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Experimental Demonstration of Underwater Optical Wireless Communication with Three-Dimensional Diversity Transmission

Xin Wan[0009-0004-3575-8791]**, Yang Ye**[0009-0000-5696-6750]**, Min Liu**[0000-0002-0392-4247]**, Chen Chen***[0000-0003-2541-6283]

School of Microelectronics and Communication Engineering, Chongqing University, Chongqing, China

*Corresponding author's e-mail: c.chen@cqu.edu.cn

Abstract. To handle the dual challenges of low-pass band-limitation and underwater turbulence, a three-dimensional (3D) diversity transmission scheme is proposed for underwater optical wireless communication (UOWC) systems. By jointly implementing diversity transmission across the three dimensions of time, frequency and space, the adverse effects induced by both low-pass frequency response and underwater turbulence can be simultaneously mitigated to enhance the overall performance of low-pass turbulent UOWC systems. The experimental results demonstrate that the proposed 3D diversity transmission scheme can significantly expand the usable signal bandwidth of the low-pass turbulent UOWC system, and hence further improve the communication rate accordingly. This 3D diversity transmission scheme can provide theoretical guidance for the design and deployment of practical UOWC systems.

1. Introduction

In recent years, underwater optical wireless communication (UOWC) has been regarded as a potential key technology for high-speed underwater interconnection thanks to the advantages of large bandwidth, high data rate, low latency, strong security and so on[1]-[2]. However, the deployment of UOWC systems in practical underwater environments still faces numerous challenges. On one hand, light sources, e.g., light-emitting diodes (LEDs) and laser diodes (LDs), typically exhibit a pronounced low-pass frequency response, which limits the available bandwidth of UOWC systems and further reduces their capacity[3]. On the other hand, underwater turbulence caused by ocean currents or air bubbles can lead to fading of the received signal, thereby degrading the bit error rate performance of UOWC systems[4]-[5]. To handle the low-pass impact in UOWC systems, researchers have proposed solutions such as pre-equalization[3],[6], orthogonal frequency division multiplexing (OFDM) using subcarrier pairwise coding[5], OFDM subcarrier interleaved index modulation[7], and frequency-domain diversity enhanced OFDM[8]. For the impact of underwater turbulence effect in practical UOWC systems, various potential solutions such as anti-turbulence modulation techniques[9], adaptive optics[10], time-domain diversity transmission[11], and spatial-domain diversity transmission[12] have been proposed.

Although some existing works have provided corresponding solutions to the low-pass effect and underwater turbulence in UOWC systems respectively, how to fully leverage different dimensional resources such as time, frequency, and space to achieve joint mitigation of these two adverse effects remains an important topic for further research.

To effectively achieve joint mitigation of both the low-pass frequency response and underwater turbulence in UOWC systems, this paper proposes a three-dimensional (3D) diversity transmission scheme, which implements diversity transmission jointly across the time, frequency, and space dimensions to simultaneously suppress the effects of low-pass frequency characteristic and underwater turbulence. The obtained experimental results effectively validate the feasibility and performance superiority of the 3D diversity transmission in UOWC systems under both low-pass and turbulent conditions.

2. Principle

Figure 1 illustrates the principle of the low-pass turbulent UOWC system based on the proposed 3D diversity transmission. The system employs a single-input multiple-output (SIMO) transmission architecture. At the transmitter, the input bits are first mapped into M-ary phase-shift keying (M-PSK) symbols, followed by two-dimensional (2D) diversity transmission in the time and frequency domains. After real-valued OFDM modulation, digital-to-analog conversion (D/A), and the addition of a direct current (DC) bias, the resulting real-valued non-negative signal is used for driving the LED or LD light source. The real-valued OFDM modulation is then implemented via inverse Fourier transform (IFFT) with Hermitian symmetry. At the receiver, two photodetectors (PDs) receive the optical signals transmitted through the underwater turbulent channel. The output electrical signal from each PD undergoes analog-to-digital conversion (A/D) and OFDM demodulation, where the OFDM demodulation is realized by Fourier transform (FFT) together with channel estimation and equalization. For the two demodulated signal streams, 3D diversity combining is performed across the time, frequency, and space domains to generate the M-PSK constellation symbols to be demodulated, and output bits are finally obtained through M-PSK constellation demapping.

