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Research on Adaptive Transmit Diversity Strategy for Reducing Interference in Underwater Optical Multi-Beam Non-Orthogonal Multiple Access Systems

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Abstract: With the rapid development of the underwater Internet of Things (IoT), the number of underwater communication nodes is rapidly increasing. The access capacity of a traditional multi-antenna communication system is limited by the number of transmitting antennas, and multi-beam communication systems using non-orthogonal multiple access (NOMA) technology can enhance the access capacity of the system. However, this can lead to serious inter-beam and intra-beam interference. To address the severe issues of inter-beam and intra-beam interference in underwater multi-beam NOMA systems, we propose an adaptive transmit diversity strategy. We design an algorithm for adaptive selection and merging beams based on the degree of interference between beams in space, which merges LED beams with high interference. Diversity technology is used to reduce interference between beams, and spatial multiplexing is still performed between LED groups with low interference. Within the same beam, we use an OFDM-NOMA scheme to match and group the users. Signals from different user groups are sent through different subcarriers to improve resource utilization. This enhances access capacity while reducing NOMA inter-user interference. Simulation results show that the bit error rate (BER) of users with the adaptive transmit diversity strategy satisfies the forward error correction (FEC) limits in the presence of high inter-beam interference and has a better reachable rate and BER performance compared to the multi-beam access system without interference management. We also analyze the system BER performance of the proposed strategy in the multi-user case, and the BER of all 32 access nodes are lower than the FEC threshold at a communication distance of 5 m. This demonstrates that the strategy can effectively reduce the interference of the multi-beam NOMA system.

Keywords: multi-beam; inter-beam interference; intra-beam interference; adaptive transmit diversity; OFDM-NOMA

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1. Introduction

With the rapid development of underwater communication technology and the underwater Internet of Things (IoT), there is a notable escalation in the number of autonomous underwater vehicles (AUV) and sensor node devices [1]. This proliferation engenders a consequential surge in data traffic requirements, compelling the exploration of wireless connectivity technologies capable of affording elevated data rates. Underwater wireless optical communication (UWOC) technology is being used by both academia and industry to support high-speed underwater wireless communication systems due to its advantages of high bandwidth, high speed, and low latency [2]. The next generation (beyond 5 G) wireless networks exhibit heightened demands for system capacity, service quality, and the capacity to accommodate a substantial number of interconnected devices. Multi-beam array communication systems are proficient in generating concurrent and independent high-gain directional beams [3], covering predetermined angular ranges. This capability overcomes the limitation of individual antenna beams with narrow coverage, facilitating a higher degree of concurrent communication and enabling the simultaneous servicing of multiple users. This is very important for improving the access capacity of the system and meeting the needs of multi-user communication.

However, despite the advantages brought by an increased number of transmitted beams, each antenna can serve only one user at a time, and the number of access users will be largely limited by the number of transmitting antennas [4], which is not able to satisfy the demand for large-scale equipment access. To address this issue, power domain non-orthogonal multiple access (PD-NOMA) technology can be employed to enhance the number of access users [5]. As a key technology for the next generation of wireless communication, PD-NOMA exhibits advantages over traditional orthogonal multiple access (OMA) in terms of connection number and sum capacity [6]. NOMA superimposes the multi-user signals in the power domain using the same resources and implements successive interference cancellation (SIC) to detect multi-user signals [7]. In this way, the system overcomes the limitation that a single antenna can only access one user and increases the number of accesses. Therefore, multi-user communication based on multi-beam NOMA has gained significant attention.

Recently, a hybrid SDMA/NOMA scheme has been employed in UWOC systems to accommodate multiple users [8]. In this scheme, NOMA serves to cater to users covered by each beam. However, multi-beam systems and multiple access users cause inter-beam interference and intra-beam interference problems, which seriously impair system performance. In [9], a thorough study was conducted on the unique patterns of intra-beam and inter-beam interference within multi-beam NOMA systems, comprehensively analyzing their distinct impacts on system performance. In [10], a linear precoding scheme with minimum mean square error (MMSE) was used to reduce inter-beam interference, but this scheme has high computational complexity in multi-user scenarios and is difficult to implement in hardware. Intra-beam and inter-beam interference can be minimized by designing a dynamic power allocation scheme [11]. However, the optimization problem for NOMA user power allocation is non-convex and difficult to solve. It is noteworthy that the aforementioned efforts predominantly focus on enhancing the system sum rate or max-min rate. However, in practical communication scenarios, the bit error rate (BER) performance of multi-beam NOMA systems also stands as a pivotal metric for assessing communication reliability. Spatial modulation (SM) activates only one LED to transmit information at any time [12,13], which decreases high inter-beam interference at the expense of spatial multiplexing. As a kind of improved method, channel-adapted spatial modulation (CASM) activates several LEDs to transmit information simultaneously [14], reducing inter-beam interference by finding the optimal LED combination. But there may still be significant interference between different combinations.

