An In-depth Study and Practical Deployment of Index Modulation Techniques in Orthogonal Frequency Division Multiplexing Systems

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***Abstract*—This paper provides an insightful overview of Orthogonal Frequency Division Multiplexing (OFDM) technology, starting with a detailed explanation of its underlying principles. OFDM is a sophisticated technique that splits a single data stream across multiple separate subcarriers, thereby increasing spectral efficiency and combating multi-path distortion. It significantly improves the data transmission rate and quality, making it an essential element in various modern communication systems. A comparative analysis is then presented to distinguish OFDM from other multiplexing technologies. The unique advantages of OFDM, including its robustness to channel fading, high spectral efficiency, and the ability to handle high data rates, make it a compelling choice for digital data transmission. The paper further delves into the applications of OFDM in real-world scenarios, demonstrating its prevalence in diverse fields such as digital television and radio broadcasting, wireless networking, and 4G/5G mobile communications. These examples illustrate the integral role of OFDM in powering our connected world. However, despite its advantages, OFDM is not without limitations. The paper elucidates issues such as high Peak-to-Average Power Ratio (PAPR), sensitivity to frequency offset and phase noise, and the necessity for complex receiver algorithms. Overcoming these challenges is a key area of ongoing research.**

Keywords—OFDM, index modulation, multiplexing technology

I. INTRODUCTION

As data communication technology continues to advance, numerous multiplexing technologies have emerged, enabling data from multiple users to be transmitted to the receiver via a single connection. Time Division Multiplexing (TDM) technology, while promising, is not yet mature. It requires all nodes to have precise clock sources, regular time corrections, and special algorithms for time slot allocation and recycling to add and remove nodes from the network. Wavelength Division Multiplexing (WDM) techniques pose their own challenges. Controlling the wavelength (frequency) interval of individual optical signals is a daunting task [1]. If the wavelength interval is too short, interference may arise. Conversely, if the interval is too long, the utilization rate suffers. Frequency Division Multiplexing (FDM), with its high channel multiplexing rate, minimal bandwidth wastage, capability for a large number of input multiplexing, and straightforward demultiplexing, has been adopted as a core component in many communication technologies [2]. Nevertheless, traditional FDM has its drawbacks, including low channel utilization and susceptibility to inter-band interference.

In response to these challenges, researchers are endeavoring to integrate index modulation technology into Orthogonal Frequency Division Multiplexing (OFDM) technology. This approach shows potential for addressing the limitations of traditional FDM and holds promise for advanced communication systems like 5G and beyond. This incorporation of index modulation with OFDM could provide more efficient bandwidth usage, reduce interference, and better cater to the demands of modern wireless communications..

A. Brief Introduction of OFDM Principles

Orthogonal frequency-division multiplexing (OFDM) is a multicarrier modulation technique. It offloads serial data streams with faster data rates into parallel data streams with slower rates. It works: first select the appropriate number of subcarriers depending on the amount of data to be transmitted. Next, we select the active subcarrier to transport the data [3]. These subcarriers are orthogonal to each other. The original information is modulated on the subcarriers, and the frequency-domain signals on each subcarrier are converted into time-domain signals using the Fourier inverse IFFT. It is then added and transmitted to the receiver using a adder. At the receiving end, the summed signal is separated, and the time domain signal is converted into a frequency domain signal by Fourier transform, respectively, and the subcarrier is removed as the accepted data [4].

B. Advantages of OFDM

First of all, OFDM has efficient bandwidth utilization. The carriers used in this modulation are called subcarriers, and they are orthogonal to each other, with the frequencies in the figure 1. The orthogonal carrier satisfies: $E = \{e^{jt}, e^{2jt}, e^{3jt}, \ldots, e^{kjt}\}$, take any two carriers in the set as the inner product, and the inner product is zero. The advantage of this carrier selection method is that it greatly saves the limited available bandwidth [5].

