Demonstration of Remote Underwater Monitoring using Underwater Wireless Communication and Satellite System

Kexin Wang(1), Zhaokang Zhou(1), Samuel Rotenberg(2), Jonatan S. Willners(3), Xu Wang* (1)

(1) School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK, EH14 4AS, corresponding author: x.wang@hw.ac.uk
(2) Infinect, GRID, Heriot-Watt university, UK, EH14 4AS
(3) The National Robotarium, Heriot-Watt university, UK, EH14 4AS

Abstract *A remote underwater monitoring system integrating underwater optical wireless communication and satellite communication systems is proposed and demonstrated. The experiment successfully achieved 9-metre underwater real-time video transmission and relayed the signal via satellite communication system to remote users situated 8,290 kilometres away. ©2023 The Author(s)*

Introduction

During the COVID-19 pandemic since 2019, significant number of people have been required to stay home to prevent the virus's spread. It was reported that over one-third of workers engaged in remote work in 2020 [1]. As remote work continues to be prevalent, there is a growing need for solutions that enable remote monitoring and control in various fields, including underwater monitoring systems (UMSs), which normally require real-time underwater video transmission (RTUVT) services.

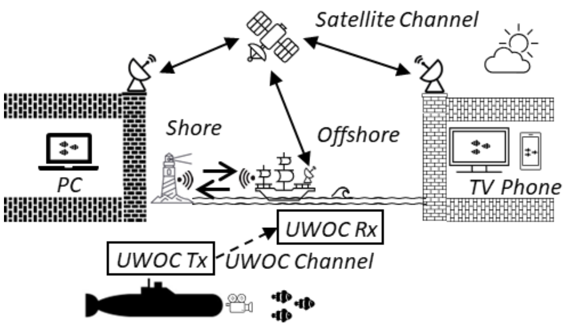

Fig. 1: The proposed long-haul remote underwater monitoring system and its application in an underwater wireless sensor network

UMSs, a subset of underwater wireless sensor networks (UWSNs), are designed to collect, process, and transmit information from underwater environments for various purposes, such as scientific research [2], environmental assessment [3], and vehicular networks [4]. UWSNs employ underwater optical wireless communication (UWOC), underwater acoustic communication, and underwater radio frequency (RF) communication as primary communication approaches. Of these, UWOC systems have the unique features of ultra-high bandwidth, low latency, and high security, making them ideal for RTUVT tasks in UMSs [5].

To address the growing demand for long-haul remote monitoring, we propose to integrate UWOC and satellite systems to provide UMSs with RTUVT services. Consequently, RTUVT can be relayed to remote users located thousands of kilometres away from local work areas, enabling real-time monitoring and response to various tasks in underwater environments. Satellite communication system can perform long-haul data distribution efficiently and relay the underwater monitoring data to remote users [6].

In this paper, we implemented a field-programmable gate array (FPGA)-based UWOC system prototype with an integrated onboard camera and, to the best of our knowledge, combined the UWOC system to satellite system for the first time. The integrated system functioned as a long-haul remote underwater monitoring system, and the RTUVT was experimentally demonstrated in this system by delivering Quarter VGA real-time underwater videos over up to 9-metre underwater channel to a remote user who was located over 8,000 kilometres away. Additionally, this system also supported offline transmission, employing advanced signal processing to enhance system performance and ensure error-free transmission in noisy underwater channels.

System Configuration

Fig. 1 illustrates the schematic plot of the proposed system. The underwater transmitter can be mounted on a remotely operated vehicle (ROV) or situated at a distributed node of an underwater wireless sensor network (UWSN). Data from the node's sensor or video from the integrated camera can be loaded to UWOC transmitter (Tx). The UWOC Tx modulates the data onto optical carrier and launch the optical signal into water. The UWOC receiver (Rx) is positioned beneath the water/air boundary, such as on a ship or a buoy. A router is placed between the UWOC Rx and the satellite system (SS), which is used to establish the connection between them, where the SS can be set up onshore or carried by a ship in offshore scenarios (Fig.1). Subsequently, the SS distributes the data to remote users via satellite link. In RTUVT, remote users can access the latest monitoring data whenever they initiate the remote user's application. Simultaneously, the monitoring data stored in the UWOC Rx can be delivered to remote users if the system operates in the offline transmission mode.

