

Adaptive Underwater Optical Communication Beam Divergence and Orientation Angle Adjustment Algorithm based on Marine Environment Perception

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Abstract

In this work, we study learning-aided adaptive control of optical beam alignment to maintain a seamless connection with high communication performance in underwater optical wireless communication (UOWC). To this end, we proposed a beam orientation and beam divergence angles adjustment (BO-BD) algorithm that enables an underwater sensor (US) to sequentially determine the beam orientation and beam divergence angles for transmitting its sensing data to an unmanned surface vehicle (USV) that may irregularly shake above the sea level. Specifically, the proposed BO-BD algorithm included two Deep reinforcement learning (DRL) agents. The BO agent selects the beam orientation angle to point the optical beam toward the USV to perform beam alignment. Moreover, given the beam orientation angle, the BD agent selects the beam divergence angle to maximize the signal-to-noise ratio (SNR) while maintaining the seamless optical link between two nodes. The simulation results demonstrate that the proposed BO-BD algorithm achieves the highest SNR while maintaining a stable UOWC link compared with existing algorithms.

I. Introduction

Underwater optical wireless communication (UOWC) has gained significant attention in recent years due to its potential for high-speed data transmission, wide bandwidth, and low latency in underwater [1].

Despite of its numerous advantages, UOWC faces various challenges in underwater channels that are significantly different from those encountered in terrestrial environments. One of the challenges is that optical signals experience severe attenuation and fading owing to absorption, scattering, and turbulence.

Another challenge of the UOWC is the misalignment between the transmitter and receiver owing to the unpredictable and irregular movement of water currents or unmanned surface vehicle (USV) at sea level, which affects network performance, such as link quality degradation and link disconnection [2].

However, most of existing studies on the link misalignment of UOWC did not consider the joint optimization of the beam orientation and beam divergence angles. To solve this problem, we aim to develop an online algorithm that jointly determines the beam orientation and divergence angles under a UOWC scenario, where the misalignment between the transmit node (i.e., underwater sensor (US)) and receive node (i.e., USV) owing to irregular shaking and movement of the USV is considered. For this purpose, we propose a deep reinforcement learning (DRL)-based beam orientation and beam divergence angles adjustment

(BO-BD) algorithm consisting of two deep Q-network (DQN). Specifically, the BO agent selects the beam orientation angle to control the optical beam pointing toward the USV for alignment. Moreover, the BD agent selects the beam divergence angle to maximize the signal-to-noise ratio (SNR) while maintaining a seamless connection of the optical link.

II. System Model

This study considers a three-dimensional (3D) UOWC scenario between US situated on the seabed and USV capable of maneuvering on the sea surface as depicted in Fig. 1. For the transmission of sensing data from the US to the USV, we consider the UOWC with a hybrid acoustic-optical communication modem. Because the US requires high-rate transmission, the UOWC considered for sensing data transmission. Conversely, underwater acoustic wireless communication (UAWC) is considered for control data transmission from the USV to the US.

The actual beam orientation angle can be represented by the actual beam azimuth and elevation angles (i.e., θ_{A_R} and θ_{E_R}). In addition, the selected beam orientation angle can be represented by the selected beam azimuth and elevation angles (i.e., θ_{A_S} and θ_{E_S}). The inclination angle θ_I between the selected orientation angle and actual orientation angle is determined as follows:

$$\theta_I = \cos^{-1} \left(\frac{D_R^2 + D_S^2 + D_E^2}{2D_R D_S} \right). \quad (1)$$

The optical signal transmitted in underwater reaches

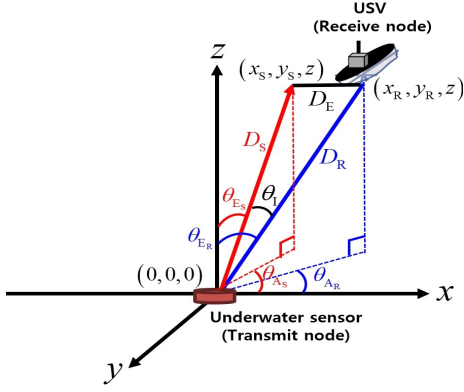


Fig. 1: UOWC system model.

the receive node under the influence of the underwater channel such as path-loss and fading. The path-loss is composed of two components: propagation loss and geometrical loss. The propagation loss can be expressed as follows:

$$P_L = \exp\left\{-c(\lambda) \frac{D_s}{\cos(\theta_i)}\right\}, \quad (2)$$

where $c(\lambda)$ is the attenuation coefficient. Thus, the propagation loss increases as the attenuation coefficient, inclination angle, and distance increase.

