1.1Ultra wide band Introduction:

The explosive growth of the wireless communication market is expected to continue in the future, as the demand for all types of wireless services is increasing. New generations of wireless mobile radio systems aim to provide flexible data rates (including high, medium, and low data rates) and a wide variety of applications (like video, data, ranging, etc.) to the mobile users while serving as many users as possible. This goal, however, must be achieved under the constraint of the limited available resources like spectrum and power. As more and more devices go wireless, future technologies will face spectral crowding, and coexistence of wireless devices will be a major issue. Therefore, considering the limited bandwidth availability, accommodating the demand for higher capacity and data rates is a challenging task, requiring innovative technologies that can coexist with devices operating at various frequency bands.
Earlier UWB radar systems were developed mainly as a military tool because they could 'see through' trees and beneath ground surfaces. However, recently, UWB technology has been focused on consumer electronics and communications. Ideal targets for UWB systems are low power, low cost, high data rates, precise positioning
capability, and extremely low interference.

Although UWB systems are years away from being omnipresent, the technology is changing the wireless industry today. UWB technology is different from conventional narrowband wireless transmission technology – instead of broadcasting on separate frequencies, UWB spreads signals across a very wide range of frequencies. The typical sinusoidal radio wave is replaced by trains of pulses at hundreds of millions of pulses per second. The wide bandwidth and very low power make UWB transmissions appear as background noise hence difficult to detect .

1.2TERMINOLOGY Description

The name ultra wideband is an extremely general term to describe a particular technology. Many people feel other names, such as pulse communications, may be more descriptive and suitable. However, UWB has become the term by which most people refer to ultra wideband technology. The question then arises as to how to spell UWB. Is it 'ultrawideband', 'ultrawideband', 'ultra wide band', 'ultrawide band', or 'ultra wideband'? In this text, quite arbitrarily, we decide to use the term *ultra wideband*. Our reasoning is that the term wideband communication has become

very common in recent years and is frequently used in communication . To show that UWB uses an even larger bandwidth the extra large ‘ultra’ is prefixed; however, both ‘ultrawideband’ and ‘ultra-wideband’ seem unwieldy, so we use ultra wideband. Many people may disagree about our choice, even vehemently.We accept their arguments and suggest that time will show the most popular choice for UWB.

1.3HISTORICAL DEVELOPMENT OF UWB

Most people would see UWB as a ‘new’ technology, in the sense that it provides the means to do what has not been possible before, be that the use of high data rates, smaller, lower powered devices, ground penetration radars, through-wall radar imaging or, indeed, some other new application. However, UWB is, rather, a *new engineering technology* in that no new physical properties have been discovered. However, the dominant method of wireless communication today is based on sinusoidal waves. Sinusoidal electromagnetic waves have become so universal in radio communications that many people are not aware that the first communication systems were in fact pulse-based. It is this paradigm shift for today’s engineers from sinusoids to pulses, that requires the most shift in focus. In 1893 Heinrich Hertz used a spark discharge to produce electromagnetic waves for his experiment. These waves would be called colored noise today. Spark gaps and arc discharges between carbon electrodes were the dominant wave generators for about 20 years after Hertz’s first experiments. However, the dominant form of wireless communications became sinusoidal, and it was not until the 1960s that work began again in earnest for time domain electromagnetics. The development of the sampling oscilloscope in the early 1960s and the corresponding techniques for generating sub-nanosecond baseband pulses sped up the development of UWB. Impulse measurement techniques were used to characterize the transient behavior of certain microwave networks. From measurement techniques the main focus moved to develop radar and communications devices. In particular, radar was given much attention because of the accurate results that could be obtained. The low-frequency components were useful in penetrating objects, and *ground-penetrating radar* was developed. See [1] and [2] for more details about UWB radar systems. In 1973 the first US patent was awarded for UWB communications [3]. The field of UWB had moved in a new direction. Other applications, such as automobile collision avoidance, positioning systems, liquid-level sensing, and altimetry, were developed. Most of the applications and development occurred in the military or in work funded

by the US Government under classified programs. For the military, accurate radar and low probability of intercept communications were the driving forces behind research and development. It is interesting to note that in these early days UWB was referred to as *baseband*, *carrier-free* and *impulse* technology. The US Department of Defense is believed to be the first to have started to use the term *ultra wideband*. The late 1990s saw the move to commercialize UWB communication devices and systems. Companies such as Time Domain [4] and in particular startups like XtremeSpectrum [5] were formed around the idea of consumer communication using UWB. For further historical reading, the interested reader is referred to [6] and [7].

I.4 UWB REGULATION OVERVIEW

For the regulation of UWB around the world there are many organizations and government entities that set rules and recommendations for UWB usage. The structure of international radio-communication regulatory bodies can be grouped into international, regional, and national levels. The International Telecommunication Union (ITU) is an impartial, international body where governments and the private sector work together on issues pertinent to telecommunication networks. The group that undertakes the work on UWB was created in 2002 to study the compatibility between UWB and other communication services. Most of the telecommunication services that occupy the allocated spectrum would prefer to keep UWB out of their frequency range. At the regional level, the Asia-Pacific Telecommunity (APT) is an international body that sets recommendations and guidelines of telecommunications in the Asia- Pacific region. The European Conference of Postal & Telecommunications Administrations (CEPT) has created a task group under the Electronic Communications Committee (ECC) to draft a proposal regarding the use of UWB for Europe. At the national level, the USA was the first country to legalize UWB for commercial use. The rules are meant to protect existing radio devices, particularly those classified as safety devices, such as aviation systems and the global positioning system (GPS). In March 2005, the Federal Communications Commission (FCC) granted a waiver that will lift certain limits on UWB. In the UK, the regulatory body, called the Office of Communications (Ofcom), opened a consultation on UWB matters in January 2005. The consultation consisted of 15 questions, asking opinions from those who are affected by the UWB technology. Ofcom sees UWB as a positive technology that if correctly regulated can bring

economic growth to the UK. The regulatory body that set the policy on UWB in Japan is called the Ministry of Internal Affairs and Communications (MIC). The first interim report was published in March 2004, which drafted two proposals on the limit of UWB emission and addressed the issue of interference. One proposal set the limit of UWB to be the same as that set by the FCC, and the other one set a slightly more restrictive limit. Overall, the report suggests that indoor use is the best environment for UWB application. Looking through each country's regulatory status gives the impression that all countries monitor the UWB development in the USA closely while they themselves have yet to make any significant progress to catch up to the level of UWB regulation on UWB. There can be two reasons for this. First, UWB has already been developed in the USA under the classification of 'military use' for many years. The second reason can be classified as politics. Many current industry wireless manufacturers and wireless service providers voice their concerns on the potential damage to their business loudly, leading the regulatory bodies to be conservative in their outlook.

I.4.1 Basic definitions and rules

The FCC rules provide the following definitions for UWB signaling:

• *UWB bandwidth:* UWB bandwidth is the frequency band bounded by the points that are 10 dB below the highest radiated emission, as based on the complete transmission system including the antenna. The upper boundary is designated *fh* and the lower boundary is designated *fl*. The frequency at which the highest radiated emission occurs is designated *fm*.

• *Center frequency:* The center frequency *fc* is the average of *fl* and *fh*, that is,

$$fc = \frac{fl+fh}{2} \tag{I.1}$$

• *Fractional bandwidth* (FB): The fractional bandwidth is defined as

$$\mathrm{FB} = 2\,\frac{fh-fl}{fh+fl} \tag{I.2}$$

• *UWB transmitter:* A UWB transmitter is an intentional radiator that, at any point in time, has a fractional bandwidth equal to or greater than 0.20 or has a UWB bandwidth equal to or greater than 500 MHz, regardless of the fractional bandwidth.

• *Equivalent isotropically radiated power* (EIRP): EIRP is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna. EIRP refers to the highest signal strength measured in any direction and at any frequency from the UWB device.

The first set of FCC key regulations for all UWB systems are as follows:

• No toys, and no operation on an aircraft, ship or satellite.

• Emissions from supporting digital circuitry is considered separately from the UWB portion, and is subject to existing regulations, not new UWB rules.

• The frequency of the highest emission, f_m, must be within the UWB bandwidth.

• Other emissions standards apply as cross-referenced in the UWB rules, such as conducted emissions into AC power lines.

• Emissions below 960 MHz are limited to the levels required for unintentional radiators.

• Within a 50 MHz bandwidth centered on f_m, peak emissions are limited to 0 dBm EIRP.

• UWB radar, imaging and medical system operation must be coordinated. Dates and areas of operation must be reported, except in the case of emergency. These systems must also have a manual switch (local or remote) to turn the equipment off within 10 s of actuation. Discussion continues on UWB measurement methodology and these first rules are likely to change.

I.5 KEY BENEFITS OF UWB

The key benefits of UWB can be summarized as:

(1) high data rates;

(2) low equipment cost;

(3) multipath immunity;

(4) ranging and communication at the same time.

The high data rates are perhaps the most compelling aspect from a user's point of view and also from a commercial manufacturer's position. Higher data rates can enable new applications and devices that would not have been possible up until now. Speeds of over 100 Mbps have been demonstrated, and the potential for higher speeds over short distances is there. The extremely large bandwidth occupied by UWB gives this potential, as we show in the next section. The ability to directly modulate a pulse onto an antenna is perhaps as simple a transmitter as can be made, leading many manufacturers to get excited by the possibilities for extremely cheap transceivers. This is possible by eliminating many of the components required for conventional sinusoidal transmitters and receivers. The narrow pulses used by UWB, which also give the extremely wide bandwidth, if separated out provide a fine resolution of reflected pulses at the receiver. This is important in any wireless communication, as pulses (or sinusoids) interfering with each other are the major obstacle to error-free communication. Finally, the use of both precise ranging (object location) and high-speed data communication in the same wireless device presents intriguing possibilities for new devices and applications. Simultaneous automotive collision avoidance radar and communication giving accident-free smooth traffic flow, or games where the players' position can be precisely known and a high-speed wireless link seamlessly transfers a video signal to the players' goggles may seem the stuff of science fiction, but with UWB the possibilities for these and other applications are there, right now.

I.6 UWB AND SHANNON'S THEORY

Perhaps the benefits and possibilities of UWB can be best summarized by examining Shannon's famous capacity equation. This equation will be familiar to anyone who has studied communication or information theory. Capacity is important, as more demanding audio-visual applications require higher and higher bit rates. Shannon's equation is expressed as

$$C = B\log(1 + \frac{S}{N}) \qquad \text{(I.3)}$$

where C is the maximum channel capacity, with units bits per second, B is the channel bandwidth in hertz, S is the signal power in watts, and N is the noise power also in watts.

This equation tells us that there are three things that we can do to improve the capacity of the channel. We can increase the bandwidth, increase the signal power or decrease the noise. The ratio *S/N* is more commonly known as the *signal-to-noise ratio* (SNR) of the channel. We also can see that the capacity of a channel grows linearly with increasing bandwidth *B*, but only logarithmically with signal power *S*. The UWB channel has an abundance of bandwidth and in fact can trade off some of the bandwidth for reduced signal power and interference from other sources. Thus, from Shannon's equation we can see that UWB systems have a great potential for high-capacity wireless communications.
Another way of looking at wireless communication is the tradeoffs between:

• the distance between transmitter and receiver;
• simultaneous communication for many users;
• sending the data very quickly;
• sending and receiving a large amount of data.

The first wireless communication systems, such as wireless communication at sea, were meant to communicate between ships separated by large distances. However, the amount of data that could be effectively transferred was extremely small and communication took a long time. Only one person can 'talk' using Morse code at a time. More recently, cellular telephone systems have simultaneous communication for many users as their fort´e. The distance between the base station and the user is limited to at most a few kilometers. It can be classified as a system where a moderate amount of data can be sent reasonably quickly. An UWB system is focused on the latter two attributes: a large amount of data that can be transmitted very quickly. This is at the expense of, in the main, distance. The precise tradeoffs are of course more complex and will depend upon the particular application.

I.7 CHALLENGES FOR UWB

While UWB has many reasons to make it an exciting and useful technology for future wireless communications and many other applications, it also has some challenges that must be overcome for it to become a popular and ubiquitous technology. Perhaps the most obvious one to date has

been regulatory problems. Wireless communications have always been regulated to avoid interference between different users of the spectrum. Since UWB occupies such a wide bandwidth, there are many users whose spectrum will be affected and they need to be convinced that UWB will not cause undue interference to their existing services. In many cases these users have paid to have exclusive use of the spectrum. Other challenges include the industry coming to agreed standards for interoperability of UWB devices. There are currently two camps of UWB supporters each with their own standard of UWB design, and currently there is no compromising ground to resolve this issue. This standard battle is a concern because in the near future consumers will be hesitant to choose which standard to buy and thus limit the potential of UWB market growth. Many technical and implementation issues remain. The promise of low-cost devices is there, but the added complexity to combat interference and low-power operation may bring cost increases similar to current wireless devices.

Among the challenges of UWB, a limited list can be given as follows:

. Coexistence with other services and handling strong narrowband interference;

. Shaping (adapting) spectrum of transmitted signals (multiband, OFDM-based UWB, etc.);

. Practical, simple, and low-power transceiver design;

. Accurate synchronization and channel parameter estimation;

. High sampling rate for digital implementations;

. Powerful processing capabilities for high performance and coherent digital receiver structures;

. Wideband RF component designs (such as antennas, low noise amplifiers, etc.);

. Multiple accessing, multiple access code designs, and multiuser interference;

. Accurate modeling of the ultra wideband channel in various environments;

. Adaptive system design and cross-layer adaptation for UWB;

. UWB tailored network design.

