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Aqua-Fi: Delivering Internet Underwater using Wireless Optical Networks

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Abstract—In this article, we demonstrate bringing the Internet to underwater environments by deploying a low power and compact underwater optical wireless system, called Aqua-Fi, to support today's Internet applications. Aqua-Fi uses a light-emitting diode (LED) or Laser to support bidirectional wide-range communication services with different requirements, low cost, and simple implementation. LEDs introduce robust short distances solutions with low power requirements. However, Laser extends the communication distance and improves the transmission rate at the cost of higher power requirements. Throughout this work, we discuss the proposed Aqua-Fi system architecture, limitations, and solutions to improve data rates and deliver reliable communication links.

INTRODUCTION

By 2030, there will be more than 40 billion devices simultaneously connected to the Internet, including computers, smart devices, machines, and eventually autonomous vehicles. Over the years, the Internet has proven to be able to absorb the increasing demands and continue to function reliably. As of today, the Internet is capable of connecting almost everything, including transmitting media data beyond Earth to interstellar space, as we witnessed from both Voyager 1 and 2 space probes. On the other hand, there has been a noticeable limitation of Internet coverage when it comes to the underwater environment. The reasons vary from the harsh underwater environments to the physical-medium limitations.

Underwater wireless communication can be realized by three types of mediums: acoustic, radio-frequency (RF), and optical. Acoustic transmission can exchange data for long-ranges but at low data rates. On the other hand, RF transmissions can achieve high throughput but at short distances due to high absorption in water. Optical wireless transmissions introduce promising solutions by allowing high throughput but for medium ranges due to several underwater-environment challenges [1]. Firstly, the water absorbs and scatter small fractions of the optical wave, which depends on the water type. Secondly, the refraction index can vary along the propagation path due to fluctuations in
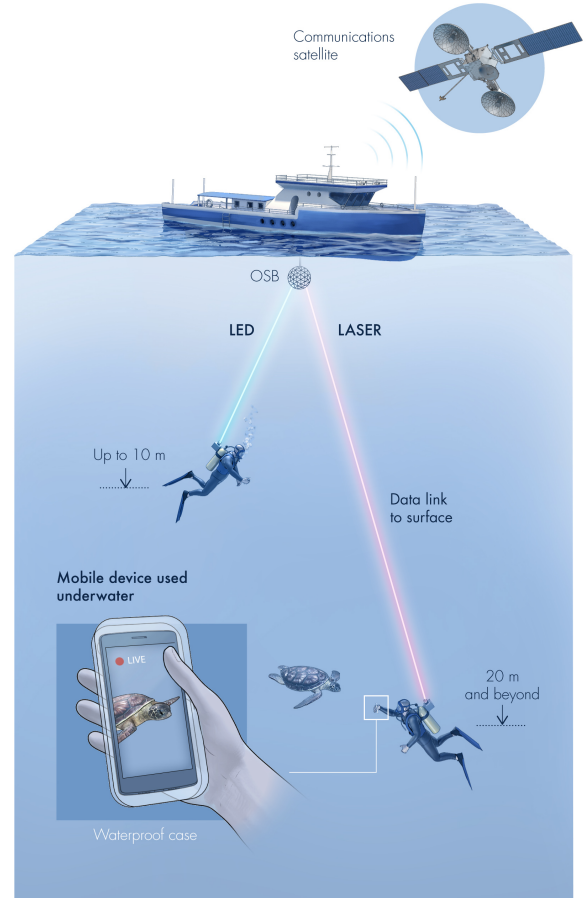
Fig. 1: High-level view of the Aqua-Fi architecture

the density, salinity, and temperature variation across the underwater environment. Thirdly, optical beams are very narrow, and thus the line-of-sight must be maintained for a reliable link performance. Fourthly, the noise from other light sources, including the Sun, can have a degradation performance effect, especially in the offshore areas. Fifthly, underwater objects can play the role of scatters and reflectors, which results in multipath interference on the received optical signal at the detector side. For example, highly turbid underwater environments can cause time dispersion of optical signals, thus decreases the symbol data rate due to inter-symbol interference. Therefore, we need to adopt several communication techniques to mitigate multipath interference, such as spatial diversity. An-

other serious problem is the link outage due to marine animals, where optical signals attract marine animals and can cause momentary loss of signal at the receiver. Appropriate error correction, signal processing, and redundancy techniques are required to ensure delivering the data correctly.