In this paper, we have comprehensively considered the interference issues in multi-beam NOMA systems and propose an adaptive transmit diversity strategy. Firstly, a multi-beam system is constructed using LED arrays with a semi-spherical structure. It can generate directional multi-cluster spatial beams based on user relative positions. We design an algorithm for adaptive selection and merging beams based on the degree of interference between beams in space, which merges LED beams with high interference. The low-interference LED clusters continue to derive spatial reuse gains. Within the same beam, we use an OFDM-NOMA scheme to match and group the users. Signals from different user groups are sent through different subcarriers to improve resource utilization. This enhances access capacity while reducing NOMA inter-user interference. Through simulations, we substantiate the feasibility and superiority of the proposed strategy in the context of the multi-beam NOMA system. Our main contributions are summarized in the following:

- In order to solve the serious inter-beam and intra-beam interference issues caused by multiple space-division beams and multiple access users, we propose an adaptive transmit diversity strategy. We design an adaptive selection merge algorithm to

combine different LED beams according to the degree of interference. Diversity techniques are used at the transmitter to reduce inter-beam interference.
- Based on the adaptive transmit diversity strategy for underwater optical multi-beam NOMA systems, a model and method for evaluating beam interference are proposed. The method can find the optimal merging scheme.
- Further, we propose an OFDM-NOMA scheme with an adaptive transmit diversity strategy, where users are grouped according to their channel gains and different user groups are assigned to transmit on different subcarriers. This will resist the influence of interference within the beam.

2. Multi-Beam NOMA System Model

A typical scenario of buoy-to-AUV downlink data transmission [15] is illustrated in Figure 1a. A semi-spherical structure of the UWOC system is deployed at the lower end of the buoy, and multiple LEDs are situated on this semi-spherical structure, constituting a multi-beam space division multiple access (SDMA) system. The multi-beam system can engage various spatial beams for communication based on the positions of user clusters. To enhance system access capacity and transmission efficiency, NOMA is employed within each beam to serve multiple users. Due to the unstable underwater environment, the disturbance of seawater can cause the transmitter to move randomly. This situation may result in the beam failing to cover the user cluster, causing communication interruption. Figure 1b,c show that when communication between the LED of the underwater multi-beam NOMA system and the user is interrupted, other LEDs can be lit based on the position of the user cluster to maintain communication. When the user clusters are close, there may be interference issues between different beams.

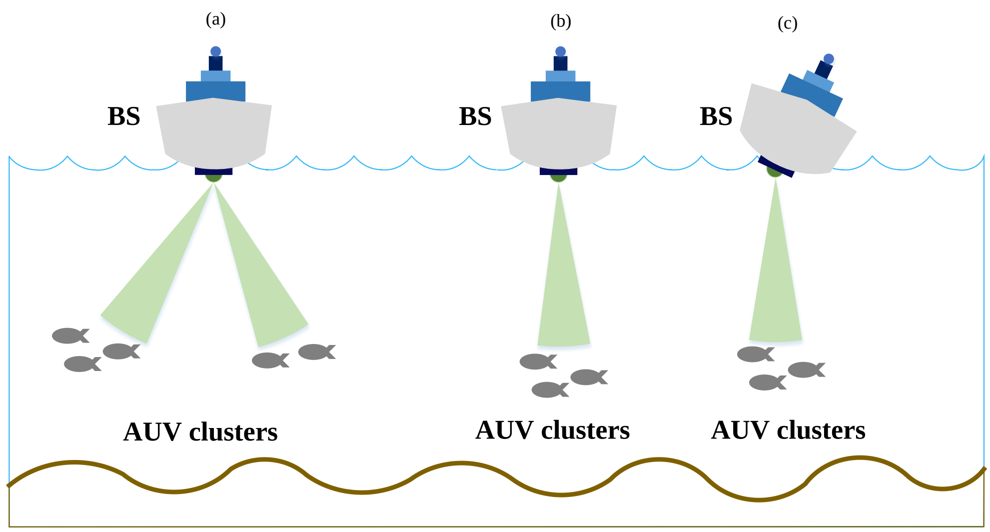


Figure 1. Illustration of a typical buoy-AUV underwater multi-beam NOMA system communication scenario. (**a**) Multi-user clusters communication, (**b**) LEDs communicate with the cluster, (**c**) communications link misalignment, change LEDs to maintain communication.

As shown in Figure 2, we assume the deployment of M LEDs at the transmitting end of a multi-beam NOMA system, serving K users belonging to distinct user clusters. The user located at the cell boundary will receive the optical signal from the adjacent LEDs. In the underwater optical multi-beam NOMA system, power allocation is determined based on the channel conditions of different users. Less power is allocated to users with good channel conditions, and more power is allocated to users with poor channel conditions. At the transmitting end, the LED array employs power multiplexing to combine the signals of multiple users through superposition coding (SC) before transmitting.

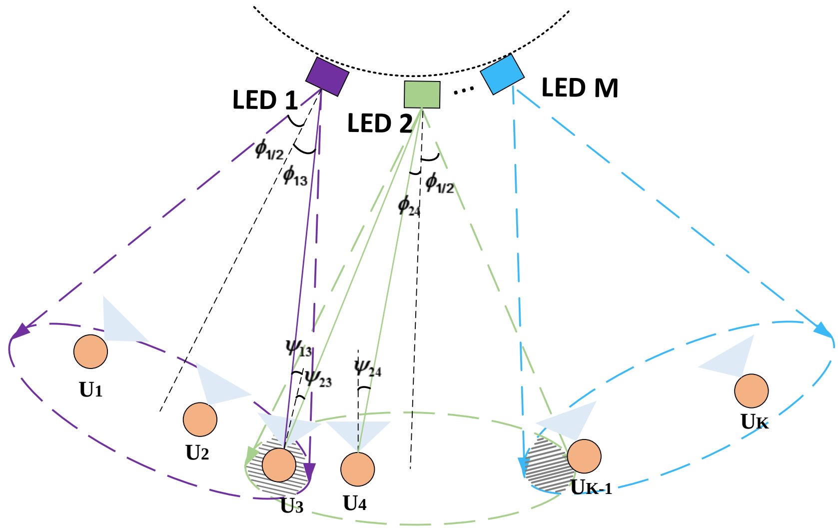


Figure 2. Diagram of underwater optical multi-beam NOMA system.