Generation of UWB waveforms

One of the essential functions in communication systems is the representation of a message symbol by an analog waveform for transmission through a channel. As was shown in Chapter 1, in UWB systems the conventional analog waveform is a simple pulse that in general is directly radiated to the air. These short pulses have typical widths of less than 1 ns and thus a bandwidth of over 1 GHz. In this chapter we will examine in detail how to generate pulse waveforms for UWB systems for simple cases of Gaussian wave shapes. We will discuss how to design pulses which meet requirements of spectral masks as mandated by government organizations. Finally, we will look at the practical constraints on pulse generation and the effects of imperfections on the pulse, and briefly discuss the effects of the channel on pulse shape.

2.1 INTRODUCTION

Sinusoidal electromagnetic waves have become so universal in radio communications that many people are not aware that the first communication systems were in fact pulse-based. Heinrich Hertz (1893) used a spark discharge to produce the electromagnetic waves for his experiment. These waves would be called colored noise today. Spark gaps and arc discharges between carbon electrodes were the dominant wave generators for about 20 years after Hertz's first experiments. Eventually, the development of rotating high-frequency generators and the electronic tube made the generation of sinusoidal currents and waves possible. A strong incentive to use sinusoidal waves was provided by the need to operate several transmitters at the same time but to receive them selectively. This led to the development of transmitters and receivers on the basis of sinusoidal waves. Regulation followed common practice and led to the assignment of frequency bands for various radio services. Today's UWB systems employ nonsinusoidal wave shapes that should have certain properties when transmitted from the antenna. Emissions in UWB communication systems are constrained by the FCC regulation 47 CFR Section S15.5(d) [14], which states that Intentional radiators that produce class B emissions (damped wave) are prohibited. Several nondamped waveforms have been proposed in the literature for UWB systems, such as Gaussian [15], Rayleigh, Laplacian, and cubic [16] waveforms, and modified Hermitian monocycles [17]. In all these waveforms the goal is to obtain a nearly flat frequency

domain spectrum of the transmitted signal over the bandwidth of the pulse and to avoid a DC component. In order to understand the characteristics of different waveforms, we first discuss the theoretical definition of a damped wave.

UWB communications

In this chapter we will look at the use of UWB wireless communications. From the treatment of individual pulse shaping and generation, which was introduced in Chapter 2, we now move on to examine various communications concepts. Particular attention will be paid to modulation methods including pulse position modulation, biphase modulation, orthogonal pulse modulation, and their combinations. Sequences of individual pulses onto pulse streams will be presented. Receiver design and pulse detection will be examined. We also move from a single-user environment to examine multiple access techniques for UWB communications. The capacity of the wireless UWB channel will also be examined. The effect of UWB on existing wireless communication methods, such as the IEEE 802.11 WLAN standards and Bluetooth, is shown. Several methods to prevent interference from these narrowband systems to UWB will also be examined. Finally, an important discussion on the relative merits and demerits of UWB as a communication method with other wideband communication techniques, such as
CDMA and orthogonal frequency division multiplexing (OFDM), is undertaken.

3.1 INTRODUCTION

Communication can generally be defined as the transmission of information from a source to a recipient. In this chapter we make our definition of communication much narrower, by restricting ourselves to wireless communication of digital data streams of information using extremely short pulses. We deliberately ignore the kind of information contained in the digital data stream and do not use *media access control* (MAC) protocols, coding schemes, or retransmission schemes to reduce errors. We concentrate on what is commonly known as the *physical layer* in the International Standards Organization (ISO) protocol stack.

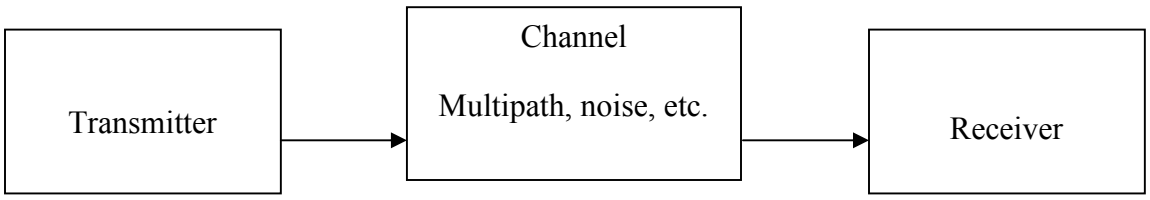


Fig. 3.1 Model of a general communications system.

A general model of a communication system is shown in Figure 5.1. The three basic elements are as follows:

- the *transmitter*, whose primary task is to group the digital data stream into symbols, to map these symbols onto an analog waveform, and then to transmit them to the air through an antenna;
- the *channel*, which represents the effect of traveling through space, including reflections and distortions as the electromagnetic pulses impinge on other objects;
- the *receiver*, which collects the electromagnetic energy from the antenna, takes the extremely weak signal, reconstructs the pulse shape, and maps it to the appropriate symbols and then to the binary bitstream.

In this chapter we examine receiver and transmitter structures in more detail, focusing

on the basic communication aspects, such as modulation.

3.2 UWB MODULATION METHODS

As we saw in Chapter 1, one single UWB pulse does not contain information by itself. We must add digital information to the analog pulse, by means of *modulation*. In UWB systems there are several basic methods of modulation, and we examine each in detail. As a helpful categorization of modulation methods, we define two basic types for UWB communication. These are shown in Figure 5.2 as *time-based* techniques and *shape-based* techniques. By far the most common method of modulation in the literature is *pulse position modulation* (PPM) where each pulse is delayed or sent in advance of a regular time scale. Thus, a binary communication system can be established with a forward or backward shift in time. By specifying specific time delays for each pulse, an *M*-ary system can be created. Another common method of modulation is to invert the pulse, that is, to create a pulse with opposite phase. This is known as *bi-phase modulation* (BPM).

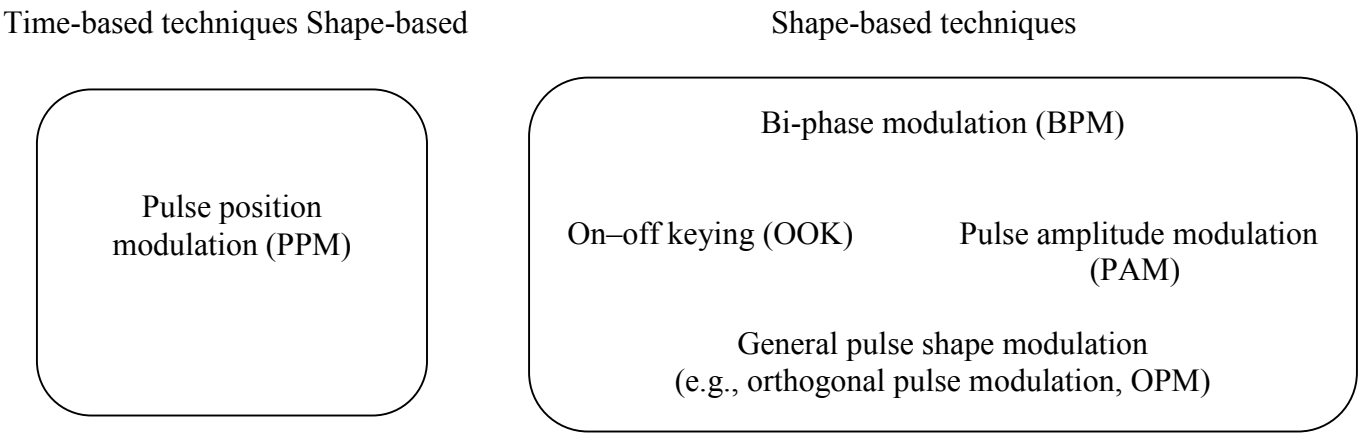


Fig. 3.2 Division of different modulation methods for UWB communications.

An interesting modulation technique is *orthogonal pulse modulation* (OPM), which requires special pulse shapes to be generated which are orthogonal to each other. Other well-known techniques for modulation are available. For example, *on–off keying* (OOK) is a modulation technique where the absence or presence of a pulse signifies the digital information of '0' or '1', respectively. *Pulse amplitude modulation* (PAM) is a technique where the amplitude of the pulse varies to contain digital information. Furthermore, some traditional modulation techniques are not available to us. For example, the widely used *frequency modulation* (FM) is difficult to apply to UWB, since each pulse contains many frequency elements making it difficult to modulate.

Note that this should not be confused with *frequency division multiplexing* (FDM) which is an entirely different technique to separate communication channels based on larger blocks of frequency (discussed later). Let us examine each of these possible modulation techniques in turn. First, we examine the two most common techniques, PPM and BPM. A simple comparison of these two modulation methods is shown in Figure 3.3. In Figure 3.3(a) an unmodulated pulse train is shown for comparison. As an example of PPM, the pulse representing the information '1' is delayed in time (i.e. the pulse appears to be moved in position to the right). The pulse representing the information '0' is sent before the nonmodulated pulse (i.e. the pulse appears to be moved in position to the left) in Figure 3.4(c). In BPM the inverted pulse represents a '0' while the uninverted pulse represents a '1'. This is clearly illustrated in Figure 3.4(d).

3.2.1 PPM

As mentioned previously, the important parameter in PPM is the delay of the pulse. That is, by defining a basis pulse with arbitrary shape $p(t)$, we can modulate the data by the delay parameter τ_i to create pulses s_i, where t represents time,

$$s_i = p(t - \tau_i) \tag{5.1}$$

The advantages of PPM mainly arise from its simplicity and the ease with which the delay may be controlled. On the other hand, for the UWB system extremely fine time control is necessary to modulate pulses to sub-nanosecond accuracy.

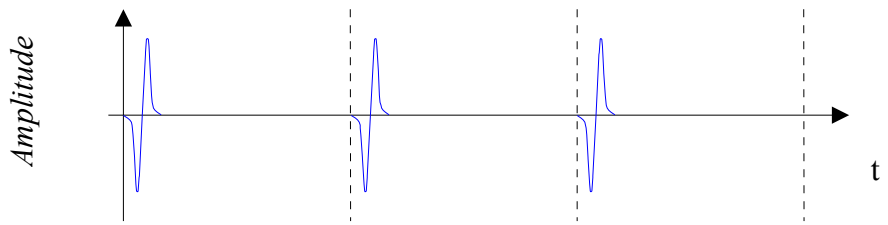
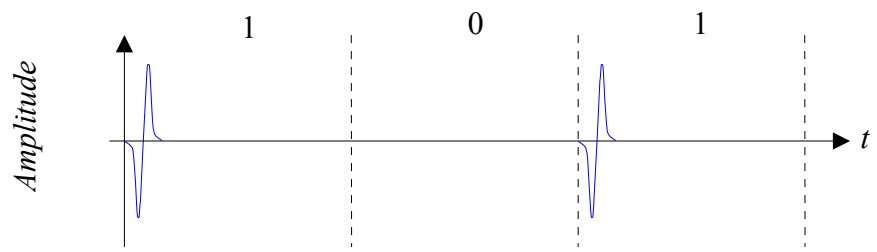


Fig. 3.3 Unmodulated pulse train

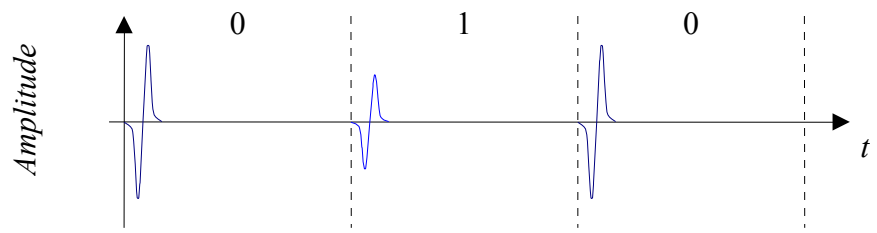
5.2.2 BPM

BPM can be defined as a kind of shape modulation. Since phase in a sinusoidal communication system is associated with the delay of a sine wave, the overuse of the term phase in UWB can be confusing. However, the use of BPM has become common in the UWB literature, so we continue to use it here. BPM is easily understood as



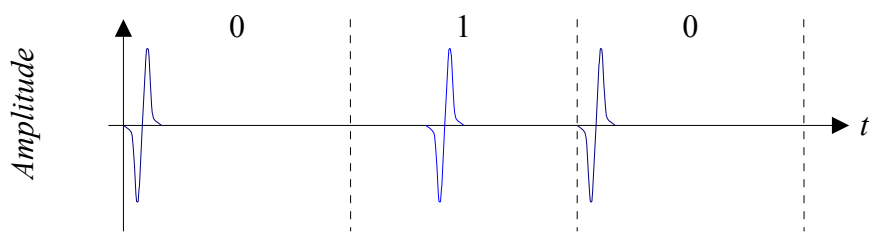
On-Off-Keying

(a)



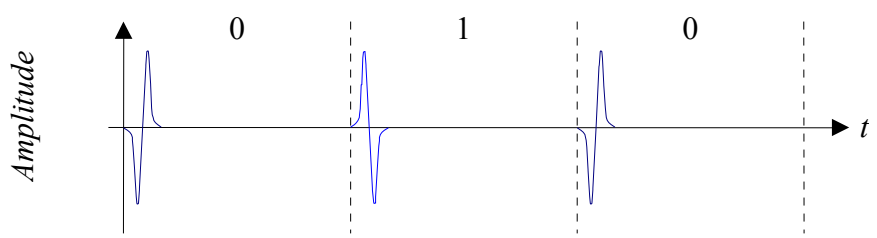
Pulse Amplitude

(b)



Pulse Position

(c)



(d)

Fig. 3.4 Pulse-Based Modulation Schemes

the inversion of a particular pulse shape; therefore, we take the equation

$$s_i = \sigma_i\, p(t), \qquad \sigma_i = 1, -1 \tag{5.2}$$

to create a binary system based on inversion of the basis pulse $p(t)$. The parameter σ is often known as the *pulse weight*, but here we will refer to it as the shape parameter. For a binary system the two resultant pulse shapes s_1, s_2 are defined simply as $s_1 = p(t)$ and $s_2 = -p(t)$.