In this article, we propose, Aqua-Fi system, as a first significant step towards realizing the vision of bringing the Internet in underwater environments, as shown in Fig. 1. Aqua-Fi incorporates an Internet bridge, a transmission optical modulator, transmitter equipped with projection optics, beam steering system, detector, and then a subsequent signal processing unit for demodulation. Aqua-Fi system has several practical advantages, which are summarized as follows:

- **Cost-Effective:** Aqua-Fi can use low power off-the-shelf components such as LEDs and Lasers to transmit Internet data with rates in Mbps range over a few meters in underwater environments.
- **Flexible:** Aqua-Fi relies on multi-hop communication using different technologies and communication nodes capabilities, as shown in Fig. 1.
- **Practical:** Aqua-Fi does not require any additional underwater infrastructure, where it can operate using self-contained batteries with low powered light communication devices. Moreover, it leverages standard packet-based communication protocols; thus, it could interoperate with other systems.

We propose two Aqua-Fi systems based on either LEDs or Lasers light sources, which are connected to Raspberry Pis at each connecting end. The LEDs based system utilizes cost-effective materials with small size and operates at low power, but with limited range. However, the Aquai-Fi laser-based system can achieve a higher range and throughput at the cost of weight, size, and power requirements compared with the LEDs one.

In the rest of this article, we first give an overview of the existing experimental and commercial optical underwater systems in addition to the terrestrial optical-based systems. Then, we discuss the main features of the underwater Internet network. Later, we propose and describe Aqua-Fi system component, followed by a discussion of the system's performance and limitations. Finally, we summarize and provide a comprehensive discussion about future work.

OPTICAL COMMUNICATION SYSTEMS

Researchers in both academy and industry are spending extensive efforts to develop experimental and commercial optical systems in both terrestrial and underwater environments [2]. In this section, we highlight the last advances in commercial and experimental underwater communication systems. Then, we discuss some

efforts on terrestrial optical-based in order to borrow some approaches to the underwater environment after considering necessary modifications.

Experimental Systems

Several lab experiments are conducted for underwater optical communication (UWOC) systems to test point-to-point communication for different ranges [3]–[7] As such, the wavelengths from 450nm to 550nm that represent the visible spectrum between the blue and green regions are chosen for their lowest attenuation performance [2], [8]. Recently, real-time video transmission using Quadrature-Amplitude Modulation (QAM) up to 8-QAM in different water types was demonstrated in [6]. Moreover, the aforementioned one-way communication experiment was extended to a bi-directional point-to-point communication scenario using laser technology in [9]. Furthermore, higher resolutions of underwater video that requires high data rate are achieved using multi-carrier Orthogonal-Frequency Division-Multiplexing, where high-orders of QAM signal is used at each sub-carrier to utilize the spectrum efficiently [3], [7]. Table I illustrates some of the systems that have been developed and experimented in the lab using different power and technologies and provide varied services quality in terms of data rate and communication range. According to the lab experiments in [3], [10]–[14], one can find that simple On-Off Keying (OOK) modulation can achieve an acceptable performance. Also, Laser-based systems can provide a much longer range than LED-based ones at the cost of power and system complexity. Furthermore, high data rates (gigabit) have not been observed for vast distances. Finally, orthogonal frequency-division multiplexing employing link diversity can achieve further distances with high data rates. In all of these cases, beam alignment is critical and complicated, where it requires sophisticated hardware support.

