

Performance Analysis of Relay-Aided NOMA in Underwater Optical Wireless Communication System under Ocean Turbulence

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Abstract—Non-orthogonal multiple access (NOMA) is a promising technique to improve the spectral efficiency. To exploit the benefits of NOMA in underwater optical wireless communication systems (UOWC) sufficiently, this paper considers a relay-aided NOMA network for UOWC. Specifically, a UOWC model including ocean turbulence and solar radiation noise is established. On this basis, the relay selection and user pairing of relay-assisted NOMA are modeled as one problem. Additionally, in order to maximize the overall sum rates, we design a stepwise optimization power allocation scheme (SOPA) that takes the primary link and relay link into account simultaneously, the effectiveness of the proposed scheme is strictly evaluated in the relay-aided NOMA UOWC model.

Keywords— NOMA, relay-aided, UOWC, relay selection, user pairing, SOPA

I. INTRODUCTION

Underwater optical wireless communication (UOWC) has gradually become an important part of the underwater communication network due to its ultra-low latency, ultra-high transmission rate and high security [1]. However, the UOWC is also threatened by several challenges, such as the attenuation of optical signals in seawater caused by the absorption and scattering and the fading of optical caused by ocean turbulence [2,3]. A cooperative relay that has the capabilities to enhance the diversity gain, is introduced into UOWC with non-orthogonal multiple access (NOMA) to tackle these matters.

In [4], the attenuation effects caused by absorption and scattering and the fading induced by turbulence in the point to point UOWC channels, are evaluated thoroughly, and the closed-form solution for the system bit error rate (BER) in a single-hop UOWC link, is deduced. Ref. [5] proposed a series of relay deployment optimization strategies for the submarine underwater optical wireless network, a global optimization problem was modeled to compute the optimal solution. To further improve the spectrum efficiency of optical communication, Ref. [6] proposed a NOMA scheme applied to the visible light communication (VLC) network, and a gain ratio power allocation (GRPA) strategy based on optical channel conditions. Ref. [7] conducted a more

detailed analysis of the NOMA performance in VLC in which the complete analytical expression of system coverage and the closed expression of the system sum rates of VLC-NOMA under a certain quality of service (QoS) were derived. Ref. [8] verified through experiments that the NOMA scheme could effectively reduce the drive current required by the light emitting diode (LED) circuit compared to the orthogonal multiple access (OMA) scheme and greatly decrease the gain bandwidth product required for the optical transmitter.

With the increasing demand for underwater communication, the application of relay-aided NOMA in the UOWC has gradually attracted the attention of many researchers [9]. However, the existing terrestrial optical wireless communication model cannot be fully applicable to the UOWC because of the great differences between the underwater wireless optical channel environment and the terrestrial channel environment. The research on the relay-aided NOMA network is as yet mostly focused on solving the problem of power allocation in the NOMA group, while researches on joint optimization of the power allocation in the relay node and the NOMA group are rare. In this paper, the user pairing jointed with relay selection and system power optimization are designed to be a unified problem model. The main contributions of this paper are summarized as follows.

(1) The transmission of UOWC based on relay-aided NOMA under ocean turbulence is modeled, and a NOMA user grouping scheme with general applicability jointed with relay selection is proposed.

(2) A step-wise optimization power allocation scheme based on the maximization of sum rates is designed. Based on the principle of NOMA, the optimization problem is solved piecewise by the particle swarm algorithm.

(3) The applicability of relay-aided NOMA in UOWC and the effectiveness of the optimization scheme proposed in this paper are verified by simulation results, and the effects of water quality, turbulence and depth on relay-aided NOMA-UOWC system are analyzed.