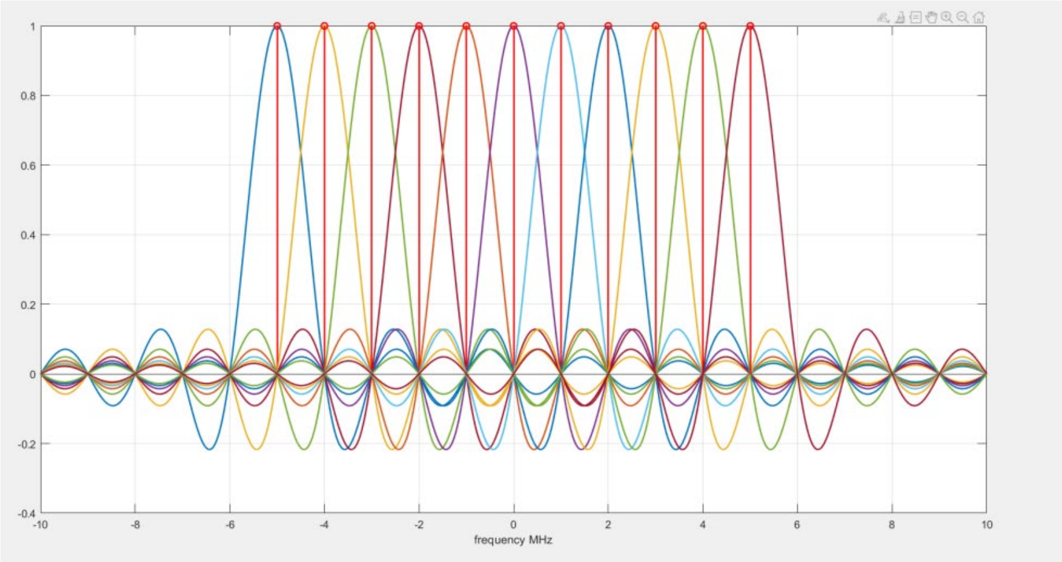

Fig. 1. Simulation of orthogonal subcarriers in MATLAB

Before introducing the second advantage, add two concepts of interference: multipath delay extension, which refers to the phenomenon of width expansion of the received signal pulse caused by multiple pathways, due to the influence of multipath effect, there may be collisions when the symbol reaches the receiving side through multipath transmission, that is, the delay extension of the pulse signal, resulting in inter-symbol interference ISI, sometimes called intercode crosstalk, seriously affecting the transmission quality of the signal. The transmission of OFDM symbols has high requirements for orthogonality, and if the orthogonality of the subcarrier is broken, it will affect the demodulation of the receiving side, which is inter-channel interference ICI [6].

OFDM effectively reduces inter-symbol interference ISI by converting high-rate data streams into parallel low-speed data streams, so that the continuous length of data symbols on each subcarrier is relatively increased. At the same time, OFDM eliminates ISI and ICI caused by multipath by adding a circular prefix.

C. Limitations and Future Prospects of OFDM

After the signal is modulated on the subcarrier, the signal in the frequency domain is converted to the time domain using the inverse Fourier transform IFFT, and the signal is superimposed. Similarly, when demodulating at the receiving end, a large number of time-domain signals need to be converted to the frequency domain using the Fourier transform FFT. Although the Fourier transform and its inverse transformation principles and algorithms are well known, they introduce delays in practice, and the length of the delay depends on the amount of data transmitted [7].

The high degree of orthogonality reduces many intersymbol interference for OFDM systems, but one fatal drawback of OFDM is that it is sensitive to phase noise and carrier frequency offset. The entire OFDM system has particularly strict requirements for the orthogonality between the individual subcarriers, no matter how small the offset will destroy the orthogonality between the subcarriers, causing ISI. Similarly, phase noise affects code element constellation points, forming ISI. Single-carrier systems do not have this problem, where phase noise and carrier frequency offset simply reduce the received SNR without causing interference with each other.

With the continuous development of high-speed communication systems, how to fully utilize channels and complete the communication process under the premise of limited channel resources and the simultaneous need of most users to transmit data has become a problem [8].

The first category of future prospects is the integration with other multiplexing technologies. For example, combined with the code division multiplexing technology CDMA, pseudorandom code is used as a spread spectrum signal to increase spectral efficiency. For example, combined with TDMA, a time-division multiplexing technology, it provides users with more selectable data transmission rates and better resource allocation. Another example is the combination with frequency division multiplexing technology FDMA to provide better time-synchronized carriers without interference [9].

