Performance Analysis of QAM Modulation and Demodulation

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Abstract. The following study will investigate the performance of Multiple Quadrature Amplitude Modulation(M-QAM) in baseband modulation systems and further analyze the bit error rates (BER) performance under different conditions of communication. The error performance of several M-QAM schemes has been extensively simulated and analyzed under ideal Additive white Gaussian noise (AWGN) channel conditions. The influences of some common channel impairments, such as frequency offset and partial band interference, on the performance of the system are also taken into consideration to assess the reliability of the system in depth. The results in this paper will show both the potential and challenges of M-QAM in practical communication systems by comparing the BER under different channel models. Notably, there are usually inevitable frequency offset and interference in wireless communications. Therefore, a study on its effect on the performance may be very necessary for the further enhancement of robustness and interference resilience in modern communication systems. This work will provide enlightenment on insights into the design of the baseband modulation system and support theoretical improvements to enhance communication quality and reliability.

Keywords: M-QAM, BER, AWGN, Frequency Offset, Partial Band Interference.

1. Introduction

1.1. Research Background

The demand for high data rates in modern communication systems has led to the development of several modulation schemes, among which M-QAM is one of the most popular techniques. M-QAM can send more than one bit per symbol by changing both the amplitude and phase of the carrier signal. This results in higher spectral efficiency, thus making it suitable for high-throughput applications such as wireless communications, broadband internet, and digital television.

However, despite such merits, M-QAM systems remain susceptible to various channel impairments, most notably AWGN that is usually modeled in analytical work. In practical environments, further channel distortions, such as frequency offset and partial band interference, can also be present. The former is due to a mismatch between the transmitter and receiver frequencies, which will potentially cause symbol misalignments. Partial band interference involves interference in some frequency bands that could degrade the signal quality and increase the BER [1,2]. With the evolution in the communication system, it has been of prime importance to know the performance of M-QAM under these impairments.

1.2. Research Focus and Objectives

This research focuses on the performance evaluation of M-QAM systems in the presence of AWGN, frequency offset, and partial band interference. The simulator models the behavior of a system subjected to these degradations by calculating the BER as the main performance metric. Different M-QAM schemes, such as 16QAM [3] and 64QAM, are considered to observe how increasing the modulation order affects system performance in noisy and distorted channels [4,5,6,7].

While it seeks to determine the performance of channel impairments in M-QAM systems and more importantly, how higher-order modulations, which will yield higher data rates, necessarily trade off against increased sensitivity to noise and interference, this paper attempts to be practical in the choice of modulation schemes in realistic environments [8].

2. System Model and Basic Theory

2.1. System Introduction

The whole system structure is presented in Fig.1. First, the system generates raw bits and modulates them into corresponding symbols according to different QAM constellations. The modulated signal will enter the channel, where the signal will be added to the AWGN, frequency offset, and interference signal. For exploring the effect on the signal, the signal is demodulated at the receiving end to recover the bits. We compare the returned bits with the original bits and can calculate the BER of the system [9].

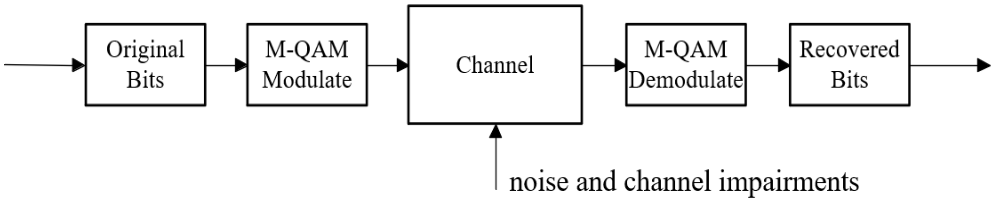


Figure 1. The block diagram of QAM systems

2.2. QAM modulation theory

The theoretical expression for the minimum Euclidean distance between points in a constellation diagram is given by Equation (1)

