Performance Assessment and Computer Simulation of the M-ary QAM Modulation Scheme

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Abstract

The most important issue in digital communication system is to receive data as similar as the data sent from the transmitter with a high speed using less channel bandwidth. This means that it is important to test the systems in terms of probability of error to view the system's performance. Each modulation technique has different performance while dealing with signals, which normally are affected with noise. One of digital modulation scheme is used is known as an M-ary Quadrature Amplitude Modulation (M-ary QAM) .In this paper performances investigation and computer simulation of M –ary QAM has been carried out for different number of levels symbols using powerful scientific software known as a Matlab with Simulink V. 2018. When increasing the number of levels, the simulated result, show that the bit error rate (BER) decrease but generally M-ary QAM is more bandwidth efficient than other M- ary modulation systems types.

Keywords:

QAM; BER; BW; Matlab and Modulation

I. INTRODUCTION

Digital modulation offers many advantages over analog modulation and greatly improves the performance of the communication systems. Many types of digital modulation schemes are possible, and the choice of which one to use depends on spectral efficiency, power efficiency, and bit error rate performance[1]. There are three main types of digital modulation schemes such as a Binary Amplitude Shift Keying (ASK), , Phase Shift Keying (PSK) and Frequency Shift Keying (FSK) as well as an M-ary QAM, M-ary FSK and M-ary PSK . In this work the QAM modulation scheme will be carried out . That scheme of modulation is one of most efficient digital data transmission systems as it achieves better bandwidth efficiency than other modulation techniques and give higher data rate. In an M-ary signaling scheme, we may send one of M possible signals $s_1(t), s_2(t) \ldots s_m(t)$, during each signaling interval of duration T_s. For almost all applications, the number of possible signals:[1,2].

$$M = 2^n \qquad (1)$$

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where n is an integer. The symbol duration T_s= n T_b, where T_b is the bit duration. In pass-band data transmission these signals are generated by changing the amplitude as in M-ary QAM. [1,2].

This research provides a thorough performance analysis of the M-ary Quadrature Amplitude Modulation (QAM) scheme, focusing on the relationship between modulation levels (M), spectral efficiency, and Bit Error Rate (BER)[11111]. The authors contribute a robust simulation framework developed in MATLAB and Simulink, which outlines a clear methodology for signal generation and performance testing within an AWGN channel[222222222]. A key highlight of the study is the comparative evaluation of theoretical and simulated error probabilities for 256-QAM.

The structure of this paper is organized as follows: Section I introduces digital modulation and its role in improving communication system performance; Section II describes the fundamentals of M-ary QAM as a combination of amplitude and phase shift keying; Section III details essential system parameters, including bandwidth, bit rate, and bandwidth efficiency; Section IV illustrates the generation and detection of signals through modulator and demodulator block diagrams; Section V outlines the methodology for the MATLAB simulation, covering the initialization and generation of constellation points; Section VI presents the theoretical performance evaluation for QAM levels ranging from 4 to 256; Section VII describes the Simulink-based simulation model, specifically focusing on the AWGN channel and error rate calculation blocks; Section VIII provides a comparative analysis between the theoretical and simulated results for 256-QAM ; and finally, Section IX summarizes the main conclusions and provides recommendations for future work, such as the use of adaptive modulation and error control coding.

II. M-ARY QUADRATURE AMPLITUDE MODULATION

Quadrature Amplitude Modulation (QAM) is combination of two digital modulation schemes which is known as amplitude shift keying (ASK) and phase shift keying(PSK) . More technically, quadrature amplitude modulation is a system of modulation in which data is transferred by modulating the amplitude of two separate carrier waves, mostly sinusoidal, which are out of phase by 90˚ degrees (sine and cosine). Due to their phase difference, they are called quadrature carriers. In quadrature amplitude modulation, a signal obtained by summing the amplitude and phase modulation of a carrier signal (a modulated sine and cosine wave or quadrature waves) is used for the data transfer. As the number of transfer points remains high, it is possible to convey more bits per every position change.[3,4].