Commercial Systems

On the practical side, several companies introduced underwater communication solutions between two nods/users, such as Bluecomm, Anglerfish, and Divecomm. Bluecomm utilizes the LED lights in underwater equipment, such as remotely operated vehicles, to establish communication links. It utilizes a high power LED that operates in shallow or deep water, depending on the application. The reported data rates vary with the communication distance, where a rate of up to 500 Mbps is achieved for very short distances; however, 5 - 10 Mbps can be achieved for longer distances. Anglerfish provides full-duplex voice communication between two divers using also LED technology. It is designed for military applications, with the claim that it

TABLE I: Results from Underwater Lab Testbeds

Data Rate	Range	Spectrum	Modulation	Receiver	Transmitter	Power
[3] 4.8 Gbps	5.4m	450nm	16-QAM OFDM	APD	Laser	15mW
[10] 1 Gbps	2m	532nm	OOK	APD	Laser	10mW
[11] 1 Mbps	3m	532nm	BPSK	PMT	Laser	3W
[12] 2.3 Gbps	7m	520nm	OOK	APD	Laser	12mW
[13] 2.28 Mbps	50m	470nm	DPIM	APD	LED	10W
[14] 161 Mbps	2m	450nm	16-QAM OFDM	APD	LED	N/A

is difficult to intercept because of the directionality and unknown modulation frequencies. Lastly, Divecomm tested a system in early 2017 that achieved 100 Mbps over a range of 30 meters. It uses mirrors to focus the received light into the photodetector. However, their last update recorded a failure to operate in seawater at 100 meters. It is worthy to note that the existing experimental and commercial UWOC system focuses only on point-to-point connections and does not show any network implementation, including the Internet. In the following section, we explore the advances in terrestrial optical-based communication systems to learn some lessons that may help in developing an Internet connection using underwater wireless optical communication.

Terrestrial optical-based systems

Li-Fi is a terrestrial optical system that uses visible light technology based on standard 802.11 protocols and transfers data via the visible spectrum. Currently, PureLifi is the only commercial system in the market, where it offers an integrated device (PL0300) implementing an 802.11 compatible stack with a USB interface supporting up to 86.4 Mbps data rate. Infrared Data Association provides a specification for gigabit transmissions using infrared light, where the IrLAN protocol allows connecting to local area networks. However, it has dropped out of use, and there are not any available modules on the market anymore. Small form-factor pluggable (SFP) is a widespread optical fiber interface that is mainly used in network switches and can achieve beyond 10 Gbps transmission rate. Koruza is an open-source implementation of a Free Space Optical (FSO) system that uses off-the-shelf SFP modules operating at the infra-red light frequencies and achieving up to 1 Gbps data rate. It is worth noting that currently, there are not available SFP transceivers operating at the 450-520 nm visible-light range.

UNDERWATER NETWORK FEATURES

In this section, we discuss the key aspects of the proposed underwater Internet solution that aims at facilitating network deployment in the underwater environment and using today's Internet applications for text and multimedia.

Flexibility

A vital feature of the proposed underwater Internet network solution is to be flexible where handheld devices can operate freely underwater with maximum bidirectional bandwidth. To provide the basis for this point, we consider an abstract model of a diver using a handheld device that can send text and multimedia information. We use different wireless technologies to have additional flexibility degrees while forming a multi-hop communication network. Several sorts of data at the diver side can be transferred first to a gateway attached to his back and equipped with different network interfaces such as WiFi and optical ones.

Wireless Links

To realize the previously mentioned flexible network, we need high bandwidth multi-hop wireless links between the divers and buoys or any other underwater communication nodes, as shown in Fig. 1. The straightforward solution would be to use RF wireless links that is suitable for short distances [2], [8]. Thus, we can use it for the link between the diver's handheld device and the main gateway, as depicted in Fig. 2. Then, the gateway relays the received signal to the nearest receiver using LED or Laser transceivers, which can accommodate high throughput for long distances. Furthermore, the proposed system should communicate vertically between the diver and surface buoy or horizontally between divers using the same optical technology. Finally, the last hop is then from the ship's receiver to the Internet via satellite or any alternative terrestrial-based wireless connection.

