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Underwater wireless optical NOMA communication experiment system exploiting GaN-based micro-LED array grouping

Yanjun Liang (梁彦军), Hongxi Yin (殷洪玺)*, An Huang (黄 安), Xiuyang Ji (季秀阳), and Jianying Wang (王建英)
School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China

*Corresponding author: hxyin@dlut.edu.cn
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This paper has proposed an experimental system for non-orthogonal multiple access (NOMA) wireless optical communication in challenging underwater turbulent environments, employing the gallium nitride (GaN)-based micro-LED array. This design of the GaN-based micro-LED array enables the independent transmission of signals from distinct data streams within the NOMA framework, facilitating direct optical power-domain superposition of NOMA signals. The experimental setup involves emulating oceanic turbulence channels, characterized by varying the level of scintillation intensity, to thoroughly investigate the bit error rate (BER) performance. The outcomes unequivocally demonstrate the superiority of our proposed NOMA scheme, as compared to conventional circuit-driven optical NOMA systems utilizing fixed LED array grouping, particularly in the presence of turbulent underwater channels. The proposed NOMA scheme exhibits consistently superior BER performance and maintains excellent linearity at the lower frequencies while effectively mitigating signal distortion at the higher frequencies.

Keywords: optical non-orthogonal multiple access; gallium nitride-based micro-LED array; oceanic turbulence channels; bit error rate.
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1. Introduction

Compared to traditional underwater wireless communication methods of acoustic and radio frequency (RF) communication, optical communication boasts several advantages, including higher data transmission rates and reduced transmission latency. In contrast to underwater wireless optical communication (UWOC) systems that rely on laser-diode (LD) light sources, UWOC systems use light-emitting diode (LED) light sources, which offer compelling benefits such as lower implementation costs and substantially reduced alignment requirements between transmitters and receivers. These advantages make LED-based UWOC systems particularly well-suited for applications in the field of marine Internet of Things (IoT), offering greater robustness. However, it is important to note that LED-based UWOC systems face a limitation in terms of modulated bandwidth, typically ranging from a few megahertz to several tens of megahertz. This bandwidth constraint can impact the performance of underwater wireless optical communication systems[1,2]. The introduction of non-orthogonal multiple access (NOMA) technology can effectively enhance the spectral efficiency of such systems, increasing the number of accommodated users and the overall system capacity.

The NOMA technology in land communications enables the superimposition of multiple user signals in the power domain, allowing them to be simultaneously transmitted while optimizing the concurrent utilization of time and spectrum resources. However, its application in the UWOC is still relatively unexplored, with most studies limited to theoretical modeling and simulation and only a few ventures into practical UWOC-NOMA experiments[3–9]. Ref. [3] introduced a power-domain-based simulation model for the underwater wireless optical NOMA. Using MATLAB simulations, the communication efficiency of NOMA scheme has been assessed under varying water conditions. The experiments conducted in Refs. [4–6] confirmed the capacity advantages of NOMA-FSO (free-space optical) communication schemes. Nevertheless, the nonlinearity of the LED limits the operational dynamic range and transmitted power of the optical transmitter. To address this, Yang *et al.* proposed a grouping modulation scheme that reduces the gain-bandwidth product requirements for driving circuits by generating multi-level optical signals[7].

On the other hand, Bin *et al.* directly generated optical-domain NOMA signals using grouped LED arrays[8,9]. However, this approach exhibits inflexibility in power allocation, potentially resulting in resource imbalance when accommodating scenarios with increased user access. NOMA technology theoretically allows for efficient simultaneous access by multiple users, providing a mechanism to ensure connectivity for a large number of users in underwater Internet of Things (IoTs). One of the most significant distinctions between underwater free-space optical (FSO) links and their terrestrial counterparts lies in the impact of oceanic turbulence. It is noteworthy that these existing experiments have often disregarded the influence of underwater turbulence on NOMA signals, making it challenging to verify the reliability and effectiveness of this technology for real-world marine communication scenarios.

