ABSTRACT

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THE PERFORMANCE OF HIGH-ORDER QAUDRATURE AMPLITUDE MODULATION SCHEMES FOR BROADBAND WIRELESS COMMUNICATIONS SYSTEMS

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The limited amount frequency spectrum available to wireless communication systems makes it difficult to satisfy the rapidly growing demand for wireless service. Spectral efficiency can be increased by using higher order modulation schemes. However this come at the cost of increased probability of error. In this paper we investigate through MATLAB simulation, the implementation of orders of Quadrature Amplitude Modulation (QAM) more commonly used in wired networks. The BER performance of 64, 128, 256, 512, 1024, 2048, 4096, and 8192 QAM signals in the presence of Rayleigh and Rician multipath channels with additive white Gaussian noise are simulated.

THE PERFORMANCE OF HIGH ORDER QAM MODULATION SCHEMES FOR BROADBAND WIRELESS COMMUNICATIONS SYSTEMS

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AM	Amplitude Modulation
E_bN_0	Energy per Bit to Noise Power Spectral Density Ratio
FM	Frequency Modulation
FSK	Frequency Shift Keying
LTE	Long Term Evolution
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PM	Phase Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
WiMAX	Wireless Interoperability for Microwave Access

CHAPTER 1

Introduction

How we communicate plays an important role in our everyday lives. Since the dawn of Society mankind has sought to create more efficient and effective ways to share information. In 1897 Guglielmo Marconi invented the first radio frequency communications system to establish continuous communication with ships across the English Channel [1]. This was the beginnings of a new paradigm in communications in which information could be shared over large distances at the speed of light. Since then there has tremendous technological advances in wireless communications overcoming greater barriers. In global positioning systems (GPS), terrestrial devices communicate with satellites in orbit around the Earth to determine the location of the device within an accuracy of three meters [2]. Wireless communications has experienced explosive growth in the past 25 years, due to demand and advances in Very Large Integrated Circuit (VLSI) and Discrete Signal Processing (DSP) technologies. It is useful to refer to mobile cellular technology when describing the recent evolution in wireless communications, since its market has experienced the most growth, and gives a good representation of the capabilities of wireless technology. Figure 1.1 shows a depiction of the advancement of wireless standards, beginning with the second generation of technology.

Cellular communications systems are perhaps the most common type of wireless communications systems. The first generation mobile wireless communications systems used analog modulation to carry voice over air between transmitter and receiver. In 1978 Bell Laboratories developed the Advanced Mobile Phone System (AMPS), it was the first cellular system to be implemented in the United States. It used Frequency Modulation (FM) over a 30 kHz channel, within the 824-894 MHz frequency band and Frequency Division Multiple Access (FDMA) for user multiplexing.

The second generation of cellular technology began with the launch of the Global System for Mobile (GSM) Communications [3]. The system was introduced to Europe in 1988.

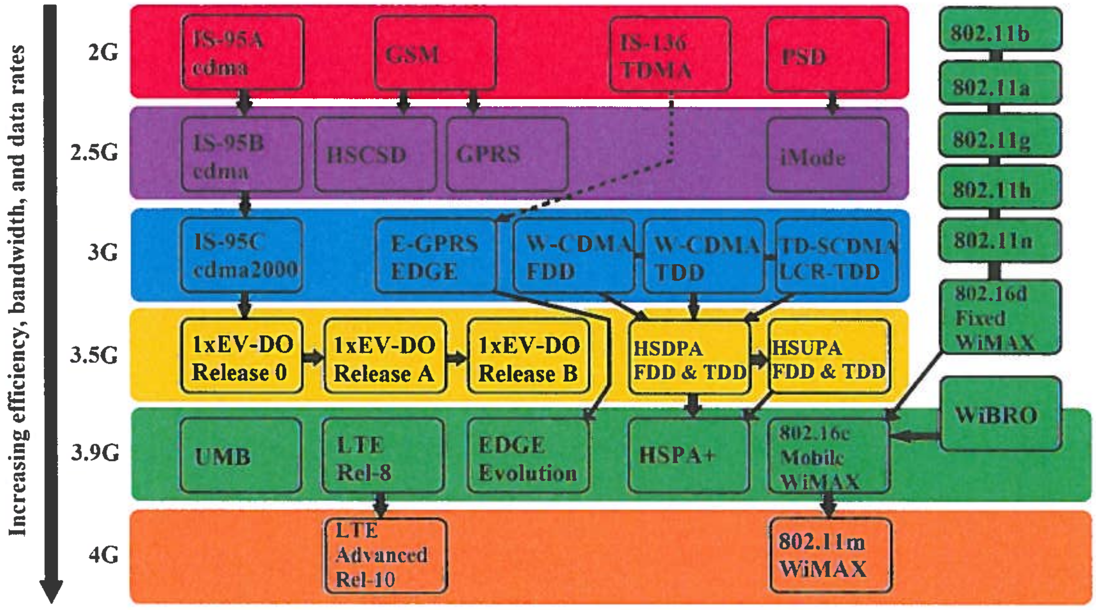


Figure 1.1 Evolution of Wireless Communication Standards 1990-2011

1.1 Motivation

The demand of high data rates in wireless applications continues to grow at an exponential rate. Additionally the number of connected mobile devices is also increasing According to Cisco, global mobile data traffic is expected to double yearly though 2016 [4]. The limited availability of frequency spectrum hinders this growth. The limited availability of spectrum makes achieving high data rates in wireless communications challenging objective. High data rates are essential for demanding applications such a real-time video streaming. High throughput is realized through tradeoffs between bandwidth, power, and system complexity. Modulation is the process of transforming an incoming stream of information into a format that is suitable for transmission over a medium. There are many different types of modulation techniques choose form. Quadrature Amplitude Modulation (QAM) has been a popular choice for implementation.

1.2 Digital Modulation Techniques

In telecommunications modulation is the process of modifying a data source into a form more suitable for transmission over a medium [5]. The properties of a signal can alternated to represent the differentiations in the data being transmitted. A general sine wave can be represented as a function of time, t as follows

$$s(t) = A\cos(\omega_c t + \theta)$$

where A is the amplitude, $\omega_c = 2\pi f_c$ is the frequency, and ϕ is the instantaneous phase.

The choice of digital modulation scheme is crucial for mobile communications systems. It is a key factor in determining the performance of a communications system. There are two basic forms modulation, analog and digital. In analog modulation an incoming data source is modulated by a continuous signal, referred to as a carrier. In digital modulation the source signal is modulated by a discrete carrier signal. Today mobile wireless systems are using digital modulation techniques. Table 1.1 shows a variety of digital modulation techniques and some of their applications. Digital signals tend to be more robust than analog signals in terms of signal integrity. Frequency, phase, and amplitude are the three fundamental properties of a signal which can be modulated.

Typical first generation wireless standards used simple analog modulation techniques, such as amplitude, phase, and frequency modulation. Modern 4G mobile standards use adaptive modulation schemes which adjust the modulation scheme depending on the signal to noise ratio [6, 7]. The implementation of digital modulation techniques began with the second generation of wireless communication standards. The shift toward digital modulation provided more information capacity, higher security, and better quality service as compared to analog formats. As seen in Table 1.2 there are two major categories of digital modulations. The first category uses a constant amplitude carrier to carry the information in phase or frequency variations, such as frequency shift keying (FSK) and phase shift keying (PSK). The second category conveys the information in carrier amplitude variations, such as amplitude shift keying (ASK) and quadrature amplitude modulation (QAM).

Table 1.1 Modulation Formats and Applications

Modulation Format	Application
MSK, GMSK	GSM, CDPD
BPSK	Deep telemetry, cable modems
QPSK, DQPSK	Satellite, CDMA, NADC, TETRA, PHS, PDC, LMDS, DVB-S, cable (return path), cable modems, TFTS
OQPSK	CDMA, satellite
FSK, GFSK	DECT, paging, RAM mobile data, AMPS, CT2, ERMES, land mobile, public safety
8, 16 VSB	North American digital TV (ATV), broadcast, cable
8PSK	Satellite, aircraft, telemetry pilots for monitoring broadband video systems
16 QAM	Microwave digital radio, modems, DVB-C, DVB-T
32 QAM	Terrestrial microwave, DVB-T
64 QAM	DVB-C, modems, broadband set top boxes, MMDS
256 QAM	Modems, DVB-C (Europe), Digital Video (US)

Table 1.2 Classification of Modulation Schemes

Modulation		
Linear **(Modulate A,ϕ)**		**Exponential** (Modulate $d\phi / dt$)
Binary	*Multilevel (>1 bit/symbol)*	FSK, MSK, GMSK, etc.
ASK, BPSK	M-PSK, QAM	

1.2.1 Non-linear Modulation

Binary phase-shift keying (BPSK) is one of the simplest modulation schemes, in which the phase of the carrier signal is modulated with two distinct states representing data being transmitted:

‘0’, $\phi = \pi$
‘1’, $\phi = 0$

This is shown in Figure 1.2, where the modulated signal is a product of equivalent baseband signal and carrier frequency. BPSK has been implemented in mobile standards since the second generation of wireless technology.