II. SYSTEM MODEL

We consider a realistic scenario with multiple NOMA

receivers in the underwater environment, with a transmitter, M relay nodes and N NOMA receiving nodes as shown in Fig. 1. A forward relay needs to be selected in real time for the optical signal amplification and forwarding before the transmission link constructed formally. Here, we temporarily ignore the impact of solar radiation noise on the receiving node over the user pairing and relay selection. The channel gain between the n -th ($n \in [1, N]$) receiving user node and the transmitter is $h_{t_n}^2 h_{t_n}^2$, which can be obtained by the following formula [10,11].

$$h_{t_n} = \underbrace{\alpha^2}_{\text{attenuation}} \cdot \underbrace{\exp(-cd)}_{\text{transmission loss}} \cdot \underbrace{\frac{A_d \eta_t \eta_d \cos \theta}{2\pi d^2 (1 - \cos \theta_0)}}_{\text{geometric loss}} \quad (1)$$

where $c = a + b$ is the attenuation coefficient of seawater, and a is the absorption coefficient of seawater and b is the scattering coefficient of sea water [13]. d indicates the transmission distance of optical signal, A_d expresses the aperture area of the optical receiver, η_t and η_d signify the transmitter optical efficient of and receiver optical efficient respectively. θ is the tilt angle from the transmitter to the receiver, and θ_0 represents the light divergence angle of the transmitter. α represents the attenuation of the optical signal caused by turbulence. Here we consider the weakly turbulent channel, so the probability density function of α can be expressed as follows [12].

$$f(\alpha) = \frac{1}{2\alpha \sqrt{(\pi \ln(\sigma_{\text{sci}}^2 + 1))/2}} \exp\left(-\frac{2(\ln \alpha - \mu_s)^2}{\ln(\sigma_{\text{sci}}^2 + 1)}\right) \quad (2)$$

where σ_{sci}^2 represents the scintillation coefficient, and $\ln \alpha$ obeys a Gaussian distribution with a mean value of μ_s and a variance of $(1/4)\ln(\sigma_{\text{sci}}^2 + 1)$.

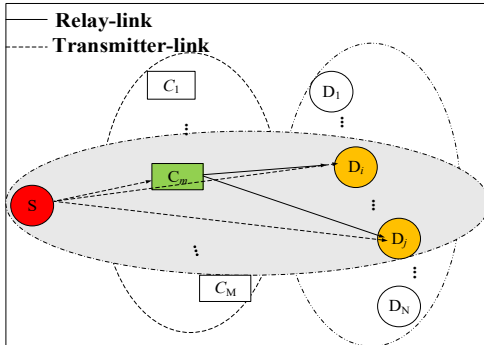


Fig. 1 Multi-user underwater wireless optical communication system model based on relay-aided NOMA

Without loss of generality, we set the channel state information (CSI) to satisfy

$$h_{t_1} > h_{t_2} > \dots > h_{t_N} \quad (3)$$

Here, we propose a user-pairing scheme joined with relay selection to ensure the maximum efficiency. Based on the CSI of receiving nodes, we select the central user i ($i \in [1, N/2]$) in each NOMA pairing group, and then, the optimal cooperative relay will be selected according to the channel

information of the central user to the relay node, which can be shown as the following expression.

$$m = \arg \max_{r \in [1, M]} |h_{r_i}| \quad (4)$$

Based on the minimum distance criterion, with the relay node m as the target node, the edge node j with the largest channel difference relative to the target node will be selected to fulfill the NOMA grouping. The selection of edge users can be indicated by the following formula.

$$j = \arg \max_{k \in [1, M]} \left(\frac{|h_{m_i}|}{|h_{m_k}|} \right), \quad (j < i) \quad (5)$$

where h_{m_i} , h_{m_k} represent the channel gains between nodes i and j to the m -th relay node, respectively.

The superimposed signal transported by the transmitter to the receiving node i and j via the relay node m can be expressed as

$$x_{t_m} = a_{i_m} P_{t_m} x_{i_m} + a_{j_m} P_{t_m} x_{j_m} \quad (6)$$

where i_m, j_m indicate the NOMA receiving node i, j selects m -th relay node as the cooperative relay, P_{t_m} represents the transmitted power when the transmitter chooses m -th relay node as the forwarding node, a_{i_m} and a_{j_m} are the power allocation coefficients of the paired users, x_{i_m} and x_{j_m} represent the modulated signals of i -th node and j -th node.