Therefore, this paper proposes a NOMA scheme based on GaN-based micro-LED arrays (GaN-based MLA-NOMA) for the UWOC system. By designing an array of GaN-based micro-LEDs and allocating specific LED groups to different user data, a flexible power control is achieved. This provides greater adaptability and performance optimization for the underwater wireless optical NOMA communication schemes. Furthermore, the GaN-based micro-LEDs offer higher modulation bandwidth and better linearity, allowing for better signal transmission quality within lower frequency ranges and avoiding signal distortion at higher frequencies. Additionally, in the experiments, the varying concentrations of bubbles are generated using an air pump to simulate the fading characteristics of turbulent underwater channels with different scintillation intensities. A test platform is established to validate the effectiveness of the proposed scheme. The experiment results demonstrate that, compared to independent LED circuit-driven NOMA schemes, the proposed NOMA scheme consistently achieves superior bit error rate (BER) performance and maintains robustness in turbulent environments. Our research focuses on optimizing the light source and flexible optical power allocation in underwater wireless communication systems. This has led to improved designs for existing NOMA experimental setups.

2. Experimental System Composition and Principles

This paper focuses on the experimental research concerning a UWOC-NOMA scheme involving the two-user pairing, as depicted in Fig. 1. We employed an arrayed design of GaN-based micro-LEDs, wherein the LED array is divided into two groups. The number of LEDs in each group varies according to the

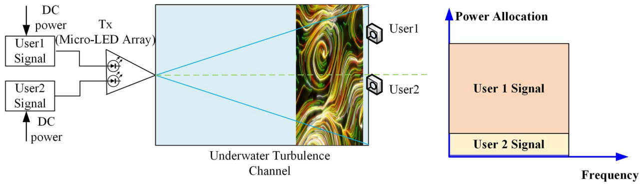

Fig. 1. Micro-LED-based UWOC-NOMA system with 2 users.

strength of the incoming data signal, and each group of LEDs is equipped with corresponding independent user signals and driver circuits. By multiplexing different user signals in the power domain, we achieve the simultaneous transmission of the user signals.

The transmission power for the ith user can be represented as

$$P_i = \eta_{P\_I}(I_i + I_{\mathrm{RF}\_i}), \quad i = 1, 2, \tag{1}$$

where $\eta_{P\text{-}I}$ represents the power-current (P-I) modulation conversion coefficient of the GaN-based micro-LED, I_i denotes the direct current (DC) bias for the ith user, and each micro-LED array undergoes individual modulation with varying DC biases, enabling direct power allocation for NOMA on optical signals. I_{RF_i} stands for the transmission signal current of the ith user. This approach allows for the flexible adjustment of the transmission power for different users to optimize power allocation.

Following transmission through the underwater turbulent channel, the optical signals are subjected to the photodetection at the optical receiver. This process yields the electrical signal for the ith user, which can be expressed as follows:

$$s_i' = \eta_{\mathrm{R}}\eta_{P\text{-}I}[(I_i + I_{\mathrm{RF}\_i}) + (I_k + I_{\mathrm{RF}\_k})]h_i + n_i, \\ i, k \in [1, 2], \quad k \neq i, \tag{2}$$

where η_{R} represents the responsivity of the photodetector, and I_k and I_{RF_k} denote the magnitude of the DC bias current and the modulated signal current for the kth user, while h_i and n_i stand for the channel gain and the noise of the ith user, respectively. It is worth noting that, given that this experiment was conducted under the prerequisite of a high signal-to-noise ratio, under the condition of equal transmission distance, any variations in the divergence angles of the two optical signals and the channel differences induced by random turbulence can be considered negligible. Hence, both channels are assumed to have identical channel gains in this context due to experimental limitations. During the demodulation process, the initial step involves assessing the signal strengths of users i and k. If the signal power of the ith user is higher, then their signal can be directly demodulated. Conversely, if the signal power of the kth user is higher, then the priority is given to demodulating the signal of the kth user. In such cases, the signal from either the ith user or the kth user is treated as noise and eliminated first. Subsequently, the demodulation process continues with the signal from the ith user or kth user.

