ADAPTIVE MULTIMODE MULTIBAND NARROWBAND SDR WAVEFORM BASED ON CONTINUOUS PHASE MODULATION (CPM)

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بسم الله الرحمن الرحيم

In the name of Allah, the most Merciful and the most Beneficent

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I certify that this research work titled “adaptive multimode multiband narrowband sdr waveform based on continuous phase modulation scheme (CPM)’’ is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources is properly acknowledged / referred.

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First of all, I thank Almighty Allah who has given me the health, knowledge and understanding of things to complete this work

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And finally, I must thank my dear family and friends for putting up with me during the development of this work with continuing support and no complaint.

NOTE: This thesis was submitted to my Supervising Committee on the October 21, 2019.

DEDICATION

I dedicate this thesis to my loving parents!

ABSTRACT

A Software Defined Radio (SDR) is a radio transceiver that is well defined in software and whose physical layer conduct, parameters, and protocols can be fundamentally modified through software as a waveform. This approach will increase the flexibility of the device by changing its operating parameters while not having an upgrade or exchange of any hardware parts. Thus, SDR provides a platform capable of supporting distinctive waveforms. The main distinction lies in the focus of implementation, a few waveforms are designed which accomplish higher data rate, whereas others prioritize range and transmission capacity. It is recognized that strategic military radios need wideband and narrowband waveforms for fulfilling most of the military requirements. Wideband networking waveform (WBNW) ensures a high data rate; this lowers the range whereas for applications requiring long-range communication, narrowband networking waveform (NBNW) tends to be a dominant choice.

Modern strategic VHF communication frameworks require increasing throughputs to support a wide variety of applications for military, commercial, and civilian applications. It requires a combination of spectral efficiency and better ber performance. To meet the heterogeneous requirement of future wireless networks, an adaptive multimode multi-band narrowband waveform for software-defined radio based on Continuous Phase Modulation (CPM) is presented in this thesis. Due to higher spectral efficiency and constant envelop property provided by CPM, we show that the proposed waveform attains higher throughput by shifting towards multiple bandwidths and for the appropriate choice of alphabet size M, pulse length L and modulation index, h.

In the next step a novel algorithm for link adaptation scheme for packet-based Narrowband networking SDR waveform is proposed. To reduce the packet re-transmissions overhead, the configurable system parameters need to be changed dynamically according to the channel conditions ensuring specific Quality of Service (QoS) requirements and reduces the computational complexity/power consumption by restricting the throughput to the required value.

At the end, the BER performance of proposed multimode multiband waveform for CPM is evaluated in AWGN and Stanford University Interim channel (SUI) channel model.

Keywords: narrowband waveform, software defined radio, continuous phase modulation scheme

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GLOSSARY

AIS Automatic Identification System

AM Amplitude Modulation

ANFIS adaptive Noise-Fuzzy Interference System

AWGN Additive White Gaussian Noise

BER Bit Error Rate

BMU Branch Metric Unit

BPSK Binary Phase Shift Keying

CPFSK Continuous Phase Frequency Shift Keying

CPM Continuous Phase Modulation

DAC digital-to-analog converter

DDFS Direct Digital Frequency Synthesizer

DSP Digital Signal Processor

FFT Fast Fourier Transform

FH Frequency Hopping

FM Frequency Modulation

FPGA Field Programmable Gate Array

GMSK Gaussian Minimum Shift Keying

GPP General Purpose Processor

HR Hardware Radio

ISI Inter Symbol Interference

NBNW Narrowband Networking Waveform

PHY Physical

PSD Power Spectral Density

PSK Phase Shift Keying

RF Radio Frequency

SDR Software Defined Radio

SNR Signal to Noise Ratio

SoC Programmable System on Chip

WBNW Wideband Networking Waveform

WCDMA Wideband Code Division Multiple Access

Chapter 1: INTRODUCTION

Radio transmission methods have increasingly advanced, giving users the opportunity to stay linked with rising transmission rates. In order to meet the challenge of providing an air interface architecture with improved range and throughput compared to traditional waveforms, a physical layer model based on modern signal processing techniques that can provide reasonable spectral efficiency and operate in a relatively low signal-to-noise ratio (SNR) is necessary. Technologies in wireless communication advance in accordance with the requirements of incorporating different functionalities using the same device or hardware. This trend has led us to a whole new area of research and development which evolved from traditional hardware radios to software-controlled radios [1]. Presently, Software Defined Radio (SDR) allows dynamic spectrum management which fulfills the challenge of performing well across different modes, bands and waveform standards.

SDR defines a collection of hardware and software technologies where some or all of the radio's operating functions on the physical layer are implemented through reconfigurable software or firmware, operating on programmable processing technologies to reproduce several communication standards [2]. The processing systems comprise Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA), Programmable System on Chip (SoC) or additional Application Specific Programmable Processors [3].

SDR technology provides flexibility and configurability as the software can be altered according to the applications in the communication system. Development cost and complexity reduce as the software can be varied and it empowers execution of RF systems where waveforms are digitally synthesized according to requirements without the need to change hardware components [4]. An SDR is capable at the same time performing different RF capacities (radar, communication), has the potential to displace different specialized frameworks. It lowers power consumption and offers improved functionality. Interoperability and efficient use of resources under varying conditions makes SDR a great area of research and development.

1.1 Narrowband Waveform vs. Wideband Waveform

SDR provides a platform capable of supporting distinctive waveforms. Wireless systems can be classified according to whether they have narrowband or wideband architecture. Figure 1.1 shows a network where some users are at short range and one user is at a larger distance. Depending on the bandwidth and range of the transmission of physical channels with which they operate, a system is defined as narrowband or wideband [5]. Keeping this criterion, communication types are broadly categorized as:

• Narrowband Communication
• Wideband Communication

Narrowband communication

Narrowband communication utilizes a narrow bandwidth of the spectrum which realizes stable long-range and low bit-rate communication.

Narrowband signals are utilized in a slower shape of communication where primarily voice or slow data streams ought to be transmitted. Such signals typically have a much wider range of reception, since narrower filters can be used to suppress unnecessary wideband interference. Transmitted energy is distributed on a smaller portion of the spectrum. Common uses are FM radio, AM radio, satellite downlinks, Global Positioning System (GPS) signals and National Oceanic and Atmospheric Administration (NOAA) weather transmissions [6].

The main disadvantage of the narrow band system is that it is not appropriate for high speed communications due to the narrow receiver bandwidth. In general, the speed is limited to less than 9,600bps [7].

Wideband communication

Wideband communication uses a wider portion of the spectrum and it supports higher data rate transmission. It allows higher bandwidth and therefore faster communication. The wideband system can reach speeds much higher than 10,000bps. Examples of wideband communication are wireless networks: Wi-Fi, Long Term Evolution (LTE), and High Speed Packet Access (HSPA) [8].

The main disadvantage of the wideband system is that it is harder to send and detect wideband signals because a high Signal to Noise Ratio (SNR) is needed as the energy of the signal is spread across the width of the spectrum. Hence transmitting on a given power level, the wider the signal, the weaker it gets.

1.2 Motivation and Problem Statement

Modern strategic VHF communication frameworks require increased data rates regardless of small channel bandwidth of 25 KHz. Increasing demands for adaptability and configurability present many challenges to the development of waveforms for highly heterogeneous wireless networks for Software Defined Radio (SDR). Generally, narrow-band waveforms provide robustness and function over longer distances, but do not have higher throughput, whereas wide-band waveforms provide much higher throughput, but are not very robust and run for longer distances. Software Defined Radio (SDR) addresses these challenges by taking into account dynamic spectrum management [9].

To support heterogeneous requirements of future wireless networks, the increased demand for higher data rates and specific Quality of Service (QoS) requirements has motivated to design a flexible waveform that supports multiple modes, multiple bandwidths/multiple data rates. To achieve these requirements, our focus on implementation is to design an adaptive multimode multiband narrowband SDR waveform based on the Continuous phase modulation (CPM) scheme that is capable of providing adaptive, high speed communication and data rate requirements.

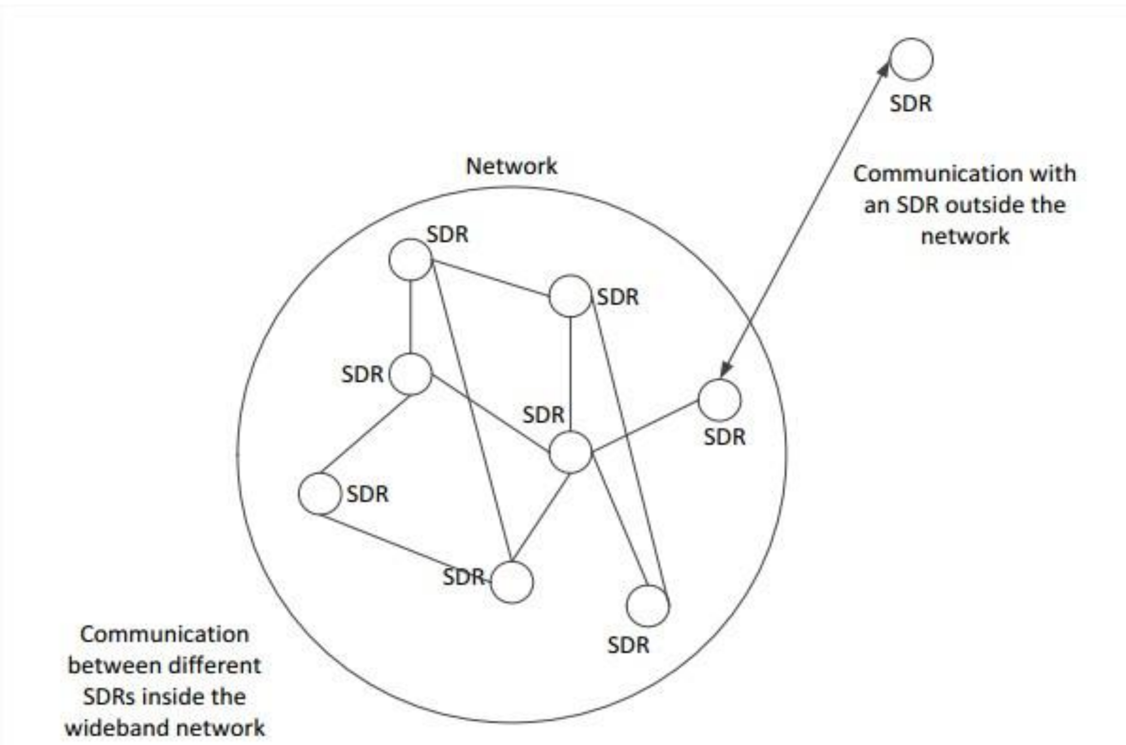


Figure 1.1: Connectivity of SDR's in Long and Short-Range Network

Chapter 2: LITERATURE REVIEW

As the applications for wireless communications increase, so do the requirements of functioning well across a range of modes, bands and waveform standards. SDR addresses these challenges by allowing for dynamic spectrum management. “SDR defines a collection of hardware and software technologies where some or all of the radio’s operating functions on the physical layer are implemented through modifiable software or firmware, operating on programmable processing technologies to reproduce several communication standards”. According to the strict standards in definitions, most of the radios are software controlled rather than software defined. Today’s modern cellular phone can support both GSM (2G) and Wideband Code Division Multiple Access (WCDMA) (3G) standards proving the fact that it is an example of software-controlled radio as the user does not need to plug into a different module to access each network [10].

In [12], design of multi-h Continuous Phase Modulation (CPM) waveform has been proposed to increase the throughput three times the data rates already accessible on UHF military satellite communication (MILSATCOM) channels. Three approaches are discussed to achieve these goals. The principal is to increase the modulation order from 4 to 8 symbols by encoding 3 bits per symbol rather than 2, expanding 50 percent of the bandwidth. Another field of interest is the partial response waveform. In other words, each symbol has been shaped over several symbols period. Another technique adds additional space to the construction of the trellis and should make compact spectrum. The third strategy examined is to increase the number of indices of modulation. The aim is to extend the trellis more by using three or more indices, increasing the minimum Euclidean distance.

An 8-ary waveform would improve throughput rate, but at the cost of power efficiency. Utilizing smaller modulation index pairs consumes less bandwidth, but also lowers coding gains. The smaller index pairs have a wider range of energy at a particular throughput rate which suggests better BER output. Utilizing smaller modulation index pairs consumes less bandwidth but, like for 4-ary case, does not buy the BER performance. Partial response waveforms required less bandwidth as compared to full response waveform. For these schemes, the gains relative to MSK are 5.8 dB and 3.2 dB respectively of partial and full response schemes. It means that gain can be achieved by switching to partial response without any change in bandwidth. The major drawback of this scheme is that partial response entails a larger degree of complexity of the receiver and needs further examination.

In [13], the upcoming NATO NBWF is analyzed regarding the necessary bandwidth system. Legacy versions of the NBWF operate historically, with a channel bandwidth of 25 kHz .The new NBWF should also require the tactical band to operate. Due to the constant envelope property of the modulation scheme, the latest waveform design is based on Continuous Phase Modulation (CPM), which is commonly used in mobile communications. A number of modes for a 25 kHz channelization define the waveform. Most of these modes are differentiated by the data rates received. The three lower rate modes, namely NR (R refers to robust), N1 and N2, offering 10 kbps, 20 kbps and 31.5 kbps respectively, can be considered as long-range modes, while the modes N3 and N4, offering 64 kbps and 96 kbps respectively can be considered as high throughput modes.

There are two possibilities for increasing the data rate. The first one is to increase the amount of information within one symbol duration by transmitting e.g. 2 Bit/Symbol instead of 1 Bit/Symbol, which is the common way of increasing the data rate. The CPM waveform follows another, the second possible approach. While keeping the amount of information constant, to increase the data rate, the symbol duration itself gets reduced and the symbol rate increases. When the symbol rate increases, it is known that the bandwidth occupation of the system increases as well, which is not desired since use of a 25 kHz channel (two-sided) is a mandatory requirement. This increase of bandwidth is compensated with the reduction of the modulation index h.

It is shown that for high throughput modes, spectral growth cannot be compensated by reduction of h as they are more immune to noise and it occupies two and three 25 KHz channels which doesn't meet the requirement as military spectrum is a very scarce resource. Certain modifications are possible in future to increase the data rate by increasing the modulation order of the mode N2 on the expense of demodulator complexity.

In [14] CPFSK-OFDM frameworks which utilize CPFSK (Continuous Phase Frequency Shift Keying) as the primary balance conspire of OFDM (Orthogonal Frequency Division Multiplexing) are executed by utilizing Software defined radio and assessed them in an AWGN ((Additive White Gaussian Noise) channel. In Orthogonal Frequency Division Multiplexing (OFDM), a high frequency data stream is divided into lower frequency streams which are instantaneously sent to a number of orthogonal subcarriers. As the symbol period is increased the relative sum of scattering in time caused by multipath delay spread diminishes. OFDM is therefore a commonly used modulation scheme for wireless broadcast networks. Using Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM), each subcarrier is modulated in widely used OFDM systems.

Alternatively, due to its continuous phase transitions, Continuous Phase Modulation (CPM) has property of rapidly decaying side lobes [15]. When utilizing CPM as OFDM's to begin with modulation scheme, this property can relieve the impacts of offset phase noise and hence decrease inter-carrier obstructions (ICI).

In this paper, we call this sort of framework an OFDM-CPM framework since after the OFDM modulator, the CPM modulator is cascaded. Pulse g (t) is the rectangular pulse and Continuous Phase Frequency Shift Keying (CPFSK) is called for L = 1, the signals.