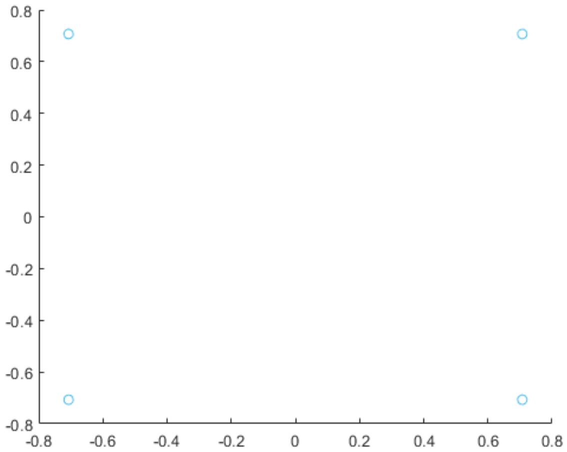
$$\mathrm{d} = \sqrt{\frac{6\log_2 \mathrm{M} \cdot \mathrm{E_b}}{\mathrm{M}-1}}. \tag{1}$$

Equation (1) is the theoretical expression for the minimum Euclidean distance between points in the constellation diagram. In the above formula, M is the number of symbols in the constellation and $\log_2$ M indicates the number of bits per symbol. E_b is the energy per bit, which is one of the main parameters characterizing system performance in terms of power efficiency. $M-1$ in the denominator normalizes for the average energy of the constellation. This distance d has a direct impact on system performance since a higher value of d decreases the probability of symbol errors in an additive noise environment. Therefore, the formula presents the trade-off between constellation size M and the system's robustness to noise as a basic measure for the study of modulation schemes such as M-QAM.

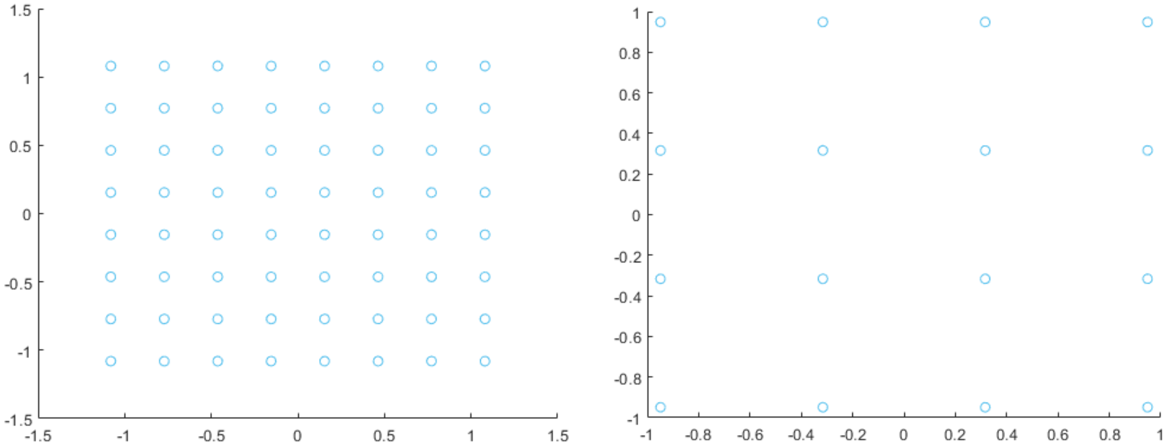
2.3. Constellation Diagrams for QAM Modulation of Different Orders

Modulation is done on the binary bits. It is basically the process of mapping the binary data onto a specific modulation constellation, such as QAM. During this process, each group of binary bits is mapped to a complex symbol, which corresponds to a point in the modulation constellation on the complex plane. This process effectively transforms the original binary data into complex symbols suitable for wireless transmission. The system reshapes the modulated symbols into the length of the frame and the number of symbols, respectively, in three-dimensional matrix form for further processing. Each frame has a certain number of symbols; the whole sequence of signals is rearranged in that structure for further transmission or processing tasks. Finally, the system visualizes the modulated signal by plotting a scatter diagram, showing the distribution of the symbols on the complex plane. This allows for a visual inspection of the modulation constellation, where the symbol spacing and phase differences can be analyzed.

This article uses constellation diagrams generated by the models for QPSK, 16QAM, and 64QAM modulation as examples which can be seen in Fig. 2. Upon comparison, it is evident that as the modulation order increases, the distance between points in the constellation diagram becomes smaller, which also implies a weaker ability to resist channel noise and distortion.



