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Research on the Progress of Modulation Technology and Data Transmission Technology in Underwater Wireless Optical Communication

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Abstract:

Recently, as an efficient data transmission method, underwater wireless optical communication has become one of the key research topics in the fields of military communication and underwater surveillance. Modulation technology and technology in the transmission process play a key role in the UWOC system, which directly affects the performance, accuracy and safety of the system. The advanced modulation techniques from Intensity Modulation (IM), Pulse Modulation, Quadrature Amplitude Modulation (QAM), and Quadrature Phase Shift Keying (QPSK) to the combination of multiple modulation techniques, as well as the development process of modulation technology in optical encryption, are summarized in this paper. In terms of data transmission technology, the technological progress process from simplex to full-duplex communication is summarized. Finally, a reference solution is proposed to solve the challenges in realizing the underwater communication goals of long-distance, high-speed, low-bit error rate, and large-capacity underwater communication at the same time, and future development is prospected.

Keywords: Underwater Wireless Optical Communication; modulation technology; data transmission; full-duplex.

1. Introduction

With the development of the times, the development and utilization of marine resources have attracted more and more researchers' attention, and underwater wireless communication is one of the focus topics that can't be bypassed. Underwater wireless communication includes underwater acoustic communication, underwater radio frequency communication and underwater optical communication. Underwater acoustic communication has high delay and low bandwidth, and the transmission distance and rate of underwater radio frequency communication are limited [1]. Underwater wireless optical communication (UWOC) is a communication technology that uses optical signals to transmit wireless data in the underwater environment. This technology enables the wireless transmission of data by using an optical transmitter to send optical signals into the water, and the receiver receives and decodes these optical signals without a physical cable connection. In recent years, UWOC has gained great attention in academia and business circles due to its advantages of sufficient bandwidth, high reliability, high transmission rate and low delay, which makes up for the shortcomings of acoustic wave and RF communication [2]. However, due to the effects of underwater turbulence, light dispersion, and absorption, the UWOC channel experiences extreme degradation, leading to challenges in its development process [2]. With the introduction and comprehensive application of phase modulation, signal processing, beam steering and other technologies, the design of underwater wireless optical communication has been gradually improved, and the difficulties have been improved. In this paper, the development process of modulation technology and key technologies in the process of data transmission in underwater wireless optical communication are reviewed. At the same time, this paper reflects the research progress of UWOC in improving noise immunity, expanding bandwidth, expanding information capacity, and improving transmission rate and security. On this basis, the future development direction and trend of these two important links in underwater wireless optical communication are also prospected.

2. Development of Modulation Tech-

nology

In the early days, modulation technology can be divided into modulation of light source and modulation in signal processing. The modulation of the light source mainly adopts Direct Detection/Intensity Modulation (DD/IM) technology, which transmits data by directly modulating the intensity of the light source, changing the driving current of the light source with the message signal to be sent or an external modulator, and directly detecting the light intensity change through the photoelectric detector at the receiving end. This technology transceiver has low cost and low implementation complexity [3], can meet the needs of high-speed data transmission, so is commonly used in submersibles and underwater monitoring systems. However, the anti-noise performance is poor, and the communication distance is limited, so the adaptability is poor, and it is difficult to maintain stable communication performance in various complex environments.

Simple Pulse Width Modulation (PWM) and Pulse Code Modulation (PCM) techniques are used in the signal processing process. Due to underwater factors such as strong scattering and absorption, these methods have limited transmission distances and data rates.

Pulse Position Modulation (PPM) technology is the most critical in pulse modulation technology, and it is the initial development stage of modulation technology. PPM is relatively simple to achieve by changing the position of the pulse over a fixed time interval to transmit information, making it suitable for low-complexity and low-cost applications. This technique improves energy efficiency and immunity through time-interval coding, pulse-to-noise differentiation, error detection and correction, but the receiver requires accurate clock synchronization and is prone to high bit error rates in multipath propagation environments [4].