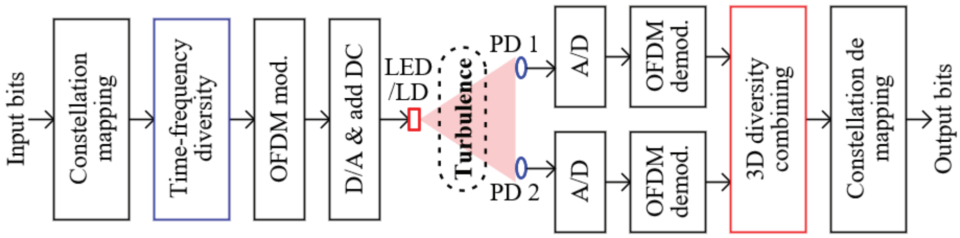

Figure 1. Schematic diagram of the low-pass turbulent UOWC system based on 3D diversity transmission.

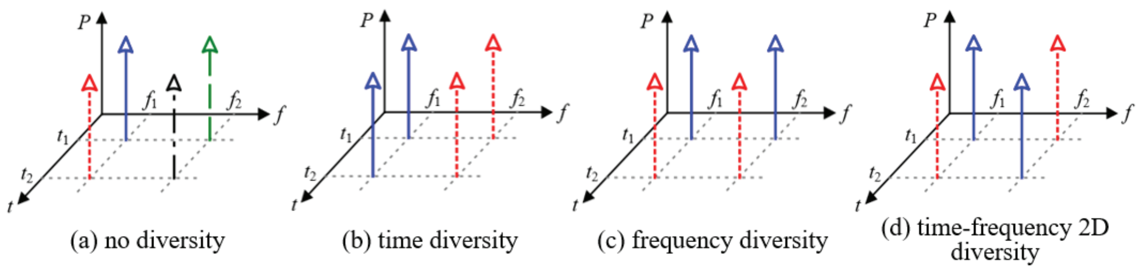

Figure 2. Comparison diagram of signal transmission schemes in the time and frequency domains: (a) no diversity; (b) time diversity; (c) frequency diversity; (d) time-frequency 2D diversity.

As illustrated in Figure 1, the proposed 3D diversity transmission scheme consists of two components: time-frequency diversity transmission and spatial diversity transmission. The time-frequency diversity transmission is implemented across both the time and frequency dimensions[13], while spatial diversity transmission is implemented across the spatial dimension. Taking two frequencies and two time slots as an example, Figure 2 compares four signal transmission schemes in the time and frequency dimensions. In the case without diversity, four subcarriers located at two time slots t_1 and t_2 and two frequencies f_1 and f_2 transmit four different M-PSK constellation symbols respectively. When time-domain diversity is applied, subcarriers at the same frequency transmit identical M_t-PSK constellation symbols across two time slots t_1 and t_2. When frequency-domain diversity is applied, two subcarriers at frequencies f_1 and f_2 transmit identical M_f-PSK constellation symbols within the same time slot. When time-frequency 2D diversity is applied, the subcarrier at frequency f_1 in time slot t_1 and the subcarrier at frequency f_2 in time slot t_2 transmit one identical M_{tf}-PSK constellation symbol, while the subcarrier at frequency f_2 in time slot t_1 and the subcarrier at frequency f_1 in time slot t_2 transmit another identical M_{tf}-PSK constellation symbol. Since two subcarriers transmit identical constellation symbols in the time-domain diversity, frequency-domain diversity, and time-frequency 2D diversity schemes, to maintain the same transmission rate as the scheme without diversity, the order of the transmitted PSK constellation symbols must satisfy $M_t = M_f = M_{tf} = M^2$.