The signal received by the m -th relay node can be written as

$$y_m = \eta_{pe} h_{t_m} x_{t_m} + n_m \quad (7)$$

where η_{pe} represents the photoelectric efficiency of the photodetector, h_{t_m} is the channel gain between the transmitter and m -th relay node, n_m signifies the noise between the transmitter and m -th relay node. Unlike terrestrial wireless communication networks, there are multiple noise sources in the marine environments [14]. Here, we pick solar radiation noise, dark current noise and shot noise as the main noise that can be obtained by the following expression.

$$n_m = \underbrace{2Bq\eta_d A_d \pi(\theta_{\text{fov}})^2 \Delta \lambda T_F L_{\text{sol}}}_{\text{solar noise}} + \underbrace{2Bq\eta_d P_{t_m}}_{\text{shot noise}} + \underbrace{\frac{4Bk_B T_e \varphi_F}{R_{\text{lr}}}}_{\text{thermal noise}} \quad (8)$$

where B is the system bandwidth, q is the elementary charge, $\Delta \lambda$ signifies the optical filter bandwidth, T_F represents the transmittance of the optical filter, L_{sol} expresses the solar irradiance, T_e is the equivalent temperature, φ_F represents the system noise figure, R_{lr} is the load resistance.

The relay node employs amplify-and-forward (AF) to forward the superimposed signal for the sake of reducing the difficulty and complexity of node deployment, and the signal transmitted by m -th relay node can be expressed as

$$x_m = G\eta_{ep} y_m \quad (9)$$

where G represents the amplification coefficient of the relay node, and η_{ep} represents the P-I modulation conversion coefficient of the LED. According to the principle of AF, the amplification coefficient G can be obtained by the following expression.

$$E[|x_m|] = G\eta_{ep} \eta_{pe} (h_{t_m} P_{t_m} + n_m) \leq P_m \quad (10)$$

where P_m represents the transmitting power of m -th relay node, and the amplification coefficient can be calculated by the following formula.

$$G = \frac{P_m}{\eta_{ep}\eta_{pe}(h_m P_{t_m} + n_m)} \quad (11)$$

As shown in Fig. 1, the receiving node receives the signal from the relay node and the transmitter under the line-of-sight link. Here, we adopt maximal ratio combining (MRC) to obtain the maximum total signal-to-noise ratio [15]. Then, the signals received by i -th node and j -th node can be given as

$$y_i = \tau_1(h_{t_i}x_t + n_{t_i}) + \tau_2(h_{m_i}x_m + n_{m_i}) \quad (12)$$

$$y_j = w_1(h_{t_j}x_t + n_{t_j}) + w_2(h_{m_j}x_m + n_{m_j}) \quad (13)$$

where τ_1 , τ_2 , w_1 and w_2 represent the combination factor, and h_{t_i} and h_{t_j} indicate the channel gains between nodes i, j and the transmitter. The received signal-to-noise ratios obtained by i -th and j -th nodes can be formulated as

$$\Gamma_{i_m} = \frac{(a_{i_m} P_{t_m} h_{t_i} / n_{t_i})^2}{(1 + a_{i_m} P_{t_m} h_{t_i} / n_{t_i})^2} \quad (14)$$

$$+ a_{i_m}^2 \frac{(P_{t_m} h_{m_i} / n_{m_i})^2 (P_{t_m} h_{m_i} / n_{m_i})^2}{(a_{j_m} P_{t_m} h_{m_i} / n_{m_i} + P_{t_m} h_{m_i} / n_{m_i} + P_{t_m} h_{m_i} / n_{m_i})^2}$$

$$\Gamma_{j_m} = \left(\frac{a_{j_m} P_{t_m} h_{t_j}}{n_{t_j}} \right)^2 + \frac{a_{j_m}^2 (P_{t_m} h_{m_j} / n_{m_j})^2 (P_{t_m} h_{m_j} / n_{m_j})^2}{(P_{t_m} h_{m_j} / n_{m_j} + P_{t_m} h_{m_j} / n_{m_j})^2} \quad (15)$$