Presently, the mainstream UWOC-NOMA approaches can be categorized into two primary categories. The first approach is the direct current-biased optical NOMA scheme (referred to as DCO-NOMA), which directly accomplishes the power allocation in the electrical domain. Subsequently, the datum transmission occurs through either a single LED or a group of LEDs. The necessary driving current for the LEDs in this scenario can be calculated as $I_{\mathrm{PR1}} = NI_{\mathrm{RF}} + \sum_{i=1}^{N} I_i$, where N represents the number of paired users[5,10]. The second approach entails assigning a varying number of LEDs to different users, enabling power distribution in the optical domain by adjusting the number of LEDs associated with each user (referred to as OPD-NOMA). In this context, the maximum required driving current for the LEDs is represented as $I_{\mathrm{PR2}} = n_{\max} I_{\mathrm{RF}} + I_{\mathrm{DC\_max}}$, with $n_{\max}$ and $I_{\mathrm{DC\_max}}$ denoting the maximum number of LEDs allocated to a user and the bias current magnitude, respectively[8].

The first approach offers the flexibility of power allocation, making it suitable for transitioning from the electrical domain NOMA to the optical domain NOMA. However, it relies on driver circuits with fixed gain-bandwidth products, limiting the modulation bandwidth. Consequently, more driving current is required to generate equivalent NOMA signals. Moreover, this approach demands larger modulation signals, i.e., higher modulation driving currents, requiring LEDs and amplifiers with broader bandwidth and linear dynamic ranges. This necessitates ensuring that no signal clipping or saturation occurs during the transmission, guaranteeing that no distortion is introduced. The second approach, while capable of achieving wider modulation bandwidths with lower driving currents, lacks flexibility in power allocation. In the scenarios with a higher number of user accesses, it may result in uneven resource distribution.

In comparison to the aforementioned approaches, the GaN-based MLA-NOMA scheme proposed in this paper exhibits enhanced flexibility in LED grouping. Each LED group can be linked to an adjustable bias current, laying the experimental groundwork for dynamic power allocation among NOMA users. This approach represents a dependable solution for addressing the challenge of equitable dynamic power allocation in NOMA scenarios.

3. Experimental Setup and Results

The experimental configuration for the UWOC system based on the GaN-based MLA-NOMA is depicted in Fig. 2. Micro-LEDs are considered an ideal light source for addressing underwater communication challenges and providing efficient, high-quality communication due to their high energy efficiency, high bandwidth, interference resistance, adjustability, and flexibility. Furthermore, compared to traditional LED light sources, micro-LEDs can be densely packed on a chip, enabling a highly integrated light source. This high level of integration is beneficial for multi-user signal transmission, supporting NOMA communication schemes, and precise control of optical power. On the sending end, the on-off keying (OOK) signals are generated through the field programmable gate array (FPGA). These signals are subsequently electrically amplified and endowed with distinct DC biases via the GaN-based micro-LED array. On the receiving end, a high responsivity silicon photomultiplier (SiPM) photodetector transforms optical signals into electrical current signals, which are then amplified through a trans-impedance amplifier to acquire voltage signals. Finally, the obtained analog signals undergo sampling utilizing a high-speed sampling oscilloscope (HO-SC) and are subjected to offline demodulation and decoding on a PC (personal computer). The system parameters set in the experiments are given in Table 1.