In order to further improve noise immunity and data transmission rates, Phase Modulation (PM) and coherent detection techniques are also being applied. Phase Modulation transmits information by changing the phase of light. Coherent detection uses a coherent receiver to detect phase information. The introduction of these two technologies can support complex modulation methods such as Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying (QPSK). The amplitude and phase information of each symbol are modulated separately to two orthogonal carrier signals, and the two modulated carrier signals are superimposed to form the final QAM signal. QAM transmits more data by varying the amplitude and phase of light, providing more transmitted data bits within the same bandwidth. QPSK transmits data by changing the phase of the carrier signal, with each symbol representing two bits of information, using four different phases, typically 45°, 135°, 225°, and 315°, representing the four binary combinations of 00, 10, 11, and 01, respectively. Compared with QAM technology, QPSK has lower system design complexity and higher spectral efficiency, which is more suitable for optical communication, but has the disadvantage of lower data transmission rate. Both technologies are susceptible to underwater multi-path effects, resulting in increased bit error rates [5]. With the advancement of technology, Orthogonal Frequency Division Multiplexing (OFDM) technology has been gradually introduced into underwater optical communication systems. OFDM is an efficient multi-carrier modulation technique that divides the data stream into multiple parallel sub-carriers, which are orthogonal to each other, and each sub-carrier transmits data independently at a lower symbol rate. As a result, OFDM is able to transmit more data within the same bandwidth with higher spectral efficiency. By dividing the data into multiple sub-carriers for transmission, the OFDM technology makes the symbol period of each sub-carrier longer, thereby reducing the impact of multi-path interference and greatly reducing the bit error rate. This technology is suitable for a variety of high-bandwidth, high-speed communication systems, but there are challenges such as implementation complexity and synchronization requirements. In UWOC systems, QAM, QPSK and other technologies are often combined with OFDM as advanced modulation technologies that can give full play to the advantages of the two technologies [5]. Advanced modulation techniques can further improve data rates, spectral efficiency, and modulation flexibility for a wide range of applications for the transmission of image, video, and sensor data underwater. In 2019, Hong et al. used 256QAM-OFDM technology based on probabilistic shaping for the first time in an underwater wireless optical communication system to achieve 35m underwater link communication, with a net data transmission rate of 12.64Gbit/s, and compared with the widely used bit power loading scheme, the capacity of this experiment was increased by 27.8% [6]. Figure 1 shows the Quadrature Amplitude Modulation--Orthogonal Frequency Division Multiplexing technique [3].

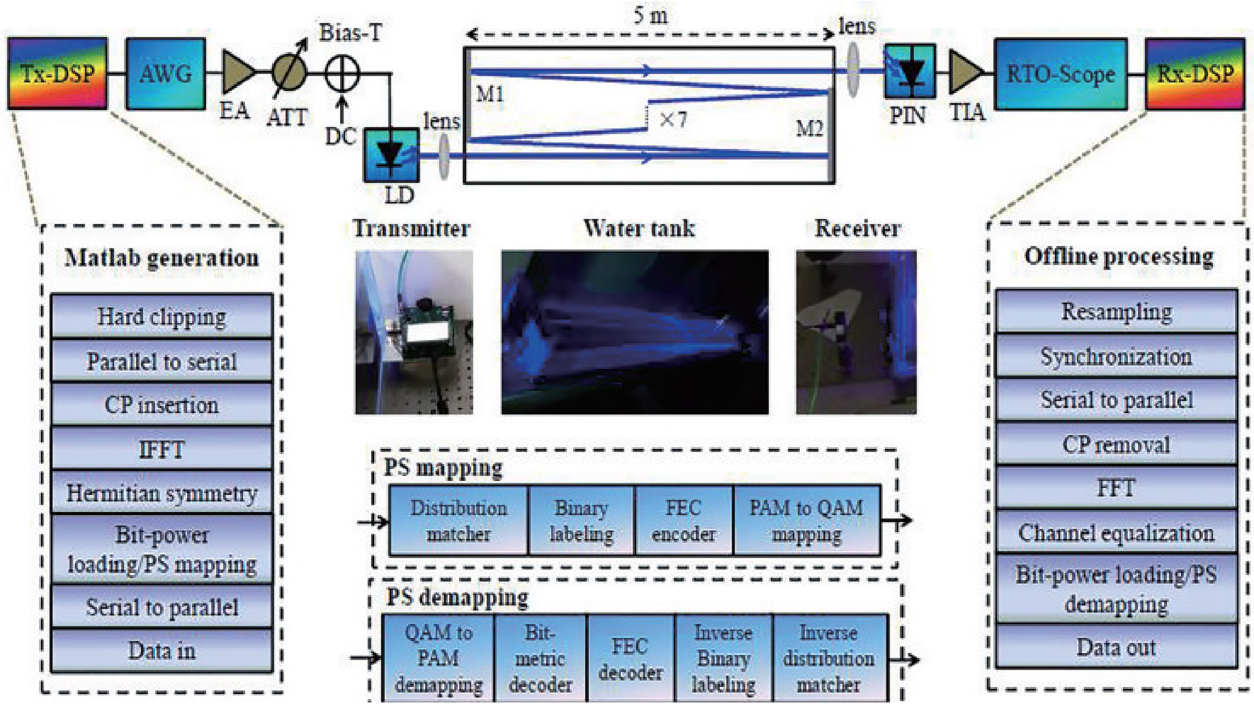

Fig. 1 QAM-OFDM technology [3]

With the improvement of people's demand for communication confidentiality, the technology of optical modulation to scramble optical signals has emerged, which has improved the security and confidentiality of underwater optical communication. The core idea of optical scrambling technology is to transform or mask the signal on the basis of the existing modulation technology during the transmission of optical signals, so as to increase the difficulty of decoding by interceptors. In 2022, Deng et al. proposed a UWOC encryption scheme based on Layer 3 chaotic encryption and chaotic Discrete Fourier Transform (DFT) precoding of Orthogonal Frequency Division Multiplexing (OFDM) modulation. Through multiple data encryption, the solution creates a large encryption space, effectively resists brute-force attacks, and successfully transmits 3Gbit/s encrypted OFDM signals in a 7-meter waterway [7].

