Breaking Through the Air-Water Interface with Software-Defined Visible Light Networking

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Abstract

"Multi-Domain Operations" paradigm has been receiving significant attention both in military and civilian worlds. This novel notion of operating networks of distributed and mostly unmanned autonomous devices in multiple domains - air, land, water, cyber, and space- in coordination to achieve a common objective, will undoubtedly be a key enabler for various applications. To realize this novel paradigm, it is imperative to establish robust communication links to transfer data between devices operating in multiple domains. However, as of today, establishing high data rate, robust, secure, and bi-directional communication links between aerial and underwater assets across the air-water interface is still an open problem. This article introduces the software-defined visible light networking to establish bi-directional wireless links through the air-water interface. We first overview the limitations of the state-of-the-art solutions for communication across air-water mediums and alternative approaches. We then present a software-defined visible light communication (VLC) modem, which is the primary building block of our proposed solution. We also discuss the challenges, limitations, and opportunities of using visible light to communicate over the air-water interface. Last, we present some key concepts and applications that can be enabled by leveraging the proposed visible light networking solution.

Introduction

"Networks of distributed and primarily unmanned autonomous devices operating in multiple domains — air, land, water, cyber, and space- in coordination to achieve a common objective" has been an emerging paradigm both in military and civilian worlds. Proving the significance of this *"Multi-Domain Operations"* vision, in March 2022, the US Department of Defense released the Joint All-Domain Command and Control (JADC2) Strategy. The proposed strategy aims "[...] to sense, make sense, and act at all levels and phases of war, across all domains, and with partners, to deliver information advantage at the speed of relevance" [1]. Moreover, there are numerous current and future civilian applications that can benefit from this novel paradigm. Environmental monitoring, data-driven aquaculture, offshore oil and gas exploration, and infrastructure monitoring are only some examples [2].

To realize this novel vision, it is crucial to establish robust, reliable, high data rate and low latency wireless links between devices operating across all domains. Intuitively, it could be expected that communication technologies leveraging radio frequency (RF) waves will adequately address most of the cross-domain connectivity requirements, with the major exception of the air-water interface. In the conductive medium of water, RF waves suffer from high attenuation, which severely limits their penetration and making virtually impossible to establish a communication link. Moreover, acoustic waves, the most efficient modality for underwater wireless communications, could not penetrate into the air due to the large impedance difference between air and water media resulting in a high reflection coefficient. Therefore, regrettably, today, establishing a high-data-rate, reliable, bi-directional communication link between aerial and undersea devices over the air-water interface is still uncharted territory.

Despite the significant research efforts in recent years, we are still far from an adequate solution. Therefore, today, still the most common way to establish communication links between aerial and underwater devices is to deploy and leverage floating surface buoys as data gateways, as shown in Fig. 1a. However, such floating surface buoys are vulnerable to

- Ocean dynamics (e.g., drifts, currents, surface waves)
- Harsh weather conditions
- Malicious activities (e.g., tampering, jamming, deactivation), which are critical especially for military use cases.

Furthermore, relying on buoys significantly limits the operational area of aerial and underwater assets, as it would be prohibitively expensive and time-consuming to deploy them to cover large ocean or lake areas. Autonomous surface vehicles (ASVs) or using unmanned underwater vehicles (UUVs) to continuously resurface and act as relays or data mules are some other alternative approaches. Regardless, both approaches fall short in terms of operational capabilities and security.

To address this need, in this article, we introduce Software-Defined Visible Light Networking, a communication technique realizing the establishment of high data rate, robust, and secure bi-directional links between aerial and underwater devices across the air-water interface. At its core, Software-Defined Visible Light Networking employs a software-defined Visible Light Communication (VLC) modem developed to offer sufficient self-optimization and adaptation capabilities for operating in temporally and spatially varying and potentially contested air-water interfaces. We summarize our core contributions as follows:

- We introduce and describe the building blocks of the proposed Software-Defined Visible Light Networking. First, we introduce the developed channel simulator capable of generating and evaluating 3D channel models. Then, we describe the design and prototype of the software-defined VLC modem.
- We present a series of experiments conducted in the ocean to demonstrate how the developed system can operate across the air-water interface bi-directionally in a real-world scenario.
- We introduce and discuss the main research challenges in Visible Light Communications and Networking across the air-water interface. Moreover, we provide a detailed agenda of research opportunities from both academic and commercial perspectives.

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- We introduce and discuss a series of concepts and applications that can be enabled by utilizing the proposed Software-Defined Visible Light Networking at the air-water interface. We then provide a roadmap of possible research avenues in the field.

Related Work

Communication over the air-water interface has received a lot of interest from the research community. For a recent survey on the topic, the reader can refer to [3]. In this section, we categorize and review the previous work under two main categories: optical communication and alternative approaches.