For example, the combination of space-time technology, space-time processing technology and multiple-input multiple-output antenna structure with antennas and error control coding and small-scale time and space diversity are used in close proximity, which greatly improves the spectral efficiency. From the current technical development, space-time technology can not only adapt to the use of cellular networks, but also to the application of ad hoc networks [10].

II. COMPARISON OF OFDM-IM WITH FDM AND OFDM

A. Explanation and Comparison of OFDM with FDM

To avoid interference between channels, FDM uses the method of adding guard bandwidths, which of course wastes a lot of bandwidth, because guard bands need to be set between every two carrier frequencies. In order to completely separate the N-way subchannel signal at reception, OFDM needs to meet the requirement that any two subcarriers be orthogonal to each other for the duration of each code element. Of course, this method not only does not generate interference, but also greatly reduces the waste of bandwidth. As shown in Figure 2.

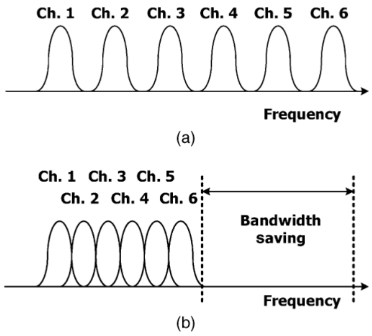

Fig. 2. Carrier utilization differences between traditional FDM and OFDM

B. *Explanation and Comparison of OFDM-IM with Traditional OFDM*

Index modulation techniques divide the information bits to be transmitted into index bits and modulation bits, where the index bits are used to select the index - determining which subcarriers are activated; Modulation bits are mapped to modulation symbols through traditional modulation (e. g. QPSK, etc.). In IM-OFDM, its index resource is subcarrier, and the concept of index modulation and subcarrier block is introduced in the frequency domain, with the subcarrier block as the modulation unit, and a part of the subcarrier is activated by the index information bits to transmit data. At the same spectral efficiency, IM-OFDM outperforms traditional OFDM in terms of bit error rate (BER) performance.

The most significant difference between OFDM-IM technology and traditional OFDM technology is that in the modulation stage, an index modulation step is added, according to the index modulation bit information, through the mapping table, the subcarrier is selected to activate it into an active subcarrier and modulate the corresponding bit data, while the unselected subcarrier is in a silent state.

The original intention of the OFDM-IM index modulation system was to improve the bit error rate and spectrum utilization of the traditional OFDM system, and the most important difference is that the number of activated subcarriers is reduced, so its number of active subcarriers is sparse compared with the traditional OFDM system, so it is more insensitive to frequency offset. On the other hand, the traditional OFDM system has a large number of unactivated subcarriers, which wastes a lot of bandwidth, through OFDM-IM index modulation technology, you can add a modulation region on the basis of the traditional OFDM modulation system to compensate for the loss of spectrum utilization caused by the inactivated subcarriers, thereby improving spectrum utilization and improving the system bit error rate performance. The figure 3 shows the difference between the bit error rate between OFDM with index modulation and traditional OFDM (The lower the bit error rate for the same number of subcarriers, the better the system performance.).

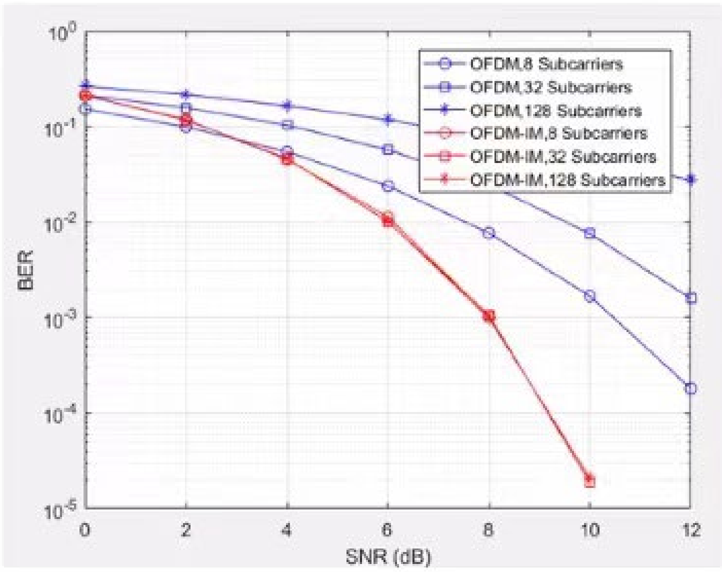

Fig. 3. The difference between traditional OFDM and OFDM-IM bit error rates has been different in the number of carriers