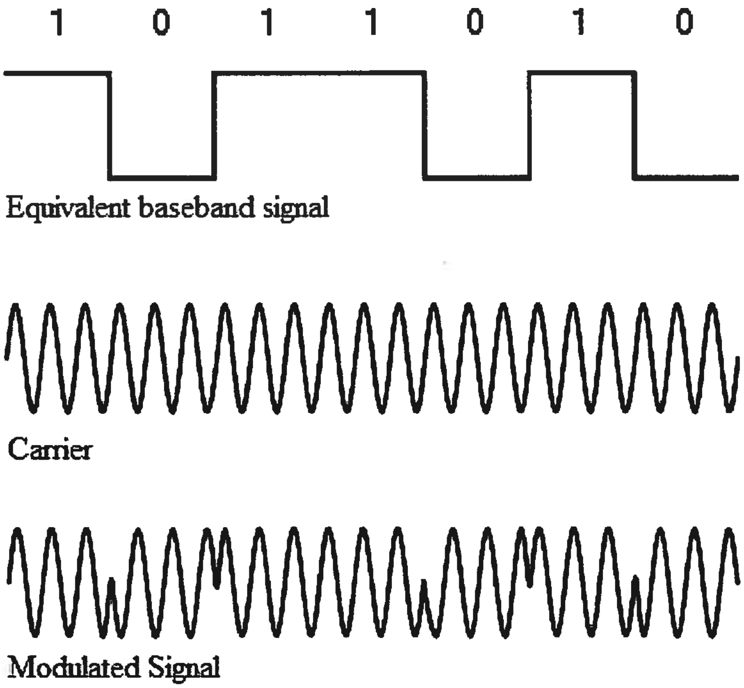


Figure 1.2 Generation of BPSK modulated signal

Quadrature phase-shift keying (QPSK) is an extension of BPSK in which four different phases or states can be transmitted opposed to two.

M-ary phase-shift keying (MPSK) is a multi-level modulation scheme. It consist of QAM 2G standards such as IS-95 and GSM used BPSK. Gaussain Miniumal Shift Keying (GMSK), and Different DQPSK. Binary Phase-shift Keying (BPSK), Quadrature Phase-shift Keying (QPSK), and Quadrature Amplitude Modulation (QAM) modulation techniques are used in 4th Generation Wireless System, LTE and WiMAX [3] [4]. For BSPK and QPSK only the phase of a transmitted signal is allowed to vary.

1.2.2 Non-linear Modulation

The simplest FSK is binary FSK (BFSK). BFSK uses a pair of discrete frequencies to transmit binary (0s and 1s) information. With this scheme, the "1" is called the mark frequency and the "0" is called the space frequency. The time domain of an FSK modulated carrier is illustrated in the figures to the right.

Minimum shift keying (MSK) Minimum frequency-shift keying or minimum-shift keying MSK is a particular spectrally efficient form of coherent FSK. In MSK the difference between the higher and lower frequency is identical to half the bit rate. Consequently, the waveforms used to represent a 0 and a 1 bit differs by exactly half a carrier period.

Gaussian minimum shift keying (GMSK) modulation is based on MSK, which is itself a form of continuous-phase frequency-shift keying. One of the problems with standard forms of PSK is that sidebands extend out from the carrier. To overcome this, MSK and its derivative GMSK can be used.

1.3 Why Quadrature Amplitude Modulation

Much research has done on the comparison of QAM with other modulation techniques. In most cases the QAM tends to have better performance overall. For instance, multiple papers show that QAM has better noise resistance, and is more adaptive for channel change, and more efficient in bandwidth utilization [8-10]. While PSK modulation schemes often demonstrate better BER performance than their QAM counterparts, it may be possible to mitigate this issue with more complex hardware [9]. It is concluded that BER performance of QPSK is better than that of 16-QAM at the expense of large spectral width. Alternatively, 16-QAM can carry more traffic than QPSK at the expense of higher BER[9].

1.4 Thesis Scope and Organization

The objective of this thesis is to investigate the performance of higher order modulation schemes in the presence of noise and fading channel environments. The thesis is organized as follows.

Chapter 2 provides a brief background of advancements in research on Quadrature Amplitude Modulation and touches on some of its applications, then proceeds to go into a detailed description of how it is implemented including mathematical descriptions of a QAM signal and calculating the probability that in error occurs during transmission. Chapter 3 examines the potential gains in the implementation of higher order QAM. We calculate the system capacities and bandwidth efficiencies of the various QAM schemes. In Chapter 4, we detail the design of a wireless communications system that implements QAM. Chapter 5 covers the components of the simulation, the mythology discussed in chapter 4 are implemented in to a MATLAB SIMULINK model. In Chapter 6, the results of the simulations are discussed and suggestions for future research are given.

CHAPTER 2

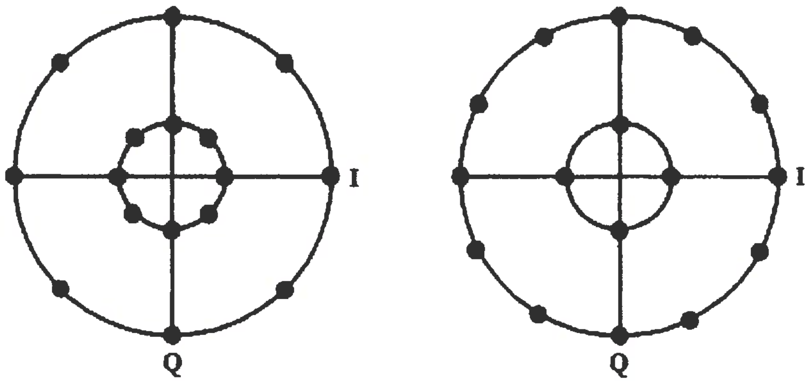
Quadrature Amplitude Modulation

2.1 Background

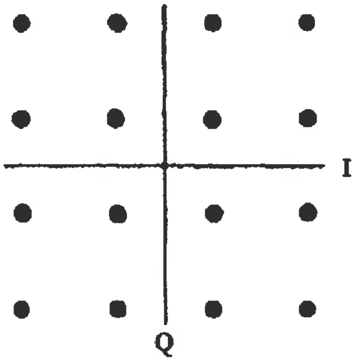
Digital phase modulation techniques were popular in the 1950s, prior to the development of QAM[11]. It was sought as an alternative to digital amplitude modulation[12]. Later, a method unifying both schemes was explored. QAM is essentially the combination of digital amplitude and phase modulation. It was first suggested in 1960 by C.R. Cahn, who published a paper describing such a system[13]. He did this by His research suggested that amplitude and phase modulation (AM-PM) systems would result in an increase in data throughput compared to an equivalent PSK system of 16 or more states. .

Shortly after its publication, Cahn's work was expanded by Hancock and Lucky [14]. They determined that errors were induced by the introduction of noise into a signal. This caused by a shift in the phasor at the receiver to represent a different constellation point than the intended one. This type of error has a direct relation to the distance between constellations points. Their solution was to place more points on the outer ring of the constellation, being that points on the inner ring were closer in proximity to each other and thus more likely to experience errors. They coined Cahn's constellation as Type I and there's as Type II.

In 1962, Campopiano and Glazer introduced the Type III constellation [15]. Points in this new type of constellation were arranged to form a square. Although the acronym QAM had not yet been suggested, they described the system as "the amplitude modulation and demodulation of two carriers that have the same frequency but are in quadrature with each other" – the first time the combination of amplitude and phase modulation had been refer to as amplitude modulation on quadrature carriers [11]. One issue they found with their type III constellation is that non-coherent detection was not possible, therefore it had to be used in a phase coherent mode. They concluded that while their Type III constellation offered modest performance over a Type II system, it had the advantage of simplicity in implementation compared to Types I and II. Examples of Type I, II, and III constellations are shown in Figure 2.1.



Type I QAM Constellation   **Type II QAM Constellation**



Type III QAM Constellation

Figure 2.1 Examples of types I, II and III QAM constellations from [16]

Although much research had gone into the design of more optimal constellations, by 1975 most interest had been centered on Type III or square QAM constellations [17-19]. This was due to the minimal gains realized by the optimal constellations verses the complexity of implementation, and advancements if coherent phase detection methods [20, 21]. Up until this time the constellation shape of square QAM had only been considered for systems with an even number of bits per symbol. In 1975 J.G Smith suggested an idea design for odd bit per symbol constellations [22]. His work proposed that odd bit symbol constellations be symmetric and that such systems were of equal implementation complexity as even bit symbol constellations. An example of his idea constellation shape for odd bit symbols is shown in Figure 2.2, where there are five bits per symbol.

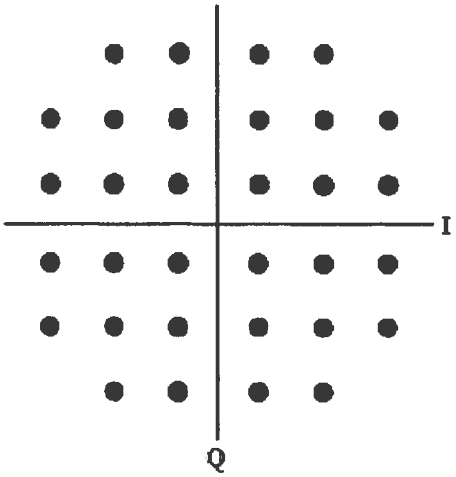


Figure 2.2 “Optimum” 32-level constellation according to Smith [22] from [16]

The first major research investigating the implementation of QAM for mobile radio came in 1987. Sundberg, Wong, and Steele published two papers proposing QAM for the transmission of voice over Rayleigh fading channels [23, 24]. In this paper they used gray code mapping as a method to assign symbols to constellation points. They found that certain assortments of bits constituting a symbol had different rates of error than others. By 1990 research on QAM had become a very popular. There are many papers that explore its implementation for mobile radio applications.