Notably, a "dual W-shaped" series-parallel arrangement has been employed for the LED arrays, as delineated in Fig. 3. Each group of LED arrays is endowed with autonomous pin connections for receiving input signals. The paramount attribute of this design resides in its exceptional thermal management capabilities, which, in comparison to traditional LEDs, vastly expands the linear range of its current-voltage (I-V) characteristics. Additionally, this arrangement offers an agile micro-LED allocation strategy for precise modulation of optical signal intensity. This affords an extensive operational scope for affecting power control among NOMA users. Each group of LED arrays is assigned an autonomous circuit for user signal access. These electronic signals exhibiting varying maximum peak-to-peak voltages necessitate DC level offsetting through a bias filtering module. The interleave modulation techniques are employed to amalgamate electronic signals originating from the two LED array groups, enabling the sharing of the optical channel capacity between the two users and consequently facilitating NOMA communication.

Figure 4 displays the driving electrical power-current characteristic curves for different light source devices. It is evident that

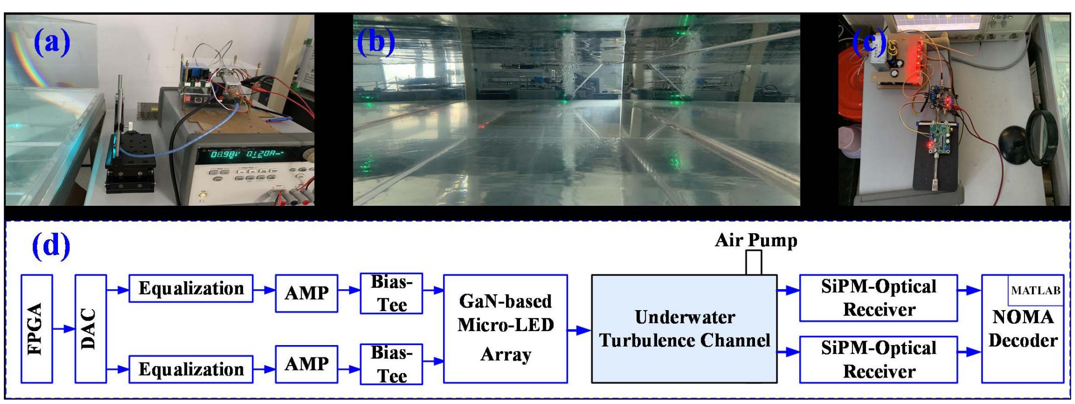

Fig. 2. Experimental block diagram for UWOC based on the GaN-based MLA-NOMA. (a) The optical transmitter, (b) the laboratory 3-m water tank, (c) the optical receiver, and (d) the experimental system structure.

Table 1. Experimental Component Parameters.

Parameter	Value
Length of the FSO link	3 m
Wavelength λ	510 nm
Photodetector responsivity @λ = 510 nm	25 A/W
DFT	256
Modulation format	QAM

the GaN-based micro-LED array light source manifests a more extensive linear range. This arises from the higher current density inherent to GaN-based micro-LEDs, which allows for a greater electrical power driving capacity and a higher modulation bandwidth when compared with conventional single-LED sources and consequently results in a larger linear range.

For the conventional blue LED, the power reached 25 mW, with an increase in current. The corresponding voltage exhibited significant fluctuations, leading to unstable data. In other words, the *P-I* characteristics showed non-linearity at this stage. To mitigate this phenomenon during practical communication experiments, the operating power needs to be kept below 25 mW as much as possible.