Without loss of generality, we assume that $K_m \in \{1, 2, \ldots, M\}$ denotes the number of multiplexed users in the LED m,$m = \{1, 2, \ldots, M\}$ and their channel qualities are sorted in descending order, i.e., $h_1 \geq h_2 \geq \cdots \geq h_{K_m}$, then the LED m transmits a signal that can be expressed as:

$$x_m = \sum_{k=1}^{K_m} \sqrt{a_k P_m} s_{k,m}, \quad (1)$$

where $s_{k,m}$ denotes the signal sent by the LED m to the user k, $k = \{1, 2, \ldots, K_m\}$, a_k denotes the power allocation coefficient of user k, and P_m is the transmit power of the LED m.

The signal received by the user k can be expressed as:

$$y_k = \underbrace{h_{k,m}\sqrt{a_k P_m} s_{k,m}}_{\text{signal to be decoded}} + \underbrace{\sum_{k'=1}^{k-1} h_{k,m}\sqrt{a_{k'} P_m} s_{k',m}}_{\text{intra-beaminterference}} + \underbrace{\sum_{m' \neq m} \sum_{k=1}^{K_{m'}} h_{k,m'}\sqrt{a_k P_{m'}} s_{k,m'}}_{\text{inter-beaminterference}} + n_k, \quad (2)$$

where $h_{k,m}$ denotes the DC gain from the LED m to the user k, and n_k denotes additive white Gaussian noise (AWGN) of zero mean and variance σ^2.

Assuming that each LED follows the Lambertian radiation model and only the line-of-sight (LOS) component is considered, the DC gain is calculated by the following equation [16,17]:

$$\hat{h}_{k,m} = \begin{cases} \eta_t \eta_r \frac{m+1}{2\pi} \cos^n(\phi_{k,m}) A_{eff}(L, \psi) L_{ch},\ 0 \leq \psi \leq \psi_c \\ 0\ ,\psi > \psi_c \end{cases}, \quad (3)$$

where η_t and η_r are the conversion efficiency of the transmitter and detector, respectively. $n = \frac{-\ln 2}{\ln(\cos(\phi_{1/2}))}$ is the Lambertian radiation order, $\phi_{1/2}$ is the LED half-power angle, $\phi_{k,m}$ is the irradiance angle of the light from LED m when it is received by the k-th detector, $A_{eff}(L, \psi) = \frac{\pi D_r^2 \cos(\psi)/4}{\pi(L\tan(\phi_{1/2}) + D_t/2)^2}$ is the detector effective area, ψ is the angle of incidence of the LED beam to the surface of the detector, D_t is the diameter of the LED condensing lens, D_r is the diameter of the receiving surface, and $L_{ch} = \exp(-c(\lambda)L)$ denotes the optical channel attenuation, where $c(\lambda)$ is the total attenuation coefficient of the seawater on the optical signal, and L is the beam propagation distance.

The underwater environment will be affected by turbulence. Due to the random fluctuation of the density, salinity, and temperature of seawater, the refractive index of the water experiences random variations. This will cause significant fluctuations in the phase and intensity of received optical signals at the receiving side. This study considers weak turbulent channels. To better reflect the effects of underwater temperature, salinity changes, and bubble perturbations in the actual test, the mixed exponential generalized gamma (EGG) distribution model is used, and the probability density function of the turbulence random attenuation coefficient can be expressed as [18]:

$$f(I) = \varpi f(I;\gamma_e) + (1-\varpi)g(I;[u_e,v_e,w_e]), \tag{4}$$

where ϖ is the respective weights between the exponential and generalized gamma distributions that satisfy $0 < \varpi < 1$. $f(I;\gamma_e)$ is the exponential distribution function parameterized by γ_e, whose probability density function can be expressed as:

$$f(I;\gamma_e) = \frac{1}{\gamma_e}\exp\left(-\frac{I}{\gamma_e}\right). \tag{5}$$

$g(I;[u_e,v_e,w_e])$ denotes the generalized gamma distribution, where u_e, v_e, and q_e are the shape parameter and scale parameter of the EGG distribution, whose probability density function can be expressed as:

$$g(I;[u_e,v_e,w_e]) = w_e \frac{I^{u_e w_e - 1}}{v^{u_e w_e}} \frac{\exp\left(-\left(\frac{I}{v_e}\right)\right)^{w_e}}{\Gamma(u_e)}. \tag{6}$$

Its flicker index can be expressed as follows:

$$\sigma_I^2 = \frac{2\varpi{\gamma_e}^2 + (1-\varpi){v_e}^2\frac{\Gamma\left(u_e+\frac{2}{w_e}\right)}{\Gamma(u_e)}}{\left[\varpi\gamma_e + (1-\varpi)\frac{v_e\Gamma\left(u_e+\frac{1}{w_e}\right)}{\Gamma(u_e)}\right]^2} - 1. \tag{7}$$