Currently 1024 and 4094 QAM are implemented in wired communication standards. The ability of these dense forms of QAM to achieve exponential increases in spectral efficiency makes them a prime candidate as a method to increase capacity. High order constellations of QAM also have the advantage of increasing data throughput. Advances in VLSI and Digital Signal Processing DSP techniques have enabled the implementation of relatively complex forms of modulation such as QAM. It can be expected that this trend will continue into the future.

2.2 Applications

Quadrature amplitude modulation is implemented in a variety of modern wireless communications standards. QAM is in many radio communications and data delivery applications. However some specific variants of QAM are used in some specific applications and standards.

For domestic broadcast applications for example, 64 QAM and 256 QAM are often used in digital cable television and cable modem applications. In the UK, 16 QAM and 64 QAM are currently used for digital terrestrial television using DVB - Digital Video Broadcasting. In the US, 64 QAM and 256 QAM are the mandated modulation schemes for digital cable as standardized by the SCTE in the standard ANSI/SCTE 07 2000.

In addition to this, variants of QAM are also used for many wireless and cellular technology applications.

2.3 Mathematical Model

Digitally modulated signals can be represented in a multitude of forms using variety of techniques derived from the three basic forms of frequency, amplitude, and phase keying. In general a modulated signal can be represented by

$$s_i(t)=\sqrt{\frac{2E_{\min}}{T_s}}a_i\cos(2\pi f_c t)+\sqrt{\frac{2E_{\min}}{T_s}}b_i\sin(2\pi f_c t)\quad 0\le t\le T;\ i=1,2... \tag{2.1}$$

where $E_{\min}$ is the energy of the signal with the lowest amplitude, and a_i and b_i are a pair of independent integers chosen according to the location of the particular signal point. M-ary QAM does not have constant energy per symbol, nor constant distance between possible symbol states, which is why some values of $s_i(t)$ will be detected with higher probability than others.

2.4 Calculating the Probability of Error

Here we discuss how to obtain the theoretical bit error rate (BER) and symbol error rate (SER) for a given QAM constellation using a general equation. The BER and SER are important factors in determining the usefulness of modulation schemes. Analysis of theoretical and experimental results of the error rates.

For square constellations of QAM, where $k=\log_2 M$ is even, the SER, P_s and BER, P_b can be described as follows [25-27]:

$$P_s=4\frac{\sqrt{M}-1}{\sqrt{M}}Q\left(\sqrt{\frac{3}{M-1}\frac{kE_b}{N_0}}\right)-4\left(\frac{\sqrt{M}-1}{\sqrt{M}}\right)^2Q^2\left(\sqrt{\frac{3}{M-1}\frac{kE_b}{N_0}}\right) \tag{2.2}$$

From [28]:

$$P_b = \frac{2}{\sqrt{M}\log_2\sqrt{M}} \times \sum_{k=1}^{\log_2\sqrt{M}} \sum_{i=0}^{(1-2^{-k})\sqrt{M}-1} \left\{ (-1)^{\left\lfloor \frac{i2^{k-1}}{\sqrt{M}} \right\rfloor} \left(2^{k-1} - \left\lfloor \frac{i2^{k-1}}{\sqrt{M}} + \frac{1}{2} \right\rfloor \right) Q\left(2i+1)\sqrt{\frac{6\log_2 M}{2(M-1)}\frac{E_b}{N_0}} \right) \right\}$$

(2.3)

For cross shaped QAM where $k = \log_2 M$ is odd, $M = I \times J$, $I = 2^{\frac{k-1}{2}}$, and $J = 2^{\frac{k+1}{2}}$:

$$P_s = \frac{4IJ - 2I - 2J}{M} \times Q\left(\sqrt{\frac{6\log_2(IJ)}{(I^2+J^2-2)}\frac{E_b}{N_0}} \right) - \frac{4}{M}(1 + IJ - I - J)Q^2\left(\sqrt{\frac{6\log_2(IJ)}{(I^2+J^2-2}\frac{E_b}{N_0}} \right)$$

(2.4)

From [28]:

$$P_b = \frac{1}{\log_2(IJ)}\left(\sum_{k=1}^{\log_2 I} P_I(k) + \sum_{l=1}^{\log_2 J} P_J(l) \right) \tag{2.5}$$

where,

$$P_I(k) = \frac{2}{I}\sum_{i=0}^{(1-2^{-k})I-1} \left\{ (-1)^{\left\lfloor \frac{i2^{k-1}}{I} \right\rfloor} \left(2^{k-1} - \left\lfloor \frac{i2^{k-1}}{I} + \frac{1}{2} \right\rfloor \right) Q\left((2i+1)\sqrt{\frac{6\log_2(IJ)}{I^2+J^2-2}\frac{E_b}{N_0}} \right) \right\} \tag{2.6}$$

and

$$P_J(k) = \frac{2}{J}\sum_{j=0}^{(1-2^{-l})J-1} \left\{ (-1)^{\left\lfloor \frac{j2^{l-1}}{J} \right\rfloor} \left(2^{l-1} - \left\lfloor \frac{j2^{l-1}}{J} + \frac{1}{2} \right\rfloor \right) Q\left((2j+1)\sqrt{\frac{6\log_2(IJ)}{I^2+J^2-2}\frac{E_b}{N_0}} \right) \right\} \tag{2.7}$$

CHAPTER 3

Implementation of High Order QAM Schemes

3.1 Bandwidth Efficiency

In communications the simple expression $M = 2^k$ is used to relate the symbols to bits. Where M is the number of unique symbols and k is the number of bits transmitter per symbol. Using Shannon's channel capacity formula we can calculate the potential capacity of a system using each proposed density of QAM. Shannon's formula is described as follows

$$C = B\log_2\left(1+\frac{P}{N_0B}\right) = B\log_2\left(1+\frac{S}{N}\right) \quad \text{[bit/s]} \tag{3.1}$$

where C is the channel capacity (bits per seconds), [29-31]. 20MHz is a commonly allocated bandwidth for channels in 4G cellular communications systems such as LTE-A and WiMAX [32, 33]. Table 4.1 shows the increase in capacity with respect to each QAM scheme.

The Shannon bound can be expressed as bandwidth efficiency, $\eta = C/B$, by using (3.1)

$$\eta = \log_2(1+S/N) \quad \text{[bit/s/Hz]} \tag{3.2}$$

The maximum achievable bandwidth efficiency is calculated using Equation 3.2. The results are shown in table 3.1.

Table 3.1 Quadrature Amplitude Modulation Bandwidth Efficiency

QAM Order	Bits per Symbol, k	Bandwidth Efficiency(per 20MHz channel)
64 QAM	6	120 Mb/s
128 QAM	7	140 Mb/s
256 QAM	8	160 Mb/s
512 QAM	9	180 Mb/s
1024 QAM	10	200 Mb/s
2048 QAM	11	220 Mb/s
4096 QAM	12	240 Mb/s
8192 QAM	13	260 Mb/s

CHAPTER 4

System Model

In this chapter we discuss the components of a wireless communications system, the design and methodology of the system parameter that will be incorporated into the simulations discussed in chapter 5. A typical communications system is shown in Figure 4.1. The components are as follows:

The data source is the origin of the message to be communicated. The message could come in a variety of forms such as audio, video, or other data. The data source is transformed into an electrical signal by a transducer. The resulting electrical waveform is referred to as the baseband signal. The baseband signal is modified by the transmitter, which prepares the signal for efficient transmission. In digital communication systems the baseband signal is then coded into binary format using coding techniques. The modulator is the focus of this research. Baseband signals are often not suitable for transmission over a given channel. The modulator modifies the baseband signal to facilitate transmission. The channel is the medium over which communication takes place, such as coaxial cable, wire, optical fiber, or over-the-air radio link. For this study the channel is a radio link, which we discuss further in section 4. The receiver translates the signal into its original form. At the receiver the signal is demodulated, decoded, and processed by transducer which converts the electrical signal back into its original form.

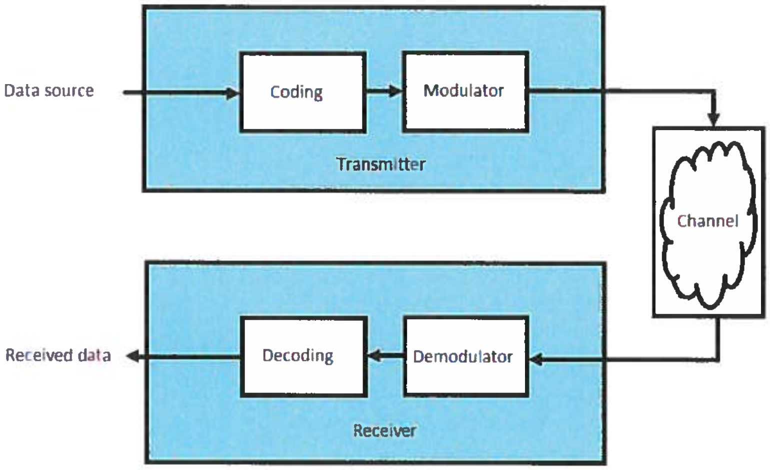


Figure 4.1 General communications block diagram.Input

The simulation model incorporates the Gray coding the map the symbols to points on the constellation. The bits sequence to signal mapping could be arbitrary provided that the mapping is one-to-one. However, a method called Gray coding is commonly used in signal assignment in QAM [34]. Gray coding assigns n-tuples with only one-bit difference to two adjacent signals in the constellation. When an M-ary symbol error occurs, it is more likely that the signal is detected as the adjacent signal on the constellation, thus only one of the n input bits is in error. An example of gray coding is shown in figure 4.2 for the case of 16 QAM.

