Orthogonal Frequency Division Multiplexing with Index Shift Keying for Reliable Underwater OWC

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***Abstract*—In this paper, we propose and investigate a novel orthogonal frequency division multiplexing with index shift keying (OFDM-ISK) scheme for reliable underwater optical wireless communication (UOWC). Compared with OFDM with index modulation (OFDM-IM) which transmits information bits via both index selection and constellation mapping, OFDM-ISK achieves better reliability performance by carrying information bits solely via the index of the activated subcarriers without performing constellation mapping. Simulation results demonstrate the feasibility and superiority of applying OFDM-ISK in UOWC systems. Particularly, a flexible trade-off between capacity and reliability can be achieved by selecting a proper subblock length of OFDM-ISK or OFDM-IM in UOWC systems.**

***Index Terms*—Underwater optical wireless communication (UOWC), orthogonal frequency division multiplexing with index shift keying (OFDM-ISK).**

I. Introduction

In recent years, with the aggravation of global climate change and resource depletion, human beings have been conducting more and more exploration of the oceans, which are rich in a variety of resources [1], [2]. Compared with acoustic communications and radio frequency communications, which have low rates and severe attenuation, respectively, underwater optical wireless communication (UOWC), with its high data rate, low delay and high safety, has been proven to be a reliable solution for underwater communication [3]–[5]. Despite the above advantages, UOWC still faces many great challenges. Specifically, the received signal-to-noise ratio (SNR) is fluctuating due to the turbulence and air bubbles in the underwater transmission environment, and the transmitter and receiver are not always perfectly aligned. Therefore, novel modulation schemes with ultra-high reliability are needed to ensure the reliability of UOWC with relatively a low received SNR [6], [7].

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Orthogonal frequency division multiplexing (OFDM) has been widely used in UOWC owing to its high spectral efficiency and resistance to inter-symbol interference. Nowadays, techniques such as OFDM with index modulation (OFDM-IM) have been proposed based on OFDM [8]. In OFDM-IM, the information bits are composed of constellation bits and index bits; thus, extra bits are carried by the index of activated subcarriers [9]–[11]. However, the reliability of the existing schemes is not sufficient. Therefore, in this paper, we propose an OFDM with index shift keying (OFDM-ISK) scheme, which carries information only by the index of activated subcarriers and has no constellation mapping compared to the OFDM-IM technique, thus obtaining better communication reliability. In addition, OFDM-ISK can be further adapted to the variable transmission conditions underwater by changing the length of the subblock.

II. Principle of OFDM-ISK

Figs. 1(a) and (b) illustrate the block diagram of OFDM-ISK transmitter and receiver, respectively. At the transmitter side, the N data subcarriers are first divided uniformly into G subblocks, each containing n subcarriers, i.e., $N = nG$. Subsequently, m information bits are split equally into each subblock, each of which contains b information bits, i.e., $m = bG$. Within each subblock, the information bits are mapped to the corresponding index bits via the corresponding look-up table, and the k subcarriers within the n subcarriers are selected as the activated subcarriers. In order to obtain ultra-high reliability, the number of activated subcarriers is set to 1, i.e., $k = 1$. The number of information bits transmitted in each subblock can be expressed as $b = \lfloor log_2\binom{k}{n}\rfloor = \lfloor log_2\binom{1}{n}\rfloor$, where, $\lfloor\cdot\rfloor$ denotes the floor operator and $\binom{\cdot}{\cdot}$ represents the binomial coefficient. After that, the G subblocks are concatenated into one OFDM block. Finally, the transmitted signal is generated via the inverse fast fourier transform (IFFT) with Hermitian symmetry (HS) and the parallel-to-serial (P/S) conversion.

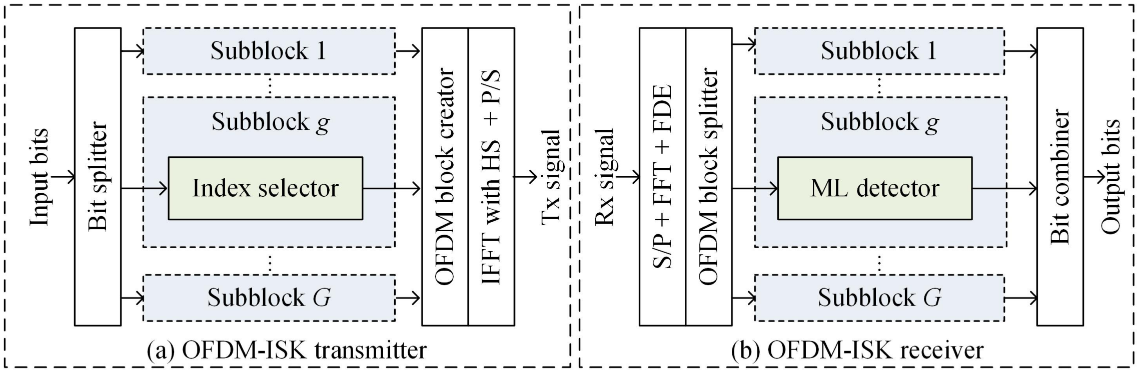

Fig. 1. Block diagram of OFDM-ISK: (a) transmitter and (b) receiver.