The signal fading caused by turbulence can be regarded as the received light intensity without the influence of turbulence multiplied by the fading coefficient [19,20]. Then the channel gain between the m-th LED and the k-th user photodiode (PD) under turbulence effect is:

$$h_{k,m} = \underset{\text{turbulence attenuation}}{\alpha} \underbrace{\exp(-c(\lambda)L)}_{\text{transmissionloss}} \underbrace{\eta_t\eta_r\frac{m+1}{2\pi}\cos^m(\phi_{k,m})A_{eff}(L,\psi)}_{\text{geometricloss}}, \tag{8}$$

where the turbulence attenuation factor α is obtained by the acceptance/rejection method [21]. Therefore, the $K \times M$ order channel gain matrix $\mathbf{H}$ of the underwater wireless optical multi-beam system is expressed as:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{K,1} & h_{K,2} & \cdots & h_{K,M} \end{bmatrix}. \tag{9}$$

At the receiving end, the achievable rate of user k on LED m can be obtained as [22]:

$$R_{k,m} = B_m \log_2(1 + \frac{H_{k,m}^2\sqrt{a_k P_m}}{\sum\limits_{k'=1}^{k-1} {H^2}_{k,m}\sqrt{a_{k'}P_m} + \sum\limits_{m'\neq m}\sum\limits_{k=1}^{K_{m'}} {H^2}_{k,m'}\sqrt{a_k P_{m'}} + \sigma^2}), \tag{10}$$

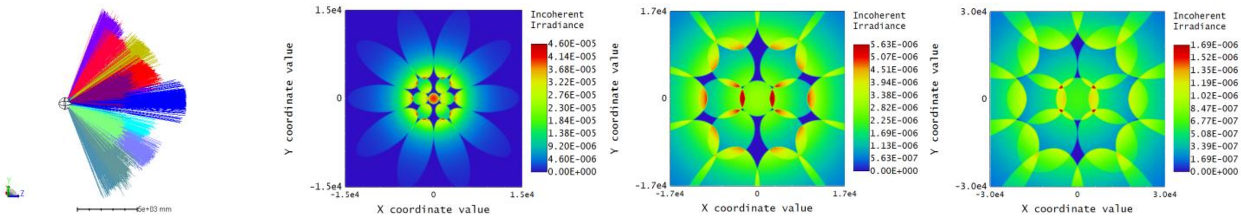
where B_m is the transmit signal bandwidth, $H_{k,m}$ is the channel gain of the user k on the LED m, and σ^2 is the noise variance.

To better characterize the spot distribution of the multi-beam system in the presence of inter-beam interference, we tracked each light path of the LED light source through ZEMAX (Zemax OpticStudio 18.9) software to obtain the spot distribution. Due to the diffusion effect of underwater beams, as the transmission distance increases, the overlapping area of beams from different LED light sources becomes larger, and the inter-beam interference increases. Table 1 lists the simulation parameters of the light paths.

Table 1. ZEMAX optical simulation parameters for multi-beam system.

Parameter	Value
Number of LEDs	17
LED half power angle	18°
LED transmitting power	1 W
Number of traced rays	106
Semi-spherical array radius	0.5 m

Figure 3a depicts a multi-beam array with a semi-spherical structure simulated using ZEMAX software. Different colors indicate different LED beams. Figure 3b–d represent the distribution of light spots at 3 m, 10 m, and 20 m of the semi-spherical multi-beam array, respectively. Due to the diffusion effect of LED beams, as the transmission distance increases, the light spot begins to exhibit aliasing at 3 m. As the transmission distance increases, spot aliasing becomes more pronounced, and the inter-beam aliasing interference increases.



(**a**) (**b**) (**c**) (**d**)

Figure 3. ZEMAX software simulation (**a**) Semi-spherical multi-beam array, (**b**) Spot distribution at 3 m, (**c**) Spot distribution at 10 m, (**d**) Spot distribution at 20 m.

In Figure 4, the signal-to-interference ratio (SIR) is used to describe the degree of non-target beam interference to the edge user of the cell [23], who is located at the intersection of two LEDs' irradiation ranges. The communication distance is within 2 m, and the user only receives the signal of the target beam. Edge users are affected by signal interference from adjacent beams at 2 m. As the communication distance increases, SIR sharply decreases. This means that the increased communication distance exacerbates the degree of light spot aliasing, the impact of non-targeted beam signals on cell edge users increases, and system reliability decreases.

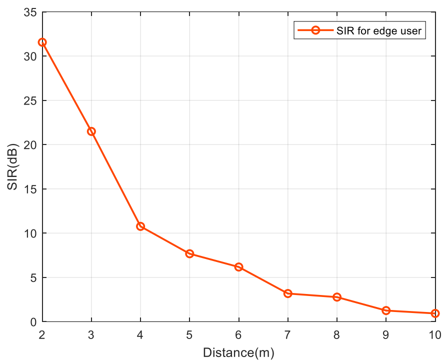


Figure 4. Relationship between SIR and transmission distance.

3. Adaptive Transmit Diversity Strategy

In the underwater optical multi-beam NOMA system, it can be seen from Equation (2) that the signal received by the user is affected by intra-beam interference and inter-beam interference in addition to the target signal. Intra-beam interference is caused by the superposition of information from users with lower decoding order than themselves in NOMA multiplexed users. Inter-beam interference results from phenomena such as optical intensity fluctuations, beam spreading, and beam drift caused by underwater turbulence. Additionally, interference from adjacent beams occurs due to the overlap of light spots, leading to undesired signals from non-target beams affecting users.

