Real-time Image-based Beam Tracking for Water-air OWC System with Mobile Receiver through Wavy Water Surface

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Abstract: *We proposed and experimentally demonstrated a real-time imaged-based beam tracking for water-air OWC systems with a mobile receiver through a wavy water surface. With tracking, the packet loss rate reduces from over 85% to below 7% and a zero-packet-loss 600 Mbit/s transmission is achieved.*

Introduction

Intensified underwater activities, including deep-sea mining, underwater rescue, and ocean ecological system monitoring, call for flexible, reliable, and high data-rate underwater communication links [1]. To transmit massive undersea information to an aerial vehicle and further relay it to a land station, optical wireless communication (OWC) is the most promising technology for short- and medium-range communication [2]. However, as illustrated in Fig. 1(a), two fundamental issues of a water-air link needed to be considered: (i) beam wandering due to the time-varying refraction when the light beam passes through the wavy ocean surface and (ii) the mobility of the drone hovering above the ocean surface. In [3], an expanded beam coverage area is proposed to compensate for the beam deflection, but the reduced power density leads to a lower signal-to-noise ratio (SNR). With beam tracking, it allows a more focused laser to achieve higher SNR in a real scenario.

Beam tracking has been implemented for satellite OWC links [4-6] and free-space optical communication [7-10]. However, investigation and demonstration for water-air OWC with a mobile receiver through a wavy water surface are very limited. The wave-induced change of light spot location on the receiver plane is rapid and quite random, requiring higher-speed and more accurate tracking [11]. A 3×3 photodiode (PD) array-based beam tracking scheme has been developed for wave mitigation [12]. But the resolution and tolerable offset range are restricted by the number of PD.

In this paper, an image-based beam tracking scheme is investigated and experimentally demonstrated for responsive and accurate tracking in the water-air OWC system. The beam offsets caused by the aforementioned wavy water surface and the receiver's mobility are effectively mitigated. Precise light spot position is calculated via an image processing algorithm. Experimental results show a significant enhancement under different wave levels, receiver moving speeds, and symbol rates via beam tracking. A zero-packet-loss 600 Mbit/s transmission and a maximum throughput of 930 Mbit/s can be realized under an average wave slope change rate (ASCR) of 0.103 rad/s, a receiver moving speed of 8 cm/s, and a 1.6-m air path. This is the first demonstration of a water-to-air OWC system with a mobile receiver using beam tracking with only transmitter side sensing.

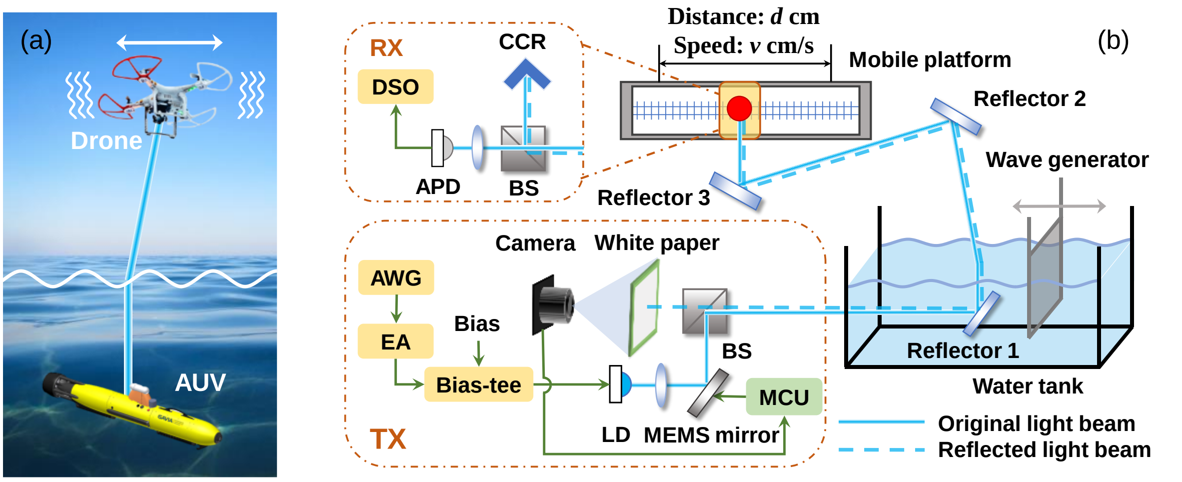

Fig. 1: (a) Illustration of water-air OWC link between an autonomous underwater vehicle (AUV) and drone and (b) Proposed imaged-based beam tracking for a water-air OWC system with the mobile receiver through a wavy water-air interface.

