Evolution of Modulation Techniques: From Analog to Digital and Beyond

Yulin Wang

College of Photonic and Electronic Engineering, Fujian Normal University, Fuzhou FJ 350108, China
136132022072@student.fjnu.edu.cn

Abstract. Modulation technology is one of the important technologies in communication systems. This article provides a review and comparative analysis of various modulation techniques used in communication systems. The study begins with a brief overview of the basic concepts of modulation techniques such as analog techniques of amplitude modulation, frequency modulation, phase modulation, quadrature amplitude modulation, binary phase shift keying, and quadrature phase Shift keying. Then, the signal-to-noise ratio of some popular modulation techniques and the bit error rate of digital modulation techniques are discussed in detail, and the comparative analysis of these techniques is studied. The discussion further extends to advanced modulation techniques such as Orthogonal Frequency Division Multiplexing and Multiple Input Multiple Output. The paper concludes by exploring future trends and challenges in modulation technology, including the role of modulation in 5G and beyond and the potential for cognitive radio and dynamic spectrum access. This study seeks to give a clear understanding of the current state of modulation technology and provide insights into future research directions.

Keywords: Modulation Methods, Communication Systems, 5G Network.

1 Introduction

With the ongoing development of modern science and technology, in today's information age, especially the current 5G era, people can receive information from different parts of the world all the time, and the realization of such a function relies on the development of communication technology. As an important part of communication technology, modulation technology is mainly responsible for converting information signals into carrier signals suitable for channel transmission to facilitate signal transmission and reception. The history of modulation technology can be traced back to the advent of radio communications. At that time, the initial communication used analog modulation technology, and people used analog signals to transmit information such as voice or images. However, with the development of digital technology, people invented digital modulation, and the information transmission of digital modulation technology is more reliable and efficient than

Y. Yue (ed.), *Proceedings of the 2024 International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2024)*, Advances in Engineering Research 240,
https://doi.org/10.2991/978-94-6463-518-8_39

analog modulation technology, so it has begun to be widely used in mobile communications. In addition, the popularity of mobile communications and the increase in application scenarios, requiring people at that time to speed up the data transmission rate accordingly. For this reason, broadband modulation technology emerged as the times require, all to increase the amount of transmitted data. It can be seen very clearly that technology and application needs are producing new advances and improvements in modulation technology to meet requirements such as faster data transmission rates. It is hoped that this paper can help those who are interested in studying modulation technology to better understand some basic knowledge in this area and provide some ideas for research directions, which will help them to prepare knowledge and sort out more in-depth related fields and topics in the future.

This paper will use the development history of modulation technology to review the principles, characteristics, performance and different application scenarios of various modulation technologies. Meanwhile, it will focus on some advanced modulation technologies, discuss the research and application of future 5G or 6G modulation technologies, and predict future development trends. Regardless of the field, modulation technology plays an important role. The topic of 5G or 6G will make the research and application of modulation technology more extensive and in-depth, which will be beneficial to the development and improvement of global communication technology.

2 Overview of Some Basic Modulation Techniques

2.1 Definition and Concepts of Analog Modulation

Analog modulation means that the signal to be modulated is an analog signal. Normally, the frequency of the electrical signal obtained by direct conversion of information sources such as voice, music, or images is very low. This type of signal is called a baseband signal. Analog baseband signals can usually be transmitted in wired channels, but cannot be transmitted directly in wireless channels. Therefore, we need to use corresponding modulation and demodulation technology to allow modulated analog signals to be transmitted in frequency bands in wireless channels. Generally, modulation refers to moving a low-pass baseband signal with a lower frequency component to a channel passband in a higher frequency range for transmission. Common analog modulation is divided into three categories according to the different parameters of the modulated wave: amplitude modulation (AM), frequency modulation (FM) and phase modulation (PM).

Amplitude Modulation. The basic principle of AM is to match the characteristics of the corresponding input signal by changing the amplitude of the carrier signal. In standard AM, the carrier signal is generally a cosine signal, and the signals $\boldsymbol{m(t)}$ and $\boldsymbol{A_0}$ that need to be modulated are multiplied together by a carrier signal to obtain the modulated signal. The detailed flow chart is provided in the Fig. 1. [1]

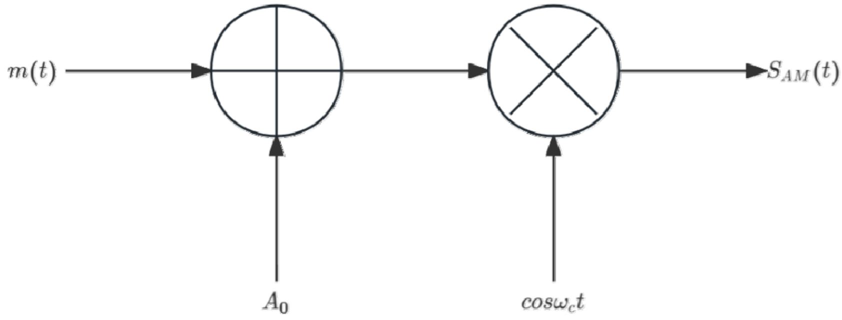

Fig. 1. Standard AM principal block diagram.