In a constellation diagram, constellation points are arranged in a square grid with equal horizontal and vertical spacing (other configurations are possible as well). In digital communication, as data is binary, it follows that the number of points in the grid usually will be a function of the power of 2 (2, 4, 8, etc). [5-8].

The Mathematical Representation of M-ary Quadrature Amplitude Modulation is given by

$$S_i(t) = \sqrt{\frac{2E_0}{T}}\, a_i \cos(2\pi f_c t) \quad i = 0,1, \dots \dots M-1. \quad (2)$$

III. PARAMETERS OF M-ARY QAM

There are several parameters of M-ary digital QAM , which will be describe some of them briefly in the following points. [1, 5,6].

A. Bandwidth (BW)

In general the bandwidth defines the frequency band needed to transmit the data signal over the channel, but it is also the frequency band occupied by the baseband binary signal to be transmitted. In general, the bandwidth is a frequency band that is occupied by the signal. The bandwidth (BW) For an M-ary QAM is given by [7,8].

$$BW = \frac{f_b}{\mathrm{Log}_2 M} \quad (3)$$

For $n = \log_2 M$, Then the $BW = \frac{f_b}{n}$

where

f_b is the bit rate in bps

n = number of bits necessary

M = number of condition ns, levels, or number of output level

B. Bit Rate and Baud Rate

Bit error rate (BER) is defined as the number of bit errors divided by the total number of transferred bits during the studied time interval. The BER is a unit less performance measure; often expressed as a percentage. The bit error can be written mathematically as.

$$BER = \frac{\text{Number of bit in error}}{\text{Total number of transfered bits}} \quad (5)$$

Baud rate is the rate of change of a signal on the transmission medium after encoding and modulation have occurred. Hence,

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baud is a unit of transmission rate, modulation rate, or symbol rate. The relationship between bit error rate and baud rate of M –ary QAM is given by

$$\text{Bit rate} = \text{baud} \log_2 M \qquad (6)$$

Where: M is number of levels.

C. Bandwidth Efficiency ((BW_η)

The bandwidth efficiency (BW_η) is define as a ratio of the transmission bit rate (bps) to the minimum bandwidth (HZ) . The (BW_η) of an M-ary QAM is given by

$$BW_\eta = \frac{\text{Transmission bit rate (bps)}}{\text{Mimimum bandwidth (Hz)}} = \frac{\mathbf{f_b}}{\frac{\mathbf{f_b}}{\mathbf{\log_2 M}}} = \mathbf{\log_2 M} \qquad (7)$$

D. Probability of ERROR P(e)

Probability of error P(e) is defined as a function of the carrier-to-noise power ratio. For M-ary QAM the probability of error are given by

$$p_b = \frac{1}{m} erfc \sqrt{\left(\frac{mE_b}{N_o}\right) \sin\left(\frac{\pi}{M}\right)} \qquad (8)$$

IV. GENERATION OF M –ARY QAM SIGNAL

Fig. 1 shows the block diagram of M-ary QAM modulator, where the M-ary-QAM signal can be generated by using a serial-to-parallel converter, that converts each n-bit groups of the input binary data sequence at rate of $f_b = 1/T_b$ bps to one of the possible M-levels. In the next stage, each M-levels or signals will be assigned by different amplitude and phase which is fed to the multipliers that are supplied by generated reference carrier frequency , then the modulated I and Q signals are added to form an M-ary QAM signal [9-12]. .

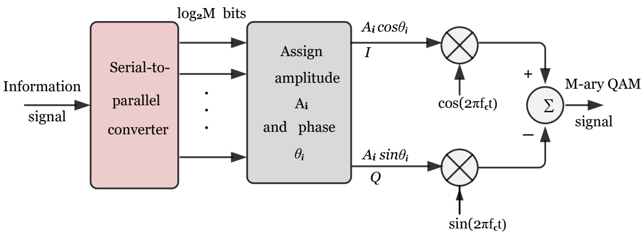

Fig1: M-ary QAM Modulator.

