

Comprehensive Performance Evaluation of M-ary QAM in Diverse and Rigorous Scenarios

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ABSTRACT

This paper conducts a comprehensive evaluation of the overall efficacy of M-ary Quadrature Amplitude Modulation (QAM). The assessment entails a detailed scrutiny of the Bit Error Rate (BER) throughout distinct phases, including Binary Coding, Gray Coding, Pulse Shaping employing a Raised Cosine Filter, and the utilization of convolution codes for error correction. Simulation results delineate the BER and Signal-to-Noise Ratio (SNR) characteristics of M-QAM, where M assumes values of 16, 64, 256, and 1024, across oversampling factors ranging from 1 to 5. The study delves into the intricate relationship between BER, SNR, and Spectral Efficiency (SE), underscoring SE as the optimized approach for spectrum utilization, facilitating the transmission of maximum data with minimal errors. As the QAM order escalates, a concomitant increase is observed in both SNR and BER. Furthermore, the investigation extends its purview to encompass diverse fading conditions, including the Gaussian noise channel, Rician fading, and Rayleigh fading. The simulation outcomes consistently reveal an upward trend in BER across all fading scenarios, indicative of a concurrent rise in error occurrences within the communication system.

1. INTRODUCTION

Modulation serves as the foundational underpinning for all essential aspects within the realm of wireless and mobile communication. It represents the technique through which statistical data intended for transmission is imparted onto the radio carrier. In contemporary scenarios, the objectives of modulation are oriented towards the compression of voluminous data into the most conservative spectrum allocation possible. The expeditiousness with which data can be conveyed within an assigned bandwidth is quantifiable through the metric of SE, denoted in bits per second per Hertz (b/s/Hz). Symbols, in their transmission capacity, can realize an augmentation in bits per symbol through the judicious incorporation of amplitude and phase combinations. QAM exemplifies this property, affording efficiency in spectrum utilization. However, it is noteworthy that QAM, while proficient in spectrum optimization, contends with challenges in demodulation under conditions of noise interference. QAM's efficacy is underscored by the incorporation of two orthogonal Pulse Amplitude Modulation (PAM) components, resulting in a nearly twofold enhancement in SE [1].

The establishment of a standardized metric for uniform spectrum performance utilization is obscured by the diverse array of services and user demands that necessitate spectrum allocation. There exist six distinct classes delineating the application domains for various performance metrics, encompassing Satellite broadcast systems, point-to-point satellite systems, terrestrial broadcast systems, terrestrial private communication systems, terrestrial point-to-point systems, and terrestrial hybrid systems [2]. In the contemporary landscape, there is a surge in the traffic of communication systems. Consequently, there arises an imperative for the deployment of higher-order modulation techniques to cater to this escalating demand. However, the conundrum lies in the inefficiency of higher-order modulation techniques in ensuring effective long-distance transmission due to the constraints imposed by the Optical Signal-to-Noise Ratio (OSNR) [3]. A myriad of modulation strategies has been devised, each offering distinct advantages such as elevated data rates, augmented system capacity, heightened visibility, flexible bandwidth operations, improved SE, expedited round-trip times, minimal latency, cost-effectiveness, provision for multi-

antenna configurations, seamless integration with the internet, and compatibility with existing communication systems [4]. The incorporation of orthogonal properties in a communication system emerges as a pivotal facet, furnishing higher data rates, enhanced SE, and power conservation [1].

This paper delineates the performance assessment of 16QAM, 64QAM, 256QAM, and 1024QAM in terms of Bit Error Rate (BER). The implementation of M-QAM is undertaken within the frameworks of binary coding, Gray coding, pulse shaping utilizing a raised cosine filter technique, and error correction through convolution coding. These operations serve as the platforms for demonstrating the BER across diverse oversampling factors. Concurrently, the SNR is subjected to evaluation for 16QAM, 64QAM, 256QAM, and 1024QAM across oversampling factors ranging from 1 to 5. BER is applicable to both Wireline as well as Wireless Communication [5] and is:

$$\text{BER for Wireline communication: } Q\sqrt{SNR} \quad (1)$$

$$\text{BER for wireless communication: } \frac{1}{2SNR} \quad (2)$$

$$\text{Where } Q(x) = \frac{1}{2\pi} \int_x^\infty e^{-\frac{x^2}{2}} dx \quad (3)$$

2. BIT ERROR RATE (BER)

The BER is defined as the ratio of the number of errors to the total number of bits transmitted.

$$BER = \frac{\text{Number of Errors}}{\text{Total number of bits transmitted}} \quad (4)$$

The calculation of the BER for M-QAM can be undertaken by

$$BER = 1 - (1 - P_{bc})^2 \quad (5)$$

$$\text{and } P_{bc} = \frac{4}{k} \left(1 - \frac{1}{\sqrt{M}} \right) Q \left\{ \sqrt{\frac{3k}{M-1}} \cdot \frac{E_b}{N_0} \right\} \quad (6)$$

$$\text{and } k = \log_2 M \quad (7)$$

As the QAM order ascends, enhancements are observed in both bandwidth and power performance. The power efficiencies for 4QAM, 16QAM, 64QAM, 256QAM, 1024QAM, and 4096-QAM are 1, 2, 3, 4, 5, and 6, respectively, signifying a progressive amelioration aligned with the ascending QAM order. Furthermore, the Energy to Noise Power Spectral Density, denoted as E_b/N_0 , for a BER of 10^{-6} manifests as 10.5, 15, 18.5, 24, 28, and 33.5 for M-QAM where M assumes values of 4, 16, 64, 256, 1024, and 4096, respectively. The correspondence between certain BER and SNR can be delineated for each modulation scheme.

$$SNR = 10 \log_{10} \frac{\text{Signal Power}}{\text{Noise Power}} \quad (8)$$

Mathematically SNR can be computed by

$$SNR = \frac{E_b}{N_0} + 10 \log_{10} \left(\frac{\text{Number of Bits per Symbol}}{\text{Over Sampling Factor}} \right) \quad (9)$$

Oversampling involves sampling signals at a rate higher than the Nyquist rate. This practice can enhance resolution, minimize noise, prevent aliasing, and mitigate phase distortion.

