Asian Journal of Research in Computer Science

7(3): 63-71, 2021; Article no.AJRCOS.67225
ISSN: 2581-8260

A Comprehensive Analysis of M-ary PSK and M-ary QAM Schemes

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Authors' contributions

This work was carried out in collaboration among all authors. Author ATB designed the study, performed the simulation and wrote the first draft of the manuscript. Author AR went through the mathematical equations, while authors ZLH and MBA managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJRCOS/2021/v7i330183
Editor(s):
(1) Dr. Hasibun Naher, BRAC University, Bangladesh.
Reviewers:
(1) Almir Karabegovic, University of Sarajevo, Bosnia and Herzegovina.
(2) Latefa Sail, Aboubekr Belkaid University, Algeria.
Complete Peer review History: http://www.sdiarticle4.com/review-history/67225

Short Research Article

Received 22 January 2021
Accepted 27 March 2021
Published 30 March 2021

ABSTRACT

In the last few decades, data communication has recorded massive improvements. These improvements were brought about by advancement in digital circuitry, its availability and persistent reduction in cost. Before the advancement of digital communication technology, analogue communication was the dominant means of transmitting data. As the internet expands across the globe, the need to transfer data over long distances increases. However, the major problem with analogue communication is that the quality of signals is lost with distance. Also, it has minimal security and does not support data integration. Digital communications provided an alternative to analogue communication. Today, digital modulations have become part and parcel of the present and future communication technologies. Despite the advantages of these schemes, the traditional channel impairments, such as noise, can affect their performance. Moreover, data transmission is mostly done over wireless channels, which are very unpredictable and are characterised by multipath fading effects. This paper presents a short research article that presents a study of digital modulation schemes (M-ary QAM and M-ary PSK) using MATLAB/Simulink under Additive White Gaussian Noise (AWGN). The result shows that, among the three modulation schemes compared, QAM has the best BER performance with minimal energy consumption.

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Keywords: BER; SER; QAM; PSK; QPSK; AWGN; SNR; EbNo.

1. INTRODUCTION

The surge in global population brought about the need for communication over long distances, which led to the increase in data traffic and an ever-growing demand for high-speed channels of communication. The early generation technologies, such as (1G), relied on analogue channels for data transmission. Analogue communication, which formed the backbone of the previous data communication technologies, has many limitations. Data transmitted over analogue channels cannot travel over a very long distance. It is susceptible to noise interference and has poor data security mechanisms. In addition, analogue communication is associated with noise, low information-carrying capacity, and low-quality communication. These deficiencies are some of the factors that necessitated the need for adopting newer means of data communication [1]. With digital communication, the problems of analogue communication were addressed, paving the way for more innovative ways of integrating many forms of data, which inspired the development of many multimedia technologies [2,3].

Contrary to analogue signals, digital signals have only two states: on and off [4]. This discrete nature of the signals is the trait that makes it easy for the recovery and reconstruction of the signal during transmission, thereby mitigating the cumulative effect of noise and other impairments on the signals [5,6]. There are several other advantages of digital communication as compared to analogue. Digital circuits are cheaper to implement and are exceedingly more reliable than analogue circuits. In addition, the level of security that could not be provided by analogue systems was achieved in digital transmission [7]. This was made possible by the ability of the digital signal to carry analogue data. Also, digital communication allows the conversion of analogue data to digital making the integration of voice, video and digital data for multimedia communication a reality [8]. From 1G to 5G, modulation schemes have always been the major issues for engineers [7,9]. The choice of the digital modulation scheme to use in the core component of a communication technology involves a tradeoff between transmission speed and energy consumption [3,10]. This choice between speed and efficiency makes M-ary QAM and M-ary PSK the most widely used modulation schemes in data communication technologies [9,11].