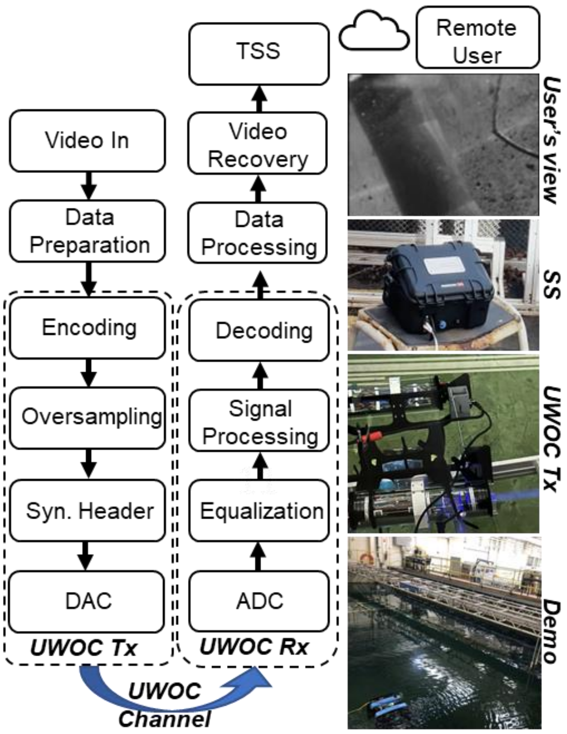

Fig. 2: Block diagram of the Long-haul remote underwater monitoring system and its operating components in demonstration.

The UWOC transmitter (Tx) included an onboard camera to capture underwater video for the RTUVT service demonstration and two batteries as an internal power supply. Two Red Pitaya boards (STEMlab 125-14), each equipped with a pair of 125-MHz digital-to-analogy converters (DAC) and analogy-to-digital converters (ADC), were utilized as the signal processing units for the UWOC Tx and Rx respectively. This UWOC prototype was designed to operate at depths of up to 100 metres. A 447-nm, 80-mW laser diode generated the optical carrier, and the divergence of the output light was tunable in the UWOC Tx. Tab. 1. summarises the system specifications of the prototype.

Fig. 2 illustrates the block diagram of the system. After generating a video segment, the segment is initially encoded using (224, 255) Reed Solomon code for forward error correction (FEC) to improve transmission quality in noisy underwater channels. The system achieves error-free transmission with a receiving bit error rate (BER) of less than 10^{-3}. 16QAM-OFDM modulation scheme is employed in real-time transmission, enabling 26-Mbps data rate while PAM4 is employed in offline transmission at the date rates of 15.63, 20.83, and 31.25 Mbps separately. BER performance of the system is measured against receiving power for different data rates. The system employed internal signal synchronization scheme for signal framing. In real-time transmission, A period of sinusoid waveform precedes the signal payload to perform a rapid signal synchronization. A sequence of training headers is placed before the sinusoidal waveform to improve transmission in offline scenarios. The signal is subsequently modulated onto the blue light emitted by the laser diode.

Tab. 1: System specifications

Name	Value
Field of View	0 to 18°
Average Optical Power	40 mW
Power Consumption	6.5 W
Data Bandwidth	20 MHz
Signal Modulation	16QAM-OFDM/ PAM4
Enclosure Weight	~5 kg
Enclosure Size	4''- 300 mm Tube
Maximum Depth	100 m
Working Wavelength	450 nm
Power Supply	22V, 6A DC
Battery Run time	18 hours

At the UWOC Rx, upon receiving the optical signal, the signal is first detected by an avalanche photodiode (APD) and converted to digital signal by ADC. No equalization was applied in RTUVT service to reduce the time consumption in the data processing. But a simplified multimodulus blind equalization [7] for 1D signal is employed in offline mode. Following the down-sampling, decoding, and error correction, the monitoring data are recovered and subsequently forwarded to a router that links to the SS transmission module (shown in Fig. 2). The SS provides access to cloud storage (Microsoft OneDrive), where the monitoring data can be stored and shared with remote users. The speed of the SS is approximately 6 Mbps for downlink and 1 Mbps

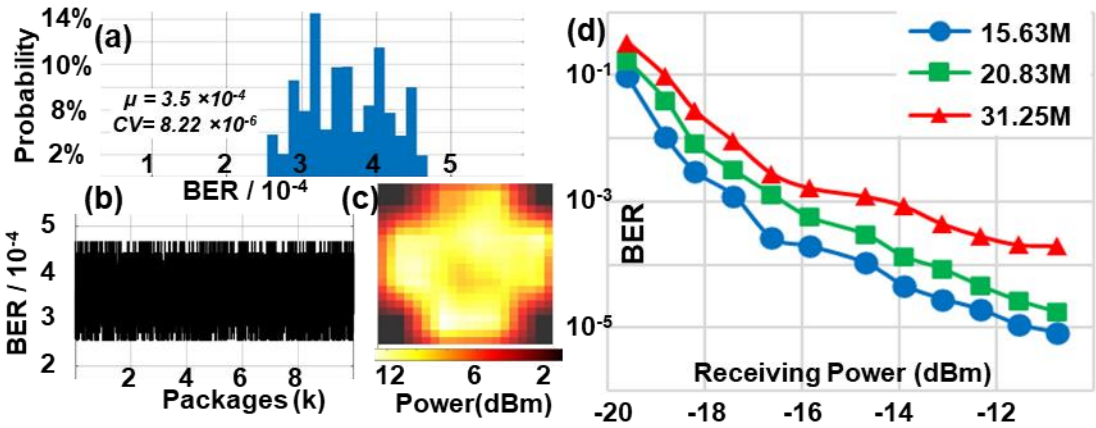

Fig. 3: (a)The bit error rate (BER) under different data rates vs. receiving powers in offline transmission. (b) BER distribution of segments and beam power distribution at the transmission of 9 metres in real-time transmission.

for uplink.