(a) QPSK



(b) 16QAM (c) 64QAM

Figure 2. Constellation maps of different M-QAM

3. System Performance Analysis

3.1. AWGN

3.1.1. Calculation formula of BER

R In an M-QAM system, the symbol error rate (SER) can be approximately calculated using the following formula

$$P_{e,MQAM} \approx \frac{4}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right)\sum_{i=1}^{\sqrt{M}/2} Q\left((2i-1)\sqrt{\frac{3E_b\log_2 M}{(M-1)N_0}}\right), \tag{2}$$

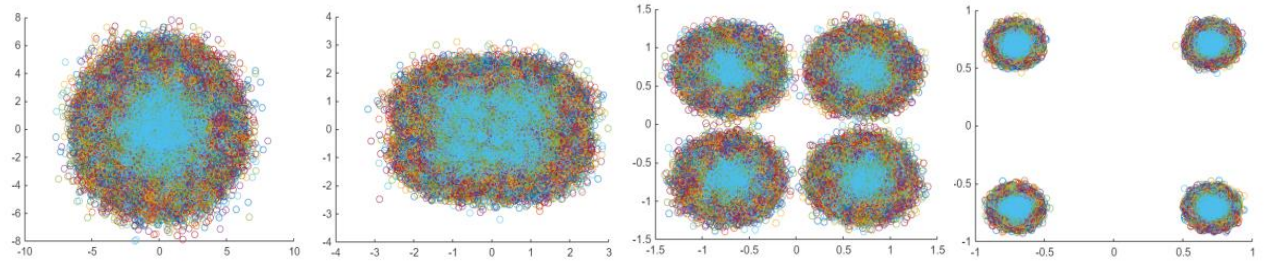
where M is the modulation order, $\log_2 M$ represents the number of bits per symbol, $Q(x)$ is the Q-function that characterizes the tail probability of the Gaussian distribution, Eb denotes the energy per bit, and N0 is the noise power spectral density. The formula consists of three parts: a scaling factor $\frac{4}{\log_2 M}\left(1-\frac{1}{\sqrt{M}}\right)$, a summation term related to the constellation points $\sum_{i=1}^{\sqrt{M}/2} Q(\cdot)$, and a coefficient $\sqrt{\frac{3E_b\log_2 M}{(M-1)N_0}}$ which reflects the relationship between the SNR and system performance. This formula provides a theoretical estimation of the SER for M-QAM modulation in an AWGN channel, effectively capturing the trade-offs between modulation order, signal energy, and noise strength.

3.1.2. Constellation Diagrams under Different QAM Modulation Schemes with Added Noise

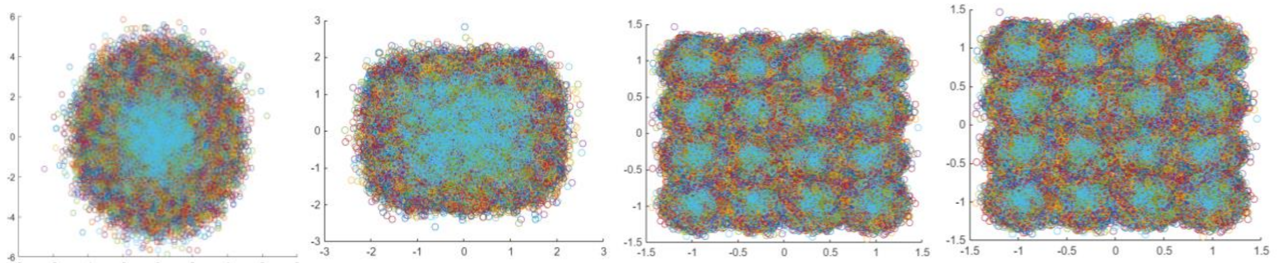
QPSK (Quadrature Phase Shift Keying), 16QAM (16-Quadrature Amplitude Modulation), and 64QAM (64-Quadrature Amplitude Modulation) are commonly used modulation schemes in digital communication systems, each offering different trade-offs between data rate and robustness [10].

