Wireless signal modulation technology

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Abstract. In this paper, based on wireless signal modulation technology, this paper introduces the more mainstream new modulation techniques, including OFDM, GFDM, and UFMC, in recent years. The second part of the article will introduce the wireless communication modulation techniques, the signal transceiver mechanism, and the principle of each part to realize the three systems. In the third part of the paper, the performance of each system in a noisy environment will be simulated and analyzed using the Matlab platform, including the BER comparison and analysis of different systems under different signal-to-noise ratios. In addition, the development of each modulation technology in recent years and the advantages of each technology will be introduced in this part, based on which the corresponding application scenarios and future development trends are also presented. In the future development of communication technology, each technology will also have its development prospect and expectation.

Keywords: Wireless, Modulation, OFDM, GFDM, UFMC.

1. Introduction

Wireless communication modulation technology emerged in the 1830s and has been developing at high speed since the birth of the first generation of wireless communication systems (referred to as 1G) around 1970 [1]. Among them, FDMA technology combined with analog modulation (FM) and 2FSK digital modulation is the main communication technology used in 1G systems. Still, it can only realize regional mobile communication due to the bandwidth limitation. In the early 1990s, the 2G generation came, which mainly used GMSK and QSK modulation technology with TDMA system. This generation's technology provided full regional roaming services compared to the previous generation. After the third generation of mobile communication systems first appeared in 2007, which mainly used QPSK modulation with CDMA systems to provide both voice and data services while it is worth noting that the high speed of CDMA technology made video applications in the communication process a reality [2]. The advent of the 4G generation mainly used OFDM and QAM modulation technologies, which one can use to transmit high-quality video images, which meets the requirements of people for wireless services.

In recent years, the emergence of 5G and 6G access technologies has gained widespread attention. In the past few years, multi-carrier technology has been proposed based on the OFDM single-carrier technology used in 4G communications. Unlike OFDM, which requires additional overhead (e.g., cyclic prefixes (CPs) to mitigate interference [3]) and is susceptible to intercarrier interference and synchronization errors, Generalized Frequency Division Multiplexing (GFDM) based on multi-carrier filter banks has become one of the key technologies for fifth generation (5G) standards. Low out-of-band leakage and immunity to phase noise and frequency offsets are the main characteristics of GFDM. Instead of each GFDM symbol, cyclic prefixes are applied to each GFDM block. Peak-to-average power ratio (PAPR) can be decreased by designing flexible pulse shaping of individual carriers [4]. For future 6G with higher spectral and power efficiency, higher reliability and lower latency requirements, hybrid multilayer coding (MLC) and bit interleaved coded modulation (BICM) schemes based on LDPC codes have also been proposed in recent years. It can achieve better BER performance and lower complexity than the traditional BICM scheme [5]. Based on this, a new waveform technology, orthogonal time-frequency space (OTFS) modulation, is proposed for the future 6G mobile communication in high-band and high-speed mobile scenarios. The research results show that compared with orthogonal frequency division multiplexing (OFDM), future

communication modulation approaches could take advantage of OTFS's improved robustness, lower peak-to-average ratio, and potential to achieve full diversity gain in an infinite number of ways [6].

2. The Principle

Wireless signal modulation is the process of processing the coded information of a signal source into a form suitable for channel transmission. The baseband signal, which is a frequency component with a lower frequency than the DC component, is typically included in the coded information of the signal source (the source) [7]. Nevertheless, the baseband signal is frequently not available for channel transmission, so the baseband signal must be converted into a band signal with a very high-frequency in relation to the baseband frequency. This is accomplished by altering the high-frequency carrier's amplitude, phase, or frequency so that it varies with the baseband signal's amplitude [8]. In the communication environment, the movement of the mobile station deteriorates the wave propagation conditions, especially the effect of fast fading causes a sharp change in the received field strength. Therefore, when choosing a modulation method, it is important to consider one resistant to interference. This can be applied to fast-fading channels, occupies a smaller bandwidth to improve spectrum utilization, and has a small out-of-band radiation to reduce interference to neighboring channels [9].