At the receiver side, the received signals are first passed through serial-to-parallel (S/P) conversion, fast fourier transform (FFT) and frequency domain equalization (FDE). Then, the index bits are demapped by the maximum likelihood (ML) detector within each subblock, and the detailed principle of ML detection is introduced in the following. Finally, the information bits of each subblock are integrated to obtain the output bits.

To demonstrate the principle of ML detection more clearly, the frequency domain signal obtained by concatenating the G subblocks is represented by

$$\mathrm{x}_F = [x(1), x(2), \cdots, x(N)]^T, \tag{1}$$

where $x(\alpha) \in \{0, 1\}$ is the transmitted signal on the α-th subcarrier, $\alpha = 1, \cdots, N$, and $(\cdot)^T$ denotes the transpose operation. In particular, $x(\alpha) = 1$ means the corresponding subcarrier is acticated; otherwise, the subcarrier is left idle. After that, the time domain signal is derived by IFFT, which is given by

$$\mathrm{x}_T = \mathrm{IFFT}\{\mathrm{x}_F\}. \tag{2}$$

Letting $h_F(\alpha)$ denote the channel fading coefficient, the frequency input-output relationship of the OFDM-ISK scheme is given by

$$y_F(\alpha) = x(\alpha)h_F(\alpha) + w_F(\alpha), \tag{3}$$

where $y_F(\alpha)$ and $w_F(\alpha)$ are the received signal and the noise signal on the α-th subcarrier in the frequency domain. The ML detector considers all possible subblock realizations by searching for all possible subcarrier index combinations in order to make the decision of the active index for each subblock by minimizing the following metric:

$$\hat{I}_\beta = \underset{I_\beta}{\mathrm{argmin}} \sum_{\gamma=1}^{2^b} |y_F^\beta - s(\gamma)|, \tag{4}$$

where $s(\gamma)$ is the γ-th possible realization in the look-up table, and $\hat{I}_\beta$ and y_F^β are the estimated index and the β-th received subblock signal, respectively.

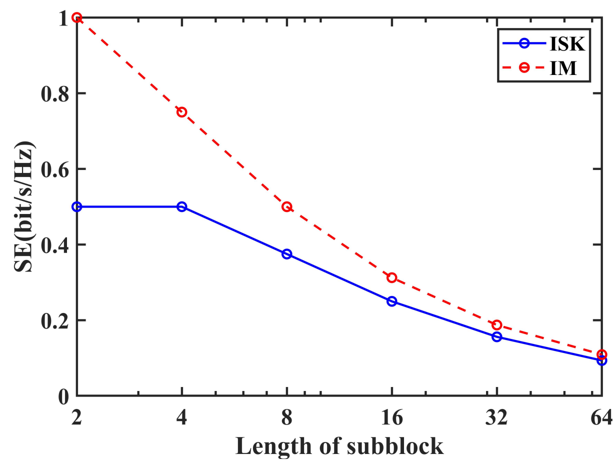

Fig. 2. Spectral efficiency vs. the length of subblock n for OFDM-ISK and OFDM-IM

III. Results and Discussions

In this section, simulations are conducted to evaluate the performance of the OFDM-ISK scheme over an additive white Gaussian noise (AWGN) channel with a low-pass frequency response measured from an experimental UOWC system. During OFDM-ISK/OFDM-IM modulation, the length of IFFT/FFT and the number of data subcarriers are set to 256 and 64, respectively. Moreover, the low-pass frequency response adopted in the simulation is the same as that reported in [12].

Fig. 2 shows the spectral efficiency versus the length of subblock for OFDM-ISK and OFDM-IM, where the constellation order of OFDM-IM is set to 2. For OFDM-ISK, the same spectral efficiency of 0.5 bit/s/Hz is achieved for both the subblock lengths of 2 and 4. With the further increase of subblock length, the achievable spectral efficiency of OFDM-ISK becomes gradually reduced. Moreover, the achievable spectral efficiency of OFDM-IM generally decreases with the increase of the subblock length. It can also be seen that, as the subblock length increases, the disparity of spectral efficiency between OFDM-ISK and OFDM-IM becomes smaller and smaller, which is because of the reduction of the weight of