2. REVIEW OF M-ARY PSK AND M-ARY QAM MODULATION SCHEMES

Data occurs in either analogue or digital form, and depending on the data format supported by a communication system, the transmission of signal could be in analogue or digital format [12,13]. For communication between analogue systems, the data to be transmitted must conform to the requirements of the transmission system, and this is the most important requirement in both analogue and digital communications [14]. A modem better explains the concept of digital to analogue transmission. A conversion of the digital data to analogue must be carried out so the data could be transmitted through a modem [15]. Modulation schemes are at the core of any communication system be it analogue or digital. Contrary to how the analogue modulation schemes transmit data, digital modulations schemes transmit digital baseband data through variation of a carrier wave's phase or frequency and envelope. The degrees of freedom offers by the envelopes allows the mapping of the baseband data onto different levels of the carrier signal (2,4,8,16 etc.) [16,17]. As a result, the schemes that provided this breakthrough are referred to as M-ary modulation. In these schemes, bits are transmitted in groups known as symbols [5]. The number of bits per symbol depends on the modulation scheme being used. Generally, the number of signal level is given by $M=2^m$, where m represents the number of bits per symbol. The names given to these schemes are driven from manipulation carried out on the amplitude to produce ASK, frequency to produce FSK, and phase to produce PSK [17-20]. As the core technology in data communications, digital modulation schemes have a wide range of applications [3]. Barnela [3] gave a highlight on the applications of these schemes in wireless communication. Liu et al [21] carried out a performance comparison of the digital modulation schemes that are used in two (DVB-T and DBTM) different terrestrial digital TV. According to the author QPSK, 16-QAM, and 64-QAM are used for hierarchical signal mapping in combination with OFDM for DVB-T, while 4-QAM, 16-QAM, and 32-QAM are used for DBTM. Ladebusch and Liss [22] also highlighted the application of QPSK, 16-QAM and 64-QAM in the terrestrial digital video broadcast. Both M-ary PSK and M-ary QAM schemes are widely used in satellite communications, with PSK schemes mostly used for satellited based transmission of applications such as video conferencing as cellular phones [23,24]. In [25], Chatterjee outline the applications of some M-ary PSK and M-ary QAM schemes for 4G wireless consumer applications. These modulation schemes are also at the heart of WiMAX technology as highlighted by Chaudhary [26]. Table 1 below gives a summary of some of the applications of M-ary PSK and M-ary QAM schemes.

In this research, an algorithm has been developed to simulate four variants of M-ary PSK and QAM using Matlab/Simulink. The performance of each M-ary PSK was compared to the corresponding M-ary QAM to measure the resilience of each scheme under the AWGN channel.

2.1.1 Phase Shift Keying (PSK)

There are several variants of PSK that can be derived by alternating the phase of the carrier wave. BPSK, QPSK and other types of M-ary PSK are all formed by shifting the phase of the carrier wave [20]. M-ary PSK is formed by keeping the peak amplitude and frequency of the carrier signal while its phase is shifted to produce two different levels of signal elements [13]. This scheme has a wide range of applications, because of its efficiency and low error rate probability [21]. QPSK has several interesting features. The most interesting among them is that it is insusceptible to noise corruption which inspired network engineers to use 2 bits per symbol. It is formed by t, different from the 1 bit used in the BPSK. This affects the baud rate and consequently the required bandwidth, resulting in another modulation scheme called Quadrature Phase Shift Keying (QPSK) [20]. The name QPSK was used because the scheme is equivalent to two BPSK modulators combined. In other words, QPSK has two distinct BPSK modulators, with one in-phase and the other out-of-phase [15,22]. BPSK is given by the mathematical expression below.

$$S_t = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t) + \pi(1-n)\dots.n = 0, \quad (1)$$

$$P_{e,BPSK} = {}^{Q}\sqrt{\frac{2E_b}{N_0}} \quad (2)$$

Where E_b represents the energy per, while N_0 is the noise power spectral density. *Q* is the power used to estimate the area under the tail of the Gaussian Distribution Function (pdf).

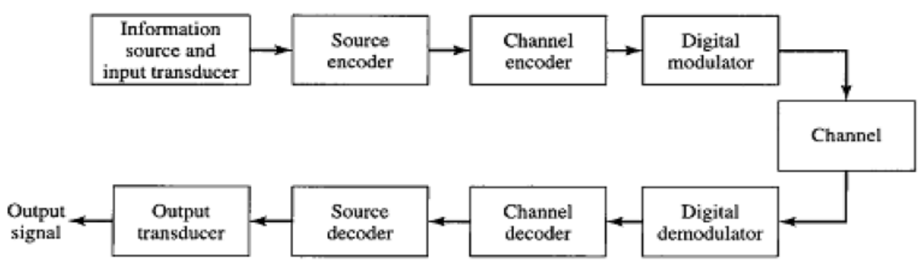

Fig. 1. The fundamentals building blocks of a digital communication system [8]