Therefore, receiving sum rates of the NOMA system can be given by

$$R_{\text{total}} = \sum_{m=1}^M R_m = \sum_{m=1}^M (R_{i_m} + R_{j_m}) \quad (16)$$

$$= \sum_{m=1}^M B \log_2 (1 + \Gamma_{i_m}) + B \log_2 (1 + \Gamma_{j_m})$$

III. POWER OPTIMIZATION BASED ON SUM RATES

The locations of nodes are difficult to deploy and the secondary replacement is hard to accomplish for the optical wireless network in the marine environment. Therefore, a priority should be given to the ability to achieve more information transmission during the limited life cycle of the node when designing the system model, namely, we need to design a power optimization algorithm to achieve more data transmission and reception under certain power consumption. Then the power allocation problem of the relay node and the NOMA pairing nodes can be expressed by the following formulas.

$$\max R_{\text{total}} \quad (17)$$

$$\text{subject to } 0 < a_{i_m} < a_{j_m} \quad (17-a)$$

$$a_{i_m} + a_{j_m} \leq 1 \quad (17-b)$$

$$M \cdot P_{t_m} + \sum_{m=1}^M P_m \leq P_{\text{total}} \quad (17-c)$$

$$P_{t_m} > 0, P_m > 0 \quad (17-d)$$

where P_{total} represents the total power of the whole system,

and the formula (17-c) shows that the transmission power of the transmitter and the relay node is strictly limited by P_{total} .

In order to reduce algorithm complexity, this section proposes a stepwise solution scheme based on the NOMA principle. We assume that the relay power can satisfy the minimum communication quality requirements of the remote users in the NOMA node. According to the principle of NOMA system power allocation assisted by the relay [16], the system can temporarily implement the power allocation coefficient of NOMA paired users to ensure the communication quality of NOMA receiving nodes with the transmitting power of the relay node being a constant. From Eq. (14) and (15), it can be seen that the NOMA node assisted by the relay not only receives the forwarded signal from the relay node but also the signal from the source node. Thus, this paper considers both the relay link and the transmitter link to the receiving node to perform the power allocation as follows.

$$\begin{cases} a_{i_m} = \frac{1}{1 + ((h_{t_i} + h_{m_i}) / (h_{m_j} + h_{t_j}))} \\ a_{j_m} = \frac{(h_{t_i} + h_{m_i}) / (h_{m_j} + h_{t_j})}{1 + ((h_{t_i} + h_{m_i}) / (h_{m_j} + h_{t_j}))} \end{cases} \quad (18)$$

After the power allocation in the NOMA group is determined, the above optimization problem can be transformed into a power distribution problem between the relay node and transmitter. A new optimization problem model is established as follows.

$$\max R_{\text{total}} \quad (19)$$

$$\text{subject to } \sum_{m=1}^M (P_{t_m} + P_m) \leq P_{\text{total}} \quad (19-a)$$

$$P_{t_m} > 0, P_m > 0 \quad (19-b)$$

The above formula is still a mixed integer programming problem that is the optimal solution of non-deterministic polynomials. However, although NOMA paired users use non-orthogonal multiple access for superimposed transmission, NOMA groups still use OMA for transmission. Then, Eq. (19) and Eq. (19-a) can be equivalent to

$$\max R_m \quad (20)$$

$$P_{t_m} + P_m \leq \frac{P_{\text{total}}}{M} \quad (20-a)$$

It can be seen from equation (20-a) that the problem can be optimally solved with the term of $P_{\text{total}} = P_{t_m} + P_m$. Then we can use the particle swarm algorithm to solve Eq. (20) by substituting $P_m = P_{\text{total}} - P_{t_m}$ into the objective function. As a bionic algorithm, the particle swarm algorithm (PSA) has natural advantages in solving optimization problems. Compared with the genetic algorithm, the particle swarm algorithm can memorize all the problem solutions, and only needs to update the search direction according to the internal speed. The algorithm is easier to implement and the convergence speed is faster [17]. The fitness function is introduced as follows.