In recent years, space modulation and MIMO technologies have begun to be applied in underwater optical communications as cutting-edge research. Spatial modulation uses the spatial dimension to transmit data, while MIMO technology designs multiple transmitters and receivers in a system, both of which can greatly improve channel capacity and reliability [8]. In MIMO technology, each signal is affected by channel fading separately and independently of each other, so that the probability that all signals are fading at the same time is much lower than the probability that a single signal is fading significantly [9]. The concept of massive MIMO has been introduced into 5G mobile communication. This significantly enhances the system's spectral efficiency and power efficiency based on modulation techniques like QAM and QPSK, making it one of the most active research directions in the field of mobile communications [9].

3. Development of Key Technologies in the Process of Data Transmission

In underwater wireless optical communication, the development of the key technology from simplex to full-duplex is an important symbol of the progress of communication technology, which improves the communication efficiency and real-time performance.

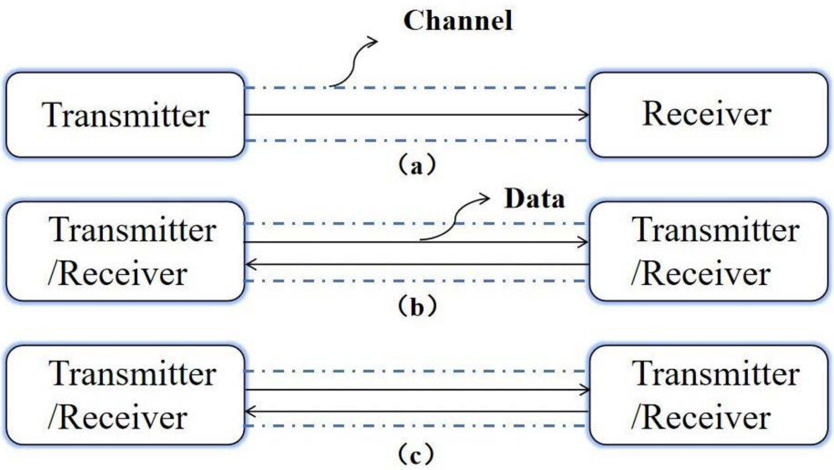

Fig. 2 Simplex-Duplex schematic

In the early days of the introduction of communication technology, simplex communication was adopted. The communication principle is shown in Figure 2(a). Simplex communication uses a single beam for data transmission. There is no feedback mechanism between the receiver and the sender. The communication efficiency is low, and the bandwidth is insufficient. So the system needs to be optimized urgently.

With the increasing demand for the use of finite spectrum resources in wireless communications, half-duplex communication (HD) has replaced simplex communication technology. HD transmits data bidirectionally but not simultaneously on the same channel, switching between sending and receiving, and using timing or control signals to manage the direction of communication. This is shown in Figure 2(b). HD is often used in walkie-talkies. Researchers have developed a variety of half-duplex UWOC systems. Due to the characteristics of half-duplex, although those systems can be deployed in a variety of communication environments and have strong adaptability, these communication systems cannot improve the throughput gain, power efficiency and data rate [10], and cannot meet higher requirements. As a result, researchers turned to full-duplex underwater wireless optical communication systems.

A full-duplex UWOC system consists of two transceiver terminals, each consisting of a transmitter, receiver, and a main processing unit (MUP) using a field-programmable gate array (FPGA), as shown in Figure 2(c) [11]. Full-duplex communication greatly improves communication efficiency and real-time performance [12]. Matching multiple modulation methods in full-duplex communication systems tries to counteract environmental factors such as underwater multi-path effects and turbulence. Additionally, it addresses internal challenges such as high power, high cost, and the short lifespan of optical transceivers. Improved power efficiency, increased communication range, faster data transfer speeds, and low power consumption are the objectives. These objectives have become the focus of today's research [10]. However, full-duplex communication cannot completely replace the half-duplex communication system at present, and half-duplex communication still retains its value and application in some specific fields such as underwater and military.

4. Conclusion

Modulation and data transmission direction improvement technologies in underwater wireless optical communications play a key role in improving system performance and coping with complex underwater environments. In this paper, the research progress and key points of modulation technology are summarized, and the progress of data transmission technology from simplex to full-duplex is sorted out and prospected. On the basis of current research, improving the performance of underwater wireless optical communication can be further tackled from the following three directions.

Researchers can change the status quo of most single modulation techniques today, and design complex advanced modulation modes according to changes in the underwater environment. In different positions or stages of underwater communication, the advantages of different modulation technologies can be brought into play according to different requirements such as long-distance transmission, high accuracy, and large communication capacity. On the basis of satisfying various communication needs, the modulation parameters are dynamically adjusted according to the underwater channel conditions and the adaptive modulation capability of the system system is improved, which can make the wireless optical communication system more intelligent and flexible. In addition, the development of integrated photonics provides new possibilities for optical scrambling technology, which further develops transmission security and reliability.

In future research, with the deep integration of modulation technology and other key technologies, the UWOC system will be able to better adapt to the complex and changeable underwater environment and meet the diverse application needs.

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