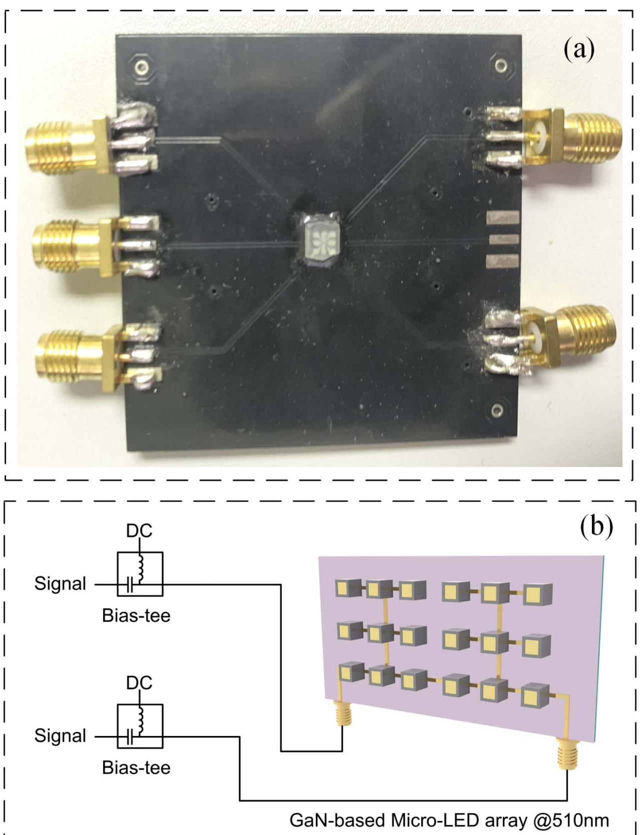

Fig. 3. Light emission source utilizing GaN-based micro-LED array. (a) The physical representation and (b) the design structure diagram.

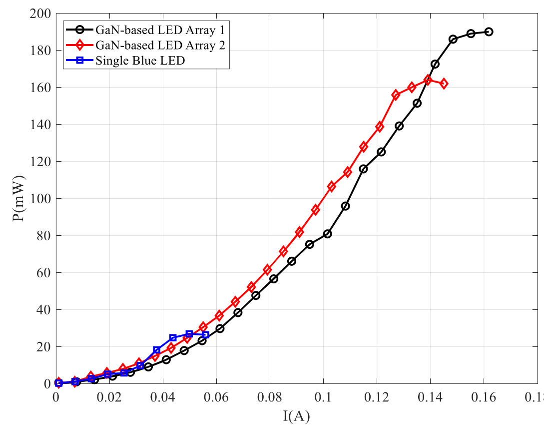

Fig. 4. Comparison of the *P-I* characteristics between the GaN-based micro-LED and the conventional blue LED.

In the experiment, an air pump is utilized to generate bubbles, simulating underwater turbulence. By manipulating the quantity and rate of bubble generation, two distinct levels of turbulences are created. To capture real-time footage of the resulting underwater turbulence, a Canon EOS-M50 Mark-II camera is employed. Additionally, 100 groups of instantaneous optical power data are collected using a UT385 optical power meter. The acquired data are subjected to statistical analysis, and the probability density function (PDF) histograms are generated, as illustrated in Fig. 5. Notably, the red curve closely conforms to a logarithmic normal distribution function[11]. This conformity provides compelling evidence that the PDF histograms of the sampled optical power closely matches the theoretical model. Through calculations based on the sampled optical power, the scintillation indices corresponding to the two levels of turbulences are determined and denoted as $\sigma_1^2 = 0.013$ and $\sigma_2^2 = 0.135$, respectively.

Figure 6 presents the BER performance of users in the GaN-based MLA-NOMA optical communication system under varying turbulence intensities, plotted against the transmission rate. To investigate the influence of power allocation on NOMA system performance, the experiments are conducted with power allocation ratios (PARs) set at 0.01 (with LED array 1 input

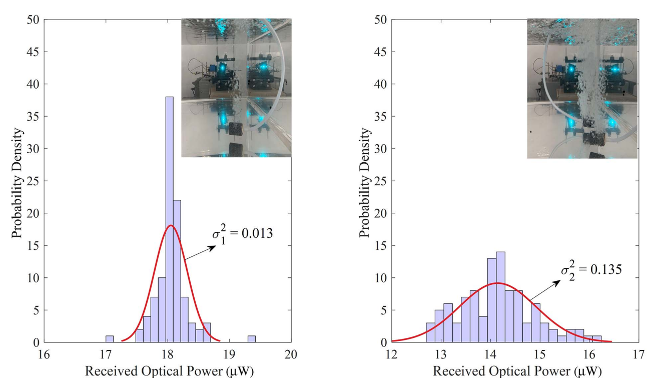

Fig. 5. Histogram and PDF of the optical power distribution obtained from turbulence simulation testing in the laboratory water tank.