In the low-pass turbulent UOWC system based on 3D diversity transmission, the same PSK constellation symbol is transmitted with diversity across the time, frequency, and space dimensions, thereby achieving diversity gain. To recover the transmitted PSK constellation symbol at the receiver, 3D diversity combining of the parallel signals after OFDM demodulation is required. Taking two PDs, two frequencies, and two time slots as an example, four subcarriers—namely, the subcarrier at frequency f_1 in time slot t_1 from the PD 1 output signal, the subcarrier at frequency f_2 in time slot t_2 from the PD 1 output signal, the subcarrier at frequency f_1 in time slot t_1 from the PD 2 output signal, and the subcarrier at frequency f_2 in time slot t_2 from the PD 2 output signal—jointly transmit one identical PSK constellation symbol. If the transmitted PSK constellation symbol at the transmitter is x, the received signals on the four subcarriers at the receiver are denoted as $y_{11,1}$, $y_{22,1}$, $y_{11,2}$, and $y_{22,2}$, with corresponding received signal-to-noise ratios (SNRs) of $\beta_{11,1}$, $\beta_{22,1}$, $\beta_{11,2}$, and $\beta_{22,2}$, respectively. In order to achieve maximum diversity gain, maximal ratio combining (MRC) is employed for 3D diversity combining, and the combined signal can be expressed as[14]:

$$x^* = \alpha(\beta_{11,1}y_{11,1} + \beta_{22,1}y_{22,1} + \beta_{11,2}y_{11,2} + \beta_{22,2}y_{22,2}) \quad (1)$$

where $\alpha=1/(\beta_{11,1}+\beta_{22,1}+\beta_{11,2}+\beta_{22,2})$ represents the power normalization coefficient.

3. Experiments and Results

Figure 3 illustrates the experimental system setup. The OFDM signal was first generated via Matlab offline and then loaded into an arbitrary function generator (AFG, Tektronix AFG31102). The AFG sampling rate and peak-to-peak voltage were 250 MSa/s and 250 mV, respectively. An optical transmitter module (HCCLS2021MOD01-Tx) emitted blue light driven jointly by the output signal from the AWG and a 12 V DC bias. The optical signal passed through a water tank with a length of 1 m before reaching the receiver side, where a bubble generator was placed inside the tank to create bubble-induced turbulence. Two optical receiver modules (HCCLS2021MOD01-Rx), each powered by a 12 V DC bias, detected the incoming optical signals[15]. The output signals from the two receiver modules were digitized by using a two-port digital storage oscilloscope (DSO, Tektronix MDO32) with a sampling rate of 1.25 GSa/s. Finally, the resultant signals acquired by the DSO were processed offline using Matlab. During OFDM modulation and demodulation, the lengths of both the FFT and IFFT were 256. With the number of data subcarriers denoted as N_{data}, the effective bandwidth of the OFDM signal could be expressed as $B=(N_{data}/256)\times250$ MHz. In subsequent experiments, the effective OFDM signal bandwidth could be changed by varying N_{data}[16]. During OFDM generation, the constellation used in the scheme without diversity was BPSK (M=2), while the constellations that are adopted in the time-domain diversity, frequency-domain diversity, and time-frequency two-dimensional diversity schemes were QPSK ($M_t=M_f=M_{tf}=4$), ensuring that all schemes achieved the same transmission rate.