Optical Communication

Optical communication separates itself from other modalities by enabling bi-directional communication across the air-water interface with high data rate, negligible multipath, and low latency [4, 5]. For optical communication, light-emitting diodes (LEDs) or lasers are the main light sources. While LEDs can sustain a wider coverage area, they suffer from low modulation bandwidth. Contrarily for lasers, high data rates can be obtained with the drawback of directivity, which requires precise alignment of transmitter and receiver pairs. Both light sources are operated in the visible light spectrum of 450–550nm wavelengths since it is more feasible to use for underwater communication due to high attenuation at higher wavelengths or non-visible light spectrum.

Despite the numerous works for the underwater communication domain, only a few researchers have focused on examining VLC for inter-medium communication. In [6], extensive evaluation of light intensity and validation of unidirectional optical links across the air-water interface is conducted. However, the lack of wireless communication performance and the bi-directionality aspect does not cover the open challenges. As in [7], a field demonstration focusing on VLC from underwater to air by utilizing diffused laser diodes is shown. Though a high data rate (850 Mbit/s) is obtained with a perfectly aligned setup, only unidirectional links are considered, and the coverage area is limited by 0.1963m^2. Furthermore, these studies rely on bench-top components and lack prototypes that are fully deployable in the field.

Alternative Approaches

Underwater acoustic-induced communication is an alternative technique that uses RF or millimeter wave radars to detect physical displacements on the water surface created by acoustic waves using an acoustical waterborne transducer. While this technique can maintain unmediated inter-medium communication, it can only support unidirectional communication (water-to-air) and operate in the presence of surface waves up to 16 cm. Low data rate (400 bps) and precise alignment requirement are some other limitations of the proposed technology [8].

Another approach that is presented in the literature for communicating through the air-water interface is using magnetic induction (MI) [9]. Even though smooth transition across the interfaces can be maintained thanks to the similar magnetic permeability of air and water mediums, due to the conductance of salty water, high attenuation limits the communication range to 10–100 m. This is slightly better than RF communication for underwater usage, where very low-frequency signals should be used to have practicable communication distances, which are limited to less than 10 m.

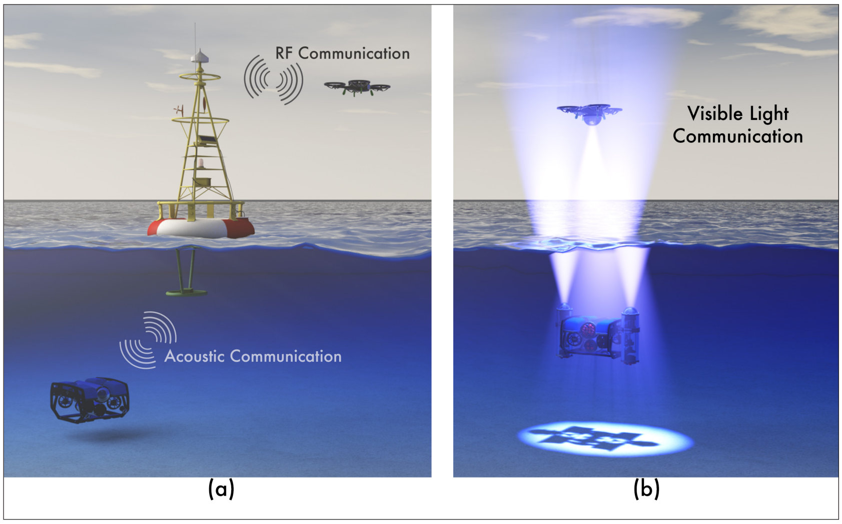

FIGURE 1. *Communication Methods Across the Air-Water Interface*: a) in state of the art, deploying a buoy system is required; b) The proposed visible light communication system establishes a bi-directional communication link between an unmanned underwater vehicle (UUV) and an autonomous underwater vehicle (AUV) through air-water interface.

Software-Defined Visible Light Networking

In this section, we describe the proposed Software-Defined Visible Light Networking solution and its building blocks.

Channel Simulator

The first step toward the design of efficient and high-performing software-defined visible light networked systems is to characterize in detail light penetration, refraction, and reflection over the air-water interface. To this end, we developed a mathematical channel model. First, we modeled the surface waves using a Third-order Stokes' wave. This way, we calculated the water surface elevation for each point over horizontal coordinates at different time instances. We then geometrically calculated each ray of light's trajectory to determine the coverage area that a VLC transmitter can illuminate with a ray tracing approach. Finally, we calculated the irradiance inside the coverage area, considering all path loss components imposed by the air-water interface. Due to the space limitations, in this article we omit the details of the considered mathematical model. We refer the interested reader to our prior work [10] for further details on this.

As a next step, using the mathematical model developed in [10], we implemented a VLC channel simulator capable of simulating 3D air-water channels. As a representative example, we use the channel simulator to model both air-to-water (A2W) and water-to-air (W2A) communication configurations for a water surface elevation of 30 cm and transceivers are placed 1.5 m above and below the water surface with a 25° beam-width. Figure 2 depicts the generated model, coverage area, and irradiance diagrams for both A2W and W2A channels.