Table 1. Modulation schemes and their applications

Modulation scheme	Application
BPSK	Cable modems, Deep space telemetry
QPSK	CDMA, DVB-T, DTMB, Satellite, Cable Modem, TFTs, IoT Devices, WiMAX
8PSK	Satellite, aircraft, telemetry pilots for monitoring broadband video systems
16PSK	Modems, Microwave digital radio
32PSK	cognitive radio network
4QAM	DTMB
16QAM	Modems, Microwave digital radio, DTMB, WiMAX
32QAM	Terrestrial microwave, DTMB
64QAM	Broadband set top boxes, Modems, MMDS, DTMB, DVB-T, WiMAX

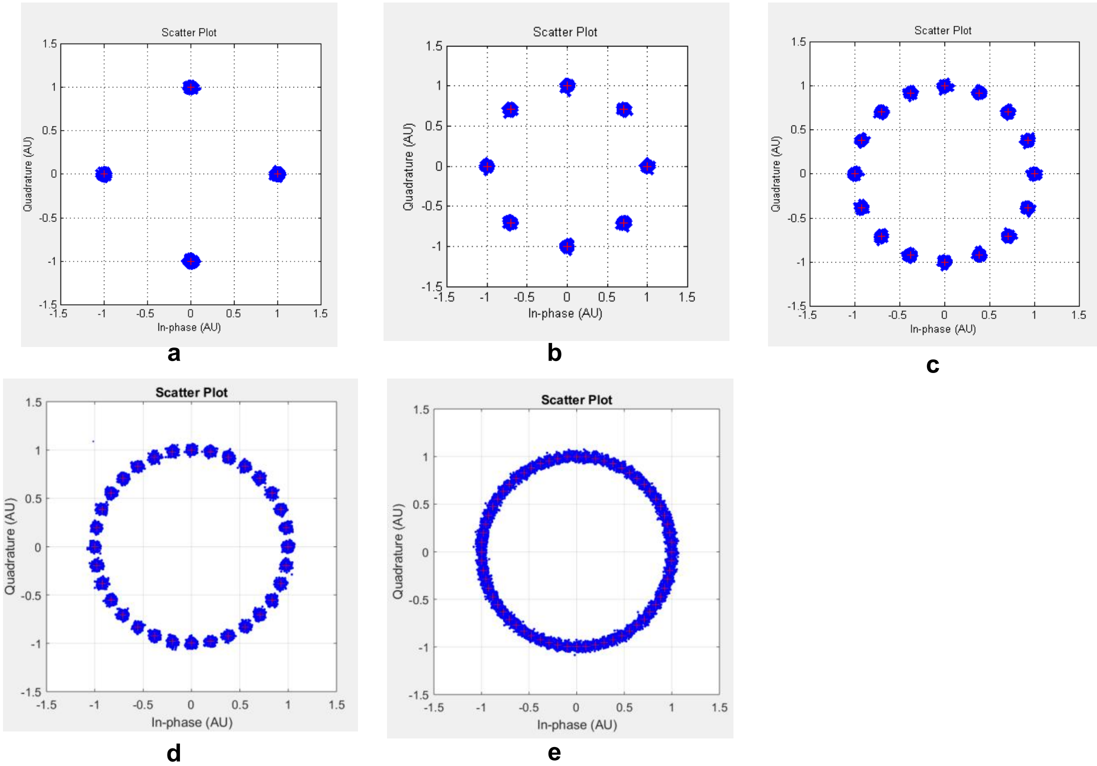

Fig. 2. Constellations diagrams of QPSK, 8PSK, 16PSK, 32PSK, and 64PSK at SNR Eb/No =30dB

QPSK which has a wide range of applications, such as in video conferencing systems, digital communication over radio frequency carrier as indicated in Table 1 above, is given by the mathematical expression below.

$$S_{QPSK}(t) = \left\{\sqrt{E_s}\cos\left[(i-1)\frac{\pi}{2}\right]\theta_1(t) - \sqrt{E_s}\sin\left[(i-1)\frac{\pi}{2}\right]\theta_2(t)\right\} i = 1,2,3,4 \quad (3)$$

$$Q_1(t) = \sqrt{\frac{2}{T_s}}\cos(2\pi f_c t) \quad (4)$$

$$Q_2(t) = \sqrt{\frac{2}{T_s}}\sin(2\pi f_c t) \quad (5)$$

$$\leq t \leq T_s 0$$

Where θ_1 and θ_2 represent the reference signals which are multiplied with the received signal in the demodulator. Ts is the symbol period, while E_0 is the energy per bit. The bit error rate of QPSK is by the mathematical expression below.

