

PERFORMANCE ANALYSIS AND EFFECT OF MULTIUSER INTERFERENCE
FOR ULTRA-WIDEBAND COMMUNICATIONS

by

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ABSTRACT

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Ultra-Wideband (UWB) is an upcoming technology for short-range high data rate applications like Wireless Personal Area Networks or medium/long-range low data rate applications like sensor networks. UWB has many captivating characteristics such as very short duration pulses (order of nanoseconds), multipath channel, large instantaneous bandwidth and time hopping pulse trains resulting in coexistence with the existing narrow band users. The Ultra Wideband communication systems employ the technique of Impulse radio of transmitting short duration pulses which result in extremely wide bandwidth and many performance benefits. Since UWB systems operate in dense multipath environments, RAKE receiver is the optimum choice for the receiver. Considering the evolving nature and the wide applications of this technology, it is important to analyze the system performance for different scenarios including the multi-user environment.

My thesis mainly targets the analysis of the bit error rate (BER) performance of the time hopping pulse position modulation (TH-PPM) UWB system with the use of Ideal Rake Receiver and the performance degradation when the Selective and Partial Rake receivers are employed. I have also analyzed the effect of changing the repetition code length on the performance. The performance analysis is carried out for varying the modulation index M by employing 4-PPM

instead of Binary PPM and simulation results show that 4-PPM offers a worse performance to the binary PPM case. Furthermore, I have evaluated the performance in the presence of Multi-user Interference using the Standard Gaussian Approximation. Finally, the performance of employing M-ary PPM in the multi-user scenario is also evaluated. The simulations are performed under the assumption of perfect channel knowledge. The IEEE UWB indoor channel model is used for Non Line of Sight (NLOS) Case C which is for 4 to 10 m distance between the transmitter and the receiver.

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CHAPTER 1
INTRODUCTION
1.1 Introduction

Wireless communication systems have evolved enormously and the ever increasing demand for wireless services is driving the wireless market to grow explosively. The goal of achieving flexible data rates, demand for higher capacity and wide variety of applications under the constraint of available resources like bandwidth and power along with co-existence with current wireless devices is a challenging task. This is where the ultra wideband communication systems come to the rescue. The Ultra wideband as the name suggests have enormous bandwidths available and has wide scope of data rate/range tradeoffs. With its enormous bandwidths, it promises to offer much higher capacity than the narrowband systems. The Ultra wideband communication systems can co-exist with the other licensed and unlicensed narrowband systems. The potential for very low cost operation is leading to its pervasive usage.

Ultra wideband communication systems have wide applications ranging from short range high data rate applications like wireless personal area networks, wireless telemedicine and many more. Long range low data rate applications include wireless sensor networks and radar imaging systems including ground and wall penetration sensors to name a few. Its application positioning technologies with a potential of sub-decimeter accuracy, suitability for wireless sensor networks due to its simple, low cost, low-power transceiver circuitry, robustness to eavesdropping due to used time hopping pseudo random (TH-PN) sequences, and easier material penetration because of wide frequency range are some of the benefits.

Performance measurement of the ultra wideband communication system is an important issue. In this thesis, I have made analysis taking into consideration different parameters that affect the UWB communication. The analysis is made on the Bit error rate performance. The Ultra wideband system is designed utilizing the Time hopping pseudo random

codes and employing the pulse position modulation scheme. The IEEE UWB indoor channel model for Case C that is the non line of sight (NLOS) case for a distance of 4 to 10 m between the transmitter and the receiver is considered for the analysis. The performance analysis is carried out for different receiver configurations including the Ideal Rake, the Selective rake and the Partial Rake receivers. Furthermore, the effect of changing the repetition code length on the performance of the UWB system is analyzed. Another parameter that affects the UWB performance is the interference. When there are multiple users present, in addition to the thermal noise, the multi-user interference is also caused which hampers the performance of the system. The analysis is carried out for varying number of interfering users present to observe the effect of increasing interfering users to the BER performance. Another parameter which affects the UWB system is the modulation technique. The effect of changing the value of the modulation index for the pulse position modulation is analyzed. The analysis is carried out for the performance of binary PPM versus that of the M-ary pulse position modulation with $M = 4$. Finally, performance analysis is also carried out when both M-ary PPM is employed along with the presence of multi-user interference.

1.2 Scope and Organization of Thesis

Considering that Ultra wideband is a rapidly evolving technology and the number of benefits it offers, I believe that it is important to analyze the performance of the Ultra wideband communication system and if it satisfactorily performs even when there are number of users operating simultaneously. The thesis explores the fundamentals of the UWB technology and emphasizes on the physical layer system design and the performance analysis of the system.

The thesis is organized into four more chapters. The Chapter 2, "Ultra Wideband Communications" introduces the core concepts of the ultra wideband technology and discusses about the several advantages and applications of the technology. The Chapter 3, "UWB System" is devoted to the UWB system design beginning with the channel model, the UWB transmitter and the receiver design. Finally, the performance is analyzed for the binary pulse

position UWB system and the simulation results are presented for the different receiver configurations. The Chapter 4, "M-ARY and Multi-user UWB system" analyzes the effect of changing the pulse position modulation to 4-PPM case and also the effect of multi-user environment. The simulation results are presented for the UWB system for 4PPM and multi-user environment. Finally, Chapter 5, "Conclusions and future work" summarizes about the results achieved for the different cases in the previous chapters and discusses about what possible work can be done to extend the work presented in this thesis.

CHAPTER 2

ULTRA WIDEBAND COMMUNICATIONS

2.1 Introduction

Ultra Wideband communications has been an extremely evolving technology because of its appealing characteristics like achieving high data rates, more capacity as compared to narrowband systems, co-existence with the existing narrowband wireless technologies.

A signal is categorized as UWB if its bandwidth is very large with respect to its center frequency. That results that the fractional bandwidth should be very high. The UWB refers to electromagnetic waveforms that are characterized by an instantaneous fractional energy bandwidth greater than about 0.2-0.25. The energy bandwidth is characterized by the frequencies f_H and f_L which limit the interval where most of the instantaneous energy of the waveform lies.

$$energyBW = f_H - f_L$$

$$f_C = \frac{f_H + f_L}{2}$$

$$fractionalBW = \frac{energyBW}{f_C} = \frac{(f_H - f_L)}{\frac{(f_H + f_L)}{2}}$$

The Federal Communications Commission (FCC) states a signal to be a UWB signal if its fractional bandwidth is greater than 0.2 or if the bandwidth is greater than 500MHz. UWB is based on the generation of very short duration pulses of the order of picoseconds. The information of each bit in the binary sequence is transferred using one or more pulses by code repetition. This use of number of pulses increases the robustness in the transmission of each bit. In UWB communications there is no carrier used and hence all the references are made with respect to the centre frequency.

In Ultra wideband communications, a signal with a much larger bandwidth is transmitted and thus with a reduced power spectral density. This approach has a potential to produce signal which has higher immunity to interference effects and improved time of arrival resolution. Ultra wideband communications employ the technique of impulse radio. Impulse radio communicates with the help of base band pulses of very short duration of the order of nanoseconds, thereby spreading the energy of the signal from dc to few gigahertz. The fact that the impulse radio system operates in the lowest possible frequency band that supports its wide transmission bandwidth means that this radio has the best chance of penetrating objects which become opaque at higher frequencies. Impulse radios operating in the highly populated frequency range below a few gigahertz must contend with a variety of interfering signals. They must also guarantee that they do not interfere with the narrow-band radio systems operating in dedicated bands. These requirements necessitate the use of spread spectrum techniques. A means of spreading the spectrum of the ultra wideband pulses is to employ time hopping with data modulation accomplished by additional pulse position modulation at the rate of many pulses per data symbol. The use of signals with gigahertz bandwidth means that multipath is resolvable down to path differential delays on the order of nanoseconds or less i.e. down to path length differentials on the order of foot or less. This significantly reduces fading effects even in indoor environments.

2.2 Benefits of UWB

Ultra wideband communications is becoming a very popular technology due its numerous features which make it attractive for consumer communications applications. The key benefits of UWB are as summarized below:

- (1) High Data rates;
- (2) Potentially low complexity and lost equipment cost;
- (3) Resistant to severe multi-path and jamming;
- (4) Very good resolution for location and tracking applications.
- (5) Co-existence with existing narrowband technologies.

1. High Data rates

The high data rates are one of the most alluring aspects of UWB. UWB systems offer very high data rates for communications of the order of 100 Mbps have been demonstrated and the potential for much higher data rates is estimated. The very high bandwidth is the reason for the possible high data rates.

According to the Shannon's capacity equation, the capacity is directly proportional to the bandwidth of the channel.

$$C = B \log \left(1 + \frac{S}{N} \right)$$

The capacity can be improved by increasing the bandwidth, increasing the signal power and decreasing the noise power. The capacity of the channel increases linearly with the increase in bandwidth, but only logarithmically with the increase in signal power. UWB channel has a very large bandwidth and from Shannon's equation it is clear that UWB systems have the potential of very high-capacity wireless communications.

The figure below is a depiction of where Ultra Wideband Technology stands in comparison to other wireless technologies in terms of data rates and the range of service. As seen in the figure below UWB promises to deliver data rates of more than 100 Mbps to about 1Gbps. But its service range remains within the band of 1 to 10 m. GSM, CDMA, WCDMA promises a very large range of 10 to 100 Km but trades off with the data rates provided which lie in the range of 100 Kbps to 1 Mbps and 10 Mbps for WCDMA with HSDPA. The IEEE 802.11 family promises data rates between 11 Mbps to 54 Mbps with 802.11n promising very high data rates of 200 Mbps to 500 Mbps.

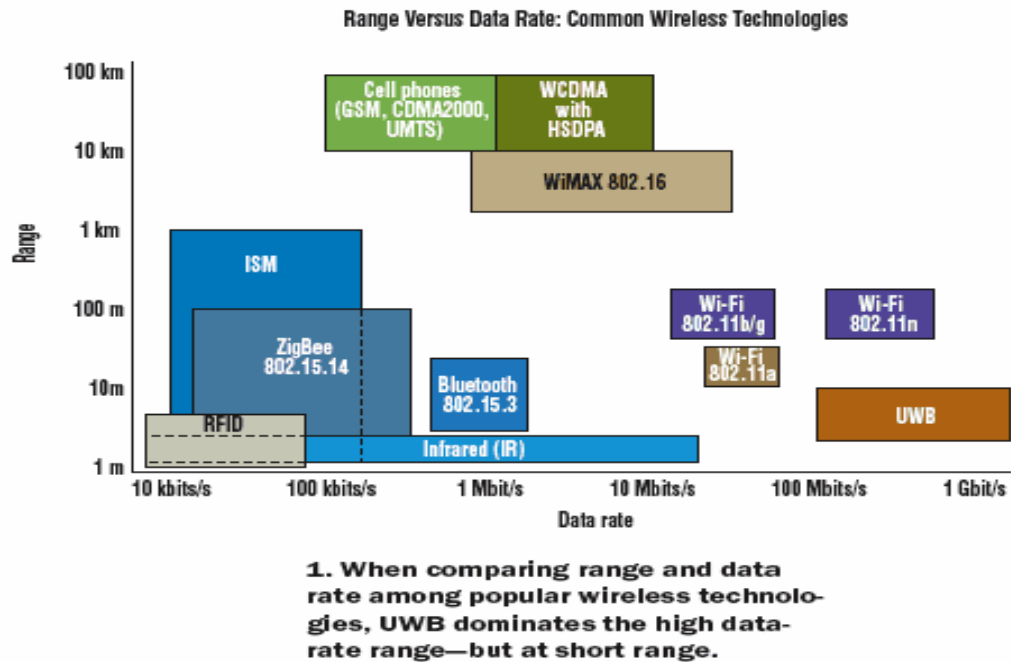


Figure 2.1 Range versus Data Rate for Common Wireless Technologies

With current chipsets, most UWB communication applications are targeting the range of 100-500Mbps which is roughly equivalent to wired Ethernet to USB 2.0. UWB data rate is 100 to 500 times that of Bluetooth, 50 times the speed of 802.11b and 10 times that of 802.11a standards. The table below summarizes the comparison of current wired and wireless standards with the UWB indoor wireless transmission.

The 110Mbps speed for a minimum transmission distance of 10m will cover and average room and suitable for wireless connectivity with home theater. The 4m speed can be used for communication between home appliances like the home server and the television and the 1m can be used for personal computer appliances.

Table 2.1 Comparison of UWB bit rates with other wired and wireless standards

Speed [Mbps]	Standard
480	UWB, USB 2.0
200	UWB (4 m minimum)
110	UWB (10 m minimum)
90	Fast Ethernet
54	802.11a
20	802.11g
11	802.11b
10	Ethernet
1	Bluetooth

2. Potentially Low complexity and low equipment cost

The base-band nature of the UWB signal transmission leads to low complexity and low cost UWB systems. The UWB transmitter produces very short time duration pulses which are able to propagate without the need of an additional RF mixing stage. The frequency translation of the signal is carried out by the mixing stage by taking a baseband signal and injecting a carrier frequency. The wideband nature of the UWB signal means it spans frequencies used by the carrier and the signal will propagate without the need of any up-conversion. The local oscillator and the complex delay and phase tracking loops are omitted at the receiver as there is no need of down-conversion of the signal. Thus, the transceiver circuitry of the UWB systems is low cost and simple, since no frequency translation, signal recovery and or power amplifiers are employed. Hence, the UWB systems can be implemented in low cost, low power integrated circuits.

3. Resistant to severe multi-path and jamming

UWB signal is noise-like due to the low energy density and the pseudo-random characteristics of the transmitted signal. Hence, unintended detection is difficult. Also due to low power UWB signals do not cause significant interference to existing radio systems. Very high multi-path resolution can be achieved due to the large bandwidth of the UWB transmitted signal. Since its bandwidth is much larger than the coherence bandwidth of the channel and any deep fades affect only a small portion of the total bandwidth, robustness against channel fading is achieved without the need of multiple antenna transceivers. UWB systems offer good low probability of interception/detection. The large bandwidth along with discontinuous transmission makes UWB signal resistant to severe multi-path interference and jamming.

4. Very good resolution for location and tracking applications

The very narrow time domain pulses offer better timing precision in UWB radios than compared to other radio systems. UWB signals offer opportunities for short range radar applications. Simultaneous automotive collision avoidance radar and communication giving accident-free smooth traffic flow is possible with the help of UWB as both precise ranging and high-speed communication in the same wireless device is possible with the help of UWB.