Access to Internet Applications

Realizing today's various Internet applications and unleashing their potentials necessitate a paradigm shift in the way current underwater networks operate. Previous underwater video streams systems [9] is incapable of being used as general-purpose wireless connections. Our particular focus is on utilizing standardized protocols to allow accessing all Internet applications and interoperating with different wireless systems in the network. Since most of these applications would require end-to-end performance guarantees, we need
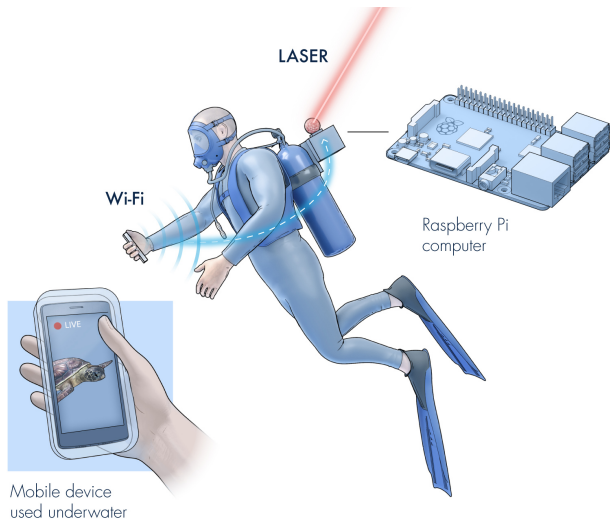
Fig. 2: Aqua-Fi System Overview

Fig. 3: Aqua-Fi setup in a lab environment showing a video call being made and data capture on the oscilloscope

to alleviate different challenges for the underwater wireless network. Underwater physical medium limits the massive bandwidth, power, and computation requirements. Multi-hop relaying across multiple buoys is a powerful solution to distribute the burden among several network nodes. Furthermore, joint context awareness at the underwater wireless and the core network is fundamental to provide adequate prioritization, reliability, and security for the coexisting applications.

AQUA-FI SYSTEM OVERVIEW

The ultimate goal of our system is to provide a high-speed point-to-point UWOC link utilizing both LEDs and lasers depending on operation requirements, as shown in Fig. 1. First, we construct the Aqua-Fi system using LEDs, which is suitable for short distances and low power requirements. Then, we extended the transmission distance and throughput by employing laser sources. Both setups are implemented in a static environment with negligible turbulence.

Aqua-Fi Raspberry Pi-Based LED System

We build the system firstly utilizing green LEDs (520nm) as the transmitters, with photodiodes as the receivers (DET10A2 from Thorlabs). We connect each transmitter to the Universal asynchronous receiver/transmitter (UART) transmit line of a Raspberry Pi 3B via a Bias Tee. As for the receiver side, we connect it also to the receiving UART line of the Raspberry Pi via an amplifier and comparator. Then, we construct the other link, in the same way, to develop a full-duplex symmetric communication system, as shown in Fig. 3.
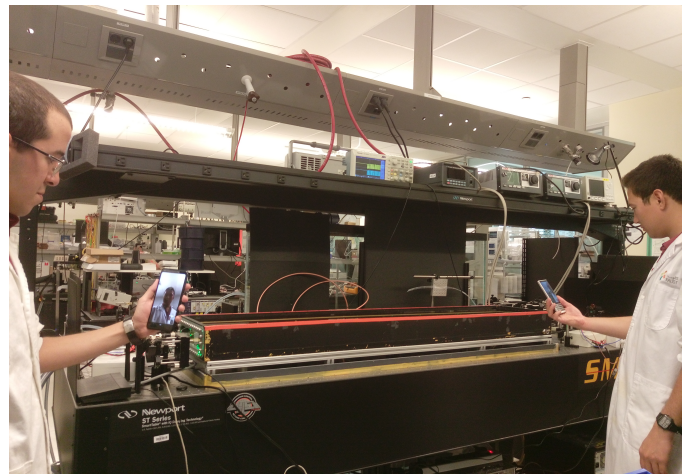
Software: We use the point-to-point protocol (PPP) to modulate the optical signal using OOK through the UART link. As for the transmitting Raspberry Pi, we configure it to forward the Ethernet interface to the PPP interface, allowing a connection to the Internet. The remote Raspberry Pi forwards the packets again from the PPP interface to the Ethernet interface that is connected to an external access point. As for the mobile phone or the tablet connects to the access point via WiFi, allowing phone connection to the Internet. The Ethernet and PPP interfaces are bridged using IPv4 forwarding and iptables; dhcpd is provided at the access point end to assign the hand-held device an IP address automatically. The system is used to start the processes on boot, as per the standard way of doing system initialization.