It is not difficult to understand that AM uses the changing pattern of the modulation signal $m(t)$ to control the amplitude of the carrier signal $cos\,\omega_c t$. Modulated signal is defined as [1]:

$$S_{AM}(t) = [A_0 + m(t)]\,cos\,\omega_c t = A_0\,cos\,\omega_c t + m(t)\,cos\,\omega_c t \tag{1}$$

The first term of the expression is generally called the carrier term, and the latter term is called the double-side band (DSB) term, which is derived based on the characteristics of its frequency spectrum. Frequency spectrum is defined as [1]:

$$S_{AM}(\omega) = \pi A_0[\delta(\omega+\omega_c) + \delta(\omega-\omega_c)] + \frac{1}{2}[M(\omega+\omega_c) + M(\omega-\omega_c)] \tag{2}$$

For the frequency spectrum analysis expression of this modulation, the Fourier transform of the modulated signal $s_{AM}(\mathrm{t})$ can be directly performed to obtain $s_{AM}(\omega)$. According to the expression, it can be inferred that the frequency spectrum is composed of two positive and negative impulse signals and DSB on both sides. In order not to allow most of the power to be used to transmit the carrier wave, another AM technology is used instead of standard AM in most cases – DSB AM. All its power will be used to transmit information. Fig. 2 displays the detailed flow chart [1].

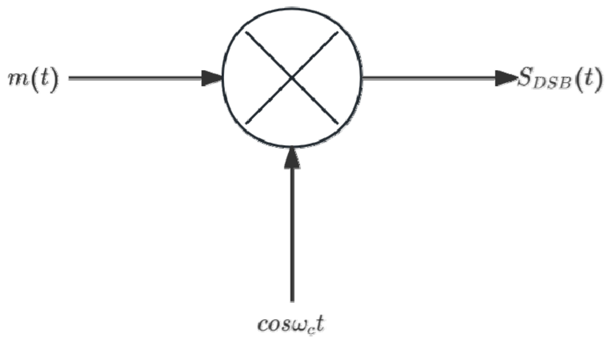

Fig. 2. DSB AM principal block diagram.

Modulated signal is defined as [1]:

$$S_{DSB}(t) = m(t) \cos \omega_c t \tag{3}$$

Frequency spectrum is defined as [1]:

$$S_{DSB}(\omega) = \frac{1}{2}[M(\omega + \omega_c) + M(\omega - \omega_c)] \tag{4}$$

DSB AM technology requires larger bandwidth and transmits repeated information, so the transmission efficiency is not very high. People improved this method and chose to transmit only one sideband information. Single Sideband (SSB) AM technology was born, which can save transmission power and reduce transmission bandwidth. Two SSB modulation principles (filtering method and phase shift method) are represented respectively in Fig. 3 and Fig. 4 [1].

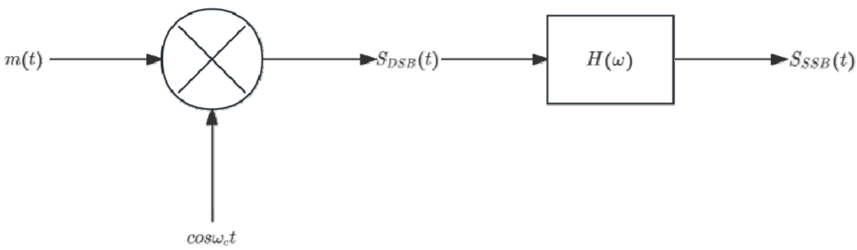

Fig. 3. SSB AM filtering method principal block diagram.

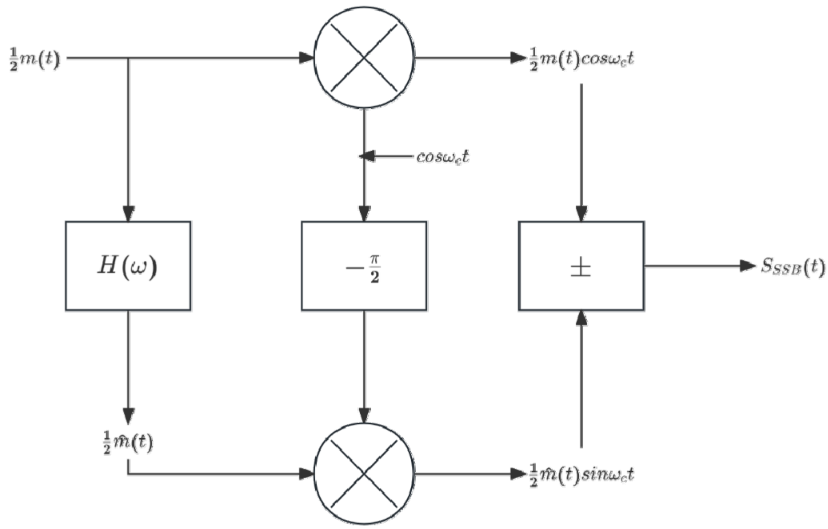

Fig. 4. SSB AM phase shift method principal block diagram.