This paper will introduce the first modulation technique for orthogonal frequency division multiplexing, OFDM (Orthogonal Frequency Division Multiplexing). OFDM is a form of multi-carrier modulation, or MCM (Multi-Carrier Modulation). The core idea of OFDM is to divide the channel's total bandwidth into many orthogonal sub-channels, convert the high-speed serial data signal into parallel low-speed sub-signals, and then use these parallel low-speed sub-signals to modulate each other orthogonal sub-carriers. So that it can achieve synchronous transmission of signals in these sub-channels [8]. Its modulation and demodulation are based on the multi-carrier transmission technique known as IFFT, which has the broadest use and the least complicated implementation [8].

For the N-channel signals to be completely separated at reception, satisfying that any two carriers are orthogonal for each code element duration TS time is necessary. The family of trigonometric functions {1, sint, cost, sinnt, cosnt,..} satisfies the mutual orthogonality between any two different functions (the integral of the product of two different functions in [a π, π] is 0), and using this property, this paper can obtain carriers that are mutually orthogonal to each other.

Where the superposition of the signals at the transmitter side in space can be written as

$$f(t) = \Sigma A_i \sin\left(2\pi \mathrm{f_i t}\right) + \Sigma B_i \cos(2\pi f_i t) \tag{1}$$

Its complex form is

$$f(t) = \Sigma B_i e^{j2\pi f_i t} \tag{2}$$

It can be seen from the complex form that when discretized for time t, OFDM is actually an operation that solves the Fourier inverse transform of the transmitted signal on each subcarrier. OFDM is also implemented using the IFFT module when modulation is performed, so this is a multi-carrier transmission scheme with the lowest implementation complexity and the widest application [10].

The second is Generalized Frequency Division Multiplexing (GFDM), a non-orthogonal multi-carrier technique based on cyclic block structure developed on the basis of traditional filter bank multi-branching multi-carrier, which has the advantages of high time-frequency focus, insensitivity to carrier frequency bias and timing error, flexible scheduling of time-frequency resources and It has the advantages of high time-frequency focus, insensitivity to carrier frequency bias and timing error, flexible time-frequency resource scheduling and high generality. The following figure shows the block diagram of the transceiver system of the GFDM system [11]. GFDM system at the transmitter side, the binary data is generated by the source. The coding operation is performed, which is generally

divided into two parts: source and channel coding, and then the mapper uses digital modulation to map the binary data vector into the constellation diagram to complete the mapping operation, and then the GFDM modulation is completed by the digital modulator, and finally the GFDM modulation is added. The cyclic prefix is sent to the antenna. The synchronization process is performed at the receiver side. Channel estimation and equalization operations are applied to the received sequence with the cyclic prefix removed. The GFDM demodulation, inverse mapping, and decoding operations are performed to obtain the binary signal [10].

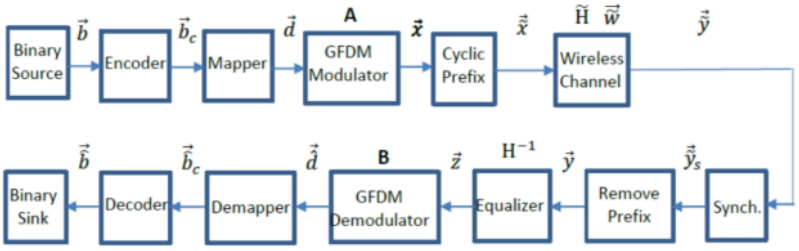


Fig 1. Block diagram of GFDM transceiver system

The third is Universal Filtered Multi-Carrier (UFMC). The UFMC technique is a filter-based multi-carrier transmission scheme, which first divides the entire bandwidth into multiple sub-bands, each consisting of a set of sub-carriers. Then it uses a finite-length unit impulse response (FIR) filter for each sub-band. Impulse Response (FIR) for each subband to suppress the spectral side flap level to obtain higher robustness. The suppression of the partials reduces the inter-block interference caused by synchronization errors. The concentrated signal power reduces the information loss in case of slight temporal misalignment, thus relaxing the synchronization requirements of the UFMC system [12]. The UFMC waveform technology was created to suit the needs of 5G applications better. This technique divides all subcarriers into subbands at the transmitter side, filters each subband, allows signals to be transmitted in parallel in the subbands, and performs a 2N-point fast Fourier transform (FFT) on the receiver side after zeroing the data. Compared with OFDM, the use of UFMC filter can effectively suppress signal trailing, and demodulation implementation is simpler without CP.

