Experimental Study of Wavy Surface Effects on Uplink Water-Air Optical Camera Communication

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ABSTRACT

This paper presents an experimental study of water-to-air optical camera communication (OCC) in the presence of wavy surface conditions. It evaluates the system performance in terms of the signal-to-noise ratio (SNR), considering various camera exposure times and regions of interest (ROI) in captured images. The results reveal a noticeable reduction in the SNR due to the presence of surface waves. However, the system performance is improved by considering the average value of several illuminated pixels produced by the point spread function as the ROI. Furthermore, the statistical characteristics of the received optical signals in the presence of surface waves are assessed.

KEYWORDS

Optical camera communication, water-to-air communications, wavy water surface, statistical distribution, goodness of fit.

1 INTRODUCTION

The connectivity of underwater sensors and airborne nodes across the water-air interface is highly desirable. These direct communication links effectively eliminate the necessity for data to pass through multiple intermediary nodes, leading to a considerable reduction in latency. This is crucial for applications that require real-time data transmission, such as environmental monitoring. Additionally, the direct link offers low power consumption compared to multi-hop communication as there are fewer intermediate nodes in the communication path, resulting in reduced energy usage. Utilizing acoustic waves encounter significant limitations, mainly reflecting off the water surface rather than effectively traversing through it. Similarly, radio frequency (RF) waves suffer from high attenuation when propagated in water. Optical wireless communication (OWC) is considered the most practical approach for inter-medium communication. However, the performance of an OWC system across the water surface, including water-to-air (W2A) and air-to-water (A2W), is influenced by the reflection and refraction of light beams that cross two different media due to various refractive indices [1]. Moreover, challenges arise due to unpredictable changes in elevation height and varying angles of the wavy surface. One possible solution is using diffused laser/LED as a transmitter which can mitigate the effects of misalignment. Utilizing diffused light spread the beam spatially and minimized the impact of link misalignment, improving the overall communication performance [2]. A diffuse-line of sight (LOS) W2A optical communication in the presence of surface waves and mobility is investigated in [3]. It is presented that a diffuse-LOS optical link can effectively mitigate intersymbol interference (ISI) caused by channel uncertainty providing a large signal coverage area and is favorable for stable communication in harsh environments. A downlink A2W OWC link is studied in [4]. The numerical results show that a wavy surface causes remarkable reductions in received power at low turbidity. Moreover, the surface waves cause significant power loss when the receiver field-of-view (FOV) is small. Therefore, a large active receiving area such as cameras is a possible technique to alleviate the influence of a harsh underwater environment. It reduces the requirement for an acquisition tracking and pointing (ATP) system, typically used to maintain alignment between the transmitter and receiver in water-air OWC links [5].

In this work, the system performance of a global shutter (GS)-based W2A OCC under a wavy surface is experimentally investigated. This study evaluates the impact of this phenomenon on the W2A optical camera communication (OCC) system performance under different camera exposure times and fluctuations caused by surface waves. As a communication link quality metric, the system signal-to-noise ratio (SNR) is measured considering different detection schemes for comparison. It is shown that using the average value of several illuminated pixels produced by the point spread function (PSF) as the region of interest (ROI) can improve the system SNR. This approach takes into account the energy spreading in the captured image, which arises from the scattering effects introduced by surface waves in the W2A communication channel. In addition, the validity of various statistical distributions in predicting turbulence-induced fading caused by surface waves in the W2A OCC link is demonstrated.

The rest of the paper is organized as follows: Section 2 describes the experimental setup. Section 3 is devoted to presenting the experimental results, and finally, the conclusion is drawn in Section 4.

2 EXPERIMENTAL SETUP

This section investigates the impact of wavy surfaces on an uplink W2A OCC system. Figure. 1 demonstrates the experimental setup and decoding process. The system employs an LED strip as the optical emitter, driven by non-return-to-zero (NRZ) on–off keying (OOK) modulation signals generated by the Arduino UNO microcontroller. This is an addressable LED strip with the capability of specifying the signal data, color and brightness for each LED. This experiment uses a blue LED centered in 462 nm wavelength and spectral irradiance of 30 mW/m^2nm. The optical beam propagates through a 30 cm water sub-channel, the water-air interface, and a 70 cm air sub-channel. A water tank with dimensions of 1.5 ×0.5×0.5 m^3 is filled with tap water to emulate an underwater channel, and a wave maker is installed on one side of the tank to generate waves of different speed levels. The wave speed, U, quantifies the wave level, and three artificial waves with average speeds of 25 cm/s, 33 cm/s, and 50 cm/s are generated. A Raspberry Pi Camera Module V2 on the receiver side is placed outside the water tank above the transmitter to capture videos in different exposure times (t_{exp}) of 10 μs, 30 μs, 50 μs, and 70 μs for each wave. The system data rate is 10 bps, which is limited by the frame rate in GS mode. The receiver side, demodulation process, and key system parameters are explained in detail in [6].

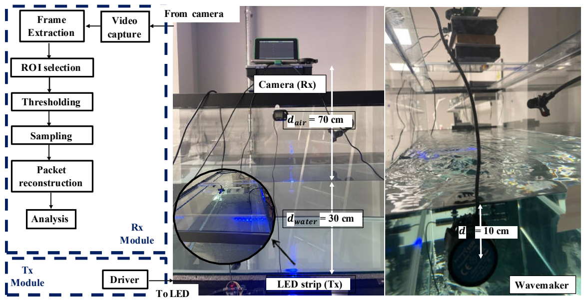

Figure 1: Experimental setup and decoding process of the proposed GS-based W2A OCC system.