In order to effectively mitigate intra-beam and inter-beam interference, we propose an adaptive transmit diversity strategy, and the system block diagram is shown in Figure 5. We assume that the underwater channel state information (CSI) of the multi-beam NOMA system is known at the transmitter. CSI is obtained by training symbols and sent back to the transmitter periodically through uplink. There are several possible ways to realize uplink for UWOC, such as underwater acoustic and visible light with multiple access techniques [24]. The transmitter selects and merges the LED beams based on CSI. The merged LEDs group adopts the diversity technique to convert the inter-beam interference into signal gain. At the same time, it can resist the fading of the signal from turbulence. OFDM-NOMA is employed within the beam to reduce the number of NOMA multiplexed users by pairing groups of users within the cluster. Through the power-domain SC, the superimposed signals are allocated to different subcarriers for transmission. Adopting this strategy can effectively reduce the number of overlapping users on the same time-frequency resources. Subsequently, the modulated signals generated by asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) modulation are emitted by the selected LED. The user receives the signal demodulated by ACO-OFDM and demodulates its signal from the corresponding subcarrier.

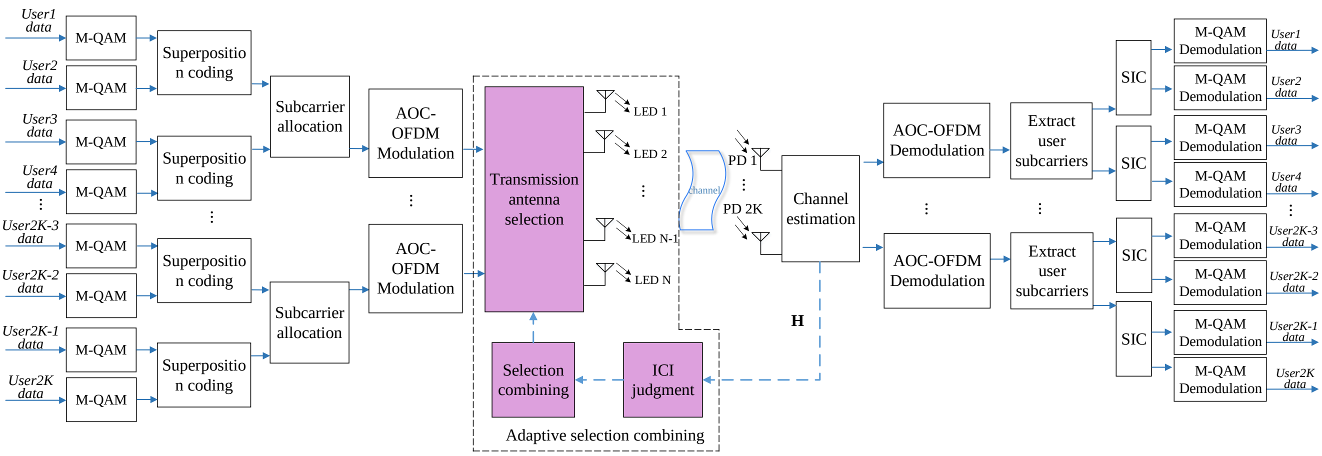


Figure 5. Block diagram of the adaptive transmit diversity strategy system.

3.1. Adaptive Selection Merge Algorithm

High inter-beam interference is a key feature of multi-beam array systems. Figure 2 shows the coverage area of neighboring LEDs and the inter-beam interference therein. At the receiving side, the interference of the user k by non-target beams can be measured as:

$$\rho_{k,m} = \frac{h_{k,m}}{\max(\boldsymbol{h_k})}, m \in [1, M], \tag{11}$$

where $\boldsymbol{h_k}$ is the $1 \times M$ order channel gain matrix of user k with different LEDs, and $\frac{h_{k,m}}{\max(\boldsymbol{h_k})}$ denotes the ratio of the non-target beam gain to the target beam gain. In order to determine the degree of influence of inter-beam interference, a threshold $\varepsilon, (0 < \varepsilon < 1)$ is set, when $\rho_{k,m} > \varepsilon$, it indicates that the inter-beam interference is more serious. The LEDs on the transmitting end need to be selected for merging employing Algorithm 1. The algorithm is expressed as follows:

Algorithm 1: Adaptive Selection Merge Algorithm

Input: Channel gain matrix **H**.
Output: LED combine index set **L**.
Initialization: Inter-beam interference tolerance threshold ε = 0.27, beam interference ratio $\rho_{k,m} = 0$, LED combine index set $L_0 = \varnothing$, index $C_0 = \varnothing$, $m = 1$, $k = 1$, $i = 1$, $j = 1$.
Steps 1: Find the element $h_{k,m}$ with $\rho_{k,m} = 1$ in each user in the channel gain matrix **H**. The strongest light signal comes from the corresponding LED, which is labeled as $C_m, m \in [1, M]$.
Steps 2: Find the LED corresponding to the element $h_{k,m}$ in the channel gain matrix **H** where each user satisfies $\rho_{k,m} \geq \varepsilon$. If the LED belongs to the index set C, it is labeled as $l_m, m \in [1, M]l_m, m \in [1, M]$, $L_k = \{l_m\}$.
Steps 3: Updating the index set $\mathbf{L} = \{L_k\}$, $k = k + 1$.
Steps 4: If $k > K$, the iteration stops. Otherwise go to Step 2 to continue.
Steps 5: Compare each subset of the index set **L** and merge the intersecting subsets until each subset of the index set **L** no longer intersects.