The USRP contains a 100MSPS AD and 400MSPS DA adapter. A mother board with 4.9GHz to 5.9GHz frequency range is also used. A gigabit Ethernet connects the individual computer to signal handling and the USRP, and baseband signals go through them. On the personal computer, all OFDM signal processing is performed. Lab VIEW is used as a programming tool. The results show that 0.75 modulation index is better than modulation index of 0.5 and 0.625 for CPFSK-OFDM systems. In the future, the evaluation of the system would be in a fading environment.

A block-based decision-feedback equalizer (DFE) is provided in [16] for Multi-h CPM in aeronautical telemetry. The strategy of this equalizer is to provide better performance over multi-path frequency restricted channels with deep nulls. This multipath interference is a universal phenomenon, especially in aeronautical telemetry, for any wireless communication links.

Multi-h CPM is a non-linear memory modulation scheme that induces ISI that is not constant but varies with the phase information. The two types of ISI tend to confuse the conventional equalizer. Challenge is the non-linear relationship between the waveforms and the bit decisions. The decision-feedback equalizer is much better than the linear equalizers particularly when the multipath channel environment is too bad. The feed-back channel of the equalizer employments bit choices to reproduce samples of the Multi-h CPM waveform. Such samples are passed through a filter to replicate the multi-path-induced distortion that is extracted from the data to the decision system prior to detection. Simulated Bit Error Rate Output of Decision Feedback Technique appears an almost 1 dB better performance over MMSE-equalized [17] for Multi-h CPM. The drawbacks to this approach are complexity and error propagation.

THE Advanced wireless systems request high speed communication by guaranteeing particular Quality of Service (QoS) necessities. A considerable investigate has been carried out to explore the potential of applying the Software defined Radio (SDR) approach to attain these objectives [18]. To optimize the rare SDR assets, effective calculations for asset allocation/utilization are required. It involves the adjustment of SDR waveform transmission parameters to changing channel conditions, QoS and data rate specifications. This process is called link adaptation. In [19] link adaptation scheme utilizing fuzzy rule-based system (FRBS) for packet-based wideband SDR waveform is proposed.

A constrained optimization problem with QoS and bandwidth constraints has been overcome by link adaptation or adaptive adjustment of the modulation technique and the number of multicodes at the physical layer.

The initial step of the proposed algorithm is the extraction of data from the system's BER output curves for all possible modes of operation. After completing the data acquisition from BER curves, complete range of inputs and outputs are selected. The proposed framework takes three inputs (QoS requirement, throughput constraint and SNR) and produces output Modulation and Multicode Index pairs.

Link adaption rule is predicated altogether on a series of guidelines within the manner of IF THEN statements. Certain rules have equal antecedent (IF part) however extraordinary consequents (THEN parts).These guidelines are known as conflicting rules. For conflicting rules, the resulting coming about in higher throughput is chosen. Additionally, if two or more consequents result in same throughput, the resulting with lesser number of phase states is chosen since it'll result in lower computational complexity and hence lower control utilization. If some input/output pairs are no longer obtainable within the acquired data, then these elements stuffed with the help of human intuition or skilled professional knowledge for instance, if an MMI pair accomplishes the given conditions at a lower SNR, then it's sincerely legitimate for higher SNR. If the throughput specification is not reachable via the accessible MMI pairs in a given QoS requirement, then the MMI pair with the highest likely throughput is selected. It is demonstrated that the proposed algorithm diminishes the complexity and power consumption through limiting the throughput to the required value required by user or application even if the channel specifications are sufficiently fair to allow high throughput rate.

Chapter 3: CONTINUOUS PHASE MODULATION SCHEME (CPM)

The fundamentals of continuous phase modulation (CPM) will be dealt with in this chapter and the impact of phase smoothing pulses on the signal.

3.1 Signal Description:

CPM as specified by the term belongs to a signal class in which information is transmitted in the signal's instant phase and this phase is continuously maintained all the way through the signal as shown in Figure 3.1.

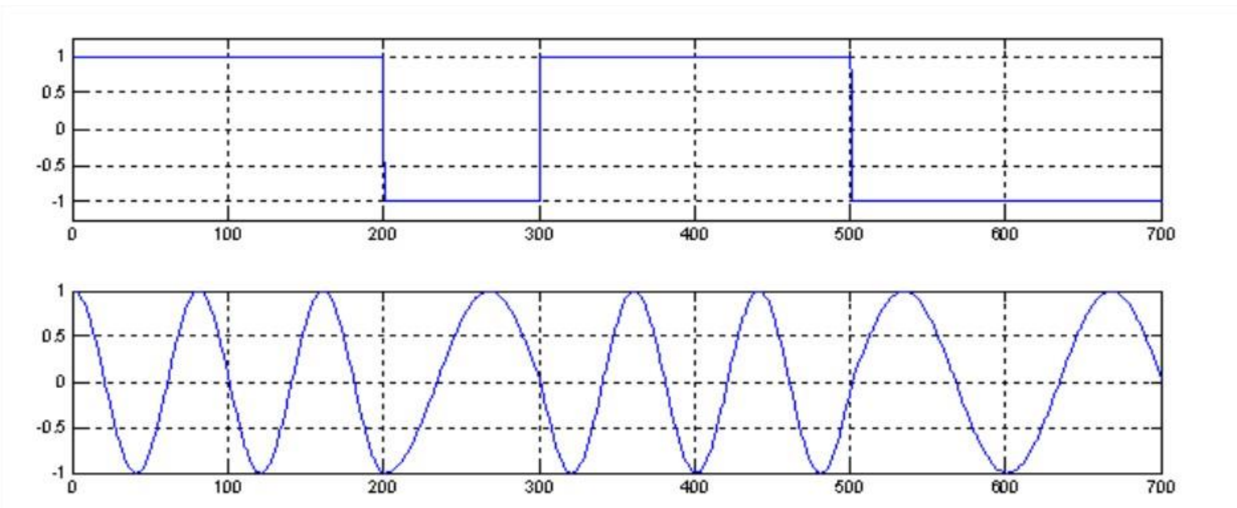


Figure 3.1: Presenting the phase change of the input bit stream signal

Limited bandwidth resources make modern (terrestrial) communication systems susceptible to adjacent channel interference. This occurs due to the energy of a signal "leaking" into to neighboring frequency bands and can hence be mitigated if the modulated signal has a power spectrum which exhibits small side-lobes and a fast-roll offs. Continuous phase modulation (CPM) is ideally suited for radio environments suffering from spectral congestion. In CPM, the signal phase transitions are continuous from one symbol to another. This phase continuity yields the much-desired compact power spectrum, with small side-lobes and fast spectral roll-off.

This is somewhat different from other coherent digital phase modulation strategies where at the beginning of each symbol (e.g. M-PSK) the carrier phase resets suddenly to zero. Because of this stability, the CPM spectrum shows less spectral side lobes and thus has higher spectral proficiency related to further digital modulation schemes such as FSK, BPSK and QPSK.

CPM is a memory-based scheme of nonlinear modulation. The phase switch in CPM signals process depends on the information transmitted in current symbol as well as on previously transmitted symbols needed for CPM transmitters [20]. CPM has a constant envelope since only the phase is modulated. It makes the use of a Class C amplifier that is inexpensive and power-efficient.

3.2 Transmitter side of CPM waveform:

The schematic modulator for CPM system is shown in figure 3.2. Input to the modulator block is sequence of uncorrelated data symbols I. The sequence of that symbols is then convolved with pulse shaping filter $q(t)$. After integrating the frequency pulse $g(t)$, we get the phase pulse $q(t)$ having area ½ and the amplitude of that pulse is chosen to allow total phase shift over each symbol interval of Ihn radians.

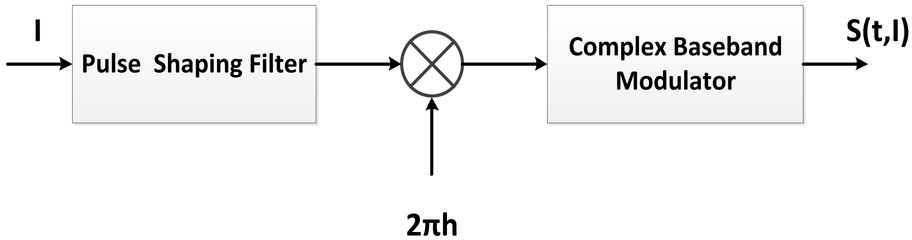


Figure 3.2: Schematic Modulator of CPM

Finally, the complex baseband representation of the CPM transmitted signal is as follows:

$$\boldsymbol{s(t,I)} = \sqrt{\frac{\boldsymbol{2E_s}}{\boldsymbol{T_s}}}\, \boldsymbol{e^{j\varphi(t,I)}} \tag{3-1}$$

Where the information carrying and time-varying phase of the nth symbol is given by:

$$\boldsymbol{\varphi(t,I) = 2\pi h \sum_{i=-\infty}^{n} I_i q(t - iT_s)} \tag{3-2}$$

With $nT_s < t \leq T_s$ is the symbol interval.

The parameter I denote a long sequence of uncorrelated M-ary data symbols, denoted by $I = I_i$ take on values *I = {±1, ±3.... ± (M - 1)}* if M is even. E_s denotes the average energy per information symbol, T_s represents one symbol period. The parameter h is called the index of modulation that controls the phase sensitivity or phase jump between the transmitted symbols and is represented as $h = {}^{r}/_{p}$ wherever (r in addition p are comparatively prime numbers) as shown in figure 3.3.

For each transmitted symbol, the modulation index h may be unique and h will be exchanged with h_k and moved inside the summation, in such a situation CPM will be recognized as the multi-h CPM signal.

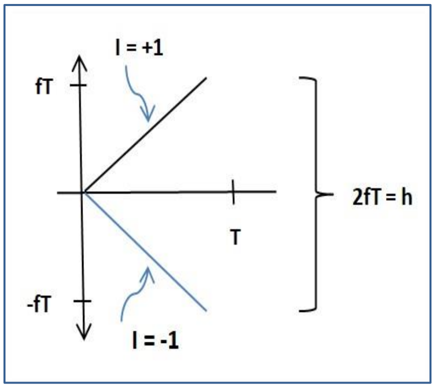


Figure 3.3: Phase jump (h) between continuous symbols

Moreover, $q(t)$ is some waveform shape or phase-smoothing response, and its derivative is the frequency pulse $g(t)$ assumed of duration LT and area ½ and the baseband pulse amplitude $g(t)$ is chosen to give Ihn radians the total phase shift over each symbol interval [15]. Defining the baseband phase response (phase pulse):

$$\boldsymbol{q(t)} = \int_{-\infty}^{t} \boldsymbol{g(\tau)d\tau}; \qquad -\infty < \boldsymbol{t} < \infty \tag{3-3}$$

If the frequency pulse $g(t)$ is satisfied, a causal CPM model is obtained:

$$\begin{cases} \boldsymbol{g(t) = 0}; & \boldsymbol{LT < t < 0} \\ \boldsymbol{g(t) \neq 0}; & \boldsymbol{0 \leq t \leq LT} \end{cases} \tag{3-4}$$

The form of the pulse $g(t)$ may exceed one symbol period (T). If $g(t)$ =0 it is called full response CPM signal for all t > LT, and if $g(t) \neq 0$ for t > LT then it is called partial response CPM [6]. Normally, it is easy to detect full response CPM but at the expense of broad spectrum.

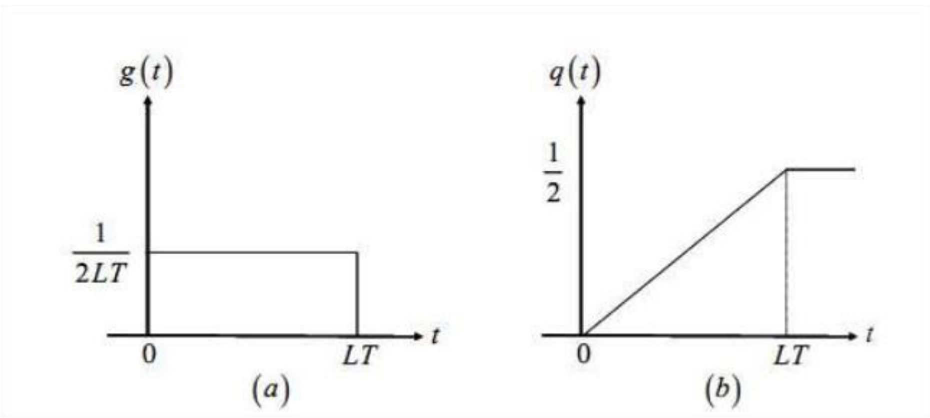


Figure 3. 4: Pulse Shape g (t) and corresponding Phase pulse q (t)

The property of signal pulse is that it is 0 for t < 0 and t ≥ LT as shown in Figure 3.4. The modulated wave for L=1 is defined as full CPM response, and partial response for L > 1. CPM is part of a group of memory signals. This memory is enforced by continuity of the phase and L > 1 adds additional information or memory, and the total number of incoming waveforms required to identify an input signal shift or previous symbols required to detect the current waveform is known as memory.

Table 3-1 includes three very common CPM pulse shapes.

Table 3-1: Commonly used types of CPM pulses

LREC	$g(t)=\begin{cases}\frac{1}{2LT} & (0\le t\le LT)\\ 0 & otherwise\end{cases}$
LRC	$g(t)=\begin{cases}\frac{1}{2LT}(1-\cos\frac{2\pi t}{LT}) & (0\le t\le LT)\\ 0 & otherwise\end{cases}$
GMSK	$g(t)=\{Q[2\pi B(t-T/2)/(\ln 2)^{1/2}]-Q[2\pi B(t+T/2)/(\ln 2)^{1/2}]\}$ $Q(t)=\int_t^{\infty}\frac{1}{\sqrt{2\pi}}e^{-x^2/2}dt$

LREC denotes a length LT rectangular pulse form. L=1 resembles primarily to the continuous phase frequency shift keying signal (CPFSK) as shown in Figure 3.5.

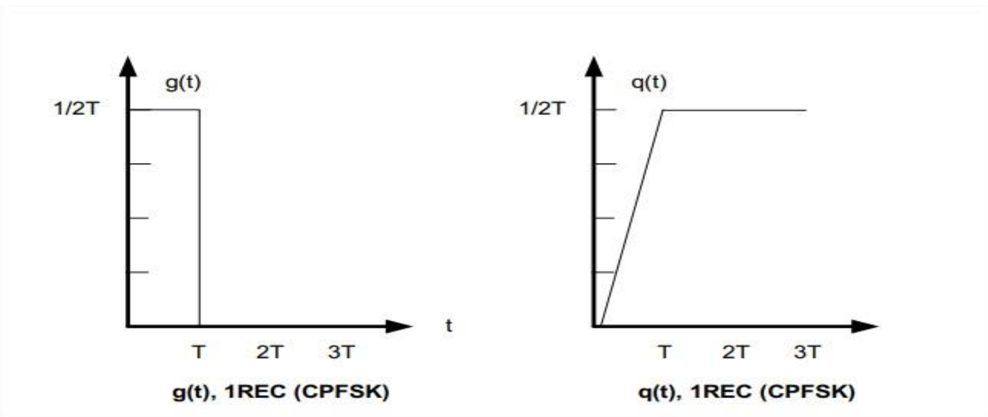


Figure 3. 5: Pulse shape g (t) and corresponding q (t) for L=1

LRC for LT length denotes raised cosine pulse. In this circumstance, the pulse category used will be of raised cosine in nature as shown in Table 3-1. Figure 3.6 is L=2 raised cosine pulse form visualization.