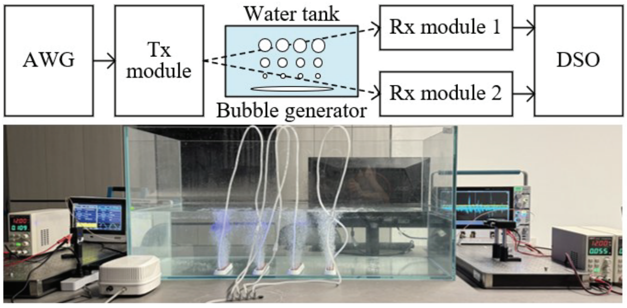

Figure 3. Experimental setup diagram of the low-pass turbulent UOWC system.

Figure 4 plots the frequency response curve of the low-pass turbulent UOWC system. The curve exhibits a low-pass band-limited frequency response characteristic, which is primarily determined by the blue LED light source in the optical transmitter module. As can be seen from Figure 4, the -3dB bandwidth of the established low-pass turbulent UOWC system is 29.3 MHz, and the -10dB bandwidth is 56.4 MHz.

Figure 5 presents the time-domain output waveforms corresponding to the two PDs in the low-pass turbulent UOWC system. It can be observed that the amplitudes of each output waveform exhibit significant fluctuations over time, reflecting the fading effect caused by underwater bubble turbulence on time-domain signals. Additionally, the time-domain output waveforms corresponding to the two PDs show different degrees of amplitude fading at the same time instant.

Figure 6 presents the bit error rate (BER) performance of the low-pass turbulent UOWC system based on spatial diversity. When the low-pass turbulent UOWC system considers only spatial diversity, the maximum bandwidth under the 7% forward error correction (FEC) threshold of BER=3.8×10^{-3} is 73.8 MHz. When the system employs spatial-frequency two-dimensional diversity and spatial-time two-dimensional diversity respectively, the maximum bandwidth increases to 77.1 MHz and 79.0 MHz. When the proposed time-frequency-space three-dimensional diversity is adopted in the low-pass turbulent UOWC system, the maximum bandwidth reaches 91.8 MHz, corresponding to a communication rate of 91.8 Mbps. Compared with spatial diversity alone, the time-frequency-space three-dimensional diversity expands the maximum bandwidth by 24.4%.

Figure 7 displays the BER performance of the low-pass turbulent UOWC system based on different diversity transmission schemes. When no diversity transmission is employed in the low-pass turbulent UOWC system, the maximum bandwidth at BER = 3.8×10^{-3} is only 38.6 MHz. When the UOWC system adopts time-frequency two-dimensional diversity based on a single-input single-output (SISO) transmission architecture, the maximum bandwidth reaches 64.7 MHz, which is 67.6% wider than that of the scheme without diversity. As can be seen, time-frequency two-dimensional diversity can jointly mitigate the low-pass frequency response and underwater turbulence to a certain extent. In comparison, spatial diversity alone expands the maximum bandwidth to 73.8 MHz, representing a 14.1% increase over the time-frequency two-dimensional diversity scheme. In contrast, the proposed time-frequency-space three-dimensional diversity achieves a maximum bandwidth of 91.8 MHz, which is 41.9% wider than that of the time-frequency two-dimensional diversity scheme. Compared with the scheme without diversity, the time-frequency-space three-dimensional diversity expands the maximum bandwidth from 38.6 MHz to 91.8 MHz, corresponding to a bandwidth expansion ratio of 137.8%.

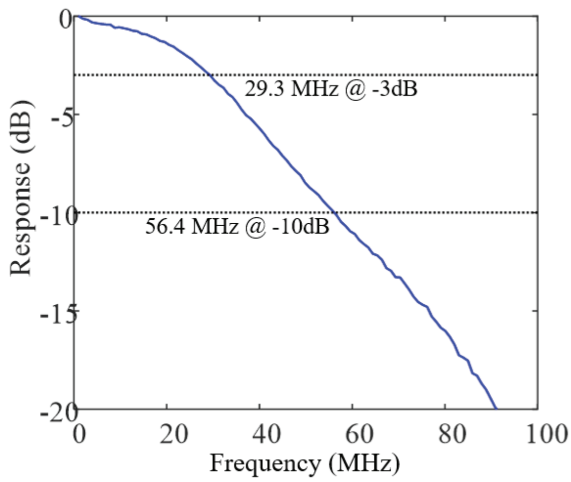

Figure 4. Frequency response diagram of the low-pass turbulent UOWC system.

