An investigation on large capacity transmission technologies for UWOC systems

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Abstract. Underwater wireless optical communication system (UWOC) is promising for underwater inspection and exploration owing to its advantages of sufficient bandwidth, high reliability, small-scale antennas, low cost and low latency. With the increasing demand for a high-speed communication system, three feasible schemes to achieve large-capacity underwater optical transmission system with tens Gbps transmission rate over relatively long transmission distance are investigated in this paper. They are Orthogonal Frequency Division Multiplexing (OFDM) with Laser diodes (LD), Wavelength division multiplexing (WDM) transmission and Orbital Angular Momentum (OAM) transmission technologies. OFDM is widely applied in the UWOC field due to its resistance to inter-symbol interference (ISI) and high spectral efficiency. Combined with other technologies, OFDM can significantly improve the performance of the system and capacity. WDM and OAM are two potential multiplexing technologies for UWOC, and they can combine to achieve large-scale transmission.

1. Introduction
Since ancient times, humankind has never stopped inquisitiveness and exploration towards the deep ocean. The earth's ocean's total area is about 360 million square kilometres, occupying more than 70% of the earth's surface area. Besides, the ocean processes abundant products and provides human being considerable food, medical and mineral resources. It can also be utilized as a transportation hub. The exploration of the ocean has vital economic, political, scientific and ecological significance for human. With the rapid development of science, the technology employed to exploit and monitor the ocean is increasingly mature. Radiofrequency, acoustic and visible light are three major transmission carriers for underwater wireless communication. Acoustic wireless communication has been regarded as the dominant underwater communication scheme for a long time due to relatively low attenuation in the underwater environment. It can transmit the sonic signal up to tens of kilometres so that it can be applied into remote underwater communication. However, underwater acoustic frequency limitations are apparent, such as low communication rate (approximately 1500m/s), serious multipath loss, expensive antennas, vulnerability to the ambient noise, and reverberation [6]. Compared with underwater acoustic communication, radiofrequency is immune to the interference or noise in shallow water environment with higher data rate (up to 10Mbps) and relatively long transmission distance (up to 100m) [4]. It is generally employed in the communication between shore and submarine. However, radiofrequency signal always suffers severe attenuation in the underwater environment, e.g. 169 dB /m for the 2.4GHz band. It requires large scale antennas so that it is less applied in underwater communication [3]. The appearance of UWOC system greatly compensates the limitations of other
two communication methods. It has benefits such as sufficient bandwidth, high reliability, small-scale antennas, low cost and low latency. Simultaneously, the attenuation of light in water (blue, green and red light) is acceptable, so it is often applied in some communication systems with high-efficiency requirements, such as real-time transmission, sensor networks.

Light has been applied as an essential wireless communication medium for several decades. Alexander Graham Bell invented the first optoelectronic communication system in 1880, which was used as a telephone system [7]. In 1960, with the invention of laser, a series of terrestrial UWOC applications started to put into use [1]. Several years later, in 1963, Duntley found blue/green light with wavelengths ranging from 450nm to 550nm has low attenuation in water [2], which is a breakthrough in the development of UWOC. Over decades, UWOC still has not achieved large-scale marketing, and a few UWOC products are put into market, such as Ambalux UWOC system [5].

Due to the limitation of attenuation, interference, modulation schemes and coding techniques, the achievable transmission distance and capacity can still be promoted. In this paper, some schemes to enable a large capacity UWOC are investigated, such as replacing Light Emitting Diode (LED) with a high-performance LD, advanced modulation format OFDM, and transmission technologies WDM and OAM.

2. Large capacity UWOC system

2.1. LD+OFDM scheme

As common UWOC transmitters, LED and LD have different characteristics. LD is characterized by strong directivity and high energy. It can be used for modulation with a wide bandwidth (usually up to GHz). It is usually used for long-distance, high-capacity or high-speed UWOC. On the other hand, LED has the advantages of small volume, low cost, low energy consumption, good resistance to electromagnetic interference, high energy conversion rate, low susceptibility to temperature, and low requirements for transmitter and receiver alignment. However, although it has high modulation capability, it is still low compared with LD and has poor directivity. It is usually used in short distance and medium speed transportation. With the development of the radiofrequency wireless field, the emergence of OFDM technology with high spectral efficiency can help overcome the limitation of LED modulation bandwidth to achieve high-speed UWOC. Additionally, the combination of OFDM and LD can achieve higher capacity and longer distance. Also, this method is selected for the resistance of the multipath effect in UWOC system, so the combination of LED and OFDM or LD and OFDM can utilise their advantages and make up for each other's disadvantages, so as to achieve high-speed underwater communication.