By selecting the merge in Algorithm 1, the index set **L** is obtained, and each subset in **L** is the set of LEDs with higher inter-beam interference, and the LED combinations are merged, while the served users are merged into a cluster accordingly. The transmit diversity is used within the LED groups to send the same data, and the space-split beams with low inter-beam interference are used between different LED groups, which balances the frequency efficiency and BER performance of the optical multi-beam NOMA system.

3.2. OFDM-NOMA Scheme

The essence of PD-NOMA is to superimpose codes on different user signals according to different power allocations at the transmitting end. The receiver employs SIC detection to separate the user target signal for demodulation. Through the LED selection and combining process outlined in Algorithm 1, the number of NOMA users served by the LED cluster increases. Consequently, the number of users multiplexed under the same resources grows, leading to heightened interference among users. This increases the complexity of SIC detection at the receiving end.

Therefore, we employ the OFDM-NOMA approach to mitigate intra-beam interference. Firstly, user grouping is determined using the D-NLUPA [25] method based on user channel gain relationships. Considering the difficulty of SIC detection at the receiving side, we pair users within each cluster in a pairwise manner. Users within the same pair share the same subcarrier and are subjected to power-domain superposition coding. Different user pairs are allocated distinct subcarriers, ensuring orthogonal transmission in the frequency domain.

The adaptive transmit diversity strategy first merges LED beams with high inter-beam interference using an adaptive selection merge algorithm, and the corresponding users served by the LEDs are also combined into a cluster. Transmit diversity is used within the LED group to transform the inter-beam interference signals into the user signal gain, which reduces the impact of the inter-beam interference, while suppressing the effects of turbulence on optical signal attenuation. Within the beam constituted by the LED group, the OFDM-NOMA scheme is used to reduce intra-beam interference by reducing the number of multiplexed users, which reduces the difficulty of SIC detection at the receiving side.

4. Simulation Results Analysis

In this section, we verify the performance of the proposed adaptive transmit diversity strategy through simulation. Therefore, based on the system and channel models in Section 2, we simulated the UWOC multi-beam NOMA system using ACO-OFDM modulation and analyzed the BER performance of the multi-beam NOMA system with adaptive transmit diversity strategy in different scenarios, and the key parameters of the simulation work are listed in Table 2. For simplicity, we assume that the number of LEDs at the transmitting end is 17, the users are set up at different locations within the communication distance, and each user adopts one PD to receive the signal.

Table 2. Simulation parameters of the multi-beam NOMA-UWOC system.

Parameter	Value
Modulation order	4-QAM
Number of subcarriers	256
Number of OFDM symbol	1000
Imaging lens diameter	50 mm
Total attenuation factor for seawater	0.15
Communication distance	5 m
Emission LED conversion efficiency	0.1289
Detector conversion efficiency	0.95

Figure 6 investigates the relationship between the BER of two NOMA users and the parameter ρ under the signal-to-noise ratio (SNR) of 30 dB. Weak users have poorer channel quality and need more power allocated to maintain the quality of service (QoS). Strong users with better channel quality are allocated less power. Thus, weak users have better BER performance than strong users. The outcomes reveal that as the value of ρ progressively increases, the interference from other beam signals on the NOMA user signals becomes more pronounced, leading to a gradual degradation in the system's BER performance. The BER of the two users is located near the FEC threshold for $\rho = 0.27$. Hence, for the subsequent experimental simulations, the inter-beam interference tolerance threshold is set to $\varepsilon = 0.27$. This indicates that the inter-beam interference is serious for $\rho > \varepsilon$, and Algorithm 1 needs to be used for selective merging.

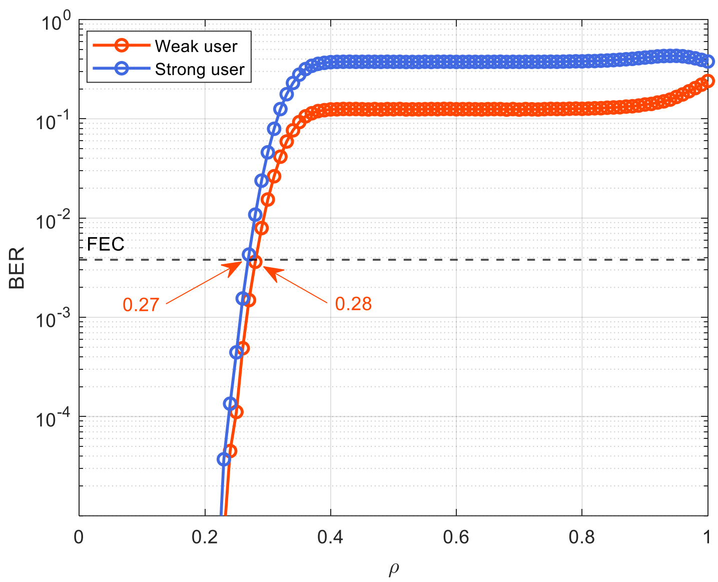


Figure 6. BER performance for NOMA users with different ρ values.

Figure 7 analyzes the BER performance of two superimposed users for different values of power allocation coefficients with SNR = 20 dB. Weak users, characterized by poorer channel quality, require more allocated power to ensure communication quality, leading to a corresponding reduction in power allocated to strong users. At the same SNR, weak users exhibit lower BERs compared to strong users. When the power allocation coefficient a_1 is around 0.8, the BER of the strong user is minimized. Therefore, in this section using the OFDM-NOMA scheme for superposition coding of two users, consider setting $a_1 = 0.8$.