3 RESULTS

The system SNR under still water (U=0) and three levels of wave speeds of 25 cm/s, 33 cm/s, and 50 cm/s considering camera exposure times of 10 μs, 30 μs, 50 μs, and 70 μs and ROIs (i.e., single center pixel, the average value of 5×5, 9×9, and 17×17 pixels around the central pixel) in a W2A OCC link are evaluated. As depicted in Fig. 2, it is evident that higher wave speeds have a considerable negative impact on the system SNR. However, the SNR is improved by enlarging the ROI and incorporating more illuminated pixels caused by PSF. Additionally, increasing the camera exposure times leads to a higher system SNR. This outcome is attributed to integrating more optical power over a longer temporal window, contributing to improved signal quality. The experimental results are demonstrated to evaluate the validity of various statistical distributions in predicting turbulence-induced fading in the W2A OCC link under a wave speed of 33 cm/s. Figure. 3 illustrates the histograms of the experimental data and the fitness of probability distribution functions, namely Gaussian, Lognormal, and generalized Gamma distribution (GGD), for different camera exposure times and ROIs. The empirical results indicate that the GGD matches perfectly with the measured data for all exposure times, ROIs, and wave speeds. This highlights the suitability of the GGD for characterizing surface fluctuations in the W2A OCC link.

The goodness of fit (GOF) test is conducted, and the results of the R^2 measures and variance σ^2 are provided in Tab. 1 for a wave speed of 33 cm/s. It is observed that the R^2 measures associated with the GGD model have the highest values, exceeding 85%, indicating a better fit compared to the Gaussian and Lognormal distributions. Moreover, considering the larger size of illuminated pixels as the ROI, curves exhibit a good fit with Gaussian distributions. This can be attributed to the fact that incorporating a larger number of pixels in the averaging process reduces the influence of fluctuations and results in a more refined representation of the distribution.

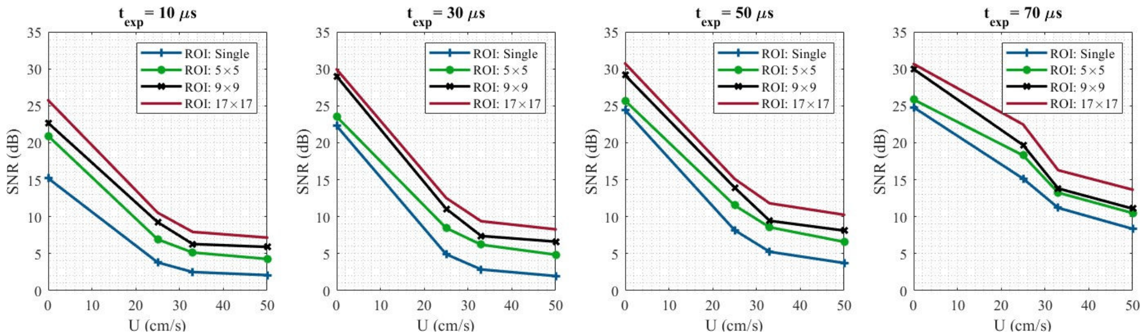

Figure 2: SNR for different wave speeds considering four different ROIs and camera exposure times of 10 µs, 30 µs, 50 µs, and 70 µs.

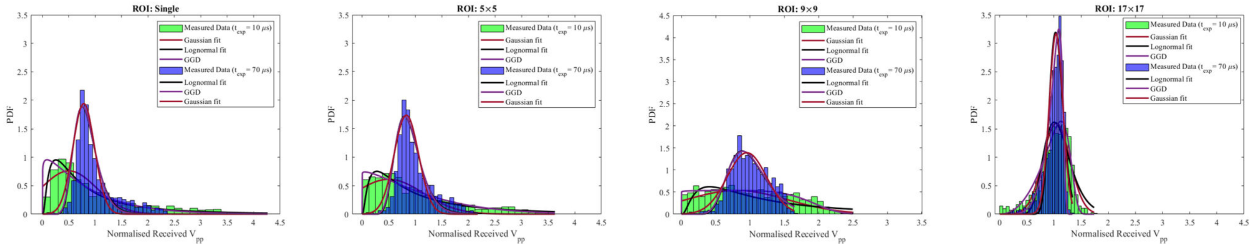

Figure 3: The accordance of different statistical distributions with the PDF histograms of the measured data through two exposure times of 10 µs and 70 µs considering four different ROIs under the wave speed of U=33 cm/s.

Table 1: GOF measurement of different histograms and the measured variance through two exposure times of 10 µs and 70 µs considering four different ROIs under the wave speed of U=33 cm/s.

ROI	t_{exp} (µs)	σ^2	Gaussian	Lognormal	GGD
single	10	0.7240	0.81	0.93	0.94
single	70	0.1578	0.81	0.89	0.87
5×5	10	0.6389	0.81	0.93	0.94
5×5	70	0.1163	0.85	0.73	0.95
9×9	10	0.3677	0.66	0.25	0.85
9×9	70	0.0733	0.89	0.93	0.93
17×17	10	0.0882	0.92	0.86	0.96
17×17	70	0.029	0.9	0.87	0.98

4 CONCLUSION

In this paper, the system performance of the W2A OCC under different surface wave speeds was studied empirically. It was indicated that the surface waves caused multiple scattering and backscattering causing the loss of some light beams due to high beam deviation angles crossing the water-air interface. The results demonstrated a notable reduction in the system SNR with increasing wave speeds. However, accounting for the area of illuminated pixels produced by PSF due to the scattering effect as an ROI could improve the system SNR in wavy conditions. Finally, the effect of the surface wave is fitted perfectly with the GGD model.

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