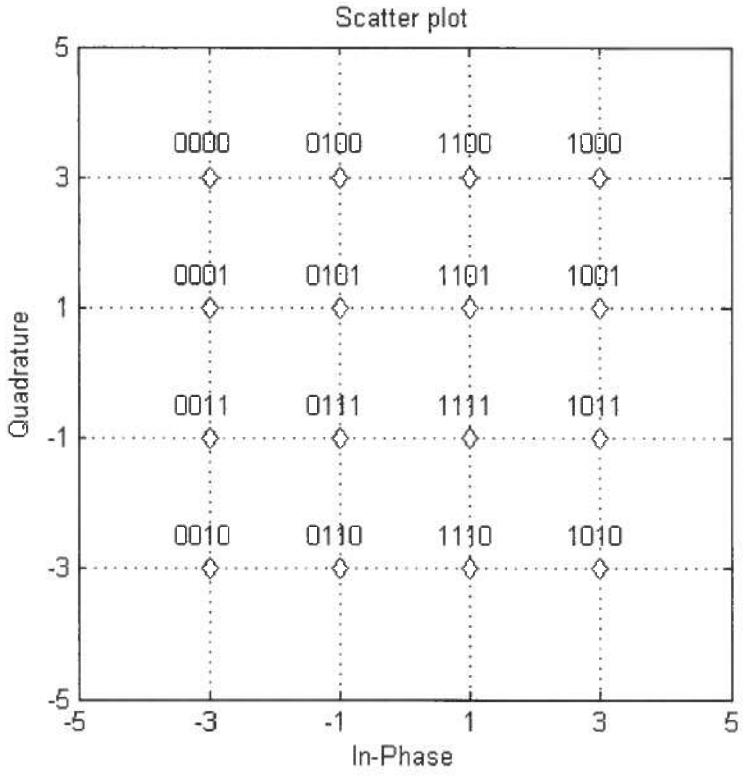


Figure 4.2 Example of Gray coding for 16 QAM

4.1 Input

The input is modeled using with a Bernoulli distribution to represent a quasi-uniform distribution of, which can be seen in Figure 2.2. The Bernoulli distribution can be described as follows

$$\Pr(X = 1) = 1 - \Pr(X = 0) = 1 - q = p \tag{4.1}$$

where probability p has a 50% chance of occurrence, meaning all possible outcomes have the same probability [35]. This method of input distribution is chosen because it is known that some values of input produce higher rates of error than others. Having a quasi-uniform distribution of all inputs ensures that the simulations will represent the overall performance of the system.

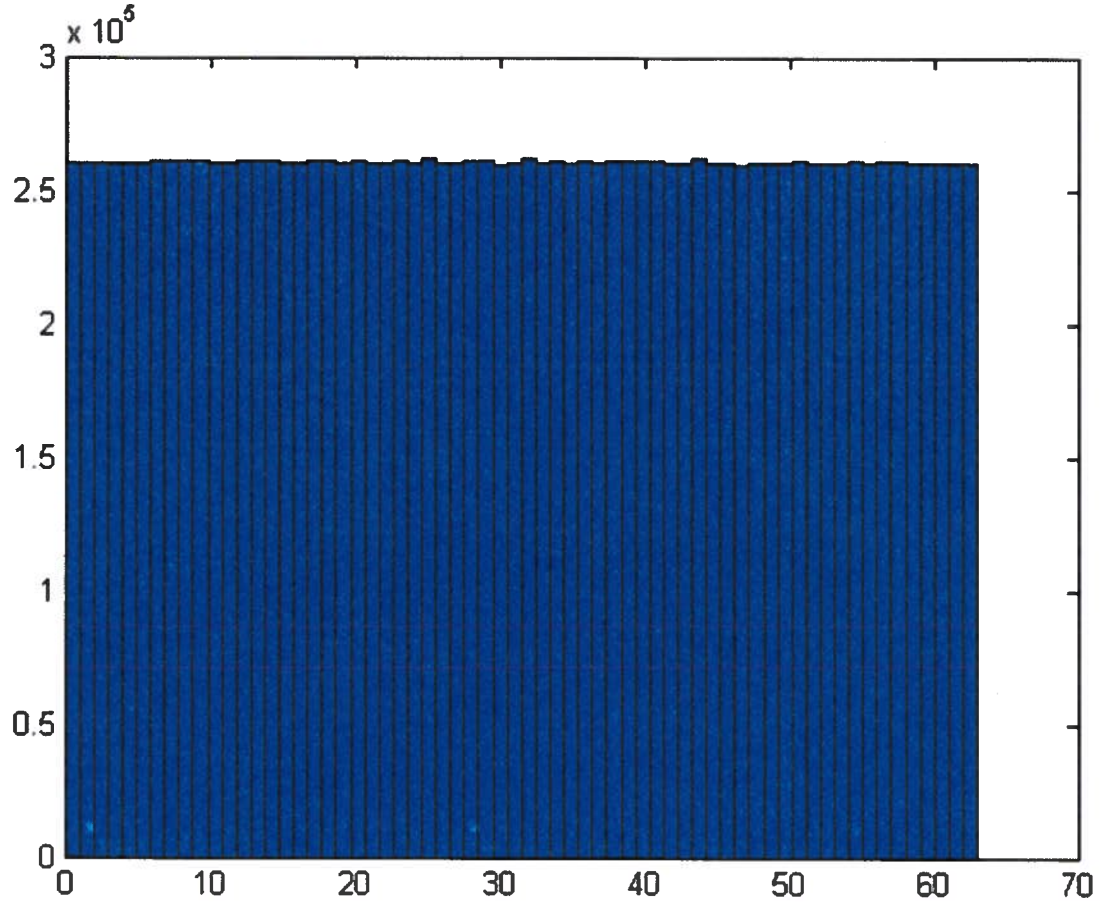


Figure 4.2 Distribution of input tuple for 64 QAM Simulation Model

4.2 Modulation

Here we give an overview of the types of QAM scheme that will be implemented in the simulation. As discussed in Chapter 2, there are two constellation types of square QAM schemes, those with even bit symbols and those with odd bit symbols. In Figure 4.3 the constellation of an even bit symbol system for the case of 256 QAM is shown. Figure 4.4 represents an odd bit symbol system for the case of 128 QAM. In both cases the constellation can be extended to represent a higher order system of the same type by expanding the number of points to M while maintaining the integrity of the constellations shape. Remembering that $M = 2^k$ is used to relate the number of bits per symbol to the number of unique symbols.