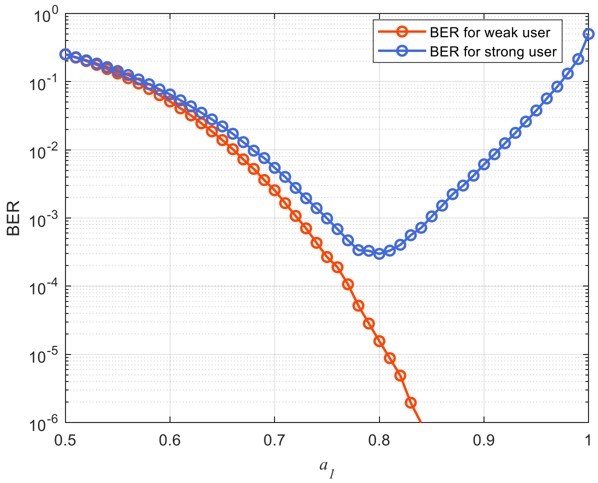


Figure 7. BER performance for NOMA users with different a_1 values.

As shown in Figure 8, the BER performance of users with the adaptive transmit diversity strategy and the conventional strategy is compared under different inter-beam interference scenarios. The conventional scheme superimposes four users' signals on the power domain with the same time-frequency resources, and the user signals with low SIC decoding order are used as the priority decoding users' interference signals. In the case of low inter-beam interference, i.e., $\rho < \varepsilon$, interference management is not required after judgment, and users with higher allocation power still have good BER performance at high SNR, while users with low decoding order have worse BER performance due to their low allocated power. In the case of high inter-beam interference, i.e., $\rho < \varepsilon$, due to the intensification of inter-beam interference, the user's received signal cannot be demodulated correctly, and its BER performance deteriorates sharply. The system that adopts the adaptive transmit diversity strategy has better BER performance, which is significantly improved compared to the conventional strategy because the adaptive transmit diversity strategy selects and combines high interference LED beams and uses transmit diversity technology to convert interference signals into signal gain. The OFDM-NOMA scheme is used within the beam to pair users two by two based on their channel gains. NOMA superimposed signals from different user groups are sent through different subcarriers. This can reduce the number of multiplexing users on the same carrier and reduce interference between NOMA users within the beam. This proves the superiority of the proposed strategy in reducing interference.

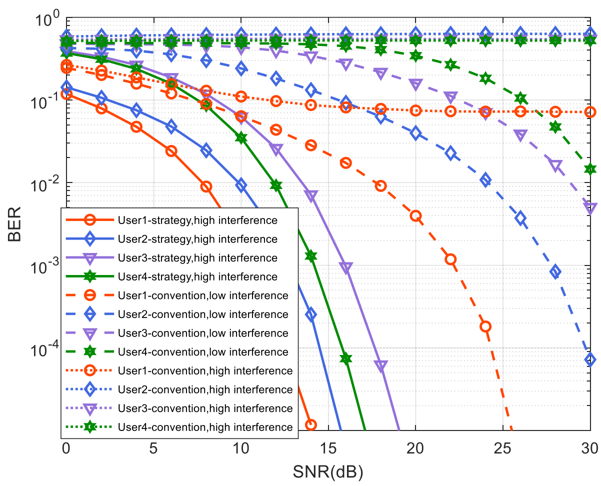


Figure 8. The BER comparison of both the conventional and proposed strategy at different interference scenarios.

Figure 9 gives the constellation diagrams of user 1 and user 2 with SNR = 25 dB. Figure 9a,b show the constellation diagrams of the signals after power allocation for user 1 and user 2, respectively. Figure 9c,d show the signal constellation diagrams for two users and four users superimposed, respectively. In the superimposed constellation, the constellation of the second user is replicated for each symbol of the first user. Each replica represents one symbol for the first user. Thus, the superimposed symbol constellation consists of $M_x = M_1 \times M_2 \times \cdots \times M_{K_m}$ symbols [26], where M is the modulation order of each user signal. Figure 9e,f show the signal constellations received by user 1 and user 2 using the conventional scheme under high-interference conditions, respectively. Due to the influence of inter-beam interference and NOMA superimposed inter-user interference, the constellation distribution of signals received by these users is chaotic. Figure 9g,h show the signal constellations of the signals received by user 1 and user 2 using the conventional scheme for the low-interference case, respectively. Due to the reduction of the inter-beam interference, the constellation points of the received signals from the users are more regularly distributed, but there is still interference. As a comparison, Figure 9i,j show the signal constellation diagrams of the two users employing the adaptive transmit diversity strategy after SIC detection. The constellation point distribution pattern shows that the interference can be effectively reduced after adaptively selecting the merging scheme and OFDM-NOMA scheme.