It is easy to see from the figure above that with the same signal-to-noise ratio, the bit error rate of OFDM with indexed modulation is smaller than that of traditional OFDM. This shows that index modulation technology brings better performance.

III. CONSTRUCTION OF THE OFDM-IM SIGNAL MODEL

A. *Explanation of the OFDM-IM Signal Mode*

If the entire signal model is visualized, five main parts will be obtained: the transmitter, the modulator, the transmission channel, the demodulator, and the receiving end, as shown in the figure 4, each subcarrier occupies one channel, and they add up to form a link(The entire system contains digital-to-analog conversions, parallel series conversions, and inverse Fourier transformations are included in the modulator.

Analog-to-digital conversions, Fourier transforms, and series-parallel conversions are all included in the demodulator.).

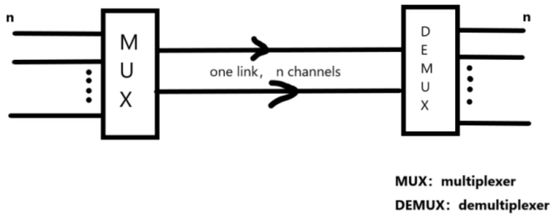

Fig. 4. Schematic diagram of the OFDM-IM model

B. Description of the Modulation and Demodulation Process in the Model

First, it is assumed that the transmitter has 20 decimal data to send. These are generated as 20 random data elements using the 'randi' function in MATLAB, referred to as data symbols. Concurrently, 64 subcarriers are generated using the 'randi' function, with 20 selected as active subcarriers for data transmission, these are called index symbols. This process is depicted in Figure 5.

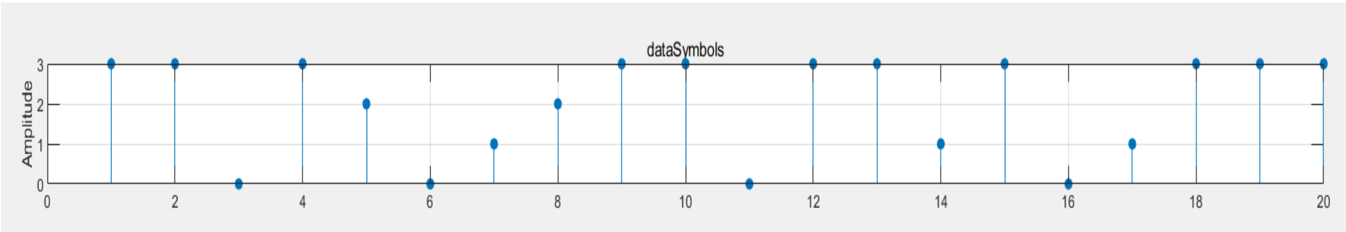

Fig. 5. The random data from the sender

Next, Quadrature Phase Shift Keying (QPSK) modulation is utilized to map the 20 data elements into modulation symbols. This allows the data to be added to the carrier, a process known as mapping, which results in 20 modulation symbols. The QPSK modulation is implemented via the 'pskomod' function. Thirdly, the modulation symbol is sent on the subcarrier, as indicated by the index symbol, to form the Orthogonal Frequency Division Multiplexing with Index Modulation (OFDM-IM) signal. In the fourth step, the Inverse Fourier Transform (IFT function) is employed to convert the frequency domain signal into a time domain signal, while adding a cyclic prefix to the time domain signal. This transformation effectively completes the process, preparing the signal for transmission. Then, create a cyclic prefix so that each OFDM symbol is preceded by a copy at the end of the symbol. The loop prefix provides a guard interval to eliminate intersymbol interference from previous symbols.