5. Co-existence with existing narrowband technologies

UWB radio signals must coexist with other radio signals. Possible interference from and onto other communication systems must be contained within regulated values that indicate the maximum tolerable power to be present in the air interface at any given frequency, as set by the emission masks. The power limitation set by the emission masks is on the effective radiated power, which is the Effective Isotropic Radiated Power (EIRP) for a given range of operating frequencies. In binary IR scheme, the average power is computed by averaging over a bit interval T_b . If energy of single pulse is E_p , then $N_s E_p$ is the total energy of the pulses representing one bit and the average power is

$$P_{av} = \frac{N_s E_p}{T_b} = \frac{N_s E_p}{N_s T_s} = \frac{E_p}{T_s}$$

Emission masks impose limits on the PSD of emitted signals. The value of emission masks at a given frequency indicates the maximum allowed EIRP with a measured bandwidth centered around f_c .

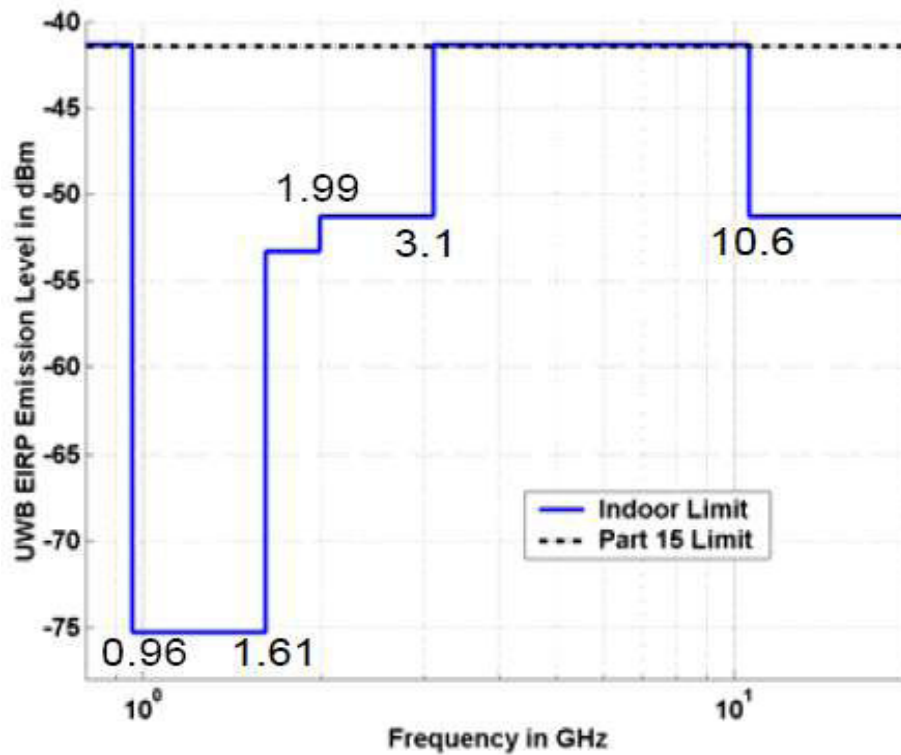


Figure 2.2 FCC indoor emission mask for UWB devices

The figure above depicts the indoor emission masks set by the FCC on UWB devices. The mask limits operations to a -10 dB bandwidth lying between 3.1 and 10.6 GHz and sets very stringent limits on out of band emission masks.

Table 2.2 Average power limits set by FCC in the U.S. for indoor UWB devices

Frequency in MHz	EIRPmb in dBm
0-960	-41.3
960-1610	-75.3
1610-1990	-53.3
1990-3100	-51.3
3100-10600	-41.3
Above 10600	-51.3

2.3 UWB Applications

UWB offers wide applications from wireless communication to radar imaging. One of the major advantages of impulse radio UWB is the ability to trade off data rate for link distance by using more or less concatenated pulses to define a bit. Thus, UWB can support very short range high data rate applications and medium to long range low data rate applications.

The ultra wide bandwidth and the variety of material penetration capabilities allows UWB to be used for radar imaging systems, including wall imaging radars, sense through wall radar imaging, ground penetration radars, surveillance systems and medical imaging. Images within or behind obstructed objects can be obtained with high resolution using UWB.

The location and communication aspects of UWB were used in a military application called the asset location system. This system was used to improve the logistics by knowing the location of the containers and other large objects within a Navy ship at all times. The tests showed that this UWB system gave very accurate results even in extreme multi-path environments and outperformed the existing RFID tags.

The excellent time resolution and accurate ranging capability of UWB can be used for vehicular radar systems for collision avoidance, guided parking etc. In addition to this a very important application is the wireless communication application. Wireless home networking

which involves ability to connect devices such as televisions, DVD players, camcorders and audio systems to remove some of the wiring clutter in the living room is a very promising commercial application.

UWB wireless connections to and from personal computers like UWB wireless mouse, wireless keyboards, wireless speakers are also another possible consumer market applications. High density use in office buildings and business cores, wireless USB, high speed WPAN/WBAN, wireless sensor networks, wireless telemetry and telemedicine are some of the possible applications.

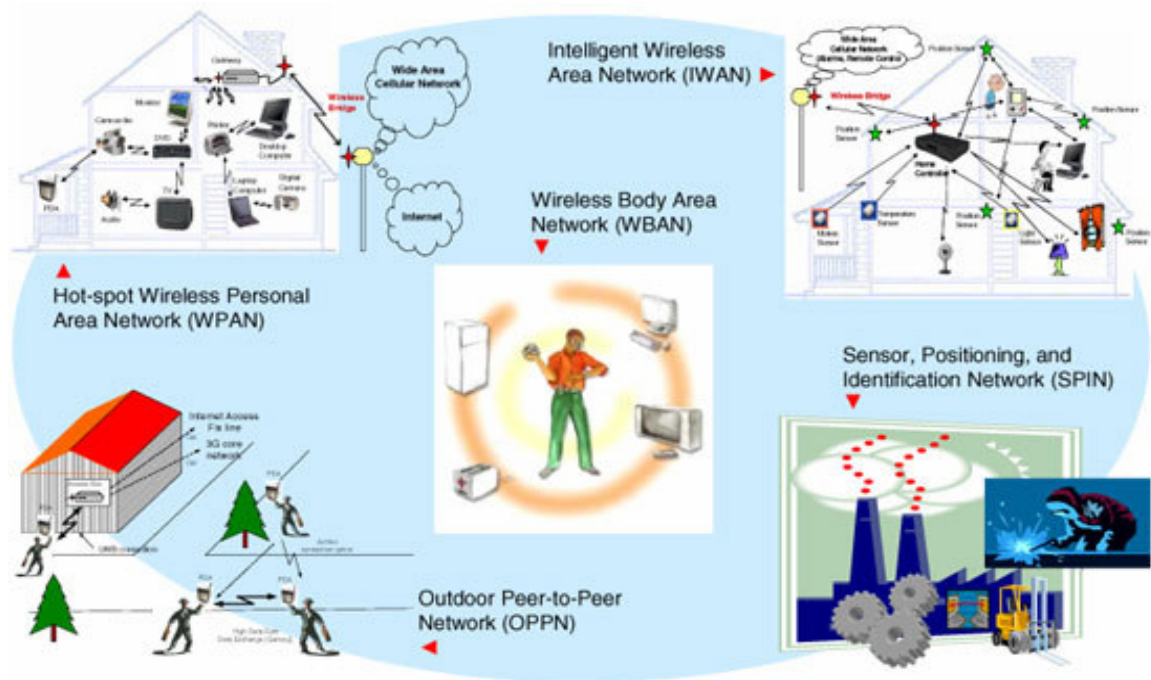


Figure 2.3 Applications for UWB (source: PULSERS White Paper [1])

The figure shows applications for UWB as perceived by the members of the European Union project PULSERS [1]. These scenarios cover the wireless local area networks (WLANs), wireless personal area networks (WPANs), sensor networks, and short range peer-to-peer networks.

CHAPTER 3

UWB SYSTEM

The Ultra wideband communication system developed here is an Impulse Radio system using pulse position modulation and time hopping sequence. Impulse radio employs the technique of transmitting very short duration pulses of the order of nanoseconds. Due to these very short duration pulses, the signal occupies extremely large bandwidth and there is no need of a carrier frequency for frequency translation. Similar to any communication system, the UWB system comprises of the transmitter, channel and the receiver.

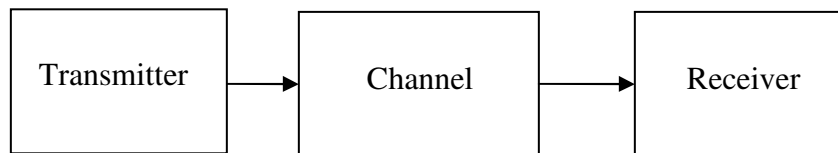


Figure 3.1 Communication system Model

The transmitter's prime motive is to convert the data stream into symbols and map these symbols onto an analog waveform and transmit via the air thru an antenna. The channel represents the effect of distortions, reflections and attenuations caused when travelling thru the air. The receiver collects the transmitted pulses, reconstructs them and maps symbols into binary stream. The next few sections give the details of the transmitter and the receiver design. The channel model selected for the ultra wideband communication is also discussed in detail.

3.1 IEEE UWB Channel Model

The signal transmitted by the transmitter reaches the receiver via the channel. The channel affects the signal by attenuating it, delaying it and distorting it. The UWB signals have a

very large bandwidth in the order of 500MHz and the signals constitute of pulses. The traditional channel models do not suffice for the UWB signals as they assume the attenuation due to materials and other propagation effects to be constant over the bandwidth. But as UWB signals have a very large bandwidth the effects are not constant over the entire band. Also the channel models assume that the received signal comprises of several delayed and attenuated signals arriving at the receiver and hence the fading and distortion is not of the individual copies of the signal. But for UWB signals, each pulse may go thru distortion in addition to the distortion in the total received signal.

The AWGN Channel is characterized by two parameters, channel gain and channel delay and the AWGN thermal noise at the receiver. Hence the structure of receiver is also simple as it has to select the waveform out of M best that matches the received signal. However, the UWB radio channel has the presence of multiple paths between transmitter and receiver which introduces complexity at both channel model and receiver structure. The channel exhibits time-varying properties that must be taken into account into the channel model. Distortion is particularly present for indoor transmissions where propagation is perturbed by a number of interfering objects. The presence of multi-path imposes severe limitations on receiver performance, which can be mitigated if the multi-path channel is characterized in detail. Several propagation measurement analyses for the indoor environment have been carried out which has given rise to several channel models. The IEEE Channel-Modeling sub-committee converged on the UWB indoor multi-path channel model based on the cluster approach formalized by Saleh and Valenzuela in 1987. The Saleh and Valenzuela (S-V) model is not UWB specific.

The S-V model is the most common statistical model developed for the NLOS indoor channel impulse response. It states that the each pulse generates multi-path contributions which are grouped into clusters. The cluster arrivals are modeled as poisson process and the multi-path contributions within a cluster are also characterized by a poisson process.

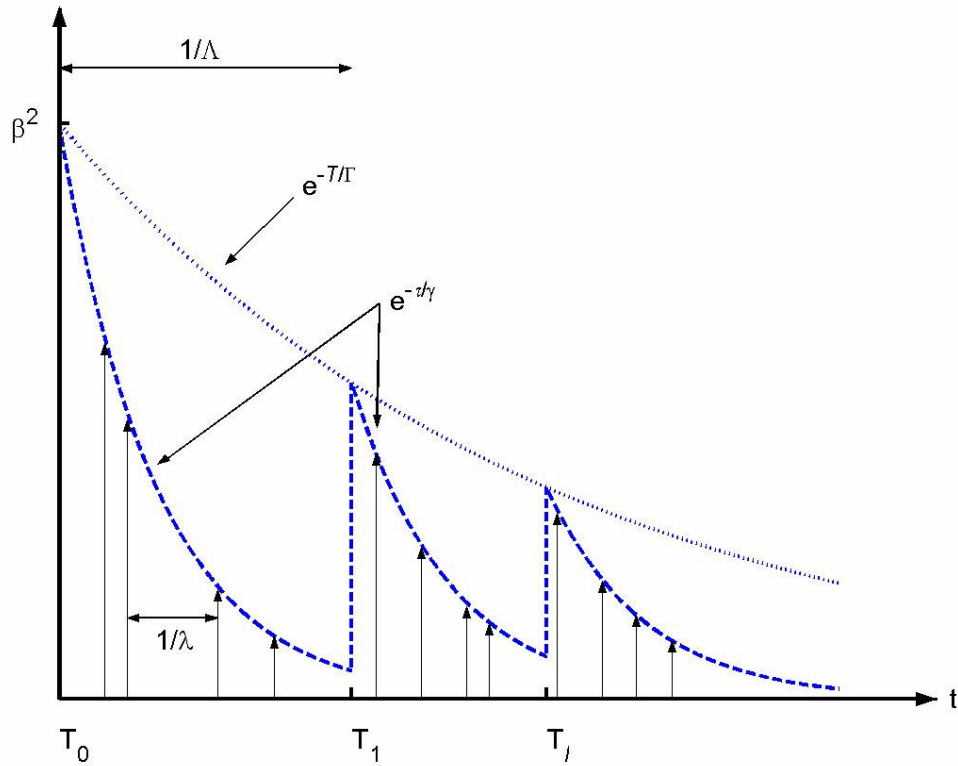


Figure 3.2 Saleh-Valenzuela Model

$$p(T_n | T_{n-1}) = \Lambda e^{-\Lambda(T_n - T_{n-1})}$$

where, Λ = cluster arrival rate, T_n and T_{n-1} are the times of arrival of the n -th and the $(n-1)$ th cluster respectively. $T_1 = 0$ for the first cluster.

$$p(\tau_{nk} | \tau_{(n-1)k}) = \lambda e^{-\lambda(\tau_{nk} - \tau_{(n-1)k})}$$

where, λ = multi-path contribution arrival rate, τ_{nk} and $\tau_{(n-1)k}$ are the times of arrival of the n -th and the $(n-1)$ th contribution within the k -th cluster respectively. $\tau_{n1} = 0$ for $n = 1$ to N .

A complex random variable a_n represents the gain of the n -th contribution in the k -th cluster having a statistically independent and Rayleigh distributed modulus β_{nk} and phase θ_{nk} uniformly distributed over $[0, 2\pi)$.

The average energy of the multi-path contribution per cluster is given by

$$\langle |\beta_{nk}| \rangle^2 = \langle |\beta_{00}| \rangle^2 e^{-\frac{T_n}{\Gamma}} e^{-\frac{\tau_k}{\Upsilon}}$$

where, Γ and Υ are power decay exponents for the cluster and the paths respectively. and β_{00} is the average energy of the first path in the first cluster.