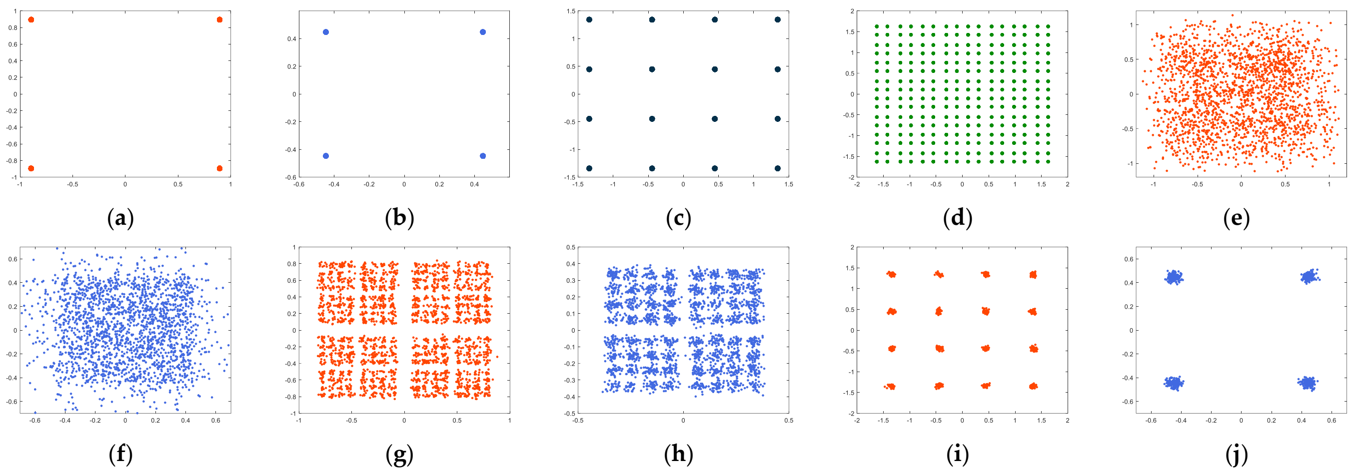


Figure 9. Constellation of (a) user 1 symbols at the transmitting end, (b) user 2 symbols at the transmitting end, (c) two users superimpose symbols, (d) four users superimpose symbols, (e) user 1 symbols using conventional scheme under high interference, (f) user 2 symbols using conventional scheme under high interference, (g) user 1 symbols using conventional scheme under low interference, (h) user 2 symbols using conventional scheme under low interference, (i) user 1 symbols using the proposed strategy under high interference, and (j) user 2 symbols using the proposed strategy under high interference.

Figure 10 depicts the BER curves of the users with the worst BER performance for the case of SNR = 20 dB with different numbers of users set in the multi-beam NOMA system. As the number of users served by the system increases, the BER of the worst user in the system also increases. Since the total transmit power of the system is limited, the more interference is generated by the increase in the number of users served. However, the BER performance of users who adopt an adaptive transmit diversity strategy is better than that of users who use conventional schemes. When the communication distance is 5 m, the BER of the worst user is lower than the FEC threshold, which verifies the feasibility of the strategy designed in this research to support multi-user communication in multi-beam NOMA systems.

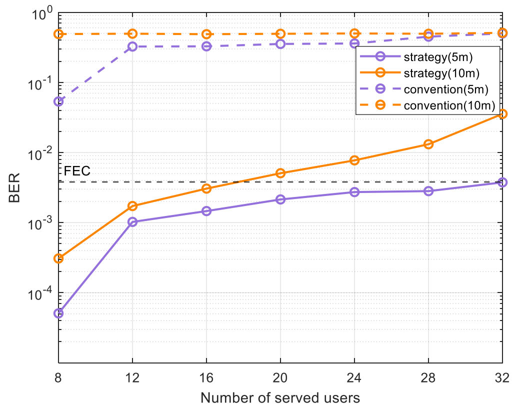


Figure 10. SNR = 20 dB, BER of users with the worst performance among different service users.

Figure 11 compares the sum rate of the two strategies at high inter-beam interference for different numbers of served users. We have assumed a channel bandwidth is 1 MHz. It can be observed from the figure that the inter-beam interference becomes more severe as the number of served users increases. The use of the adaptive transmit diversity strategy reduces the spectral efficiency of the system; however, the strategy is able to convert the interference signal into signal gain and improves the SINR. Therefore, the sum-rate performance of the system with the adaptive transmit diversity strategy is better than that of the conventional scheme and is especially significant in the case of a large number of users.

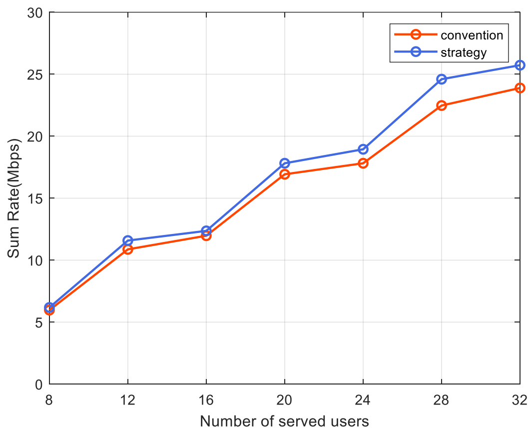


Figure 11. Sum rate of two strategies under high inter-beam interference.

5. Conclusions

In this paper, we investigate methods to reduce inter-beam interference and intra-beam NOMA user interference in underwater optical multi-beam NOMA systems. We propose an adaptive transmit diversity strategy. The strategy makes an adaptive selection of LEDs for merging based on the interference level of the beams and utilizes the diversity technique to transform the beam interference into signal gain. At the same time, the OFDM-NOMA scheme is employed within the beam to pair NOMA users in groups. Users within a group are superposition coding in the power domain, and different subcarriers are assigned between user groups and multiplexed in the frequency domain to reduce intra-beam interference and reduce the difficulty of detecting the signal at the receiver. Simulation results show that more BER gains are obtained with the adaptive transmit diversity strategy than with the conventional scheme at the same SNR. In addition, we analyze the BER performance of the system with this strategy for different numbers of serving users and verify the feasibility of the adaptive transmit diversity strategy for multi-user communication in multi-beam NOMA systems.

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