$H(\omega)$ is the Hilbert transformer, $m(t)$ will become $\hat{m}(t)$ through this transformer. This transformation is linear and suitable linear time invariant system. The Hilbert transform is defined as:

$$H[x(t)] = x(t) * \frac{1}{(\pi t)} \quad \text{(Convolution definition)} \tag{5}$$

The above three are conventional AM analog modulation techniques. It can see the progress and improvements of different AM technologies.

Frequency Modulation. The basic principle of FM is to transmit information by changing the frequency of the carrier wave. The frequency of the carrier wave changes with the strength of the input signal, while the amplitude of the carrier wave remains unchanged. This modulation is more resistant to noise than the previous AM technology. In short, it is more stable in transmitting information. This is why FM radio is often used for music and high-quality sound broadcasts because it can provide better performance and clearer sound than AM. The principal explanation for this modulation is that the instantaneous angular frequency offset of the carrier changes proportionally with the modulating signal. Thus, we can derive its expression step by step. The instantaneous angular frequency offset change with m(t) is defined as:

$$\frac{\mathrm{d}}{\mathrm{d}t}\varphi(t) = K_f m(t) \tag{6}$$

where K_f is the frequency offset constant with unit of rad/s/V/.

$\varphi(t)$ is defined as:

$$\varphi(t) = K_f \int_{-\infty}^{t} m(\tau)\mathrm{d}\tau \tag{7}$$

The modulated signal is defined as [1]:

$$S_{FM}(t) = A\cos\left[\omega_C t + K_f \int_{-\infty}^{t} m(\tau)\mathrm{d}\tau\right] \tag{8}$$

Phase Modulation. The basic principle of PM aims to change the phase angle of the carrier wave based on the change in intensity of the modulation signal on a fixed frequency carrier signal. In other words, the instantaneous phase offset of the carrier changes proportionally to the modulating signal, allowing this modulation technique to use bandwidth more efficiently. We can also use this definition to derive its expression step by step. The instantaneous phase offset change with $m(t)$ is defined as:

$$\varphi(t) = \mathrm{K_p} m(t) \tag{9}$$

where $\mathrm{K_p}$ is the frequency offset constant.

The modulated signal is defined as [1]:

$$S_{PM}(t) = A\cos\left[\omega_c t + K_p m(t)\right] \tag{10}$$

2.2 Definition and Concepts of Digital Modulation

The transmission signal targeted by digital modulation is a digital signal. For example, if you want to transmit binary data like 00110001, you can use digital modulation technology. There are similarities between the fundamental ideas of analog and digital modulation, but because discrete values are features of digital signals. The current common digital modulation technology utilizes to accomplish digital modulation, the carrier is controlled by switch keying based on the discrete value properties of digital signals. The usual essential keying approach is to key the carrier's amplitude, frequency, and phase. There are three basic digital modulation methods: amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). This section will mainly introduce PSK and the improved special quadrature amplitude modulation (QAM) method in detail, because they are the two most common digital modulations in mobile communication systems.

Binary Phase Shift Keying. The carrier wave of the binary phase shift keying (BPSK) modulation method will have two phases. The starting phases 0 and π are commonly used to represent binary 0 and 1 respectively.

A modulated signal with a carrier phase of 0 is defined as:

$$s_0(t) = \cos\omega_c t \tag{11}$$

A modulated signal with a carrier phase of 1 is defined as:

$$s_1(t) = \cos\omega_c(t+\pi) = -\cos\omega_c t \quad (12)$$

A simple BPSK modulation principle is described in Fig. 5 [2].

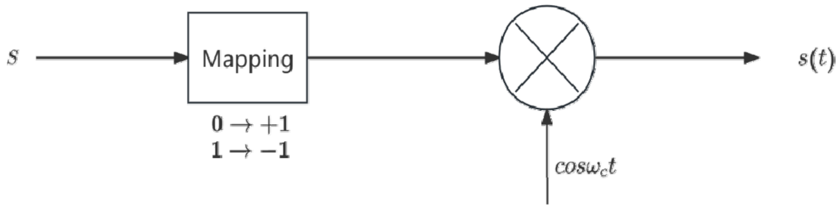

Fig. 5. BPSK modulation principal block diagram

Suppose there is a piece of input data: 101110, and Fig. 6 shows the waveform comparison between its baseband signal and the modulated BPSK signal.