Experiments Results and Discussion

Fig. 2 also shows photos of the UWOC Tx, SS transmitter, RTUVT demo in the water tank, and remote user's view of the real-time underwater video. A RTUVT service was demonstrated using the proposed UMS. The local UWOC setup was at Heriot-Watt University, Edinburgh, while the remote user was located more than 8,290 km away. The remote user successfully watched the real-time underwater video with a delay of approximately 50 seconds. In the 9-meter real-time transmission experiment, Fig. 3 (a) displays the BER distribution of real-time video segments. 10,000 video segments were recorded, in Fig. 3 (b), to measure the bit error rate (BER). The mean value (μ) was approximately 3.5×10^{-4}, while the coefficient of variation (CV) was around 8.22×10^{-4}, indicating that the system performed a good and stable transmission for RTUVT service. The beam's power distribution at the receiver was measured and depicted in Fig. 3 (c), where the beam size was around 10 cm.

BERs were measured by comparing binary sequences after FEC encoding and before FEC decoding in the offline transmission mode against receiving optical power for the data rates of 15.63, 20.83, and 31.25 Mbps respectively. The transmission distance in this experiment was fixed at 3.5 meters, and the receiving power was adjusted by introducing different attenuation between the Tx and Rx. In offline transmission, all data rates enable error-free transmission with receiving power levels of -17.33, -16.58, and -14.37 dBm respectively. The 15.63-Mbps case exhibited the lowest BER, providing the best transmission performance.

Conclusion

The integration of UWOC and satellite communication systems has been proposed to configure a long-haul remote underwater monitoring system, which enables remote work in different scenarios. Real-time underwater video transmission service was experimentally demonstrated on this system. The remote user was able to view Quarter VGA real-time underwater video while being located more than 8,290 km away from the underwater location.

The underwater monitoring system can conduct real-time or offline transmission. In real-time transmission mode, this system performed a stable error-free transmission with the mean and coefficient of variation of 3.5×10^{-4} and 8.22×10^{-4}, respectively. The BER under different data rates and receiving powers was also measured in the offline transmission experiment. All data rates reached error-free levels with the assistance of a 1D multimodulus blind equalization.

This prototype can be attached to an ROV and undergo field trials in the future. The UWOC link and equalization methods have the potential to be further optimized. The proposed system exhibit as a solution for RTUVT services.

Acknowledgements

The authors thank the EPSRC ORCA (EP/R026173/1) PRF for support. K. W. wishes to thank Mr. Luke Erni, Mr. Zizun Wei, and Mr. Yihong Gao for their kind help on the experiment.

References

[1] E. Brynjolfsson, J. J. Horton, A. Ozimek, D. Rock, G. Sharma, and H.-Y. TuYe, "COVID-19 and Remote Work: An Early Look at US Data," *National* Bureau *of Economic Research Working Paper Series,* vol. **No. 27344**, 2020, doi: 10.3386/w27344.

[2] M. Salhaoui, J. C. Molina-Molina, A. Guerrero-González, M. Arioua, and F. J. Ortiz, "Autonomous Underwater Monitoring System for Detecting Life on the Seabed by Means of Computer Vision Cloud Services," *Remote Sensing,* vol. **12**, no. 12, p. 1981, 2020. [Online]. Available: https://www.mdpi.com/2072-4292/12/12/1981.

[3] J. H. Kim, K. H. Park, and K. S. Joo, "Development of low-cost, compact, real-time, and wireless radiation monitoring system in underwater environment," *Nuclear Engineering and Technology,* vol. **50**, no. 5, pp. 801-805, 2018/06/01/ 2018, doi: https://doi.org/10.1016/j.net.2018.03.023.

[4] M. A. Bonuccelli, G. Giunta, F. Lonetti, and F. Martelli, "Real-time video transmission in vehicular networks," in *2007 Mobile Networking for Vehicular Environments*, 11-11 May 2007 2007, pp. 115-120, doi: 10.1109/MOVE.2007.4300815.

[5] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A Survey of Underwater Optical Wireless Communications," *IEEE Communications Surveys & Tutorials,* vol. **19**, no. 1, pp. 204-238, 2017, doi: 10.1109/COMST.2016.2618841.

[6] Tactical Wireless Communications, "Tactical Space Systems," May 2021. [Online]. Available: https://www.tactical-wireless.com/2021/05/tactical-space-systems/. [Accessed: 05 05, 2023].

[7] J. M. Filho, M. T. M. Silva, and M. D. Miranda, "A family of algorithms for blind equalization of QAM signals," in *2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, 22-27 May 2011 2011, pp. 3388-3391, doi: 10.1109/ICASSP.2011.5947112.