One of the reasons for the use of BPM, especially in comparison with PPM (which is a mono-phase technique), is the 3 dB gain in power efficiency. This is simply a function of the type of modulation method. That is, BPM is an *antipodal modulation method*, whereas PPM, when separated by one pulse width delay for each pulse position, is an *orthogonal modulation method*.

A simple example can illustrate this advantage of BPM. Since PPM must always delay pulses, in the limit when pulses are transmitted continuously PPM must always 'waste' the time when pulses are not transmitted. If PPM delays by one pulse width, then BPM can send twice the number of pulses and, thus, twice the information, so as to achieve a system which, given all other things being equal, has twice the data rate. Another benefit of using BPM is that the mean of σ is zero. This has the important benefit of *removing* the comb lines or spectral peaks that were discussed in Chapter 1, without the need for 'dithering'. This of course assumes that transmitted bits are equally likely; however, this is a common and reasonable assumption in most digital communication systems. According to McCorkle [54], BPM in UWB presents several other benefits: First, it exhibits a peak-to-average power ratio of less than 8 dB. Thus, an

implementation using bi-phase does not require any external snap-recovery or tunnel diodes or power-amplifier circuitry. Instead, it can be driven directly from a low-voltage high-speed complementary metal-oxide-semiconductor (CMOS) IC. Finally, for reasons of clocking, bi-phase modulation has reduced jitter requirements. In PPM, the clocking path must include elements to accurately control arbitrary time positions on a fast (pulse-to-pulse) basis. This control requires a series of wide-bandwidth circuits where jitter accumulates. But a biphase system needs only a stable, low-phase-noise clock as the pulses occur on a constant spacing. Synchronization circuits can be narrowband so that they do not add significant jitter. As a result, less power and real estate are needed to implement the required circuits.

5.3.2 PAM

PAM for UWB can be represented as

$$s_i = \sigma_i \, p(t), \qquad \sigma i > 0 \tag{5.5}$$

where the pulse shape parameter σ takes on positive values greater than zero. As an example, we can set $\sigma_i = 1, 2$ and obtain the binary pulse set $s_1 = p(t)$, $s_2 = 2p(t)$. In general, amplitude modulation is not the preferred way for most short-range communication. The major reasons for this include the fact that, in general, an amplitude-modulated signal which has a smaller amplitude is more susceptible to noise interference than its larger-amplitude counterpart. Furthermore, more power is required to transmit the higher-amplitude pulse.

In sinusoidal systems, amplitude-modulated systems are usually characterized by a relatively low bandwidth requirement and power inefficiency in comparison with angle modulation schemes. Thus, the major advantage (low bandwidth) can be seen to be anti-ethical to UWB, and in most UWB applications power efficiency is of high importance.

5.3.3 OOK

OOK for UWB can be characterized as a type of PSM where the shape parameter s is either 0 or 1,

$$s_i = \sigma_i \, p(t), \qquad \sigma_i = 0, 1 \tag{5.6}$$

For example, the 'on' pulse is created when $\sigma_i = 1$ and the 'off' pulse when $\sigma_i = 0$; thus, $s_1 = p(t)$ and $s_2 = 0$.

The major difficulty of OOK is the presence of multipath, in which echoes of the original or other pulses make it difficult to determine the absence of a pulse. OOK is also a binary modulation method, similar to BPM, but it cannot be extended to an *M*-ary modulation method, as can PPM, PAM, and OPM.

5.3.4 Summary of UWB modulation methods

In this sub-section we conclude the discussion of modulation methods for UWB communications with Table 5.1, which summarizes the advantages and disadvantages of each of the modulation methods.

Table 5.1 Advantages and disadvantages of various modulation methods.

Modulation methods	Advantages	Disadvantages
PPM	Simplicity	Needs fine time resolution
BPM	Simplicity, efficiency	Binary only
OPM	Orthogonal for multiple access	Complexity
PAM	Simplicity	Low noise immunity
OOK	Simplicity	Binary only, low noise immunity

5.4 PULSE TRAINS

We examined the creation of single pulses in Chapter 2. In this chapter we have looked at sets of pulses which are used for the modulation of digital information onto analog pulse shapes. We now turn our attention to sequences of pulses, called pulse trains, which will be able to transmit much larger volumes of information than a single set of pulses. In general, an unmodulated pulse train $s(t)$ with a regular pulse output can be written as

$$s(t) = \sum_{n=-\infty}^{\infty} p(t - nT) \tag{5.7}$$

where T is the period or the pulse-spacing interval and $p(t)$ is the basis pulse. The effects of changing the pulse duration and repetition rate of each pulse have been examined and the results are as follows:

• Increasing the pulse rate in the time domain increases the magnitude in the frequency domain (i.e. the pulse rate influences the magnitude of the spectrum).
• The lower the pulse duration in the time domain, the wider the spectral width (i.e. the pulse duration determines spectral width).
• A random pulse-to-pulse interval produces a much lower peak magnitude spectrum than a regular pulse-to-pulse interval since the frequency components are unevenly spread over the spectrum and the addition of magnitude is less effective. Therefore, the pulse-to-pulse interval controls the separation of spectral components.

5.4.1 Gaussian pulse train

As an example of a pulse train, let us consider the Gaussian doublets of Figure 2.2 with PPM.
As briefly mentioned in Chapter 1, assuming PPM is the modulation method, there is the problem of spectral peaks when a regular pulse train is used. These energy spikes can cause interference with other RF systems at short range and limit the amount of useful energy

transmitted. One method to overcome these spectral peaks is to 'dither' the transmitted signal by adding a random offset to each pulse, removing the common spectral components. However, when we attempt communication with this model the random offset is unknown at the receiver, making it extremely difficult to acquire and track the transmitted UWB signal. Another method with similar random properties, but using a known sequence, is to use *pseudo-random noise* (PN) codes to add an offset to the PPM signal. Since these codes are known and easily reproducible at the receiver, the problem for the receiver becomes mostly acquisition of the signal, but tracking is made much easier.

5.4.2 PN channel coding

The use of a PN time shift has other benefits besides just reducing the spectral peaks resulting from regular pulse emissions. Since the PN code is a channel code it can be used as a multiple access method to separate users in a similar manner to the CDMA scheme. By shifting each pulse at a pseudo-random time interval the pulses appear to be white background noise to users with a different PN code. Furthermore, the use of PN codes makes data transmission more secure in a hostile environment. The impact of PN time offsets on energy distribution in the frequency domain is illustrated in Figure 5.5.

5.4.3 Time-hopping PPM UWB system

We can now combine the techniques introduced to build a simple UWB transmitter. We will use a time-hopping code and binary PPM, with a single reference pulse shape $p(t)$. This system is perhaps the most common in the literature (e.g., see [10]). It only requires a single template pulse for reception, and most of the complexity of this system resides in providing accurate timing for the generation of the transmitted sequence and subsequent reception. In Figure 5.6 we show the output of this simple UWB transmitter. We describe it here for the single-user case, but we can

extend it easily and simply for the multi-user case by using different time-hopping codes, which in general will be PN codes. First, we note that there is one pulse transmitted in each frame of time *Tf* . The *pulse repetition frequency* (PRF), as described previously, is

$$\text{PRF} = \frac{1}{\text{Tf}} \tag{5.11}$$

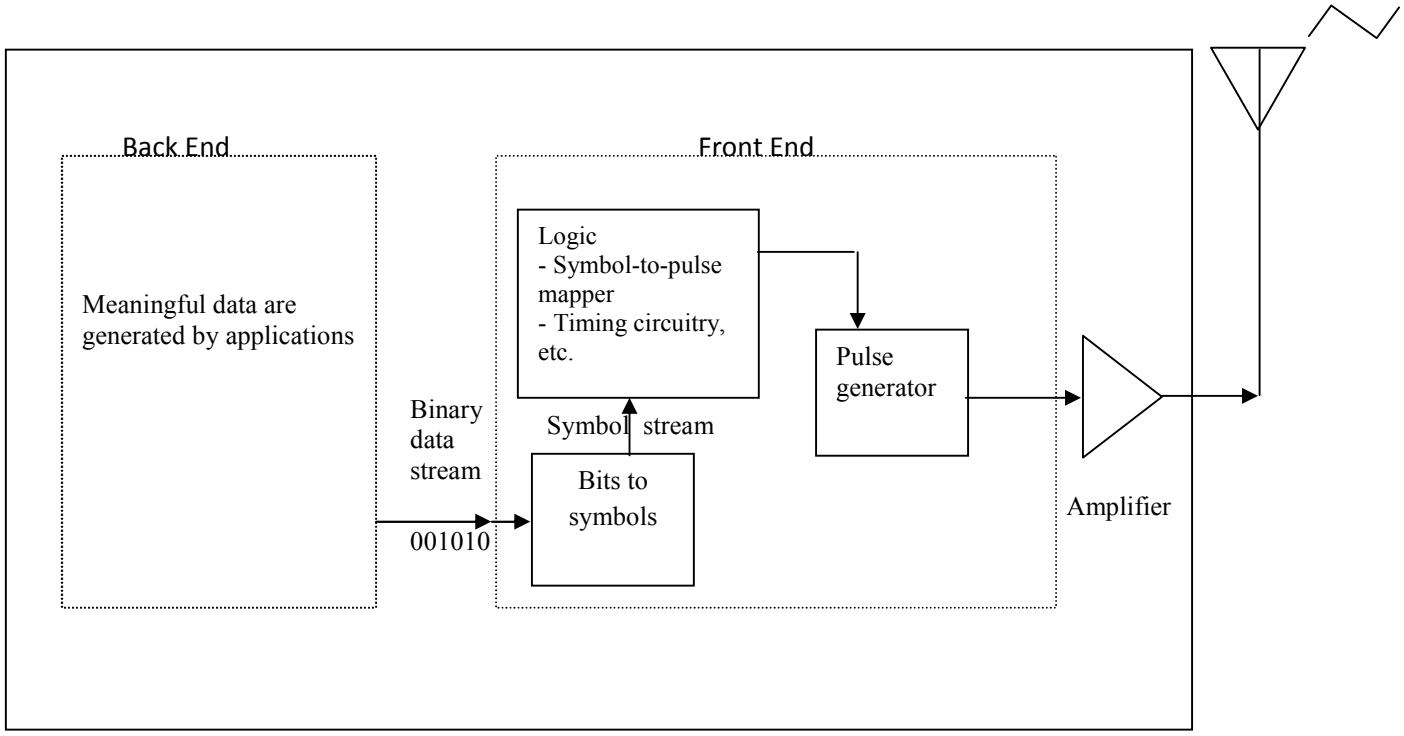
The frame time should be at least long enough to overcome the delay spread of the channel, which, as described in Chapter 4, is generally of the order of hundreds of nanoseconds for an indoor environment, in order to avoid interference from reflected pulses. Thus, the frame time will be of the order of 1000 times the actual pulse width. The unmodulated pulse stream is represented as

$$s(t) = \sum_{n=-\infty}^{\infty} p(t - nT_f) \tag{5.12}$$

Frm pres.

5.5 UWB TRANSMITTER

A general UWB transmitter block diagram is shown in Figure 5.7. First, meaningful data are generated by applications that are quite separate from the physical layer transmitter. Applications might be an e-mail client or a web browser on a personal computer, a calendar application on a personal digital assistant (PDA), or the digital stream of data from a DVD player. From the perspective of the physical layer the data may be anything at all. This part of the wireless device is often called the 'back end'. This terminology is not immediately apparent, but it is common to refer to it as from the receiver's point of view.



This binary information stream is then passed to the 'front end', which is the part of the transmitter which we are concerned about. If higher modulation schemes are to be used the binary information should be mapped from bits to symbols, with each symbol representing multiple bits. These symbols are then mapped to an analog pulse shape. Pulse shapes are generated by the pulse generator. Precise timing circuitry is required to send the pulses out at intervals which are meaningful. If PPM is employed the timing must be even more precise, usually less than one pulse width. Pulses can then be optionally amplified before being passed to

the transmitter. In general though, to meet power spectral requirements, a large gain is typically not needed and may be omitted. Although this is an extremely simplistic transmitter model, which omits any forward error-correcting scheme, it serves the purpose to show that UWB transmitters can be quite simple. This is to be compared with other wireless transmitters, such as OFDM. See Figure 5.17 for comparison.