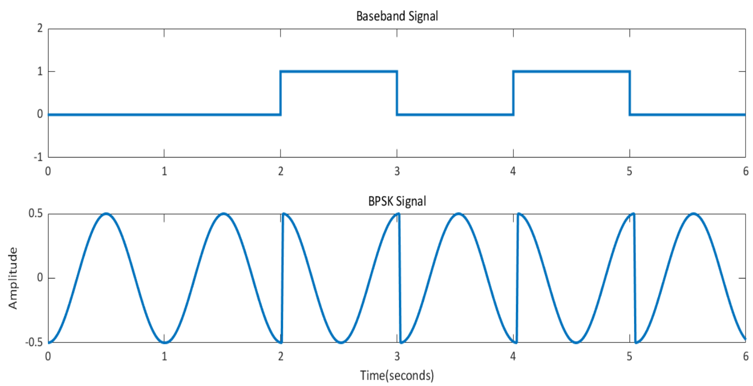

Fig. 6. 101110 baseband signal and BPSK modulated signal waveform.

It can be clearly seen that the different phase waveforms correspond to 0 and 1 of the baseband signals.

Quadrature Phase Shift Keying. BPSK can use the two phases of the carrier to represent 0 and 1 respectively for data transmission. Similarly, it is feasible to use the four phases of the carrier for data transmission. This is the Quadrature Phase Shift Keying (QPSK) modulation method. The four phases of π/4,3π/4,5π/4 and 7π/4 of the carrier are usually used to represent the Gray code ordering of 00, 01,11 and 10 respectively.

A modulated signal with a carrier phase of π/4 is defined as:

$$\cos\left(\omega_c t + \frac{\pi}{4}\right) = +\frac{\sqrt{2}}{2}\cos\omega_c t - \frac{\sqrt{2}}{2}\sin w_c t \quad (13)$$

A modulated signal with a carrier phase of 3π/4 is defined as:

$$cos\left(\omega_c t + \frac{3\pi}{4}\right) = -\frac{\sqrt{2}}{2} cos\, \omega_c t - \frac{\sqrt{2}}{2} sin\, w_c t \tag{14}$$

A modulated signal with a carrier phase of 5π/4 is defined as:

$$cos\left(\omega_c t + \frac{5\pi}{4}\right) = -\frac{\sqrt{2}}{2} cos\, \omega_c t + \frac{\sqrt{2}}{2} sin\, w_c t \tag{15}$$

A modulated signal with a carrier phase of 7π/4is defined as:

$$cos\left(\omega_c t + \frac{7\pi}{4}\right) = +\frac{\sqrt{2}}{2} cos\, \omega_c t + \frac{\sqrt{2}}{2} sin\, w_c t \tag{16}$$

The QPSK modulation principle is shown in Fig.7. [2]

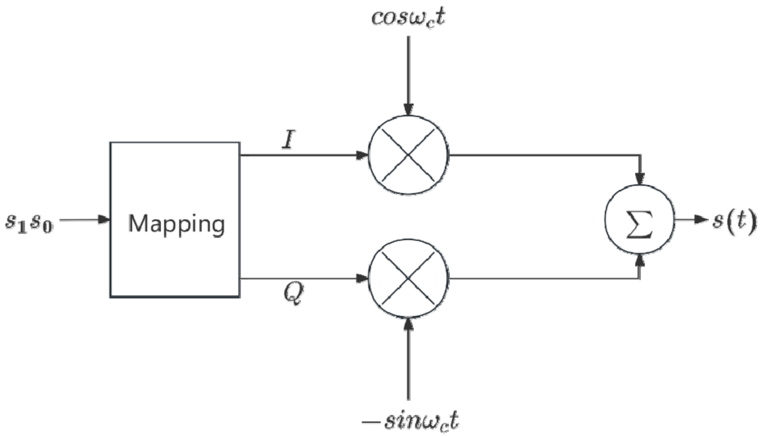

Fig. 7. QPSK modulation principal block diagram.

The modulation of QPSK can be realized by using In-phase and Quadrature-phase (IQ) modulation. The QPSK modulation mapping relationships are shown in Table 1.

Table 1. QPSK modulation mapping relationships.

$s_1 s_0$	I & Q data	Output signal phase
00	$+\frac{1}{\sqrt{2}},\ +\frac{1}{\sqrt{2}}$	$\frac{\pi}{4}$
01	$-\frac{1}{\sqrt{2}},\ +\frac{1}{\sqrt{2}}$	$\frac{3\pi}{4}$
11	$-\frac{1}{\sqrt{2}},\ -\frac{1}{\sqrt{2}}$	$\frac{5\pi}{4}$
10	$+\frac{1}{\sqrt{2}},\ -\frac{1}{\sqrt{2}}$	$\frac{7\pi}{4}$

Assume there is a piece of input data:111010100001, and it can get the waveform comparison between its baseband signal and the modulated QPSK signal in Fig. 8.