The physical layer protocol, through the employment of Forward Error Correction (FEC) coding, proficiently facilitates the accurate transmission of bits. However, the exigency for a heightened bit rate necessitates a proportional increase in coding, thereby incurring a greater overhead. In the pursuit of advancing Bit Error Rate (BER), it is discerned that an efficient modulation scheme supersedes the efficacy of a coding scheme [6]. It is imperative to note that the system cannot seamlessly recover the entire Codeword in instances where the quantity of errors surpasses the error-correcting capacity.

In this particular scenario, the BER is susceptible to degradation, yet the implementation of interleaving procedures serves as a mitigating mechanism for this issue [3]. Various advanced techniques contribute to the amelioration of BER performance across diverse systems. These include the utilization of Inverse Fast Fourier Transform (IFFT) in Orthogonal Frequency Division Multiplexing (OFDM) [7], incorporation of band-edge subcarriers within the Long-Term Evolution (LTE) system, application of modified regularized least sequence channel estimation, integration of bit-level scrambling within Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems [8], antenna selection strategies in MIMO systems [9][10][11], adoption of ordered Subcarrier Multiplexing (SCM) [12], inter-cell interference cancellation in MIMO [13], judicious selection of Intrinsic Mode Function (IMF) [14], deployment of Return to Zero Differential Phase Shift Keying (RZ-DPSK) receivers [15], and an array of additional methodologies. These techniques collectively contribute to the enhancement of system performance in terms of BER.

Given that W represents the bandwidth of the assigned channel, S denotes the area encompassed by the zone cluster (or cell cluster), establishing the frequency reuse unit. The parameters n_a and n_c respectively signify the number of channels within a zone cluster and the traffic per channel. The comprehensive evaluation of spectrum efficiency has been articulated through the incorporation of spatial efficiency (η_s), temporal efficiency (η_t), and band efficiency (η_b) [16] as:

$$\eta_W = \eta_s \cdot \eta_t \cdot \eta_b \quad (10)$$

where
$$\eta_s = \frac{1}{S} \left[\frac{1}{m^2} \right] \quad (11)$$

$$\eta_t = a_c \left[\frac{erl}{channel} \right] \quad (12)$$

$$\eta_b = \frac{n_a}{W} \left[\frac{channel}{Hz} \right] \quad (13)$$

and
$$\eta_W = \frac{n_a a_c}{SW} \left[\frac{erl}{Hz - m^2} \right] \quad (14)$$

$$C_{CA} = N_{s/c} \cdot N_{cs} \cdot A_s \cdot SE \quad (15)$$

Here C_{CA} represents the capacity of mobile handling area, $N_{s/c}$ is the number of sectors per site, N_{cs} signifies the number of cells of in sites, A_s is the amount of spectrum. SE is denoted as a spatial recurrence pattern across the identical channel frequency. Temporal performance is elucidated by the ratio of active time to the number of channels, while band efficiency delineates the relationship between the number of bands and channels.

Small cells present an opportunity to augment mobile spectrum capabilities, albeit at the expense of intricate logistical challenges. Each petite mobile unit necessitates a dedicated physical space entailing installation, power provisioning, and backhaul connectivity to the central network [1]. A repertoire of methodologies, including the Link Adaptation method [17], Fog Radio Access Network (F-RAN) [6], Spectrum Partition Factor Reduction, Radio Frequency (RF) energy harvesting [18], Received Signal Strength (RSS) threshold adjustment [19], Direct Device-to-Device (D2D) discovery [20], Soft Reservation Mechanism [21], and numerous others, has been

employed to enhance SE. Given that the BER is intricately tied to SE improvements, this paper is poised to delineate a comprehensive performance assessment of BER under various scenarios and parameters.

3. M-ary QUADRATURE AMPLITUDE MODULATION (M-QAM)

M-ary QAM is a modulation scheme widely employed in digital communication systems to transmit digital data efficiently over radio frequency channels [22]. The key idea behind M-QAM is to maximize the information throughput by encoding multiple bits per symbol. Common M-QAM variants include 16-QAM, 64-QAM, 256-QAM, and 1024-QAM, where the number corresponds to the total signal states available. As the order of M-QAM increases, the modulation becomes more complex, enabling higher data transmission rates but also making the system more susceptible to noise and interference.

The trade-off lies in balancing the increased data rate with the challenges posed by higher-order modulation, such as increased susceptibility to errors and a higher SNR requirement for reliable communication. Achieving superior SNRs is imperative for overcoming interference. This interference can arise from reduced inter-symbol spacing within the constellation, a consequence of the escalation in the order of QAM.

In M-ary QAM, the transmitted signal is denoted by

$$s_i = a_i \sqrt{\frac{2}{T_s}} \cos \omega_c t + b_i \sqrt{\frac{2}{T_s}} \sin \omega_c t \quad (16)$$

here $a_i \sqrt{\frac{2}{T_s}} \cos \omega_c t$ and $b_i \sqrt{\frac{2}{T_s}} \sin \omega_c t$ are the basis functions for two dimensional space $\phi_1(t)$ and $\phi_2(t)$.

$$a_i = \pm \frac{d}{2}, \pm \frac{3d}{2}, \dots, \pm \frac{(\sqrt{M}-1)d}{2} \quad (17)$$

$$b_i = \pm \frac{d}{2}, \pm \frac{3d}{2}, \dots, \pm \frac{(\sqrt{M}-1)d}{2} \quad (18)$$