With this channel simulator, complex water surface waves can be modeled, and communication performance can be simulated for different transmission/reception distances, water clarity, water wave distribution, and transmitted optical power or beam-width. As a result, this simulator allows conducting link and network level evaluations or estimations considering the positioning of inter-medium communication nodes for different channel conditions at varying temporal and spatial settings. Hence, this simulator can assist and feed essential information to network operators or automatic control algorithms for optimum operational results and effective deployment of multi-domain assets, which can be enabled by systems implemented over software-defined architecture.

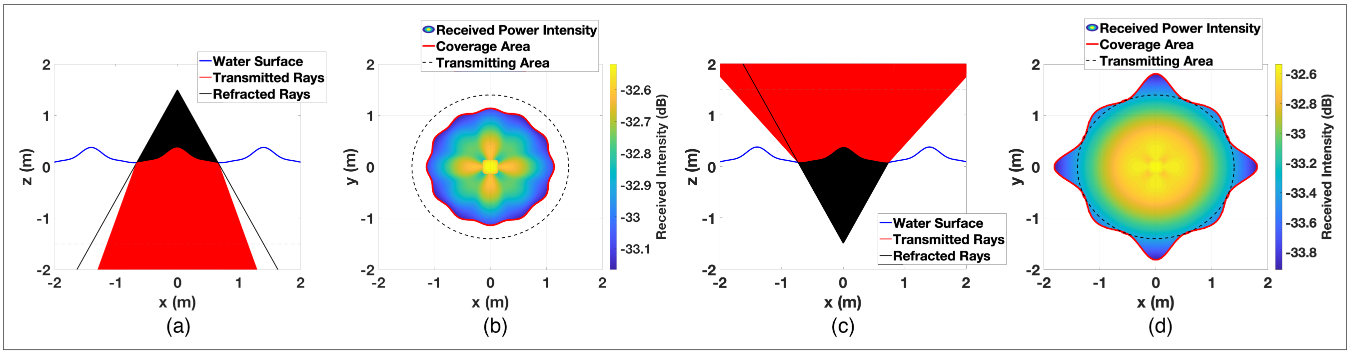

FIGURE 2. *Simulation model for inter-medium VLC systems:* vertical cross-sections of (a) air-to-water and (c) water-to-air channels modeled with cnoidal waves are shown. Received power intensity is shown over a horizontal cross-section of (b) air-to-water and (d) water-to-air channels. Dashed lines denoted as the transmitted rays and area showcase illumination projection without the water medium.

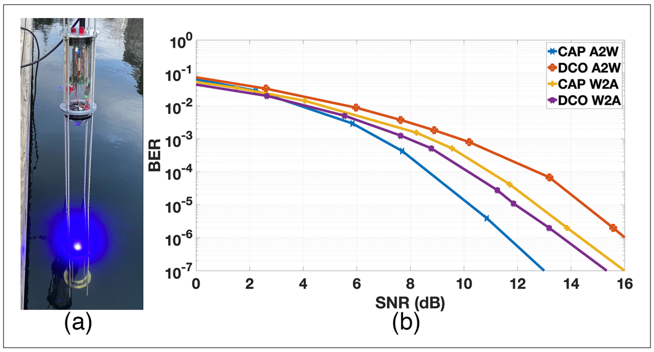

FIGURE 3. a) experimental setup and water-to-air communication for ocean experiments; b) BER analysis are conducted in coastal ocean water for both air-to-water (A2W) and water-to-air (W2A) configuration for CAP and DCO-OFDM modulation schemes.

Software-Defined VLC Modem

In this section, we introduce the software-defined VLC modem, which is the basic building block of software-defined visible light networking. The VLC modem is a robust, secure, self-optimizing communication device developed based on the software-defined radio (SDR) paradigm. It offers self-optimization and adaptation capabilities that are vital to operate in a channel like the air-water interface, which is temporally and spatially varying and can be potentially contested. Moreover, the flexible nature of the software-defined architecture ensures the establishment of robust and reliable communication links under various highly volatile channel conditions such as water surface waves, turbidity, turbulence, background noise, etc.

We use a MicroZed Xilinx Zynq-7000 programmable system-on-chip (SoC) as the core of our proposed software-defined VLC modem. The SoC incorporates ARM and FPGA processors on a single substrate, which offers embedded hardware and software reprogrammability with a small packaging and low energy consumption. We integrate the SoC with an analog-to-digital converter (LTC1740CG, 14-bit parallel outputs, 6 Msample/s) and a digital-to-analog converter (LTC1668, 16-bit parallel inputs, 50 Msample/s) for transmitting and receiving signals to/from the VLC front-end. The developed VLC front-end, on the transmitter chain, incorporates a single n-channel MOSFET (TI CSD-18535KTT) driving four series connected LEDs (OSRAM OSLON SLL 80 GBCS8PM 465 nm blue LED). On the receiver chain, VLC front-end leverages a silicon avalanche photodetector (Thorlabs APD430A2, 400 MHz bandwidth) to receive light signals.

