Optimizing Communication System Performance through Hybrid Modulation: A Comprehensive Analysis and Guideline

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Abstract. There is a clear need for dependable high-speed communication systems in light of 5G's recent rapid development. The enormous data that recently developed immersive media generate need to be transmitted, and traditional modulation techniques are unable to provide a suitable level of communication. Consequently, to improve communication system performance, hybrid modulation is needed. This paper examines the communication process and conducts a performance analysis to establish a reasonable method for choosing a hybrid modulation scheme. The constellation diagram, power spectral density, bandwidth efficiency, eye diagram, and bit error rate are the main components that determine a communication system's performance. Based on the analysis, the author concludes that to achieve a better-performing communication system, there must be a compromise between these performance factors. Specific recommendations are provided regarding performance indicators listed in the article, such as the constellation diagram, power spectrum density, bandwidth efficiency, eye diagram, and bit error rate. This work aims to address these issues to provide new researchers with guidance when selecting a hybrid modulation approach and to suggest a line of inquiry in the increasingly complicated and time-consuming age of large data volumes.

Keywords: Digital communication; modulation method; hybrid modulation.

1. Introduction

The state of telecommunications technology has advanced significantly in the fifth generation of wireless systems [1]. The modulation technique has a considerable impact on communication performance in modern digital telecommunication environments. For instance, the requirements for telecommunications reliability have strengthened as media with large amounts of data are developed in recent years, particularly immersive media like virtual reality and 6 Dimensions of Freedom (6DoF) Video [2, 3]. Sometimes, the modulation performance under the traditional Phase Shift Keying (PSK), Frequency Shift Keying (FSK), and Amplitude Shift Keying (ASK) schemes falls short of what 5G requires. For example, higher-ordered modulations are typically used to achieve higher bandwidth efficiency. However, in both ASK and PSK scenarios, the Bit Error Rate (BER) rises in tandem with the modulation's base number, defying the goal of a more dependable communication system. Even while FSK does not experience BER increases with the increased base number, the amount of bandwidth used will significantly rise.

Bandwidth efficiency and bit error rate (BER) are generally traded off in traditional modulation scenarios. To meet the increasing need for communication systems, hybrid modulation techniques have been developed [4, 5]. Combining the benefits of several advanced modulation techniques, it is incorporated through common modulations. However, a vast array of hybrid modulation techniques have been identified and introduced as hybrid modulation technology advances. Establishing guidelines for selecting the modulation technique that best suits a given communication application is crucial.

In digital communication scenarios, this paper compares conventional modulation techniques like ASK, PSK, and FSK with QAM and several innovative hybrid modulations. It also analyzes their performance in three dimensions that should be taken into account in real-world communication systems and provides recommendations for modulation technique selection.

2. Analysis on Performances

As Figure 1 illustrates, the digital communication scenario can be broken down into multiple steps. Therefore, the issue can be broken down in accordance with how it flows through the system to view the overall performance of the communication system. The demodulation aspect uses the appropriate demodulation flow chart as an example in the following. Plus, an additive white Gaussian noise channel is assumed for the channel.

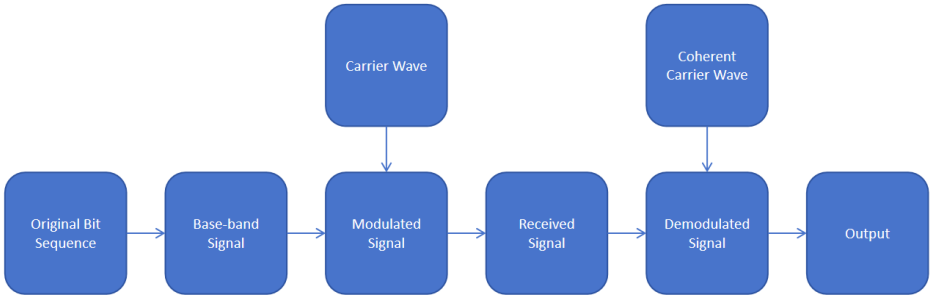


Fig 1. Flowchart of digital communication

2.1. Constellation Diagram

The original bit sequence is first transformed into a base-band signal, which can be shown as a few points in a constellation diagram, using constellation mapping. The 64-QAM constellation diagram is displayed in Figure 2. The constellation points in 64-QAM represent each symbol's projection on its quadrature and in-phase axes. Typically, one uses constellation point positioning to reduce the theoretical BER. More information can be transmitted with a higher order modulation technique, but dependability will suffer.