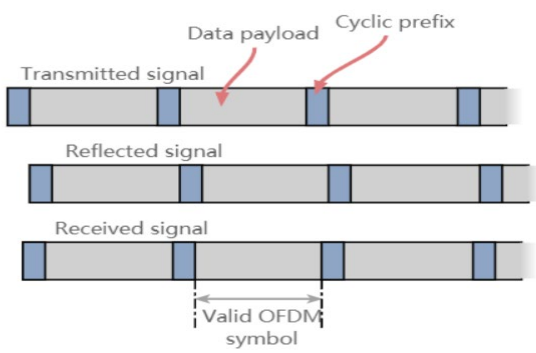

Fig. 6. The schematic diagram of cyclic prefix

Finally, draw the real and imaginary parts of the time domain signal with cyclic prefixes. As shown in Figure 6, 7 and 8.

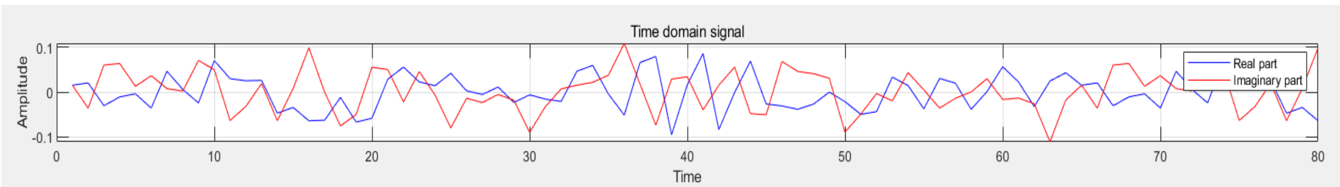

Fig. 7. The modulated signal in time domain

At this point, the modulation process at the sending end is complete. Upon receiving the time-domain signal transmitted by the sender, the cyclic prefix is first removed. The signal then undergoes a Fourier Transform to convert it into the frequency domain. Subsequently, the 'pskdemod' function is used to demodulate the Phase Shift Keying (PSK) modulation. Following the demodulation process, 20 data elements are obtained. This initial quantity corresponds to the sender's data, confirming successful transmission. For accuracy, an analysis of the bit error rate will be performed, further assessing the integrity of the transmitted data..

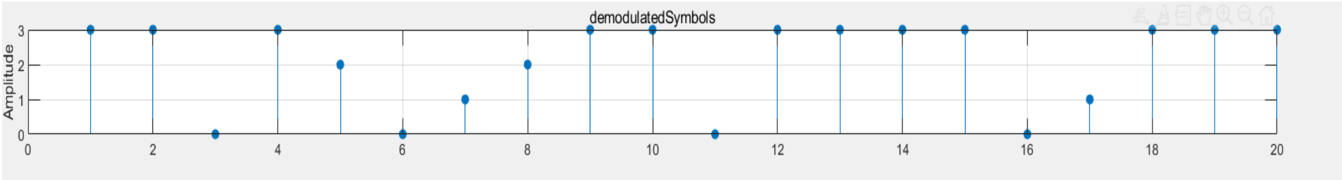

Fig. 8. The signal after demodulating

C. *Incorporation of Index Modulation Techniques into OFDM Systems*

The biggest difference between OFDM with index modulation and traditional OFDM is in the modulation and demodulation process. When generating an OFDM-IM signal, modulation is achieved through the subcarrier indicated by the mapping table, based on the index bit information. During demodulation, according to the received OFDM-IM signal, the index information and data symbol information are recovered through the detection module of the subcarrier block to realize the demodulation operation.

IV. Analysis of Rate, Bandwidth, and Accuracy of the Modulation Model

A. *Analysis of Rate*

The increase in the data rate of OFDM-IM systems has been pursued, and the rate increase has now been achieved through serial-parallel conversion. When calculating the information transmission rate, the transmission rate of OFDM is equal to the transmission rate of a single subcarrier multiplied by the total number of subcarriers. However, to complete the calculation accurately, some parameters are important to pay attention to: the number of subcarriers of the data transmission, the modulation mode of each subcarrier, and the channel coding rate.