Ocean Experiments

We conducted a series of experiments in the ocean to showcase that the proposed system can operate through the air-water interface bi-directionally in real-world scenarios. In these experiments, we used Carrierless Amplitude and Phase Modulation (CAP) and DC-biased Optical OFDM (DCO-OFDM) modulation schemes over a 1 MHz bandwidth, supporting 1 Mbit/s of data rate. Our experimental setting, as shown in Fig. 3a, features two software-defined VLC modems pre-aligned with threaded aluminum rods eliminating misalignment loss and easing the depth control of the modem that is located underwater. We used a spectrophotometer to characterize water clarity of the deployment location, which is measured to be 4.90 (absorbance) and 89.4 percent (transmittance). Figure 3b shows the obtained bit-error-rate (BER) versus signal-to-noise ratio (SNR) performance results. It can be observed that for A2W configuration, CAP outperforms DCO-OFDM at lower SNR values by maintaining lower BER. On the other hand, for W2A configuration, it is observed that DCO-OFDM performs slightly better than CAP. However, both modulation schemes can maintain communication at SNR values between 7–10 dB for both communication links, proving the functionality and efficiency of the proposed software-defined VLC modem.

Challenges and Opportunities

In this section, we discuss research challenges and opportunities in Visible Light Communications and Networking across the air-water interface.

Although visible light communication offers major advantages over other modalities for inter-medium and underwater communications (e.g., high data rate, low power consumption, etc.) there are still open challenges and opportunities for both academic research and commercial perspective.

Water surface waves and light diffusion: Although visible light modality is the most feasible approach for inter-medium communication, reflective index difference, random elevation height, and angle fluctuation of wavy water surface directly impinges on the light intensity and the path of the transmitted ray. Even though underwater and aerial devices are perfectly aligned over the vertical planes, the surface distribution of water surface can disrupt the communication link [11]. For such cases diffusing the light source over a wider coverage area can be a solution to increase the chance of having enough irradiance to accomplish successful communication reception with a reduction of received optical power. Diffusing the light at will can be a challenging task, considering that transmitting light sources' view angle is inherently determined by its reflector or own structure. For such purposes, commercially available liquid crystal (LC) lenses can be useful for varying the transmission angle by diffusing the light in response to an applied voltage.

Non-coherent nature: Another inherent challenge of visible light communication is its non-coherent nature. To accomplish efficient modulation for non-coherent devices, intensity modulation and direct detection (IM/DD) are usually used, where

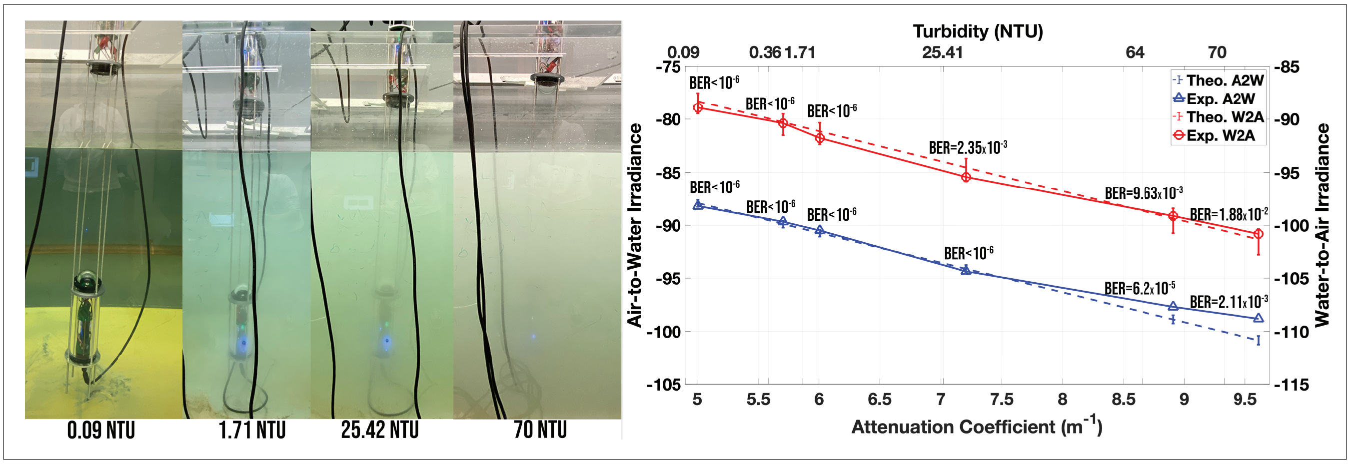

FIGURE 4. Testbed with different water turbidity levels for inter-medium communication is shown (left). Experimental results of the impact of water clarity on light intensity for air-to-water and water-to-air channels are given (right).