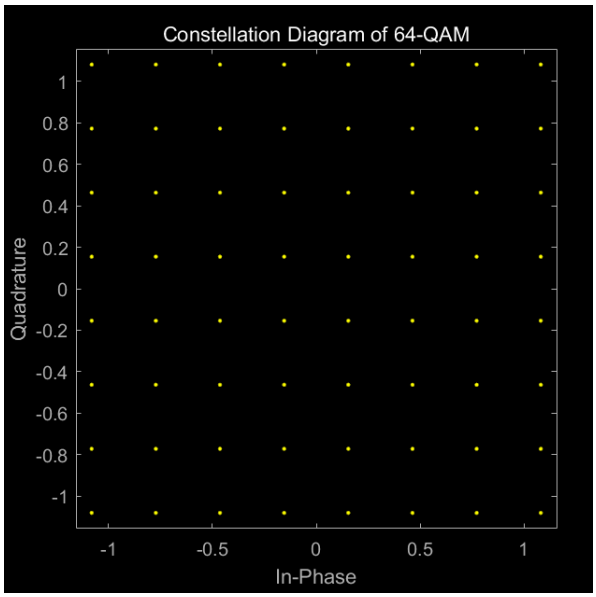


Fig 2. Constellation diagram of 64-QAM

2.2. Power Spectrum Density (PSD)

The pulse amplitude modulation (PAM) filter is applied to the base-band signal. The impulse response of a PAM filter is typically the square root of the impulse response of a raised-cosine filter in order to achieve a dependable transmission with Inter Symbol Interference (ISI) as low as feasible. The base-band signal is then multiplied by the carrier wave to move it to a band that corresponds to

the channel. The sidelobes of the modulated signal will be lost due to the band-limiting nature of raised-cosine filters, which results in a loss of power during PAM [6, 7].

2.3. Bandwidth Efficiency

The data rate that can be transmitted if a channel's bandwidth is available is indicated by bandwidth efficiency. One of the most important performance factors is bandwidth efficiency in order to meet the speed requirements of sophisticated communication networks.

A unique hybrid modulation technique that combines FSK and PSK was reported in a research study in 2015 [8]. The bandwidth efficiency of the hybrid modulation technique was computed by the researchers and contrasted with that of 2PSK and 2FSK. The hybrid efficiency's bandwidth is 1.34 times that of 2PSK and double that of 2FSK.

It is shown that the spectral efficiency of a hybrid QAM-MPPM technique is 20% higher than that of standard QAM [9]. Additionally, compared to OFDM, the suggested OFDM-HNIM has a comparatively higher average attainable rate [10]. These studies demonstrate that bandwidth efficiency can be raised by combining several primary modulation techniques.

2.4. Eye Diagram

The signal will weaken after passing over the channel, and noise will undoubtedly be incorporated into the signal. Eye diagrams are frequently used in simulations and actual communication systems to examine the receiver's side of the signal waveform. It shows the received signal in several segments within a brief time frame. An eye diagram displays several performances. Specifically, the more the inaccuracy created by an out-of-synchronized clock, the higher the slope of the received signal. The adjudication process is affected by the demodulation technique. Figure 3 displays the 4-psk eye diagram. A signal waveform under relatively severe noise interference is displayed in this eye diagram.