The conditional BER of M-QAM is

$$P_b(k) = \frac{1}{\sqrt{M}} \sum_{j=0}^{(1-2^{-k})\sqrt{M}-1} (-1)^{\left\lceil \frac{j \cdot 2^{k-1}}{\sqrt{M}} \right\rceil} \left(2^{k-1} - \left\lfloor \frac{j \cdot 2^{k-1}}{\sqrt{M}} \right\rfloor - 1 \right) \cdot \text{erfc} \left((2 \cdot j + 1) \sqrt{\frac{3(\log_2 M)r}{2(M-1)}} \right) \quad (19)$$

$$P_b(k) \text{ can be extended by } j = 0, 1, 2, \dots, \left\{ (1-2^{-k})\sqrt{M} - 1 \right\}$$

where $\left\{ (1-2^{-k})\sqrt{M} - 1 \right\}$ denotes the actual number of terms per conditional probability, where the floor function $\lfloor x \rfloor$ represents the largest integer not exceeding x . Now, considering the BER for M-QAM, where M is the square number and $M = 2^N$ is

$$P_b = \frac{1}{\log_2 \sqrt{M}} \sum_{k=1}^{\log_2 \sqrt{M}} P_b(k) \quad (20)$$

For extended distances, lower modulation orders become necessary, exemplified by Binary Phase Shift Keying (BPSK). Conversely, for shorter distances, the adoption of higher-order modulation, such as M-QAM, proves beneficial in achieving enhanced throughput. Thus D2D communication capabilities can effectively implement M-QAM.

A comparison between 256-QAM and 64-QAM reveals that 256-QAM provides a 33% increase in effective bandwidth efficiency. However, it is essential to note that 256-QAM exhibits superior SNR, heightened sensitivity, and improved resilience against factors like phase noise and interference.

BER formulations for digital systems in relation to SNR can also be articulated as

$$P_e(64QAM) = \frac{7}{12} Q\left(\frac{SNR}{21}\right)^{1/2} \quad (21)$$

$$P_e(256QAM) = \frac{5}{32} Q\left(\frac{SNR}{85}\right)^{1/2} \quad (22)$$

$$P_e(1024QAM) = \frac{31}{160} Q\left(\frac{SNR}{341}\right)^{1/2} \quad (23)$$

The signal power is correlated with the energy within a single symbol as

$$E_s = P_s T_s \quad \text{and} \quad E_b = \frac{E_s}{\log_2 M}$$

$$\text{So} \quad P_e(64QAM) = \frac{7}{12} Q\left(\frac{2E_b}{7N_0}\right)^{1/2} \quad (24)$$

$$P_e(256QAM) = \frac{15}{32} Q\left(\frac{8E_b}{85N_0}\right)^{1/2} \quad (25)$$

$$P_e(1024QAM) = \frac{31}{160} Q\left(\frac{10E_b}{341N_0}\right)^{1/2} \quad (26)$$

N_0 represents the power density of noise, and $Q(\cdot)$ is the frequently tabulated function associated with the solution to the integral beneath the upper tail of the Gaussian Probability Density Function (PDF), reflecting the statistical nature of Additive White Gaussian Noise (AWGN) [23].

When the symbol rate is denoted as f_s for a QAM system, the approximated radio frequency (RF) bandwidth can be expressed as $f_s(1+\alpha)$, where α denotes the roll-off factor of the filter [24]. The utilization of a raised cosine filter contributes to the mitigation of Inter-Symbol Interference (ISI) while concurrently determining the additional bandwidth extending beyond the Nyquist bandwidth, denoted by the Roll-Off factor [24]. Consequently, the raised cosine filtering process was implemented for the assessment of BER in conjunction with QAM. With an escalation in the order of QAM, there is a proportional increase in the number of bits contained within a symbol, leading to enhanced system performance.

4. RESULTS AND DISCUSSIONS

4.1 Implementation of M-ary QAM on Various Operations

The simulation employs processes including Pulse Shaping using a Raised Cosine filter, Gray Coding, Binary Coding, and Error Correction using Convolution Code. Modulation schemes, namely 16-QAM, 64-QAM, 256-QAM, and 1024-QAM, are implemented on a dataset comprising 900,000 bits, considering sampling factors of 1, 2, 3, 4, and 5. White Gaussian Noise is introduced as an additional component to the channel. The ratio of bit energy to noise power density (E_b/N_0) is held constant at 10 dB, accompanied by Binary Coding Phase offset and Gray Coding Phase offset set at zero. The filter span within the Filter is designated as 10.