V. DETECTION OF M –ARY QAM SIGNAL

Fig. 2 illustrates the block diagram of M-ary QAM demodulator, the received signal is splitted to I and Q signals, where are individually multiplied by a carrier frequency. The carrier frequencies are generated by the carrier recovery, where one of the two carrier is shifted by 90°. The output signal is passed through the low pass filter to reject the higher frequencies, then the output is fed to the parallel to serial converter to get the binary data sequence back [1,5, 14].

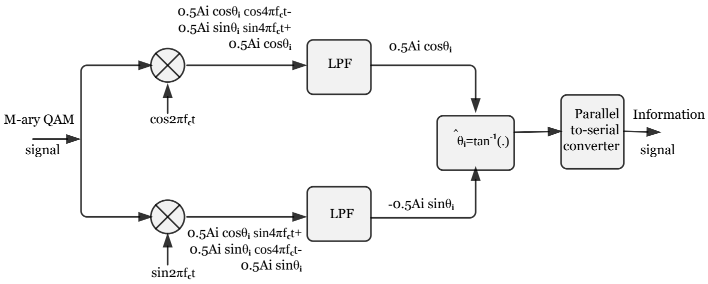

Fig 2: M-ary QAM Demodulator.

VI. SIMULATION OF M –ARY QAM SYSTEM USING MATLAB CODE [7]

. MATLAB code was written to simulate an M-ary QAM, the M, value of the number of levels can be changed from 2 up to any number of levels where, $M = 2^n$, n = 1,2,3, … etc.

The following model shows the MATLAB implementation of M-ary QAM. The model generates a random binary sequence which represents the input data. Then the program generates the constellations of the phase points corresponding to the number of symbols chosen. According to theses consolation points and the randomly generated bits sequence the MQAM signal is generated. Then the spectrum of the signal is. plots of the signal in time domain and its spectrum and constellation diagram. The main parts of the program are [13].

1. Initialization

   In this section the definition and initialization of the variables of program.

2. Input Parameters

   2.1 Determining the numbers of symbols

   2.2 Determining the Baud rate and Carrier frequency

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2.3 Definition the baud and carrier frequency as constant variable
2.4 Generation of the input random binary sequence

3. Calculating the MQAM constellation points.
4. Generating the M-QAM signal according to the input binary sequence.
5. Plotting the MQAM signal in Time Domain.
6. Finding the spectrum of the MQAM signal.
7. Plotting the spectrum of the MQAM signal.
8. Plotting the constellation diagram.

In this paper as an example it consider

9. M = 16
10. baud=4000؛
11. fc=4000؛
12. data rate=4000*4=16000bps
13. The 16QAM signal is shown in Fig. 3 , Fig. 4 shows Spectrum of 16-QAM, and Fig. 5 16-QAM constellation diagram.