$$P_{e,QPSK} = Q\left[\sqrt{\frac{2E_b}{N_0}}\right] \quad (6)$$

2.1.2 Quadrature amplitude modulation (QAM)

Quadrature Amplitude Modulation (QAM) is produced through the combination of both Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK). QAM falls under the category of non-constant envelope modulation techniques that have greater bandwidth*utilization compared to M-PSK with the same common signal power. M-ary QAM is one of the most widely used modulation schemes because of their bandwidth and energy efficiency. Low-level M-ary QAM schemes are widely used in wireless communication technology. Other forms of QAM have specified relevance. 64-QAM and 256-QAM are used in digital cable television and cable modem [6,18].

When data transmission rate requirement is greater than what 8PSK can provide, QAM is the most suitable alternative since its constellations are rectangular, thereby allowing more space between the adjacent constellations in I and Q planes. Higher-order M-ary QAM schemes give space for transmission of more bits per symbol, leading to more energy consumption to avoid bits

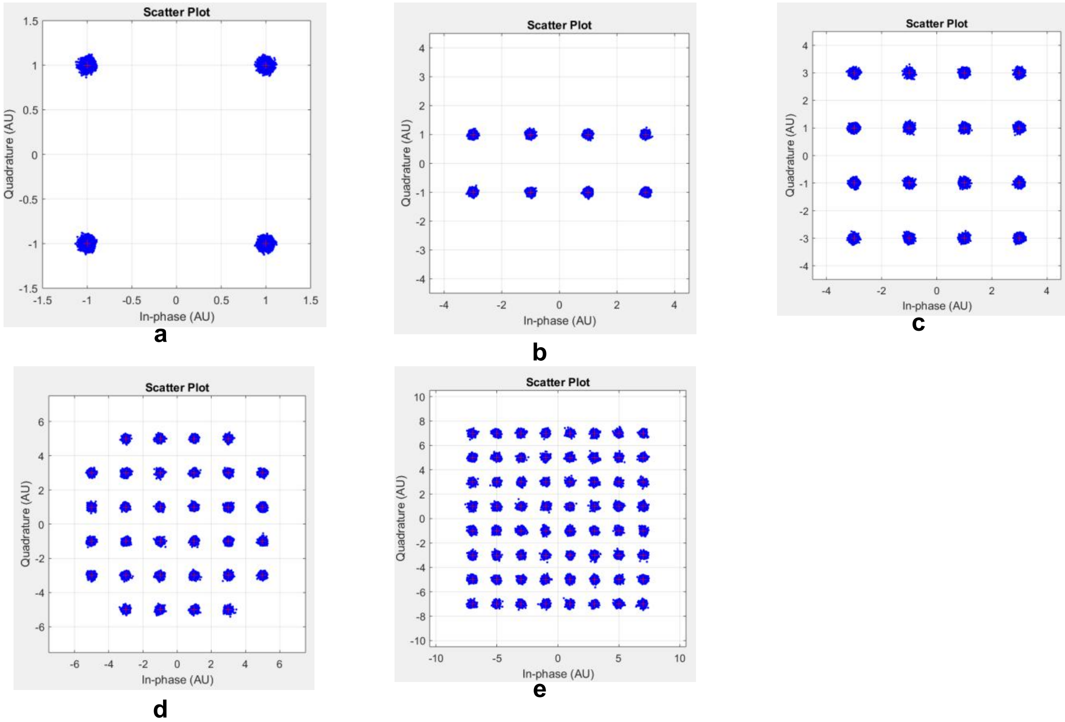

Fig. 3. Constellations diagrams of 4QAM, 8QAM, 16QAM, 32QAM, and 64QAM at SNR Eb/No = 30dB

corruption due to transmission impairments, such as noise [20]. Generally, all forms of M-ary QAM can be expressed mathematically using the expression below.

$$S_i\,(t) = \left\{\sqrt{\frac{2E_{min}}{T_s}}\,a_1\cos(2\pi f_c t) + \sqrt{\frac{2E_{min}}{T_s}}\,b_1\sin(2\pi f_c t)\right\} \quad (7)$$

$$0 \le t \le T_s,\ i = 1,2,3,4$$

E_{min} represents the energy signal with the smallest amplitude, while a_1 and b_1 represent a pair of integers selected depending on the location of a given signal point [18,20]. M-ary QAM mean probability of error over Additive White Gaussian Noise channel, which is the channel we are using in this experiments, is given mathematically by the equations below as expressed in [20].