$$\text{fit}(P_{t_m}) = R_m \quad (21)$$

The PSA initializes K groups of particle swarms, and each group of particle swarms generates a random initial transmitter emission power $P_{t_m}^{(k-1)} P_{t_m}^{(k-1)}$ ($1 \leq k \leq K$) that represents the initial value of the k -th group. In order to facilitate labeling, this paper introduces the mark symbol s_k to indicate the value of the emission power in the k -th particle swarm. During the t -th iteration of the k -th particle, the current power value s_k and speed value v_k are updated by the following formula.

$$v_k^{(t)} = \chi v_k^{(t-1)} + c_1 r_1 (pbest_k - s_k^{(t-1)}) + c_2 r_2 (gbest - s_k^{(t-1)}) \quad (22)$$

$$s_k^{(t)} = s_k^{(t-1)} + v_k^{(t-1)} \quad (23)$$

where χ represents the inertia weight. When χ becomes larger, the global optimization ability of the model is enhanced, and the local optimization ability is weakened. c_1 and c_2 represent acceleration coefficients that reflect the intensity of particle self-learning and group learning.

It can be seen from Eq. (22) that the next point of the particle will be affected by the previous speed value and direction value, and the next motion of the particle will be determined by the experience of the last motion and the experience sharing of other particle groups. The pseudo code of the stepwise optimization algorithm designed in summary is shown in Algorithm 1.

Algorithm 1 Stepwise optimization power allocation algorithm

Initialize: The number of particle swarm K , the maximum iteration M , the initial adaptive function value $L^{(*)} \leftarrow 0$.

Output: The optimal source node transmission power P_t .

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1: for  $k \leftarrow 1$  to  $K$ 
2:   Initialize the initial source node transmission
   power factor  $s_k$  and the velocity factor  $v_k$ .
3: Calculate the adaptive function value  $L^{(k)}$  according to
   Eq. (13)
4:   if  $L^{(k)} > L^{(*)}$  then
5:      $pbest_k \leftarrow s_k, gbest \leftarrow s_k$ 
6:      $L^{(k)} \leftarrow L^{(*)}$ 
7:   end if
8: end for
9: while not stop
10:  for  $m = 1$  to  $M$ 
11:    Update the source node transmission power
    factor  $s_k$  and the velocity factor  $v_k$  according to Eq. (22)
    and Eq. (23).
12:    if  $\text{fit}(s_k) > \text{fit}(pbest_k)$  then
13:       $pbest_k \leftarrow s_k$ 
14:    end if
15:    if  $\text{fit}(pbest_k) > \text{fit}(gbest)$  then
16:       $gbest \leftarrow pbest_k$ 
17:    end if

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18:   end for
19:    $P_{tm} \leftarrow gbest, P_m \leftarrow P_{total} - P_t$ 
20: end while

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IV. SIMULATION EXPERIMENTS AND ANALYSIS

In this section, we conduct simulation comparison experiments to verify the effectiveness of the SOPA algorithm proposed in this paper based on the relay-aided NOMA network. The parameters used in the simulation are shown in Table 1.

The depth of the transmitter in simulation scenarios of relay-aided NOMA is set to 23m, the relay nodes are located in the depths of 18m, 26m respectively, and the depths of the receiving nodes are in the order given set to 23m, 17m, 19m and 26m severally, and the specific location of each node can be shown in Figure 2.