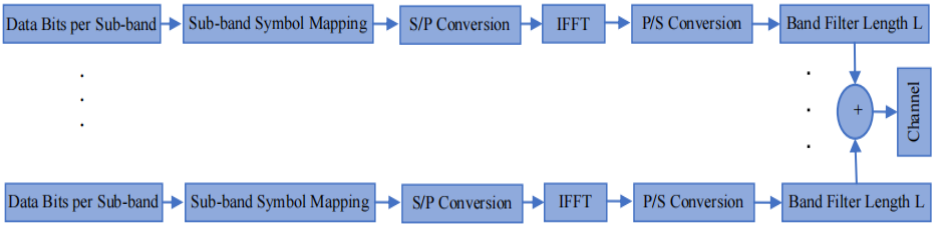


Fig 2. UFMC transmitter solution flow chart

3. signal modulation technology

3.1. OFDM System

OFDM is now the most widely used multi-carrier technology, which has been used as its physical layer technology by standards such as LTE and WiFi [13]. This belongs to the category of infinite channel high speed data transmission technology, which can resist many kinds of interference, and its anti-interference performance and operation stability are outstanding compared to other technologies. Here, Matlab software will be used to simulate and analyze the noise immunity of the system. The transmitter side is used to generate binary bit data using a random function. Then the bit data is taken for QPSK modulation to obtain the mapped constellation points, which are then fed into the IFFT module for frequency domain to time domain transformation. Finally, Gaussian white noise is added to the channel. The signal arrives at the receiver through the Gaussian white noise channel, where the

receiver first performs the cyclic prefix removal, then the FFT transform to exchange the bit data positions, and finally the QPSK demodulation to obtain the original bit stream data [14]. Thereafter, the statistical plot of the signal was then obtained by analyzing its BER under different signal-to-noise conditions, and the specific BER curve is shown in Figure 2 [14].

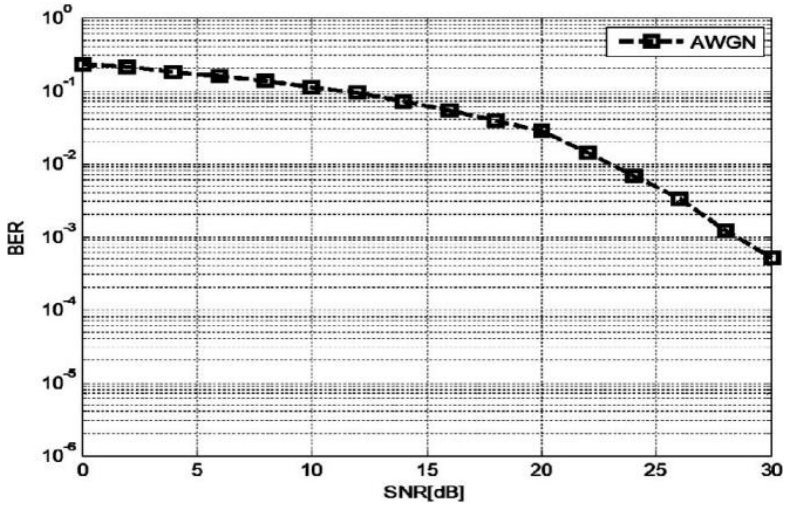


Fig 3. UFMC and OFDM in signal-to-noise ratio and BER

Based on this analysis, it is understood that because of the need to achieve high-rate transmission in wireless signal transmission, the bandwidth required for transmission will also increase, and the traditional single-carrier technology has a poor ability to resist channel fading. The multi-carrier parallel transmission technology solves this problem to a great extent. The general FDM technology transmits information through multiple subcarriers in parallel. To ensure that the subcarriers do not interfere with each other, it is necessary to set up isolation bands between the subcarriers. The multi-carrier parallel transmission technology has solved this problem to a great extent [7]. It can support multi-user access.