5.6 UWB RECEIVER

A general UWB receiver block diagram is shown in Figure 5.8. The receiver performs the opposite operation of the transmitter to recover the data and pass the data to whatever 'back end' application may require it. There are two major differences between the transmitter and the receiver. The first is that the receiver will almost certainly have an amplifier to boost the signal power of the extremely weak signals received. The second is that the receiver must

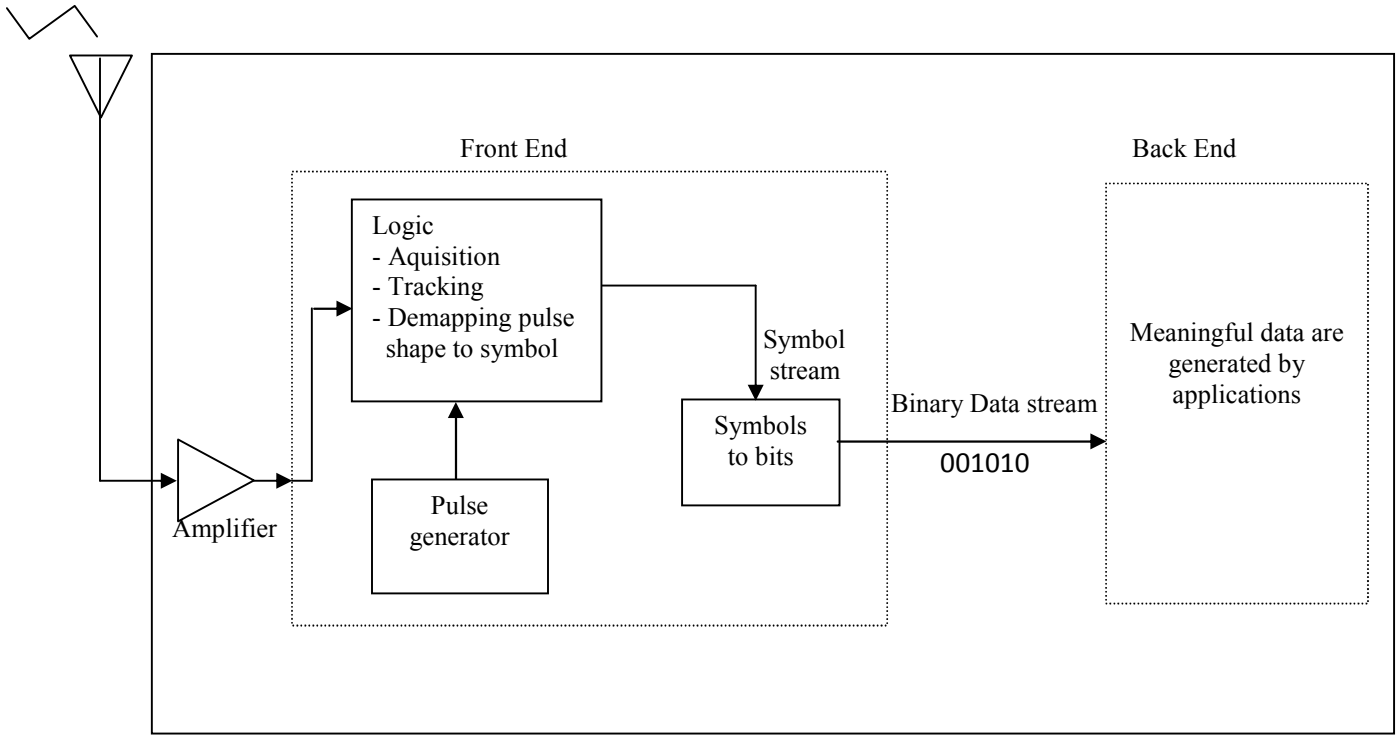


Fig. 5.8 A general UWB receiver block diagram.

perform the functions of *detection* or *acquisition* to locate the required pulses amongst the other signals and then to continue *tracking* these pulses to compensate for any mismatch between the clocks of the transmitter and the receiver. Communication requires both the transmission and reception of signals. We have mostly concentrated on the wireless transmission side up to this moment. We will now focus on the detection of pulses, that is, the acquisition and tracking of the pulse trains.

5.6.1 Detection

Having generated a signal with the desired spectral features, it is also necessary to have an optimal receiving system. The optimal receive technique, the technique often used in UWB, is a correlation receiver, usually known as a *correlator*. A correlator multiplies the received RF signal by 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. With the proper template waveform the output of the correlator is a measure of the relative time positions of the received monocycle and the template.

If we assume PPM as the modulation method the correlator is an optimal early/ late detector. As a very simple example, when the received pulse is one-quarter of a pulse early the output of the correlator is +1, when it is one-quarter of a pulse late the output is −1, and when the received pulse arrives centered in the correlation window the output is zero. It is critical to note that the mean value of the correlator is zero. Thus, for in-band noise signals received by a UWB radio the correlator's output has an average value of zero. Moreover, the standard deviation or rms of the correlator output is related to the power of those in-band noise signals.

5.6.2 Pulse integration

When a monocycle is buried in the noise of other signals, it is extremely difficult to detect a single UWB pulse and the confidence with which we can receive the transmitted information is low. However, by adding together multiple correlator samples (i.e. multiple pulses), it becomes

possible to receive transmitted signals with much higher confidence. This process is called *pulse integration*. Through pulse integration, UWB receivers can acquire, track, and demodulate UWB transmissions that are significantly below the noise floor. The measure of a UWB receiver's performance in the face of in-band noise signals is called the *processing gain*.

5.6.3 Tracking

Tracking is the process by which the receiver must continually check to see whether the pulses are arriving at the expected time and, if not, to adjust that time. A simple example will serve to show the process. Assume that the transmitter and receiver start with their clocks synchronized. As time passes the effects of heat and differences in manufacture cause one of the clocks or oscillators to become slightly faster. If this difference is not corrected, eventually the receiver will not be able to correctly demodulate the pulses. The time drift at sub-nanosecond orders must be vigilantly watched, in particular.

5.6.4 Rake receivers

As discussed in Chapter 4, the wireless channel suffers from *multipath*, where reflections and other effects of the channel cause multiple copies of the transmitted pulse to appear at the receiver. If a *rake receiver* is used, these extra pulses can be used to improve reception at the cost of increased receiver complexity. The increased complexity comes from the additional circuitry required to track multiple pulses and demodulate them. The name *rake* receiver comes from the fact that the delay profile of the received pulse looks like an upturned garden rake.

5.7 MULTIPLE ACCESS TECHNIQUES IN UWB

Up to now we have implicitly assumed that there has only been one user using the UWB system at any one time. Although consumer UWB systems are in their infancy, we must consider how best to design a UWB system where there is more than one user.

Naturally, all traditional multiple access methods should be considered; however, here we consider time, frequency, code, and space division multiple access. As an interesting special case for UWB, we look at orthogonal pulses as a novel multiple access technique.

5.7.1 Frequency division multiple access UWB

A common multiple access technique in narrowband communication is to divide users up based on frequency bandwidth. This is known as frequency division multiple access (FDMA). Each user uses a different carrier frequency to transmit and receive on. In UWB, FDMA is achieved by using pulses which have a narrower bandwidth than the total available bandwidth; however, they are still extremely broadband. Channelization can be achieved by multiplying by a sinusoidal carrier. The total effect can be thought of as an extremely broadband OFDM system.

5.7.2 Time division multiple access

In time division multiple access (TDMA), each user uses the same codes and the same bandwidth; however, a different time offset is needed to avoid interference. In general, this requires that all users be synchronized, which is not an easy task as the number of users increases. In general, this technique would only be applied to the downlink (from a central base station) to mobile users.

5.7.3 Code division multiple access

One multiple access technique possible in UWB is to assign a different spreading code to each user. This is known as code division multiple access (CDMA). As an example, let us take Equation (5.14) and modify it so that we can separate *k* users out by different code. We refer to the *k*th user's output from the transmitter as

$$S^k(t) = \sum_{n=-\infty}^{\infty} p(t - nT_f - T_{p_n}^{(k)} - T_{c_n}^{(k)})$$

In Equation (5.15) the *k*th user has a different binary data stream, so we label this $T_{p_n}^{(k)}$ however, to distinguish the user we must have a distinct time-hopping code, which we distinguish as $T_{c_n}^{(k)}$.

5.7.4 Orthogonal pulse multiple access system

As an example of OPM let us look closely at the modified Hermite orthogonal pulse system proposed by [17]. An *M*-ary communication system can be constructed from any set of orthogonal pulse shapes, such as *hn*(*t*) or *pn*(*t*). For simplicity, let us consider only modified

Hermite pulse (MHP) waveforms. We arbitrarily assume that 2-bit binary codes 00, 01, 10, and 11 are represented by MHP pulses of orders $n = 1, 2, 3, 4$. By assigning multiple-bit patterns to single pulse shapes, higher data rates can be achieved than simply by sending different pulse shapes. Furthermore, this can be extended to a coded scheme if desired.

Since MHP pulses are orthogonal, a multi-user system can be created using the same four pulse shapes, for example, by assigning MHP pulses of order $n = 1,2$ to user 1 for the binary $0,1$ and $n = 3,4$ to user 2 for $0, 1$. For a binary communication system using OPM, we wish to know whether a pulse representing either 0 or 1 is received. To achieve this, we need to generate a local copy of each pulse shape and integrate it with the received pulse. Conventionally, two complete sets of hardware are needed in order to produce two pulses of different shapes. However, because MHP shapes of lower order can be generated by integrating a pulse of higher order, a low-complexity multiple pulse generator can be constructed. We use the modified Hermite orthogonal pulse of the particular order from the first pulse generator to generate a different-order modified Hermite orthogonal pulse at the second pulse generator. The configuration of the second pulse generator is much less complex than if the different-order modified Hermite orthogonal pulses were produced from scratch based on a source signal. Also, only a single source signal is required to produce two different-order pulses. A Matlab model of the circuit to obtain double pulse generation is outlined in Figure 5.9. We can see that by utilizing one of the properties of the pulses (i.e. by differentiating or integrating them) another pulse can be created, with the order of the pulses being one more or one less than the original pulse, respectively. In Figure 5.9 the order $n = 2$ is input to the system, along with a pulse of specified width. The width of the input pulse is determined by the desired width of the output pulse and is approximately twice the length of the output pulse. While the input pulse is on the pulse will be produced, but once the input pulse is zero any output will be suppressed. In an actual circuit the power would be removed from the input, so that no output would result in any case. In particular, the additional pulse is created by integrating the output from a pulse of order n. Thus, a pulse of order $n - 1$ is created.

I. INTRODUCTION

RECENT advancements in wireless communications generated a renewed interest in ultra-wideband (UWB) techniques [or as they are alternatively referred to—*impulse radio* (IR)] for communications applications. Unlike conventional wireless communications systems that are carrier-based, UWB-based communications is baseband. It uses a series of short pulses that

spread the energy of the signal from near DC to a few gigahertz. One typical technique is to assign a window in time and shift the position of the pulse within that window. This is classical pulse position modulation (PPM). The increased interest in UWB communications is motivated by the assessment that this technology can provide high data rate communications. Very low power spectral densities and high processing gain will enable overlay and ensure only minimal mutual interference between UWB and other applications. The ultra-wide bandwidth makes communications robust with respect to multipath fading [1]–[3]. High ratio between the signal and information bandwidth (processing gain) makes this technology attractive to multiple access applications [1], [4], [5]. Since gigahertz unoccupied slices of bandwidth are not available at microwave frequencies, under FCC regulations UWB radio must be treated as spurious interference to all other communication systems. In addition, UWB radios operating over the densely populated frequency range below a few gigahertz, must contend with a variety of interfering signals. These important requirements hint to similarities between UWB and more familiar spread-spectrum (SS) technologies, such as direct-sequence (DS). In this paper, we are concerned with analyzing jam resistance properties of UWB systems. Jam resistance is provided by the SS processing gain and it is defined as the power advantage the jammer may have without disrupting communications.

UWB Waveforms

UWB emissions are constrained by FCC regulation 47 CFR Section 15.5(d), which states that "Intentional radiators that produce class B emissions (damped wave) are prohibited." Various nondamped waveforms have been proposed for IR including Gaussian [4], Rayleigh, Laplacian, and cubic monocycles [6]. In general, the goal is to obtain a flat frequency spectrum of the transmitted signal over the bandwidth of the pulse and to avoid a DC component. In this paper, we first address the jam resistance properties of a UWB system with a rectangular pulse waveform. Such analysis is important since it provides insight into the mechanisms affecting the performance of UWB. More practical waveforms can be grouped in two categories according to their time symmetry. Gaussian and Laplacian monocycles have even symmetry, while Rayleigh and cubic monocycles have odd symmetry. In this paper, in additional to the rectangular waveform, we will study UWB utilizing Gaussian and Rayleigh monocycles. Performance of the

latter entails complex mathematical formats that are difficult to reduce to closed-forms, hence, we rely mainly on computer-aided numerical analysis. For a rectangular pulse p(t) with pulsewidth, T_p we have

$$p(t)=\sqrt{\frac{1}{T_p}} \quad : \quad 0 < t < T_p \tag{1}$$

Comparing with a rectangular waveform, the principal characteristic of monocycle signals is that they have zero DC content to allow them to radiate effectively. The time domain representation of the Gaussian monocycle, $p_g(t)$ is [6]

$$p_g = A_g\,[1- (\frac{t}{\sigma} - 3.5)^2]\ \exp\,[- 0.5\ (\frac{t}{\sigma} - 3.5)^2] \tag{2}$$

where the relation between the pulsewidth T_p and the parameter σ is chosen $T_p = 7\sigma$. This pulsewidth contains 99.99% of the total energy in the Gaussian monocycle. The Rayleigh monocycle $p_r(t)$ is given by

$$p_r = A_r\,(\frac{t-3.5\sigma}{\sigma^2})\ \exp\,[- 0.5\ (\frac{t}{\sigma} - 3.5)^2] \tag{3}$$

The amplitudes A_g and A_r are chosen such that each monocycle has unit energy. Fig. 1 shows the monocycles with pulsewidth $T_p = 1$ ns.

The frequency spectra of the Gaussian and Rayleigh monocycles are given, respectively, by [6]:

$$S_g(f) = A_g\,\sqrt{2\pi\sigma^2}\,(2\pi\sigma f)^2\ \exp\,[-\frac{(2\pi\sigma f)^2)}{2}] \tag{4}$$

and

$$S_r(f) = A_r \sqrt{2\pi}\,(2\pi\sigma f)\exp\left[-\frac{(2\pi\sigma f)^2}{2}\right] \quad (5)$$

The effective bandwidth is defined as $W = f_H - f_L$, where f_H and f_L are the frequencies measured at the (- 3dB) emission points. A numerical evaluation according to this definition, shows that the Gaussian and Rayleigh monocycles have the same effective bandwidths [6]

$$W_g = W_r = \frac{0.1853}{\sigma} \quad (6)$$

Since pulsewidth $T_p = 7\sigma$, the bandwidths W_g and W_r are related to T_p as following:

$$W_g = W_r = \frac{c}{T_p} \quad (7)$$

Where c = 1.2971. Fig. 2 shows the frequency spectrums of monocycles with pulse duration $T_p = 1$ ns.