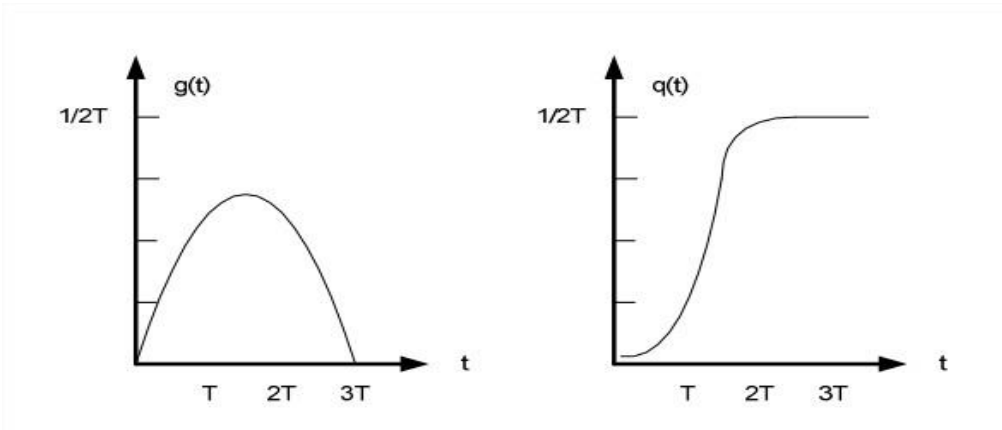


Figure 3. 6: Showing raised cosine pulse shape for L=2 and its derivative

As presented in Table 3-1 the third pulse is Gaussian minimum shift keying (GMSK) pulse with added parameter bandwidth (B) which shows the real Gaussian pulse bandwidth of -3dB. In electronic cellular communication systems, this type of pulse is mostly used. The phase variation grows in a type of trellis based on the incoming signal and draft of entire phase routes produced by the set of all likely input sequence is called the phase tree. For M= 2 and L=1 then $I_i = \pm 1$ would be the input symbols. Figure 3.7 displays the step tree for the said configuration.

The use of smooth pulses can achieve smooth phase trees through minimum discontinuities just like raised cosine (RC) and GMSK pulses. Such pulses show better efficiencies in the spectrum. For example, for the same input symbol transformations, two different phase trajectories are plotted to demonstrate their effect in Figure 3.8.

The phase tree rises linearly with the time, but the phase changes are restricted by $0 \leq \theta \leq 2\pi$ or from $-\pi$ to π as the wave repeats itself cyclically after every 2π cycle.

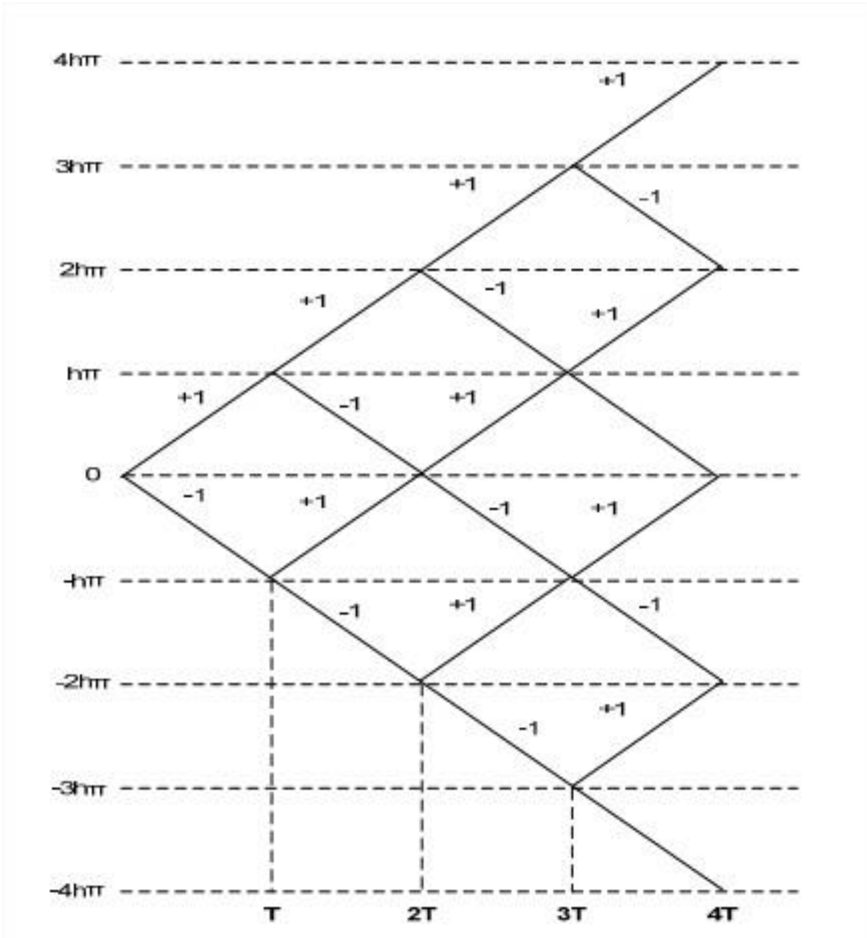


Figure 3.7: Phase tree for binary CPFSK

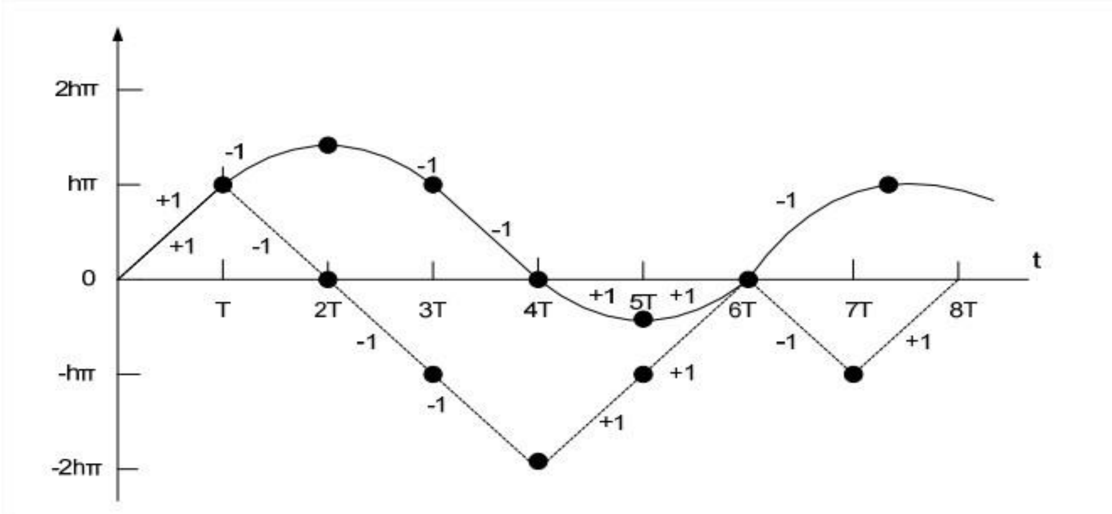


Figure 3.8: IREC (plain) vs. 3RC (pointed) plot presenting smoother pulses continuity rate

3.3 Channel Models:

For simulation purposes, two types of channel models were used:

1. Additive White Gaussian Noise (AWGN).
2. Stanford University Interim Channel (SUI) Model.

3.3.1 Additive White Gaussian Noise (AWGN):

For all frequencies, zero-mean white Gaussian Noise (WGN) has the identical energy spectral density. The term 'white' is employed within the sense that in the visible band of electromagnetic radiation, white light comprises equivalent quantities of all frequencies. The noise is an additive, i.e. the signal obtained is equal to the signal received plus noise.

$$r(t) = s(t) + w(t) \quad (3\text{-}5)$$

This noise encompasses a uniform spectral density & amplitude Gaussian distribution. thermal & electrical amplification noise, mostly have properties of white Gaussian noise, enabling accurate simulation with AWGN.

3.3.2 SUI Channel Model:

In this plan, we are going to recreate SUI networks as assumptions for tactical structures. The transmission for strategic channel like all additional remote channels depends upon landscape, tree density, antenna altitude, wind hustle, and season (time of the year). Stanford University Interim channel is basically based on the ERCEG demonstrates. ERCEG show [21] was created on the premise of bulk information collected by AT&T Remote, USA. [22].The received signal approaches to the receiver by passing through a few distinctive ways and at slightest one way is changing. The received signal is shown as:

$$r(t) = h(t) * s(t) + w(t) \quad (3\text{-}6)$$

Where h (t) is channel impulse response due to multipath variation at separations within the range of the signal wavelength. The SUI channels are a group of six channel versions/models speaking to three types of terrain and a number of doppler spreads, delay spreads and line-of-sight / non-line-of-site conditions that are normal of the continental Joined together States [21]. The channels are précised within the Table 3-2. The territory types, A, B, C are similar as those characterized in ERCEG demonstrate [21].

Table 3- 2: SUI channel Groups

Channel	SUI-1	SUI-2	SUI-3	SUI-4	SUI-5	SUI-6
Terrain Category	C	C	B	B	A	A
Terrain Type	Flat	Flat	Hilly	Flat	Hilly	Hilly
Tree Density	Light	Light	Light	Moderate to Heavy	Moderate to Heavy	Moderate to Heavy
Line of Sight	Strong	Strong	Weak	Weak	Weak	Weak
Delay Spread	Low	Low	Low	Moderate	High	High
Path Loss	Low	Low	Intermediate	Intermediate	High	High
Doppler Spread	Low	Low	Low	High	Low	High

3.4 Receiver side of CPM waveform:

This section is the design of the receiver used to demodulate the current CPM waveform.

The ideal way to identify the CPM signal is the Maximum Likelihood sequence estimator (MLSE) collector which is executed utilizing Viterbi calculation. This ideal recipient comprises of a correlator promptly taken after through MLSE finder that examines the path within the state trellis with least Euclidian distance. For flexibility and clarification, further consideration will be given to the generation of the signal model used in correlation computation and branch metric computation for particular CPM trellis.

3.4.1 MLSE CPM Receiver:

This segment presents the ideal MLSE CPM receiver in a narrow band channel to detect CPM waveform. In it we'll create the overall trellis for CPM and after that portray the generation block of metric and template signal.

3.4.1.1 General State Trellis:

The modulation index h regulates a phase tree trellis ' tolerance or number of phase states. Let's say that h= m / p makes a rational number together with m and p. The terminal phase for full response CPM at any time t= nT (L=1) will be[15].

$$\theta = \left\{ 0, \frac{\pi m}{p}, \frac{2\pi m}{p}, \dots \dots \dots, \frac{(p-1)\pi m}{p} \right\} \qquad (3\text{-}7)$$

For even m

$$\theta = \left\{ 0, \frac{\pi m}{p}, \frac{2\pi m}{p}, \dots \dots \dots, \frac{(2p-1)\pi m}{p} \right\} \qquad (3\text{-}8)$$

When m reaches odd values

For partial response, CPM increases the number of terminal phases if the pulse shape spans over duration of more than one time.

$$S = \begin{cases} pM^{L-1} & (even\ m) \\ 2\,pM^{L-1} & (odd\ m) \end{cases} \tag{3-9}$$

In equation 3-9, p is the denominator of h, M be the length of the alphabet (for M=2 binary signals) and L would be the symbol period. S= 4 means that the number of states would be four for full response binary CPM signaling with h=1/2, M=2 and L=1.

$$\theta = \left\{ 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2} \right\} \tag{3-10}$$

Illustration for this state trellis is outlined in Figure 3.9.

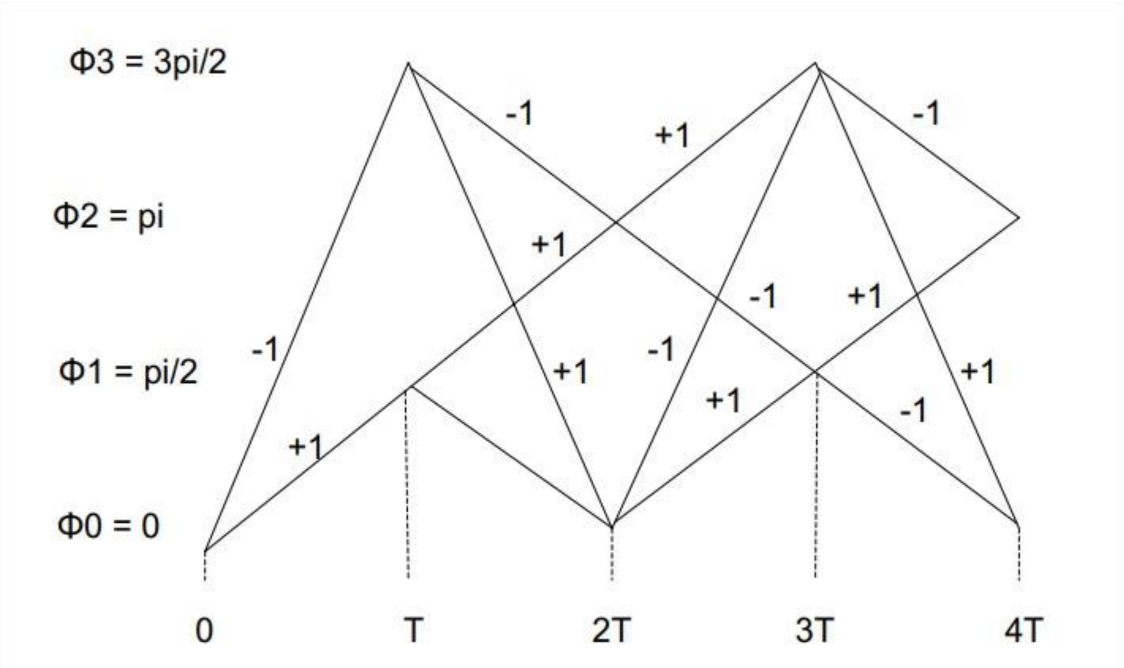


Figure 3.9: Binary CPM signals with full-response phase trellis with h=1/2

As presently the general state trellis representation has been made, the following portion of this study will deal with branch metric and template signals.

3.4.1.2 Branch Metric and Template Signals:

The complex envelope of the received signal is given by

$$r(t) = s(t, I) + w(t) \tag{3-11}$$

Where $s(t, I)$ the M-ary symbol is related to the information symbol I.

Ideal collector for CPM comprises of a metric calculation block encouraged by template signal generator this then feeds the MLSE Viterbi algorithm as shown in Figure 3.10

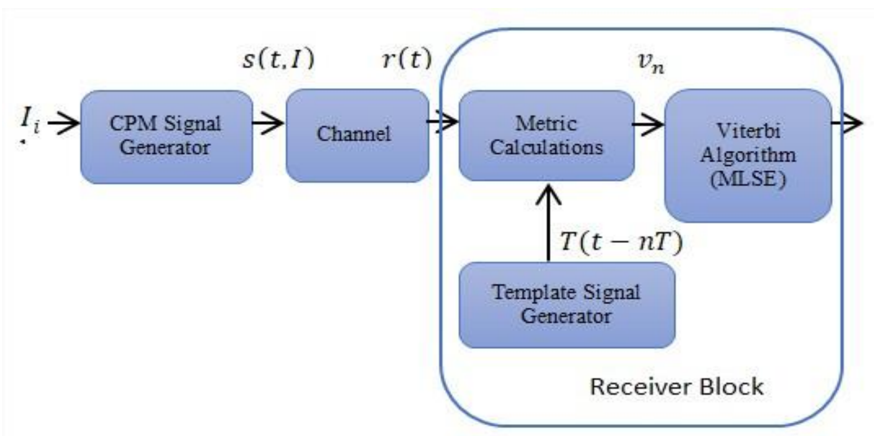


Figure 3.10: MLSE receiver block diagram

In addition, the branch metric calculation block calculates the correlation between the generation of template signals waveform $t(I_i, \theta)$ and the received signals $r(t)$ as shown in figure 3.10. $v_n(I_i, \theta)$ represents the nth-received that reaches the trellis with the related phase θ of signal. The criterion of maximum likelihood (ML) results in the assessment of a received signal

$r(t)$ based on uncertain likelihoods $p\big(s(t,I)\big|r(t)\big)$. Indicator that reduces the likelihood of wrong choices must detect the received signal throughout the whole interval axis and select the infinitely long I_i sequence that minimizes the likelihood of error. This is stated as maximum likelihood sequence estimation (MLSE) [10].