QPSK is a phase modulation technique that has each symbol carrying 2 bits of information by using four different phase shifts to encode the signal. This will provide better spectral efficiency compared to BPSK, with fairly good noise immunity, hence it is suitable for low SNR environments. 16QAM combines both amplitude and phase modulation, where each symbol represents 4 bits of information attained by mapping 16 different symbols on the complex plane. It gives higher data rates compared to QPSK; a factor that makes it effective in applications where bandwidth is limited. However, 16QAM has a greater vulnerability to noise, hence a higher BER under poor channel conditions.64QAM extends this further, where in this case, each symbol represents 6 bits of information, mapped across 64 distinct points on the complex plane. While 64QAM offers the highest data rate, it demands a high SNR for reliable communication, as the symbols are closely spaced, increasing the likelihood of errors in noisy environments [11,12].

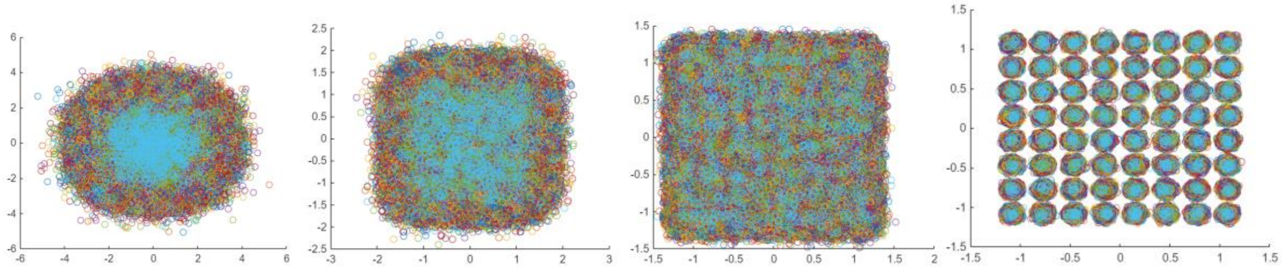
In order to investigate the impact of noise with different signal-to-noise ratios (SNR) on various QAM modulation schemes we add the Gaussian white noise with SNR ranging from -10 dB to 20 dB to the channel. The constellation diagrams for QPSK, 16QAM and 64QAM modulation schemes are recorded accordingly. The noise levels with SNR of -10 dB, 0 dB, 10 dB and 20 dB are used as representatives, as shown in the Fig.3 below.



QPSK Images with a SNR of -10, 0, 10, 20



16QAM Images with a SNR of -10, 0, 10, 20



64QAM Images with a SNR of -10, 0, 10, 20

Figure 3. Constellation maps of different M-QAM with added noise

It can be seen that, for the same noise level, e.g., SNR = 10 dB, the constellation diagram for 64QAM modulation is far more cluttered and disordered as compared to that of the 16QAM modulation. For 64QAM constellations, the symbols are very compact in the complex plane, with almost negligible distance between them. This makes the system vulnerable to noise, as even small variations in the signal can result in the misinterpretation of a symbol, thus increasing the BER. In contrast, the 16QAM constellation has more widely spaced symbols, thus greater separation between them. The increased spacing of the symbols, in turn, provides improved error resilience since noise-induced deviations are less likely to cause symbol misclassification.

This observation points to one of the fundamental trade-offs in modulation schemes: while the modulation order increases, more bits are transmitted per symbol, which results in a higher data rate. However, this also means that the signal's sensitivity to noise increases. The reduced distance between adjacent symbols in higher-order modulation schemes like 64QAM means that the system's ability to resist channel noise is compromised, particularly in environments with lower signal-to-noise ratios. In contrast, lower-order schemes like 16QAM, while offering lower data rates, tend to be more robust against noise and, therefore, are preferable in conditions where the signal quality is less stable or the SNR is lower. Thus, the choice of modulation scheme must carefully balance the need for high data rates with the system's robustness to noise, depending on the specific requirements of the communication system and the quality of the transmission channel.

3.1.3. BER under the Influence of Noise

The theoretical BER of the system can be computed using Equation (2). By storing the actual simulation data of SNR values ranging from -10 to 20 and plotting the results, we can see the BER trends for different QAM modulation orders. We then compare the theoretical BER, derived from the formulas, with the actual simulated BER for QPSK, 16QAM, and 64QAM modulation schemes on the same linear graph Fig. 4.

