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A Comprehensive Review of Recent Advances and Challenges in Underwater Wireless Optical Communication

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Abstract: Recent advances and development in underwater wireless optical communication (UWOC) clearly indicate high speed data transmission, which has attracted considerable attention of researchers. Over moderate distances of tens of meters UWOC can achieve a data rate on the order of Gbps. Due to high attenuation the underwater channel is challenging environment. UWOC systems also suffer from scattering and severe absorption introduced by underwater channel. In this paper, after study of the recent research works on UWOC and the advantageous commercialized systems, we provide a comprehensive study of the state-of-the-art of UWOC research in three looks: channel modulation, coding techniques and channel characterization of UWOC. We also address critical design issues and the challenges associated with recent UWOC systems.

Keywords: Undersea wireless optical link, Optical Channel, Modulation Techniques (DPIM, SIM), Coding Techniques (LDPC codes.).

I. INTRODUCTION

With an advance of globe climate change and resource depletion of land, there has been growing interest in the research of ocean exploration system. Underwater wireless communication (UWC) technology make able the realization of ocean exploration systems, and thus attracts more and more attention. UWC refers to transmitting data in an unguided water environment through the use of wireless carriers, i.e., acoustic waves, optical waves and radio-frequency (RF) waves. In underwater missions use of robotics has been increase in order to increase accuracy and operability. Remotely-operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) relay signals to ships, submarines, communication buoys and other underwater vehicles. Cabled or fibre-based techniques offer high speed and reliable communication. The use of fiber or cables is challenging in difficult-access locations and in deep sea as they will limit the range and maneuverability of the underwater vehicle. In such cases, we use wireless communication techniques. Optical communication can provide high data rates on the order of Mbps to Gbps up to several tens of meters. Optical transmission does not practically suffer from latency due to high propagation speed of optical wave in water. Therefore, optical communication is an attractive alternative solution to long range acoustic communication [1], [2].

II. UWOC, STATE-OF-THE-ART

Here we present the state-of-the-art of the most recent works on UWOC including theoretical studies on channel modeling and transmission schemes and summarize conclusion.

A. Characterization of aquatic optical channel

Key step of underwater optical channel is modeling and characterization for efficient, reliable, and robust UWOC system design. In [3], using an elaborate Monte Carlo simulator we presented a realistic model for an underwater wireless optical channel which took into computation different parameters including the water type and the characteristics of transmitter (Tx) / receiver (Rx). The channel delay spread is negligible in highly turbid water. As a result, in most practical cases, the channel can effectively to think maturely as frequency non-selective which does not prevail any inter-symbol interference (ISI) at the Rx. In [4], the author describes a high-sensitivity, high-dynamic range experimental method for measuring the frequency response of the underwater optical channel. in the forward direction for the purpose of wireless optical communications for different water turbidities while investigating the effect of Tx-Rx misalignment. Measuring both spatial and temporal signal dispersion, they confirmed that in clear waters there is little or no temporal dispersion.

On the other hand, a mathematical model was proposed in [5] in which refractive index will change with water depth, temperature, salinity and other environmental conditions. This phenomenon usually occurs in surface-to-bottom UWOC links and will cause the non-straight light propagation, thus aggravate link misalignment of UWOC. Also, in [6], a theoretical model was developed where both random sea-surface slopes and water beam scattering effect were taken into account for a vertical surface-to- bottom (between a buoy-based Tx and a submerged Rx) UWOC link. In [7], Hanson adopted the Kolmogorov spectrum model to present the underwater optical turbulence. Motivated by [7], the authors of [8] characterized a UWOC channel model that includes both scattering/absorption and underwater optical turbulence.

B. Impact of link misalignment

Angle scattering is highly peaked in the forward direction in UWOC system. Therefore, the optical beam has a high directivity, which create problem for system implementation. When we are communicating with an ROV, link misalignments are unavoidable in underwater systems. Misalignment errors can gravely impact the performance and reliability of the communication link. This is specially the case for small field-of-view (FOV) receivers. As a matter of fact, inserting a lens in front of the photo-detector (which has typically a very small active area) has the advantage of increasing the received optical intensity. However, this seriously limits the Rx FOV and, hence, increases the sensitivity to link misalignment [9].

An efficient solution may be to use an array of LEDs at the Tx and/or an array of photodiodes (PDs) at the Rx. An arrays of seven LEDs and seven PDs in the form of truncated hexagonal pyramid structures were used in [10] to achieve quasi-omnidirectional patterns. The further advantage of such arrays is that we can set value of the angle of arrival of the optical signal at the Rx in order to perform beam steering at the Tx or to correct the Rx position/direction.

C. Modulation Schemes of UWOC

UWOC channel modulation techniques have attracted much attention in recent years due to its capability to impact the system performance considerably. Since UWOC can be regarded as implementing FSO in underwater environment, the conventional intensity modulation (IM) techniques that used in FSO communication systems can also be applied to UWOC systems. The most widely used modulation is on-off keying (OOK) due to its implementation simplicity. Pulse position modulation (PPM) scheme is another popular modulation technique used in UWOC systems. Compared with OOK modulation, PPM has much higher energy efficiency and doesn't require dynamic thresholding, but at the expense of lower bandwidth utilization rate and more complex transceivers. We concluded that, although pulse position modulation (PPM) is optimal in the sense of energy efficiency, digital pulse interval modulation (DPIM) [11] makes a good compromise between link performance and complexity. It has a better bandwidth efficiency and peak-to-average optical power ratio (PAPR) compared to PPM. DPIM also has higher spectral efficiency than PPM and PWM [12]. The most critical problem of DPIM is the error spread in demodulation.

Another coherent modulation scheme implemented in UWOC is the subcarrier intensity modulation (SIM). The interest of SIM is the much higher spectral efficiency [13]. But SIM also requires complex modulation/demodulation devices and suffers from poor average power efficiency [14]. By using SIM, orthogonal frequency-division multiplexing (OFDM) can also be achieved in UWOC systems [14, 15]. The interest of the SIM schemes is the higher spectral efficiency that they can offer but at the expense of reduced energy efficiency due to the DC bias used to avoid negative amplitudes.

D. Channel Coding of UWOC

As it can be deduced from the previous discussions, due to the severe absorption and scattering effects induced by sea water, the transmitted optical signal will experience considerable attenuation. This undesirable effect will directly degrade the BER performance of UWOC system. In order to mitigate the impact of aquatic optical attenuation and maintain a low BER in low SNR underwater environment, forward error correction (FEC) channel coding techniques can be implemented in UWOC systems.. As a matter of fact, the most important noise sources are the thermal noise and the shot (quantum) noise in the case of using a PIN PD or an APD, respectively [16]. In simple and classical block codes such as Baker, Manchester, or Reed-Solomon (RS) codes can be used but are not capable of providing the optimal performance for UWOC, especially in the environment with strong interference. Thus, more complex and powerful channel coding schemes such as low-density parity-check (LDPC) code employed. LDPC code is a highly efficient linear block code. It is constructed by employing sparse parity check matrices and can provide an error-correction performance close to the Shannon limit [12].

III. CONCLUSIONS AND PERSPECTIVES FOR FUTURE RESEARCH

Research work on UWOC has been increasing day by day. Many research works have been taken into an account but still it requires research work to overcome several challenges. We provide in the following some directions for future research on these systems i.e., channel modeling, efficient transmission techniques and Mitigating link misalignment.

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