Indoor Channel. IEEE VTS 53rd Vehicular Technology Conference, 2001, Spring, vol. 2, pp. 1159-1163.

[22] Cramer, J.M., Scholtz, R.A., Win, M.Z., On the Analysis of UWB Communication Channels. IEEE Military Communications Conference, 1999, vol. 2, pp. 1191-1195.

[23] Cramer, R.J.-M., Win, M.Z., Scholtz, R.A., Impulse Radio Multipath Characteristics and Diversity Reception. IEEE International Conference on Communications, 1998, vol. 3, pp. 1650-1654

[24] Ghassemzadeh, S.S., Jana, R., Rice, C.W., Turin, W., Tarokh, V., A Statistical Path Loss Model for In-Home UWB Channels . IEEE Conference on Ultra Wideband Systems and Technology, 2002

[25] Lee, H., Han, B., Shin, Y., Im S., Multipath Characteristics of Impulse Radio Channels. IEEE VTS 51st Vehicular Technology Conference, 2000, Spring, vol. 3, pp. 2487-2491.

[26] Time Domain, "Time Modulated Ultra-Wideband For Wireless Applications"

[27] James M Wilson, "Ultra Wideband Technology Update at Spring 2003 IDF", INTEL Developer Update Magazine"

[28] Maxim, "An Introduction to Direct-Sequence Spread- Spectrum Communications"

[29] Steven J. Merrifield, "Spread Spectrum Communication Concepts"

[30] Roger L Peterson, Rodger E.Ziemer, David E. Borth " Introduction to Spread Sprectrum Communications"

[31] John G Proakis, " Digital Communiations"

[32] Simon Haykin, " Communication Systems"

[33] R.E. Ziemer, W.H Tranter, "Principles Of Communications "

[34] A Batra, J Balakrishnan, A Dabak, "Multi-Band OFDM: Why it wins for UWB" Comms Design. June 2003

[35] A Batra, J Balakrishnan, A Dabak, "Multiband OFDM moves to higher data rates" EE Times. May 2004

[36] " Ultra-Wide Band Compatability" *Report to the Radiocommunications Agency ,* January 2002.

[37] William Turin,et al " AutoRegressive modelling of an indoor UWB channel" AT&T Labs-Research

[38] Ultra-Wide Band Technology Intel White Paper: "Enabling high-speed wireless personal area networks"

[39] B Berksoy, N Bhuvanendran, L Wei: "Optimal Pulses for Ultra-Wide Band Communication Systems on Gaussian and Dense Multi-path Channels" ISIT 2004

[40] G. Corral, S. Sibecas, S. Emami, and G. Stratis, Pulse Spectrum Optimization for Ultra-Wideband Communication, 2002 IEEE Conference on UltraWideband Systems and Technologies, pp.31- 36

[41] M. Hamalainen, V. Hovinen, R. Tesi, J. Iinatti and M. Latva-aho, On the UWB system Coexistence with GSM900, UMTS/WCDMA, and GPS, IEEE JASC, Dec. 2002, pp.1712- 1721.

[42] Ramires-Mireles F., M. Z.Win, and R. A. Scholtz, Signal Selection for the IndoorWireless Impulse Radio Channel, Proceedings IEEE VTC conference, May 1997.

[43] B. Berksoy and L.Wei Pulse waveform optimization for UWB signal with PPM on Gaussian channels, Accepted, Proceedings of IEEE VTC Fall, 2003, Orlando, USA, recent results section.

[44] B.Berksoy and L. Wei Pulse Waveform Optimization for UWB/PPM on Gaussian and Dense Multi-path Channels,

[45] John McCorkle,"DS-CDMA: The Technology Of Choice For UWB" IEEE P802.15 Wireless Personal Area Networks. 19th july 2003