Signal Model

Consider a single-user UWB pulse position modulated and time-hopping communication system. The time-hopping binary PPM signal of a single user can be written [4]

$$B(t) = \sum_{k=-\infty}^{+\infty} \sqrt{E_p}\; p(t - kT_f - c_k T_c - a_k\delta) \quad (8)$$

$E_p \rightarrow$ Energy Per Pulse.

$T_f \rightarrow$ Pulse repetition time interval.

$c_k \rightarrow$ Time Hopping Sequence.

$c_k T_c \rightarrow$ An Additional Time Shift To The Kth Pulse.

$\delta \rightarrow$ Pulse Position Offset.

$a_k \rightarrow$ Information Binary Sequence.

$T_c \rightarrow$ it is duration of an addressable time bin.

Here,

$c_k T_c + \delta << T_f$ which means the pulse must be in it's frame.

Time Hopping Sequence (c_k) will be known to receiver side beforehand, thus $c_k T_c$ can be calculated to demodulate the signal. Here,

$c_k T_c$ =[0,0, -.07e-9, +.09e-9,0]

This additional time shift will place the pulse anywhere in a frame thus making the eavesdropper difficult to trace and demodulate the pulses.

The optimal receiver for a single user using UWB communications as defined so far, is a pulse correlation receiver. The template waveform used in the correlation receiver is given by

$$V(t) = p(t) - p(t-\delta) \tag{9}$$

For a received signal

$$Y(t) = G(t) + J(t) \tag{10}$$

Where J(t) is the interference waveform, the correlation receiver computes the decision statistic

$$D_q = \sum_{k=0}^{N_p-1} \int_{\tau+KT_f}^{\tau+(K+1)T_f} Y(t) \;\; V(t - kT_f - c_k T_c - \tau) \tag{11}$$

Where τ represents the delay with respect to the time origin and $q = [j/N_p]$. Note that we assume perfect synchronization (known τ). Decisions are made according to

$$d_q = \{ 0, \text{ if } D_q \geq 0$$
$$1, \text{ if } D_q \leq 0\} \tag{12}$$

To simplify the theoretical analysis of jam resistance performance, we make the following additional assumptions:

1) No time-hopping code is used, i.e.,$c_{k1}= 0$.
2) To derive the performance of UWB in the presence of interference, we assume 2-PPM symbols. The pulse position time shift for data "0" equals the pulsewidth, i.e.,$\delta = T_p$. Thus, the two PPM symbols are $s_1(t) = p(t)$ and $s_2(t) = p(t-T_p)$.
3) The parameter N_p is the number of UWB pulses transmitted for each data symbol. System performance is a function of the signal-to-interference ratio (SIR) per bit E_b/J_0, where $E_b = N_pE_p$ and J_0 is the interference power spectral density. The average power of the transmitted signal needs to be consistent with FCC regulations. For a given scenario (distance, pulse interval T_f, pulsewidth T_p), E_b is determined by the FCC constraint. For highest capacity $N_p = 1$. Alternatively, at the expense of capacity, $N_p > 1$ can be used to reduce the transmitted peak power. For simplicity, and without loss of generality, we assume that for each data symbol, a single UWB pulse is transmitted ($N_p = 1$). This assumption implies the information bit interval equals the UWB pulse interval, $T_b = T_f$.
4) The interference J(t) is assumed a passband signal with carrier frequency f_J. It is modeled as a continuous-time wide sense stationary zero-mean random process with bandwidth W_J and power spectral density (see Fig. 3)

$$S_J(f) = \begin{cases} J_0/2, & |f - f_J| \le W_J \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

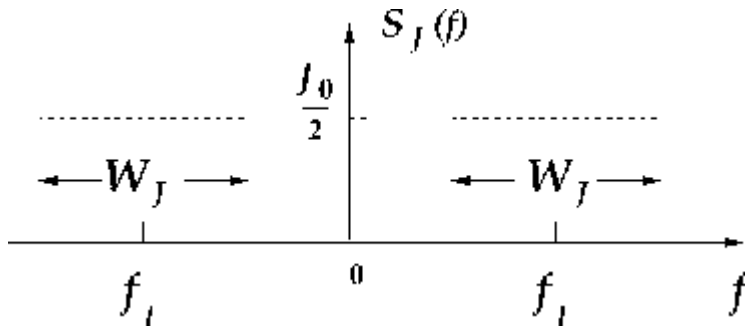


Fig. 3. Power spectral density of interference J(t).

It follows that the time autocorrelation $R_J(\tau)$ of the interference is:

$$R_J(\tau) = J_0 \frac{Sin\, \pi W_J \tau}{\pi \tau} \text{Cos}\, 2\pi f_J \tau \tag{14}$$

5) System performance is assumed interference limited. The effect of thermal noise is neglected.

With those assumptions, the signal received over a bit interval

$kT_b \le t \le (k+1)T_b$, $(-\infty < k < +\infty)$, is given by

$$Y_k(t) = \sqrt{E_p}\; p(t - kT_f - dT_p) + J(t) \tag{15}$$

where d □ {0,1} is the information bit.

Since by assumption $\int_0^{T_f} p(t)^2 dt = 1$, the cross correlation $\int_0^{T_f} p(t - dT_p) V(t) dt$ over the pulse interval T_f between the UWB pulse and the template at the receiver is 1 for d=1 and -1 for d=0 . Hence, the correlator output corresponding to an information bit is given by:

$$y(kT_b) = \int_{kT_b}^{(k+1)T_b} Y_k(t) V(t - kT_f)\,dt$$

$$= \pm\sqrt{E_p} + j(kT_b) \tag{16}$$

where $\pm\sqrt{E_p}$ corresponds to the transmitted information bit "1" and "0," respectively, and $j(kT_b)$ represents the interference component.

The interference component at the output of the correlator can be expressed

$$j(kT_b) = \int_{kT_b}^{(k+1)T_b} J(t) V(t - kT_f)\,dt$$

$$= \int_0^{T_f} J(t + kT_f) V(t)\,dt \tag{17}$$

The *processing gain* is defined as the ratio of the output to the input SIR

$$PG = \frac{SIR_{out}}{SIR_{in}} \tag{18}$$

The *jam resistance* JR is defined as the margin that the processing gain provides above the minimum SIR, SIR_D, required to meet system performance specs.

$$JR = PG - SIR_D \tag{19}$$

JR, PG and SIR_D all are in dB.

Let the average power of the interference waveform J(t) at the receiver input be P_J, and the average signal power be P_s. The average signal power can be expressed $P_s = E_p / T_b$. Then, the input SIR is given by

$$SIR_{in} = E_p / T_b P_J \tag{20}$$

From (16), the signal power at the output of the correlator is given by E_p . The interference power at the output depends on the statistical characteristics of the interference and on theUWB pulse.

$$SIR_{out} = \frac{E_p}{E[j^2(kT_b)]} \tag{21}$$

From (18) and (20), (21), the processing gain is given by

$$PG = \frac{T_b P_J}{E[j^2(kT_b)]} \tag{22}$$

The interference J(t) is modeled by a random process, hence, the functional $j(kT_b)$ defined in (17) are random variables. Since interference is assumed zero-mean and wide-sense stationary, its power at the correlator output is expressed

$$E[j^2(kT_b)] = E\left[\int_0^{T_f} J(t_1 + kT_f)\, V(t_1) dt_1 \; X \int_0^{T_f} J(t_2 + kT_f)\, V(t_2) dt_2\right]$$

$$= \int_0^{T_f} \int_0^{T_f} R_J(t_1 - t_2)\; V(t_1) V(t_2) dt_1 dt_2. \tag{23}$$

II. PERFORMANCE ANALYSIS

A. Jam Resistance With Rectangular Pulses

The mathematical model of the rectangular pulse p(t) is given in (1). At the receiver, the template for p(t) is

$$V_p(t) = \begin{cases} \sqrt{\frac{1}{T_p}} & 0 < t < T_p \\ -\sqrt{\frac{1}{T_p}} & T_p < t < 2T_p \end{cases} \tag{24}$$

Using (24) in (23), the time autocorrelation of the interference samples can be expressed

$$E[j^2(kT_b)] = 1/T_p \int_0^{T_p}\int_0^{T_p} R_J(t_1 - t_2)\, dt_1 dt_2 + 1/Tp \int_{T_p}^{2T_p}\int_{T_p}^{2T_p} R_J(t_1 - t_2)\, dt_1 dt_2$$
$$-1/Tp \int_0^{T_p}\int_{T_p}^{2T_p} R_J(t_1 - t_2)\, dt_1 dt_2 - 1/Tp \int_{T_p}^{2T_p}\int_0^{T_p} R_J(t_1 - t_2)\, dt_1 dt_2.$$

Set $t_1 - t_2 = \tau$. Since the interference is assumed wide sense stationary, $R_J(\tau) = E[J(t) - J(t-\tau)]$ and $E[j^2(kT_b)]$ can be reduced to the single integral

$$E[j^2(kT_b)] = \int_{-T_p}^{T_p} \left(1 - \frac{|\tau|}{T_p}\right)[2R_J(\tau) - R_J(\tau + T_p) - R_J(\tau - T_p)]\, d\tau. \tag{25}$$

Define the parameters $\alpha = T_pW_J$, $x = W_J\,\tau$, $\beta = T_f/T_p$ and $\gamma = f_JT_p$. Note that α is the interference time-bandwidth product over the duration of the pulse, $\beta = T_f/T_p$ is the UWB spreading ratio, and γ is number of cycles of the interference carrier frequency during an UWB pulse. Substitute $R_J(\tau)$ from (14) in (25). After some algebraic manipulations, (25) can be expressed

$$E[j^2(kT_b)] = J_0\Phi(\alpha, \gamma) \tag{26}$$

Where

$$\Phi(\alpha, \gamma) = 2\Phi_0(\alpha, \gamma) - \Phi_1(\alpha, \gamma) - \Phi_2(\alpha, \gamma) \tag{27}$$

The quantities $\Phi_0(\alpha, \gamma)$, $\Phi_1(\alpha, \gamma)$ and $\Phi_2(\alpha, \gamma)$ are defined, respectively

$$\Phi_0(\alpha, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \frac{\sin(\pi x)}{\pi x} \cos 2\pi \frac{\gamma}{\alpha} x dx \tag{28}$$

$$\Phi_1(\alpha, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \frac{\sin \pi(x+\alpha)}{\pi(x+\alpha)} \cos 2\pi \frac{\gamma}{\alpha} (x + \alpha) dx \tag{29}$$

and

$$\Phi_2(\alpha, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \frac{\sin \pi(x-\alpha)}{\pi(x-\alpha)} \cos 2\pi \frac{\gamma}{\alpha} (x - \alpha) dx \tag{30}$$

From (21) and (23), the output SIR is then given by

$$SIR_{out} = \frac{E_p}{J_0 \Phi(\alpha,\gamma)} \tag{31}$$

Since $E_p = P_s T_b$, $J_0 = P_J / W_J$, $T_b W_J = (T_p W_J)(T_b / T_p) = \alpha\beta$, we finally have

$$SIR_{out} = \frac{P_s}{P_J} \frac{\alpha\beta}{\Phi(\alpha,\gamma)} = SIR_{in} \frac{\alpha\beta}{\Phi(\alpha,\gamma)} \tag{32}$$

$$PG_{out} = \frac{\alpha\beta}{\Phi(\alpha,\gamma)} \tag{33}$$

Let us discuss further the physical meaning of the parameters α, β, and γ in (33).

1) The parameter $\alpha = W_J T_p$, serves as a measure of the ratio of the interference and the UWB bandwidths. Specifically, $\alpha \to 1$ corresponds to an interference bandwidth commensurate with that of the UWB signal, and $\alpha \to 0$ represents a narrowband interference. The latter is the case greater practical interest.

2) The variable $\beta = T_f/T_p$ is the spreading ratio of UWB signals. Typical values of β are greater than 100. The corresponding duty cycle of UWB pulses is less than 1%.
3) The parameter $\gamma = f_J T_p$ measures the number of jammer carrier cycles during the UWB pulse. Since we consider only inband interference, $0 \le \gamma \le 1$.

When the interference is narrowband such that $\alpha \to 0$, we have the following approximations:

$$\Phi_0(\alpha \to 0, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \cos 2\pi \frac{\gamma}{\alpha} x dx \tag{34}$$

$$\Phi_1(\alpha \to 0, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \cos 2\pi \frac{\gamma}{\alpha} (x + \alpha) dx \tag{35}$$

and

$$\Phi_2(\alpha \to 0, \gamma) = \int_{-\alpha}^{\alpha} \left(1 - \frac{|x|}{\alpha}\right) \cos 2\pi \frac{\gamma}{\alpha} (x - \alpha) dx \,. \tag{36}$$

Combining these result in (27), we have

$$\Phi(\alpha \to 0, \gamma) = \frac{\alpha}{(\pi\gamma)^2} (1 - cos 2\pi\gamma)^2 \,. \tag{37}$$

From (33), when $\alpha \to 0$ the processing gain for a rectangular pulse is

$$PG(\alpha \to 0) = \frac{\beta(\pi\gamma)^2}{(1 - \cos 2\pi\gamma)^2} \tag{38}$$

To evaluate the jam resistance JR (defined in (19)) of an UWB system with a rectangular pulse, we assumed that the required system performance is a bit error probability of $P_b = 10^{-6}$. For 2-PPM, the corresponding $SIR_D = 13$ dB, hence, the jam resistance JR = PG - 13 (dB).