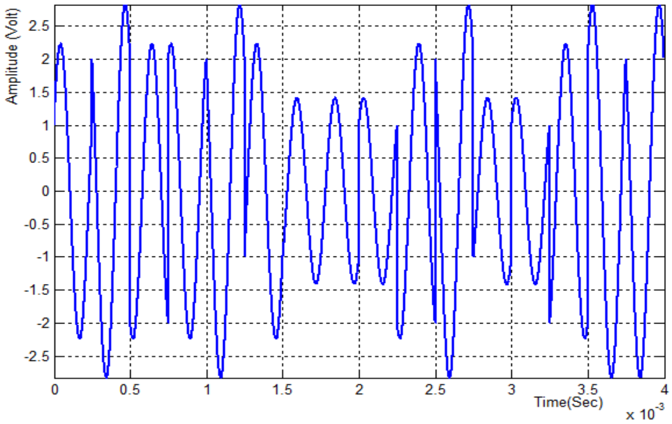

Fig 3: 16-QAM modulated signal

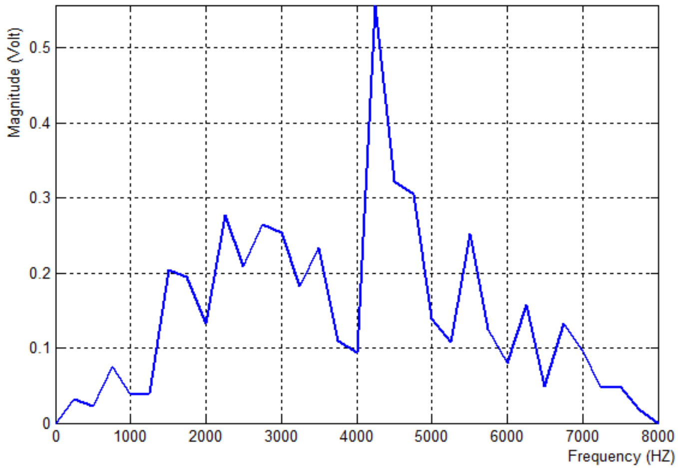

Fig4: Spectrum Of 16-QAM signal

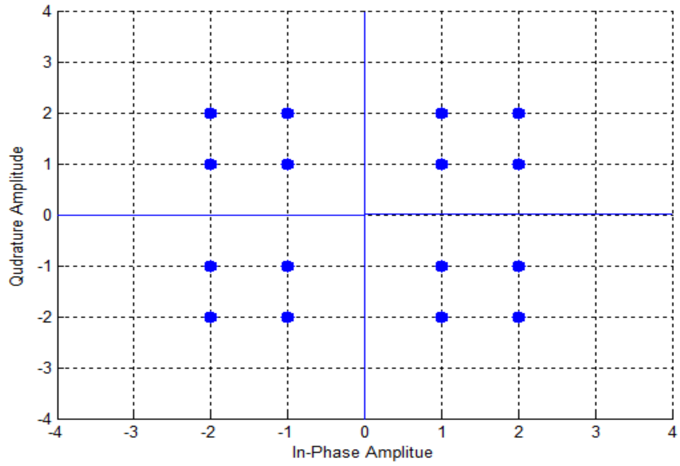

Fig5: 16QAM constellation diagram

VII. PERFORMANCE EVALUATION OF M –ARY QAM SYSTEM

In an M-ary QAM signaling it may send one of M possible signals, $S_1(t),S_2(t),S_3(t),\ldots.S_M(t)$ during each signaling interval of duration T_s. For almost all applications, the numbers of possible signals are $M=2^n$, where n is an integer. The symbol duration $T_s = nT_b$, where Tb is the bit duration. The BER of some M- ary QAM levels will be discussed and analyzed in detail in the following points. using graphical plots.

A. Theroitical Evaluation the M – ary QAM Performance

Referring to equation (8) the probability of error or bit error rate of M – ary QAM (M=4, 8, 16, 32, 64, 128 and 256) is obtained

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by written a Matlab program and the obtained result is shown in Fig 6.

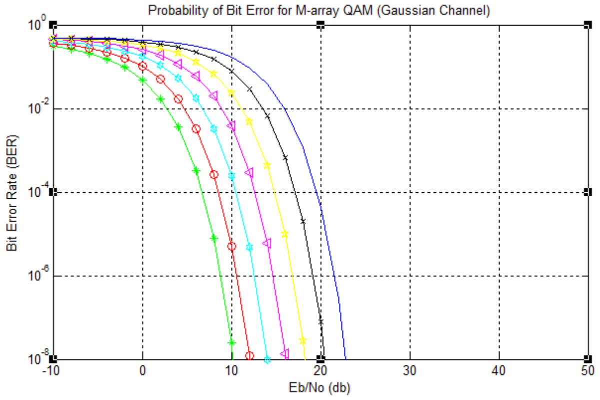

Fig6: Probability of Bit Error of M- ary QAM

B. Evaluation the of Performance of M-ary QAM System using Simulink [7].

Fig. 7 illustrated the *Simulation model for 256-QAM* which is implemented using Simulink . That simulation model include the following parts:

1. Random Integer Generator: Generate random uniformly distributed integers in the range [0, M-1], where M is the M-ary number in this case M=256..
2. Rectangular QAM Modulator Baseband: Modulate the input signal using the rectangular quadrature amplitude modulation method. This block accepts a scalar or column vector input signal. The input signal can be either bits or integers. When you set the 'Input type' parameter to 'Bit', the input width must be an integer multiple of the number of bits per symbol.
3. AWGN Channel: Add white Gaussian noise to the input signal. The input signal can be real or complex. This block supports multichannel processing. When using either of the variance modes with complex inputs, the variance values are equally divided among the real and imaginary components of the input signal.
4. Rectangular QAM Demodulator Baseband Demodulate the input signal using the rectangular quadrature amplitude modulation method. This block accepts a scalar or column vector input signal. When it locates the 'Output type' parameter to 'Integer', the block always performs Hard decision demodulation. When it locates the 'Output type' parameter to 'Bit', the output width is an integer multiple of the number of bits per symbol. In this case, the 'Decision type' parameter allows you to select 'Hard decision' demodulation, 'Log-likelihood ratio' or 'Approximate log-likelihood ratio'. The output values for Log-likelihood ratio and approximate log-likelihood ratio decision types are of the same data type as the input values.
5. Error Rate Calculation: Compute the error rate of the received data by comparing it to a delayed version of the transmitted data. The block output is a three-element vector consisting of the error rate, followed by the number of errors detected and the total number of symbols compared. This vector can be sent to either the workspace or an output port. The delays are specified in number of samples, regardless of whether the input is a scalar or a vector. The inputs to the 'Tx' and 'Rx' ports must be scalars or column vectors. The 'Stop simulation' option stops the simulation upon detecting a target number of errors or a maximum number of symbols, whichever comes first.
6. Display Result: It is block to display the results of BER, Total Errors and Total Symbols.

After setting all the elements and the simulation parameters and running the model it obtain the model simulation Results for 16QAM as shown in Fig. 8.

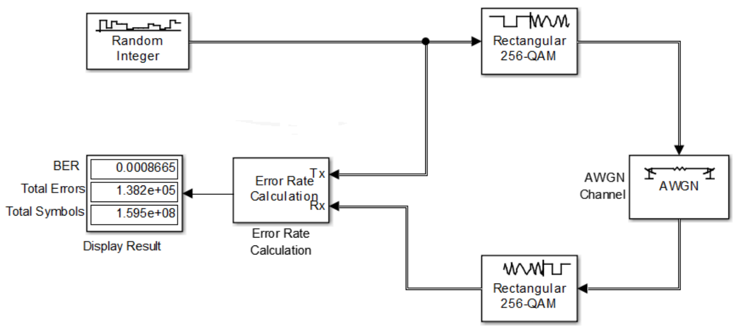

Fig7: Simulation model for 256-QAM

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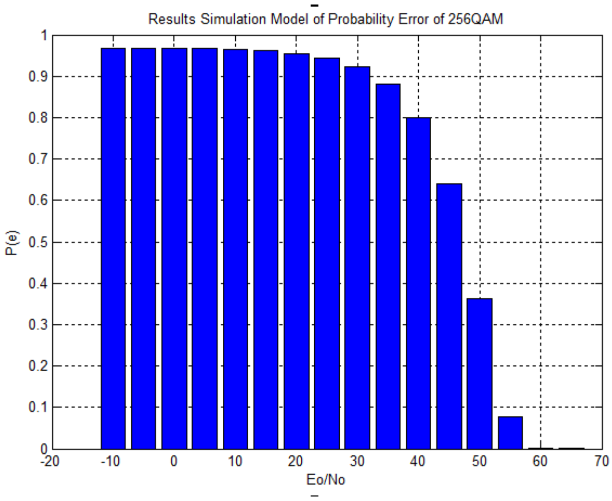

Fig8:. Model Simulation Results for 256 - QAM

VIII COMPARATIVE PERFORMANCE ANALYSIS BETWEEN THE THEORETICAL AND SIMULATION RESULTS OF M –ARY QAM SYSTEM

The comparative between the results of 256QAM theoretical and 256QAM simulated are given in Fig. 9.

In theoretically of 256QAM the first value for E_b/N_o= -10 then P_e= 0.86504 when the E_b/N_o is increase the value the P_e is reduced until arrive to P_e=0.12*10 $^{-12}$ when the E_b/N_o=45.