transmitted waveforms are generated in baseband and should be positive and real-valued. This results in eliminating the usage of negative spectrum and correspondingly halving the utilizable data rate and bandwidth. This inherent requirement leads to the challenge of designing and implementing efficient and non-conventional physical layer schemes for the VLC systems. The majority of VLC systems are still focusing on pulse time modulation schemes such as On-Off Keying (OOK), Manchester Encoding, Pulse Width Modulation (PWM), Pulse Position Modulation (PPM), etc. However, to increase the data rate and efficiently use the available bandwidth, spectrally efficient, multi-order, and multi-band capable modulation schemes are being investigated [12]. For example, orthogonal frequency division multiplexing (OFDM) is a widely used physical layer for Wi-Fi, mobile communication, Internet of Things (IoT) nodes, however, this modulation scheme cannot be used for VLC as it is. Instead, several variations of it, such as DC-biased optical (DCO), asymmetrically clipped optical (ACO), and Flip, are discussed and compared in literature for terrestrial, underwater [5], and inter-medium [3, 10] VLC systems. Carrierless amplitude and phase (CAP) modulation is another popular physical layer that is being used for VLC systems due to its spectral efficiency and ease of implementation [13]. In summary, while multi-carrier modulation schemes are suitable for VLC systems, it is imperative to optimize them with multi-order and multi-band capabilities for achieving higher spectral efficiencies and data rates.

Directional transmission: To increase the communication distance with a constant transmission power, beamwidth can be narrowed to focus the transmitted light power at the desired location where the receiver node is located. Lasers are inherently directional front-ends for VLC, which can be useful for communication at extended distances or eavesdropper-free operations. However, such narrow directivity profiles require precise transceiver alignment and for devices working in harsh environments such task can be challenging. However, utilization of beamsteering, beamforming, and multiple-input and multiple-output (MIMO) systems are still uncharted territories for inter-medium VLC systems. Though electrically tunable, optical beamforming with no moving parts is researched in literature as a proof-of-concept, it is far from system-level integration. Widely used approaches for mechanical beamsteering of optical sources are fast-steering mirrors, gimbals, and similar mechanically moving mirrors or prisms [11]. With such systems, successful communication links can be maintained by adjusting the beam direction despite the narrow beamwidth to the desired location with the help of channel feedback mechanisms conveying information about varying water surfaces, or unintentional movement due to ocean drift or windy air conditions.

Channel properties: Water clarity, turbidity, surface wave height, turbulence and attenuation are some of the channel properties that have an immediate effect on the communication link. For such a harsh channel, communication systems have to be aware of the channel conditions and self-optimize and adapt communication properties accordingly. As an example, the impact of water clarity is shown in Fig. 4. In order to obtain water turbidity, zinc oxide (ZnO) is used to generate suspending particles, which creates scattering for the light rays traveling underwater without creating a spectral absorbance. ZnO concentration gradually increased, and for each step, BER, irradiance, turbidity, and attenuation coefficient measurements are conducted [10]. Testbed and water clarity condition is presented in Fig. 4 (left) as well as the experimental results that validate the channel simulator are shown in Fig. 4 (right). Thus, sensor information gathered by Internet of Underwater Things (IoUT) devices can be used to adjust the communication parameters to obtain optimal links. Such systems can be accomplished by software-defined architecture that has the flexibility of adapting to varying channel conditions. One of the advantages of VLC is that, unlike the RF domain, there is no competition for spectrum allocation or licensing, meaning that every node can use the colossal bandwidth that is utilizable by the VLC system. However, in scenarios where multiple devices are sharing the same illuminated coverage area must have the ability to sense the spectrum and adapt the communication configuration accordingly. For such scenarios, aritificial intelligence (AI) algorithms can be utilized for communication spectrum sensing, autonomous modulation recognition, beamsteering, optimal positioning of drones or any other physical channel condition optimization problems [3].

With the use of software-defined architecture, channel conditions can be assessed and communication configurations can be reconfigured adaptively. As an example, bit error probability of CAP modulation can be obtained through an empirical model, which uses different CAP parameters that affect data rate, utilized bandwidth and filtering properties. With this mathematical model, BER with respect to spectral efficiency corresponding to different CAP parameters can be obtained for given channel SNR as shown in Fig. 5. This model leads to an optimization problem that can be solved according to the system constraints and channel conditions. Hence, optimum CAP system configuration can be selected for a given SNR to maintain minimum BER while utilizing maximum spectral efficiency [13].

Positioning: Optical communication usually requires direct line of sight for sufficient receiver power intensity. Thus, aerial and underwater nodes have to be aligned or located inside the coverage area of transmission at the particular position of the receiving node. In particular, if the nodes are mobile, this