The Binary Coding

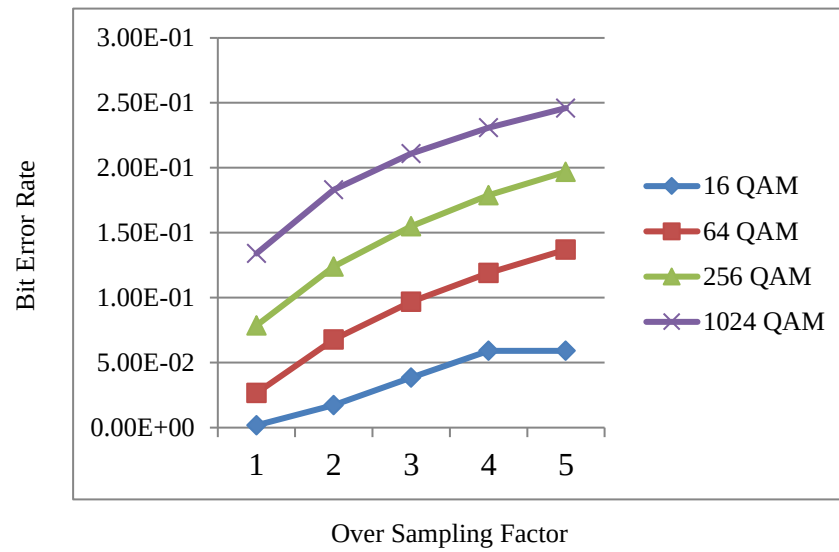


Figure 1: BER of M-QAM with binary coding under different oversampling factors

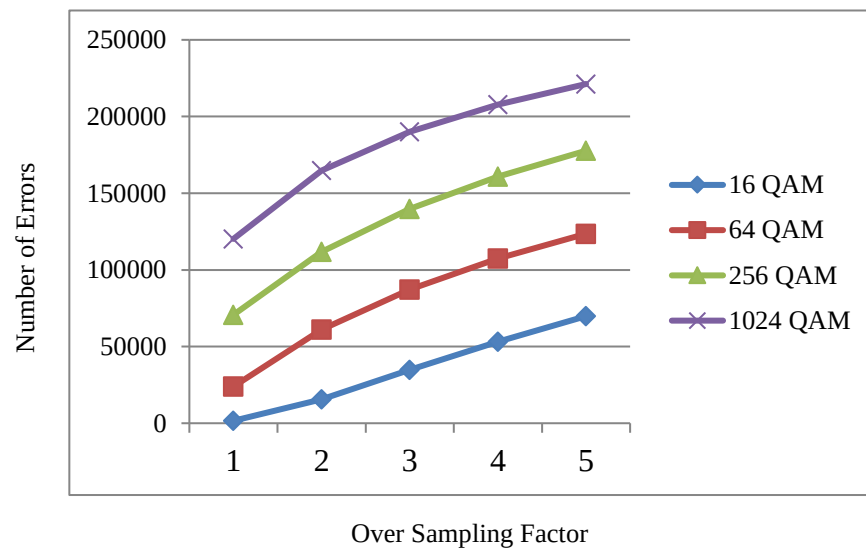


Figure 2: Number of Errors of M-QAM with binary coding under different oversampling factors

Table 1 BER and Number of Errors of M-QAM with binary coding under different oversampling factors

Over Sampling Factor	16 QAM		64 QAM		256 QAM		1024 QAM	
	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors
1	1.79e-03	1613	2.66e-02	23935	7.86e-02	70700	1.34e-01	120212
2	1.73e-02	15529	6.79e-02	61092	1.24e-01	111701	1.83e-01	164739
3	3.86e-02	34750	9.70e-02	87266	1.55e-01	139775	2.11e-01	189984
4	5.91e-02	53179	1.19e-01	107361	1.79e-01	160761	2.31e-01	207819
5	7.76e-02	69821	1.37e-01	123569	1.97e-01	177720	2.46e-01	221197

Digital data, representing a compilation of binary bits known as binary code, is encoded, stored, and transmitted in this form. The simulation results pertaining to binary coding are delineated in both Table 1 and Figure 1 and Figure 2. Notably, the BER exhibits an escalation with the rise in oversampling factor values for M-QAM. Consequently, it follows that the system's performance undergoes a decrement as both the oversampling factor and the order of QAM experience an increase.

The Gray Coding

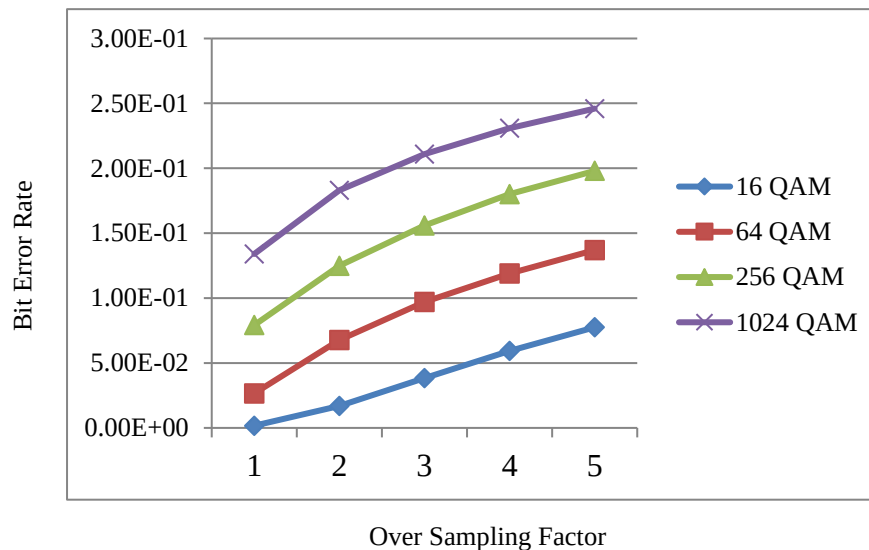


Figure 3: BER of M-QAM with Gray coding under different oversampling factors

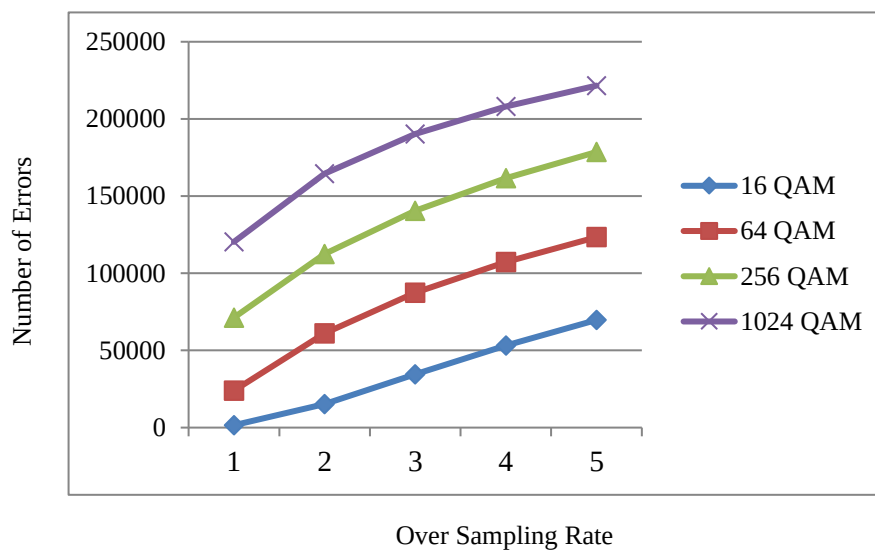


Figure 4: Number of Errors of M-QAM with Gray coding under different oversampling factors

The Gray code alternatively recognized as a reflected code or binary reflected Gray code manifests an enhanced BER performance within M-QAM in comparison to binary coding. It constitutes an encoding scheme wherein consecutive numbers differ by a single digit. Table 2 and Figure 3 and Figure 4 succinctly illustrate the BER of M-ary QAM with Gray coding under diverse oversampling factors.