OFDM employed multiple orthogonal subcarriers to transmit high-speed data stream. As shown in Figure 1, first of all, serial binary data with high rate becomes parallel binary data with low rate through serial to parallel conversion. Then the resulting data stream is mapped to the subcarrier through quadrature amplitude modulation (QAM). After that, Hermitian transformation is adopted to change the complex number to real number. Next, inverse fast Fourier transformation (IFFT) in the process enables the frequency domain signal to be a discrete time-domain signal. Simultaneously, a cyclic prefix (CP) is added before each OFDM frame, and the resulting signal is turned to serial code again via the parallel to serial conversion. Then, through the digital to analogue conversion module, the obtained OFDM code is transmitted by driving 450nm LED or LD to generate light, while the signal demodulation at the receiving end is just the opposite to that at the transmitting end. In this process, the key technologies include symbol synchronization, channel estimation and channel equalization. OFDM has apparent benefits for UWOC compared with traditional frequency division multiplexing technology, whose sub-carrier cannot overlap and the reserved protection band will lead to low spectrum efficiency. The subcarriers of the OFDM spectrum are orthogonal to each other with their main lobes overlapping each other without ISI, leading to high spectrum utilization. In addition, because OFDM enables data to be transmitted in multiple subcarriers in parallel, the symbol period of OFDM is more extended, which significantly reduces the impact of inter symbol interference. Because
CP is added as a guard interval, the system’s demand for channel equalization effect is reduced. The information can be flexibly modulated to different wavelets to reduce the fading, be more specific, the seriously-fading channel, the information transmission is reduced, and in the lightly-fading channel, the information transmission is increased. OFDM technology’s major limitation is the high peak to average power ratio because it needs the superposition of multiple sub-signals. The system with OFDM may be sensitive to phase noise and frequency offset that can destroy the orthogonality of sub-carriers, thus affect the performance of the system. The number of training sequences, LED bias voltage, and driving voltage et al. will also affect the system’s performance, which should be attached importance.

Figure 1. the process of OFDM in UWOC

There have been some reports the application of OFDM in UWOC systems. In 2014, Izumi Mizukoshi employed 405nm LD and APD as the transceiver to transmit and receive light signal with IM/DD OFDM modulation and achieved 968Mbit/s transmission rate in a 2-m underwater channel [18]. D. Tsonev achieved a 3-Gbps transmission rate via a single 50μm gallium nitride µLED OFDM-Based wireless VLC Link within 5cm transmission range [19].

In 2015, Oubei et al. proposed a 16-QAM-OFDM UWOC system with LD and achieved 4.8Gbps rate within a 5.4-m long tank [20].

In 2016, Yu Chieh Chi et al.achieved 8.8 Gbps UWOC system at a distance of 6.4 m by 16QAM-OFDM technology with a GaN blue LD [21]. C. Shen et al. [22] realized transmission
distance of 12 meters with a speed of 2 Gbps, the transmission distance of 20 meters with a speed of 1.5 Gbps with blue laser correspondingly.

In 2017, Chun MingHo et al. employed a 405 nm laser and 16 QAM OFDM technology to obtain a communication rate of 10Gbps in a 10m underwater channel [23]. T.C.Wu et al.[24] realized a transmission distance of 1.7m with a rate of 12.4Gbps, and transmission distance of 10.2m with a rate of 5.2Gbps using OFDM. And then, Y. Chen et al. [25] realized underwater wireless optical communication with transmission rate up to 5.5Gbps in 26m long air underwater channel (5m air and 21m underwater) via 520nm green laser, APD detector and OFDM technology.

In 2018, C. Y. Li et al. used OFDM modulation through 680nm vertical-cavity surface-emitting laser (VCSEL) lasers to achieve underwater transmission of 6 meters with a transmission rate of 10Gbps [26].

In 2019, X. Hong, C. Fei, G. Zhang, and S. He, firstly presented a demonstration of OFDM modulation using PS technology in UWOC system for the first time [27]. The probabilistically shaped 256-QAM-OFDM transmission in UWOC can achieve a rate of about 12.64Gbps after 35 meters of underwater transmission with a limited bandwidth of 2.75Ghz, which is 27.8% higher than the common bit power loading scheme [28].

In 2020, Fei et al. demonstrated a 7.33 Gbps transmission in a 15 m water tank by employing OFDM with post nonlinear equalization [29]. Besides that, OFDM can also be combined with other technologies to promote system's capacity, such as Volterra series-based post nonlinear equalization [30], fibre-wireless hybrid transmission [8], multiple-input and multiple-output (MIMO) [17]. This paper will discuss two other potential multiplexing technology, including WDM [28] and OAM.