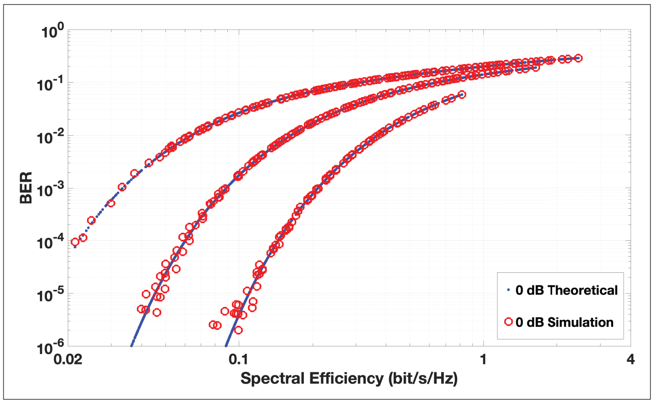

FIGURE 5. BER with respect to spectral efficiency corresponding to different CAP parameters obtained for 0 dB SNR [13]. Both simulation results and theoretical computations are shown red circles and blue dots respectively.

task becomes more challenging considering the environmental effects. Though this requirement can be maintained for terrestrial nodes more precisely using positioning information such as global positioning system (GPS), underwater devices lack such positioning systems [14]. Thus, in order to establish an autonomous communication link between aerial and underwater assets, information about the positioning of underwater devices have to be known at the aerial node or vice versa. As a solution to this, a hybrid multi-modal acoustical and optical system can be used by leveraging conventional underwater device positioning systems. By using static nodes, acoustical triangulation can be utilized to estimate the position of underwater assets. Similarly to GPS data, this position information requires minimal data rate (< 50 bps), which can be accomplished by any underwater acoustical modem. This information can be obtained through either ground nodes, where the acoustical data is relayed to aerial devices or through inter-medium VLC from the static nodes, whose locations are stationary and known to aerial devices.

Concepts and Applications

In this section, we introduce a series of concepts and applications (illustrated in Fig. 6) that can be enabled by utilizing the Software-Defined Visible Light Networking at the air-water interface.

Underwater vehicle position update: As discussedearlier, positioning and localization of mobile underwater devices can be challenging due to the lack of designated positioning systems similar to GPS. Hence, submarines and commercial or military-grade UUVs generally use inertial navigation systems (INS), which use accelerometers and gyroscopes to measure, calculate and determine the position of individual assets. However, ocean currents, acceleration, and angular velocity can lead to errors in accelerometer measuring and cumulative errors that result in inaccurate position information for long-lasting operations. Even for the military or navigation purpose INS can lead to positioning errors of 100 meters in 10 minutes. For this reason, usually, these underwater vehicles need to periodically surface and update their location through GPS. However, the periodic surfacing of underwater vehicles can be detrimental to military or tactical operations, as well as inefficient in terms of time and power consumption. As state-of-the-art, acoustic triangulation or similar methods are being used to implement local positioning systems for mobile underwater assets, however, such methods can be infeasible to deploy vastly in terms of time and cost over large ocean areas. Knowing that aerial devices can leverage the widely available GPS modules, this position information can be transferred accurately within the defined coverage area to the underwater nodes without the need for surfacing of underwater vehicles while keeping their covertness underwater [14].

Diver navigation, communication, and safety: Another important use case of inter-medium VLC is applications that involve divers that can accomplish a wide variety of goals underwater, such as environmental monitoring, photography, exploration, search, and rescue operations. For such applications, divers need to communicate with the ground nodes or floating systems (e.g., ships) for their navigation and safety. As described previously, continuous low-latency communication and navigation of divers can be accomplished with the help of underwater or inter-medium VLC, for which the divers need to operate at further distances than their deployment point.

Wireless remote periscope: Submarines or any other UUV that aims for stealth operation has to preserve their covertness underwater, and surfacing of these vehicles is usually avoided. However, the usage of a periscope or similar imaging devices may be needed to observe nearby targets or threats that cannot be detected underwater. With mobile aerial devices, visual search for targets in the air or on the water surface can be conducted and identified through video streaming at a high data rate and low latency without the need for surfacing and endangering its secrecy.

Mobile buoy: Covering extensive areas of the ocean by deploying floating buoys as a gateway or relay nodes for implementing an underwater sensor network is challenging in terms of time and cost. However, instead of deploying buoys, aerial devices can be used as mobile buoys, which can cover single or multiple underwater sensor nodes or mobile vehicles by broadcasting or acting as a gateway node. In this way, the extensive underwater area can be controlled at a lower cost and time-efficient manner.

AUV operation assistance: The use of autonomous underwater vehicles (AUVs), is a long awaited development in IoUT domain which can accomplish different goals with multiple autonomous nodes while operating in unison [15]. Autonomous oil and gas exploration or infrastructure monitoring are some of the most important use cases of AUVs, which can reduce cost and deployment time vastly. Considering the harsh environment that divers or operators of underwater vehicles face, AUVs can accomplish tasks that cannot be possible with human-operated systems. However, these AUVs need to be in continuous communication with either a central node that assigns and commands task or other nodes that needs to work collaboratively, which may require navigation, sensor, imaging, or command/control information. Considering the challenges in underwater acoustical modality, a low latency, high data rate communication system with the flexibility of maintaining connectivity to the ground or aerial nodes can offer major advantages for operating multiple AUV nodes.