3.5 CPM Equalizer:

Equalization could be a procedure utilized to boost the signal performance by compensating the caused ISI when channel's modulation bandwidth exceeds a channel's coherence bandwidth. In our system, the channel bandwidth is 25 KHz, 50 KHz, 75 KHz and 100 KHz that is for high throughput rates greatly inclined to inter symbol interference. So equalizers should be versatile due to fluctuation in channel behavior.

Ordinary equalization methods utilize a pre-assigned time space (occasional for the time shifting circumstance) during which training signal is transmitted and known in progress by the collector. The equalizer coefficients within the receiver are at that point altered or adjusted by utilizing a few versatile calculations (e.g. ZF, MMSE,) so that the output of the equalizer is closely aligned with the training series.

3.5.1 Algorithm for Adaptation of Equalizer:

3.5.1.1 Zero Forcing (ZF) Equalizer:

ZFE is a linear equalization algorithm that reverses the channel's frequency response. On other hand to reestablish it, the reverse of the channel is applied to the received signal. The title Zero Forcing resembles to reduce or to zero the inter symbol interference (ISI) in a noise-free circumstance. This will be valuable when compared to noise, ISI is important. For a frequency response channel $F(f)$ the zero forcing equalizer $C(f)$ is created by $C(f) = 1 / F(f)$. In this way the arrangement of channel and equalizer therefore provides a flat frequency response and linear phase $C(f)F(f) = 1$.

A very brief detail of this type of equalizer has not been shared in this thesis because it's not a very good choice to use this type of equalizer for wireless channel with huge noises the main equalizer that will be focused for remaining part of this thesis is MMSE Equalizer.

3.5.1.2 Minimum Mean Square Error (MMSE) Equalizer:

After passing through channel the transmitted signal undergoes amplitude and phase distortion. The receiver's goal is to estimate the transmitted signal s (t) based on the distorted noisy signal r(t) received. MMSE is the kind of an equalization algorithm that we use to minimize the mean square error between the signal s (t) being transmitted and its estimate $\hat{s}(t)$ [17].

$$\hat{\boldsymbol{s}}(\boldsymbol{t}) = \boldsymbol{E}[\ (\boldsymbol{s}(\boldsymbol{t}) - \hat{\boldsymbol{s}}(\boldsymbol{t}))^{2}] \tag{3-12}$$

Or

$$\boldsymbol{MSE} = \boldsymbol{E}[\ (\boldsymbol{e}(\boldsymbol{t}))^{2}] \tag{3-13}$$

Also

$$\mathbf{e} = \boldsymbol{s} - \sum_{k=0}^{N-1} \boldsymbol{w}_{\boldsymbol{k}} \boldsymbol{r}_{\boldsymbol{k}} \tag{3-14}$$

Where e is the estimation error and $\boldsymbol{w}_{\boldsymbol{k}}$ are tap weights of wiener filter.

A more vigorous equalizer can be achieved if $\boldsymbol{w}_{\boldsymbol{k}}$ tap weights are picked to reduce the mean square error (MSE) of entire ISI terms plus noise the output of equalizer. After some algebra the MMSE estimator is given by:

$$\hat{\boldsymbol{s}} = (\boldsymbol{R}_{\boldsymbol{rr}}^{-1}\ \boldsymbol{R}_{\boldsymbol{sr}}) \tag{3-15}$$

Where $\boldsymbol{w} = \boldsymbol{R}_{\boldsymbol{rr}}^{-1}\ \boldsymbol{R}_{\boldsymbol{sr}}$ is the Wiener filter, $\boldsymbol{R}_{\boldsymbol{rr}}$ is autocorrelation between received signals with itself and $\boldsymbol{R}_{\boldsymbol{sr}}$ **is** the input signal cross-correlated to the received signal.

Chapter 4: RESEARCH METHODOLOGY

In this chapter, the approach for research methodology is explained. The study required a throughput analysis of multimode multiband CPM (Phase 1) and Link adaptation Methodology of multimode multiband CPM (Phase 2).

4.1 Phase 1: Proposed Multimode Multiband CPM Waveform:

Future operational prerequisites are requesting that frameworks be multifunctional. Emerging military systems are also expected to integrate features such as electronic surveillance and security features in addition to the need for radios to support multiple voice and data waveforms across broader RF frequencies, thus further raising system design challenges.

To overcome these issues, multi-band wireless terminals with software-defined radio (SDR) technology has been proposed for strategic communication networks.

SDR gives a proficient and comparatively reasonable solution to the multi-band, multi-functional wireless device building problem. Through dynamic loading of new waveforms and protocols, an SDR is competent of being reconfigured to function with diverse waveforms. Where multiband frameworks are required, the common approach is to switch between the suitable narrowband arrangements or to switch between the diverse frequencies spectrums. Frequency agility offers numerous more benefits such as adaptable utilize of range or dynamic adaptation to distinctive wireless systems. Frequency adaptability places a few extreme limitations on the plan of the supporting radio frontend (RFE). Ordinarily a radio is outlined with a narrowband or multiband perspective—multiband is where a limited set of narrowband signals are utilized. In this case, filters can be configured to pick the band of interest and reduce the influence of other signals or noise that might interfere.

Hence, the benefits offered by utilizing SDR, such as the adaptability of being reprogrammable and supporting different adaptive algorithms, will make it possible to operate distinctive modes of RF transmission. These mobile devices are required to maintain higher data rates with the improved functionality and resources available to end users. On the other hand the use of frequency bands thus increasing the complexity of costs, volume and receiver.

4.1.1 Throughput Analysis:

The numerical system for the computation of achieving a throughput of the proposed narrowband waveform is currently proposed [19]. The available RF Multiple bandwidths for the narrowband waveform are assumed to be 25 kHz, 50 kHz, 75 KHz, and 100 kHz. Utilizing these accessible bandwidths B_{RF}, we compute the maximum sampling rate allowed (f_s) (chips/sec). Note that the CPM block generates the data at the rate f_s, which is given as:

$$\boldsymbol{f_s = \frac{2B_{RF}}{B_{norm}Ns}} \tag{3-16}$$

Where B_{RF} is the RF bandwidth, Ns is the up-sampling factor and B_{norm} denote the normalized bandwidth which is calculated from transmitted data using it's normalized, two-sided Power Spectral Density (PSD). Fig. 4.1 shows the method of finding the normalized bandwidth (B_{norm}). For B_{RF} = 25 KHz, M=4 and $Ns = 4$, B_{norm} is calculated to be approximately equal to 1.68 when taking Fast Fourier Transform (FFT). fs comes out to be:

$$\boldsymbol{f_s = \frac{2\,(25\;KHz)}{(1.68)(4)}} \tag{3-17}$$

$$\boldsymbol{f_s \approx 74132} \tag{3-18}$$

Therefore, the incoming signal is sampled at 74 KHz.

The k^{th} user overall throughput is given as follows:

$$\boldsymbol{R_k = f_s log_2(M)} \tag{3-19}$$

where M is the modulation order and R_k is the throughput of the k^{th} user.

Putting the values in above equation gives:

$$R_k \approx 14.82\ Kbps \tag{3-20}$$

So, the throughput of the proposed multimode multiband CPM is calculated to be 15Kbps.

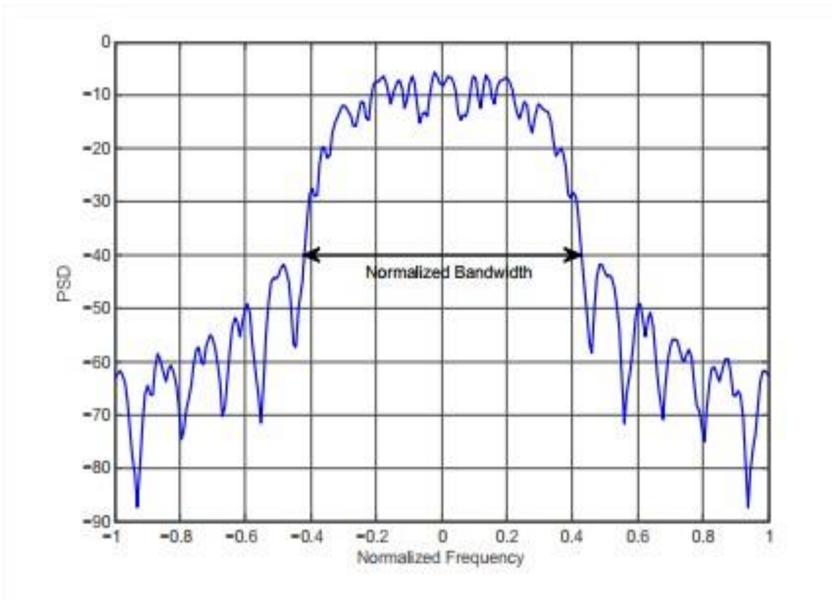


Figure 4.1: Method of finding normalized bandwidth

Same calculations have been done for multiple bandwidths of 25 kHz, 50 kHz, 75 KHz, and 100 kHz for the modes described in section 4.1.2.

4.1.2 Multimode Multiband CPM Transmission Modes of Operation:

In the proposed approach, existing and emerging heterogeneous systems continue to operate. This radio will be able to receive and transmit frequencies in most applications for public safety as shown in Table below. Tables below in this section summarize the frequency bands which are used, and the CPM modes of communication that are used in each band.

The CPM waveform is described by many modes that are possible for different values of *M*, *h*, and *L*. Table 4-1, 4-2 and 4-3 suggests a parametric depiction of thirty-six (36) proposed CPM modes, giving user data rates/throughput(R) extending from 17.4 kbps to 70.8 kbps in 25 kHz channel bandwidth. While Table 4-4, 4-5 and 4-6 gives throughput calculations for channel bandwidth of 50 KHz. Same calculations have been done for multiple bandwidths of 75 KHz and 100 KHz.

In the first column of the following Table, thirty-six (36) unique modes are demonstrated with their user data rates (R) in the last column. Furthermore, L denotes the symbol duration, which specifies that all modes use the partial response as well as full response modulation, and has chosen to be 1, 2, and 3. The parameter M indicates the number of different symbols to be transmitted, which is 2-ary, 4-ary and 8-ary for all the different modes; h is representing the modulation index (max. phase change in a symbol duration) i.e. {1/2, 1/4, 1/8, 1/16}.

4.1.2.1 Transmission Modes of Operation under AWGN:

1. ***For B_{RF} = 25 KHz:***

M=2					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	0.7071	17.678	R=fs	7.378 dB
	h=1/4	0.4957	25.217		10.98 dB
	h=1/8	0.2814	44.421		16.56 dB
	h=1/16	0.2131	58.658		22.42 dB
L=2	h=1/2	0.5897	21.197	R=fs	7.384 dB
	h=1/4	0.4044	30.910		12.11 dB
	h=1/8	0.2658	47.028		17.73 dB
	h=1/16	0.2111	59.214		23.78 dB
L=3	h=1/2	0.5724	21.838	R=fs	7.379 dB
	h=1/4	0.383	32.637		12.44 dB
	h=1/8	0.251	49.801		18.17 dB
	h=1/16	0.2102	59.467		24.28 dB

Table 4- 1: Throughput calculation for M=2 in 25 KHz bandwidth

M=4					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	1.6862	07.413	14.826	7.205 dB
	h=1/4	0.8823	14.168	28.335	8.135 dB
	h=1/8	0.5526	22.620	45.241	13.74 dB
	h=1/16	0.3151	39.670	79.340	19.49 dB
L=2	h=1/2	1.1373	10.991	21.982	5.557 dB
	h=1/4	0.6606	18.922	37.844	9.505 dB
	h=1/8	0.4349	28.742	57.484	15.39 dB
	h=1/16	0.2837	44.061	88.121	21.33 dB
L=3	h=1/2	1.0817	11.556	23.112	5.55 dB
	h=1/4	0.6364	19.642	39.283	10.07 dB
	h=1/8	0.4141	30.186	60.372	16.05 dB
	h=1/16	0.2774	45.061	90.123	22 dB

Table 4- 2: Throughput calculation for M=4 in 25 KHz bandwidth

M=8					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	1.4097	04.434	13.301	5.877 dB
	h=1/4	0.8653	07.223	21.669	6.604 dB
	h=1/8	0.4978	12.555	37.666	11.85 dB
	h=1/16	0.3163	19.760	59.279	17.67 dB
L=2	h=1/2	1.078	05.798	17.393	4.243 dB
	h=1/4	0.6207	10.069	30.208	7.824 dB
	h=1/8	0.3948	15.831	47.492	13.76 dB
	h=1/16	0.273	22.894	68.681	19.67 dB
L=3	h=1/2	1.0576	5.9096	17.729	4.316 dB
	h=1/4	0.6051	10.329	30.987	8.584 dB
	h=1/8	0.3724	16.783	50.349	14.45 dB
	h=1/16	0.2647	23.612	70.835	20.42 dB

Table 4- 3: Throughput calculation for M=8 in 25 KHz bandwidth

2. ***For B_{RF} = 50 KHz:***

M=2					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	0.7071	35.36	R=fs	7.378 dB
	h=1/4	0.4957	50.43		10.98 dB
	h=1/8	0.2814	88.84		16.56 dB
	h=1/16	0.2131	117.32		22.42 dB
L=2	h=1/2	0.5897	42.39	R=fs	7.384 dB
	h=1/4	0.4044	61.82		12.11 dB
	h=1/8	0.2658	94.06		17.73 dB
	h=1/16	0.2111	118.43		23.78 dB
L=3	h=1/2	0.5724	43.68	R=fs	7.379 dB
	h=1/4	0.383	65.27		12.44 dB
	h=1/8	0.251	99.60		18.17 dB
	h=1/16	0.2102	118.93		24.28 dB

Table 4- 4: Throughput calculation for M=2 in 50 KHz bandwidth

M=4					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	1.6862	14.826	029.65	7.205 dB
	h=1/4	0.8823	28.335	056.67	8.135 dB
	h=1/8	0.5526	45.241	090.48	13.74 dB
	h=1/16	0.3151	79.340	158.68	19.49 dB
L=2	h=1/2	1.1373	21.982	043.96	5.557 dB
	h=1/4	0.6606	37.844	075.69	9.505 dB
	h=1/8	0.4349	57.484	114.97	15.39 dB
	h=1/16	0.2837	88.121	176.24	21.33 dB
L=3	h=1/2	1.0817	23.112	046.22	5.55 dB
	h=1/4	0.6364	39.283	078.57	10.07 dB
	h=1/8	0.4141	60.372	120.74	16.05 dB
	h=1/16	0.2774	90.123	180.25	22 dB

Table 4- 5: Throughput calculation for M=4 in 50 KHz bandwidth

M=8					
Modes (Varying h)		B_{norm}	Sampling Rate (fs) (KHz)	Data Rate (kbps)	SNR at 10e-3
L=1	h=1/2	1.4097	0.8867	26.60	5.877 dB
	h=1/4	0.8653	1.4446	43.34	6.604 dB
	h=1/8	0.4978	2.5110	75.33	11.85 dB
	h=1/16	0.3163	3.9519	118.56	17.67 dB
L=2	h=1/2	1.078	11.596	34.79	4.243 dB
	h=1/4	0.6207	20.139	60.42	7.824 dB
	h=1/8	0.3948	31.662	94.98	13.76 dB
	h=1/16	0.273	45.788	137.36	19.67 dB
L=3	h=1/2	1.0576	11.819	35.46	4.316 dB
	h=1/4	0.6051	20.658	061.97	8.584 dB
	h=1/8	0.3724	33.566	100.70	14.45 dB
	h=1/16	0.2647	47.223	141.67	20.42 dB

Table 4- 6: Throughput calculation for M=8 in 50 KHz bandwidth

4.1.2.2 Reduced Number of Modes:

The CPM Multiband waveform described by many modes earlier for different values of *M*, *h*, and *L* have been reduced based on the better BER performance.