Asymmetric Power Availability

The Aqua-Fi design considers different power requirements and availability. For underwater nodes, where low power requirement is necessary, we use a transmitter that operates at 5 V. As for the detection; we utilize the DET10A2 photodiode that operates with low power and gives an output signal from 0 to 80 mV. On the other hand, the transmitter at the surface nodes operates with 12 V battery to send a strong signal. The detector at the surface node utilizes the Thorlabs PDA10A2 receiver, which is a photodiode with an integrated trans-impedance amplifier, with higher power requirements; thus, it allows an output signal up to 1 V.

Aqua-Fi Laser System

We modify the Aqua-Fi LED-based system with 0.3W 520nm SN-LDM-T-P TO-Can lasers from SaNoor Technologies. As can be seen from previous
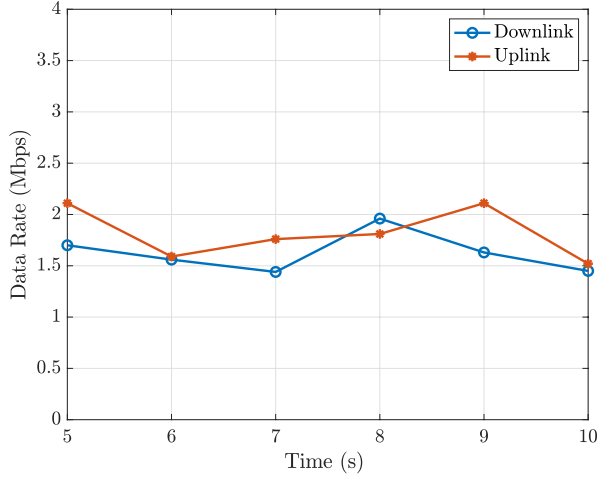
Fig. 4: Sum of four parallel data streams through uplink and downlink versus transmission time.
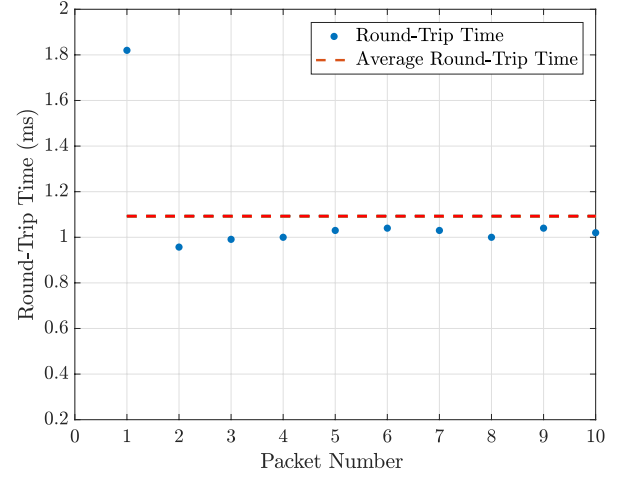

Fig. 5: Packet latency of Internet optical link.

work in Table I, LED systems typically have a lower data rate due to their lower switching speeds, thus switching to lasers allow us to develop a faster system. The range of lasers is also considerably higher, but this is due to their higher power requirements compared to LEDs. They are also considerably more expensive and have much higher pointing requirements.

Software Changes: We were able to increase the UART link rate to 1 Mbps using OOK transmission. The rest of the software was kept the same.