Table 2 BER and No. of Errors of M-QAM with Gray coding under different oversampling factors

Over Sampling Factor	16 QAM		64 QAM		256 QAM		1024 QAM	
	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors
1	1.70E-03	1534	2.66E-02	23962	7.92E-02	71273	1.34E-01	120339
2	1.70E-02	15339	6.78E-02	61006	1.25E-01	112565	1.83E-01	164619
3	3.84E-02	34552	9.71E-02	87417	1.56E-01	140382	2.11E-01	190317
4	5.92E-02	53240	1.19E-01	107230	1.80E-01	161630	2.31E-01	208082
5	7.75E-02	69736	1.37E-01	123403	1.98E-01	178579	2.46E-01	221598

Pulse Shaping Using Raised Cosine Filter

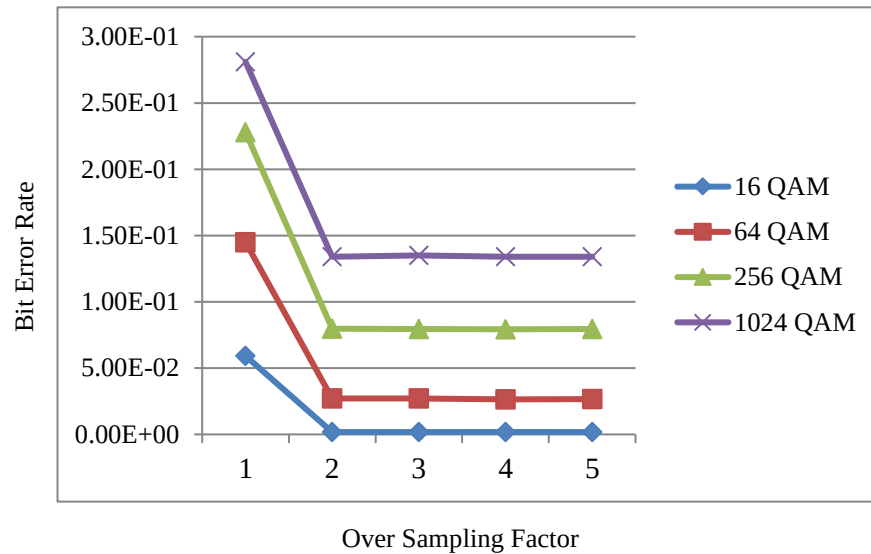


Figure 5: BER of M-QAM on the Pulse shaping using raised cosine filter for various over sampling factors

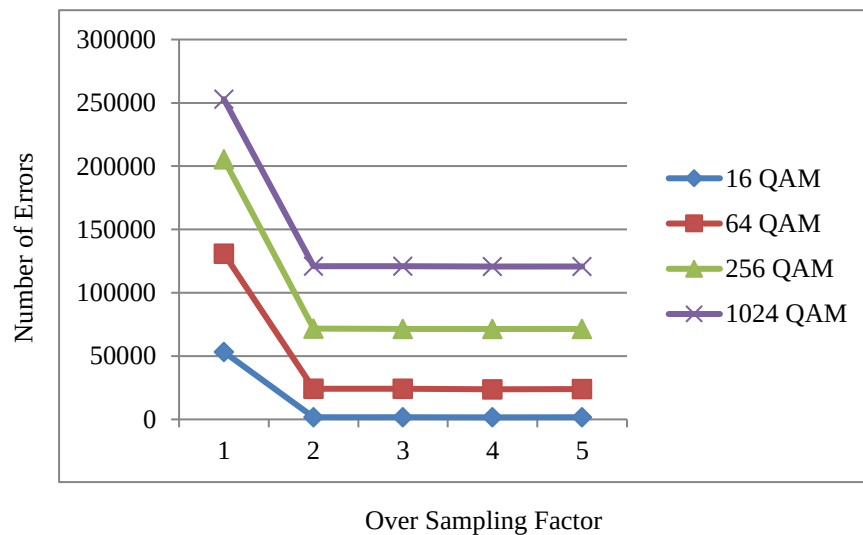


Figure 6: No. of errors of M-QAM on the Pulse shaping using raised cosine filter for various over sampling factors

Table 3 BER and No. of errors of M-QAM on the Pulse Shaping using Raised Cosine Filter for various over sampling factors

Over Sampling Factor	16 QAM		64 QAM		256 QAM		1024 QAM	
	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors
1	5.92E-02	53298	1.45E-01	130926	2.28E-01	205346	2.81E-01	252916
2	1.80E-03	1617	2.70E-02	24303	7.96E-02	71609	1.34E-01	120987
3	1.79E-03	1608	2.70E-02	24303	7.95E-02	71558	1.35E-01	121064
4	1.77E-03	1590	2.64E-02	23778	7.93E-02	71385	1.34E-01	120820
5	1.81E-03	1632	2.67E-02	24056	7.94E-02	71446	1.34E-01	120769

The application of the raised cosine filter involves a pulse shaping technique aimed at minimizing Inter-Symbol Interference (ISI). In the simulation, a pair of square-root raised cosine filters are employed to execute both pulse shaping and matched filtering. The BER exhibits enhancement as the oversampling factor ascends from 1 to 2. Remarkably, oversampling factors 3, 4, and 5 yield a constant BER for each M-QAM. Additionally, the simulation results (Table 3, Figure 5 and Figure 6) illustrate amelioration in BER as the order of QAM increases. However, a noteworthy observation emerges that there is degradation in the performance of the system, incorporating pulse shaping via the raised cosine filter, upon the implementation of higher-order QAM and an increased value of the oversampling factor.