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For the second half of the subcarrier, using 8PSK modulation, a symbol (symbol) is 3 bits (bit), because the bitrate is 1/3, indicating that 3 * (1/3) = 1 bit of these 3 bits are information bits.

B. *Analysis of Bandwidth*

When the power density spectrum is a continuous spectrum, we can know the bandwidth of the signal according to the power density spectrum, and the definition of the power density spectrum is: when the power spectral density of the wave is combined with a coefficient, the power carried by each unit frequency wave will be obtained, and the power density spectrum. I plotted the power density spectrum of the hypothetical time domain signal in MATLAB, as shown figure 9.

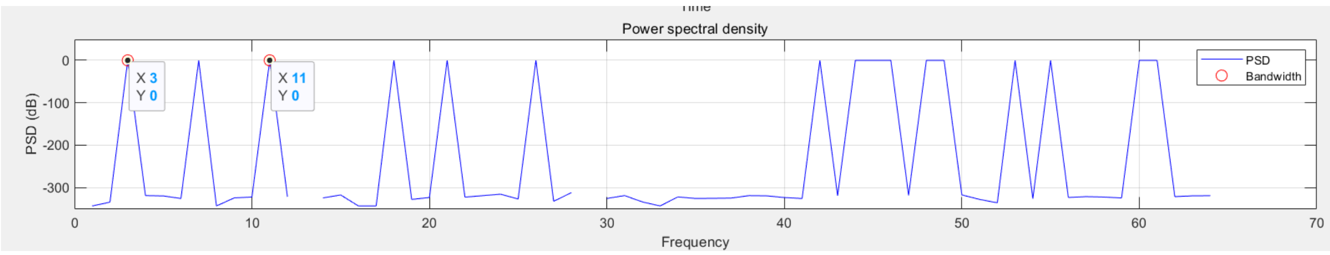

Fig. 9. The PDS diagram in MATLAB

The frequency difference between the two turns represents the bandwidth of the time domain signal.

C. *Accurancy of the IM-OFDM Model*

The rate and mode of information dissemination are of course important, but the accuracy of data transmission is more important in the data transmission process, which is the key to evaluating the performance of an OFDM-IM system.

If you analyze it with the specific model I established, as shown in the figure 10, 11 and 12. It is easy to find that there are two data transmission errors in the transmission process of 20 data, and after calculation, 2/20*100%=10%, the bit error rate is 0.01 (the bit error rate is stable at 0.01 after multiple random generation).