Table 4-7 suggests a parametric depiction of ten proposed CPM modes, giving user data rates/throughput(R) extending from 17.4 kbps to 88.1 kbps in 25 kHz channel bandwidth while Table 4-8 represents proposed CPM modes, giving user data rates/throughput(R) extending from 34.8 kbps to 176.2 kbps in 50 KHz channel bandwidth.

It can be seen from the above tables that increase in the data rate (R) is achieved with an increase of the symbol rate or the sampling rate (f_s) where the symbol rate (f_s) is somehow reciprocal to the normalized bandwidth (B_{norm}) as shown in equation . According to the proposed multiband waveform concept, by increasing RF bandwidth from 25 KHz to 50 KHz channel, will increase the symbol rate (f_s), which in turn increases the data rate (R) as shown in table 9 and 10. Therefore, by shifting towards multiple bandwidths of 25 KHz, 50 KHz, by utilizing the same normalized bandwidth and ber performance the throughput increases from 17.4 Kbps to 34.8

Kbps for mode 1 and it goes same for all other modes. Following the same method, calculations for 50 KHz and 100 kHz are done as well. It can be observed that all modes have a distinctive normalized bandwidth occupation. The lower the normalized bandwidth it needs, the higher will the user data rate or throughput (R).

Table 4- 7: Proposed CPM reduced modes in 25 KHz channel bandwidth

Modes	M	h	L	Normalized Bandwidth (B_{norm})	Sampling Rate (KHz)	Data Rate (kbps)	E_b/N_0 to reach BER of 10-3
Mode 1	8	1/2	2	1.078	5.8	17.4	4.2 dB
Mode 2	8	1/4	2	0.6207	10.1	30.2	7.8 dB
Mode 3	4	1/2	3	1.0817	11.5	23.1	5.5 dB
Mode 4	8	1/8	3	0.3724	16.8	50.3	14.4 dB
Mode 5	4	1/4	2	0.6606	18.9	37.9	9.5 dB
Mode 6	4	1/8	1	0.5526	22.6	45.2	13.7 dB
Mode 7	8	1/16	2	0.273	22.9	68.7	19.7 dB
Mode 8	4	1/8	2	0.4349	28.7	57.5	15.4 dB
Mode 9	4	1/16	1	0.3151	39.7	79.3	19.5 dB
Mode 10	4	1/16	2	0.2837	44.1	88.1	21.3 dB

Table 4- 8: Proposed CPM reduced modes in 50 KHz channel bandwidth

Modes	M	h	L	Sampling Rate (KHz)	Data Rate (kbps)
Mode 1	8	1/2	2	11.6	34.8
Mode 2	8	1/4	2	20.1	60.4
Mode 3	4	1/2	3	23.1	46.2
Mode 4	8	1/8	3	33.6	100.8
Mode 5	4	1/4	2	37.9	75.7
Mode 6	4	1/8	1	45.2	90.5
Mode 7	8	1/16	2	45.8	137.4
Mode 8	4	1/8	2	31.7	95.0
Mode 9	4	1/16	1	79.3	158.7
Mode 10	4	1/16	2	88.1	176.2

Table 4-9: Proposed Multimode Multiband CPM transmission modes of operation for B_{RF} = 25 KHz, B_{RF} = 50 KHz, B_{RF} = 75 KHz, B_{RF} = 100 KHz

Mode	M	h	L	B_{norm}	E_b/N_0 to reach BER 10-3	Data Rate (kbps)			
						B_{RF} = 25 KHz	B_{RF} = 50KHz	B_{RF} = 75KHz	B_{RF} = 100 KHz
Mode 1	8	1/2	2	1.078	4.2 dB	17.4	34.8	52.2	69.6
Mode 2	8	1/4	2	0.6207	7.8 dB	30.2	60.4	090.62	120.83
Mode 3	4	1/2	3	1.0817	5.5 dB	23.1	46.2	069.34	092.45
Mode 4	8	1/8	3	0.3724	14.4 dB	50.3	100.8	151.05	201.40
Mode 5	4	1/4	2	0.6606	9.5 dB	37.9	75.7	113.53	151.38
Mode 6	4	1/8	1	0.5526	13.7 dB	45.2	90.5	135.72	180.96
Mode 7	8	1/16	2	0.273	19.7 dB	68.7	137.4	206.04	274.73
Mode 8	4	1/8	2	0.4349	15.4 dB	57.5	95.0	172.45	229.94
Mode 9	4	1/16	1	0.3151	19.5 dB	79.3	158.7	238.02	317.36
Mode 10	4	1/16	2	0.2837	21.3 dB	88.1	176.2	264.36	352.49

4.1.2.3 Transmission Modes of Operation under SUI Channel:

As shown in Table 3-2, set of 6 SUI channels and their parametric view are described representing three Terrain types i: e (A, B, C). SUI-5 and SUI-6 have high delay spread and path loss with a weak line of sight component because these two channels represent the terrain type A which is characterized by heavy tree density. The other terrain types have low delay spread. All these contributing to the value of K factor of the channel.

Depending on Terrain category SUI-3 lies in Category B with flat/moderate tree density having low delay spread and intermediate path loss. Hence there are few obstructions in the signal propagation from a transmitter to a receiver that's why SUI-3 model has been selected for CPM transmission modes of operation. Table 4-10 shows the performance comparison analysis of proposed modes of CPM narrowband waveform under AWGN and SUI-3 channel where St represents the number of phase states in the receiver trellis. It can be seen that the performance for AWGN is better than SUI-3 channel occupying same modes of operation.

Table 4- 10: Performance comparison analysis of proposed CPM modes under AWGN and SUI-3 channel Model

Modes	M	h	L	St (states)	Eb/No to reach BER of 10^{-3} (dB)	
					AWGN	SUI-3
Mode 1	8	1/2	2	16	4.243	13.25
Mode 2	8	1/4	2	32	7.824	11.39
Mode 3	4	1/2	3	32	5.55	12.32
Mode 4	8	1/8	3	512	14.45	23.31
Mode 5	4	1/4	2	16	9.505	20.84
Mode 6	4	1/8	1	8	13.74	14.83
Mode 7	8	1/16	2	128	19.67	22.2
Mode 8	4	1/8	2	32	15.39	28.39
Mode 9	4	1/16	1	16	19.49	19.42
Mode 10	4	1/16	2	64	21.33	21.32

4.2 Phase 2: Link Adaptation in Multimode CPM Narrowband Waveform:

The Advanced wireless systems request high speed connectivity by guaranteeing particular Quality of Service (QoS) requirements. Extensive research was conducted to explore the capability of using the Software Defined Radio (SDR) methodology to achieve these objectives [19]. So to fulfill these requirements, the advancements for the recent SDR-based wireless systems are moving towards narrowband and advanced networking that is capable of giving versatile and high-speed connectivity. Sometimes SDR is discussed in the context of a radio that can dynamically modify its operation to provide the user with maximum perceived performance and optimum spectral efficiency.

Effective resource allocation algorithms / usage are required to maximize the use of limited SDR resources. This includes adjusting the transmission parameters of the SDR waveform to changing channel conditions, QoS and data rate requirements. This process is called link adaptation. If the parameters of the waveform are not dynamically modified related to channel requirements it increases bit error transmission rate and therefore packet retransmissions. A familiar link adaptation technique is chosen to decrease computational complexity by limiting the power utilization and the throughput depending upon the user throughput requirement even if the channel requirements are sufficient to tolerate for higher throughput rates.

4.2.1 Proposed Link adaptation algorithm:

A novel adaptation algorithm is proposed for SDR Narrowband networking waveform. Multimode and adaptive CPM is used by the waveform. A restriction optimization problem and to decrease the re-transmissions overhead, the configurable framework parameters have to be altered dynamically agreeing to the conditions of the channel. In addition, the changing QoS requirement of different applications/user is met by changing parameters of the system in the physical layer and/or adaptive CPM narrowband waveform through link adaptation. Suggested adaptation scheme has been shown to achieve better performance by efficiently reducing overhead packet retransmission.

Figure 4.2 demonstrates the proposed link adaptation scheme. The objective of the proposed link adaptation scheme is to dynamically alter the alphabet size M, modulation index I and pulse length L (MIL), taking QoS, throughput requirements and channel SNR. The primary two inputs (i.e. QoS and throughput) are indicated by user or required by a particular application, though the third input is the received SNR from channel that is estimated at the receiver while our focus isn't on the estimation of SNR.

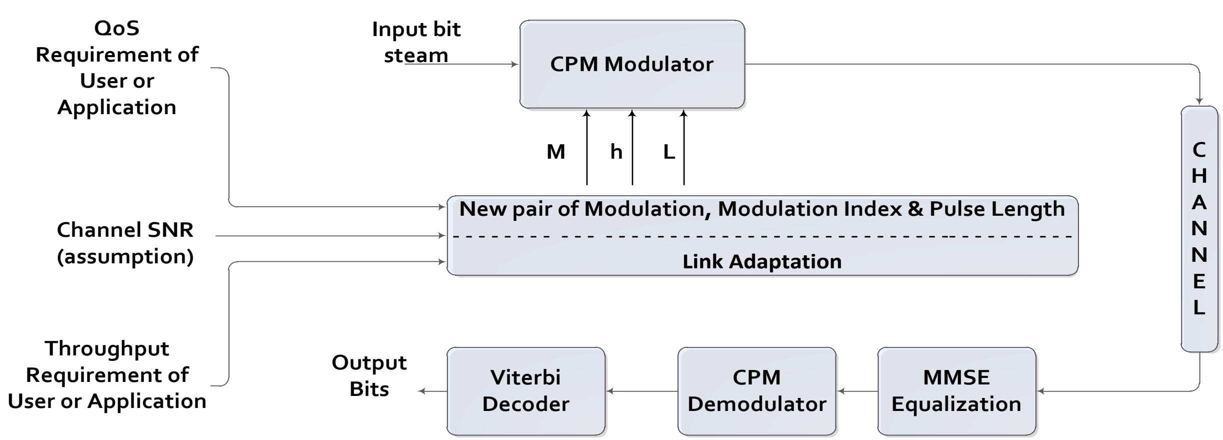


Figure 4. 2: Proposed Link Adaptation Model

4.2.2 BER data acquisition Curves of proposed modes of operation:

The first step of the proposed algorithm is to obtain data from the system's BER output curves of all possible modes of operation. BER system performance is evaluated for all possible multimode outputs of Alphabet size M, Modulation Index I and Pulse length L.

4.2.2.1 Data Acquisition under AWGN:

Figure 4.3 shows an example with a set of BER curves for *Alphabet size M=8, Modulation Index I= 1/8 and Pulse length L=3,* or mode 4 as shown earlier in Table 4-7. Likewise, BER curves are obtained by simulation for all multimode CPM narrowband waveforms. The values are then obtained through the BER curve collection by drawing the horizontal line (for a particular QoS requirement) for each BER curve and noticing the intersection/crossing point. This will provide the least SNR that ensures the BER that ensures the achievable throughput for a particular Alphabet size M, Modulation Index I and Pulse length L. This method is again repeated for the whole set of BER curves acquired through simulation further discussed in chapter 5.

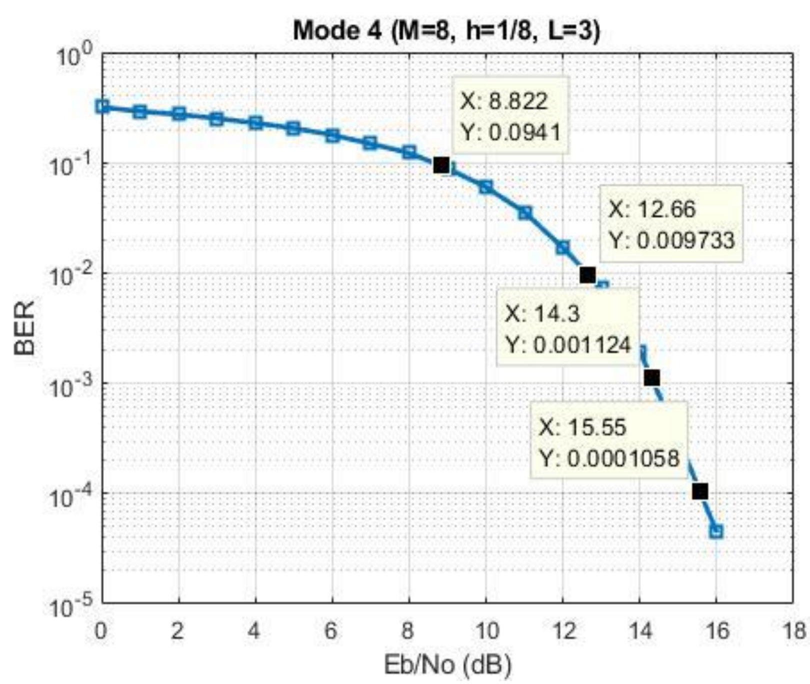


Figure 4.3: BER Performance for Mode 4

Table 4-11 displays the minimum SNR values (in dBs) that ensure that the BER is within the maximum allowable value.

Modes	QoS	SNR	Modes	QoS	SNR	Modes	QoS	SNR	Modes	QoS	SNR
Mode 1	10^{-1}	0.04	Mode 4	10^{-1}	8.54	Mode 7	10^{-1}	13.2	Mode 10	10^{-1}	15.03
	10^{-2}	2.55		10^{-2}	12.64		10^{-2}	17.69		10^{-2}	19.25
	10^{-3}	4.24		10^{-3}	14.46		10^{-3}	19.64		10^{-3}	21.31
	10^{-4}	5.78		10^{-4}	15.65		10^{-4}	20.87		10^{-4}	22.63
Mode 2	10^{-1}	2.1	Mode 5	10^{-1}	2.95	Mode 8	10^{-1}	8.908			
	10^{-2}	5.9		10^{-2}	7.38		10^{-2}	13.29			
	10^{-3}	7.8		10^{-3}	9.49		10^{-3}	15.38			
	10^{-4}	8.6		10^{-4}	11.2		10^{-4}	-			
Mode 3	10^{-1}	0.45	Mode 6	10^{-1}	6.22	Mode 9	10^{-1}	12.13			
	10^{-2}	3.67		10^{-2}	11.29		10^{-2}	17.25			
	10^{-3}	5.54		10^{-3}	13.73		10^{-3}	19.46			
	10^{-4}	6.78		10^{-4}	15.32		10^{-4}	21			

Table 4- 11: Minimum SNR values (in dBs) that guarantee the BER Performance under AWGN

4.2.2.2 Data Acquisition under SUI-3 Channel Model:

Same process has been repeated for the whole set of SNR values under SUI-3 channel as discussed earlier in section 4.2.2.1 through simulation discussed further in chapter 5 to acquire the data acquisition table 4-12.