2.2. WDM scheme

As shown in Figure 2, due to different absorption/absorption coefficients, different light colours are frequently used as communication media in UWOC within different water environments and different application scenarios. Among them, red light, blue light and green light are most often used in underwater communication due to their merits in that environment. The peak wavelengths of red, green and blue LDs are 660 nm, 520 nm and 440 nm. Blue light LD is the most commonly used in UWOC. The blue light is less absorbed in pure seawater, and technology related to blue LED is relatively mature, with good performance. Greenlight LD is suitable for coastal seawater, because its wavelength is longer, so the loss will be smaller, but its technology is not mature and in the initial stage. In contrast, red light LD is often used for turbid seawater, because it receives less scattering effect, and it also has larger modulation bandwidth, higher power and lower price. WDM technology is gradually applied to UWOC, which can effectively combine the three types of light to achieve high-capacity communication.
Figure 2. The absorption coefficient of visible light in water [10]

WDM is a communication technology that combines a series of diverse wavelengths (colours) optical signals with information via multiplexers at the transmitter and then transmits along with a single optical fibre. At the receiver, the optical signals with different wavelengths are separated by using a demultiplexer. This technology enables bidirectional communications over one strand of fibre as well as multiplication of capacity. In underwater optical communication, the use of WDM technology can significantly improve the system’s capacity and effectively alleviate the demand for system bandwidth. Up to now, WDM has been developed and researched the potential of it in UWOC. In 2017, M. Kong et al. first proposed and experimentally proved a WDM-UWOC that is based on red, green and blue laser light, and achieved a transmission speed of 9.51 Gbps with 10m transmission range, in which red light and green has 4.17Gbps transmission speed, blue light has 1.17Gbps. By adequately mixing RGB light to form a beam of white light, combining OFDM and 32-QAM (or high-factor modulation), WDM-UWOC system has excellent potential to achieve long-distance and high transmission speed. In that experiment, as shown in figure 3, the 32 QAM-OFDM signal drives the red, green and blue light LD respectively to generate the light that works as a transmission medium to pass through the tank full of water, a 10-meter underwater channel. Before multiplexing, red, green and blue light, pass by collimators (lens) to obtain the parallel light. Because they come from different directions, the three beams are combined into a beam by a combiner. Two mirrors are placed at both ends of the tank. After travelling the tank, the mixed light is converged by Plano-convex lens, and then the light of different colours is separated by red, green and blue dichroic filters to enter APD for detection. Among them, beam combiner acts as multiplexer and R/G/B dichroic filters as a demultiplexer. However, to chase for high capacity, some parts of the system can be promoted including the performance Blue LD to achieve high speed; better fibre coupler and the better collimator can help reduce loss and increase transmission distance and performance.

As introduced above, it has been proved that laser diode can build a fast UWOC link of approximately Gbit / s level, and can achieve greater capacity by multiplexing red, green and blue LD light. However, although the modulation bandwidth of LD is broader than that of LED, various potential security problems brought by LD cannot be ignored. Therefore, the LED based UWOC system is gradually developing due to its advantages of low cost, easy alignment and higher than 100Mbps underwater transmission capacity. Although monochrome LEDs have the ability to realize the underwater VLC over 1.2-m water channel of about 3 Gbit / s [9], WDM can also realize the data rate system above 10 Gbps by combining multi-colour LEDs to independently modulate different signal sequences on probabilistic-shaping (PS)- bit loading-DMT modulation to maximize the spectral efficiency (SE), which has the highest achievable speed for UWOC based on LED so far [11]. By
utilizing 8 LEDs with diverse wavelengths of 456 nm, 480 nm, 500 nm, 526 nm, 556 nm, 583 nm, 631 nm and 660 nm, the crosstalk between each channel is optimized. Additionally, a Si/GaAs-substrate multichromatic 4x4 LED array chip, and a feasible two-cavity optical filter is proposed in this paper for its potential for future high capacity WDM-UWOC transmission.

![Image of experimental setup]