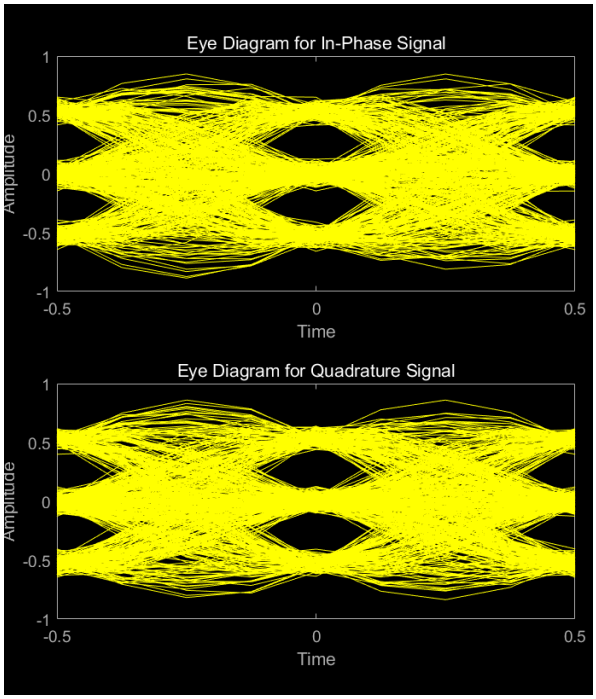


Fig 3. Eye diagram of 4-PSK

2.5. Bit Error Rate

Coherent demodulation is the process of multiplying the received signal by the carrier wave once more at the receiver's end. Subsequently, the demodulated signal is run through a matching filter whose impulse response is modeled after the PAM filter's impulse response at the transmitter end.

Lastly, the amplitude and phase of the demodulated signal are used to determine the bit sequence that the communication system is intended to send.

Figure 4 presents a BER comparison between QAM and PSK, indicating that QAM performs worse against noise than PSK. Table 1 lists the BER of the previously described PFSK in comparison to 2PSK and 2FSK at a Signal to Noise Ratio (SNR) of -20dB [8]. However, compared to regular MPPM, the hybrid QAM-MPPM has a substantially reduced BER [9]. It demonstrates how a hybrid modulation technique could result in a larger BER.

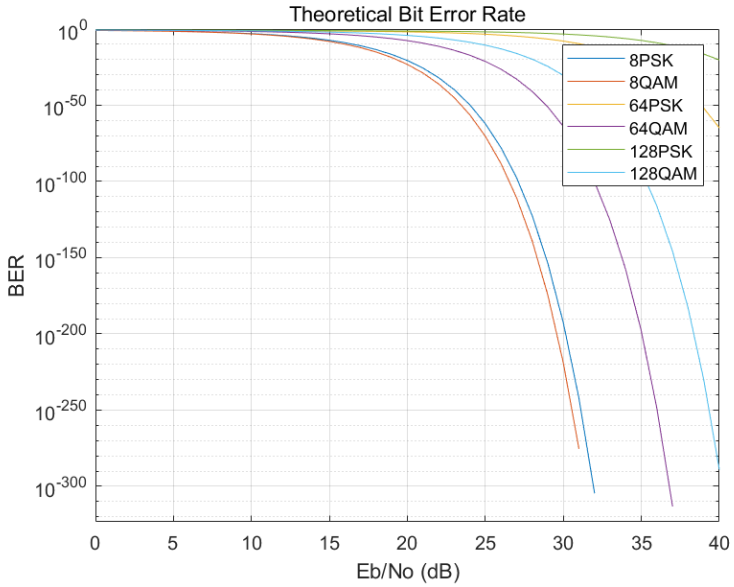


Fig 4. Comparison of BER between PSK and QAM

Table 1. Three Modulation Scheme comparing

Symbol Rate (MHz)	Phase modulation BER (%)		Frequency modulation BER (%)	
	PSK	Hybrid Modulation	FSK	Hybrid Modulation
0.1	0.01	0.2	0.4	0.47
1	10. 17	18.63	20.99	30.47
10	35.20	40.25	38.72	48.6

3. Principle of Selecting Modulation Method

3.1. Low Sidelobe Power Leak

PSD analysis suggests that a modulation technique with less sidelobe power is more competitive in terms of power efficiency when the PAM filter's roll-off factor is set. However, achieving an endlessly small sidelobe power is challenging because real-world electrical components make it almost impossible to create a low pass filter with a nearly vertical slope. Nevertheless, many devices, including graphic equalizers in audio processing, have a very steep slope due to the fact they use finite impulse response (FIR) filter technology. To eliminate extraneous parts it appears to be feasible to process the signals digitally and convert them to an analog signal.