Table 1 Simulation parameters

Parameters	Values
System bandwidth B	20MHz
Total transmitted power P_{total}	2000mW
Number of relays M	2
Number of receiving nodes N	4
Divergence angle of the transmitter θ	30°
Aperture area of the optical receiver A_d	0.01m ²
P-I modulation conversion coefficient η_i	0.9A/W
Responsibility of the photodetector η_d	0.9W/A

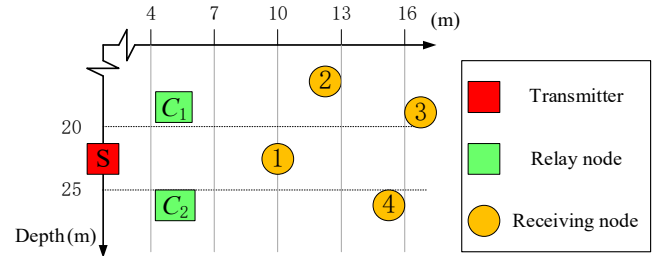


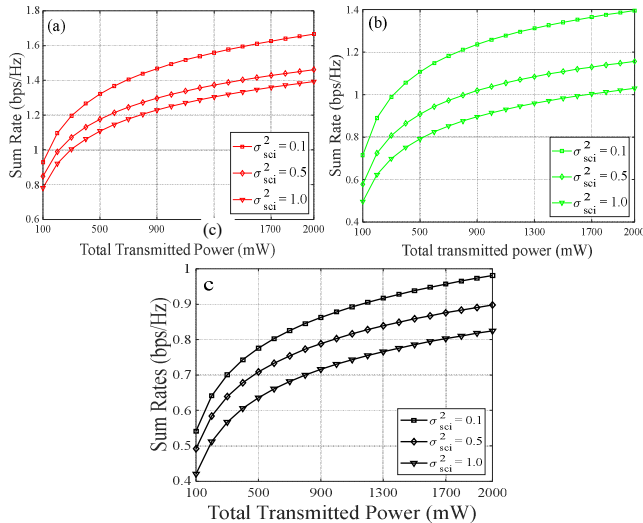
Fig. 2. Diagram of simulation scenarios of Relay-aided NOMA

The results of power allocation and system sum rates of relay-aided NOMA network in typical clear seawater can be summarized in Table 2 where the FPA stands for the fixed power allocation scheme under that the transmitting powers of the relay node and the transmitter are equally distributed, and the DUP stands for the direct user-pairing scheme under that the nodes are directly paired according to the principle of maximum distance. It can be seen that the relay selections of NOMA users under the three schemes are different, and our simulation results show that the SOPA algorithm proposed in this paper can always obtain the maximum sum rate. Compared with the FPA, the SOPA algorithm can increase the sum rate of NOMA-UOWC by 20.86%, and even more, the SOPA algorithm can increase the sum rate by 73.20% in comparison with the DUA algorithm.

Table 2 Comparison of sum rates for three schemes of NOMA-UOWC with power allocation and aided relay

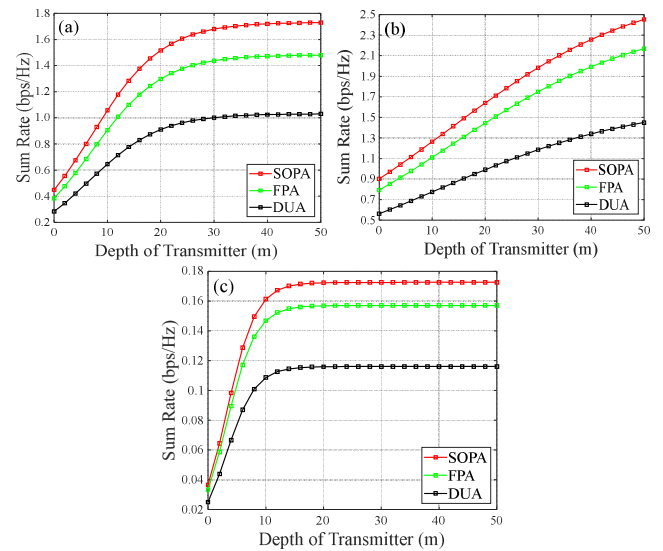
	Relay selection	P_{t_m} (mW)	P_m (mW)	R_{total} (bps/Hz)
SOPA	$C_1(i=1, j=4)$	445.73	554.27	1.68
	$C_2(i=2, j=3)$	356.85	643.15	
FPA	$C_1(i=1, j=4)$	500.00	500.00	1.39
	$C_2(i=1, j=4)$	500.00	500.00	
DUA	$C_1(i=1, j=3)$	278.62	721.38	0.97
	$C_1(i=2, j=4)$	315.28	684.72	