Error Correction Using Convolution Code

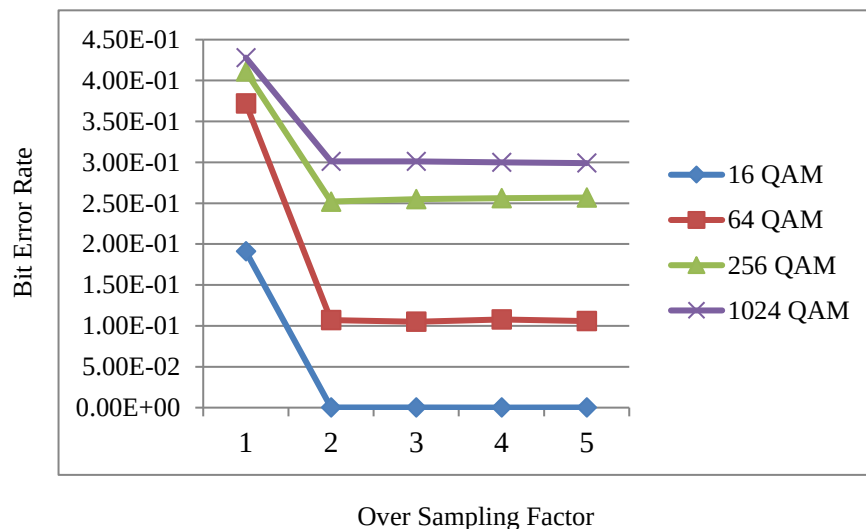


Figure 7: BER of M-QAM on the Error Correction Using Convolution Code for Various Oversampling Factor

Table 4 BER of M-QAM on the Error Correction using Convolution Code for various Oversampling Factors

Over Sampling Factor	16 QAM		64 QAM		256 QAM		1024 QAM	
	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors	BER	No. of Errors
1	1.91E-01	172323	3.72E-01	334823	4.11E-01	370061	4.28E-01	384071
2	1.04E-04	94	1.07E-01	95905	2.52E-01	226641	3.01E-01	269852
3	1.01E-04	91	1.05E-01	94721	2.55E-01	229142	3.01E-01	270093
4	8.89E-05	80	1.08E-01	97006	2.56E-01	230590	3.00E-01	269777
5	1.14E-04	103	1.06E-01	95368	2.57E-01	230849	2.99E-01	268758

Within convolutional coding, the n digit code block extends its reliance beyond solely k digits of distinct messages within the current unit, incorporating information digits from preceding spans as well. This coding strategy is instrumental in rectifying both random errors and burst errors. The integration of Forward Error Correction (FEC) through convolutional coding facilitates error correction, subsequently enhancing the BER performance. Simulation outcomes, as portrayed in Figure 7 and Figure 8 and Table 4, demonstrate a consistent BER across oversampling factors 2, 3, 4, and 5 for 16QAM, 64QAM, 256QAM, and 1024QAM.

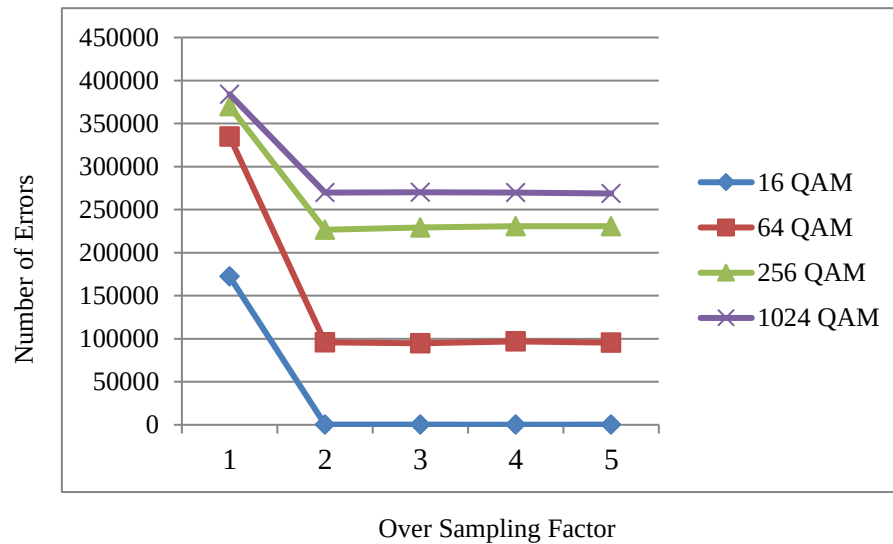


Figure 8: No. of Errors of M-QAM on the Error correction using convolution codes for various oversampling factors

4.2 SNR for M-ary QAM across Different Oversampling Factors

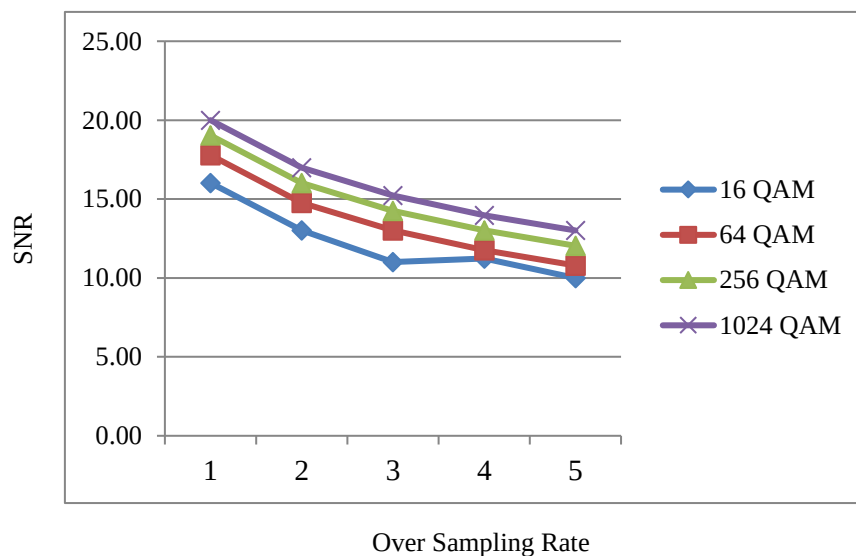


Figure 9: M-QAM SNR with Different Oversampling Factors

The SNR is contingent upon both the order of QAM and the oversampling factor. As the order of QAM escalates, there is a concomitant increase in SNR. The utilization of higher-order QAM in the communication system allows for the transmission of a greater number of bits. Conversely, an elevation in the oversampling factor results in a reduction in the SNR value for a given E_b/N_0 . The simulation outcomes reveal optimal performance for 1024QAM at an oversampling factor of 1.