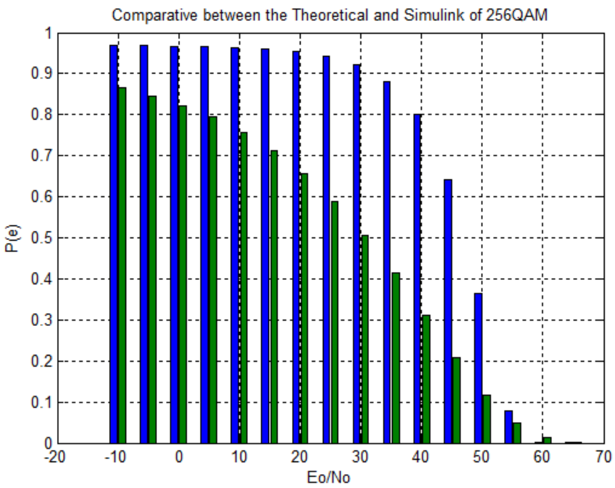

Fig.9: Comparative performance analysis of 256 QAM

IX CONCLUSION

Multi level of QAM (M- ary QAM) error performance, baud rate, bandwidth, and bandwidth efficiency have been discussed in this work. The simulation results presented the 16-QAM modulated signal in both time and frequency domains as well as the constellation diagram are obtained by written Matlab code. Also the BER theroiticaly obtained of the 4, 8, 16, 32, 64, 128 and 256 - QAM system and It observes that it was quite clear that as the level increases decreases i.e a less signal energy is needed to get a better BER.. In an addition to that the BER of 256- QAM system is obtained by using Simulink and compared by the theoretical result and it observes in the theoretical the first value for E_b/N_o= -10 then P_e= 0.86504 when the E_b/N_o is increase the value the P_e is reduced until arrive to P_e=0.12*10 $^{-12}$ when the E_b/N_o=45 .

IIX Recommendations

Based on the analysis and simulation results obtained for multi-level Quadrature Amplitude Modulation (M-ary QAM) systems, several recommendations can be proposed for future work and system optimization 1. election of Appropriate Modulation Order:
The study demonstrates that as the modulation order increases, bandwidth efficiency improves, but the system becomes more susceptible to noise. Therefore, the choice of modulation order should be adaptive and based on the prevailing channel conditions. Lower-order schemes such as 16-QAM or 64-QAM are suitable for noisy or fading environments, whereas higher-order schemes like 128-QAM and 256-QAM are recommended for high-quality channels with sufficient signal-to-noise ratio (SNR) 2. Adoption of Adaptive Modulation Techniques:
It is recommended to employ adaptive modulation in practical systems, where the modulation level varies according to the instantaneous channel quality. This technique can enhance spectral efficiency while maintaining acceptable error performance under varying transmission conditions 3.Incorporation of Forward Error Correction (FEC):
To mitigate the high bit error rate (BER) observed in higher-order QAM schemes, the use of error control coding such as convolutional codes, Turbo codes, or low-density parity-check (LDPC) codes is suggested. The combination of modulation and coding (coded modulation) can significantly improve overall system reliability 4. Enhanced Channel Modeling:
Future work should include simulations over more realistic channel models, such as Rayleigh or Rician fading channels,

in addition to the Additive White Gaussian Noise (AWGN) model. This will provide a more comprehensive

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understanding of QAM performance in wireless communication environments 5. Experimental Validation: It is further recommended to validate the MATLAB and Simulink simulation results through hardware implementation using platforms such as Software Defined Radio (SDR) or FPGA. Experimental testing under real transmission conditions will enhance the reliability of the theoretical and simulated results 6. Analysis of Power and Bandwidth Trade-Offs:
Further research should investigate the trade-offs between transmit power, bandwidth efficiency, and BER for various QAM levels. Such analysis is essential for optimizing energy efficiency in modern communication systems, including 5G and emerging IoT networks 7. Comparative Study with Other Modulation Schemes:
For a more comprehensive assessment, future studies may compare QAM performance with other digital modulation techniques such as Phase Shift Keying (PSK), Frequency Shift Keying (FSK), or Orthogonal Frequency Division Multiplexing (OFDM). This will help identify the most suitable modulation technique for specific communication scenarios.

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