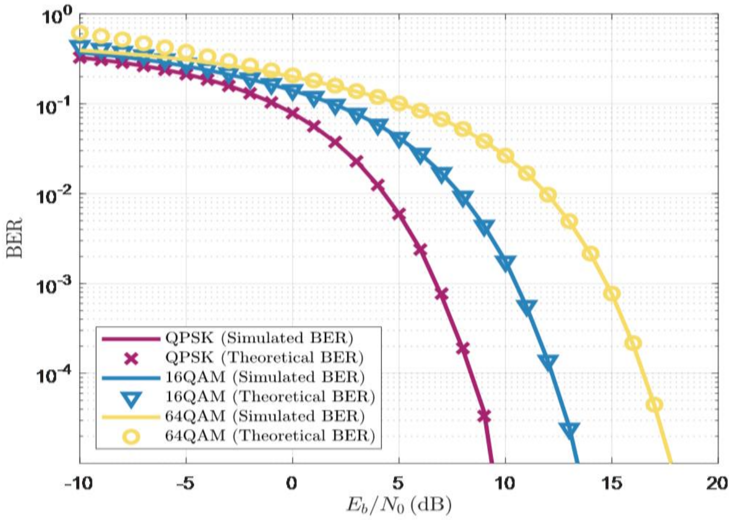


Figure 4. BER of M-QAM under the influence of noise

The results clearly indicate a uniform variation pattern, and this can be clearly depicted in the figure. The theoretical BER values are found to agree rather well with the actual simulation results, thereby justifying the accuracy of the analysis. One can also find that with the same SNR condition, a larger modulation order corresponds to a higher BER value. The immediate observation which can be very well made based on the higher-order modulation schemes is that with the increase in modulation order, the system becomes more vulnerable to noise. As a result, the noise resistance performance of the system deteriorates, leading to the increased possibility of errors. This happens because higher-order modulations require finer decision boundaries that are more susceptible to distortions caused by noise. These findings underscore the trade-off between data rate and error performance in M-QAM systems, where achieving higher data throughput may come at the cost of reduced robustness to noise.

3.2. Impact of Frequency Offset on Performance

3.2.1. Normalized Frequency Offset

Frequency offset in communication systems refers to the difference in carrier frequency between the received signal and the transmitted signal. Frequency offset typically causes phase changes in the signal, which can affect signal demodulation and subsequently impact the BER.

The normalized frequency offset x represents a point's shift relative to the previous point, where the shift is $x \times 2\pi$. The specific formula can be expressed simply as the following equation

$$\mathrm{Tx}_{\mathrm{signal\ 2}}(\mathrm{t}) = \mathrm{Tx}_{\mathrm{signal\ 1}}(\mathrm{t}) \cdot \mathrm{e}^{\mathrm{j}2\pi \mathrm{f}_{\mathrm{offset}}\mathrm{t}}. \tag{3}$$

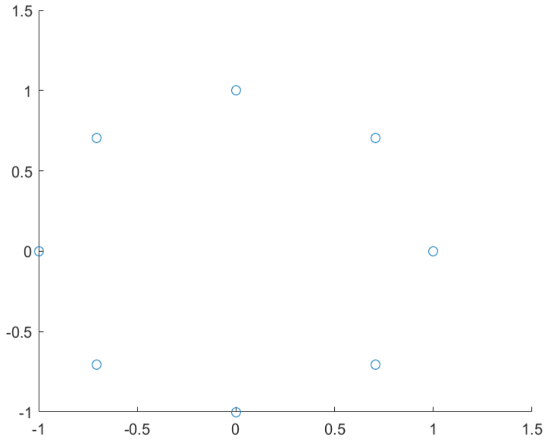
3.2.2. Changes in Constellation Diagrams under Different Modulation Schemes

The normalized frequency offset manifests in the constellation diagram as a rotation of each point around the center by an angle of. To observe this effect more intuitively, we simulated 1024 × 1000 symbols and 1024 × 10000 symbols and selected two frequency offset angles: a relatively large value of 0.125 and an extremely small value of 0.0000001. By comparing the changes in the constellation diagrams under different modulation schemes, we can analyze how the modulation order influences the impact of frequency offset. This can be seen in Fig 5.