As the order of QAM experiences an escalation, a comprehensive evaluation of the overall throughput in terms of BER is conducted. This assessment is undertaken within specified processes and diverse fading scenarios, including Pulse Shaping utilizing a Raised Cosine Filter, Gray Coding, Binary Coding, and Error Correction utilizing Convolution code. The observed improvement in BER indicates a corresponding increase in the number of errors, as elucidated in the simulation results for M-QAM across various oversampling factors within the Binary Coding and Gray Coding operations, alluding to predetermined parameters.

Furthermore, the simulation outcomes for Error Correction and Pulse Shaping are delineated for the same set of parameters. The results exhibit a discernible trend wherein the number of errors grows with the augmentation of the QAM order, while a reduction in the number of errors is observed with an increase in the oversampling factor. Interestingly, the BER maintains constancy across 16QAM, 64QAM, 256QAM, and 1024QAM for oversampling factors 2, 3, 4, and 5. This stability in BER contrasts with the increment in the oversampling factor, which concurrently leads to a reduction in the SNR for a given E_b/N_0 .

Table 5 SNR of M-QAM for different over sampling factors

OSF	16 QAM	64 QAM	256 QAM	1024 QAM
1	16.02	17.78	19.03	20.00
2	13.01	14.77	16.02	17.00
3	11.01	13.01	14.26	15.22
4	11.24	11.76	13.01	13.98
5	10.00	10.79	12.04	13.01

Post-simulation, an augmentation in the Signal-to-Noise Ratio (SNR) is observed with the escalation of the QAM order across all oversampling factor values (Figure 9 and Table.5). Consequently, in the realm of communication, the adoption of higher-order QAM enables the transmission of a larger bit payload. However, it is imperative to acknowledge that this advantage comes at the cost of an increased BER, attributable to the rise in the number of errors incurred during transmission.

4.3 Implementing M-QAM in Varied Fading and Noisy Environments

Various stochastic and fading models have been employed, encompassing Gaussian Noise, Rician Fading, and Rayleigh Fading. Within this simulation framework, the SNR per bit (E_b/N_0) assumes values of 0, 5, 10, 15, 20, 25, and 30, while the QAM order spans 16, 64, 256, 512, and 1024. Notably, for the Rayleigh fading condition, a diversity order of 1 is adopted. Conversely, in the Rician fading scenarios, the K factor is set to zero, with a concurrent diversity order of 1. Specifically, under the Gaussian noise channel, the BER experiences an increase, ascending from 0.1409 to 0.2909 when E_b/N_0 is set to zero.

Additive Gaussian Noise

The scrutiny of numerous stochastic phenomena occurring in nature finds applicability in the Additive Gaussian noise model. This model entails the linear combination of wideband or white noise, characterized by a constant spectral density and adhering to a Gaussian distribution of amplitude. It is imperative to note, however, that this prototype lacks suitability for the analysis of phenomena such as fading, frequency discernment, interference, nonlinearity, or scattering. The term "Additive Gaussian noise channels" is also recognized as "AWGN" (Additive White Gaussian Noise).

Rayleigh Fading

The PDF of Rayleigh fading is

$$P(r) = \begin{cases} \frac{t}{\sigma^2} \exp\left(\frac{-r^2}{2\sigma^2}\right); & \text{when } (0 \leq r \leq \infty) \\ 0; & \text{when } (r < 0) \end{cases}$$

Here σ denotes the RMS magnitude of the signal acquired antecedent to envelope recognition, while σ^2 represents the temporal mean power of the signal acquired prior to envelope recognition. The Cumulative Distribution Function (CDF) serves as a tool for assessing the probability associated with the received signal. Within the realm of the multipath fading channel, the unpredictable alterations in delays across distinct signal paths necessitate a statistical characterization. This form of delay is exclusively amenable to statistical representation. The modeling of the impulse response is executed in the guise of a zero-mean complex-valued Gaussian process, thereby endowing the channel with the attributes of a Rayleigh fading channel [15][16][28].

Rician fading conditions

The transmission of signals along varied trajectories is accompanied by inherent fractional cancellation effects within the domain of radio signal propagation. This gives rise to a consequential occurrence known as multipath interference, where differences in signal strength among distinct paths result in modifications to path characteristics, potentially causing either shortening or lengthening. This intricate scenario culminates in the manifestation of Rician fading, a phenomenon marked by variations in signal strength due to the interplay between a dominant line-of-sight signal and scattered signals. The amplitude gain intrinsic to Rician fading finds precise delineation through the utilization of the Rician distribution.

Table 6 BER analysis for M-QAM under a Gaussian Noise Channel

E_b / N_0 (dB)	Bit Error Rate (BER)				
	16 QAM	64 QAM	256 QAM	512 QAM	1024 QAM
0	1.41E-01	2.00E-01	2.55E-01	2.90E-01	2.91E-01
5	4.20E-02	1.01E-01	1.59E-01	2.06E-01	2.13E-01
10	2.00E-03	2.70E-02	7.90E-02	1.20E-01	1.33E-01
15	1.84E-07	7.72E-05	2.00E-02	5.30E-02	6.60E-02
20	1.40E-19	2.63E-08	5.05E-04	8.00E-03	1.70E-02
25	2.17E-57	5.81E-22	1.14E-08	5.43E-08	4.50E-08
30	2.02E-18	1.24E-64	6.96E-23	1.69E-11	1.18E-08