Table 4- 12: Minimum SNR values (in dBs) that guarantee the BER Performance under SUI-3 channel

Modes	QoS	SNR	Modes	QoS	SNR	Modes	QoS	SNR	Modes	QoS	SNR
Mode 1	10^{-1}	7.71	Mode 4	10^{-1}	8.579	Mode 7	10^{-1}	15.69	Mode 10	10^{-1}	11.59
	10^{-2}	11.1		10^{-2}	16.07		10^{-2}	19.95		10^{-2}	17.59
	10^{-3}	13.25		10^{-3}	23.3		10^{-3}	22		10^{-3}	21.26
	10^{-4}	14.41		10^{-4}	25		10^{-4}	24		10^{-4}	24.35
Mode 2	10^{-1}	4.803	Mode 5	10^{-1}	14.78	Mode 8	10^{-1}	17.81			
	10^{-2}	9.03		10^{-2}	18.86		10^{-2}	24.39			
	10^{-3}	11.42		10^{-3}	20.81		10^{-3}	28.38			
	10^{-4}	12.58		10^{-4}	22.11		10^{-4}	-			
Mode 3	10^{-1}	2.988	Mode 6	10^{-1}	6.431	Mode 9	10^{-1}	9.363			
	10^{-2}	8.953		10^{-2}	11.85		10^{-2}	16.12			
	10^{-3}	12.07		10^{-3}	14.83		10^{-3}	19.41			
	10^{-4}	-		10^{-4}	16.99		10^{-4}	21.3			

4.2.3 Selection of Output Matrix for Alphabet Size, Index and Pulse length:

Upon finishing data acquisitions from BER curves, respective modes based on output (MIL) are now chosen to cover the full spectrum of inputs and outputs. The three inputs to the proposed link adaptation scheme are the QoS requirement (taken as negative BER logarithm), the throughput requirement (R) and the SNR. The produced output is Alphabet size, Modulation Index and Pulse length (MIL)

For the output MIL, the possible values of M are 4 and 8, the possible values of I are 1/2, 1/4, 1/8, 1/16 and the possible values for L are 1, 2 and 3 as per reduced modes of operation discussed in Table 4-7. So, the total numbers of 10 possible modes {M1, M2….M10} have been selected for the output MIL as shown in table 4-13.

Table 4- 13 OUTPUT AIL (ALPHABET SIZE, MODULATION INDEX, and PULSE LENGTH)

Value	AIL	Value	AIL
M1	(8, 1/2, 2)	M6	(8, 1/8 , 1)
M2	(8, 1/4, 2)	M7	(8, 1/16, 2)
M3	(4, 1/2, 3)	M8	(4, 1/8, 2)
M4	(8, 1/8, 3)	M9	(4, 1/16, 1)
M5	(4, 1/4 , 2)	M10	(4, 1/16, 2)

The selection of the output modes (MIL) is centered on the group of intuition rules based on IF-THEN argument. The ' IF ' portion of the rule is termed as the ' antecedent ' and 'THEN' portion of the rule is termed as the ' consequent '. As stated above, it requires three inputs (QoS requirement, throughput requirement and channel SNR) and produces the output Alphabet size Modulation Index and Pulse length (MIL).

Based on the inputs and outputs, a total of 112 rules are defined using { E1, E2, E3, E4},{ S1, S2, S3, S4},{ R1, R2,….,R7} and {M1, M2,….,M10} are the set of values for the necessary QoS, SNR, R and MIL production. The maximum limit for the set of values for the necessary QoS, SNR and R are shown in Table 4-14.

QoS		SNR (dB)		Data Rate (Kbps)			
E1	10^{-1}	S1	0 – 5	R1	15 – 25	R5	55 – 65
E2	10^{-2}	S2	5 – 10	R2	25 – 35	R6	65 – 75
E3	10^{-3}	S3	10 – 15	R3	35 – 45	R7	75 – 88
E4	10^{-4}	S4	15 – 20	R4	45 – 55		

Table 4- 14: Required Ranges for QoS, SNR, and R

Several rules have the same (IF part) but different (THEN parts). Such laws are considered as contradictory rules and described as follows:

- When two or more output modes results in the same throughput, the results in a smaller number of phase states St in the receiver trellis are chosen as shown in Table 12, which results in a higher throughput.
- If the output MIL meets the stated requirements at a lower SNR, then it is absolutely valid for high SNR.
- If the throughput specification cannot be accomplished by the required output MIL under the specified QoS condition, the output MIL resulting in the maximum possible throughput is chosen.

Figure 4.4 shows the link adaptation methodology based on conflicting rules discussed above.

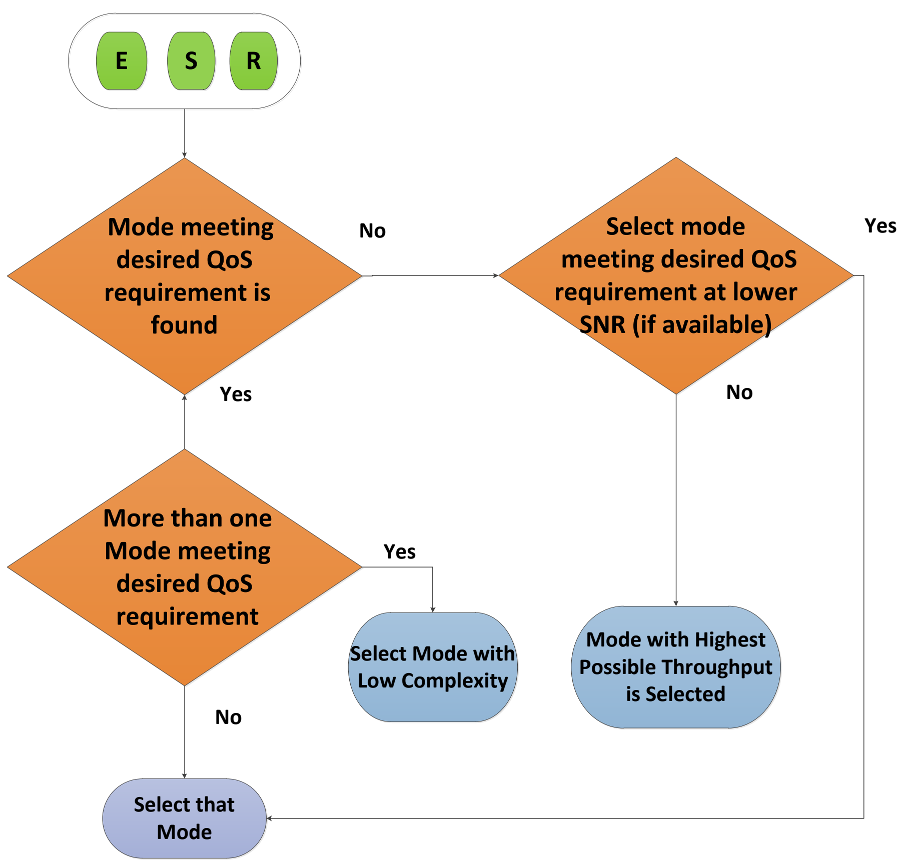


Figure 4.4: Link Adaptation Methodology

4.2.3.1 MIL selection under AWGN:

The complete output matrix under AWGN for total number of 112 rules are formed using {E1, E2, E3, E4}, {S1, S2, S3, S4}, {R1, R2, . . . , R7} and {M1, M2,….M10} from set of values for the required Quality of service, SNR, throughput rate and the desired output mode M as shown in Table 4-15. For example, output mode M1 is selected achieving input requirements based on quality of service (E1) i: e, 10-1 , SNR value of 0.04 dbs that lies in the range of S1 which is [0 - 5] dBs and throughput rate of 17 kbps that lies in the range of R1 which is [15 - 25] kbps. Same method has been followed for the formation of all other output modes M.

QoS	SNR	R1	R2	R3	R4	R5	R6	R7
E1	S1	M1	M2	M5	M5	M5	M5	M5
	S2	M1	M2	M5	M6	M8	M8	M8
	S3	M1	M2	M5	M6	M8	M7	M9
	S4	M1	M2	M5	M6	M8	M7	M10
E2	S1	M1	M3	M3	M3	M3	M3	M3
	S2	M1	M2	M5	M5	M5	M5	M5
	S3	M1	M2	M5	M6	M8	M8	M8
	S4	M1	M2	M5	M6	M8	M7	M9
E3	S1	M1	M1	M1	M1	M1	M1	M1
	S2	M3	M2	M5	M5	M5	M5	M5
	S3	M3	M2	M5	M6	M4	M4	M4
	S4	M3	M2	M5	M6	M8	M7	M9
E4	S1	M3	M3	M3	M3	M3	M3	M3
	S2	M1	M2	M2	M2	M2	M2	M2
	S3	M1	M2	M5	M5	M5	M5	M5
	S4	M1	M2	M5	M6	M10	M7	M9

Table 4- 15: Human Intuition Based MIL Selection under AWGN

4.2.3.2 MIL selection under SUI-3 Channel.

Table 4-16 shows the complete output matrix under SUI-3 channel for total number of 112 rules formed by following the same method as discussed in section 4.2.3.1.

QoS	SNR	R1	R2	R3	R4	R5	R6	R7
E1	S1	M3	M2	M2	M2	M2	M2	M2
	S2	M1	M2	M9	M4	M9	M9	M9
	S3	M1	M2	M5	M4	M10	M10	M10
	S4	M1	M2	M5	M4	M8	M7	M10
E2	S1	M3	M3	M3	M3	M3	M3	M3
	S2	M3	M2	M2	M2	M2	M2	M2
	S3	M1	M2	M6	M6	M6	M6	M6
	S4	M1	M2	M5	M4	M8	M7	M9
E3	S1	M1	M1	M1	M1	M1	M1	M1
	S2	M1	M3	M3	M3	M3	M3	M3
	S3	M1	M2	M2	M6	M6	M6	M6
	S4	M1	M2	M5	M4	M8	M7	M9
E4	S1	M3	M3	M3	M3	M3	M3	M3
	S2	M3	M3	M3	M3	M3	M3	M3
	S3	M1	M2	M2	M2	M2	M2	M2
	S4	M1	M2	M5	M6	M10	M7	M9

Table 4- 16: Human Intuition Based MIL Selection under SUI-3 Channel

Chapter 5: SIMULATIONS AND RESULTS

In this chapter, proposed Multimode Multiband CPM Narrowband waveform performance is verified by MATLAB based simulations.

5.1 System Model I:

The fundamental system model I beneath consideration has been explained in this area comprises of a continuous phase modulator CPM at the side of transmitter. The properties and features of the wave are already discussed in section 2.1.

Towards the end of the transmitter, the received waveform is demodulated and is at that point decoded by a CPM demodulator continued by a Viterbi decoder. AWGN channel is connected with transmitter and receiver as appeared in figure 5.1.

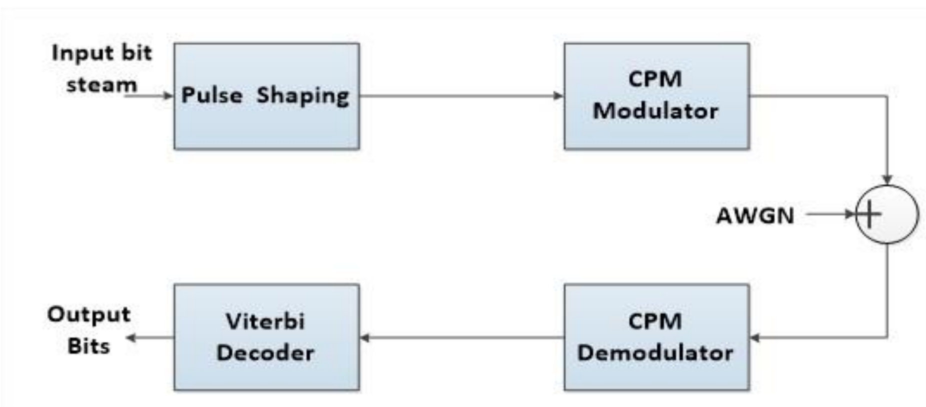


Figure 5. 1: Block Diagram of CPM Modulator/Demodulator under AWGN

The proposed solution is implemented by using *comm.CPM modulation* system object. *BT* product is kept 0.3, Frequency pulse shape is selected as Gaussian pulse shape and initial phase offset is 0 with 8 samples per symbol

Depending upon the system model presented in figure 5.1, the BER performance of multimode Narrowband CPM waveform in the AWGN channel has been evaluated. The simulations have been carried out using MATLAB.

Figure 5.2 displays the corresponding bit error rate (BER) curves for multimode CPM using M=2, L ranges from 1 to 3 and taking values of h as 1/2, 1/4, 1/8, 1/16. It can be seen that the use of small modulation indexes consumes less bandwidth and increased throughput is achieved, but does not buy the BER performance as presented in table 4-1. Expanding L from 1 to 3 increments the total number of phase states using formula pM^{L-1}.Therefore it efficiently increases throughput of the system. The price that we have to bear in expanding the number of states is the complexity towards the end of the receiver and the reduced quality of the BER as shown in figure below. Same process has been repeated for M=4 and M=8 as shown in figure 5.3 and 5.4.