$$P_e \cong 4\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{2E_{min}}{N_0}}\right) \quad (8)$$

2.1.3 Additive white gaussian noise (AWGN)

The noise factor has an overall effect on the performance of the communication systems. It may be defined as an unwanted signal that combines with the signal as it passes through a transmission medium. Many sources generate a variety of noise each with its peculiarity. Thermal noise, which is inherent in all conductors is the most difficult to deal with because of its presence in virtually all metallic and non-metallic conductors. Therefore, this type of noise presents a significant threat to the quality of signals thus decreasing the reliability of channels as data travels from one end to another [5,8]. The thermal movement of electrons in the electric parts of a communication channel produces a disturbance that causes signal corruption, such disturbance is referred to as Additive White Gaussian Noise (AWGN). The degree of this noise in a signal determines the precision with which signal constellation are demodulated. The more accurate the demodulation of the constellations, the lesser the error rate probability and vice versa. The term Additive White Gaussian Noise (AWGN) refers to the noise that is added to the signal during transmission from the source to the destination. Therefore, AWGN symbolises the collective effect of thermal noise produced by the thermal movement of excited electrons in electrical devices such as resistors, wires etc [17,23]. The word white signifies that the noise has a horizontal effect on both positive and negative frequencies [17].

2.1.4 Bit Error Rate (BER)

Bit Error Rate is the performance measure used to evaluate the performance of any digital modulation scheme. In digital communications, there is the likelihood that bits sent is received without any distortion, corruption or any other impairment that might cause the bit state to change. The measure of the probability of occurrence of these errors is called the bit error rate probability or simply BER [25].

Bit Error Rate $(\mathrm{P_b}) = \frac{\text{Total number of transferred bits}}{\text{Total number of bits transferred}}$ [27]

The level of BER varies from one modulation scheme to another and on the amount of bit energy during transmission. For example, if the level of bit energy is kept constant for transmission using a low-level modulation scheme and another using a higher-level modulation scheme, there will be more errors in the transmission that uses a higher-order modulation scheme. This is a result of its symbols size which requires a significant amount of energy compared to a low-level scheme. Different modulation scheme employed depending on the underline purpose for designing a communication system [28-30].

3. SIMULATION SETUP

As against the usage of Simulink building blocks for building a model of a communication channel, we opted to design an algorithm. The algorithm consists of an SNR vector, an M-level vector that holds different levels of the modulation schemes (8-QAM,16-QAM), an AWGN channel and a built-in MATLAB function for the simulation of the schemes. The algorithm can be broken into three subunits. The first unit consists of an SNR vector that consists of the SNR vector [0:2:30], and random symbols generator. The second section of the algorithm consists of a modulator and demodulator and a scatter plot generation module. The modulated signal is then combined with a given level of SNR and passed to the next section of the algorithm. In the last section of the algorithm, the modulated signal is passed into an AWGN and the BER of the recovered signal is estimated. Finally, the BER results of the simulation are stored in a vector on the workspace where the data is extracted for plotting of the figures.

4. RESULTS AND DISCUSSION

In this work, we have compared the bit error rate performance of the two most widely used digital modulation schemes in digital communication. The BER performance has been carried under the Additive White Gaussian Noise (AWGN) channel to simulate channel impairments, which encumber the transmission of signals across guided and unguided media in data communication. Using the constellations diagrams, we have demonstrated how M-ary PSK is often more vulnerable to noise corruption than M-ary QAM.