Furthermore, the geometrical loss reflecting the effect on the misalignment can be expressed as follows:

$$G_L = \begin{cases} \frac{A_r \cos(\theta_i)}{2\pi D_s^2 [1 - \cos(\theta_d)]}, & \theta_D \geq \theta_i \\ 0, & \text{otherwise} \end{cases}, \quad (3)$$

where A_r denotes the aperture size and θ_D is beam divergence angle. The Geometrical loss can be calculated when the beam divergence angle is greater than or equal to the inclination angle.

Another significant factor that influences the channel is fading. The overall fading coefficient of the N layers is expressed as follows:

$$F_M = \prod_{n=1}^N F_n. \quad (4)$$

Consequently, received power of the receive node can be calculated as follows:

$$P_R = P_T \eta_T \eta_R P_L G_L F_M. \quad (5)$$

III. Proposed Algorithm

We formulate our optimization problem as a Markov decision process (MDP) with two agents (i.e., BD and BO agents). The MDP for the BD agent and BO agent consist of tuple (S^{BD}, A^{BD}, r^{BD}) and (S^{BO}, A^{BO}, r^{BO}) , where S , A and r represent the state space, action space and reward function, respectively.

The action space of the BD agent defined as the set of beam divergence angles, and the reward is the SNR. On the other hand, the elements of action space of the BO agent refer to whether to increase, decrease, or maintain the beam orientation angle, and the reward depends on the difference between the selected beam orientation angle and the actual orientation angle.

To address the MDP problem, we implement the BO-BD algorithm which can jointly adjust the beam orientation angle and beam divergence angles. Under proposed algorithm, the US acts as a DRL decision maker with two DRL agents who determine difference actions, each learning through DQN.

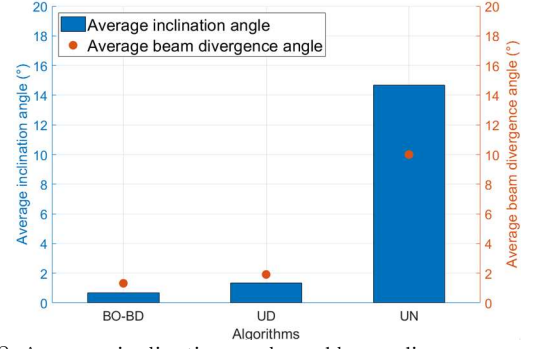


Fig. 2: Average inclination angle and beam divergence angle.

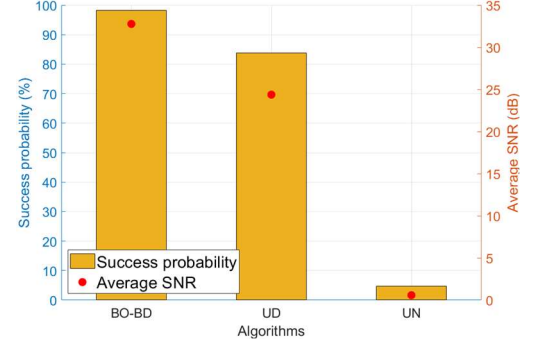


Fig. 3: Average SNR and link alignment probability.

IV. Simulation Result

To analyze the performance of the proposed algorithm, we performed the simulation by utilizing GPS data from the USV as the location data of receive node.

Fig. 3 illustrates the average inclination angle and the corresponding average beam divergence angle. The 'BO-BD' algorithm learned the position of USV using DRL-based method and adjusted the beam orientation angle to minimize the inclination angle, while maintaining the average beam divergence angle within 2° .

Fig. 4 illustrates the UOWC performance, such as SNR and reliability. The 'BO-BD' algorithm selects optimal beam divergence angle that maximize the SNR while preventing link disconnection owing to variations in the inclination angle caused by the irregular movement.

V. Conclusion

In this study, we propose the BO-BD algorithm, which jointly optimizes the beam angle to ensure the UOWC link quality. As a result, the proposed algorithm establishes the reliable UOWC link with the high alignment probability and maximized SNR.

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