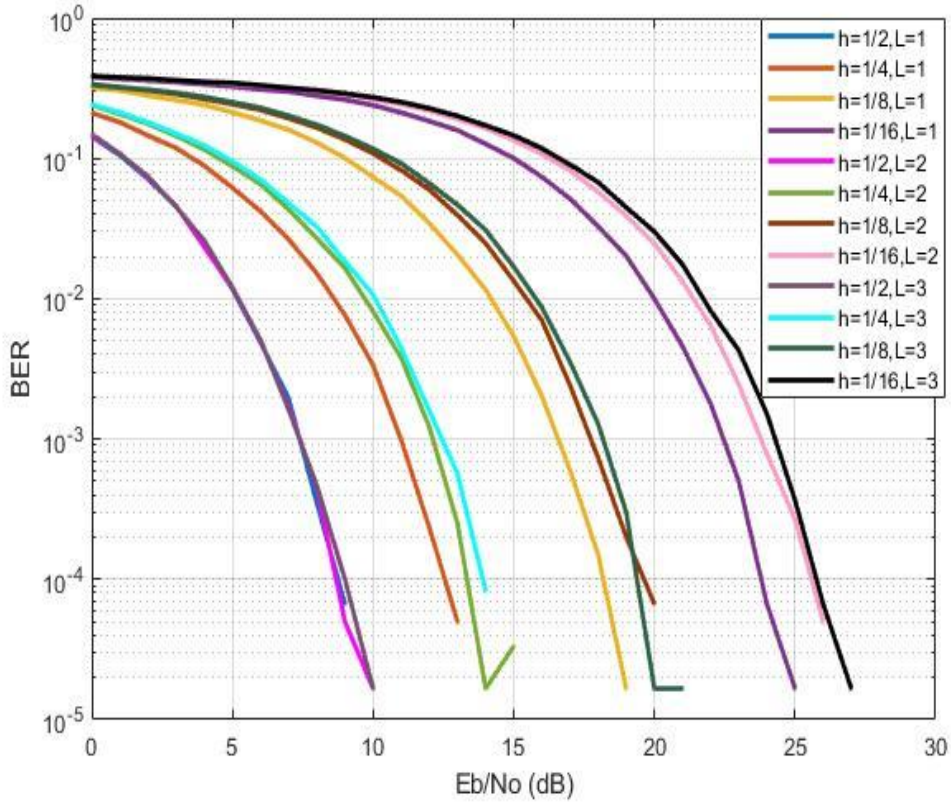


Figure 5. 2: BER Performance of Multimode CPM Narrowband waveforms for M=2

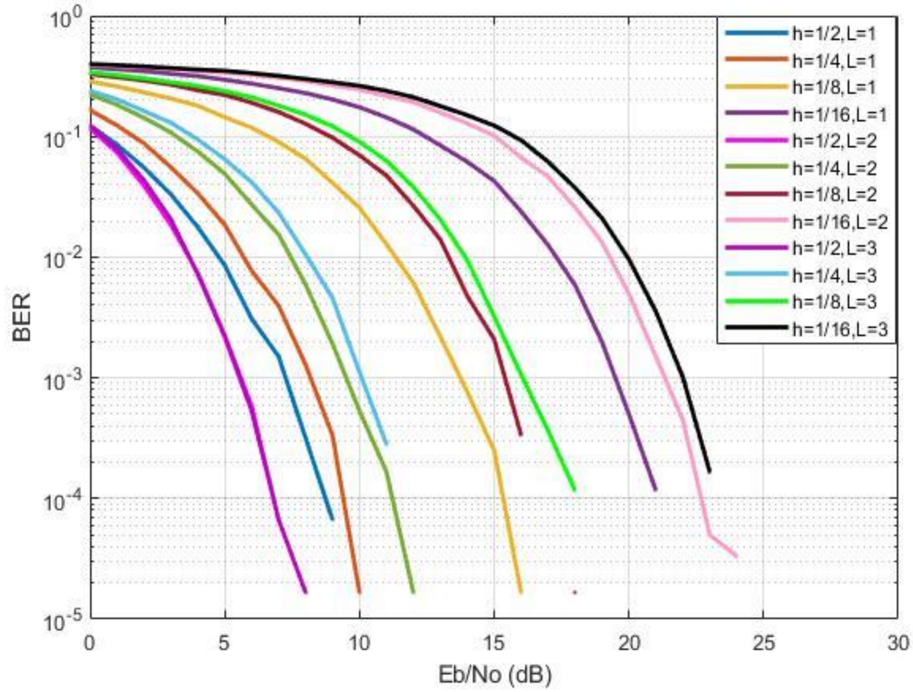


Figure 5. 3: BER Performance of Multimode CPM Narrowband waveforms for M=4

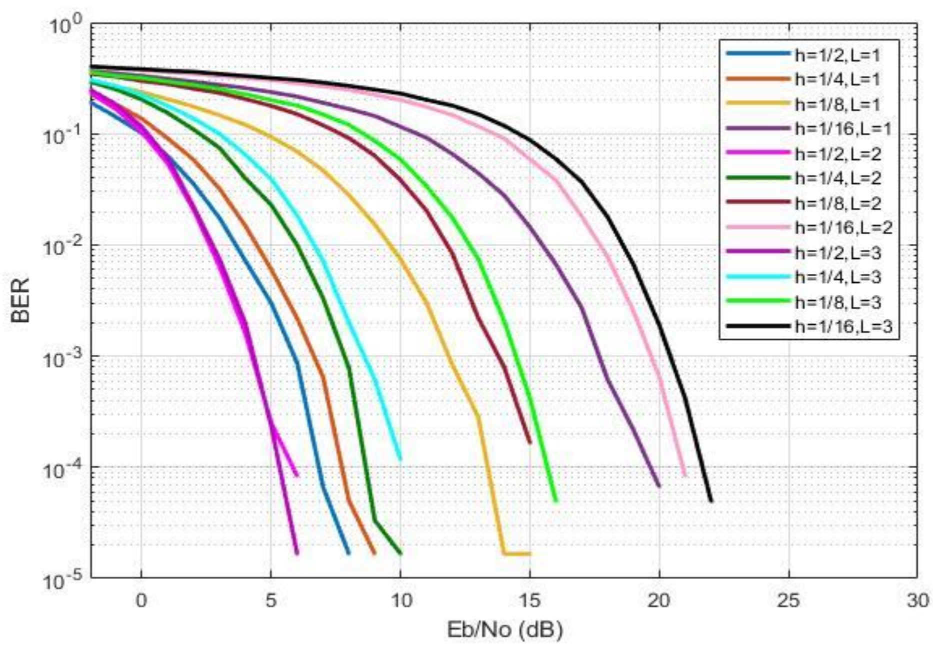
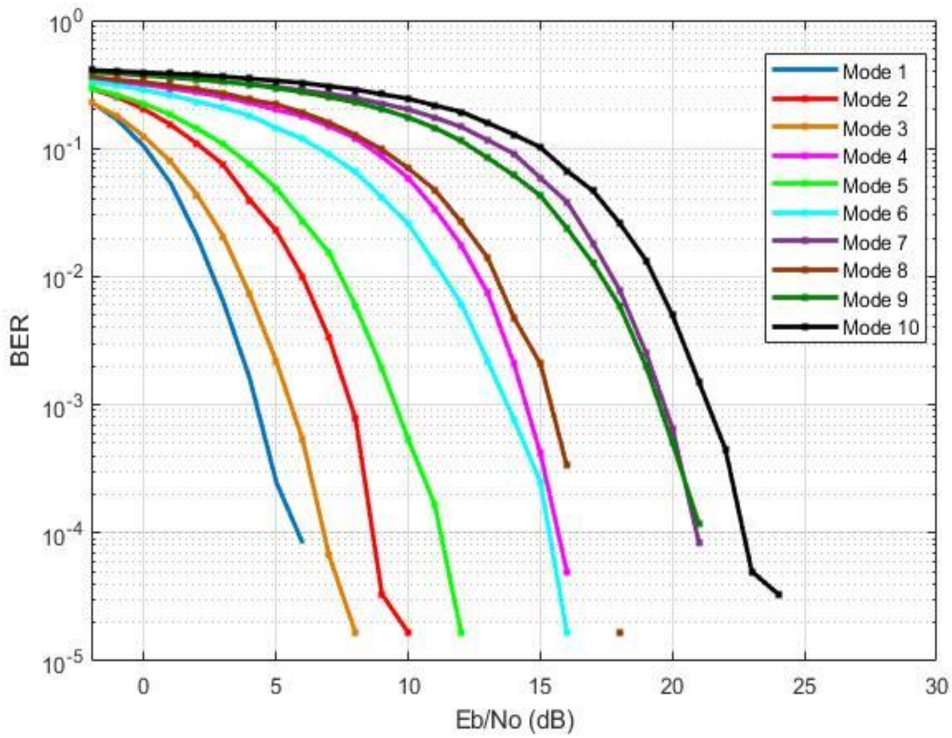


Figure 5. 4: BER Performance of Multimode CPM Narrowband waveforms for M=8

Figure 5.5 displays the corresponding bit error rate (BER) curves for the extracted proposed ten modes presented in table 4-7. The modes are extracted from table 4-1 to 4-3 on the basis of better BER performance. It can be seen that for modes 1, 2, 4, and 7 the use of small modulation indexes consumes less bandwidth and increased throughput of 17.4 kbps to 68.7 kbps is achieved, but does not buy the BER performance.

Figure 5. 5: BER Performance of 10 Proposed Reduced Multimode CPM Narrowband waveforms.



Comparing mode 6 and mode 8, expanding L increments the total number of phase states using formula pM^{L-1} (where p =8, M = 4 and L = 2) represents mode 8. Therefore it efficiently increases throughput of the system from 45.2 kbps to 57.5 kbps. The price that we have to bear in expanding the number of states is the complexity towards the end of the receiver and the reduced quality of the BER of about 1.65 dbs.

For modes, 7 and mode 10, decreasing the alphabet size consumes less bandwidth and increased throughput of 68.7 kbps to 88.1 kbps is achieved, but does not buy the BER performance. However, it must be noted that mode 10 is providing the highest throughput rate of 176.2 kbps while shifting towards multiple bandwidths of 25 KHz to 50 KHz with smallest modulation index, small alphabet size, least consumption of normalized bandwidth, but the price that has to pay is the poor BER performance at Eb/No of 21.3dB.

Table 4-1 shows the normalized bandwidth (Bnorm) for multimode CPM waveforms. Taking values of h as 1/2, 1/4, 1/8, 1/16, pulse length L= 1 and Modulation order M = 2 it can be shown that bandwidth decreases for decreasing h. The use of small modulation indexes consumes less bandwidth with increased throughput. The denominator of h represents phase states in the receiver trellis. So according to the formula pM^{L-1}, with increasing phase states (p) much higher throughput is achieved but the complexity increases at the receiver side. Minimum phase jump leads to more compact power spectrum, hence making the system more spectrally efficient. Figure 5.6 shows the normalized power spectral density plots for M=2, L=1 and taking values of h as 1/2, 1/4, 1/8, 1/16 for normalized bandwidth calculations as shown in table 4-1. Whereas figure 5.7 and 5.8 shows normalized power spectral density plot for L=2 and L=3 for same values of M and h. Same process has been repeated to get normalized power spectral density plots for M=4 and M=8.

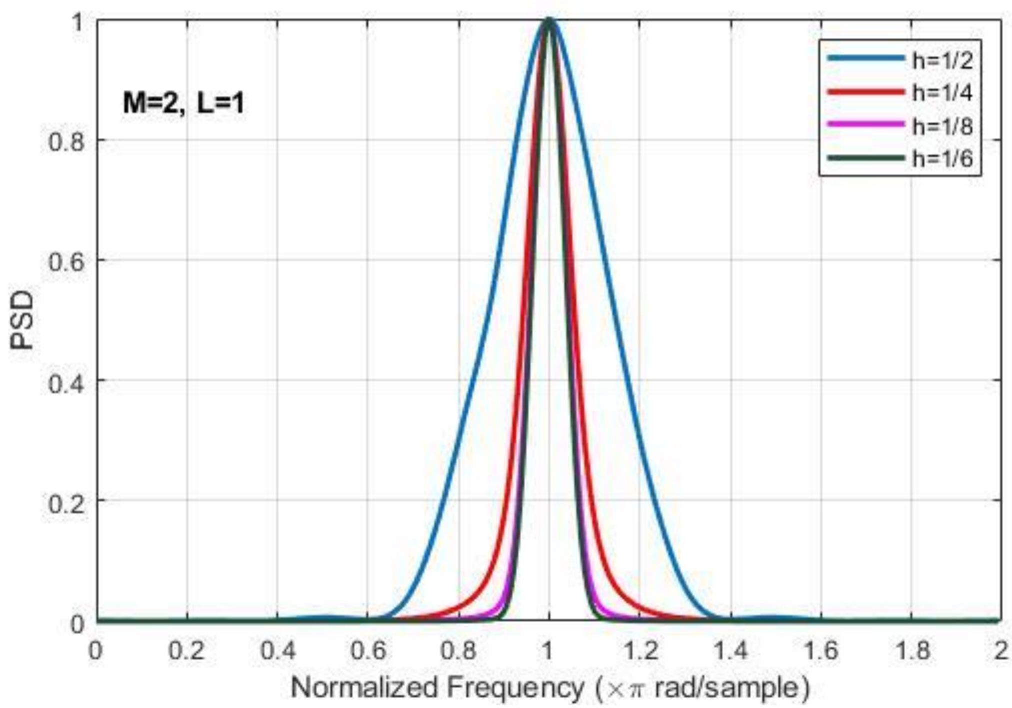


Figure 5. 6: PSD plot of Multimode CPM Narrowband waveforms for M=2, L=1

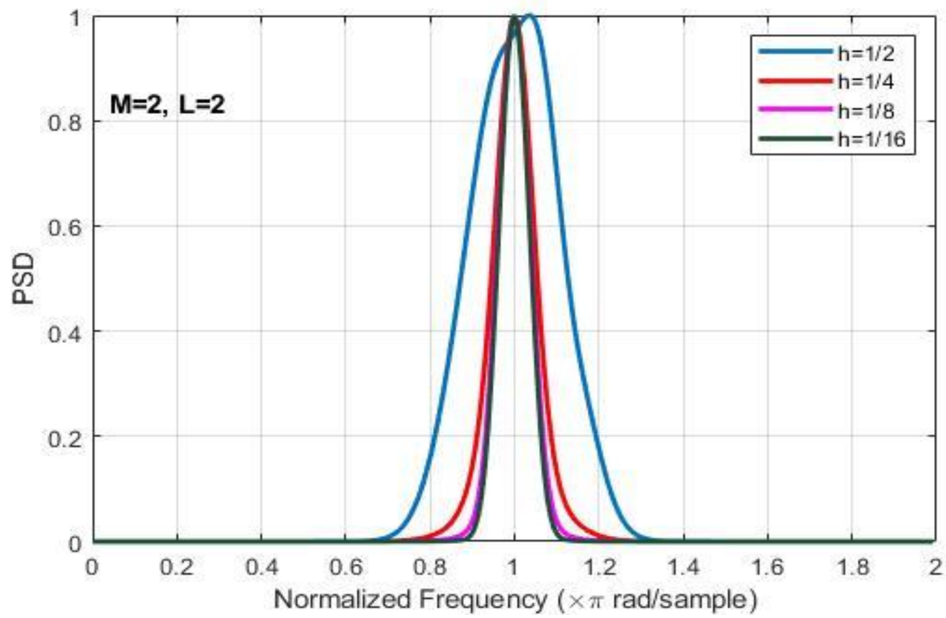


Figure 5. 7: PSD plot of Multimode CPM Narrowband waveforms for M=2, L=2

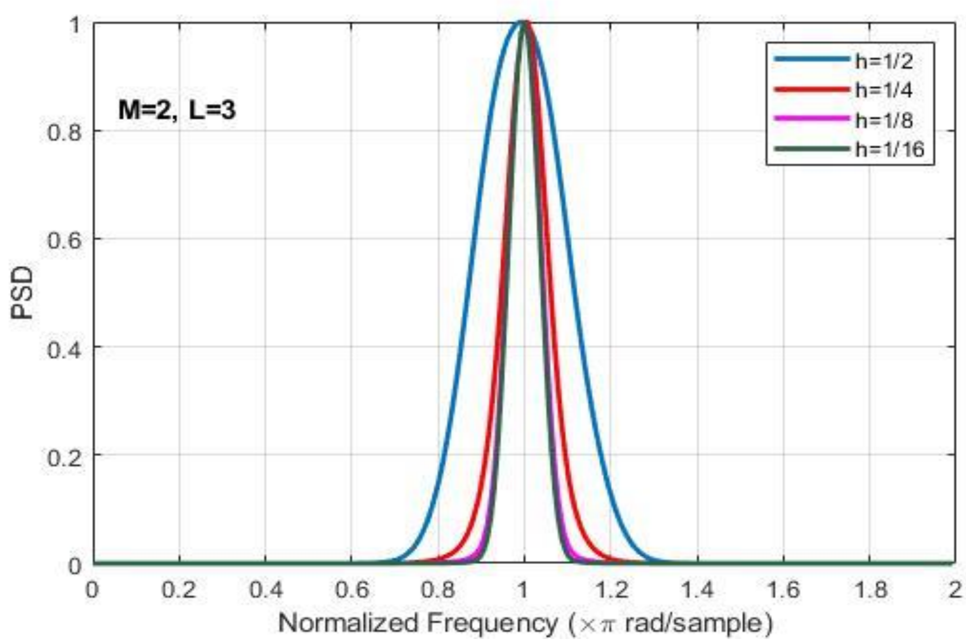


Figure 5. 8: PSD plot of Multimode CPM Narrowband waveforms for M=2, L=3

Higher throughput rates cannot be accomplished with full response CPM, so for high throughput rate we have to move to Partial response signaling for example L = 2.

From extracted modes of operation as shown in table , by comparing mode 6 and mode 8, the bandwidth utilized by the partial response, i.e. L >1 is far less than a full response waveform i.e. L=1 using the same indices with an increase in throughput as shown in figure 5.9.

For Partial response case as in mode 8, pulse extends to 2T duration or else we can say that approximately every single pulse spans over two symbol period. So partial response signaling introduces additional memory which in turns results in smoother phase transitions from one symbol interval to another. This would lead to lower bandwidth occupation and therefore higher data levels.