QPSK Number of Symbols 1024000

Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.0000001

QPSK Number of Symbols 10240000

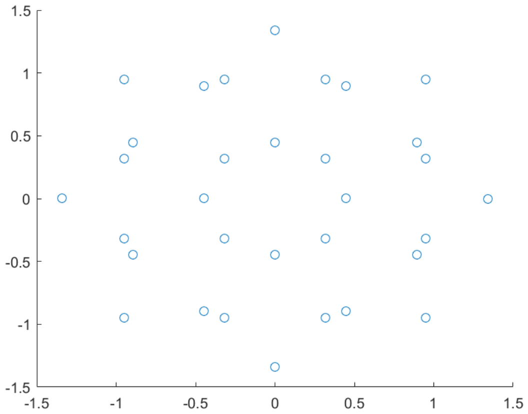


Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.125

16QAM Number of Symbols 1024000

Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.0000001

16QAM Number of Symbols 10240000



Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.01

64QAM Number of Symbols 1024000

Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.0000001

64QAM Number of Symbols 10240000

Normalized Frequency Offset 0.125 Normalized Frequency Offset 0.0000001

Figure 5. Constellation maps of different Frequency Offset

Through comparison, we can observe that the impact of symbol numbers on frequency offset is multifaceted. For higher-order modulation, the impact of frequency offset is usually more significant because the signal points are closely packed; hence, they are prone to phase shifts [13]. On the other side, the lower-order modulation will be more robust to frequency offset and can tolerate a certain amount of frequency deviation.

3.3.3. Analysis and Conclusion

From the images, it can be observed that with an increase in the number of phase shifts, their cumulative effect also grows with the number of transmitted symbols, particularly in long transmissions. Systems with fewer symbols or shorter transmission times are less affected since the phase errors accumulate more slowly. Thus, while higher-order modulation increases spectral efficiency, it is more sensitive to frequency offset and requires more precise frequency synchronization. In a similar way, the systems with longer transmission duration or more symbols become more sensitive to the accumulation of frequency offset. Balancing modulation order, symbol count, and frequency offset tolerance is crucial in system design and optimization.

3.3. Effect of Partial Band Interference

3.3.1. Generation of Band Interference Using QPSK Modulation

1) Bit Stream Generation and QPSK Modulation

The code first generates a random bit stream and then maps it to the QPSK symbols. QPSK modulation is one of the most usable modulation schemes in which every symbol caries 2 bits. The bit stream is first modulated using the function qammod to get complex symbols. To normalize the modulated symbols in such a way that they have an average unit power, it normalizes the system by setting the parameter UnitAveragePower=true. This normalizes the symbols to unit average power so that the signal is comparable at different power settings.

2) Power Control

In order to simulate how different interference power affects the system, the simulation code implements power control. Here, the power of the interference signal is changed based on the ratio between the powers of the interference signal and the effective signal, referred to as the Jamming-to-Signal Ratio (JSR) in decibels. That is, the JSR value in dB defines the logarithmic ratio of the interference signal power to the effective signal power. It can be evaluated by using the following expression

$$\mathrm{JSR\ (dB)}=10^{\log_{10}}\left(\frac{\mathrm{P_{jammer}}}{\mathrm{P_{signal}}}\right). \tag{4}$$

The goal of JSR is the scaling of the amplitude of the interference signal by using a gain factor. In order to apply the JSR, the code uses the following formula to calculate the gain factor and adjust the interference signal power

$$\text{Power Adjustment Factor}=10^{\frac{\text{JSR}}{20}}. \tag{5}$$

This formula converts the JSR value from dB to a linear gain. By performing element-wise multiplication on the modulated interference symbol matrix, the amplitude of the interference signal is scaled by the corresponding multiple of the original effective signal's amplitude. Particularly, the gain factor scales the interference signal's power due to a given JSR value. For instance, if the JSR is 10 dB, the gain factor will be around 3.16, which means that the power of the interference signal will be 3.16 times the effective signal power. In the case where the JSR is -10 dB, the gain factor will be approximately 0.316, meaning that the interference signal power will be 0.316 times the effective signal power. This approach allows the code to simulate interference with varying strengths and adjust the interference signal's impact on the system as needed.