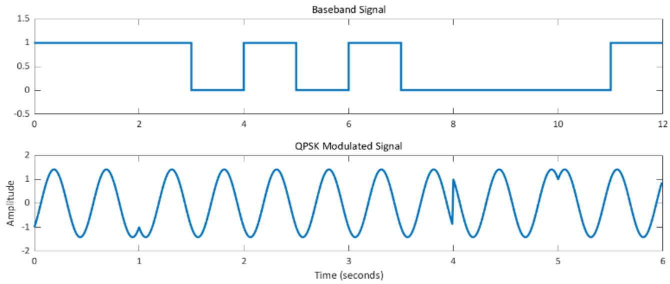

Fig. 8. 111010100001 baseband signal and QPSK modulated signal waveform.

It can be clearly seen that the different phase waveforms correspond to 00, 01, 11 and 01 of the baseband signals.

Quadrature Amplitude Modulation. As the quantity of phases grows, so does the amount of bits that one symbol may send. However, the number of phases cannot be raised forever, since as the number of phases rises, the phase difference between adjacent phases increases. The difference will eventually diminish, which will lead to a decline in the anti-interference capabilities of the signal. Whether it is BPSK, QPSK or a higher-order PSK modulation method, it only makes the phase of the carrier change with the input data, but the amplitude of the carrier does not change. As long as the amplitude and phase of the carrier can change with the input data, Can transmit more data, this is the Quadrature Amplitude Modulation (QAM) method. This section will introduce the modulation method of 16QAM. There are 16 combinations of amplitude and phase, namely: 0000,0001, 0011, ... ,1111. The modulation principle of 16QAM is shown in Fig. 9 [2].

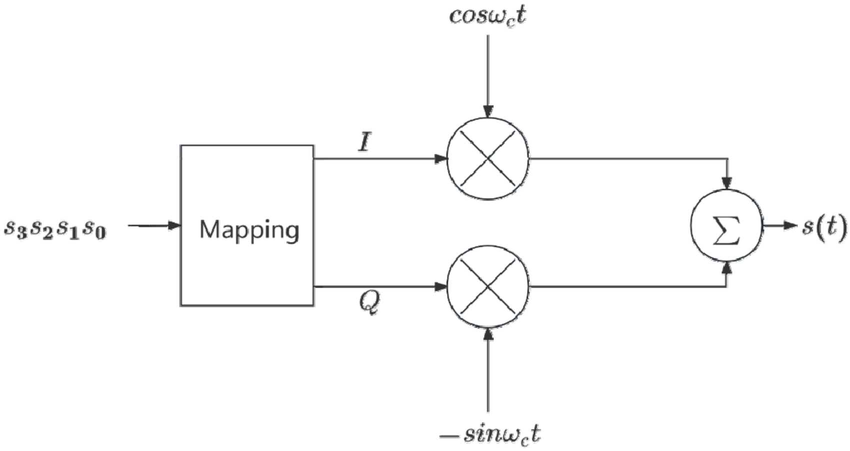

Fig. 9. 16QAM method principal block diagram.

It can be achieved using IQ modulation as well as QPSK. The 16QAM mapping relationships are shown in Table 2.

Table 2. 16QAM mapping relationships.

$s_3s_2s_1s_0$	I & Q data
0000	$+3A, +3A$
0001	$+A, +3A$
0011	$-A, +3A$
0010	$-3A, +3A$
0110	$-3A, +A$
0111	$-A, +A$
0101	$+A, +A$
0100	$+3A, +A$
1100	$+3A, -A$
1101	$+A, -A$
1111	$-A, -A$
1110	$-3A, -A$
1010	$-3A, -3A$
1011	$-A, -3A$
1001	$+A, -3A$
1000	$+3A, -3A$

Assuming that a 400-bit binary data stream is randomly generated and defined according to the 16QAM modulation method, each signal, that is, each transmitted symbol can carry 4 bits of information, and thus 100 transmitted symbols can be obtained. Fig. 10 depicts a comparison of the waveform diagrams for the baseband and modulated 16QAM signals.