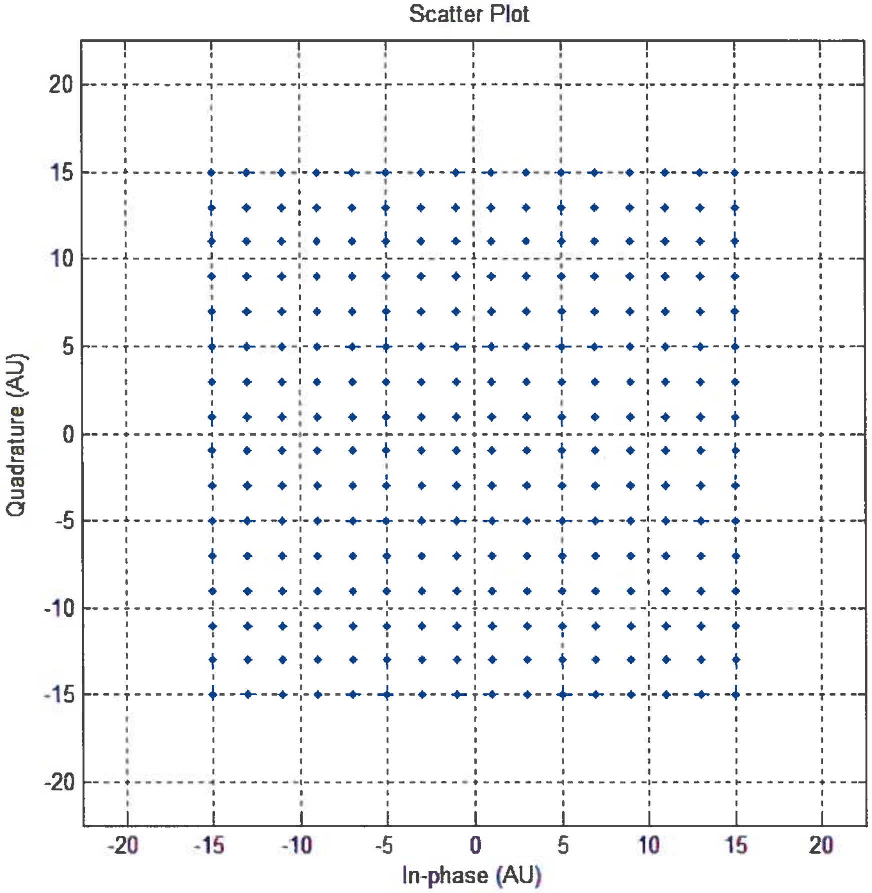


Figure 4.3 Even constellation of 256 QAM

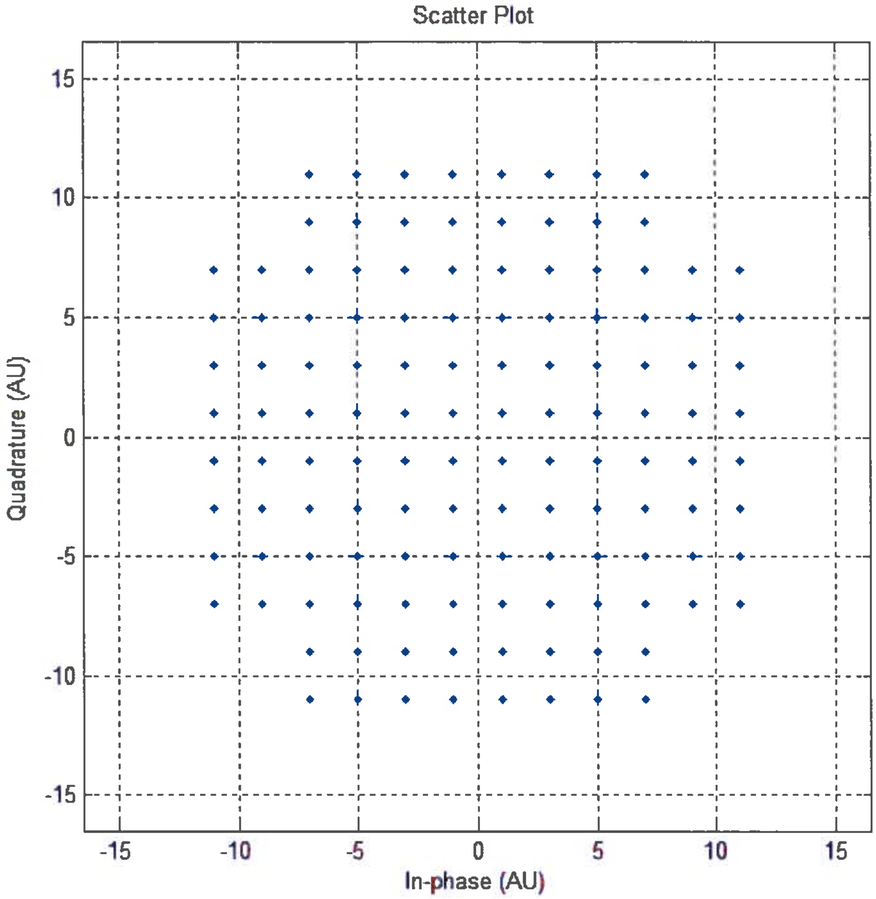


Figure 4.4 Odd Constellation of 128 QAM

4.3 Channel

There are several conditions present in real world environments that can distort the original signal at the receiver. These conditions include noise added by the environment and the multipath effects of reflection, diffraction, and scattering. It is important to include these environmental factors into the model, to have a representation as close to reality as possible.

Additive white Gaussian noise (AWGN) is a channel model in which the only impairment to communication is a linear addition of wideband or white noise with a constant spectral density (expressed as watts per hertz of bandwidth) and a Gaussian distribution of amplitude. The model does not account for fading, frequency selectivity, interference, nonlinearity or dispersion. However, it produces simple and tractable mathematical models which are useful for gaining insight into the underlying behavior of a system before these other phenomena are considered. The channel capacity for the AWGN channel is given by Equation 3.1.

The Rayleigh probability distribution function is commonly used to incorporate the multipath effects of a typical system. The Rayleigh PDF is useful in fading channel environment of wireless communication systems, where multiple signals are scattered, diffracted, and reflected at the receiver.

$$p_r(r) = \begin{cases} \frac{r}{\sigma^2} e^{-r^2/2\sigma^2} & \text{for } (r \geq 0) \\ 0 & \text{for } (r < 0) \end{cases} \tag{4.2}$$

where σ is the rms value of the received voltage signal before the envelope, σ^2 is the time-average power of the signal before the envelope.

Rician

$$p_r(r) = \begin{cases} \frac{r}{\sigma^2} e^{-(r^2+A^2)/2\sigma^2} I_0\left(\frac{Ar}{\sigma^2}\right) & \text{for } (A \geq 0, r \geq 0) \\ 0 & \text{for } (r < 0) \end{cases} \tag{4.3}$$

Where A is the peak amplitude of the dominate signal and $I_0(\square)$ is the modified Bessel function of the first kind and zero-order.

The Rician PDF is another The Rician PDF if often expressed in terms of K. It is given by $K = A^2/(2\sigma^2)$.

$$p_r(r) = \begin{cases} \dfrac{2r}{\sigma^2} e^{-\frac{-K+1}{A}(r^2 + \frac{AK}{K+1})/2\sigma^2} I_0\left(2r\dfrac{K(K+1)}{A}\right) & \text{for } (A \geq 0, r \geq 0) \\ 0 & \text{for } (r < 0) \end{cases} \tag{4.4}$$

where A is the peak amplitude of the dominate signal, and K is the defined as the ratio between the deterministic signal power and the variance of the multipath.

4.4 Basic Structure

Figure 4.3 shows the basic structure of an QAM transmitter and receiver.

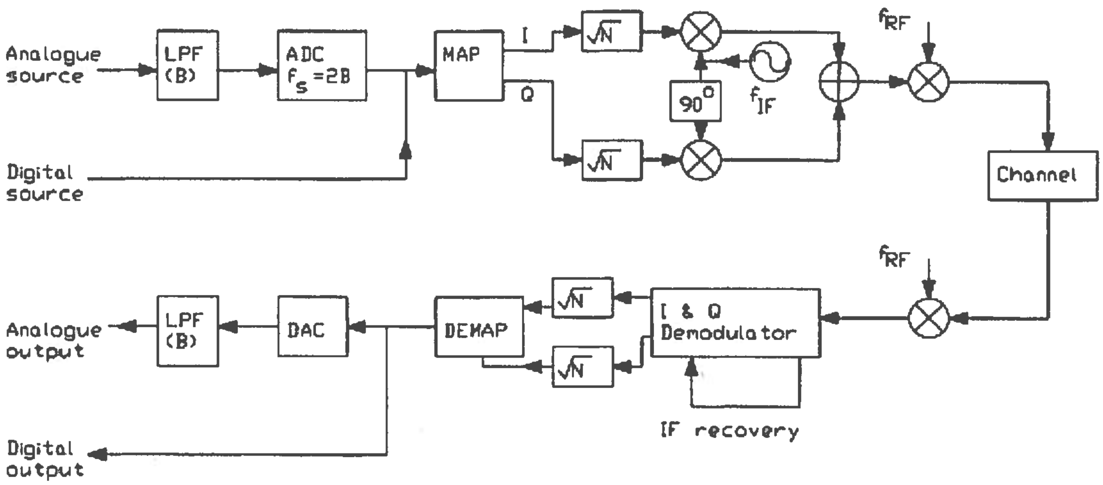


Figure 4.5 Basic QAM modem schematic from [16]

CHAPTER 5

Simulation

5.1 Simulation Models

Here we discuss the method used to create the simulation models, and discuss key parameters. The simulation models were created using Simulink, an extension of the MATLAB 2012 software suite [27]. The simulation model block functions are as follows:

- The Bernoulli Binary block is used to generate a random sequence of numbers with a Bernoulli probability distribution.
- The Rectangular QAM Modulator Baseband block, to the right of the Random Integer Generator block, modulates the signal using baseband QAM.
- The AWGN Channel block models a noisy channel by adding white Gaussian noise to the modulated signal.
- The Rayleigh block introduces noise in the angle of its complex input signal
- The Rician block introduces noise in the angle of its complex input signal.
- The Rectangular QAM Demodulator Baseband block, demodulates the signal.
- The Error Rate Calculation block counts symbols that differ between the received signal and the transmitted signal

Figures 5.1-5.3 show the SIMULINK simulation models for 64 QAM transmitted over AWGN, Rayleigh fading + AWGN, and Rician fading + AWGN channels respectively.