Fig. 4 illustrates the relationship between the jam resistance and parameter γ for UWB with a rectangular pulse and spreading ratio β=100. Various cases of interference are shown

(parameterized by α). The curves in the figure (except the one labeled $\alpha \rightarrow 0$) were generated using (33). The curve for $\alpha \rightarrow 0$ was generated using (38). It is observed that the jam resistance approaches its minimum value when γ is in the neighborhood of 0.4 (corresponding to an interference carrier of $f_J = 0.4 / T_p$). Also, shown in the figure is the case of wideband interference, α=0.5 . In this case, the largest $\gamma = f_J T_p$ shown is 0.75, such that the full range of the interference bandwidth is still contained within the UWB bandwidth. In the wideband case, the jam resistance is seen to hover around the level of 7 dB (corresponding to β dB – SNR_D = 20 – 13 dB).

Some understanding of the mechanism of interference suppression in UWB PPM communications can be gained from (14) and (25). The interference power in (25) is reduced through time gating over the interval of $2T_p$ .This is the processing gain associated with the spreading-despreading operation. An additional interference suppression mechanism is obtained through the subtraction of time-shifted autocorrelation functions. From (14), it is observed that the autocorrelation of the interference takes on positive and negative values as a function of the time lag τ. From (25), the interference power is computed from subtracting values of the interference autocorrelation function. For a narrowband interference, the correlation is high, and the subtraction operation will, in general, entail an additional suppression of interference. For some values of the interference carrier, (25) results in enhanced interference (corresponding to subtracting a negative value of the autocorrelation function). For wideband interference α=0.5, this effect is diminished since the interference values become uncorrelated. Indeed, this is borne out by Fig. 4, where for α=0.5 the jam resistance is closer to the value predicted by the spreading ratio.

B. Jam Resistance With Monocycles

Two different monocycles are chosen for analysis, Gaussian and Rayleigh. Temporal and spectral characteristics of the monocycles are shown in Figs. 1 and 2, respectively. For binary PPM, the receiver correlates the received signal with the waveform $V(t) = p(t) - p(t-\delta)$, where the pulse p(t) is the appropriate monocycle.

Our goal is to evaluate the jam resistance (19), or equivalently, the processing gain (22). Using (14) in (23), we get

$$E[j^2(kT_b)] = \int_0^{T_f}\int_0^{T_f} J_0 \frac{\sin \pi W_J \tau}{\pi\tau} \times \cos 2\pi f_J \tau \, V(t_1)V(t_2)\, dt_1 dt_2 . \quad (39)$$

Set $W_J\, t_1 = t_1'$, $W_J\, t_2 = t_2'$ and recall the definitions $\alpha = T_p W_J$, $x = W_J\, \tau$, $\beta = T_f/T_p$ and $\gamma = f_J T_p$, and . Then $E[j^2(kT_b)]$ can be expressed

$$E[j^2(kT_b)] = J_0 \Theta(\alpha, \gamma) \quad (40)$$

Where $\Theta(\alpha, \gamma)$ is given by the expression

$$\Theta(\alpha, \gamma) = \int_0^{2\alpha}\int_0^{2\alpha} \frac{\sin \pi(t_1' - t_2')}{\pi(t_1' - t_2')} \times \cos 2\pi \frac{\gamma}{\alpha}(t_1' - t_2')\, V(\frac{t_1'}{W_J})V(\frac{t_2'}{W_J})\, dt_1' dt_2' . \quad (41)$$

Since by assumption $E[J(t)] = 0$, clearly the mean value of the interference component at the output of the receiver $E[j(T_b)] = 0$. From (22) and (40), the UWB processing gain for monocycles is given by

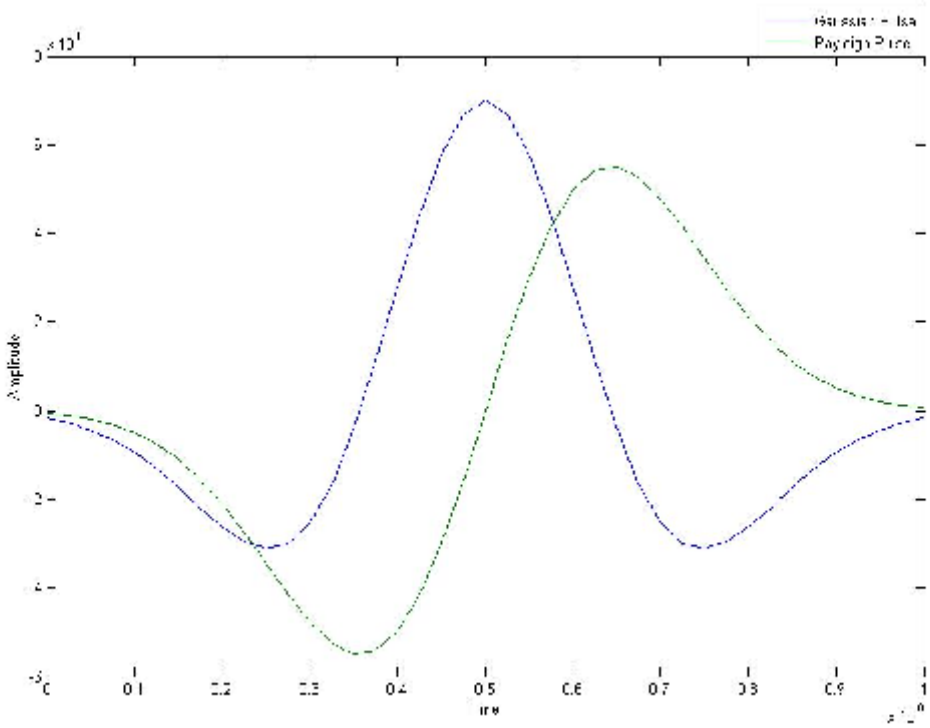
$$PG = \frac{\alpha\beta}{\Theta(\alpha,\gamma)} \quad (42)$$

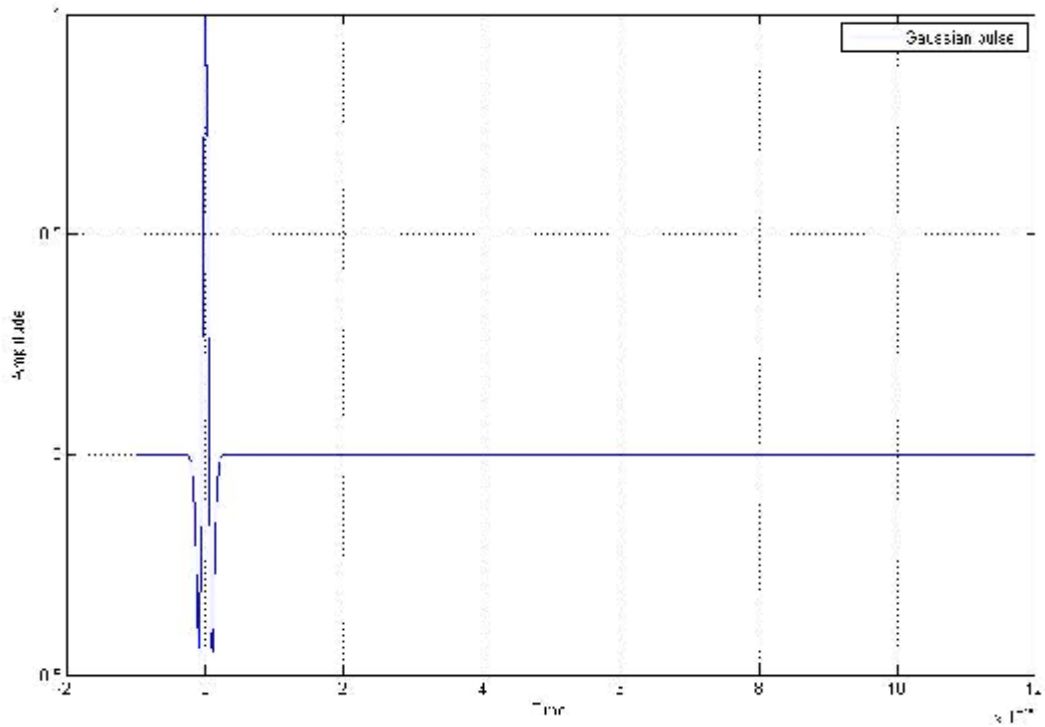
Where $\Theta(\alpha, \gamma)$ is computed for either the Gaussian or Rayleigh monocycle.

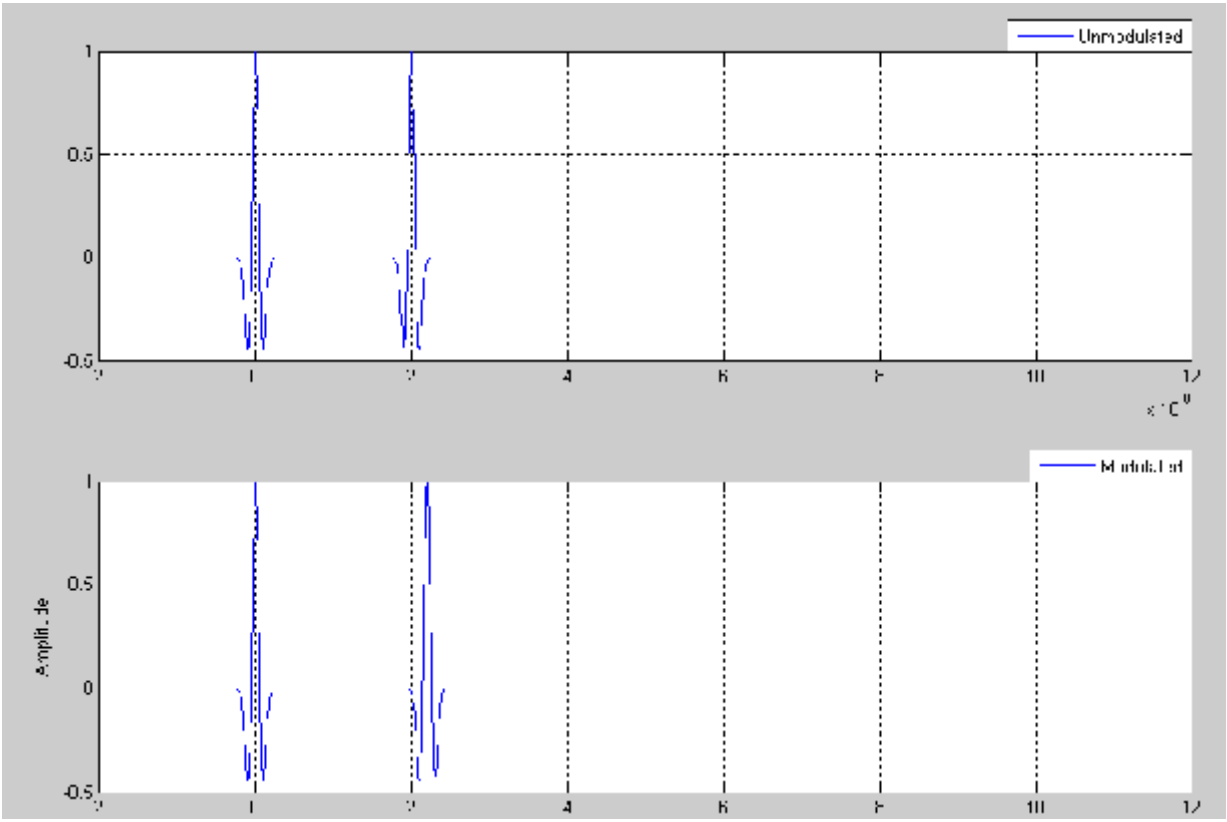
Comparing the processing gain of monocycles in (42) with that of the rectangular pulse in (33), we observe that they have the same format except for the different factors Θ and Φ, which are determined by the specific pulse waveform.