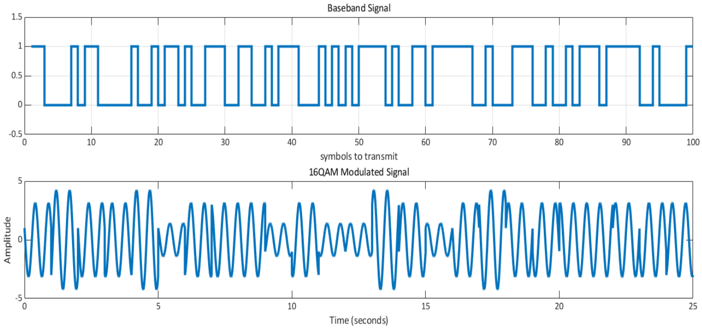

Fig. 10. baseband signal and 16QAM modulated signal waveform.

Compared with BPSK and QPSK, the 16QAM modulation signal waveform can be clearly felt. Not only the phase changes, but also the amplitude changes. It can directly to feel the effect of this modulation method on the transmission of information. Utilization increases significantly.

3 Comparative Analysis of Some Different Basic Modulation Techniques

As technology advances, the emergence of these basic modulation techniques is a normal trend. The most important aspect of evaluating a modulation technology is analyzing its performance. Selecting the appropriate modulation technology in different application scenarios can maximize utilization. This paper will introduce the performance aspects and applications of some basic modulation techniques.

3.1 Performance Analysis

For modulation systems, the most representative indicator is the signal-to-noise ratio (SNR). Assume that all systems have equal input signal power S_i at the receiver input end and the additive noise is Gaussian white noise with a mean value of 0, a bilateral power spectral density of $\frac{n_0}{2}$, and the bandwidth of the baseband signal $m(t)$ is f_m, and meet the conditions:

$$\begin{cases} \overline{m_{(t)}} = 0 \\ \overline{m^2(t)} = \frac{1}{2} \\ |m(t)|_{max} = 1 \end{cases} \tag{17}$$

A comparison of various analog modulation systems is shown in Table 3 [1]. PM is not considered in the table because it is rarely used or used to generate FM.

Table 2. The comparison of various analog modulation systems

Modulation method	Transmission bandwidth	Output SNR $(\frac{S_0}{N_0})$	Equipment complexity
AM	$2f_m$	$\frac{1}{3}(\frac{S_i}{n_0 f_m})$	Easy
DSB AM	$2f_m$	$(\frac{S_i}{n_0 f_m})$	Medium
SSB AM	f_m	$(\frac{S_i}{n_0 f_m})$	Complex
FM	$2(m_f + 1)f_m$	$\frac{3}{2}m_f^2(\frac{S_i}{n_0 f_m})$	Medium

Table 2 shows that SSB has the highest frequency band utilization and the smallest bandwidth. On the contrary, the bandwidth of FM increases with the growth of m_f (FM index), and the frequency band utilization is the lowest. In terms of SNR comparison, FM has the best anti-noise performance, DSB and SSB are about the same, and AM is the worst. Therefore, AM is easily disturbed by noise.

When comparing digital modulation technologies, bit error rate (BER) is a very important evaluation indicator. The BER of BPSK and QPSK is defined as [1]:

$$P_{BPSK} = \frac{1}{2} erfc \sqrt{\frac{S_0}{N_0}} \tag{18}$$

$$P_{QPSK} = 1 - \left[1 - \frac{1}{2} erfc \sqrt{\frac{S_0}{2N_0}}\right]^2 \tag{19}$$

When the SNR is low, the bit error rate of BPSK is lower than that of QPSK. in an inferior SNR working environment, the anti-noise performance of BPSK is better than QPSK. But in terms of the amount of data transmitted, BPSK transmits much less data than QPSK.

3.2 Application-Specific Analysis

Different modulation methods have corresponding suitable usage scenarios. There is no modulation technology that will be permanently obsolete. In this section, the paper will step by step discuss some of the past or present use cases of some modulation techniques.

In the process of understanding and learning modulation techniques, AM is the first modulation technique to learn. In the early 20th century, AM broadcasting emerged as the first modulation method for radio broadcasts. It covers medium, longwave and shortwave frequency bands and features low propagation loss, shallow penetration depth and wide broadcast ambit [3]. It can be said that AM broadcast transmission is the relatively lowest cost method. The modulation method used in broadcasting is FM, and many old radios continue to use FM. FM broadcasting has higher sound quality and fidelity than AM radio because of its wider bandwidth and immunity to noise interference. This is ideal for use cases that provide better stereo quality and reception. In modern times, there are studies how to use FM radio broadcasting as a basis to transmit images together with other modulation methods to warn drivers. The study designed a system that enables FM broadcast infrastructure to quickly disseminate traffic incident notifications without the need for an Internet connection, thus ensuring wide coverage of public roads [4].