Nowadays, the fifth generation of mobile communication systems are rapidly spreading worldwide. The purpose of communication is no longer just to transmit information but more about the pursuit of transmission rate, delay, and quality. To achieve this purpose, the emergence of the MIMO-OFDM system is eye-catching. The multiple-input multiple-output (MIMO) technique [15] transmit diversity and receive diversity and provides spatial multiplexing gain using multiple antennas, which can greatly increase the system capacity and break the capacity bottleneck of single-antenna systems. Therefore, combining MIMO technology with OFDM technology can increase system capacity, improve system performance and solve the frequency selective fading problem of the channel without increasing the system bandwidth, which constitutes a MIMO-OFDM system [16]. This has emerged as one of the essential technologies for the fifth-generation mobile communication system (5G), which will enable consumers to receive high-speed and dependable transmission services while also considerably enhancing the functionality of the communication system. The following figure shows the block diagram of the implementation of the MIMO-OFDM system[17].

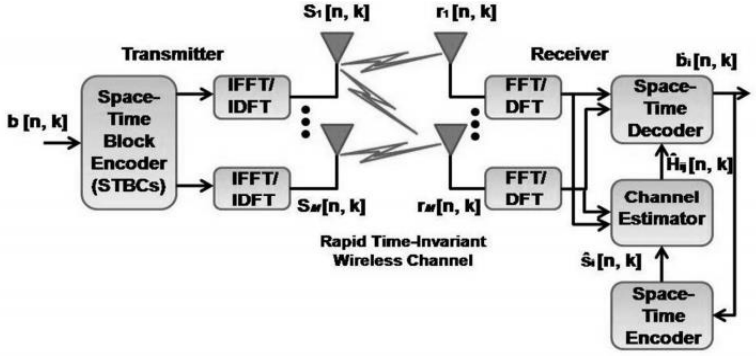


Fig 4. Implementation of the MIMO-OFDM system

3.2. GFDM System

However, it has also been shown that disadvantages such as severe out-of-band leakage, high peak average power ratio (PAPR), sensitivity to synchronization errors, and low spectral efficiency due to long cyclic prefix (CP) determine that the conventional OFDM waveform is not the best solution for the air interface waveform of future integrated communication systems in the sky and earth [10-13]. Therefore, in this paper, two more out of various improved multi-carrier technology schemes, Generalized Frequency Division Multiplexing (GFDM) and Universal Filtered Multi-Carrier (UFMC) waveforms, are proposed [15].

GFDM is a non-orthogonal multi-carrier technique based on cyclic block structure developed from the traditional filter bank multi-branch multi-carrier. It has the advantages of high time-frequency focus, insensitivity to carrier frequency bias and timing error, flexible scheduling of time-frequency resources, and high versatility. Because GFDM has a lower peak-to-average power ratio (PAPR) and uses a raised pulse-shaping cosine to produce a more efficient bandwidth with lower out-of-band radiation (OOB), it overcomes the problem that OFDM technology cannot meet the requirements of 5G. In addition, GFDM is flexible in setting its symbols, supports fragmented spectrum techniques, and is compatible with multiple-input multiple-output (MIMO) techniques [18].

In order to get a clearer picture of the performance of the GFDM system, the BER of this system is compared here with the OFDM system under QPSK modulation, 10 MHz channel bandwidth, and 4 × 4 MIMO conditions using Matlab software. The parameters such as the number of subcarriers, number of subframes, number of transmit and receive antennas, Channel Quality Indicator（CQI) delay, the maximum number of retransmissions, number of resource blocks, and system bandwidth are set before the simulation, while the data transceiver link parameters are adjusted to appropriate parameters [19]. The following figure compares BER simulation results for GFDM and OFDM [20].