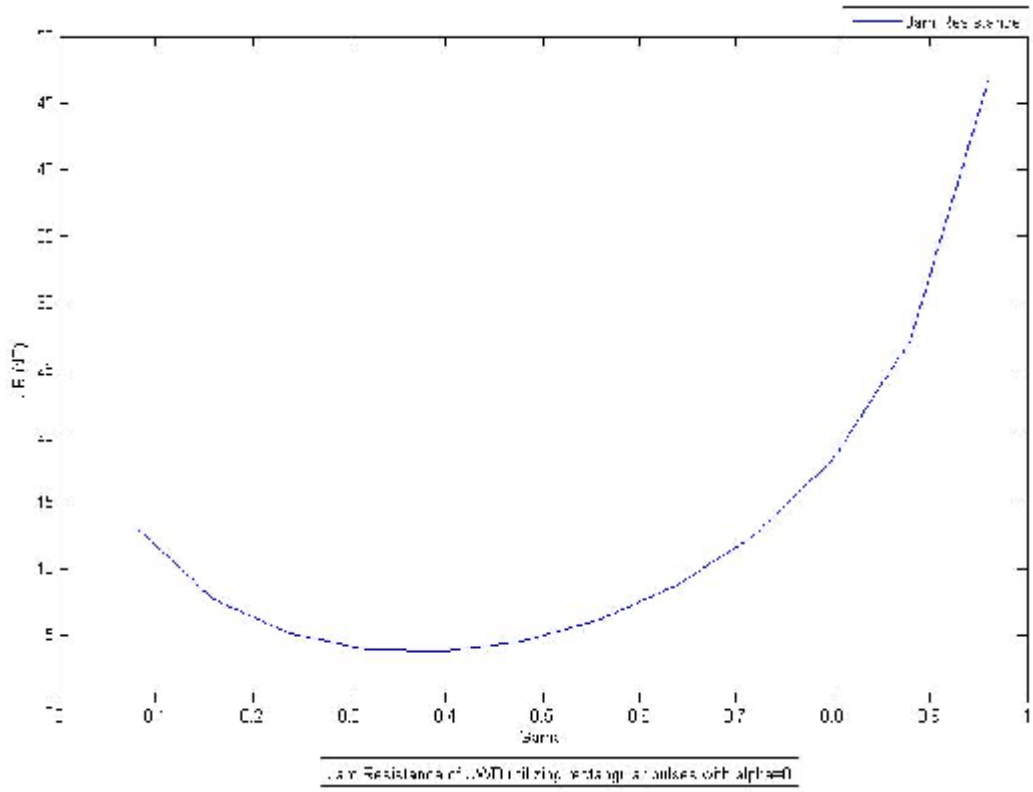
Similar to the analysis for rectangular pulse, we chose a spreading ratio of β=100 for computing the jam resistance of monocycles. In Fig. 5, jam resistance of three types of waveforms is plotted for an interference carrier with $0 < \gamma < 1$ and two values of the interference time-bandwidth product over the duration of the UWB pulse. Other than the case of $\gamma > 0.6$, the suppression ability of the monocycles significantly exceeds that of the rectangular pulse. For all waveforms,

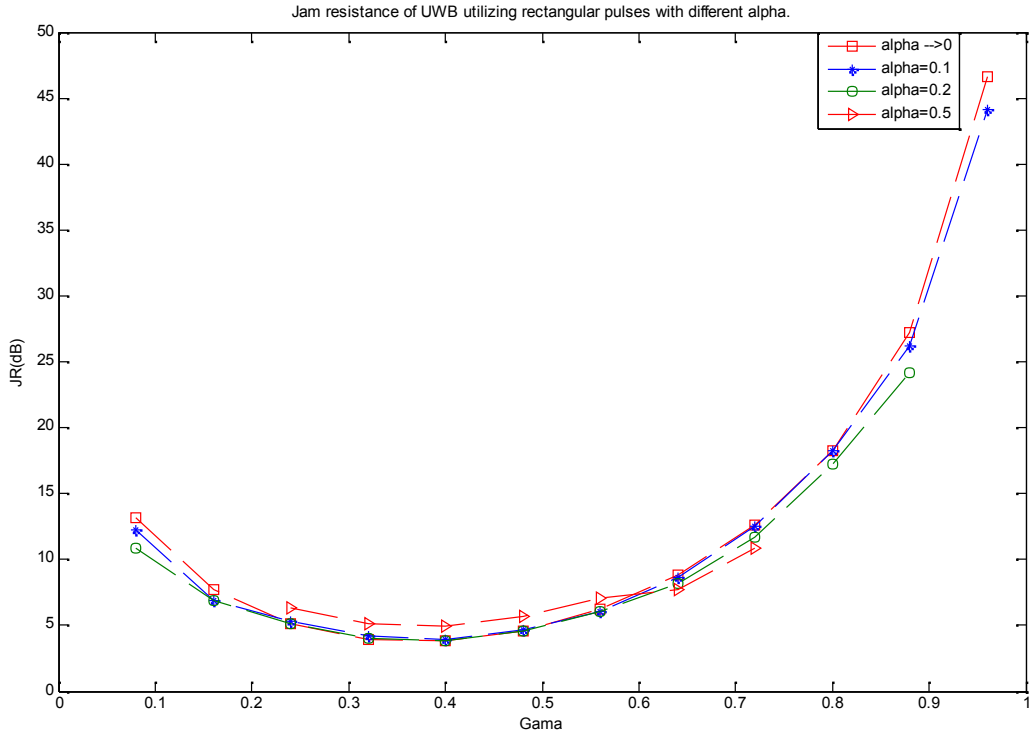
the curves for $\alpha = 10^{-1}$ almost overlap with those for $\alpha = 10^{-3}$. The Gaussian pulse provides the highest overall jam resistance. The different performance of the Gaussian and Rayleigh pulses can be explained from the frequency domain characteristics of the pulses and interference. The performance evaluation in this paper is done with predominantly low frequency interference. From Fig. 2, it is obvious that the UWB Gaussian pulse matched filter will filter out more of the low frequency interference than the Rayleigh pulse matched filter.

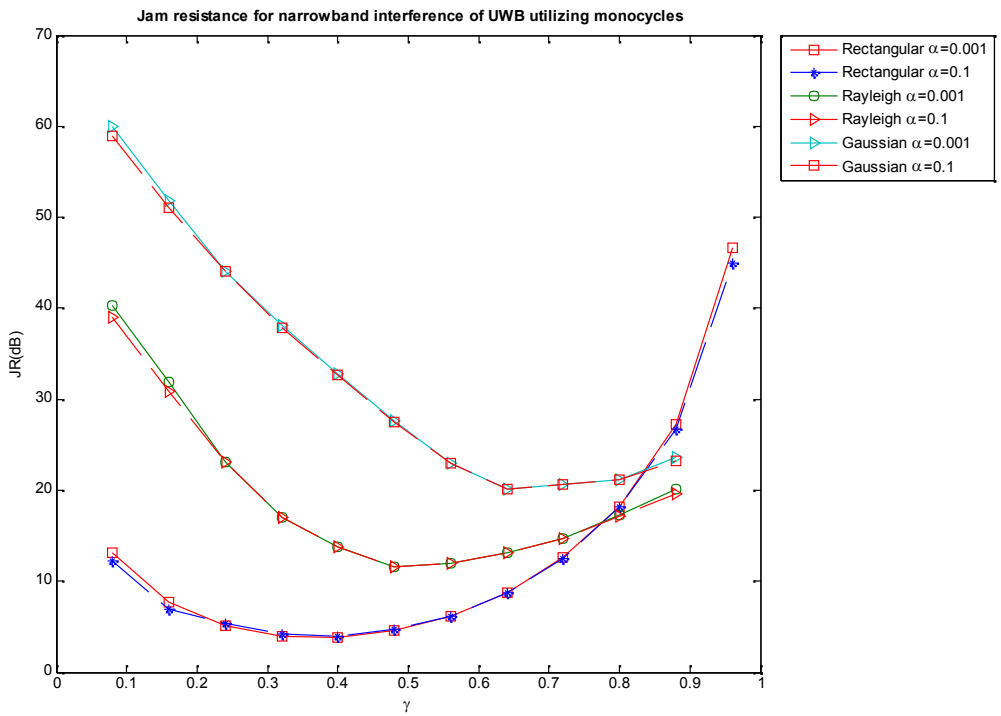


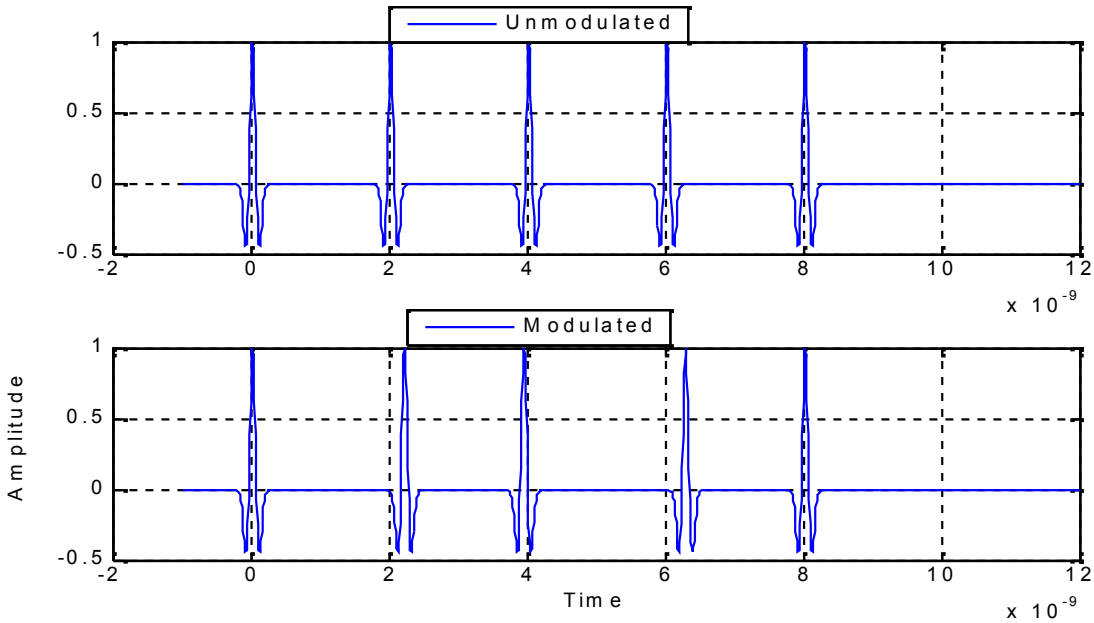

Gaussian pulse
Amplitude
Time

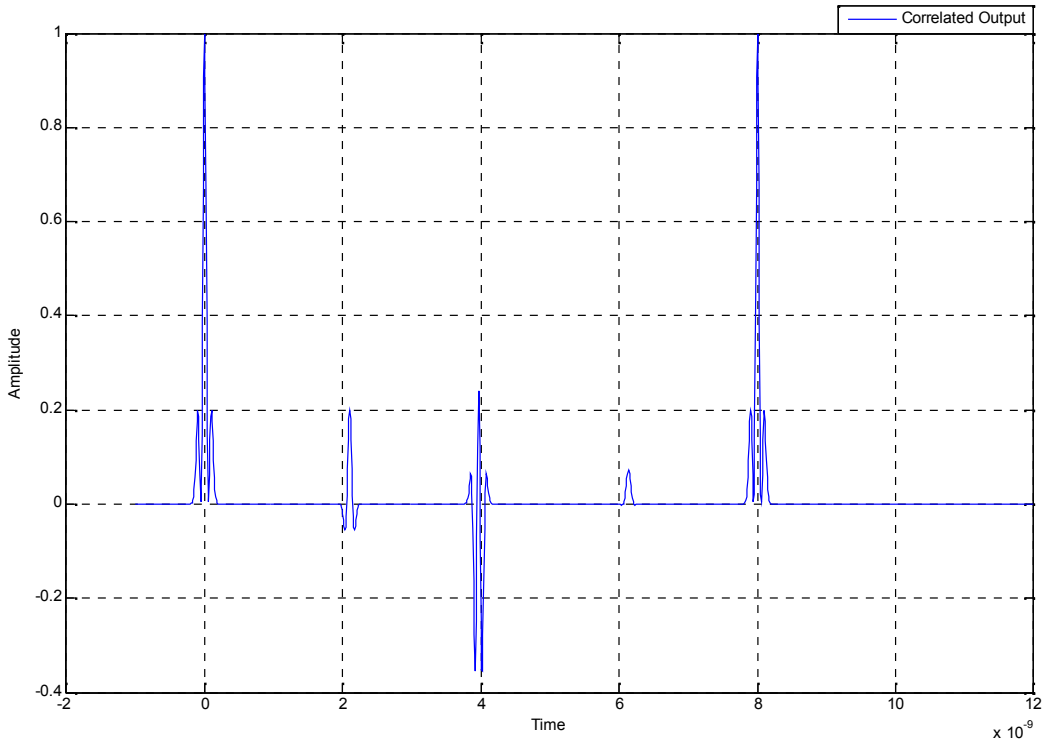

Unmodulated
Modulated
Amplitude

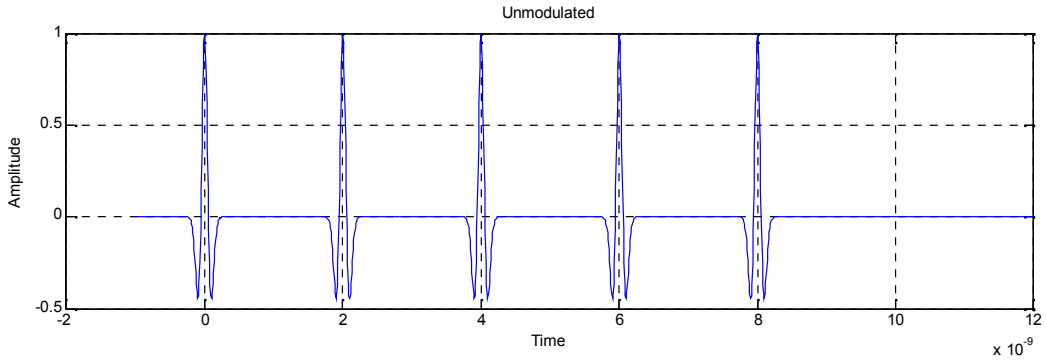


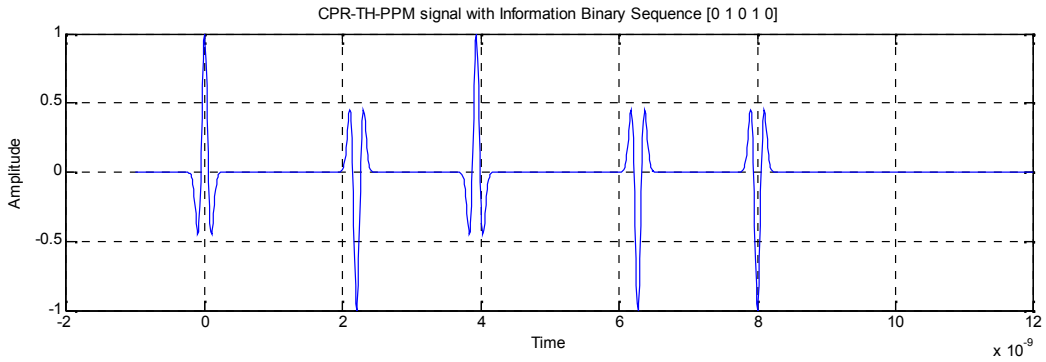

Jam resistance of UWB utilizing rectangular pulses with different alpha.
alpha -->0
alpha=0.1
alpha=0.2
alpha=0.5
JR(dB)
Gama
0
5
10
15
20
25
30
35
40
45
50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