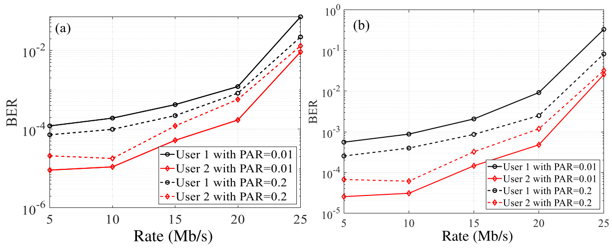

Fig. 6. Variation of the BER for NOMA users with transmission rate under different turbulence intensities. (a) $\sigma_1^2 = 0.013$ and (b) $\sigma_2^2 = 0.135$.

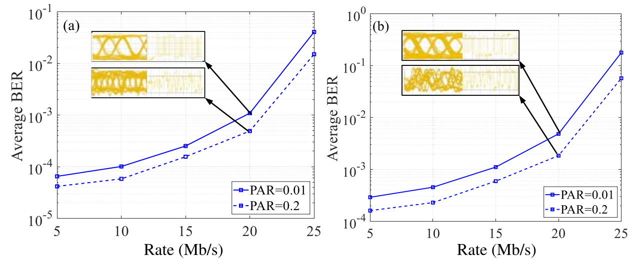

Fig. 7. Variation of the average BER for NOMA users with transmission rate under different turbulence intensities: (a) $\sigma_1^2 = 0.013$ and (b) $\sigma_2^2 = 0.135$.

current at 0.01 A and LED array 2 input current at 0.10 A) and 0.2 (with LED array 1 input current at 0.041 A and LED array 2 input current at 0.092 A). The sampling rate used in the experiments is 2×10^6 Sa/s, which is equivalent to a sampling interval of 500 ns.

As the data rate of the input signal increases, the BER of NOMA users exhibits varying degrees of elevation. It is important to note that, at an input current of 0.041 A, the BER for user signals reaches its minimum value of 1.91×10^{-5} at a data rate of 10 Mb/s. This phenomenon can be attributed to the influence of the bias-tee on the optical transmitter, resulting in a high voltage standing wave ratio (VSWR) in the low-frequency portion of the system's frequency response under conditions of low data rate and low allocated power. Consequently, when operating at lower data rates, appropriately increasing the power allocation proves effective in minimizing the BER and enhancing overall system performance.

Furthermore, based on the experimental data, we have computed curves illustrating the average BER as a function of the transmission rate for the GaN-based MLA-NOMA optical communication system under different turbulence conditions. These curves are presented in Fig. 7. The introduced inset displays eye diagrams and signal waveforms for different power allocation coefficients. The left part of the inset represents the eye diagram of the signal waveform, while the right side shows the signal waveform itself. It is evident that an increase in the power allocation coefficient or an enhancement in turbulence intensity results in varying degrees of narrowing of the eye diagram. Particularly, the increase in turbulence intensity causes distortion and closure of the eye diagram, significantly impacting the reliability of the signal. The graph notably demonstrates that the NOMA system achieves the superior average BER performance when the power allocation coefficient is set to 0.2. In conjunction with the BER performance of the individual users shown in Fig. 6, it can be inferred that this phenomenon correlates closely with the received optical signal waveform. When the power allocation coefficient is low, the received waveform closely resembles the amplitude variation observed in traditional OMA signals, featuring only two distinct amplitudes. As a result, the demodulation of high-power signals becomes relatively straightforward, with reduced susceptibility to errors. However, this scenario also amplifies interference for low-power signals. With the gradual increase of the power allocation coefficient, the received signal waveform undergoes a transformation into a more complex waveform characterized by four distinct amplitudes. Although this may introduce some interference in the demodulation of high-power user signals, it concurrently elevates the probability of successful demodulation for low-power signals. Consequently, from the perspective of overall system fairness, moderately augmenting the power allocation coefficient proves to be an effective strategy for enhancing the communication performance of underwater wireless optical NOMA systems.