To make the channel model UWB specific, the IEEE group suggested some modifications to the existing S-V Model. The β_{nk} was modeled as a lognormal distribution and the phase term θ_{nk} will assume $+\pi$ or $-\pi$ with equal probability.

$$\beta_{nk} = 10^{\frac{X_{nk}}{20}}$$

where, X_{nk} assumed to be Gaussian random variable with mean μ_{nk} and standard deviation σ_{nk} .

$$X_{nk} = \mu_{nk} + \xi_n + \zeta_{nk}$$

Where, ξ_n Gaussian random variable representing cluster channel coefficient fluctuations having variance σ_ξ^2 and ζ_{nk} representing ray fluctuation with variance σ_ζ^2 .

Hence as per the average energy equation

$$G = \sum_{n=1}^N |a_n|^2$$

$$G \leq 1$$

$$G = \frac{G_0}{D^\gamma}$$

which leads to $\mu_{nk} = \frac{10 \log_e (\langle |\beta_{00}| \rangle^2) - 10 \frac{T_n}{\Gamma} - 10 \frac{\tau_k}{\Upsilon} - (\sigma_\xi^2 + \sigma_\zeta^2) \log_e 10}{\log_e 10} + \frac{-(\sigma_\xi^2 + \sigma_\zeta^2) \log_e 10}{20}$

The channel impulse response is modeled as

$$h(t) = X \sum_{n=1}^N \sum_{k=1}^{K(n)} \alpha_{nk} \delta(t - T_n - \tau_{nk})$$

where, X = log-normal random variable representing channel amplitude gain

$$X = 10^{\frac{g}{20}}$$

$$g_0 = \frac{10 \log_e G}{\log_e 10} - \frac{\sigma_g^2 \log_e 10}{20}$$

where, g is Gaussian random variable with mean g_0 and variance σ_g^2 and G is the total multipath gain.

The total multi-path gain G , which measures the total amount of energy collected over the N received pulses when a pulse with unit energy is transmitted.

$$G = \sum_{n=1}^N |a_n|^2$$

$G \leq 1$ and is related to the attenuation suffered by the transmitted pulses during propagation. In multi-path environments, G decreases with distance according to

$$G = \frac{G_0}{D^\gamma}$$

where G_0 is the reference value for power gain evaluated at $D = 1\text{m}$ and γ is the exponent of power attenuation law.

The channel coefficient α_{nk} is defined as

$$\alpha_{nk} = p_{nk} \beta_{nk}$$

where, $p_{nk} = \pm 1$ with equal probability

On extensive measurement data analysis, IEEE came up with initial set of values for different environmental scenarios. The list is as shown in the table below.

Table 3.1 IEEE UWB Channel Model Parameter Setting

Scenario	$\Lambda(1/ns)$	$\lambda(1/ns)$	Γ	Υ	σ_{ξ} (dB)	σ_{ζ} (dB)	σ_g (dB)
Case A LOS (0-4m)	0.0233	2.5	7.1	4.3	3.3941	3.3941	3
Case B NLOS (0-4m)	0.4	0.5	5.5	6.7	3.3941	3.3941	3
Case C NLOS (4-10m)	0.0667	2.1	14	7.9	3.3941	3.3941	3
Case D Extreme NLOS Multipath channel	0.0667	2.1	24	12	3.3941	3.3941	3

3.2 Generation of UWB Signal

In UWB, the signal has a very high bandwidth of the order of 500MHz and each bit is represented by several pulses. The digital information contained in the bits needs to be mapped to the analog pulses which are transmitted and this is done via the help of modulation. The most common modulation technique for UWB is the pulse position modulation (PPM). In PPM each pulse is delayed or sent in advance of the regular time scale. So depending on the data bits, the pulse can be delayed accordingly. PPM is advantageous because of its ease of controlling the delay and simplicity. However, fine time resolution is necessary in UWB system to modulate pulses which are in sub nanosecond range. The spectral peaks when PPM is used along with Gaussian second order pulse can cause interference with other RF systems and hence the signal must be time shifted. This time dither is introduced with the help of PN codes. The PN codes can also act as code division multiple access codes such that different users will have different codes. By dithering the pulses with this code duration, they will act as noise for users with different PN codes. All these techniques are combined in a UWB transmitter. The details are explained in the next section.

3.2.1 PPM-TH-UWB Transmitter

The binary source generates the bits to be transmitted at rate $R_b = \frac{1}{T_b}$ represented by

$$b = (\dots b_0, b_1, b_2, \dots, b_k, b_{k+1}, \dots)$$

The next block is the code repetition coder which introduces redundancy and acts as the channel coder. It repeats the bits generated by the binary source N_s times so the bits are

now generated at the rate $R_{cb} = \frac{N_s}{T_b}$

$$b = (\dots b_0, b_0, b_0, \dots, b_0, b_1, b_1, b_1, \dots, b_1, b_k, b_k, \dots, b_k, b_{k+1}, \dots) = (\dots a_0, a_1, a_2, \dots, a_k, a_{k+1}, \dots) = a$$

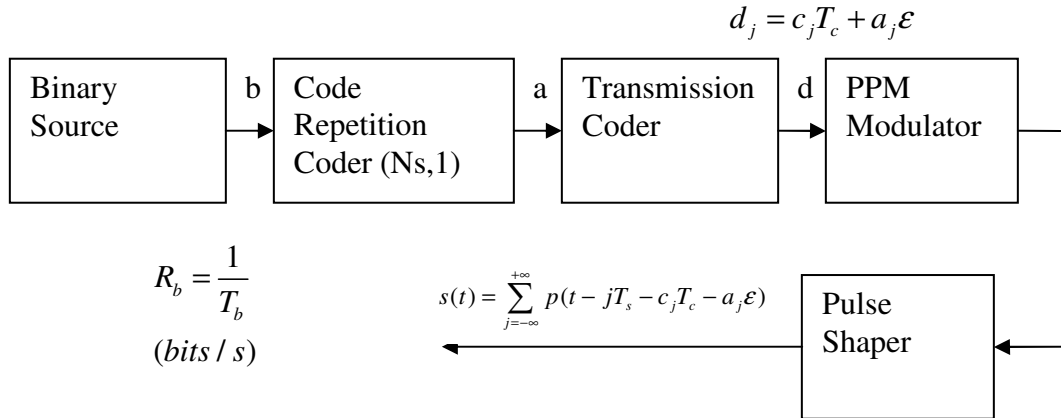


Figure 3.3 PPM-TH-UWB Transmitter design

The transmission coder generates a pseudo random code with a period N_p and applies this code to the repeated bits generating a new sequence of bits d .

$$c = (\dots c_0, c_1, c_2, \dots, c_j, c_{j+1}, \dots)$$

$$d_j = c_j T_c + a_j \epsilon$$

where, T_c is the chip time and c_j is the pseudo random code whose value lies between $0 \leq c_j \leq N_h - 1$.

The Pulse position modulator generates Dirac pulses that are shifted in time from nominal positions jT_s by d_j . So depending on the data bit it shifts the pulse if bit=1 and causes no time shift if bit=0. The shift generated by PPM modulator $a_j\mathcal{E}$ is much smaller than the shift introduced by the TH code c_jT_c except for when $c_j = 0$.

The pulse shaper generates a pulse with impulse response $p(t)$ such that the output of pulse shaper filter is non-overlapping pulses. The Gaussian second derivative pulse is used for this purpose.

The signal at the output of the PPM-TH-UWB transmitter is represented as

$$s(t) = \sum_{j=-\infty}^{+\infty} p(t - jT_s - c_jT_c - a_j\mathcal{E})$$

where, c_jT_c = time dither introduced by the TH code,

$a_j\mathcal{E}$ = time shift introduced by the PPM modulator,

and one bit duration $T_b = T_s N_s$

This signal $s(t)$ is transmitted by the UWB transmitter over the channel and received at the receiver end. The detailed description of each component of the time shift is described below:

(a) Uniform Pulse train spacing:

A pulse train of the form $\sum_{j=-\infty}^{\infty} p(t - jT_s)$ consists of monocycle pulses spaced T_s

seconds apart. The pulse repetition time may be about hundred to thousand times that of the monocycle width which results in a very low duty cycle signal. Multiple access signals

composed of uniformly spaced pulses are vulnerable to catastrophic collisions in which large number of pulses from two signals is received at the same time instants.

(b) Pseudorandom Time Hopping:

To eliminate the catastrophic collisions in multiple accessing, each link is assigned a distinct pulse shift pattern c_j which is the time hopping code. These hopping codes are periodic pseudorandom codes with period N_p . The time hopping code therefore provides an additional time shift to each pulse in the pulse train, with the monocycle undergoing an additional shift of $c_j T_c$ seconds. We assume that $\frac{N_h T_c}{T_s} \leq 1$ and a large enough value of $N_h T_c$ and with well designed codes; the multiple access interference can be modeled as a Gaussian random process.

(c) Data Modulation:

The data sequence of the transmitter is a binary symbol stream that conveys information in some form. Since pulse position modulation is employed, in this modulation method, when data symbol is 0 no additional time shift is modulated on the monocycle, but a time shift of ϵ is added to the monocycle when the symbol is 1. The data modulation further smoothes the power spectral density of the pseudorandom time hopping modulation.

A major challenge when designing UWB systems is the selection of appropriate modulation technique. Data rate, transceiver complexity, BER performance, spectral characteristics of the transmitted signal, and robustness against impairments and interference are all related with the modulation scheme. With respect to BER performances, comparing OOK, PPM, PAM modulation schemes, the BER for both OOK and PPM is same when the average transmitted pulse energies are the same. For M-ary cases, the SER for PPM reduces as the value of M increases and SER increases with M in the PAM case. Spectrally efficient M-PAM can be considered to achieve higher data rates at moderate power efficiency. With respect to transceiver cost and complexity, a scheme that enables non-coherent demodulation like

OOK, positive PAM or PPM should be employed as opposed to BPSK or M-ary PAM. As per the simulations carried out in [18] PPM performance degrades in multipath and multi-user scenarios. OOK and M-ary PAM are more susceptible to timing jitter. To summarize, according to the results presented in the paper BPSK can be preferred for its high power efficiency, OOK for simple transceiver structure, M-ary PAM for high data rates and M-ary PPM for improved power efficiency. In this thesis, I have focused on designing the UWB system employing the PPM modulation and later the performance for M-ary PPM is also analyzed.

The choice of the impulse response of the pulse shaper filter is crucial since it affects the PSD of the transmitted signal. Generating pulses of duration of the order of nanosecond with an inexpensive technology has become possible after the UWB Large Current Radiator (LCR) antennas were introduced. The LCR antenna is driven by current and the antenna radiates power proportional to the square of the derivative of the current. The pulse shape that can be easily generated by the pulse generator actually has a bell shape like the Gaussian pulse which can be described as follows:

$$p(t) = \pm \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left(\frac{t^2}{2\sigma^2}\right)} = \pm \frac{\sqrt{2}}{\alpha} e^{-\left(\frac{2\pi t^2}{\alpha^2}\right)}$$

where, $\alpha = 4\pi\sigma^2$ is the shape factor and σ^2 is the variance.

The pulse should have zero dc offset to be radiated efficiently. The most currently adopted pulse shape is the second derivative of the Gaussian pulse described as:

$$\frac{d^2 p(t)}{dt^2} = \left(1 - 4\pi \frac{t^2}{\alpha^2}\right) e^{-\left(\frac{2\pi t^2}{\alpha^2}\right)}$$

The second derivative Gaussian pulse is usually referred to as the pulse at the receiver. The second derivative pulse can be obtained at the transmitting antenna if antenna is fed with a current pulse shaped as the first derivative of Gaussian waveform as the radiating pulse being proportional to the second derivative of the drive current. Pulse width is tightly related to the shape factor α . Reducing the value of α shortens the pulse and thus enlarges the bandwidth

of the transmitted signal. Gaussian pulse has infinite duration resulting in unavoidable overlap between pulses and hence ISI. Hence a limited duration is defined by limiting the energy below a given threshold. Differentiation of the Gaussian pulses influences the ESD and both peak frequency and the bandwidth of the signal vary with increasing differentiation order. Meeting the emission masks set by the regulation authorities is demanded of the pulse shaper. The second derivative Gaussian pulse fits the emission mask limits set by FCC and hence it is selected for the pulse shaper.

3.3 UWB Receiver

The primary task of a receiver is to collect the received signal which is an attenuated, distorted and delayed version of the transmitted signal, and decode the useful signal from it. The electro-magnetic waves in indoor conditions are most affected by reflection, diffraction and scattering due to collision with obstacles in the surrounding. The UWB receiver has some added challenges to handle as compared to the other communication receiver structures. The UWB signal is composed of non-overlapping pulses with each pulse having a specific pulse duration within a given time interval. However, the channel can affect the transmitted signal introducing varying delays and thus causing inter-symbol interference. The multi-paths will also result in delayed replicas of the signal causing ISI. Moreover, when we consider the case of multiple users transmitting at the same time, the signal of one user can be interference to that of other user. So two noise components mainly affect the useful signal of a user namely the thermal noise caused by the movement of electrons within the receiver antenna and circuitry and the other noise is caused due to the multi-user interference noise. So the receiver design involves finding an optimal way to extract the useful signal from the received signal.

The multi-path delayed and attenuated versions of the transmitted signals can be efficiently separated at the receiver and then combined in order to improve the signal-to-noise ratio. The RAKE receiver does just this. It collects the delayed versions of the original signal by providing a separate correlation receiver for each of multi-path signals.

In this section, analysis of the UWB receiver structures typically the RAKE receiver structure is presented. For the time being, I have considered the single user case and hence the analysis involves only the thermal noise. Multi-user interference is analyzed in the next section. Also it is assumed that there is perfect synchronization between transmitter and the receiver and there is perfect channel knowledge or perfect channel estimation.

The received signal can be represented as

$$r(t) = r_u(t) + n(t)$$

where, $r_u(t)$ is the useful signal at the receiver and $n(t)$ is additive noise assumed to be Gaussian process with PSD $N_0 / 2$.

The useful received signal $r_u(t)$ is the delayed and attenuated version of the transmitted signal $s(t)$ after traveling via the channel.

$$r_u(t) = \alpha s(t - \tau)$$

where, α is the channel gain dependent on the distance D between transmitter and receiver

$$\alpha = \frac{c_0}{\sqrt{D}^\gamma}$$

where, γ is path loss exponent and c_0 is constant obtained at reference distance of $D_0 = 1m$ and reference gain $c_0 = 10^{-A_{db}/20}$.

$$\tau = D / c = D / 3 * 10^8 \text{ m / s}$$

τ is the time delay, which is assumed to be known to the receiver.

Hence, the received signal becomes $r(t) = \alpha s(t - \tau) + n(t)$.

The RAKE receiver consists of a correlator, which converts the received signal into set of decision variables, $\{Z\}$ and detector makes a decision on which signal is transmitted based on the decision variable $\{Z\}$. The transmitter sends M different waveforms $S_m(t)$ with

$m=0,1,\dots,M-1$. The received signal is cross-correlated with the M possible transmitted waveforms and the maximum over the M resulting values is selected as the transmitted signal.