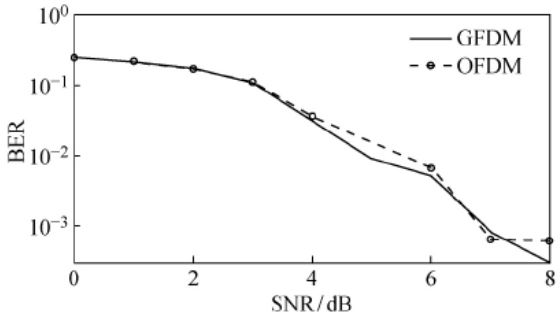


Fig 5. Comparison of BER simulation results of GFDM and OFDM.

According to the above figure, it can be seen that under the same conditions, the two perform similarly when the signal-to-noise ratio is in the range of 0-3 dB, after which the GFDM system basically outperforms the OFDM system. Thus, this paper can conclude that in the case of larger signal-to-noise ratio, this paper prefer GFDM system instead of OFDM for information transmission.

In recent years, after considering various factors such as spectral efficiency, out-of-band leakage, multi-service adaptability, and compatibility with key 4G/5G technologies, combined with its stronger adaptability to synchronization errors. The generalized frequency division multiplexing (GFDM) technology is proposed as an air interface transmission waveform for future satellite mobile communication systems and even for integrated communication systems between heaven and earth with adaptable modifications. Low out-of-band radiation facilitates the coexistence of satellite GFDM systems with terrestrial mobile communication systems, making integrating into terrestrial wireless networks easier. High spectral efficiency enables satellite GFDM systems to utilize satellite frequency resources to achieve higher transmission efficiency fully. multi-service compatibility makes satellites better able to support a variety of service scenarios, with typical applications such as short packet burst IoT services [21]. More importantly, GFDM has a stronger adaptation to synchronization errors than OFDM due to the relaxation of the strict orthogonality restriction between subcarriers. This loose

uplink synchronization characteristic makes it more suitable for highly dynamic satellite-ground communication environments [22].

Finally, because the GFDM system significantly reduces out-of-band leakage, it can realize flexible configuration of the fractional and dynamic spectrum and enable it to be used in low-latency scenarios by configuring data blocks. the same as OFDM technology, it can also be compatible with MIMO technology to improve system performance.

3.3. UFMC System

UFMC conforms to modern 5G communications specifications as a very advanced waveform design technology. Each subband of UFMC consists of many adjacent subcarriers. Compared with OFDM technology, UFMC technology can reduce out-of-band radiation without significantly increasing the symbol length. Therefore, UFMC technology has the advantage of lower data transmission delay compared to FBMC technology.

UFMC is a new modulation technique considered in 5G communication systems. It overcomes some of the drawbacks of the modulation techniques used in 4G communication systems. Instead of using cyclic preprocessing [23], each subband flicker is applied in OFDM. Compared to OFDM, the use of a UFMC filter can effectively suppress signal trailing, and demodulation implementation is simpler without CP [24]. In order to have a higher understanding of the performance associated with UFMC, here, a simulation of UFMC versus OFDM in terms of signal-to-noise ratio versus BER is performed using Matlab software, as shown in [25]. The BER under AWGN (additive Gaussian white noise) channel is chosen here as the performance indicator for accuracy. And the filter type of the system of UFMC is chosen as FIR Chebyshev filter with QPSK modulation for the subcarrier and QPSK modulation for the subcarrier of the OFDM system.