Underwater sensor networks: With the rapid development in *zero-power* wireless sensors leveraging wake-up radio or similar modules, underwater environmental sensing over wide ocean areas and large time periods can be maintained with IoUT devices. Deploying floating buoys that can send or receive data through these sensor nodes can be challenging and inefficient in terms of power. Single or multiple aerial devices can operate autonomously in unison to gather desired information from IoUT devices that are positioned over extensive ocean areas through inter-medium VLC. These sensor nodes can consume ultra-low power during sensing operation and if sensing data needs to be obtained, big chunks of data gathered over a long period of time can be bi-directionally received with a high data rate by triggering the wake-up radios while enabling wireless power transfer over the visible light spectrum.

Tactical surveillance and stealth communication: Stealth operation of underwater vehicles is vital for tactical surveillance, ocean area discovery, and a wide variety of military applications. Wave propagation of traditional acoustic or RF communications obstruct the possibility of secure, eavesdropper-free, stealth communication. Usually, submarines use passive sonars that only listen to the events happening nearby to detect the tar-

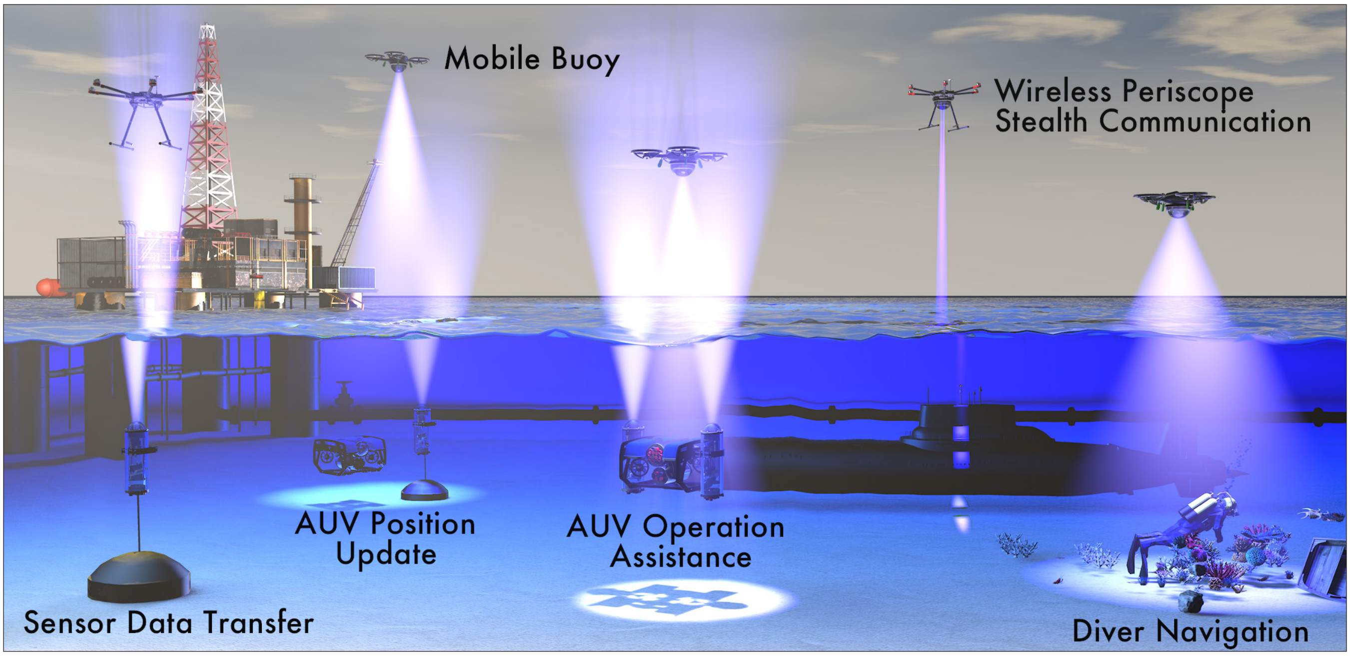

FIGURE 6. Sensor data transfer, AUV operation assistance, diver navigation, mobile buoy, wireless periscope, stealth communication, and underwater vehicle position update are some of the applications that are illustrated in this figure.

gets or threats instead of using active sonars that send acoustic pings that can reveal their presence or location, which means that even transmitting acoustic signals for communication purposes can compromise the covertness of the submarines. Thus, for such purposes, covert communication and the directionality of VLC can be useful for peer-to-peer communication while preventing any unforeseen eavesdroppers. While maintaining secure communication between aerial and underwater nodes, similar communication structures can be utilized for terrestrial or underwater communication individually with VLC. Another interesting possibility that can be applied to VLC modems for inter-medium communication is adding light detection and ranging (LIDAR) capability by using the same or a separate transmitter front-end. Considering the high attenuation of electromagnetic (EM) signals and high reflection factor of acoustical signals at the air-water interface, detecting submarines with an aerial device by using conventional radars or sonars is not possible. However, thanks to the better penetration and propagation characteristics of visible light pulses through the air-water interface, they can be used for tracking submarines or any other marine animals within the precision of the LIDAR system [3].