For the 2PPM-TH-UWB case $M = 2$ and the signal transmitted is

$$S_m(t) = \sqrt{E_{TX}} \sum_{j=0}^{N_s-1} p_0(t - jT_s - c_j T_c) \quad \text{for bit} = 0$$

$$S_m(t) = \sqrt{E_{TX}} \sum_{j=0}^{N_s-1} p_0(t - jT_s - c_j T_c - \varepsilon) \quad \text{for bit} = 1$$

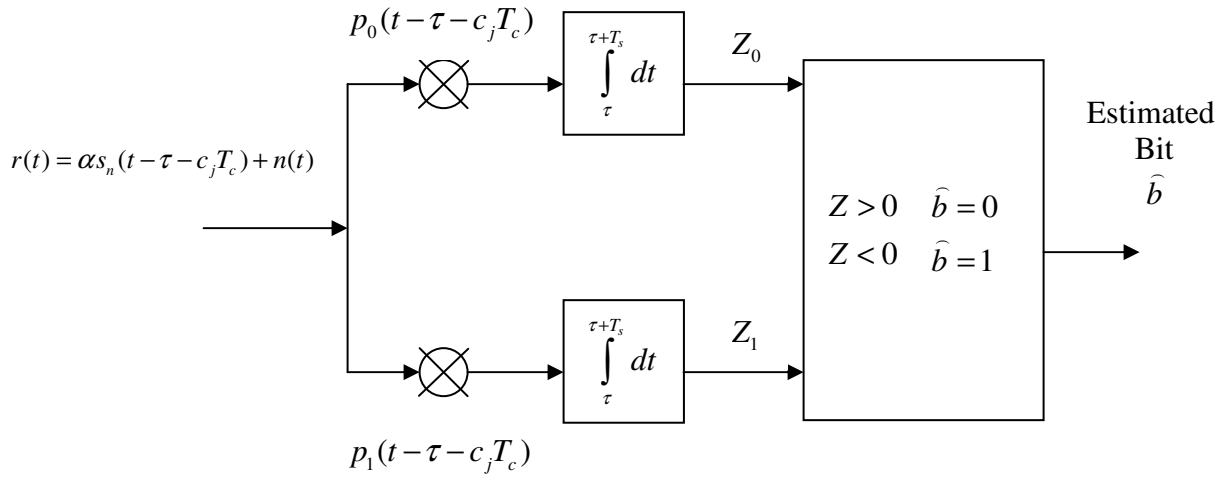


Figure 3.4 2PPM-TH-UWB Receiver Structure

The above receiver structure can be simplified with the use of single correlator as shown in figure below.

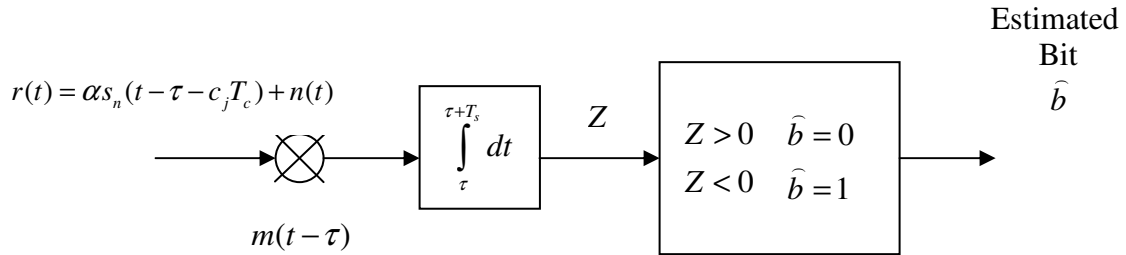


Figure 3.5 Single correlator scheme for 2PPM-TH-UWB Receiver Structure

The correlation mask $m(t)$ multiplies the incoming signal at the receiver.

$$m(t) = p_0(t - \tau - c_j T_c) - p_0(t - \tau - c_j T_c - \varepsilon)$$

The probability for bit error is calculated as the following

$$\begin{aligned}\Pr_b &= \frac{1}{2} \Pr(Z > 0 | b = 1) + \frac{1}{2} \Pr(Z < 0 | b = 0) = \Pr(Z < 0 | b = 0) \\ \Pr_b &= \Pr(\alpha \sqrt{N_s E_{TX}} + n_0 - n_1 < 0) = \Pr(\sqrt{N_s E_{RX}} + n_0 - n_1 < 0) \\ \Pr_b &= \Pr(n_1 - n_0 > \sqrt{N_s E_{RX}}) = \frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{N_s E_{RX}}{2N_0}}\right)\end{aligned}$$

The signal is formed by N_s pulses, which is considered as one bit at the receiver. The received signal is cross-correlated with the mask that is matched with train of pulses representing entire symbol.

3.3.1 RAKE Receiver Configurations

The signal propagated over an indoor channel is affected by multiple delayed and attenuated replicas of the transmitted pulse corresponding to different propagation paths between transmitter and receiver. Hence can be represented as

$$r(t) = \sum_j a_j S_m(t - \tau_j) + n(t)$$

Considering the IEEE channel model the received signal is

$$r(t) = \sqrt{E_{RX}} \sum_j \sum_{n=1}^N \sum_{k=1}^{K(n)} \alpha_{nk} a_j p_0(t - jT_s - c_j T_c - a_j \varepsilon - \tau_{nk}) + n(t)$$

The different replicas of the transmitted pulse are combined using the Maximum Ratio Combining (MRC) in which weighting factors are applied to the different contributions to maximize the SNR.

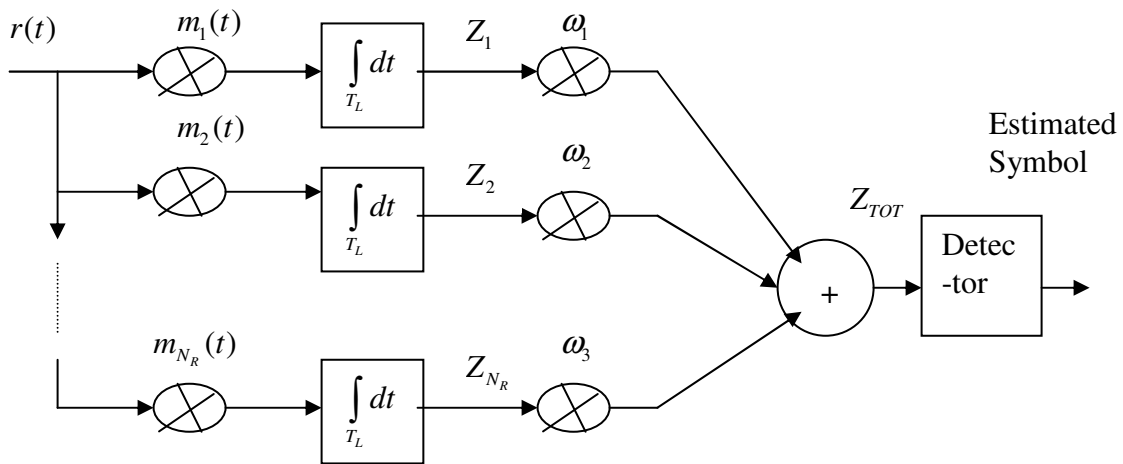


Figure 3.6 RAKE Receiver with parallel correlators

The typical RAKE receiver configurations considered in this section are the Ideal or All RAKE, Selective RAKE and Partial RAKE. The All RAKE (ARAKE) attempts to collect the signal energy from all the resolvable multi-path contributions using Maximal Ratio Combining (MRC). This configuration can be further simplified with the help of just one correlator.

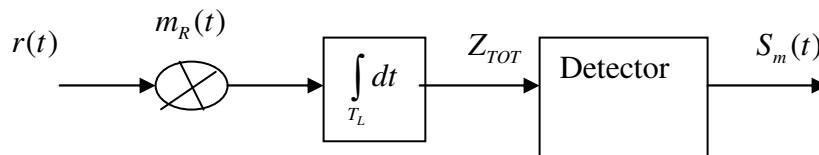


Figure 3.7 RAKE Receiver with single correlator structure

$$Z_{TOT} = \int_{T_L} r(t)m_R(t)$$

$$m_R(t) = \sum_{j=1}^{N_R} \omega_j m(t - \tau_j)$$

The performance of the ARAKE is very good but its implementation is impractical due to increased complexity with increased bandwidth as a very large number of multi-paths needs to be combined. Due to this increased complexity, there needs to be a tradeoff between performance vs. complexity. A viable solution to reduce this complexity is to consider only a few

of resolvable multi-paths. Two of the techniques employed are the Selective RAKE and the Partial RAKE.

The Selective RAKE (SRAKE) combines the best L_c paths out of the total L paths where $L_c < L$. In this scheme the number of branches of the RAKE reduces but receiver still needs to keep a track of all the multi-path components to select the best L_c paths.

The Partial RAKE (PRAKE) on the other hand combines the first L_c arriving paths without making any selection decisions on the incoming multi-path contributions. Hence, the simplest process is the PRAKE, which eliminates selection process and does not need to combine all the paths unlike ARAKE. But the performance degrades considerably.

3.4 Performance Analysis of 2PPM-TH-UWB System

In this section the 2PPM-TH-UWB system performance is analyzed for different cases. The transmitter, channel model and the receiver are simulated using MATLAB version 7.0.1 and the results are presented in the next subsections. The simulation is carried out for 100,000 bits to calculate the bit error rate. The modulation scheme used is binary pulse position modulation with time shift introduced by PPM is $0.5 \times 10^{-9} s$. Time hopping is used in the transmitter with parameters: average transmitted power is -30dBm, sampling frequency $f_c = 50 \times 10^{-9} Hz$, $T_s = 60 \times 10^{-9} s$, $T_m = 0.5 \times 10^{-9} s$, the cardinality of the TH code is $N_h = 5$ and the periodicity of the code is $N_p = N_s$. The second order derivative Gaussian pulse is used for pulse shaping with shape factor $\tau = 0.2 \times 10^{-9} s$. The following subsections present the results achieved for code repetition of 3 and 5 and the comparison between the two for the Ideal, Selective and the Partial RAKE receivers.

3.4.1 Performance Comparison of Ideal, S-RAKE, P-RAKE for $N_s = 3$ with 2 and 5 branches

The figure below compares the performance of the RAKE receivers. The Ideal RAKE receiver gives the best results since it processes all the multi-path contributions resolved at the receiver.

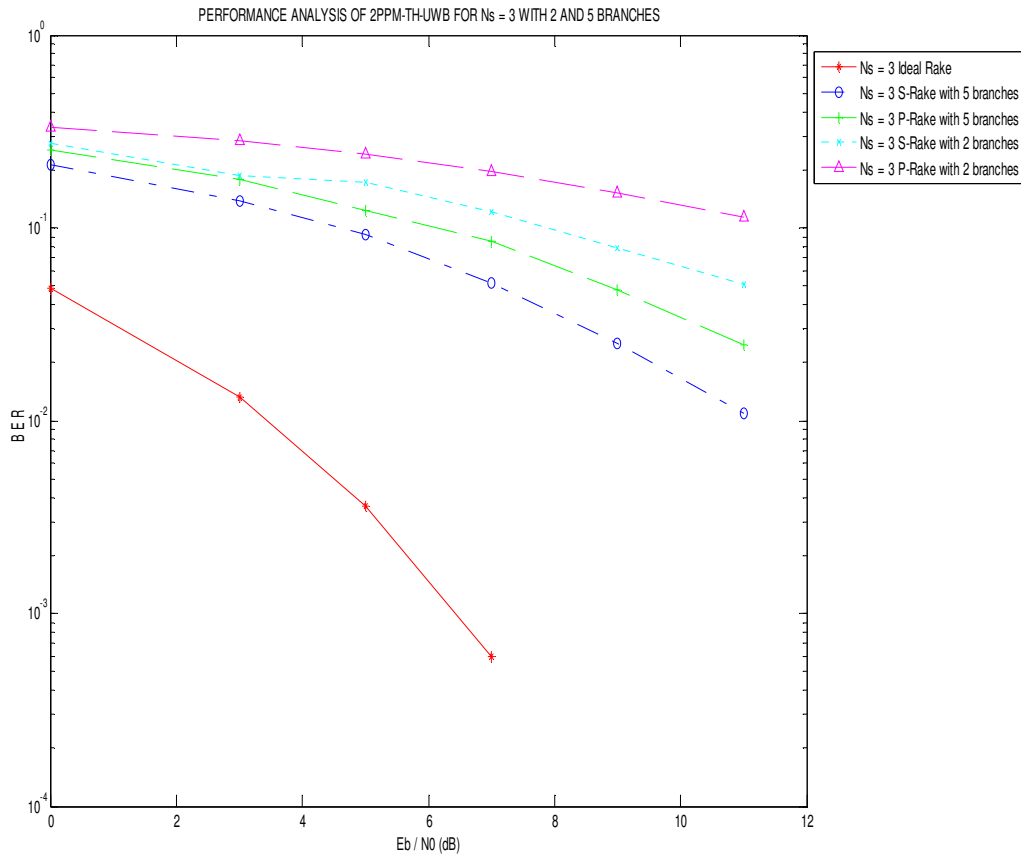


Figure 3.8 Performance Analysis of 2PPM-TH-UWB for $N_s = 3$ with 2 and 5 branches

The blue line corresponds to the SRAKE which reduces the receiver complexity by decreasing the number of multi-path components taken into account. The dark blue line corresponds to 5 multi-path branches taken into account while the light blue line corresponds to 2 multi-path branches taken into account by the selective RAKE. The PRAKE eliminates the best branch selection process and selects the first arriving multi-path components is the simplest method but gives the worst result. The PRAKE with 5 branches gives results similar to

SRAKE with 2 branches. The energy collected by the first five paths is nearly same as that collected by the best two paths.

3.4.2 Performance Comparison of Ideal, S-RAKE, P-RAKE for $N_s = 5$ with 2 and 5 branches

The figure below compares the performance of the RAKE receivers. As seen in the case of $N_s = 3$, the Ideal Rake outperforms the SRAKE and the PRAKE receivers.