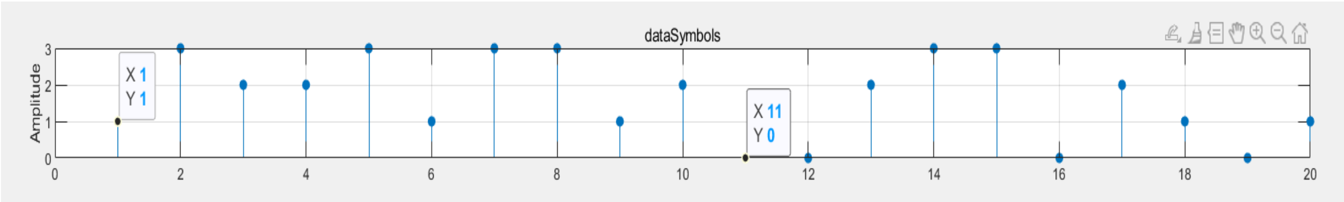

Fig. 10. Figure10 the random data from the sender

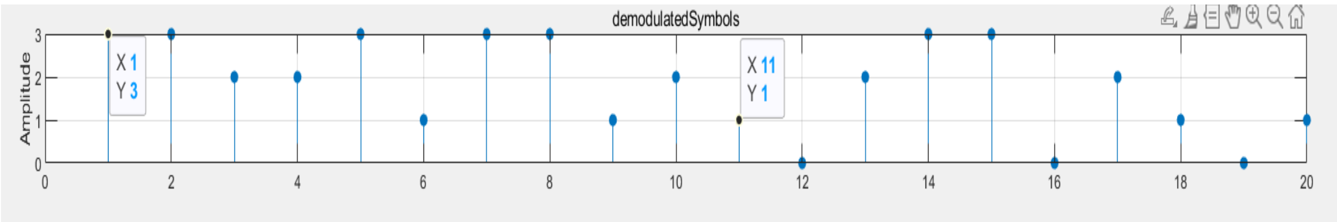

Fig. 11. Figure 11 the received data from the receiver

How to improve the accuracy of the system has become the focus of research by all parties. Without changing the existing model and mainstream technology, we can improve the accuracy by choosing the appropriate signal-to-noise ratio, but the variable of noise is very uncontrollable, so it is difficult to achieve. This is still the current mainstream issue and the future development direction.

V. Application of OFDM Technology in the Real World

A. *Mature Applications about OFDM*

From a technical point of view, the fourth generation of communication technology (4G) will take traditional OFDM technology as the core. The fourth generation of communication technology combines 3G and WLAN, and OFDM has been widely used in broadcast audio, video and civil communication systems, more specific applications include: asymmetric digital subscriber loop (ADSL), ETSI standard digital audio broadcasting (DAB), digital video broadcasting (DVB), high-definition television (HDTV), wireless metro network, wireless local area network (WLAN), some areas that do not cover 4G. CDMA, the core technology in 3G, has also begun to introduce OFDM technology ideas to improve its performance.

B. *More Improved OFDM Technology*

OFDM technology is widely used in underwater acoustic channels because it can effectively combat intersymbol interference caused by multipath effects. However, the Doppler effect generated by ocean waves seriously destroys the orthogonality between subcarriers and amplifies the interference between carriers. An emerging modulation technology, namely subcarrier index orthogonal frequency division multiplexing technology SIM-OFDM, came into being, but because the number of activated subcarriers in each OFDM block is variable, a feedforward is required to clarify the mapping method between the subcarrier index bit and the subcarrier index, which makes the scheme less practical, and then the enhanced subcarrier index orthogonal frequency-division multiplexing technology ESIM-OFDM is generated, which controls the state of two consecutive subcarriers through an index bit, but the spectral efficiency is very low. At present, scientists are working to combine the principles of MIMO and OFDM-IM to further improve the spectral efficiency of OFDM-IM.

In 5G, OFDM technology has also been widely used, specifically in the following aspects: High-speed data transmission: OFDM technology can divide serial high-speed data streams into multiple parallel low-speed subcarriers for transmission, thereby improving data transmission efficiency. Spectral efficiency: OFDM technology can divide the spectrum into multiple sub-bandwidths, and data can be transmitted in each subcarrier, so spectral efficiency can be improved. High-speed mobile communication: OFDM technology can support high-speed mobile communication, which can maintain stable transmission rate and signal quality under high-speed movement. Multi-user access: OFDM technology can support multi-user access and can transmit data of multiple users at the same time. In 5G, MIMO technology is used to achieve multi-user access.

VI. Conclusion

In summary, this paper presents an overview of numerous modulation techniques linked to Frequency Division Multiplexing (FDM), with a special emphasis on Orthogonal Frequency Division Multiplexing (OFDM) and Index Modulated Orthogonal Frequency Division Multiplexing (IM-OFDM). A fundamental model of OFDM with index modulation has been established, simulating the entire process of modulation and demodulation. This simulation, to a significant extent, encapsulates the characteristics of the whole system, providing a more comprehensive pictorial representation of the analog system. The overall system model essentially aligns with our expectations. Future endeavors will entail introducing white noise into signal transmission and employing various modulation methods to further explore orthogonal frequency division multiplexing techniques integrated with index modulation. At present, IM-OFDM technology has matured and found applications in many communication fields, establishing a relatively comprehensive system. However, its stability and synergy with other technologies remain in the nascent stages. Looking ahead, the exploration and expansion of OFDM technology in 5G, marine, space, artificial intelligence, and other domains are focal points for researchers and scientists. Navigating the challenges and uncharted territories of OFDM integration in these fields is a fascinating avenue of investigation, promising further technological advancements and insights..

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