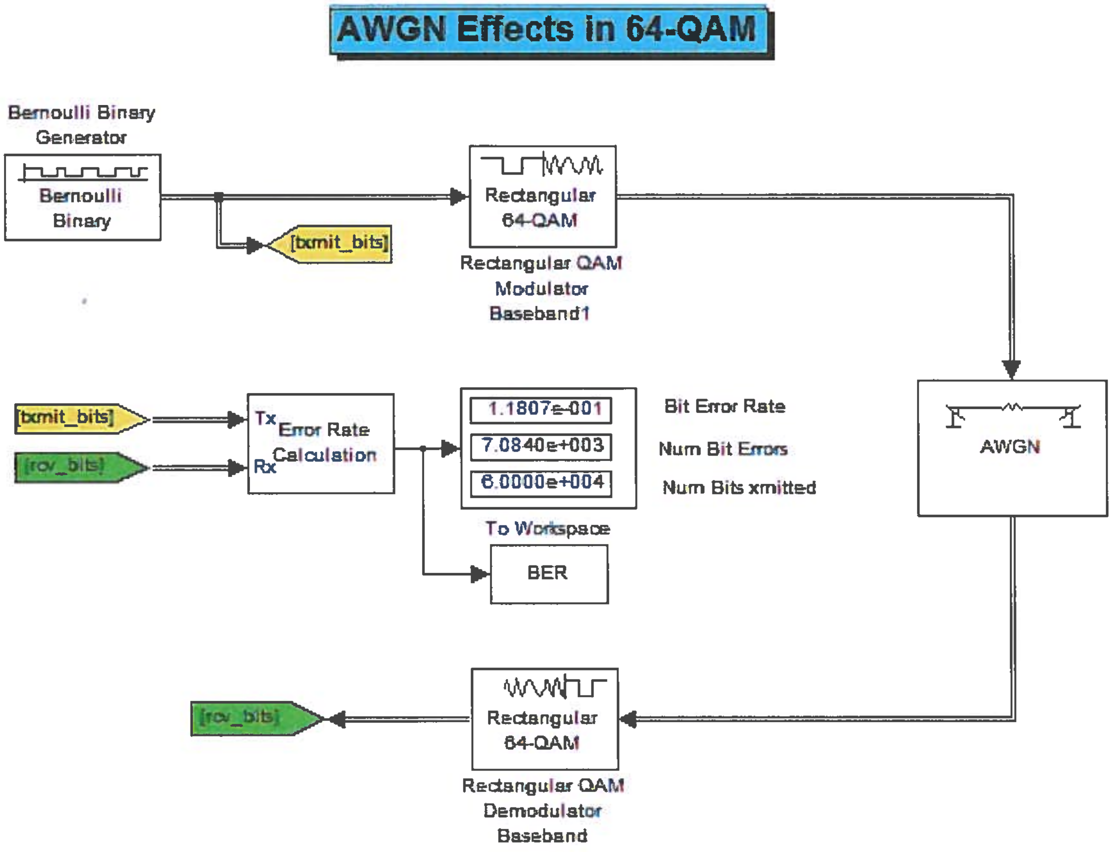


Figure 5.1 Simulink simulation model of 64 QAM transmission over AWGN channel

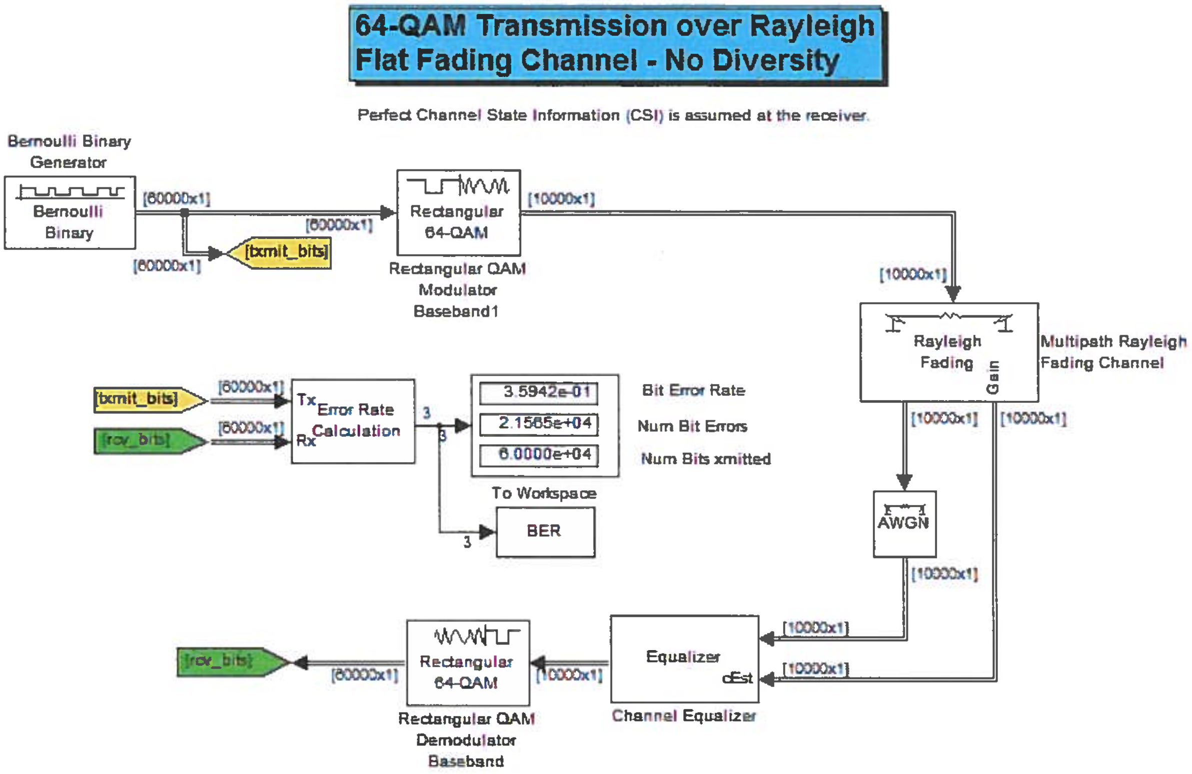


Figure 5.2 Simulink simulation model of 64 QAM transmission over Rayleigh flat fading channel with AWGN

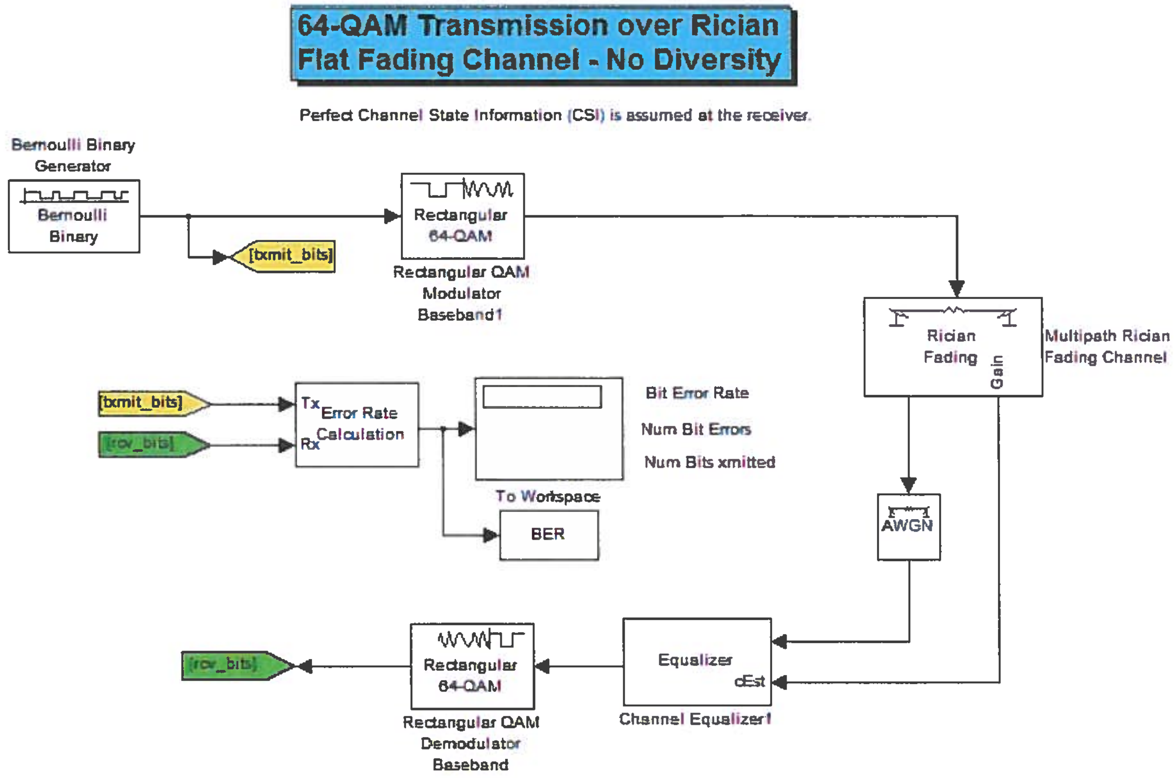
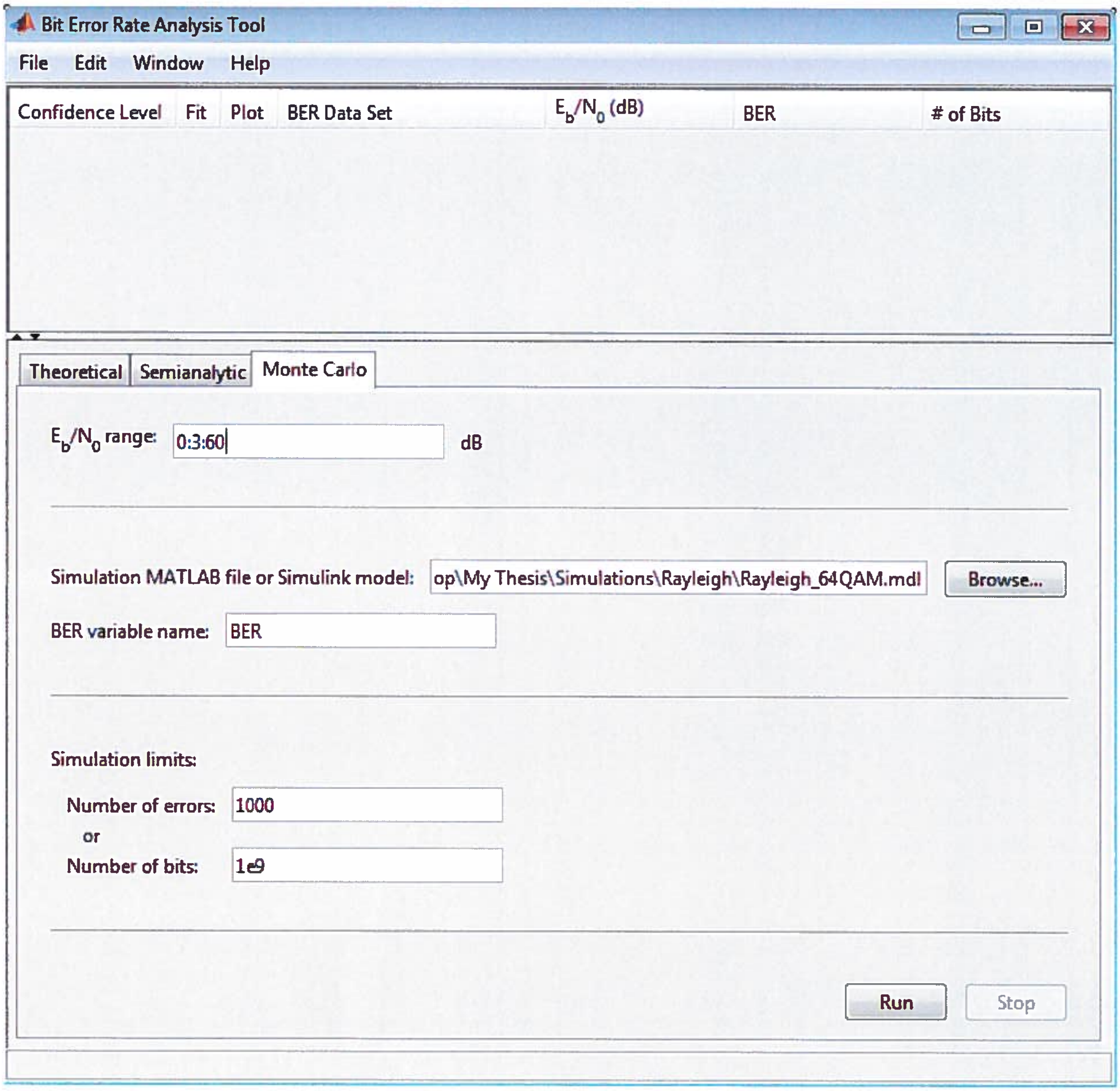