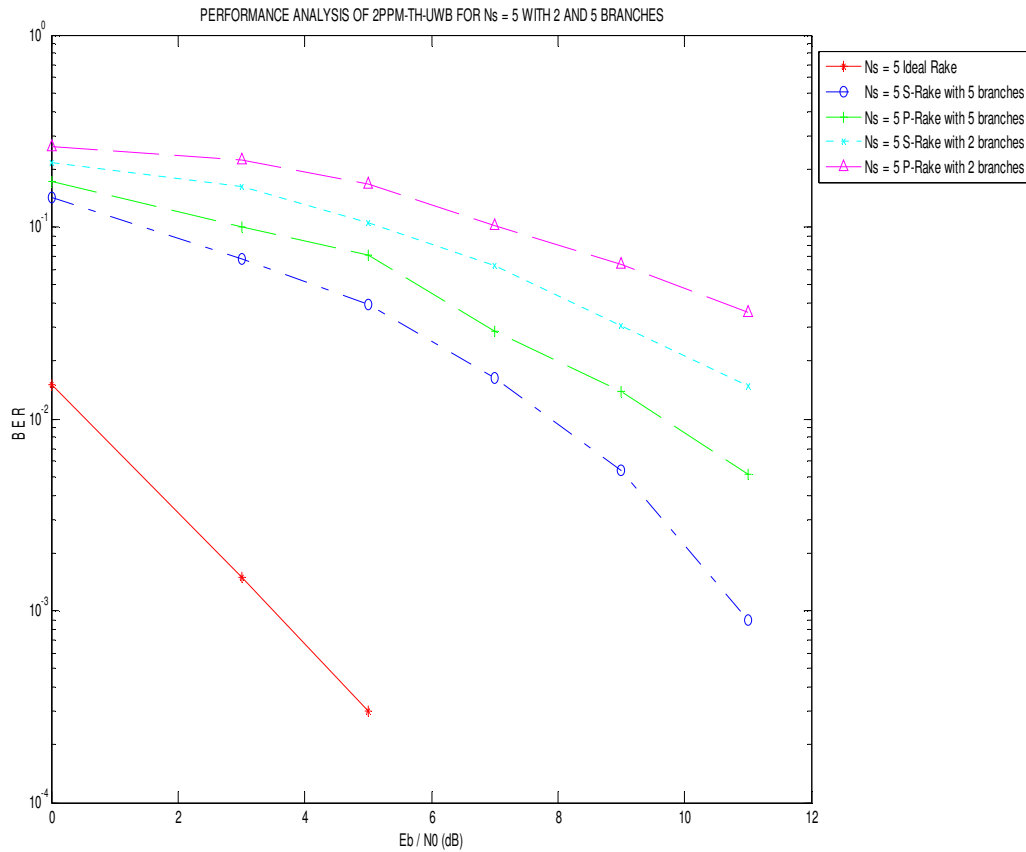


Figure 3.9 Performance Analysis of 2PPM-TH-UWB for $N_s = 5$ with 2 and 5 branches

The figure above compares the performance of the RAKE receivers. As seen in the case of $N_s = 3$, the Ideal Rake outperforms the SRAKE and the PRAKE receivers. The results for the SRAKE and PRAKE are verified once again with taking $N_s = 5$ case. The SRAKE performs better than the PRAKE as it collects the best multi-path components as opposed to the first arriving components in PRAKE. There is about 2 dB gain when SRAKE is used instead

of the PRAKE. But the PRAKE is simple as compared to the SRAKE as it does not involve selecting the best components.

3.4.3 Performance Comparison of Ideal, S-RAKE, P-RAKE for $N_s = 3$ and $N_s = 5$

In the above figure, the performance is compared for the $N_s = 3$ and $N_s = 5$ binary pulse position time hopping UWB system.

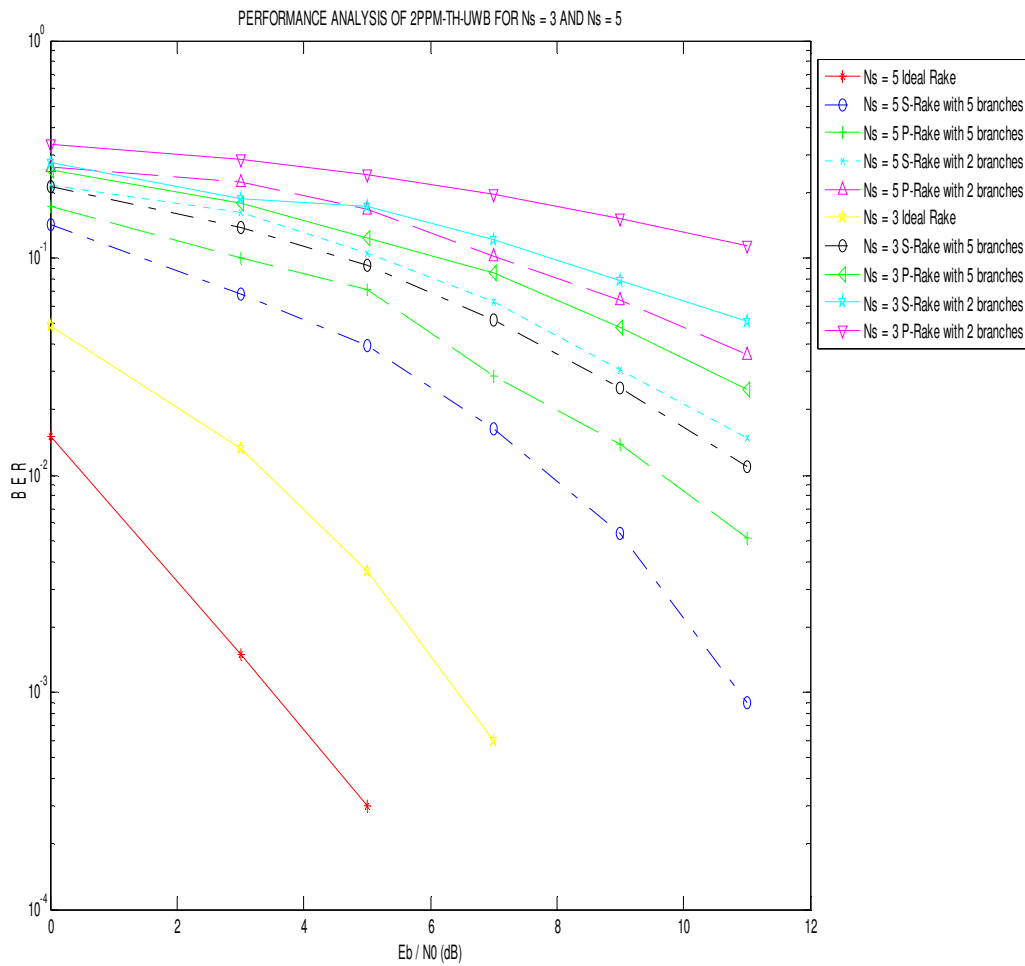


Figure 3.10 Performance analysis of 2PPM-TH-UWB system for $N_s = 3$ and $N_s = 5$

It is observed that the Ideal RAKE with $N_s = 5$ outperforms the Ideal RAKE with $N_s = 3$. There is about 3dB gain when the code repetition length is 5 as compared to that of 3. This is

because as the number of code repetitions increase, the signal repetitions increase and hence the signal is less prone to errors. The repetition coder makes the code robust and the robustness increases with the increase in the code repetition. It is also evident that as the number of RAKE branches increase, the performance improves as more number of multi-path branches is captured. It is observed that the SRAKE with 5 branches and $N_s = 5$ gives the best performance after the Ideal Rakes followed by the 5 branches PRAKE with $N_s = 5$. As expected the $N_s = 3$ with 2 branches PRAKE gives the worst performance as it collects the first arriving two branches of multi-path contributions and also since the code repetition is only 3 it does affect the immunity to errors.

CHAPTER 4

M-ARY PPM AND MULTI-USER UWB SYSTEM

So far the case of Binary PPM was analyzed and interference taken into consideration was only the thermal noise generated by the receiver circuitry. In this section, the effect of multi-user interference is analyzed. Also the UWB system is simulated for 4PPM-TH system instead of binary PPM.

4.1 Effect of 4-PPM on UWB System

In this section the UWB system is analyzed when the modulation is changed from binary pulse position modulation to M-ARY pulse position modulation with $M = 4$. In 4PPM UWB system the pulse is shifted based on two bits wherein two bits represents one symbol. A pulse is transmitted in one of the 4 possible time shifts caused by PPM. In this case I have considered that bits '00' will be mapped to no PPM shift ϵ whereas '01' will cause the signal to be shifted by ϵ and '10' and '11' will cause shifts of 2ϵ and 3ϵ respectively.

The M-ary PPM-TH UWB receiver is shown in the figure below. The decision variables at the output of the signal correlator can be expressed as

$$Z_0 = \alpha S_{m_0} + n_0$$

$$Z_1 = \alpha S_{m_1} + n_1$$

$$Z_{M-1} = \alpha S_{m(M-1)} + n_{M-1}$$

$$\text{where, } S_{mk} = \sqrt{E_{TX}} \int_0^{T_s} p_0(t - m\epsilon) p_0(t - k\epsilon) dt$$

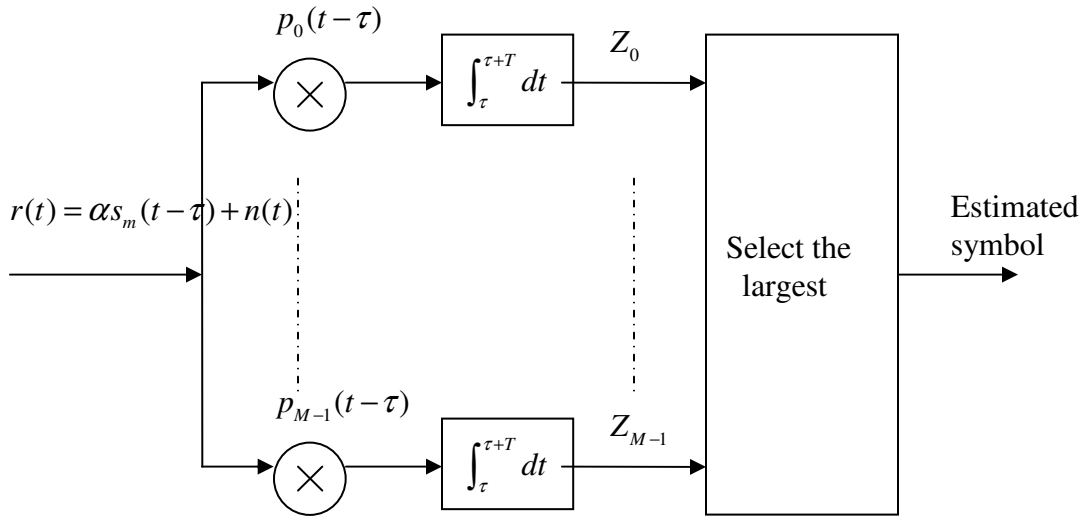


Figure 4.1 M-PPM TH UWB Receiver Structure

If the M generated waveforms have equal probability $1/M$ the average error probability is the probability of misdetecting one of the symbols. Assuming if $s_0(t)$ is transmitted, then error will occur if any of Z_k is greater than Z_0 , where $k \neq 0$. The average probability of error is complimentary to the average probability of correct, which can be evaluated by averaging over all possible Z_0 values the joint probability that all noise components are smaller than the useful output

$$\Pr_e = 1 - \Pr_c = 1 - \int_{-\infty}^{\infty} \Pr ob(n_1 < Z_0, \dots, n_{M-1} < Z_0 | Z_0) p(Z_0) dZ_0$$

since these probabilities are identical for $m = 2, 3, \dots, M-1$

$$= 1 - \int_{-\infty}^{\infty} \Pr ob(n_x < Z_0 | Z_0)^{M-1} p(Z_0) dZ_0$$

where, n_x is a Gaussian random variable with zero mean and variance $N_0 / 2$.

$$\Pr_e = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left(1 - \left(\frac{1}{\sqrt{2\pi}} \int_{-\infty}^y e^{-x^2} dx \right)^{M-1} \right) e^{\left[-\frac{1}{2} \left(y - \sqrt{\frac{2E_{RX}}{N_0}} \right)^2 \right]} dy$$

The above probability of symbol error is obtained when any of the other $M-1$ signals is transmitted. Since $M = 2^k$, each symbol conveys k bits of information, $E_s = kE_b$. Since the signals are equiprobable, all symbol errors are equiprobable and occur with probability $\frac{\Pr_e}{2^k - 1}$

and the average number of bit errors per k -bit symbol is $\sum_{n=1}^k n \binom{k}{n} \frac{\Pr_e}{2^k - 1} = k \frac{2^{k-1}}{2^k - 1} \Pr_e$.

So, the bit error rate is $P_b = k \frac{2^{k-1}}{2^k - 1} \Pr_e$.

4.2 Performance Analysis of 4PPM-TH-UWB System

In this section the 4PPM-TH-UWB system performance is analyzed for the Ideal, SRAKE and the PRAKE receivers as in the binary PPM UWB case in chapter 3. The transmitter, channel model and the receiver are simulated using MATLAB version 7.0.1 and the results are presented in the next subsections. The simulation is carried out for 100,000 bits to calculate the bit error rate. The modulation scheme used is M -ary pulse position modulation with $M = 4$, time shift introduced by PPM is $0.5 \times 10^{-9} s$. Time hopping is used in the transmitter with parameters: average transmitted power is -30dBm , sampling frequency $f_c = 50 \times 10^{-9} \text{Hz}$, $T_s = 60 \times 10^{-9} s$, $T_m = 0.5 \times 10^{-9} s$, the cardinality of the TH code is $N_h = 5$ and the periodicity of the code is $N_p = N_s$. The second order derivative Gaussian pulse is used for pulse shaping with shape factor $\tau = 0.2 \times 10^{-9} s$. The following subsections present the results achieved for the Ideal, Selective and the Partial RAKE receivers for 4PPM-TH-UWB and the results are compared with that of 2PPM-TH-UWB system.

4.2.1 Performance comparison of 4PPM-TH-UWB and 2PPM-TH-UWB system

In the figure below the performance of the binary PPM UWB system is compared with M-ary UWB system with $M = 4$. It is observed that the performance of the system improves as M decreases in the PPM-TH-UWB system. As predicted, the 2 PPM Ideal RAKES outperforms the SRAKE and the PRAKE as all the multi-path components are considered. However the 4PPM Ideal Rake gives better performance as compared to the 2PPM SRAKE and PRAKE. The binary PPM system outperforms the 4PPM system as the SNR per symbol is fixed due to the FCC power limits and hence the SNR per bit reduces for 4PPM and hence we see performance degradation.