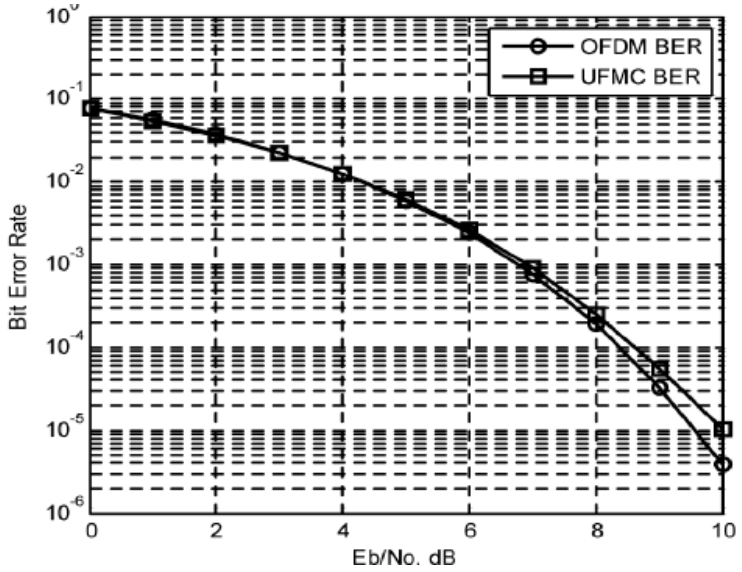


Fig 6. Comparison of BER simulation results of UFMC and OFDM.

According to the above figure, the performance of the two systems is similar under the same conditions when the signal-to-noise ratio is 0-6 dB, and the performance of the OFDM system is significantly better than that of the GFDM system after the signal-to-noise ratio reaches 6 dB. In the case of a large signal-to-noise ratio, it is more effective to prefer the OFDM system instead of GFDM for information transmission.

In addition, modern communication systems require high speed, low latency, quasi-synchronous transmission, high spectral efficiency, and other performance. While the traditional OFDM technology cannot meet the requirements of modern communication systems due to some characteristics inherent in its design structure, the proposed UFMC-based modulation technology for high-speed data transmission systems better solve this problem. Among the waveforms mentioned in this paper, For the future generation of wireless communications, UFMC, a revolutionary multi-carrier modulation

technology, has been put out as a promising waveform contender [26]. In normal UFMC, the entire bandwidth is split up into a number of subbands, each of which contains a number of subcarriers.UFMC then employs a subband filtering method in which a pulse-shaping filter filters each subband before transmission. Thus, the filter length can be greatly reduced compared to other multi-carrier methods UFMC is also considered to be the best choice for short-pulse communications [27]. The subband filtering approach provides design flexibility and reduces Inter-Symbol Interference (ISI). Since it does not require cyclic prefixes, better spectral efficiency can be achieved, thus reducing out-of-band leakage. In addition, the filter characteristics and system parameters of the UFMC system can be changed to meet the requirements of the real communication system thanks to the design flexibility of the system.

3.4. Compare analysis

Table 1. Contrast Analysis

	Advantage	disadvantage	Application
OFDM	Resistant to frequency selectivity and narrowband interference and high channel utilization,etc. .	Extremely susceptible to phase noise and carrier frequency deviation, large peak-to-average ratio, need for a broad linearity range, etc.	BroadBand wireless access, wireless local area network, 4G/5G communication system, etc
GFDM	Low out-of-band radiation, high time-frequency focus, etc.	High PAPR value	An alternative waveform solution for the physical layer of 5G cellular systems/satellite mobile communication systems, etc.
UFMC	High spectral efficiency, low out-of-band leakage, and good anti-frequency bias performance	High hardware complexity	Short packet burst, low latency, wide synchronous communication scenarios, 5G communication systems, etc.

4. Conclusion

In this paper, the basic principles of OFDM, GFDM, and UFMC modulation systems and their performance analysis are introduced in detail. The application scenarios of each system in real life are briefly introduced. The results show that the three systems perform similar noise immunity at low signal-to-noise ratios. When the signal-to-noise ratio gradually increases, the GFDM and UFMC systems show better noise immunity than the OFDM system. The UFMC system has particularly outstanding anti-creation performance. In addition, the article also introduces the signal transceiver process and the principle of each part of each system in detail so that the reader can understand the implementation process of each system in more detail. The technologies described in this paper are considered to be the key technologies for the next generation of cell phones 5g and even the next generation of communication 6G, and their superior performance has received the attention and favor of researchers. In recent years, the technologies covered in this paper have been widely used in mobile communications, IoT and machine-type communications and currently have a wide range of application scenarios. Considering that GFDM and UFMC technologies still have more far-reaching application prospects, it is suggested that their performance in multi-user and heterogeneous environments can be further investigated.

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