A hybrid optical amplifier is an optical amplifier that combines multiple gain media or technologies to achieve optical signal amplification. Optical amplifiers are used in fiber optic communication systems to increase the strength of optical signals for transmission over long distances without converting the signals into electrical form. To implement this amplifier, some researchers used the BPSK modulation method and discussed it from the performance of the amplifier. The study also explores how BPSK affects free space optical (FSO) system performance [5]. FSO technology offers versatile solutions for specific communication challenges and enhances performance in various applications [6]. In satellite communication application scenarios, digital modulation technology is very critical. For example, the multiple phase shift keying (MPSK) modulation strategy is essential to increasing the ka-band mobile satellite communication systems' bandwidth utilization. Choosing the highest-order MPSK modulation scheme is the key to achieving the target bit error rate under different weather conditions and environments. Higher-order MPSK modulation techniques can increase broadband utilization, but it also limits error tolerance. Therefore, in practical applications, transmission efficiency is increased when the system automatically chooses the highest-order MPSK modulation method based on the target bit error rate performance [7]. QAM, as today's mainstream modulation method, has many application scenarios. And Using radio over fiber (RoF), a single broadband network is created. It can support optical and wireless technologies, extensively studied for its advantages in digital RoF systems. Digital RoF systems use high order QAM signals like 64-QAM and 256-QAM to achieve long fiber transmission distances within required EVM limits [8].

3.3 Orthogonal Frequency-Division Multiplexing

With the continuous improvement of the weight of the code required to be transmitted, the transmission bandwidth is getting wider and wider. The transmission channel of mobile communication may be a wireless channel in large cities in large cities. To deal with this challenge, orthogonal frequency-division multiplexing (OFDM) has developed vigorously. This modulation technology is different from the traditional modulation method. It is to divide the input data stream into multiple low -speed sub -carrier waves, and form multiple orthogonal sub -load channels on the frequency domain. Each child carrier can independently modulate and transmit data.

Because different sub -carriers are orthogonal, they avoid interference with each other. OFDM technology improves the system's spectrum efficiency and data transmission rate by transmitting multiple sub -carrier waves in parallel on the frequency domain. Each child carrier can carry different data streams to achieve multi -user transmission at the same time.

In the application of OFDM, it can be used in a variety of situations, especially in wireless communications. In addition, in recent years, OFDM has sparked great interest in research as a potential modulation system for future radars. As a result of the improving hardware capabilities, OFDM development has received sufficient attention despite the challenging requirements of OFDM sampling rate and processing power for automotive applications [9].

3.4 Multiple-Input and Multiple-Output

Different from conventional analog modulation technology and digital modulation technology, multiple-input and multiple-output (MIMO) is a technology which uses multiple transmit antennas and multiple receive antennas to increase the performance of communication systems. This modulation method transmits data through multiple independent channels to enhance the reliability and system anti-interference ability.

In 5G applications, MIMO modulation technology is widely used. Large-scale MIMO is an important support technology for 5G NR, which can improve reliability and data rates in challenging environments. The massive MIMO system in 5G uses the large -scale antenna array at the base station to allow multiple parallel communication through space division multiple access (SDMA), thereby improving the data rate and link reliability and improving energy efficiency [10].

4 Future Trends and Challenges in Modulation Techniques

4.1 Modulation for 5G and Beyond

5G and 6G, which we must work hard to conquer in the future, are the hottest topics now. How to develop a modulation method that can transmit more information and have better anti-noise performance based on the existing 5G modulation technology is now the basic problem to overcome 6G.

According to some experts, 5G modulation techniques will likely be improved in the future for satellite communications, offering more flexibility and better pre-compensation. The research on the integration of ground mobile and satellite communications in 6G will involve the harmonious integration of high, medium and low earth orbit satellite and ground communications. Non-orthogonal multiple access (NOMA) technology enhances user access capacity by sharing resources, especially beneficial in satellite communications due to longer time delays [11].

Other researchers are also working hard to study new modulation methods and try to combine them with previous ones. For example, index modulation technology refers to an innovative method used to improve spectrum and energy efficiency in wireless communication systems. The combination stands for OFDM with indexed modulation (OFDM-IM), another important technology that utilizes subcarrier indexing to transmit data. By assigning different indexes to subcarriers, OFDM-IM can improve spectral efficiency by conveying additional information through the index field. SIM-OFDM is an enhanced variant of OFDM-IM that selectively activates subcarriers based on incoming bits. This selective activation optimizes subcarrier utilization, thereby increasing spectral efficiency compared to conventional OFDM systems. Through their experiments, they demonstrated that OFDM-IM and SIM-OFDM exhibit excellent bit error performance and spectral efficiency compared with classical OFDM [12]. This empirical evidence highlights the practical advantages of employing indexed modulation techniques in wireless networks. Despite existing technological limitations, experts feel that indexed modulation's potential to enhance spectral efficiency and dependability without requiring additional time or frequency resources makes it a promising solution to meeting the growing demands of wireless communication networks.