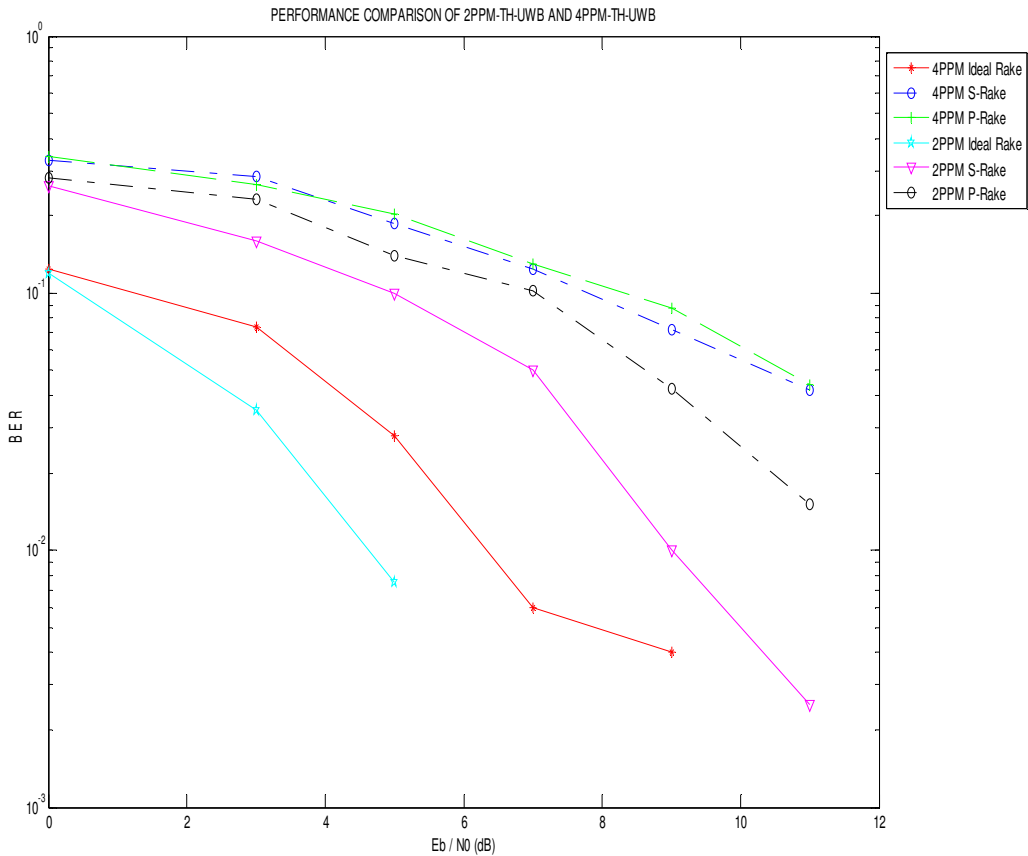


Figure 4.2 Performance Comparison of 2PPM-TH-UWB and 4PPM-TH-UWB system

4.3 Effect of Multi-User Interference on PPM-TH-UWB System

Multiple users can access the same physical medium with the help of multiple access techniques. These multiple access techniques can be based on time division, frequency division and code division multiple accesses. In impulse radio UWB system, the data symbols are encoded using the Time Hopping codes. These TH codes can serve the purpose of distinguishing users by assigning different TH codes to different users. This kind of multiple access technique is called the time hopping multiple access (THMA). The THMA is similar to CDMA as it also employs codes to differentiate between users. But THMA also separates the users in time dimension. The transmitted signal of one user is seen as an interfering signal by the other user. Hence, a reference receiver must be capable of isolating the useful signal from the other users' signals which are interference signals. Multi-user interference (MUI) can be removed if there is perfect synchronization, ideal channel and orthogonal codes which is difficult to achieve in practice. It is assumed that the total effect of interfering signals at the receiver will be modeled as additive Gaussian noise. This is known as Standard Gaussian Approximation.

In the following section, the system performance is evaluated for the 2PPM-THMA UWB system under the standard Gaussian approximation. It is assumed that the TH codes are randomly generated and are independent and equally probable. Also each transmitter/receiver pair uses a unique code which is known at the receiver. The reference transmitter/receiver pair are assumed to be perfectly synchronized.

The 2PPM-THMA UWB signal transmitted by user n can be expressed as follows:

$$S_{TX}^{(n)}(t) = \sum_{j=-\infty}^{\infty} \sqrt{E_{TX}^{(n)}} p_0(t - jT_s - c^{(n)}_j T_c - a^{(n)}_j \epsilon)$$

where, $c^{(n)}_j$ is the j -th coefficient of the TH sequence used by n -th user and $c^{(n)}_j T_c$ is the time shift introduced by TH code.

$a^{(n)}_j \mathcal{E}$ is the time shift introduced by PPM shift. $a^{(n)}_j$ is the binary value conveyed by j pulse of user n .

The radio waves propagate over a multi-path free channel with impulse response

$$h^{(n)}(t) = \alpha^{(n)} \delta(t - \tau^{(n)})$$

The time delays $\tau^{(n)}$ are assumed to be independent and identically distributed random variables over $[0, T_s)$. Also the channel output is corrupted by thermal noise $n(t)$.

The received signal at the reference receiver is represented by sum of all the transmitted signals originating from $N(u)$ transmitters.

$$r(t) = \sum_{n=1}^{N_u} \sum_{j=-\infty}^{\infty} \sqrt{E_{RX}^{(n)}} p_0(t - jT_s - c^{(n)}_j T_c - a^{(n)}_j \mathcal{E}) + n(t)$$

$$\text{where, } E_{RX}^{(n)} = E_{TX}^{(n)} (\alpha^{(n)})^2$$

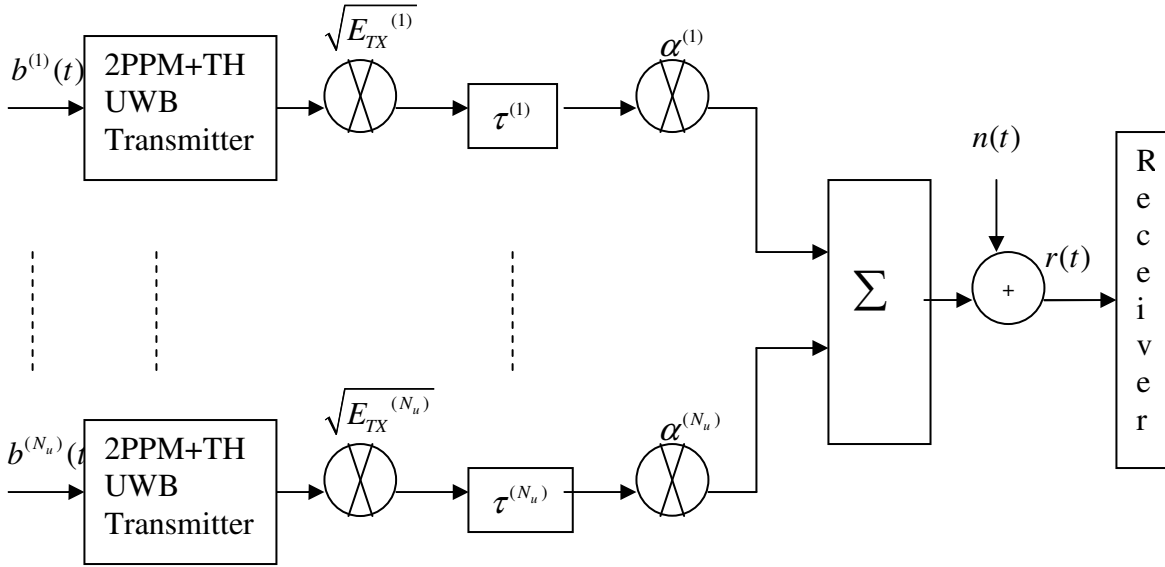


Figure 4.3 MUI UWB System Model

As shown in the MUI UWB System model, the receiver receives the signal which is the sum of all the transmitted signals by the N_u users. Under the assumption of perfect synchronization between the transmitter and the reference receiver, the time delay is known at the receiver. Let transmitter TX1 be the desired signal, then it can be assumed that $\tau^{(1)} = 0$.

The received signal is the sum of the useful signal, the thermal noise and the MUI.

$$r(t) = r_u(t) + r_{MUI}(t) + n(t)$$

$$r_u(t) = \sum_{j=0}^{N_s-1} \sqrt{E_{RX}^{(1)}} p_0(t - jT_s - c_j^{(1)}T_c - a^{(1)}_j \mathcal{E})$$

for $t \in [0, T_b]$

$$r_{MUI}(t) = \sum_{n=2}^{N_u} \sum_{j=-\infty}^{\infty} \sqrt{E_{RX}^{(n)}} p_0(t - jT_s - c_j^{(n)}T_c - a^{(n)}_j \mathcal{E} - \tau^{(n)})$$

The receiver used is the correlation receiver as described in section 3. It employs soft decision maximum likelihood detection. The decision variable Z can be expressed as

$$Z = \int_0^{T_b} r(t)m(t)dt$$

where $m(t)$ is the correlation mask.

$$m(t) = \sum_{j=0}^{N_s-1} v(t - jT_s - c_j^{(1)}T_c)$$

$$v(t) = p_0(t) - p_0(t - \mathcal{E})$$

The ML decision rule states if $Z > 0 \Rightarrow \hat{b} = 0$
 $Z < 0 \Rightarrow \hat{b} = 1$

Here the decision variable Z is the sum of decision variables of the useful signal, the MUI and the thermal noise. The bits generated at the source are assumed to be equally probable and hence the BER can be calculated as follows:

$$\Pr_b = \frac{1}{2} \Pr(\hat{b} = 1 | b = 0) + \frac{1}{2} \Pr(\hat{b} = 0 | b = 1)$$

$$\Pr_b = \Pr(\hat{b} = 1 | b = 0)$$

$$\Pr_b = \Pr(Z < 0 \Rightarrow b = 0)$$

Under the Standard Gaussian approximation both Z_{mui} and Z_n are zero mean Gaussian random processes with variance σ_{mui}^2 and σ_n^2 .

$$\Pr_b = \frac{1}{2} \operatorname{erfc}\left(\sqrt{\frac{SNR_{spec}}{2}}\right)$$

$$SNR_{spec} = \frac{E_b}{\sigma_n^2 + \sigma_{mui}^2}$$

$$SNR_{spec} = ((SNR_n)^{-1} + (SIR)^{-1})^{-1} = \left(\left(\frac{E_b}{\sigma_n^2} \right)^{-1} + \left(\frac{E_b}{\sigma_{mui}^2} \right)^{-1} \right)^{-1}$$

Each term can be evaluated as follows:

$$E_b = (Z_u)^2$$

$$\begin{aligned} &= \left(\sqrt{E_{RX}^{(1)}} \sum_{j=0}^{N_s-1} \int_{jT_s+c_j^{(1)}T_c}^{jT_s+c_j^{(1)}T_c+T_c} p_0(t-jT_s-c_j^{(1)}T_c) v(t-jT_s-c_j^{(1)}T_c) dt \right)^2 \\ &= E_{RX}^{(1)} N_s^2 (1-R_0(\mathcal{E}))^2 \end{aligned}$$

where, $R_0(t)$ is the autocorrelation function of the pulse waveform $p_0(t)$

$$\sigma_n^2 = 2\sigma_{n_0}^2 + 2Cov(n_1, -n_0)$$

$$= N_s N_0 (1-R_0(\mathcal{E}))$$

$$SNR_n = \frac{N_s E_{RX}^{(1)}}{N_0} (1-R_0(\mathcal{E})) = \frac{E_b}{N_0} (1-R_0(\mathcal{E}))$$

For MUI, a pulse originating from a transmitter other than TX1 is considered as interfering pulse by the receiver. The total interfering MUI energy on N_s pulses at output of receiver is

$$\sigma_{mui}^2 = \sum_{n=2}^{N_u} \left(\frac{N_s}{T_s} E_{RX}^{(n)} \int_0^{T_s} \left(\int_0^{2T_m} p_0(t-\tau)v(t) \right)^2 d\tau^{(n)} \right)$$

As all delays are identically distributed over $[0, T_s)$

$$\begin{aligned} \sigma_{mui}^2 &= \frac{N_s}{T_s} \left(\int_0^{T_s} \left(\int_0^{2T_m} p_0(t-\tau)v(t) \right)^2 d\tau \right) \sum_{n=2}^{N_u} E_{RX}^{(n)} \\ &= \frac{N_s}{T_s} \sigma_M^2 \sum_{n=2}^{N_u} E_{RX}^{(n)} \end{aligned}$$

Hence the SIR can be represented as

$$\begin{aligned} SIR &= \frac{E_{RX}^{(1)} N_s^2 (1-R_0(\epsilon))^2}{\frac{N_s}{T_s} \sigma_M^2 \sum_{n=2}^{N_u} E_{RX}^{(n)}} = \frac{(1-R_0(\epsilon))^2}{\sigma_M^2} \frac{N_s T_s}{\sum_{n=2}^{N_u} \frac{E_{RX}^{(n)}}{E_{RX}^{(1)}}} \\ SIR &= \frac{(1-R_0(\epsilon))^2}{\sigma_M^2} \frac{1}{R_b \sum_{n=2}^{N_u} \frac{E_{RX}^{(n)}}{E_{RX}^{(1)}}} \end{aligned}$$

Putting together all the equations for SNR_n and SIR into Pr_b , we get the bit error probability to be

$$Pr_b = \frac{1}{2} \operatorname{erfc} \left(\frac{\left(\left(\frac{E_b^{(1)}}{N_0} (1-R_0(\epsilon)) \right)^{-1} + \frac{(1-R_0(\epsilon))^2 \gamma_R}{\sigma_M^2 R_b \sum_{n=2}^{N_u} \frac{E_{RX}^{(n)}}{E_{RX}^{(1)}}} \right)^{-1}}{2} \right)^{-1}$$

The theoretical BER is calculated based on the above equation.

4.4 Performance Analysis of Multi-User UWB System

In this section, the bit error rate is calculated for a multi-user UWB system. Analysis is carried out for 6 interfering users and 10 interfering users. It is observed that the 6 users system gives a better performance as compared to the 10 users system. The performance degrades as the number of users increase in the system. This is because with the increase in the number of users, there are more interfering signals generated which interfere with the useful signal of TX1 and in turn degrade the system performance.

4.4.1 Performance of 6 interfering users

As seen in the figure below, the simulated and the theoretical values are compared for the case of 6 interfering users. The probability of error measured by the simulation is higher than that predicted by the standard Gaussian approximation.