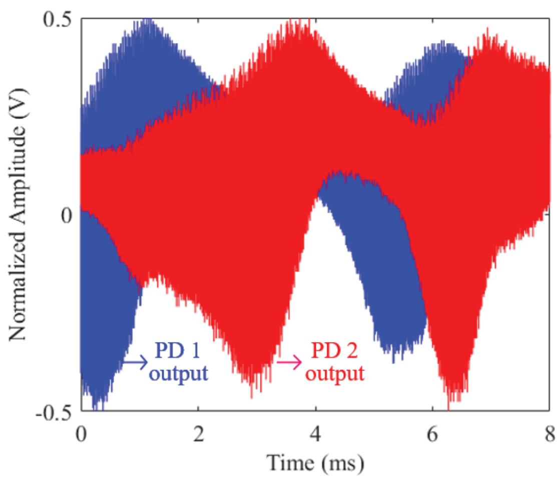

Figure 5. Time-domain waveform diagram of the low-pass turbulent UOWC system.

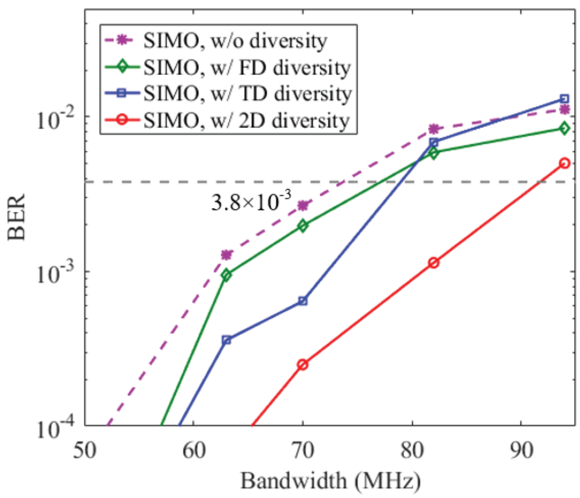

Figure 6. BER performance diagram of the low-pass turbulent UOWC system based on spatial diversity.

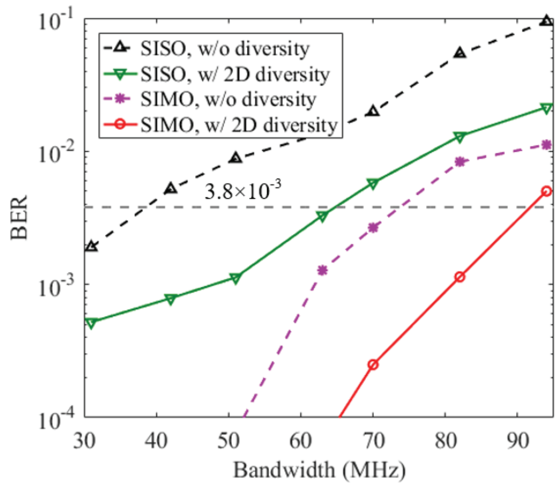

Figure 7. BER performance diagram of the low-pass turbulent UOWC system based on spatial diversity.

4. Conclusion

In summary, the proposed time-frequency-space three-dimensional diversity transmission scheme can effectively achieve joint mitigation of low-pass frequency response and underwater turbulence, significantly expand the maximum effective signal bandwidth of the low-pass turbulent UOWC system and enhance the transmission rate. Future work will further exploit the spatial dimension resources of the low-pass turbulent UOWC system, construct a multiple-input multiple-output (MIMO) architecture, and investigate corresponding diversity and multiplexing transmission schemes.

Acknowledgment

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