3.2. More Information in Less Power

In real-world communication systems, it generally proves more cost-effective to maintain long-term operation and use if more information can be carried while consuming less power, which translates to a better bandwidth efficiency. It is advised to use higher-order modulation methods in order to maximize energy band use. Additionally, hybrid modulation techniques are frequently suggested as a solution to the energy band usage issue. What’s more, economic development depends

on lowering the energy cost of communications, particularly in this era of huge and growing amounts of data.

3.3. Robustness Against Out of Sync Clock

The use of synchronization technology comes with higher maintenance costs, complexity, and effort requirements. A modulation technique, such as 2-PSK, that is limited to coherent demodulation is not very effective. Simultaneously, a hybrid modulation technique that has a smoother eye diagram slope aids in less complicated clock synchronization needs. Many other details, like noise levels and inter-symbol interference, may also be found by looking at the eye diagram. In the design of a communication system, these factors are also vital to take into consideration in addition to the capability to tolerate asynchronous clocks.

3.4. High Anti-Noise Level

It is evident how to select the modulation method after learning about a modulation system's performance. A crucial metric for assessing a communications system's dependability is the bit error rate. As was already recognized, the anti-noise capability of various hybrid modulation techniques is sometimes weaker. These modulations might not be the best choice in situations where low BER is highly desired. A constellation diagram can be designed using the same methodology as a low-BER system. Maximizing the Euclidean distance between each constellation point is necessary to obtain a theoretically reduced BER system. This means that a maximum Euclidean distance arrangement corresponds to the optimal modulation of least theoretical BER when the transmitter side is sending with equal probability, which is nearly often the case in practical systems. As we investigate this, bees have already demonstrated that the greatest method for making use of space is through the construction of honeycomb structures. It serves as a reminder that the best anti-noise capability is found in a constellation diagram of a honeycomb construction.

The optimal bit error rate can occasionally be as low as 10 to the power of -100. While this appears to be nearly zero bit misjudgments, in actual systems, the bit error rate can be influenced by a wide range of additional factors, including non-Gaussian distributed noise, correlations between the transmitted signal and noise, etc.

3.5. Complexity

In the end, complexity affects a number of different aspects of an actual communication system. Prior to starting a project, basic costs and implementation challenges are always taken into account. Numerous instances of extraordinarily potent communication systems exist, but their expensive cost prevents them from being implemented. Many creative concepts must also be shelved because they are too challenging to put into practice. Furthermore, the development and adoption of industry standards are negatively impacted by too complicated modulation techniques. When constructing communication systems, engineers need to take all of these factors into account, particularly when dealing with composite modulation techniques that are more intricate than conventional modulation techniques.

4. Conclusion

In this study, by taking tips on the flow of communication systems, the author examines how step-by-step analysis of a communication system can be used to optimize modulation scheme performance. There should be sufficient Euclidean distance between each constellation point. It is intended for the sidelobes to have less power. The more anti-time interference ability it possesses, the smaller the slope of the peak of the eye diagram. Even while it is ideal for BER—the most essential communication system performance—to be close to zero, the system's physical architecture will still have some impact. The author also clarifies a few ancillary details that the investigation uncovered. This report can serve as a guide for future research on hybrid modulation approaches by examining

the aforementioned factors. Each of these works contributes to the development of a trustworthy communication network. By using the performance indicators in the communication system that is discussed in the article as examples, this article hopes to motivate researchers. It seems encouraging that this report will be useful for researching 6G. Hybrid modes of modulation will be used in communications to meet the current and future demands for communication system performance, particularly in light of the increasingly sophisticated development of immersive, multi-sensory videos and even meta-verses that need massive amounts of data, like point clouds and light fields. The hybrid modulation will still shine brightly.

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