3) Frequency Domain Mapping and Inverse Transformation

The program arranges the modulated interference signal in a frequency domain matrix in a certain way and then applies the Inverse Fast Fourier Transform to this matrix. The inverse transform serves to convert the frequency domain signal back into the time domain, generating the final interference waveform. During this process, the signal is appropriately normalized to ensure that the resulting time-domain signal has the correct amplitude.

4) Frequency Domain Mapping and Inverse Transformation

Finally, the interference signal, after undergoing the IFFT process, is stored in the interference variable and returned as the output. At this point, the interference signal is ready in the time domain for further analysis or for combination with other signals. The whole process is shown in the Fig 6.

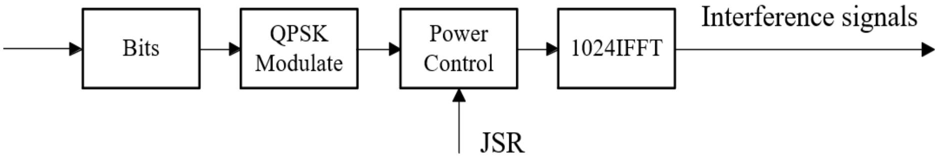


Figure 6. The block diagram of generating interference signals

3.3.2. Interference Factors

1) Centralized Partial Band Interference

Interference Signal Bandwidth: The interference signal mentioned here occupies a portion of the effective signal bandwidth. In communication systems, interference signals refer to those signals that do not belong to the valid communication signal but still reside within the same frequency band. Centralized partial band interference refers to interference signals that are concentrated within a specific frequency band of the effective signal's bandwidth, rather than being evenly distributed across the entire frequency band.

Interference Bandwidth: Let the operational bandwidth of the effective signal be denoted as B_s, and the bandwidth range of the interference signal be B_i. This implies that the interference signal occupies only a portion of the effective signal's bandwidth, rather than the entire frequency band.

2) Interference Factor

The Interference Factor (γ): The interference factor γ is used to quantify the proportion of the interference signal relative to the effective signal's bandwidth. It is defined as

$$\gamma = \frac{\mathrm{B_i}}{\mathrm{B_s}}, \tag{6}$$

Where:

$\mathrm{B_i}$ is the bandwidth of the interference signal, i.e., the width of the frequency band occupied by the interference signal.

B_s is the operational bandwidth of the effective signal, i.e., the bandwidth used by the communication system to transmit the valid signal.

Interference factor γ is one of the important parameters that characterizes the share of the frequency the spectrum occupied by the interference signal. It is directly involved in system performance regarding interference strength, BER, JSR, and spectral efficiency. A higher interference factor γ indicates that the interference signal has a greater impact on the system and is typically associated with degradation in communications performance, such as an increased bit error rate. By analyzing γ, the performance of the system in interference can be evaluated and optimized. Particularly in various modulation schemes, like QPSK, 16QAM, and 64QAM.

3) The BER Results of Different QAM Under Different JSR

Experiments were conducted with the parameter $r = \frac{250}{1024} = 24.4\%$and without other impairments. The BER results of M-QAM under different JSR conditions are shown in Fig 7.

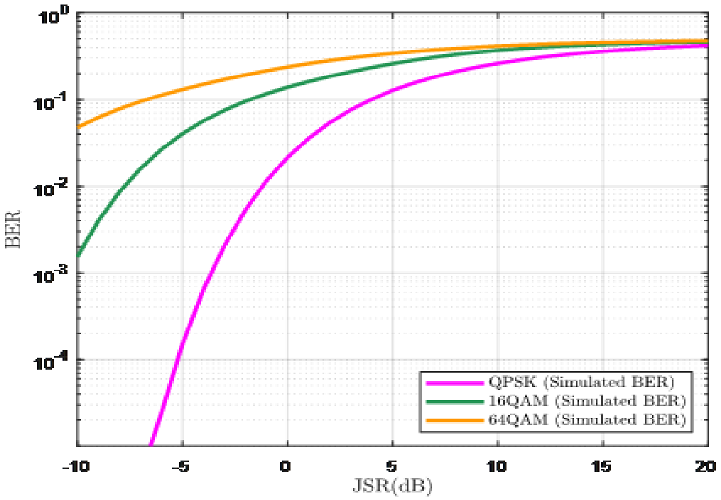


Figure 7. The BER results of different QAM under different JSR

4) image analysis

To begin with, Higher-Order QAM Exhibits Weaker Interference Resilience to Partial Band Interference:

The results indicate that higher-order QAM modulation schemes (e.g., 16QAM, 64QAM) exhibit weaker resistance to partial band interference compared to lower-order QAM schemes (such as QPSK). This is because higher-order modulation schemes carry more bits per symbol, leading to higher symbol density and smaller distances between constellation points. Therefore, when part of the frequency band is interfered with, the symbols in these higher-order modulation schemes are more likely to be misinterpreted, resulting in higher bit error rates (BER). Overall, higher-order QAM modulation schemes perform worse in such interference environments, exhibiting weaker interference resilience.

Furthermore, The Impact of JSR (Jamming-to-Signal Ratio) on BER:

As the JSR increases (i.e., the interference signal becomes stronger relative to the noise signal), the relative strength of the signal increases, and the system's BER performance improves. This is because a higher JSR implies that the signal is more prominent compared to the interference, reducing the impact of interference on the signal, which in turn allows the system to detect the signal more accurately, thereby lowering the BER. This aligns with intuition: when the interference signal is stronger, the system is better able to receive the effective signal clearly, reducing the bit error rate.

Besides, The Effect of Interference Factor:

With the interference signal occupying 24.4% of the bandwidth, the system is subject to interference over a significant portion of the spectrum. For higher-order QAM modulation schemes, this frequency overlap results in more substantial performance degradation, as the constellation points in higher-order QAM are denser, with smaller distances between symbols. This makes the signal more susceptible to interference, leading to an increased bit error rate. Therefore, under the same interference conditions, the performance degradation in higher-order QAM systems is more pronounced, while lower-order QAM schemes (e.g., QPSK) exhibit relatively stronger resistance to interference.

4. Conclusion

4.1. Summary of Research Findings and Conclusions

This study investigates the performance of baseband modulation systems utilizing M-QAM, with a particular focus on the impact of higher modulation orders on system performance. The results indicate that as the order of QAM increases, the distance between constellation points decreases, leading to reduced resistance to noise and other channel impairments. Although higher-order QAM schemes, such as 64QAM, provide higher data transmission rates, their performance under noise, frequency offset, and band interference significantly deteriorates, resulting in a substantial increase in BER. Thus, selecting the appropriate modulation order requires balancing data transmission speed with system robustness. Advanced algorithms, such as carrier synchronization, symbol timing recovery, channel estimation, and equalization, will also be necessary in practical communications to mitigate channel impairments.

4.2. Implications and Significance

These results have an important meaning for the design and optimization of communication systems. The modern tendency in communication systems is the continuous increase in data transmission rates. In this context, the most important challenge is the need to find an appropriate balance between high-speed transmission and the possibility of the system's resistance to noise and interference. In such conditions, the analysis of the M-QAM system with different channel conditions gives significant insight into the choice of modulation schemes for various applications. While higher-order M-QAM modulations yield increased data rates, it makes them more susceptible to noise and impairments, therefore, requiring sophisticated compensation techniques. It reassures that this study emphasizes how this understanding of the trade-off between transmission speed and reliability may guide the design of robust communication systems in realistic environmental conditions.

4.3. Future Research Directions

In this respect, future research work should further consider the performance of M-QAM systems under more complex and dynamic channel conditions. As communication technologies are continuously evolving, traditional modulation schemes and compensation algorithms may struggle to handle new types of channel impairments introduced by high-speed mobility or multi-path fading. It thus follows that future work needs to shift attention to algorithm development, especially deep learning-based adaptive channel estimation, real-time modulation scheme optimizations, and hence enhance robustness in demanding environments. Hybrid modulation techniques, combined with MIMO, shall also be another interesting topic for further investigations, regarding their application on emerging 5G/6G networks, hence opening further perspectives for enhancement of the efficiency and reliability of a communication system.

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