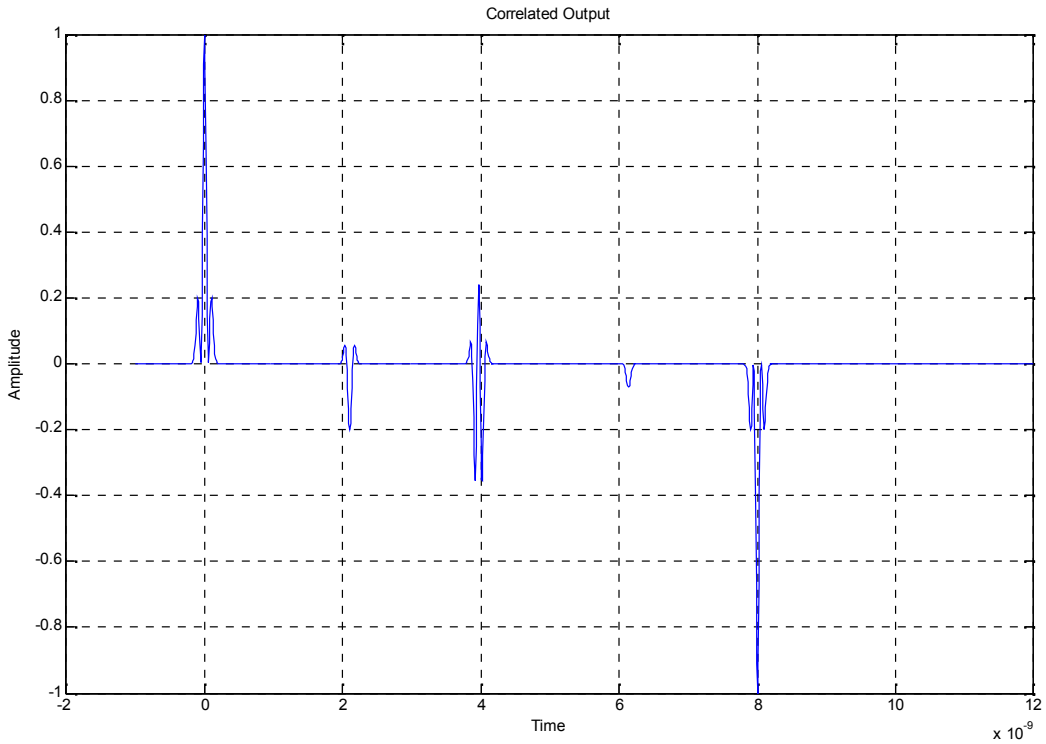

Jam resistance for narrowband interference of UWB utilizing monocycles
JR(dB)
γ
Rectangular α=0.001
Rectangular α=0.1
Rayleigh α=0.001
Rayleigh α=0.1
Gaussian α=0.001
Gaussian α=0.1

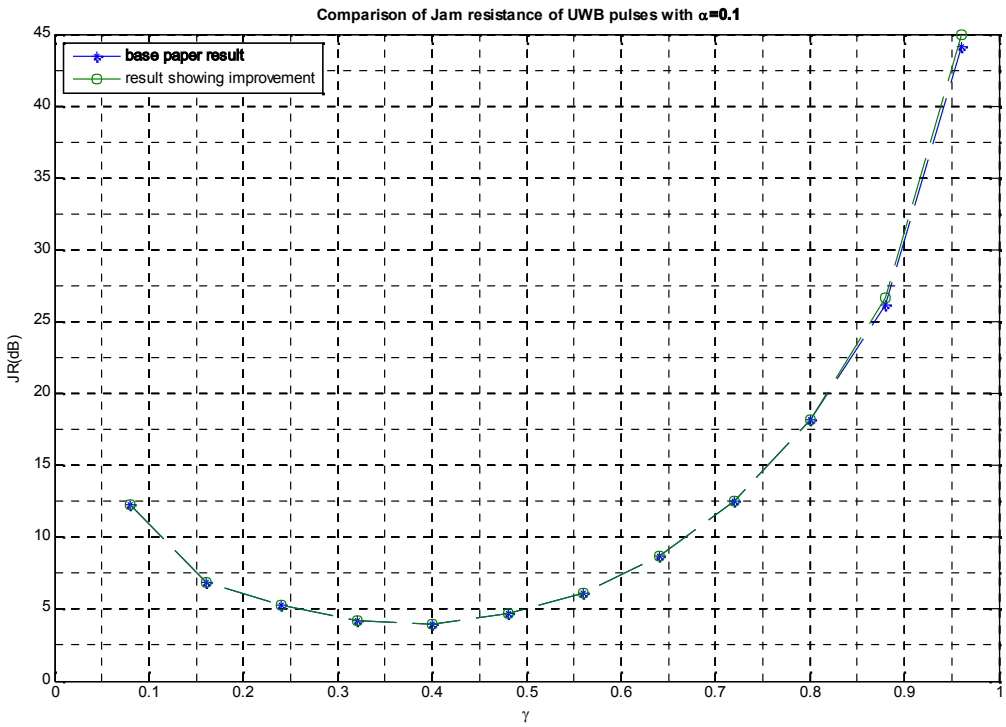

Unmodulated
Modulated
Amplitude
Time
x 10^-9

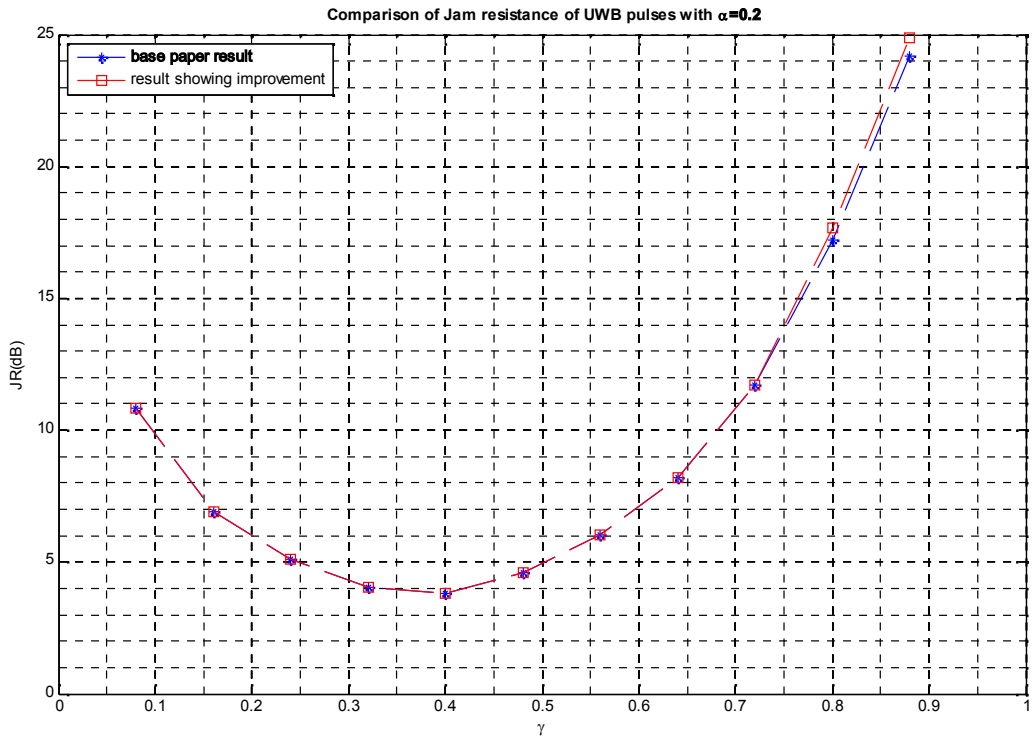

Correlated Output
Amplitude
Time
x 10^-9
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-2
0
2
4
6
8
10
12

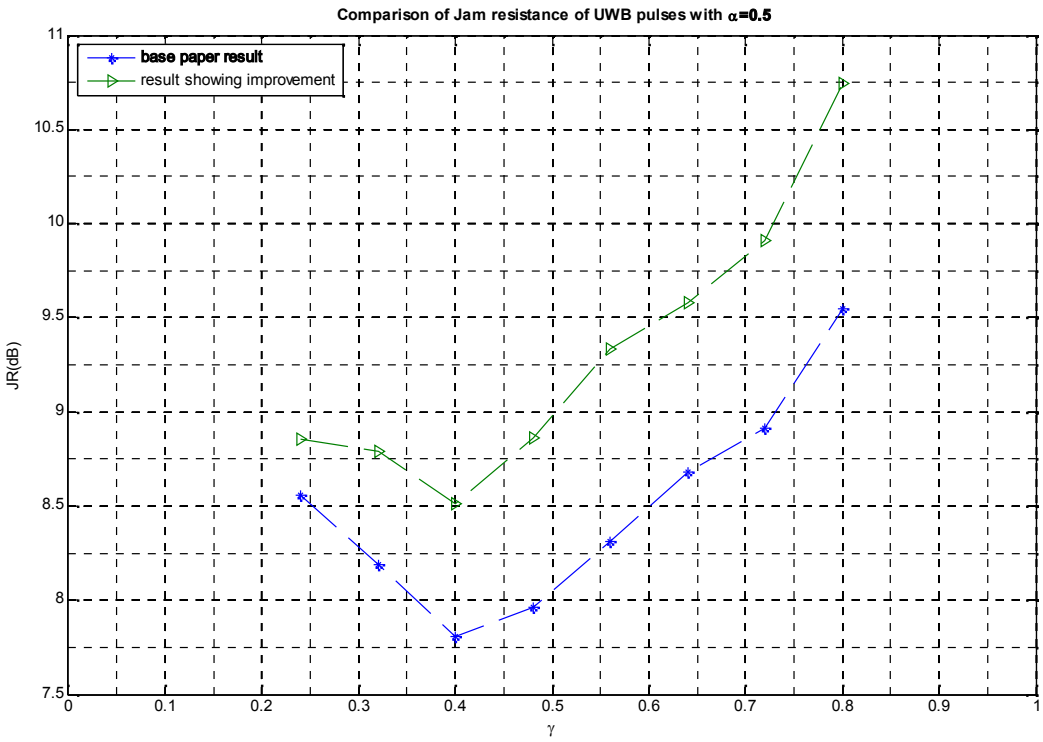

Unmodulated
Amplitude
Time
x 10^-9


CPR-TH-PPM signal with Information Binary Sequence [0 1 0 1 0]
Amplitude
Time
x 10^-9


Correlated Output
Amplitude
Time
x 10^-9


Comparison of Jam resistance of UWB pulses with α=0.1
base paper result
result showing improvement
JR(dB)
γ
0
5
10
15
20
25
30
35
40
45
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Comparison of Jam resistance of UWB pulses with α=0.2
base paper result
result showing improvement
JR(dB)
γ
0
5
10
15
20
25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Comparison of Jam resistance of UWB pulses with α=0.1

For the value of γ	Base paper result (dB)	Improved result (dB)
0.91	31	31.5
0.95	42.5	43.5
0.96	43.5	45

Comparison of Jam resistance of UWB pulses with α=0.2

For the value of γ	Base paper result (dB)	Improved result (dB)
0.77	15	15.4
0.80	17.2	17.8
0.87	24.1	24.9

Comparison of Jam resistance of UWB pulses with α=0.5

For the value of γ	Base paper result (dB)	Improved result (dB)
0.4	7.8	8.5
0.7	8.6	9.6
0.8	9.6	10.75

CHAPTER 5

CONCLUSION AND FUTURE WORK

We analyzed the performance of UWB with binary PPM in the presence of interference. Closed-form expressions were provided for the jam resistance of a PPM UWB system utilizing rectangular pulses. A simple closed form approximation was obtained for the special case of narrowband interference. The analysis was then extended to two more practical UWB waveforms, namely Gaussian and Rayleigh monocycles. Jam resistance of UWB utilizing rectangular pulses with different "α" has been plotted and shown how the jam resistance differ for $\alpha \rightarrow 0$, $\alpha=0.1$, 0.2 and 0.5. Jam resistance for narrowband interference of UWB utilizing monocycles has been plotted. For $\alpha=0.1$ and $\alpha=0.001$ jam resistance utilizing Rayleigh and Gaussian monocycles has been shown. Jam resistance utilizing rectangular pulse for $\alpha=0.1$ and $\alpha=0.001$ has been plotted for the comparison in the same figure.

For making more secure time hopping pulse position modulation (TH-PPM) and coded phase reversal time hopping pulse position modulation (CPR-TH-PPM) were taken in to consideration. For time hopping pulse position modulation an additional time shift sequence was taken and plotted. Correlated output has been plotted which shows how the modulated pulses are shifted w.r.t. unmodulated pulses on time scale. For coded phase reversal time hopping pulse position modulation a pseudo random code was taken to plot the modulated pulses with above additional time shift sequence. Correlated output plot shows how the modulated pulses are shifted and in phase difference w.r.t. unmodulated pulses on time scale.

Jam resistance for the coded phase reversal time hopping pulse position modulation has been plotted for α=0.1, 0.2 and 0.5. For first and second value of α jam resistance is showing a small improvement. Jam resistance is further enhanced for the third value of α. Comparison table which illustrates the improved jam resistance for the above three values of α.

Further the jam resistance for other monocycles like Laplacian and cubic monocycles can be exploited. Jam resistance for the above two monocycles can be further calculated for the different forms of pulse position modulation. Comparison can be drawn for all four different monocycles i.e Gaussian, Rayleigh, Laplacian and cubic monocycles.