The effect of ocean turbulence on the performance of NOMA network is further investigated as follows. As the scintillation coefficients are set to 0.1, 0.4 and 1.0 respectively, that the performance of the proposed SOPA is compared with those of the FPA and DUA algorithms, can be shown in Fig. 3. Noticeably, there is no obvious linear relationship between the system sum rates and the transmitted powers. With the increase of the transmission power, the increasing trend of the sum rate is gradually weakening, which is caused by the interference between the paired nodes in the NOMA group. The SOPA algorithm can effectively reduce the impact of turbulence on system performance in contrast to the FPA and DUA algorithms. Especially, when the transmitting power is 2000mW, the SOPA algorithm can bring a sum rate gain of 0.29bps/Hz and 0.71bps/Hz compared with FPA algorithm and DUA algorithms respectively in the case of $\sigma_{sci}^2 = 0.1$. When the scintillation coefficient rises to 0.5, the sum rate of NOMA-UOWC with the SOPA algorithm is increased by 0.31bps/Hz, 0.59bps/Hz compared with the FPA and DUA algorithms, and when the scintillation coefficient is 1.0, the sum rate gain of SOPA algorithm relative to FPA and DUA algorithm is 0.34bps/Hz, 0.57bps/Hz.

**Fig. 3** Sum rates versus transmitted powers for the relay-aided NOMA-UOWC system for (a) SOPA algorithm, (b) FPA algorithm and (c) DUA algorithm.

In our simulation work, the receiving rate of NOMA node will change significantly with the depth of the node

under the same transmission condition. According to the formula in the previous section, we believe that this change is closely related to the solar radiation noise. The sum rate versus the depth of transmitter for Aided-NOMA system in three typical seawaters referring to Ref. [13] can be shown in Fig. 4. It can be clearly seen that in clean seawater, the system rate reaches 1.73bps/Hz with the SOPA algorithm in the depth of 42m, and the sum rate hardly increases when the depth increases after 42m. We call it the equilibrium depth. The equilibrium depth of the system with FPA and DUA algorithms in the clean seawater are 40m, 36m around. Similarly, in coastal water, the system has a balance point within the depth of 50m and the equilibrium depths of the system with SOPA, FPA and DUA algorithms are subequal. But in pure seawater, the system sum rate increases linearly with the increase of depth when the depth of transmitter is less than 50m, i.e., the solar radiation noise still has a greater influence on the node receiving signal-to-noise ratio in this depth range.

**Fig. 4.** Sum rates versus depth of transmitter for relay-aided NOMA-UOWC system for (a) clear seawater, (b) pure seawater, (c) coastal water.

V. CONCLUSION

This paper presents a relay-aided NOMA scheme for the underwater wireless optical communication. A NOMA user pairing scheme jointed with relay selection is proposed considering the influence of relay selection on NOMA user pairing. Then, we design a stepwise power optimization scheme based on the sum rate and the solutions are obtained by the particle swarm algorithm. The effectiveness of the proposed scheme is verified by our simulation experiment, and the relay-aided NOMA-UOWC system with the SOPA scheme performs better robustness to the underwater turbulence compared with FPA and DUA schemes. Moreover, this paper studies the influence of solar radiation noise on the NOMA-UOWC system under different water qualities, the simulation results indicate that as the attenuation of seawater decreases, the impact of solar radiation noise on the UOWC

system increases.

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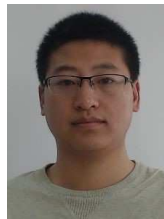
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