Multi-domain/modality operations: VLC can be applied in both air and water mediums, establishing a wide variety of applications. On top of this, augmenting different modalities of RF and acoustical signaling, multi-domain and multi-modality operations can be utilized with software-defined modems. Multi-modality can increase the applicable communication distance and establish communication between IoUT with satellites, space assets or long-distance ground nodes, with the usage of RF relaying [3]. Another use case of multi-domain/modality communication can be applied for latency-sensitive applications. Due to the low speed of sound underwater, communication between long-distance separated IoUT devices is affected by an extremely long transmission latency. Approximating the speed of sound as 1500 m/s, propagation delay at 10 km is approximately 6.67 seconds, which can be detrimental for applications where low latency is necessary. However, the same communication distance can be maintained with two aerial devices that communicate to underwater assets through the air-water interface with VLC and relays the data between each other through RF communication, which can propagate over long distances in air while maintaining a propagation delay of less than a second. This relaying method can also be useful when two underwater or aerial assets are unable to communicate over long distances due to obstacles or security reasons.

Conclusions

In this article, we presented Software-Defined Visible Light Networking, a communication technique enabling high data rate, robust, and secure bi-directional links between aerial and underwater devices across the air-water interface. First, we presented the building blocks of the proposed solution, including a simulator for the air-water interface and a prototype of the software-defined VLC modem. We also presented a series of experiments conducted in the ocean to demonstrate how the developed system can operate across the air-water interface bi-directionally in a real-world scenario. Then, we discussed the main research challenges in Visible Light Communications and Networking across the air-water interface and accordingly provided an agenda of research opportunities. Finally, we introduced a set of concepts and applications that can be enabled by utilizing the proposed Software-Defined Visible Light Networking at the air-water interface.

References

[1] U.S. Department of Defense, "Summary of the Joint All-Domain Command & Control (JADC2) Strategy," 2022.
[2] T. Melodia *et al.*, "Advances in Underwater Acoustic Networking," *Mobile Ad Hoc Networking: Cutting Edge Directions*, 2nd ed., S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, Eds. Inc., Hoboken, NJ: John Wiley and Sons, 2013, pp. 804–52.
[3] H. Luo *et al.*, "Recent Progress of Air/Water Cross-Boundary Communications for Underwater Sensor Networks: A Review," *IEEE Sensors J.*, vol. 22, no. 9, 2022, pp. 8360–82.
[4] H. Kaushal and G. Kaddoum, "Underwater Optical Wireless Communication," *IEEE Access*, vol. 4, 2016, pp. 1518–47.
[5] Z. Zeng *et al.*, "A Survey of Underwater Optical Wireless Communications," *IEEE Commun. Surveys & Tutorials*, vol. 19, no. 1, 2017, pp. 204–38.
[6] M. S. Islam and M. F. Younis, "Analyzing Visible Light Communication Through Air–Water Interface," *IEEE Access*, vol. 7, 2019.
[7] X. Sun *et al.*, "Field Demonstrations of Wide-Beam Optical Communications Through Water–Air Interface," *IEEE Access*, vol. 8, 2020, pp. 160,480–89.
[8] F. Tonolini and F. Adib, "Networking Across Boundaries: Enabling Wireless Communication Through the Water-Air Interface," *Proc. ACM Special Interest Group on Data Communication (SIGCOMM)*, New York, NY, USA, 2018, p. 117–31.
[9] Y. Li *et al.*, "A Survey of Underwater Magnetic Induction Communications: Fundamental Issues, Recent Advances, and Challenges," *IEEE Commun. Sur-*

veys & Tutorials, vol. 21, no. 3, 2019, pp. 2466–87.
[10] K. Enhos *et al.*, "Software-Defined Visible Light Networking for Bi-Directional Wireless Communication Across the Air-Water Interface," *2021 18th Annual IEEE Int'l. Conf. Sensing, Communication, and Networking (SECON)*, 2021, pp. 1–9.
[11] C. J. Carver *et al.*, "Air-Water Communication and Sensing with Light," *2022 14th Int'l. Conf. COMmunication Systems NETworkS (COMSNETS)*, 2022, pp. 371–74.
[12] N. Chi and M. Shi, "Advanced Modulation Formats for Underwater Visible Light Communications," *Chin. Opt. Lett.*, vol. 16, no. 12, Dec 2018.
[13] K. Enhos *et al.*, "Modeling and Optimization of Visible Light Carrierless Amplitude and Phase Modulation Links," *2022 IEEE Int'l. Conf. Commun. (ICC)*, 2022.
[14] J. B. Saif and M. Younis, "Underwater Localization Using Airborne Visible Light Communication Links," *2021 IEEE Global Commun. Conf. (GLOBECOM)*, 2021, pp. 01–06.
[15] D. Unal *et al.*, "Software-Defined Underwater Acoustic Networking Platform for Underwater Vehicles," *2022 IEEE Int'l. Conf. Commun. (ICC)*, 2022.

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