Principle of Imaged-based Beam Tracking

When passing through the wavy water surface, a light beam will be refracted, resulting in a light spot offset at the receiver. In the scheme, we use a corner cube retroreflector (CCR) at the receiver (Rx) side to reflect partial light back to the transmitter (Tx) for tracking. The reflected light at Tx is projected on a white paper to form a tracking spot. The tracking spot offset also indicates the light spot offset at the Rx side. A Tx-side camera module captures the tracking spot location and feeds it back to a microcontroller unit (MCU) for micro-electromechanical systems (MEMS) mirror tilting. Tracking spot offset can also be induced by drone movement. Both effects induced by water wave and Rx movement can be mitigated by beam tracking. A new image-based beam tracking algorithm, illustrated in Algorithm 1 below, is developed. In the initialization, an image is captured and image intensity equalization is performed to filter the background light. The range of tracking spot intensity (***hi*** to ***lo***) is derived with ***hi***=255 and ***lo***=the minimum intensity level of the top 10% pixels. During tracking, repeated snapshots are taken and lens correction is applied to ensure correct spatial information. The tracking spot is identified by finding a cluster of consecutive pixels that satisfy (i) grayscale values within the set range (***hi*** to ***lo***) and (ii) the cluster size > ***p_num*** (the minimal pixel number of the tracking spot). The centroid of the cluster pixels is calculated as the tracking point location. Then the light spot offset is deduced. The offset is used to control the MEMS mirror to compensate for the light spot offset. An error tolerance value is set to ignore minute offset changes.

Algorithm1. Image-based Beam Tracking Algorithm

Input: minimal tracking spot cluster size: ***p_num***;
target light spot position: (x_i, y_i);
beam steering parameter: (x_a, y_a);
tolerance offset error: (***err_x***,***err_y***)

Output: beam steering angle: **(*x_angle*, *y_angle*)**

1. image intensity equalization and threshold finding: ***hi*** = 255, ***lo*** = the minimum intensity level of the top 10% brightest pixels;
2. **while** true
3. take a snapshot with lens correction and transfer pixels, ***p*[]**, to grayscale;
4. find all target pixels, ***p_tg*** (x_p, y_p) whose values are between ***hi*** and ***lo***;
5. **if** consecutive target pixel number > ***p_num***,
6. output: x_c = mean(x_p), y_c = mean(y_p);
7. **end if**
8. calculate offset: $x_d = x_c - x_i$, $y_d = y_c - y_i$;
9. **if** $|dx|$ > ***err_x*** and $|dy|$ > ***err_y*, then**
10. do beam steering with angle: ***x_angle*** = $x_a \times dx$, ***y_angle*** = $y_a \times dy$;
11. **end if**

Experimental Setup and Implementation

Fig. 1 (b) shows the experimental setup of the proposed image-based beam tracking scheme for a water-air OWC system with a mobile receiver. A water tank with a dimension of 68×30×38 cm (length×width×depth) is filled with 0.14-m-deep of tap water. Note that this study focuses on wave-induced impairment; thus, water transmission distance is not the primary consideration. However, a longer air path will lead to a larger offset of light beam deviating from the detector, increasing tracking difficulty [11]. A periodically moving plate creates different wave levels by controlling the plate's moving speed. The modulation signals are generated by an arbitrary waveform generator (AWG, Tektronix 7122 C) and amplified by an electrical amplifier (EA) of 16-dB gain. The amplified signal, coupled with a 6.0-V bias via a bias-tee (Mini-Circuits ZFBT-6GW+), is applied to a pigtail laser diode (LD, 495 nm, 33 mW). A MEMS mirror (Mirrorcle, A8L2.2-4600AL-TINY48.4-A/TP) is employed with a diameter of 4.6-mm and a maximal beam steering angle of ±5 degrees for both x- and y-axis. The light is focused by a lens first and reflected by the MEMS mirror. Three reflectors are placed to direct the light to a mobile platform in our confined lab space. In real scenarios, the reflectors are not needed, and a drone will be above the water surface as an OWC relay. A mobile platform is employed to emulate the movement of the drone hovering above the water. After passing through a 0.14-m water path and a 1.4 or 1.6-m air path, the light is split by a 50:50 beam splitter (BS) at the Rx side. Half of the light is reflected by a CCR (Thorlabs, HRR201-P0) to the Tx side. A camera (MT9V034) behind the white paper captures images at 110.6 frames per second (fps). The other half of the light is detected by a 1-GHz APD (Hamamatsu, C5658). The beam size at the Rx side is 4 mm and a lens is placed in front of the APD. The detected signal is recorded by a digital storage oscilloscope (DSO) for further offline signal processing. We collect 100 packets, each containing 10,000 symbols, for analysis under different experimental conditions.