Digital data occurs in 0’s and 1’s. Noise as impairment can alter a bit state from 0 to 1 or 1 to 0. Bit error rate occurs when noise causes a change in a bit value (0 to 1, or 1 to 0). The effect of noise on digital data is not only limited to individual bits but also affects a symbol; a symbol is a group of bits. When bits are transmitted separately in a channel (e.g 1100) they are more likely to be affected by noise than when transmitted in blocks. It is safe to say that less energy is required to protect a bit from corruption, while more energy is needed to protect a symbol from corruption. The number of bits per symbol increases as the level of modulation schemes increases, 8-QAM and 8-PSK will each have 3 bits per symbol while 32-QAM and 32-PSK have 5 bits per symbol. This indicates that there is a strong correlation between the number of bits per symbol of a modulation technique and the achievable data rate of such a scheme. Looking at Fig. 2(a) and Fig. 3(a), we can see that the constellation diagrams of 4-QAM and QPSK are almost similar. However, QPSK, even though has the same symbol rate as 4-QAM, has less energy consumption (see Fig. 4(a)) compared to 4-QAM. This is maybe because, in QAM, both amplitude and phase of a signal are shifted, while in PSK, only the phase of the signal is manipulated. This pattern can also be observed looking at Fig. 2(b) and Fig. 3(a) except that 8-QAM, in this case, performed better than 8-PSK with regards to energy consumption. For 16-PSK, 16-QAM, 32-PSK, 32-QAM and 64-PSK and 64-QAM, Figs. 6, 7, and 8 show the performance of the schemes. In each figure, it can be observed that and QAM performs better than PSK in terms of error rate probability and energy consumption. The poor performance of PSK is a result of the arrangement of constellation points (see Figs. 2 and 3) which makes one-point overlap another when the signal picks up some noise presence.

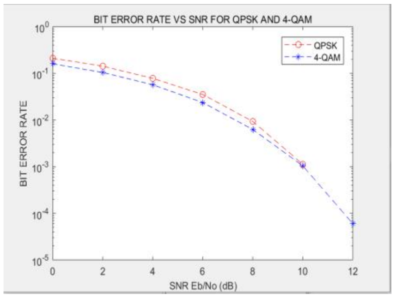

Fig. 4. BER graph for QPSK and 4-QAM

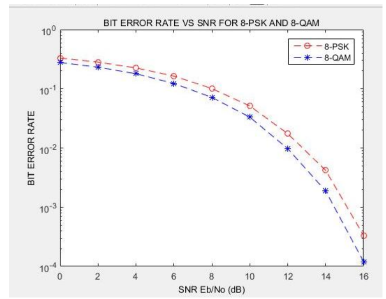

Fig. 5. BER graph for 8-PSK and 8-QAM

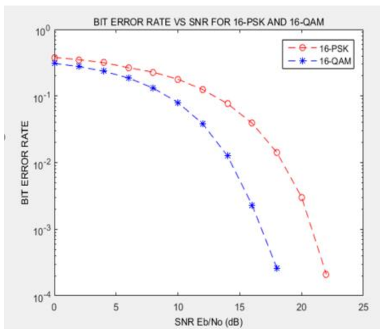

Fig. 6. BER graph for 16-PSK and 16-QAM

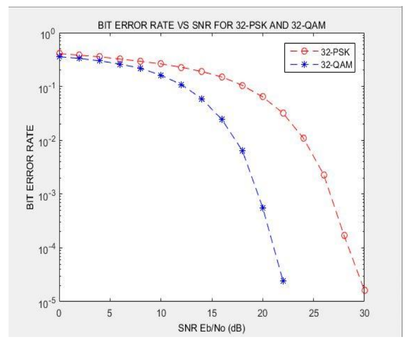

Fig. 7. BER graph for 32-PSK and 32-QAM

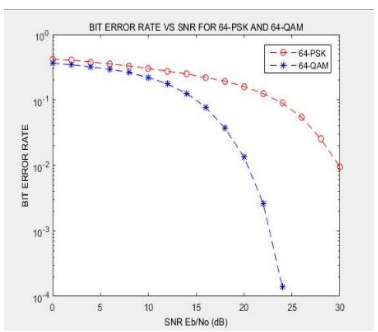

Fig. 8. BER graph for 64-PSK and 64-QAM

4. CONCLUSION

In this paper, an algorithm has been developed to simulate M-ary QAM and M-ary PSK and compare their respective performances. In terms of bit error rate probability and energy consumption, the outcome of the simulation revealed that M-ary QAM schemes performed better than M-ary PSK in terms of their BER performance and energy consumption. Considering the performance of the modulations investigated, the choice of which modulation scheme to use in a communication system, in some cases, is a tradeoff between data transmission rate and energy consumption. While other researchers focused on only the schemes that are widely used, we have shown why other schemes, such as 64-PSK, are not used due to their proneness to noise corruption. Also, the pairwise based comparison approach followed in this work, which is in contrast to the approach used in the reviewed work, gives the basis for comparing M-ary PSK and M-ary QAM schemes of the same order.

ACKNOWLEDGEMENTS

This work is sponsored by tertiary education trust fund (tetfund).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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