Figure 5.3 Simulink simulation model of 64 QAM transmission over Rician flat fading channel with AWGN

A channel equalizer is implemented to estimate the effects of a given medium over which a received signal is transmitted. In the case of the model the receiver has perfect knowledge of distortions induced by the channel. This allows us to fundamental behavior of QAM over a given channel. The equalizer in the simulated models divides incoming signal by the gain of the channel to retrieve the original message. The equalizer can be seen in Figure 5.1 accepting it inputs from the channel output and channel gain.

5.2 Results

The BER performance plot where generated using the BERTool provided in MATLABs Communications Toolbox. It implements equations 2.2-2.7 to calculate the results of the simulation. Figure 5.4 shows the BERTool parameters for the case of 64 QAM over Rayleigh fading channel. We simulate the model shown in 5.2 for an E_b / N_0 range of 0 to 60 with samples plotted every three steps. The simulations are stopped when 1000 errors are reached or 1e9 bits are processed. For higher orders of QAM the simulation limits are increased to increase the accuracy of the fitted curve.



E_b/N_0 range: 0:3:60 dB

Simulation MATLAB file or Simulink model: op\My Thesis\Simulations\Rayleigh\Rayleigh_64QAM.mdl

BER variable name: BER

Simulation limits:

Number of errors: 1000
or
Number of bits: 1e9

Figure 5.4 MATLAB Communications Toolbox BERTool

Here we analyze results of MATLABs BERTool on the models created with SIMULINK. The results of the BER simulation for even and odd symbol, QAM constellations are shown in Figures 5.5 and 5.6 respectively. Analyzing the plots at a BER of 10^{-4}, it can be seen that for each increase in the number of bit per symbol an additional ~2-3dB of $E_b N_0$ is required to achieve that same performance.

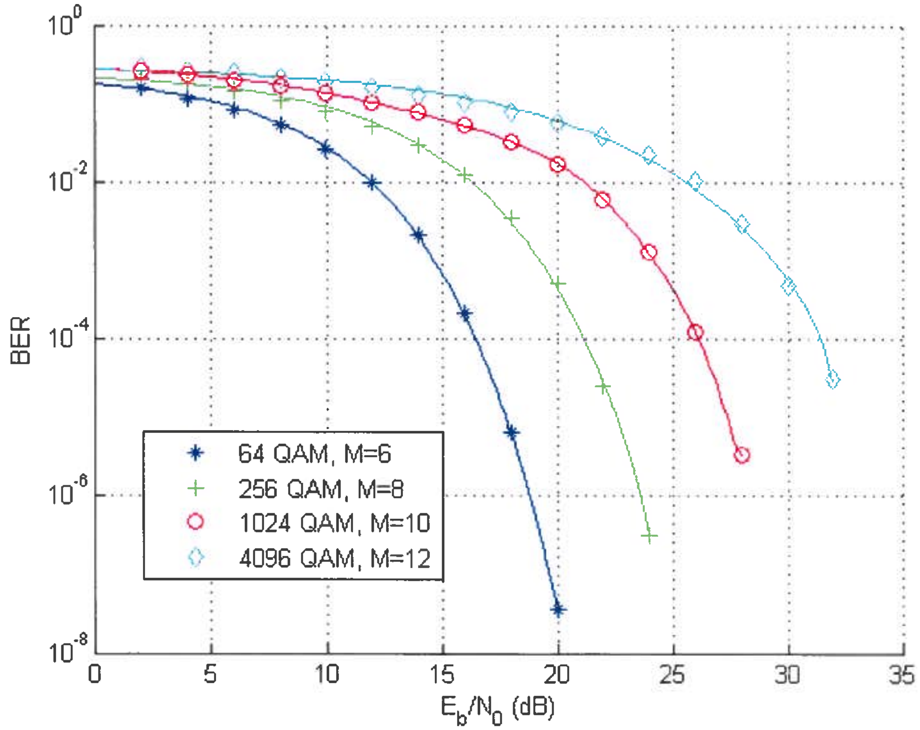


Figure 5.5 Simulated BER performance of even bit symbol constellations in the presence of Additive White Gaussian Noise

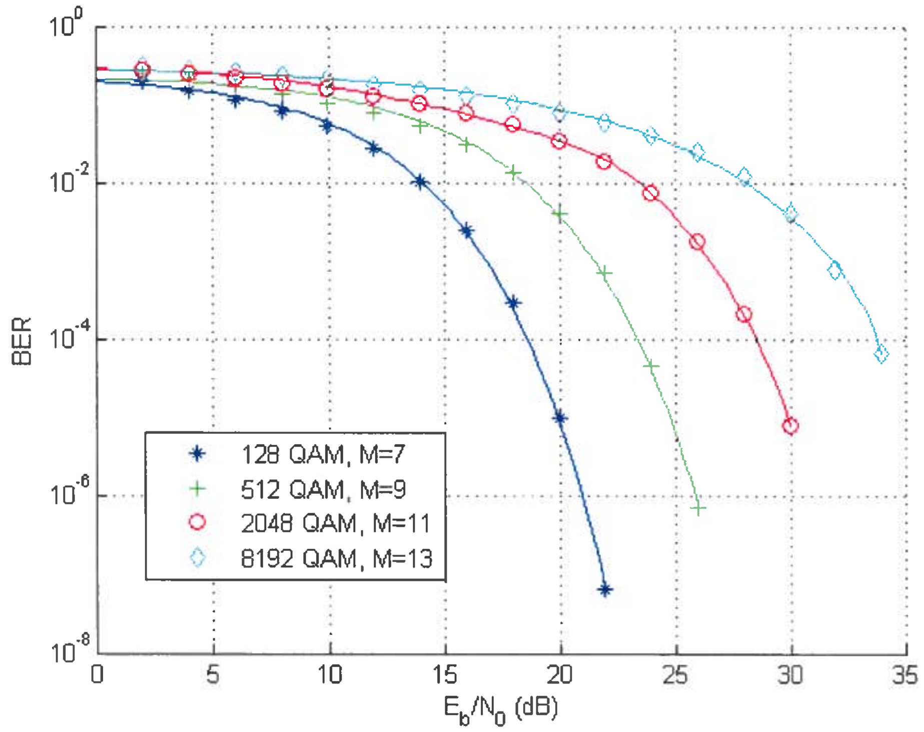


Figure 5.6 Simulated BER performance of odd bit symbol constellations in the presence of Additive White Gaussian Noise

The BER plots of the simulation of QAM over Rayleigh fading channel with AWGN is shown in Figures 5.7 and 5.8. Analyzing the plots it can be seen that to achieve a BER of 10^{-5} requires an additional ~1dB of $E_b N_0$ per increase in the number of bits per symbol to maintain performance. We also the difference in dB is relatively uniform at all values of BER.