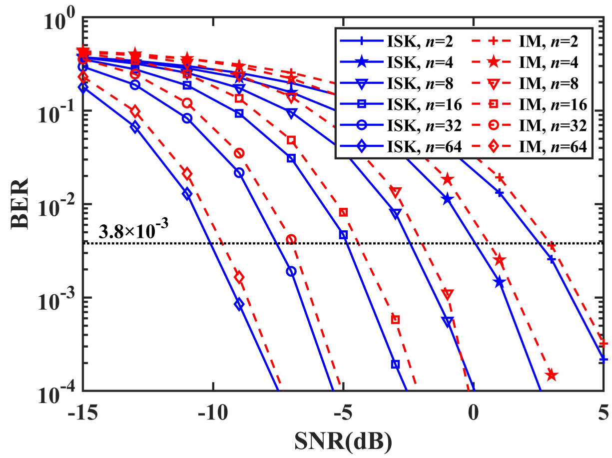

Fig. 3. BER vs. SNR over an AWGN channel without low-pass effect

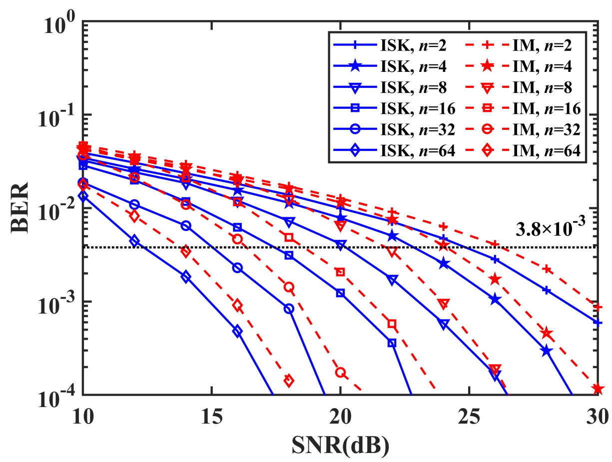

Fig. 4. BER vs. SNR over an AWGN channel with low-pass effect

constellation mapping in the achievable spectral efficiency.

Fig. 3 shows the BER performance versus SNR for OFDM-ISK and OFDM-IM over an AWGN channel without low-pass effect. As we can see, the BER performance of OFDM-ISK is gradually improved with the increase of subblock length n. Moreover, since no constellation is transmitted on the activated subcarrier within each subblock, OFDM-ISK always obtains a slightly better BER than OFDM-IM. Fig. 4 depicts the BER performance versus SNR for OFDM-ISK and OFDM-IM over an AWGN channel with low-pass effect. Clearly, the BER performance of both OFDM-ISK and OFDM-IM is greatly degraded by the adverse low-pass effect, since the high-frequency subblocks will suffer from much more severe SNR reduction than the low-frequency subblocks, leading to degradation of the overall BER performance. In practical implementation of OFDM-ISK/OFDM-IM based UOWC systems, efficient low-pass mitigation schemes should be applied to improve the overall system performance.

In Fig. 5, we present the received SNR margin ΔSNR versus spectral efficiency using both OFDM-ISK and OFDM-IM for UOWC systems. Here, the received SNR margin ΔSNR is defined as the SNR gap between the SNR required for OFDM-ISK/OFDM-IM with an arbitrary subblock length to reach the BER threshold of 3.8×10^{-3} and the SNR required for OFDM-IM with a subblock length of $n = 2$. As we can see, with the increase of subblock length n, the achievable spectral efficiency is gradually reduced while the received SNR margin ΔSNR is gradually increased for both OFDM-ISK and OFDM-IM. Moreover, the use of OFDM-ISK can provide a slightly higher ΔSNR than OFDM-IM. Based on the results presented in Fig. 5, we can obtain a flexible trade-off between achievable spectral efficiency (i.e., rate) and received SNR margin (reliability) by adjusting the subblock length n in OFDM-ISK/OFDM-IM based UOWC systems.

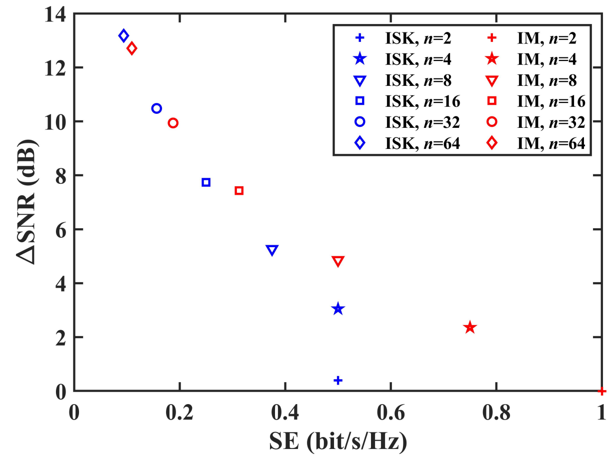

Fig. 5. ΔSNR vs. spectral efficiency

IV. Conclusion

In this paper, we have proposed an OFDM-ISK scheme for UOWC systems. In OFDM-ISK, the information bits are solely carried by the index of the activated subcarriers and no constellation symbols are transmitted by the activated subcarriers within each subblock. By adaptively adjusting the subblock length n in OFDM-ISK/OFDM-IM, we can achieve a flexible trade-off between rate and reliability. Therefore, reliable UOWC transmission can be enabled by applying OFDM-ISK/OFDM-IM with a proper subblock length to adapt to the dynamic underwater channel environments.

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