These experimental results have revealed that the DCO-NOMA scheme requires a maximum LED driving current of no more than 0.06 A, which can be seen in Fig. 4. Furthermore, when the bias current reaches 0.05 A, the optical power no longer increases with further current increments and may even exhibit a declining trend. To ensure a fair comparison among the experiments, a power allocation ratio of 0.2 is employed. Table 2 outlines the implementation details of the three NOMA communication schemes. In the DCO-NOMA scheme, User 1 and User 2 are each allocated three conventional blue LEDs, forming a single group of LED light source arrays for the experimental testing. In the OPD-NOMA scheme, the 3 LEDs are divided into two groups of light source transmitters based on the signal strength of NOMA users within each group. Depending

Table 2. Comparison of Three Different Optical NOMA Communication Experimental Schemes.

Experimental Method	Superposition Method	LED Grouping Method	Driving Current	Ref.
DCO-NOMA	Electric field superposition	No grouping	Fixed	[5,10]
OPD-NOMA	Optical field superposition	Fixed grouping	Fixed	[8]
GaN-based MLA-NOMA	Optical field superposition	Grouping based on power allocation	Flexibly controllable	This work

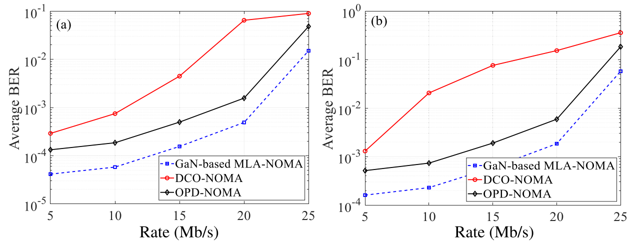

Fig. 8. Comparison of the average BER for GaN-based MLA-NOMA, DCO-NOMA, and OPD-NOMA at different transmission rates: (a) $\sigma_2^2 = 0.013$ and (b) $\sigma_2^2 = 0.135$.

on the allocated power, the electrical current signal of User 1 is input to a single LED light source transmitter, while the electrical current signal of User 2 is connected to an array composed of 2 LEDs. The experimental results, as shown in Fig. 8, unequivocally demonstrate that the proposed GaN-based MLA-NOMA system consistently achieves optimal BER performance across varying levels of turbulence. Furthermore, the NOMA scheme, which directly superimposes signals in the optical domain, outperforms NOMA schemes that perform signal superposition in the electrical domain, particularly in highly turbulent environments. This superiority stems from the fact that the power distribution in the electrical domain necessitates higher driving currents for the NOMA signal superposition, implying the requirement of amplifiers with a wider dynamic linear range to ensure the distortion-free performance. In comparison to the DCO-NOMA scheme, this grouping approach requires lower maximum driving currents, thus reducing demands on gain-bandwidth products and cost. Consequently, the proposed array grouping and flexible dynamic power allocation scheme proves to be more suitable for the underwater wireless optical NOMA communication in turbulent conditions.

4. Conclusion

This paper proposes an experimental wireless optical NOMA communication system designed for underwater turbulent environments, utilizing GaN-based micro-LED arrays. Through the design of GaN-based micro-LED arrays, the independent signal transmission for different data streams within the NOMA framework is achieved, allowing for the direct superposition and transmission of NOMA signals in the optical power domain. These experiments simulate varying levels of scintillation intensity in underwater turbulent channels and provide an extensive investigation into the BER performance. These results clearly demonstrate that, in comparison to conventional LED circuit-driven NOMA schemes, the proposed NOMA approach exhibits superior BER performance in the UWOC.

Acknowledgements

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