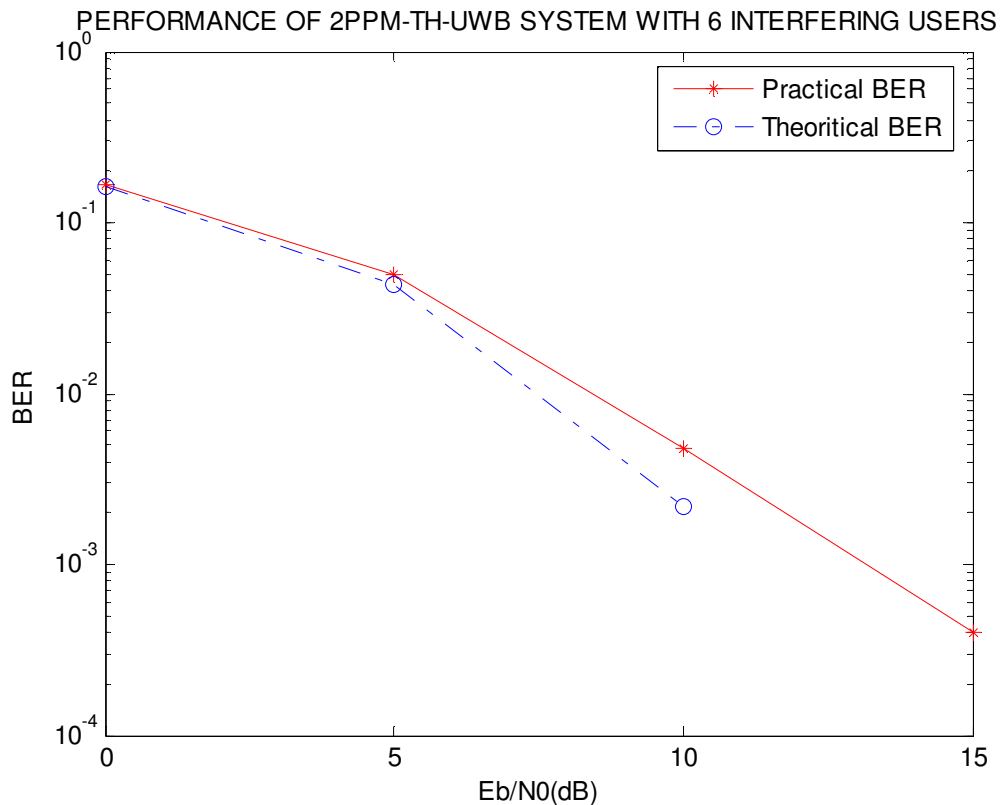


Figure 4.4 Performance Analysis of 6 interfering users for 2PPM-TH-UWB systems

4.4.2 Performance of 10 interfering users

As seen in the figure below, the simulated and the theoretical values are compared for the case of 10 interfering users. The probability of error measured by the simulation is higher than that predicted by the standard Gaussian approximation.

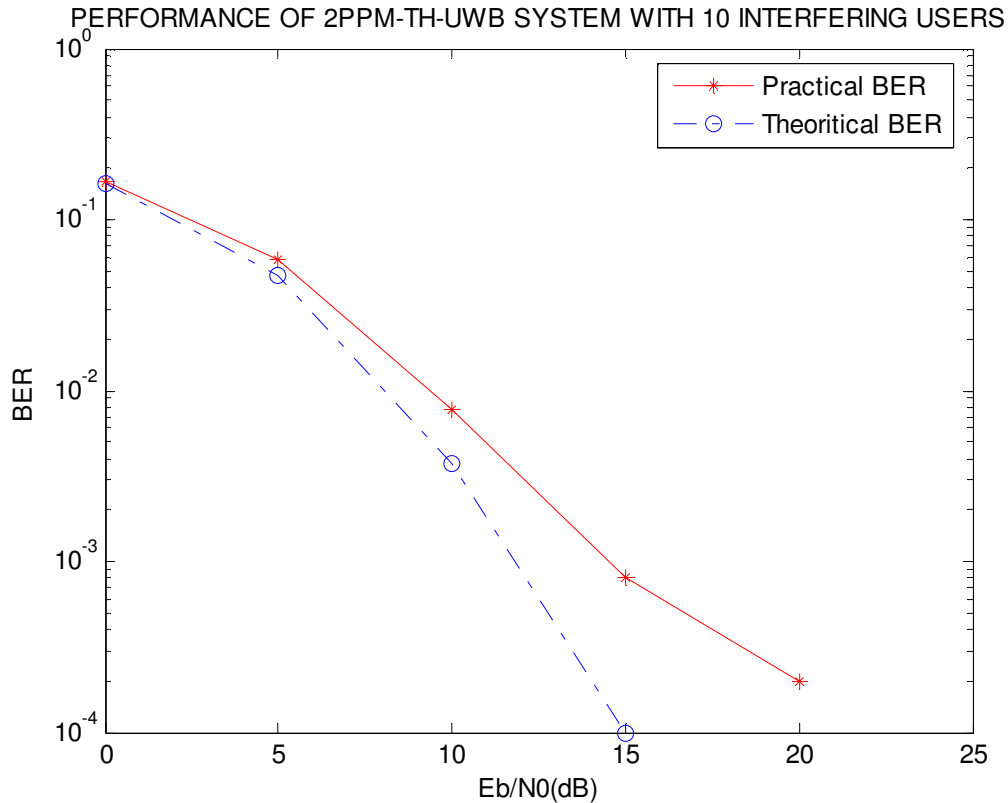


Figure 4.5 Performance Analysis of 10 interfering users for 2PPM-TH-UWB systems

4.4.3 Performance comparison of 6 and 10 interfering users

As seen in the figure below, the simulated bit error probabilities for the 2PPM-TH-UWB system with 6 interfering users and 10 interfering users are compared. The probability of error of the 10 user system is higher than that of 6 users. This is because as the number of users increase, the system performance degrades due to increase in the number of interfering signals at the receiver.

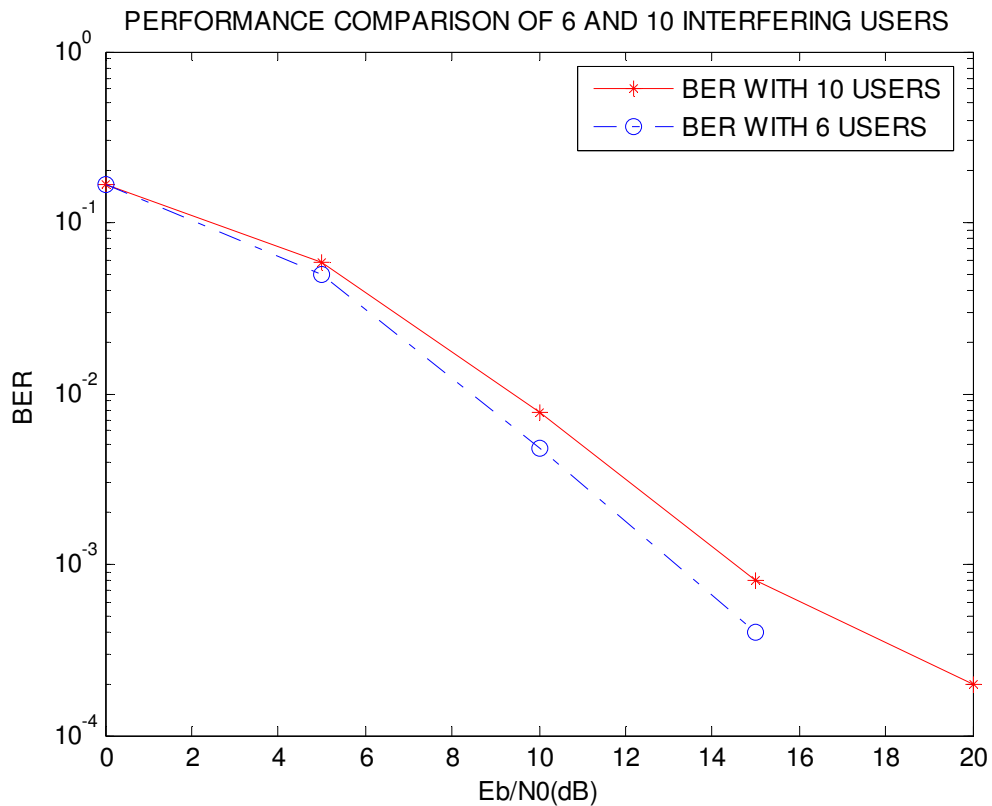


Figure 4.6 Performance Comparison of 6 and 10 interfering users for 2PPM-TH-UWB systems

4.5 Effect of Multi-User Interference and 4PPM on UWB System

In the sections above the effect of the 4PPM and Multi-user interference was analyzed separately on the UWB system. But it is an important case to see how the M-ARY PPM modulation affects the performance of the system when multiple users are accessing the system. The 4PPM-Multi-user system is designed in the same fashion as that for the binary case. The multiple accesses is achieved with the help of time hopping codes using the time hopping multiple access (THMA) scheme. It is assumed that the time hopping codes are equally probable and independent. Each code is randomly generated and corresponds to a PN sequence assigned to each user. The pulse position modulation with $M = 4$ is employed which means that each symbol corresponds to two bits. The pulse is shifted depending on the bits

value and there is no shift if the bit combination is '00'. Bits '00' will be mapped to no PPM shift ϵ whereas '01' will cause the signal to be shifted by ϵ and '10' and '11' will cause shifts of 2ϵ and 3ϵ respectively.

The 4PPM receiver as shown in figure 4.1 is implemented and the multiple user scenario is created by having multiple 4PPM-TH-UWB transmitters, transmitting the signal at the same time. The signal from the transmitter TX1 is considered to be the useful signal and the signals from all the other transmitters act as interference signals to the useful signal. The typical system block diagram is as shown below:

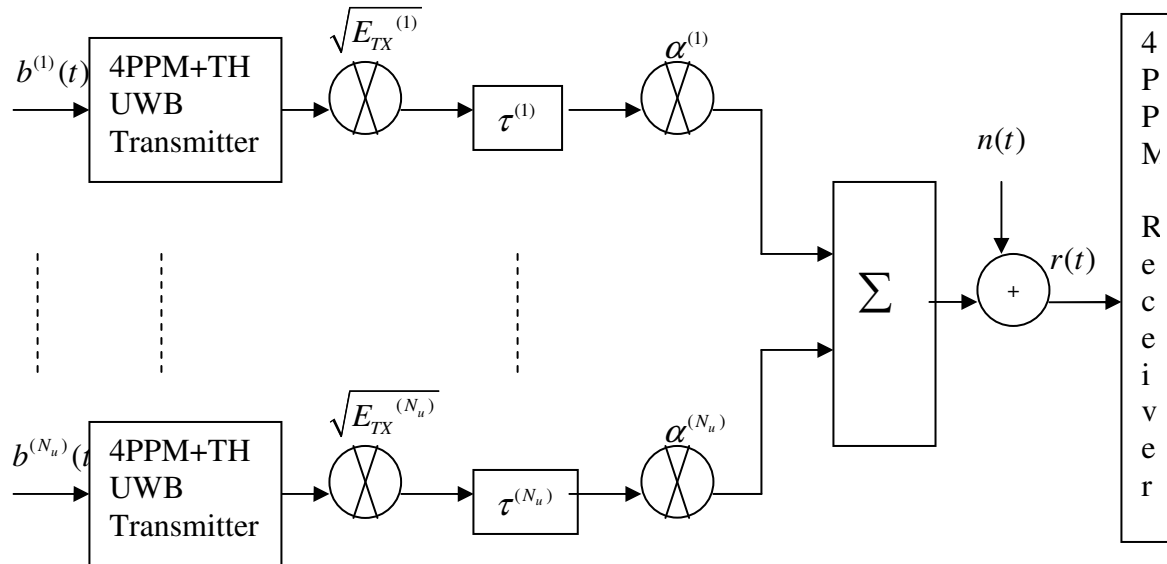


Figure 4.7 Multi-User UWB system with 4PPM

As seen in the above figure, the functionality is similar to that of the Multi-user case with binary pulse position modulation except that now the modulation is replaced by 4PPM and hence 4PPM transmitters and receivers are implemented. The received signal is a combination of the useful signal, the interference signals from the other users and the noise signals and the bit error probability analysis follows the same as derived in the previous section.

Performance Analysis of the Multi-user system with 4PPM is carried out for 6 and 10 interfering users and there results are compared with the same for the multi-user scenario with the binary PPM modulation. It is observed that the performance degrades as the number of users increase and the modulation index increases.

4.5.1 Performance of 6 interfering users

The figure below shows the performance of the Multi-user system with 4PPM for 6 interfering users. It is observed that as the value of M increases the bit error rate increases degrading the performance of the system. It is observed that at the error probability of 10^{-3} the binary PPM system has a gain of about 6 dB as compared to the multi-user system with 4PPM modulation employed. Thus, even in the multi-user scenario the performance degrades as the modulation index M increases.

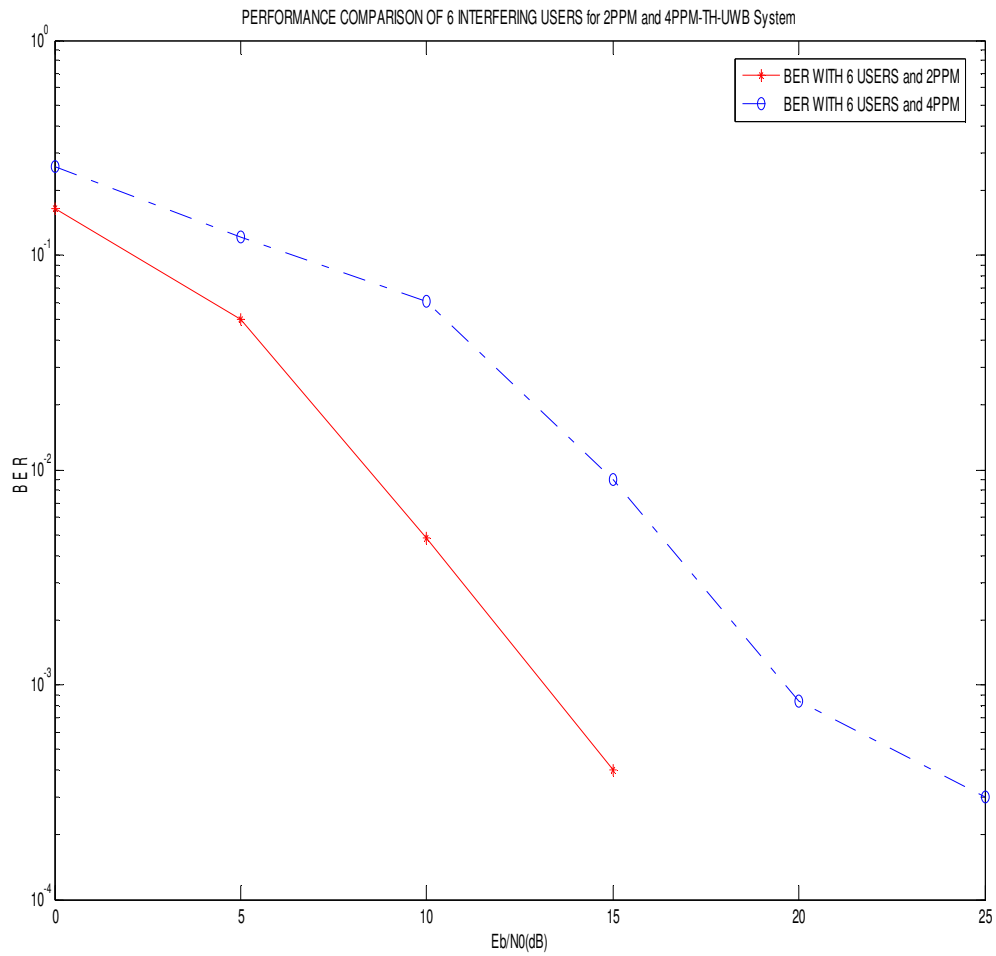


Figure 4.8 Performance Analysis of Multi-User UWB system with 4PPM for 6 interfering users

4.5.2 Performance of 10 interfering users

The figure below shows the performance of the UWB system in the presence of 10 interfering users with binary PPM and 4PPM modulation schemes employed. As verified for the 6 interfering users' case, the binary PPM multi-user system outperforms the 4PPM multi-user system.