Experimental Results and Discussion

ASCR was proposed as a parameter for objective wave effect characterization in [11]. A higher ASCR implies a higher beam spot fluctuation speed or larger slope change per frame. We first investigate the average bit error rate (BER) and

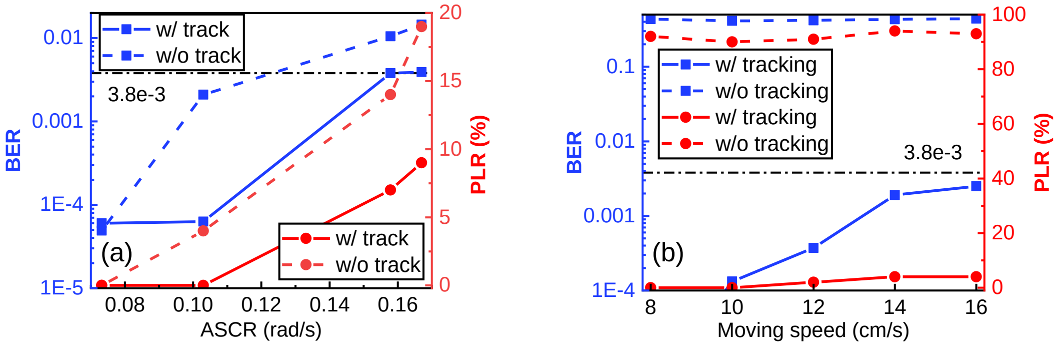

Fig. 2: BER and PLR performance of 800-Mbaud OOK signals versus (a) ASCR with a stationary receiver and 1.4-m air path and (b) moving speed with no wave added, 20-cm moving range, and 1.6-m air path.

the packet loss rate (PLR) performances of 800-Mbaud OOK signals for different ASCRs and moving speeds of the Rx terminal. In Fig. 2(a), the Rx is stationary, but the wave effect is introduced. The air distance is 1.4 m. In Fig. 2(b), the Rx terminal is moving while no wave is added. The moving range is 20 cm and the air distance is 1.6 m. A packet is considered lost if its BER is below the Hard-Decision Forward Error Correction (HD-FEC) limit (3.8×10^{-3}). The average BER is calculated from all packets, including the lost packets. The solid and dash lines represent the cases with and without tracking, respectively. Apparently, the OWC system with tracking outperforms that without tracking in all cases. Without tracking, PLRs are all above 90% for different moving speeds. While with tracking, no packet is lost when wave ASCR is below 0.103 rad/s or the moving speed is below 10 cm/s. In addition, the average BER is below HD-FEC for ASCR smaller than 0.158 rad/s or moving speed smaller than 16 cm/s. PLR is below 9% and 4% for different ASCRs and moving speeds, respectively. Increasing ASCR or moving speed will deteriorate the communication performance as tracking speed is limited by the MEMS response time.

We then investigate the performance of BER, PLR, and throughput under different symbol rates of OOK signals with ASCR of 0.103 rad/s and 8 cm/s moving Rx terminal, as shown in Fig. 3. Without tracking, PLRs are above 85% for all symbol rates. The maximum throughput is only 120 Mbit/s. While with tracking, transmission with zero packet loss can be achieved for OOK signal ≤ 600 Mbit/s. The maximum throughput is 930 Mbit/s. PLRs do not exceed 7% for symbol rates below 1 Gbaud.

Conclusions

In summary, we proposed and experimentally demonstrated an image-based beam tracking system to compensate for the wave and mobile receiver-induced beam wandering. The effect of wave ASCR, Rx terminal moving speed, and symbol rate are investigated and compared for the OWC system with and without tracking. With the help of beam tracking, a zero-packet-loss 600 Mbit/s transmission and a maximum throughput of 930 Mbit/s can be realized under an ASCR of 0.103 rad/s, a moving speed of 8 cm/s, and a 1.6-m air path. On the other hand, PLR surges to 89% under the same scenario when without tracking. The preliminary experiment results show that beam tracking provides more than 80% PLR reduction and a maximum of 8.1 times throughput enhancement for the OWC system with a mobile receiver and wavy water surface. Based on imaged-based tracking, precise tracking spot offset can be obtained. The preliminary demonstration proves the effectiveness of beam tracking for high-speed water-air OWC systems.

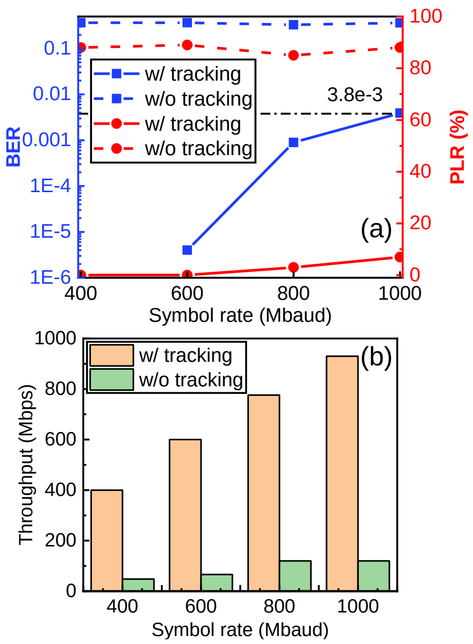

Fig. 3: (a) BER and PLR performance and (b) throughput versus symbol rate of OOK signals with a wave ASCR of 0.103 rad/s, moving speed of 8 cm/s, moving range of 10 cm, and 1.6-m air path.

Acknowledgments

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