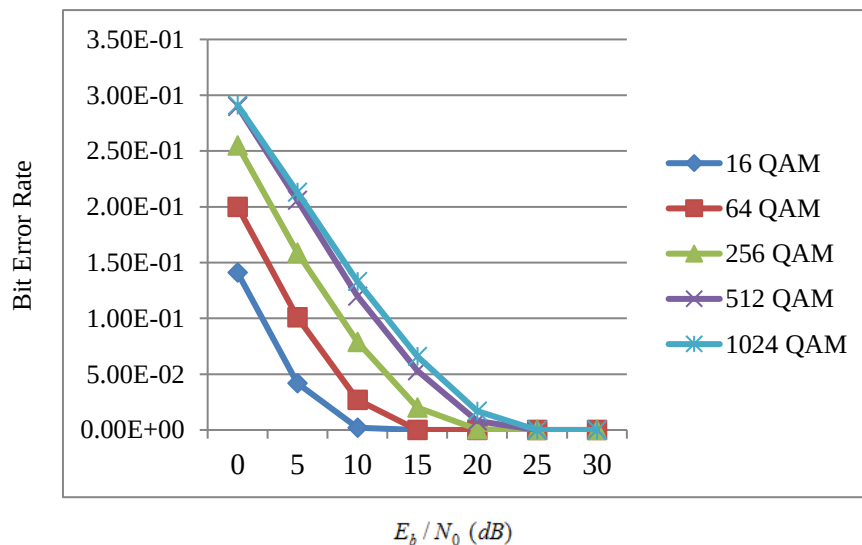


Figure 10: BER analysis for M-QAM within a Gaussian Noise Channel

Table 7 BER assessment for an M-QAM system operating in the presence of Rayleigh fading conditions

E_b / N_0 (dB)	Bit Error Rate (BER)				
	16 QAM	64 QAM	256 QAM	512 QAM	1024 QAM
0	1.68E-01	2.47E-01	2.89E-01	3.18E-01	3.20E-01
5	1.03E-01	1.54E-01	2.05E-01	2.42E-01	2.49E-01
10	4.23E-02	7.66E-02	1.24E-01	1.64E-01	1.74E-01
15	1.48E-02	3.06E-02	6.09E-02	9.32E-02	1.05E-01
20	4.80E-03	1.06E-02	2.41E-02	4.25E-02	5.14E-02
25	1.50E-03	3.40E-03	8.30E-03	1.59E-02	2.03E-02
30	4.96E-04	1.10E-03	2.70E-03	5.30E-03	7.00E-03

Table 8 BER assessment for an M-QAM system operating in the presence of Rician fading conditions

E_b / N_0 (dB)	Bit Error Rate (BER)				
	16 QAM	64 QAM	256 QAM	512 QAM	1024 QAM
0	1.68E-01	2.47E-01	2.89E-01	3.18E-01	3.20E-01
5	1.03E-01	1.54E-01	2.05E-01	2.42E-01	2.49E-01
10	4.23E-02	7.66E-02	1.24E-01	1.64E-01	1.74E-01
15	1.48E-02	3.06E-02	6.09E-02	9.32E-02	1.05E-01
20	4.80E-03	1.06E-02	2.41E-02	4.25E-02	5.14E-02
25	1.50E-03	3.40E-03	8.30E-03	1.59E-02	2.03E-02
30	4.96E-04	1.10E-03	2.70E-03	5.30E-03	7.00E-03

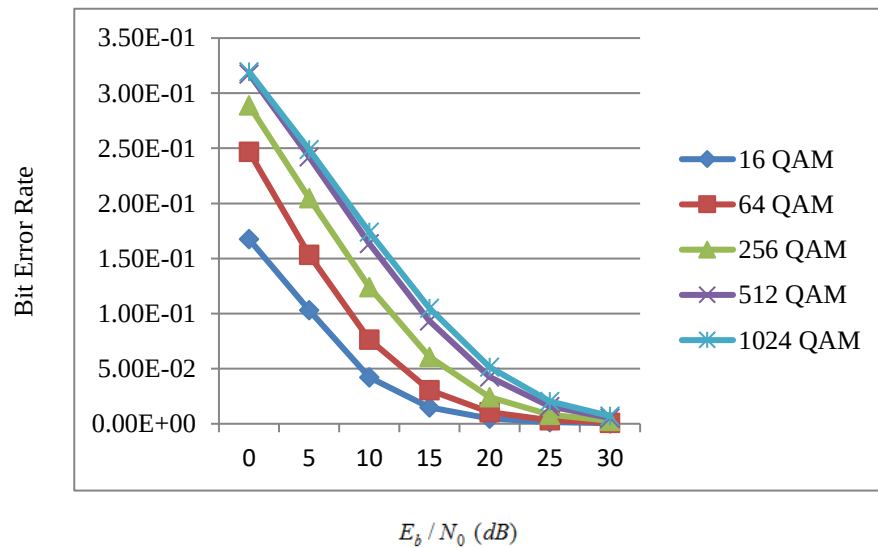


Figure 11: BER analysis for a QAM system in the presence of both Rayleigh and Rician fading conditions

Figure 10 and Figure 11 visually present all outcomes for the Gaussian noise channel, Flat Rayleigh Fading conditions, and Rician Fading conditions. Corresponding numerical values are detailed in Table 6, Table 7 and Table 8. It is noteworthy that the BER for QAM remains identical under both Rayleigh and Rician fading conditions.

5. CONCLUSION

In this paper, the focus is on the fundamental aspects of BER for M-ary QAM. The implementation of M-ary QAM encompasses various operations, including binary coding, Gray coding, the application of pulse shaping with a raised cosine filter, and error correction using convolution code. These operations exert an influence on BER corresponding to the increasing order of QAM. The magnitude of errors expands with the modulation order, and BER increases with an elevated oversampling factor for both Binary and Gray coding. The processes involving pulse shaping with a raised cosine filter and error correction using convolution code serve to mitigate BER as the oversampling factor increases for each QAM order. However, as the order of modulation increases for each operation, BER tends to ascend. This section further clarifies the diminishing Signal-to-Noise Ratio (SNR) with an upsurge in the oversampling factor for each QAM order. This segment within the paper establishes a comprehensive performance evaluation of M-ary QAM under various challenging conditions, including additive Gaussian noise, Rayleigh fading, and Rician fading. Here, BER diminishes as the E_b/N_0 (energy per bit to noise power spectral density ratio) increases, while BER escalates with the enhancement of the QAM order.

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