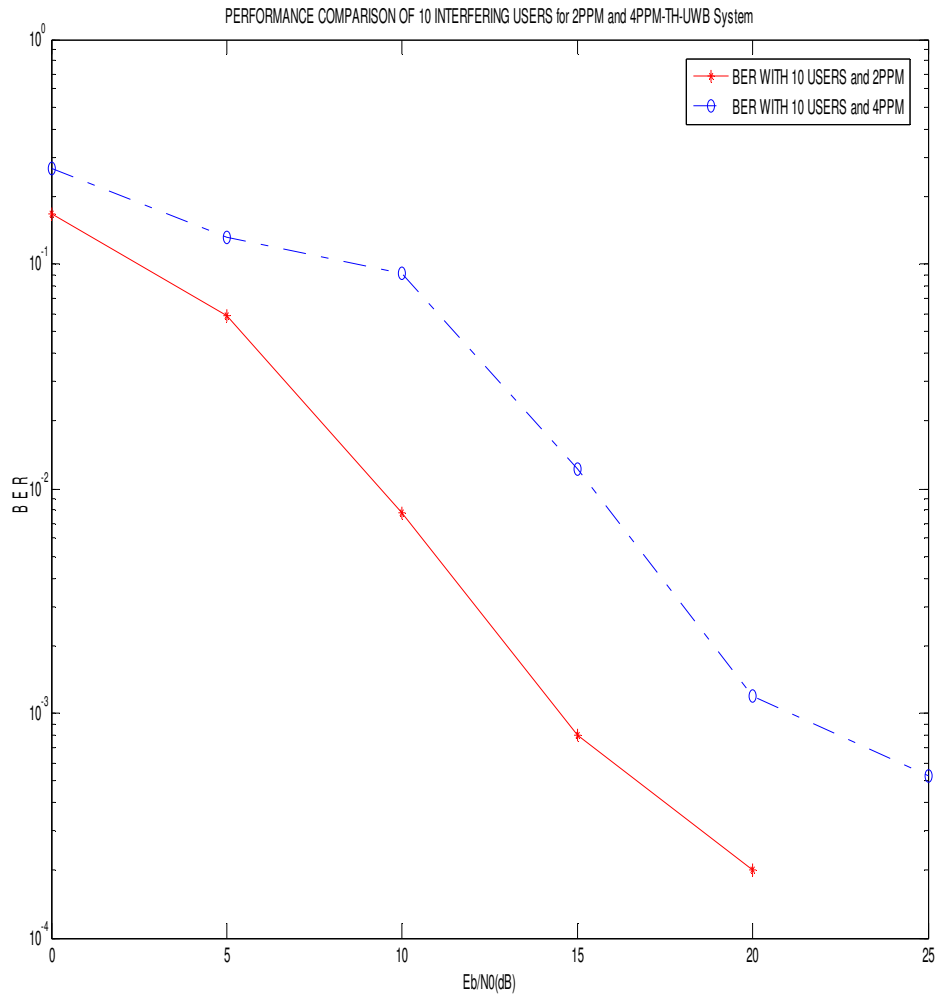


Figure 4.9 Performance Analysis of Multi-User UWB system with 4PPM for 10 interfering users

4.5.3 Performance of 6 and 10 interfering users

The figure below depicts the performance of 6 and 10 interfering users with binary and M-ary pulse position modulation. The performance of the 6 interfering users is better as compared to that of 10 users as the number of interfering signals generated by the interfering users to the desired user is comparatively less. Also the binary PPM case outperforms the 4PPM employed system.

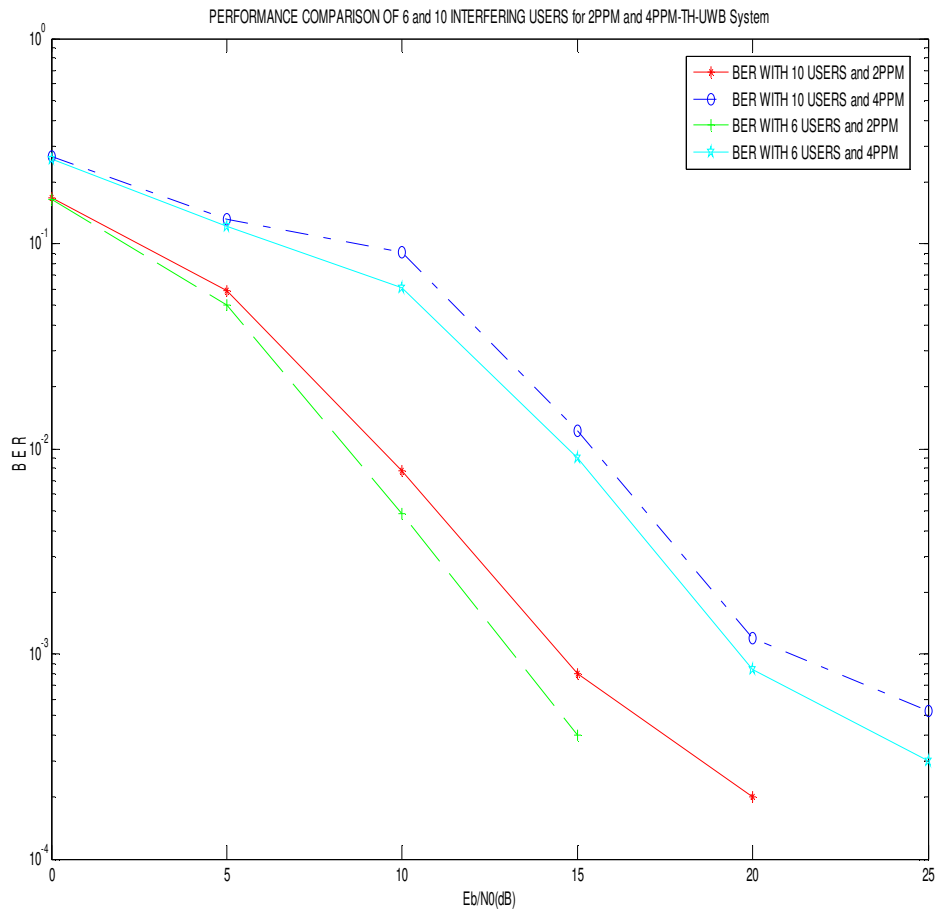


Figure 4.10 Performance Analysis of Multi-User UWB system for 6 and 10 interfering users

Thus, to summarize, the performance of the ultra wideband communication system degrades as the number of interfering users increase and as the modulation index increases.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

Considering UWB is a rapidly evolving technology being targeted for the use in both short range and low range applications for flexible data rates, the performance analysis of the UWB system is an important issue. In the work presented in this thesis, I have tried to achieve the performance curves for various cases. It is observed that the Ideal RAKE outperforms the SRAKE and the PRAKE. While the PRAKE is simple to implement, its performance degrades as compared to the selective RAKE. Furthermore, as the value of the repetition code N_s increases, the performance improves. Also, the binary PPM UWB analysis is extended to the 4PPM case. It is observed that as the value of M increases the performance degrades. The performance is also evaluated in the multiple user scenarios which add the effect of multi-user interference in addition to that of thermal noise. It is seen that the performance degrades when the number of users increase as the increased number of users, increase the number of interfering signals transmitted by each user to the useful signal. Finally, the combined effect of multi-user interference along with 4PPM is analyzed and it is observed that the performance drops considerably by about 6 dB.

5.2 Future Work

The analysis carried out in this thesis was performed in an indoor environment and Non Line of sight UWB Channel Model case CM3 configuration. It remains to be seen what would be the effect of multi-user interference and the M-ary pulse position modulation on the other channel model configurations in the case of Line of Sight. The analysis can be carried out for the other channel model configurations and also in the outdoor environment. The work presented in this thesis can be extended further to the Pulse Amplitude Modulation (PAM) UWB

system as PAM is the other widely used modulation techniques for UWB. It would be interesting to see the comparison between the two modulation techniques in these different scenarios. Moreover, the thesis assumes that the channel impulse response is known. The channel estimation is an important issue as the RAKE receivers are the optimum receivers for multi-path environments and they require the channel coefficients. The work can be extended to have a detailed analysis of the various channel estimation algorithms and how they can be implemented. The different channel estimation algorithms can be compared and then the performance can be analyzed when channel is estimated and compare it with the performance when the channel is known.

REFERENCES

- [1] Moe Z. Win and Robert A. Scholtz, "Ultra-Wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications" IEEE Transactions on Communications, VOL. 48, NO. 4, APRIL 2000.
- [2] R.A. Scholtz, "Multiple access with time-hopping impulse modulation", Proc. IEEE Military Commun. Conf.,pp.11-14, Oct 1993
- [3] Moe Z. Win and Robert A. Scholtz, " Impulse Radio: How it Works", IEEE Communications Letters, VOL. 2, NO. 2, February 1998.
- [4] Jeff Foerster, "Ultra-Wideband Technology for Short-or Medium-Range Wireless Communications", Intel Tech. J.,Q.2, 2001
- [5] F. Ramirez-Mireles and R.A. Scholtz, " Multiple-access performance limits with time hopping and pulse position modulation", Proc. IEEE Military Commun. Conf., pp. 529-533, Oct 1998
- [6] A. R. Forouzan, M. Nasiri Kenari and J.A. Salehi, " Performance Analysis of time-hopping spread spectrum systems multiple-access systems: coded and uncoded schemes", IEEE Transactions on Wireless Communications, Vol. 1, Issue: 4, pp. 671-681, Oct 2002.
- [7] G. Durisi and S. Benedetto, "Performance evaluation of TH-PPM UWB systems in the presence of multiuser interference", IEEE Communication Letter, Vol. 7, pp. 224-226, May 2003
- [8] G. Durisi G. Romano, " On the validity of Gaussian approximation to characterize the multiuser capacity of UWB TH PPM", in Proc. IEEE Conf. on Ultra Wideband Systems and Technologies 2002, Digest of Papers, pp. 157-162, 2000.
- [9] Li Zhao and A.M. Haimovich, " The capacity of an UWB multiple-access communications system", ICC 2002, IEEE International Conference on Communications, Vol. 3, pp. 1964-1968, April/May 2002.

- [10] Hao Zhang and T. Aaron Gulliver, "Performance and Capacity of PAM and PPM UWB Systems with Multiple Receive Antennas"
- [11] J.R. Foerster, "The effects of multipath interference on the performance of UWB systems in an indoor wireless channel", Proc. IEEE Vehic. Tech. Conf., pp. 1176-1180, May 2001.
- [12] Reza Pasand, Saeed Khaleshosseini, John Nielsen, Abu Sesay, "Performance Analysis of Synchronous M-ary Time Hopping PPM UWB Multiple-Access communication Systems", MILCOM 2004.
- [13] Liuqing Yang and Giannakis, G.B., "Ultra-wideband communications: an idea whose time has come", IEEE Signal Processing Magazine, Vol. 21, Issue 6, Nov 2004 pages 26-54.
- [14] G.R. Aiello and G.D. Rogerson, "Ultra-wideband wireless systems", IEEE Microwave Mag., vol. 4, no. 2, pp. 36-47 2003
- [15] Bastidas-Pugo, Ramirez-Mireles, Munoz-Rodriguez, "Performance of UWB PPM in residential multipath environments", Vehicular Tech. Conf., 2003 Vol. 4, pages 2307-2311.
- [16] Guvenc I. and H. Arslan, "One the modulation options for UWB system", IEEE Military Communications Conference, 2003, 892-897
- [17] "PULSERS White Paper", WWRF Meeting, Eindhoven, The Netherlands, December 2002.
- [18] Lijja Ge, Guangrong Yue, Affes S, "On the BER performance of pulse position modulation UWB radio in multipath channels", Ultra Wideband systems and Technologies, 2002 Digest of Papers, IEEE Conference 2002.
- [19] Saleh A, Valenzuela R, "A Statistical Model for Indoor Multipath Propagation", IEEE Journal on Selected Areas in Communications, Vol. 5, Issue 2. 1987 pages 128-137
- [20] Erkucuk,S, Dong In Kim, "UWB-IR System Performance for Implementable Rake Receivers", CCECE 2007, pages 1179-1182
- [21] Maria-Gabriella Di Benedetto, Guerino Giancola, "Understanding Ultra Wide Band Radio Fundamentals", Pearson Education 2004

- [22] Maria-Gabriella Di Benedetto, Thomas Kaiser, Ian Oppermann, "UWB Communication Systems A Comprehensive Overview", EURASIP Book Series on Signal Processing and Communications, Vol. 5
- [23] Huseyin Arslan, Zhi Ning Chen, Maria-Gabriella Di Benedetto,"Ultra Wideband Wireless Communication", John Wiley and Sons, Inc 2006
- [24] Ian Oppermann, Matti Hamalainen, Jari Linatti,"UWB Theory and Applications", John Wiley and Sons, Ltd. 2004
- [25] M. Ghavami, L.B. Michael, R. Kohno, "Ultra Wideband signals and systems in communication engineering", Second Edition, John Wiley and Sons Ltd., 2007
- [26] J. Proakis, "Digital Communication", Fourth Edition, McGraw -Hill, 2001
- [27] T. Rappaport, "Wireless Communications: Principles and Practice", Second Edition, Pearson Education,2004.

BIOGRAPHICAL INFORMATION

Mukta Athavale, the author of this thesis, received her Bachelors of Engineering degree in Electronics Engineering from University of Mumbai, India in 2005. She then worked with TATA Consultancy Services Pvt. Ltd, a premier software solutions firm in India for a year. She then started her studies for Masters in Electrical Engineering at University of Texas at Arlington. Due to her interest in Wireless Communications, she did various projects in this field and then worked as an intern at Qualcomm Inc. for 8 months. During her internship, she worked on GSM Base Station Emulators to achieve desired audio quality during the GSM network based calls. Meanwhile she joined the Wireless Communication and Networking Lab under Dr. Qilian Liang. She was also the Graduate Teaching Assistant to Dr. Liang for the Wireless Communications graduate level course at UTA. Her research interests lies in the field of wireless communications.