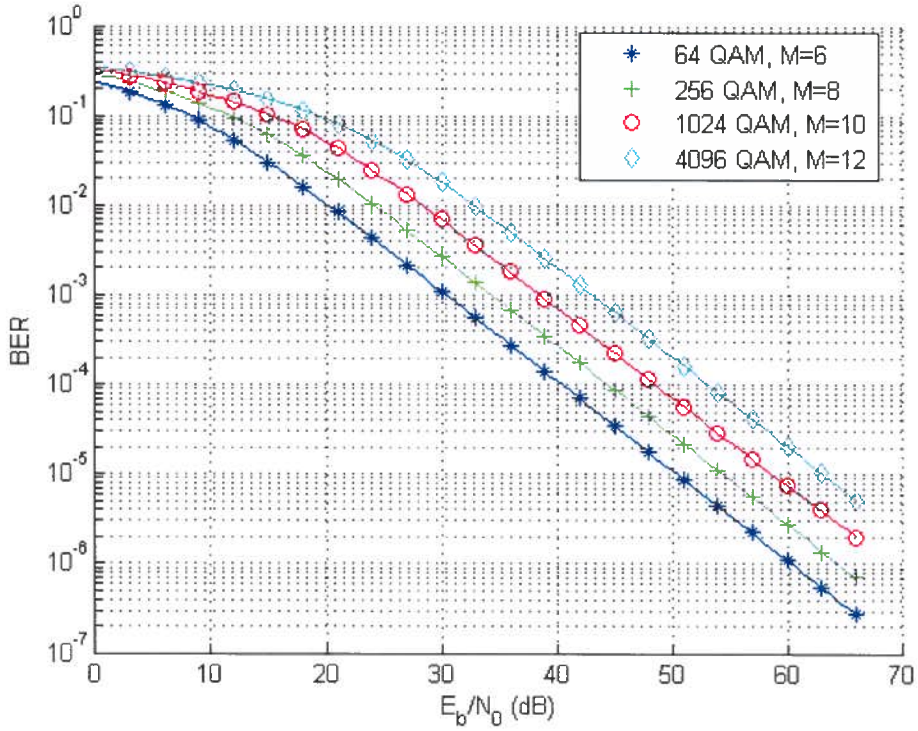


Figure 5.7 Simulated BER performance of even bit constellations in the presence of Rayleigh flat fading channel with additive white Gaussian noise

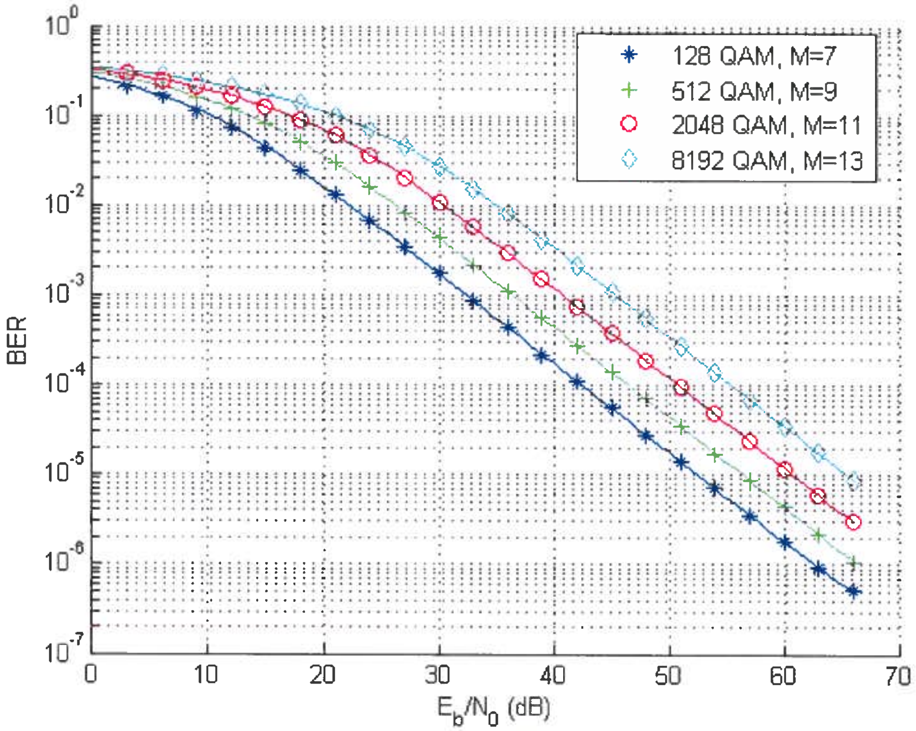


Figure 5.8 Simulated BER performance of odd bit constellations in the presence of Rayleigh flat fading channel with additive white Gaussian noise

The BER plots of the simulation of QAM over Rician fading channel with a K factor of 5 and AWGN is shown in Figures 5.9 and 5.10. Analyzing the plots it can be seen that to achieve a BER of 10^{-5} requires an additional ~1dB of $E_b N_0$ per increase in the number of bits per symbol to maintain performance.

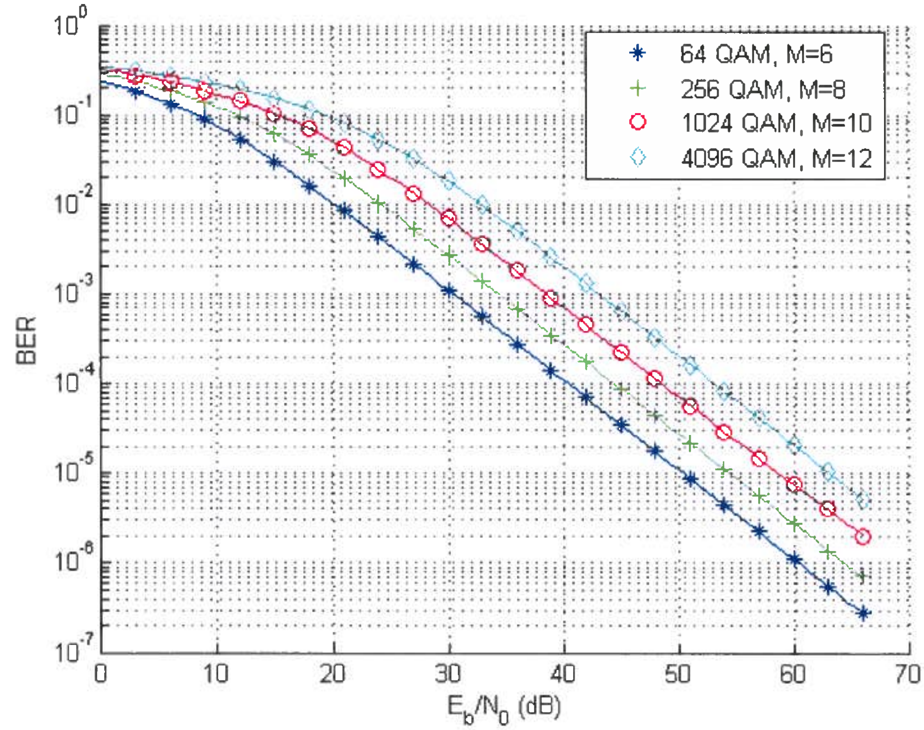


Figure 5.9 Simulated BER performance of even bit constellations in the presence of Rician flat fading channel with additive white Gaussian noise

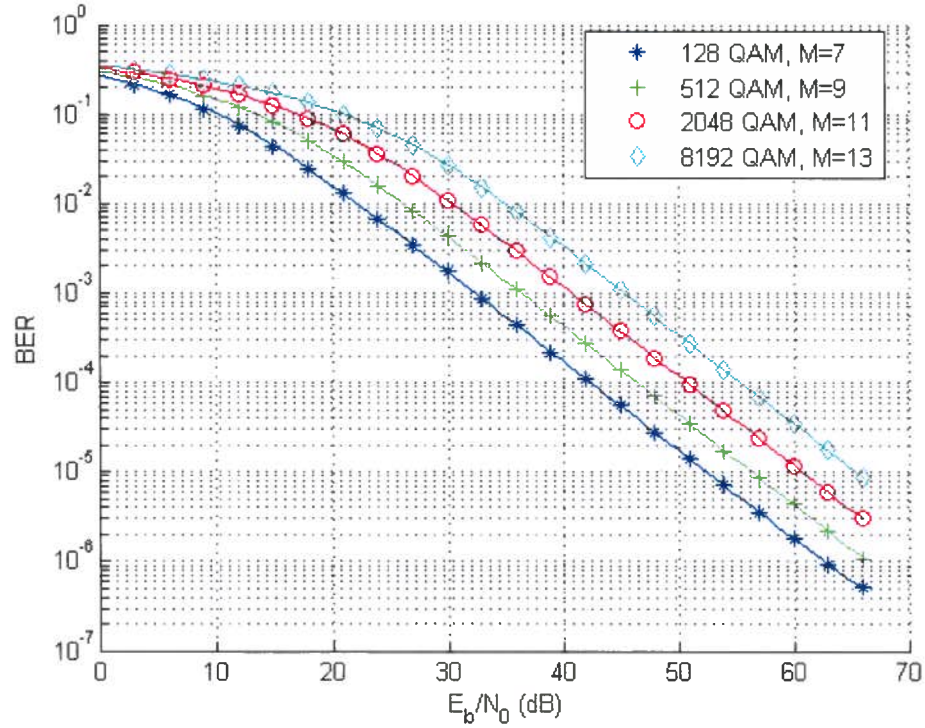


Figure 5.10 Simulated BER performance of odd bit constellations in the presence of Rician flat fading channel with additive white Gaussian noise

CHAPTER 6

Discussion

6.1 Conclusion

In this paper, we have simulated rectangular QAM schemes of the order 64, 128, 256, 512, 1024, 2048, 4096, and 8192 over AWGN, Rayleigh, and Rician channels. We also performed theoretical calculations to obtain maximum throughput. Our results show that the throughput of the system is increased when transmitting more bits per symbol. This increase in throughput comes at the expense of higher BER, which can be mitigated by increasing the energy per bit to noise power spectral density ratio of the system. It is clear that there has to be a compromise between higher throughput, higher BER, and the energy output. Based on our results, it is important to further investigate the implementation of high order QAM in wireless broadband systems. This research will be continued to reinforce the results in this paper.

6.2 Future Work

Our results show that further investigation is needed to determine the practicality implementing high order QAM in wireless broadband systems. In the future we will add empirical models to the simulation. This will allow us to examine the performance of high order QAM in the presence of large-scale path loss. Additionally, we will to incorporate Orthogonal Frequency Division Multiplexing (OFDM), which is being highly adopted by modern broadband communications systems, into the system model to get a better idea of the performance. Also, it may be interesting to investigate the effects more optimal QAM constellations would have in our model.

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