Figure 3. The experimental setup of the WDM system based on R/G/B LD

2.3. OAM scheme

As discussed before, OFDM technology can effectively improve the system's transmission rate and spectrum efficiency by eliminating ISI and realizing high-speed UWOC, combination of WDM and OAM will also further increase the system's capacity. OAM technology demonstrates a method that employs an azimuthal phase to modify a light beam's spatial profile and phase. OAM beam has helical phase wavefront, phase factor $e^{i\theta}$, OAM carried by each photon is $m$, here, $m$ is mode value or topological charge that can be any integer, $\theta$ is directional phase angle, and $h$ is Planck constant divided by $2\pi$. OAM of different modes does not affect each other. The axial central light intensity in the direction of beam propagation is zero. With the orthogonality of OAM beams, multiple OAM beams with different topologies can be used as carriers for information transmission to realize channel multiplexing, in order to double the channel capacity and spectral efficiency. It has already been proved has a significant improvement in transmission capacity and spectrum efficiency. Figure 4 displays the concept and principle of underwater wireless OAM multicasting link. Submarines here can act as transmitters or receivers. Besides, there are some underwater other users(channels). Key modules for the OAM multicasting link include a light source, signal modulation, OAM generation/multiplexing, OAM demultiplexing/detection and receiver signal processing. Then, the core technologies can be discussed later.
OAM beams are first demonstrated in labs in 1992 by L. Allen [15]. From then on, it has been adopted in the underwater optical communication link. In 2016, Baghdady, J et al. used two 445 nm fibre-pigtailed LDs, OAM technology and NRZ-OOK modulation format, and achieved 3Gbps communication rate in a 2.96M long water tank [16]. In the same year, Ren, Y., Li, L., Wang, Z. et al., realized the transmission effect of up to 40Gbit / s and more than 2m through 520nm LD based on four green OAM beams. Moreover, they also studied the effects of reducing the turbulence caused by scattering, turbidity, water flow and thermal gradient, and found that the thermal gradient can lead to the maximum distortion, while the turbidity can lead to the maximum transmission loss. They has done sufficient research work for the application of OAM modulation technology in underwater optical communication [14].

The key technologies of orbital angular momentum optical communication include the generation of orbital angular momentum beams, multiplexing / demultiplexing devices. The OAM beam photons can be produced using complex methods such as spiral phase method, computer-generated hologram method, and mode conversion method. At the transmitting end, some methods that can be applied to generate OAM multiplexed beams are beam splitter, photon integration technology, vortex Damman grating, composite phase hologram. Among them, composite phase hologram is widely used. The traditional schemes of OAM demodulation mainly include the schemes based on helical phase plate, diffractive optical elements, phase hologram, interference or diffraction, optical geometry transformation, mode conversion method, OAM spectrum analysis. In 2017, J. K. Miller et al. proposed alternative multiplexing and demultiplexing suitable for UWOC, which is log-polar optics in the blue/green region for multiplexing channels and achieved a data rate of 12 Gbit/s [12].

OAM can also be combined with other multiplexing technologies to further increase the transmission capacity in UWOC systems, such as WDM and PDM. In 2016, J. Baghdady successfully achieved a WDM-OAM-PDM system with an effective data rate of 10 Gbit/s through a 2.96 m water channel [13]. They employed 447.0 nm and 448.8 nm GaN laser diodes as transmitters, which realizes WDM transmission. OAM phase plates were placed after laser diodes to induce eight beams of orthogonal spatial states.

3. Conclusion
With the development of marine resources and the increasing exploration of the underwater environment, the underwater environment's communication needs larger communication capacity to achieve faster, more real-time communication and lower delay. As a powerful candidate, UWOC has the benefits of high communication speed, reliability and low latency. By optimization or replacing specific new methods with some parts of the conventional underwater visible light communication system, the large-capacity transmission is possible. For example, low spectrum efficiency OOK and
other modulation technologies are still widely used in underwater wireless communication systems, and the multiplexing technologies can be promoted as well.

In this paper, three primary replacement schemes are proposed. In the first scheme, OFDM and LD are adopted to replace LED with conventional OOK modulation. The advantage of this scheme is that OFDM has high spectral efficiency. It can overcome the multipath effect of underwater unlimited optical communication, and reduce the demand for equalization effect. It can help overcome the limitation of LED modulation bandwidth to achieve high-speed UWOC. It can also be combined with LD to achieve higher capacity and longer distance. On the other hand, the main drawback of OFDM technology is the high peak to average power ratio, hence the apparatus's costs can be expensive. Besides, its susceptibility to the deviation of phase noise and frequency can destroy the orthogonality of subcarrier and then affect the system's performance, which cannot be ignored. In addition to OFDM technology, WDM multiplexing technology can also be used in the current UWOC. It is an ideal means of capacity expansion by multiplexing LD or LED light. It can achieve larger capacity and longer distance by multiplexing and demultiplexing red, green and blue LD light. Of course, in this system, LD with higher modulation bandwidth, better fibre coupler and the better collimator can be applied to help reduce loss and increase transmission distance. As for the UWOC-WDM system with LED, the number of LED colours used is only five at most. Suppose we can realize the transmitter with more than five colours of LED and feasible filter scheme, in that case, significant progress for the higher transmission capacity can be achieved. OAM technology, as a type of SDM, can be combined with other multiplexing technologies to further increase the capacity such as PDM and WDM. However, the application of OAM technology in high-speed UWOC is still new research filed. It is confronted with the challenges of the complex underwater environment and the dynamic factors such as wave, turbulence, and seawater media's inhomogeneity. OAM multiplexing is still an experimental technology, which has only been proved in the laboratory so far, and there are still disputes about it.

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