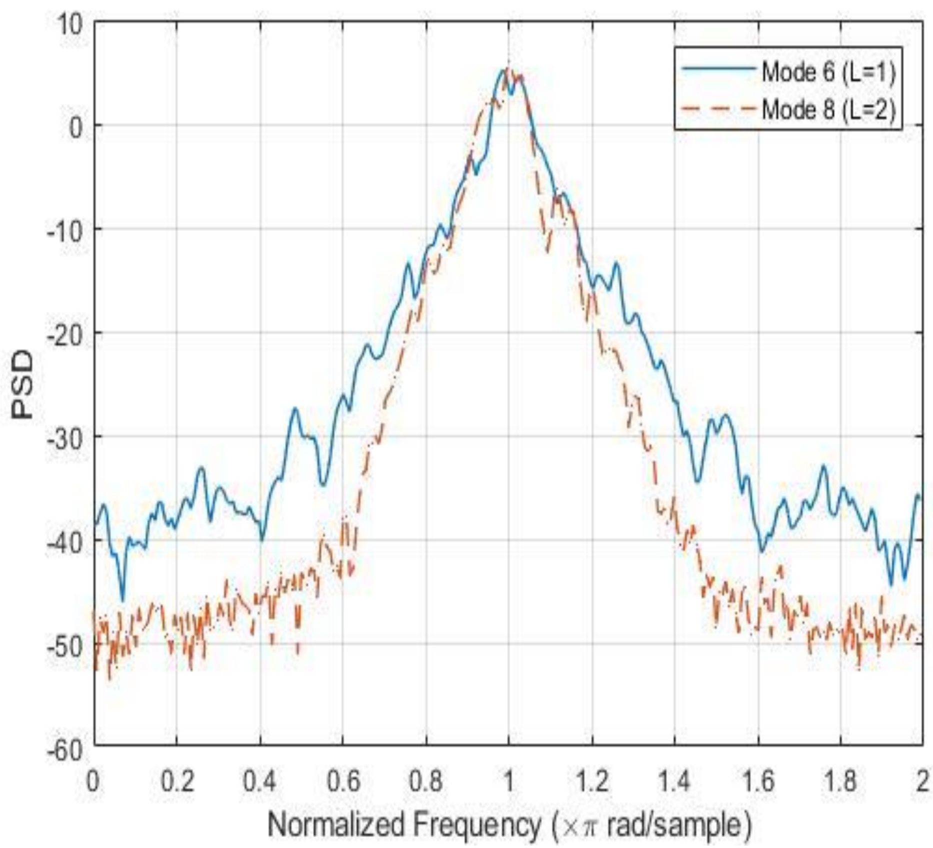


Figure 5. 9: PSD plot of proposed multimode CPM waveform with different L

Figure 5.10 shows the power spectral density plot comparison between mode 1 and mode 2. It can be seen that bandwidth decreases for decreasing h as discussed earlier.

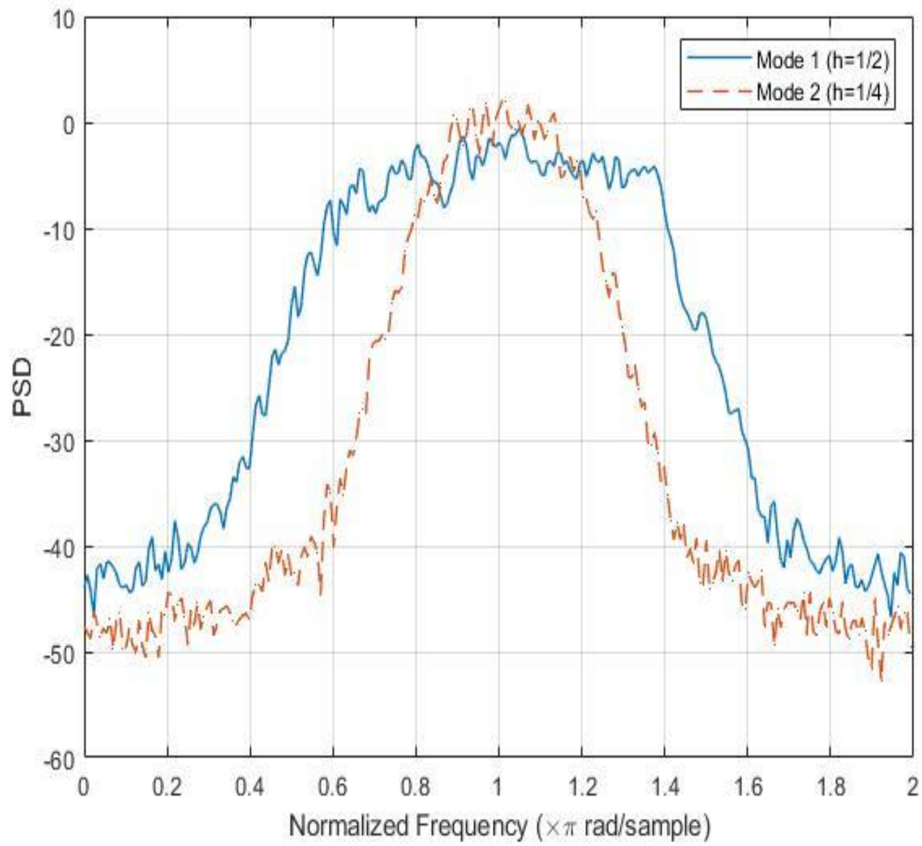


Figure 5. 10: PSD plot of proposed multimode CPM waveform with different h

5.2 System Model II:

The system Model II underneath consideration has been explained in this segment contains a continuous phase modulator CPM at the transmitter side. The properties and features of the wave are already deliberated in section 2.1.

The received waveform at the receiver end is demodulated and at that point decoded by a CPM demodulator proceeded by a Viterbi decoder. The transmitter and receiver are associated with a

SUI channel model that has been discussed already in section 3.3.2, accompanied with AWGN as shown in figure 5.11.

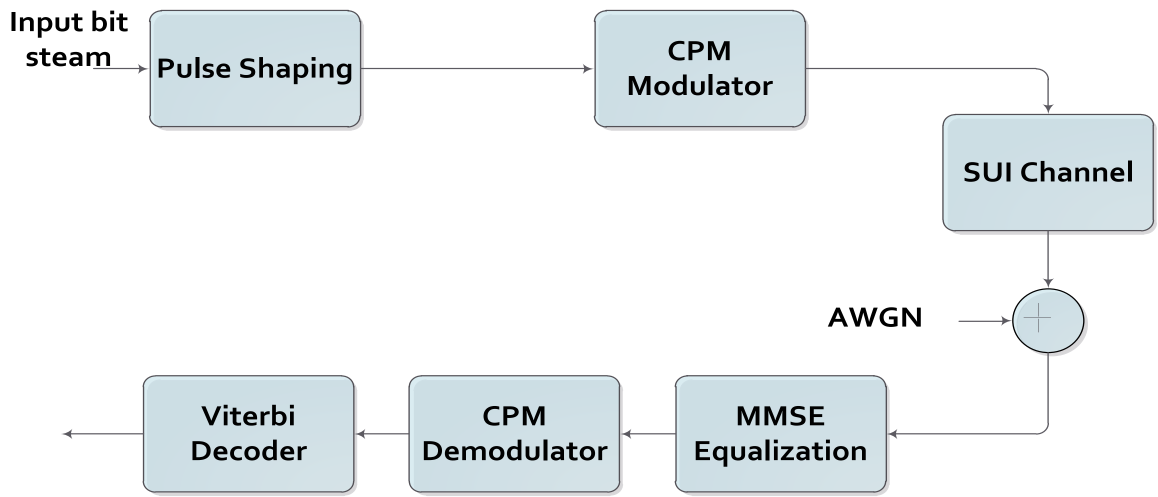


Figure 5. 11: Block Diagram of CPM Modulator/Demodulator under SUI channel

Figure 5. 12: Simulation parameters for SUI channel

SUI 1	Tap 1	Tap 2	Tap 3
Delay	0.0	0.4	0.9
Power (dB)	0	-15	-20
K- factor	4	0	0
Doppler (Hz)	0.40	0.30	0.50

SUI 2	Tap 1	Tap 2	Tap 3
Delay	0.0	0.4	1.1
Power (dB)	0	-12	-15
K- factor	2	0	0
Doppler (Hz)	0.20	0.15	0.25

SUI 3	Tap 1	Tap 2	Tap 3
Delay	0.0	0.4	0.9
Power (dB)	0	-5	-10
K- factor	1	0	0
Doppler (Hz)	0.10	0.30	0.50

SUI 4	Tap 1	Tap 2	Tap 3
Delay	0.0	1.5	4.0
Power (dB)	0	-4	-8
K- factor	0	0	0
Doppler (Hz)	0.20	0.15	0.25

SUI 5	Tap 1	Tap 2	Tap 3
Delay	0.0	4.0	10.0
Power (dB)	0	-5	-10
K- factor	0	0	0
Doppler (Hz)	2.00	1.50	2.50

SUI 6	Tap 1	Tap 2	Tap 3
Delay	0.0	14.0	20.0
Power (dB)	0	-10	-14
K- factor	0	0	0
Doppler (Hz)	0.40	0.30	0.50

In the absence of any channel, the ideal case, the transmitted seed, sub-seeds and payload are received with zero BER. SUI channel model is the set of all 6 channels named as Rician and Rayleigh fading channels. SUI parameters for 3 tap channel that we have used for simulation purpose are shown in figure 5.12.

Rician is a multi-path fading channel with one strong dominant path being the Line of Sight (LOS). Signal reaches the receiver by passing through a few distinctive paths and at slightest one path is changing. Rayleigh is a multi-path fading channel without LOS. Due to LOS, performance of Rician fading channel is way better/strong than Rayleigh fading channel. Simulation performance beneath SUI Channel models for mode 7 is shown in Figure 5.13.

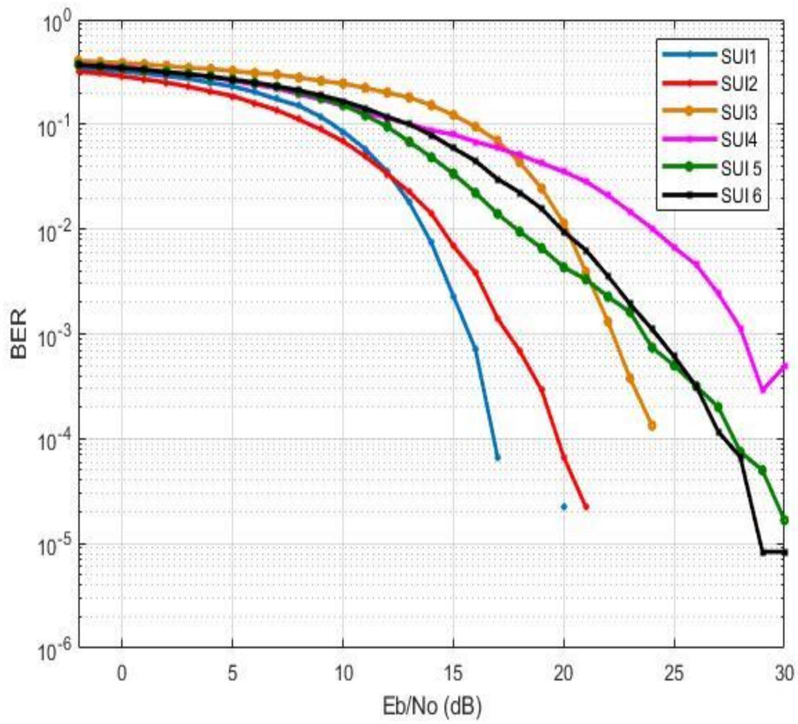


Figure 5. 13: BER Performance for SUI Channel Model of CPM for Mode 7 (M=8, h=1/16, L=2)

Figure 5.13 shows that performance of channel SUI-1 is much better than the other SUI channel models due to strong line of sight component, flat terrain type and light tree density. SUI-4 shows the worst performance due to weak line of sight component, heavy tree density and high Doppler spread.

Figure 5.14 shows the corresponding bit error rate (BER) curves for the proposed ten modes under SUI-3 channel presented in table 4-10.

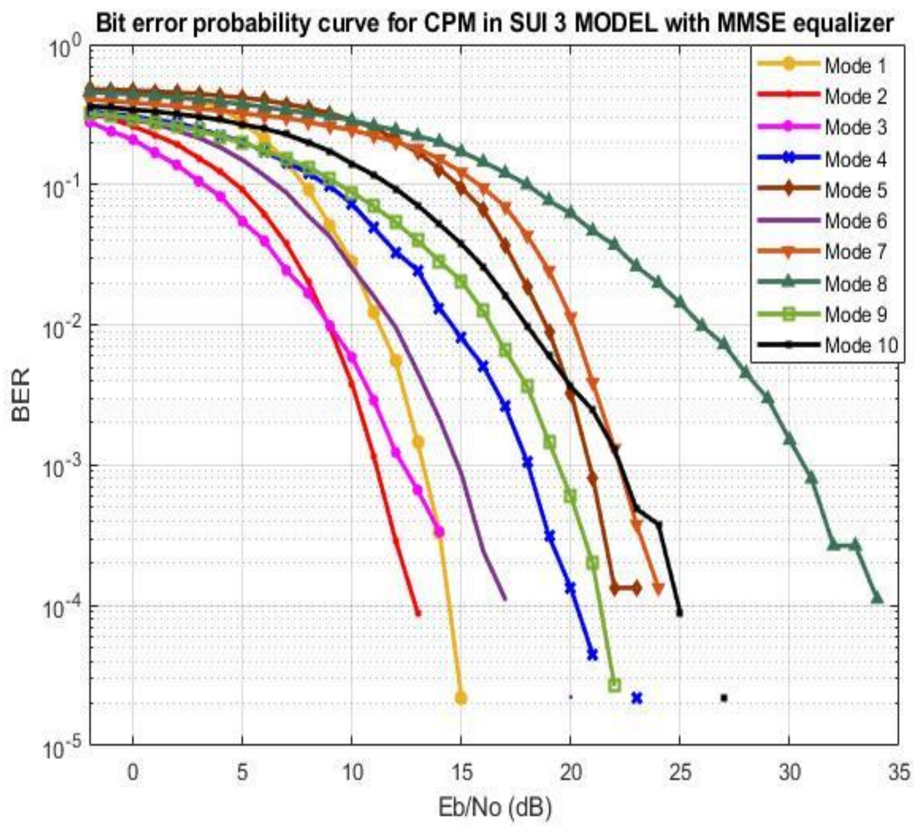


Figure 5. 14: BER Performance of 10 Proposed Modes of CPM Narrowband waveforms under SUI-3 channel

Chapter 6: CONCLUSION AND FUTURE RECOMMENDATIONS

6.1 Conclusion:

Continuous phase modulation (CPM) is an effective system in relations of bandwidth and throughput necessities in military surroundings. Initially, the fundamentals of this phase modulation scheme are conferred. A family of adaptive multimode continuous phase modulation (CPM) narrowband waveform for software defined radio (SDR) has been presented that supports multiple bandwidth /multiple data rates where range and throughputs are significantly improved to support heterogeneous requirements of future wireless networks compared to legacy systems ensuring specific Quality of Service (QoS) requirements. Performance comparison of the receiver is aimulated in AWGN and SUI channel models which tends to be quite reasonable. It is evident from the results that the Bit error rate and throughput efficiency could be achieved by the proficient use of explicit parameters (pulse width L, modulation index h and M-ary signaling).

6.2 Future Recommendations

Proposed Narrowband CPM waveform can be extended to support multiple number of users and wideband networking waveform. To promote increase throughput a system with good rational value of modulation index h e.g. 1/4, 1/8 etc. is utilized. Such standards greatly increase the complexity of receiver so that extra work can be done to decrease its complexity. Cognition at the MAC layer will be introduced in the next step to improve Quality of Service. Proposed waveform will be implemented practically on actual SDR platforms using Digital Signal Processor (DSP) or Field Programmable Gate Array (FPGA) and will be tested in field for the claimed higher communication range.

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