4.2 Cognitive Radio and Dynamic Spectrum Access

Similarly, as bandwidth requirements continue to increase, subsequent OFDM and MIMO technologies can increase spectrum utilization efficiency several times, but they are still unable to meet the growth demand. Currently, it is necessary to improve the spectrum management method. In this way, cognitive radio (CR) technology was born and developed vigorously. CR technology permits opportunistic usage of licensed frequency bands by letting secondary users to access them while prime users are not utilizing them. It operates based on self-awareness, reconfigurability and intelligent adaptive behavior, allowing dynamic access to frequency bands [13].

Dynamic spectrum access (DSA) technology can be used in conjunction with cognitive radio technology to achieve intelligent spectrum management and optimization to adapt to changing wireless communication environments and needs. Various strategies such as optimal channel selection, cooperative spectrum sensing, and transaction-based spectrum optimization has been suggested as a way to increase IoT spectrum efficiency. Dynamic spectrum sharing and cognitive IoT are two areas where there are still obstacles standing in the way of improving the spectral efficiency of heterogeneous IoT networks [14].

5 Conclusion

In this paper, we can fully realize the obvious progress and development of modulation technology from the basic analog and digital modulation technology principles, performance and application scenarios to the research of some advanced modulation technologies popular today. Especially in the modulation technology for future 5G and even 6G research, there is a certain direction. It can provide researchers who want to further explore modulation technology with a general direction for studying 5G or 6G. Strengthening research on satellite communications and terrestrial communications or index modulation is a reference research direction. It is hoped that more and more researchers will be able to propose more effective and innovative modulation methods in the future.

. References

1. Fan, C., Cao, L.: Principles of Communication. 7th edn. National Defence Industry Press, Beijing (2012).
2. Chen, A.: The Communication Principle is Simple and Profound. 1st edn. Tsinghua University Press, Beijing (2018).
3. Yu, T., Chen, Y. : The Development and Future of Communication and Broadcasting Antennas for Amplitude Modulation Radios. IEEE 2nd International Conference on Electronics and Communication Engineering (ICECE) 2019, pp. 190-194. Xi'an, China (2019).
4. Bozomitu, R. G., Hutu, F. D., De Pinho Ferreira, N.: Drivers' Warning Application Through Image Notifications on the FM Radio Broadcasting Infrastructure. IEEE Access 9, 13553-13572 (2021).
5. Vanmathi, P., Sulthana, A. K. T.: Hybrid Optical Amplifier Performance in OAF Using OOK and BPSK Modulations. International Conference on Intelligent Computing and Control Systems (ICCS) 2019, pp. 695-699. Madurai, India, (2019).
6. Rahman, M. M., Badrudduza, A. S. M., Sarker, N. A., Ibrahim, M., Ansari I. S., Yu, H.: RIS-Aided Mixed RF-FSO Wireless Networks: Secrecy Performance Analysis With Simultaneous Eavesdropping. IEEE Access 11, 126507-126523 (2023).
7. Li, J., Li, Y.: Modeling Ka-band satellite communication system with MPSK. 2nd IEEE International Conference on Computer and Communications (ICCC) 2016, pp. 1785-1789. Chengdu, China (2016).
8. Babir, M. R. N., and Choudhury, P. K.: On the performance of high order QAM signals for analog and digital radio over fiber systems. 4th International Conference on Advances in Electrical Engineering (ICAEE) 2017, pp. 379-382. Dhaka, Bangladesh (2017).
9. Nuss, B., Diewald, A., Schoepfel, J., Martini, D., Pohl, N., Zwick, T.: 76GHz OFDM Radar Demonstrator with Real-Time Processing for Automotive Applications. IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM) 2020, pp. 1-4. Linz, Austria (2020).
10. Khan, M. F., and Pesch, D.: On Performance of multi-user Massive MIMO for 5G and Beyond. IEEE 95th Vehicular Technology Conference: (VTC2022-Spring) 2022, pp. 1-5. Helsinki, Finland (2022).
11. Chen, S., Sun, S., Kang, S.: System integration of terrestrial mobile communication and satellite communication —the trends, challenges and key technologies in B5G and 6G. China Communications 17(12), 156-171(2020).
12. Mgobhozi, B., Nleya, B.: Efficient Index Modulation Techniques for 5G and Beyond. International Conference on Electrical, Computer and Energy Technologies (ICECET) 2023, pp. 1-6. Cape Town, South Africa (2023).
13. Joon, R., Tomar, P.: Cognitive Radio Wireless Sensor Networks: A Survey. Fifth International Conference on Computational Intelligence and Communication Technologies (CCICT) 2022, pp. 216-222. Sonepat, India (2022).
14. Li, F., Lam, K. -Y., Meng, L., Luo, H., Wang, L.: Trading-Based Dynamic Spectrum Access and Allocation in Cognitive Internet of Things. IEEE Access 7, 125952-125959 (2019).