System Performance

We measure Aqua-Fi system performance by throughput, latency, and packet loss, assuming a static underwater channel and fully aligned optical beam with both the transmitter and receiver. First, we use four parallel streams, which denotes four different traffic carried via the Internet optical link. Then, we measure the throughput using *iperf3*, where the sum of the four streams can acheive a maximum of 2.11 Mbps, as shown in Fig. 4. Moreover, we observe approximate symmetry between both links, which verifies the link stability. As for the latency, we measured it using *ping* and observed the round-trip time for different packets, as shown in Fig. 5. At no load, the measured latency has an average of 1.03 ms, while under stress test, it can increase up to 85.5ms. The delay increase is due to physical link performance because the CPU load was low as measured with *top*. As for the packet loss, it was 0% when we measured it with flood *ping*, it had no packet loss when we used *iperf3* and adopted the TCP test. When we increased the rate to 17 Mbps, UDP test reported packets loss.

LIMITATIONS AND FUTURE WORK

In this section, we shed light on factors that limit Aqua-Fi performance, followed by several future directions that we should consider to improve the system performance.

Limitations

The Aqua-Fi system implementation suffers from some challenges that limit the overall performance. The conducted experiment in the lab or pool environments owns static communication channels, which requires manual adjustment of the receiver amplifier. However, when the system is implemented in a real sea/ocean environment, any motion could result in nonnegligible turbulence that affects the communication channel quality and link alignment.

Although using Raspberry Pi allows employing several processing techniques for the signal and flexible control with other peripheral devices, the UART limits the output data rate performance in the megabit range. Raspberry Pi has a serial peripheral interface, inter-integrated circuit, and UART connections, which are not suitable for a system targeting gigabit performance. Thus, it is necessary to find/develop alternatives with higher speed interfaces, that can process the data quickly enough as required. The system also needs to maintain a low power in order to function underwater with a limited room to mount batteries.

Future Work

Improving Data Rate: To improve the data rate significantly, we suggest replacing the Raspberry Pis with standard SFP transceivers driving the lasers/receivers, which is common in FSO systems. SFP is capable of transferring gigabit data rate and integrating with

automatic gain controller (AGC) at the receiver, and with the automatic power control at the transmitter. Also, we can use a proper encoding scheme, such as 8b/10b, and utilize the benefits of Ethernet standards such as error-correcting codes, which do not exist in PPP. All of these are standard off-the-shelf components, keeping costs low.

In the SFP transceiver, we will replace the infrared lasers with 520 nm lasers, i.e., the same one used from SaNoor Technologies. One way to monitor the transmit power is by using an external photodiode. As for boosting the voltage and current to accommodate a higher power laser, we can use high-speed op-amps in a differential amplifier configuration connected to a constant current driver. As for the receiver, we will use visible light photodiodes with integrated trans-impedance amplifiers (capable of 1.25 Gbps), which also integrate AGC functionality (part FCI-H125G-010 from OSI Optoelectronics). Moreover, we will need to use SFP to Ethernet converters (MC220L Gigabit Ethernet Media Converters from TP-Link) to bridge the optical network to Ethernet, which thus allows connections to an access point and the Internet.

Control System: Developing a robust control system to track the optical beam and align it with the receiver can affect the Aqua-Fi system performance significantly. Beam alignment can be done using either out-of-band or in-band techniques. The out-of-band method uses a different band for the control mechanism to localize and track each station. The acoustic signal can be used to track the source, where its low data rate is sufficient to do so. Another approach is by using the cameras to track the laser beam and adjust the alignment visually. As for the in-band system, the laser signal is used to ensure the best alignment angle by measuring the signal-to-noise ratio or received signal strength indicator values. Thus, when the in-band system is required, it must be factored into the protocols used as time is needed to utilize the lasers for measurements.

Underwater Optical Receivers: Designing optical receivers with high response levels at visible light ranges is essential to obtain reliable links. Moreover, extending the single photodiode to a planar or spherical array would increase the received signal strength and reduce the pointing requirements. Furthermore, utilizing solar arrays enables harvesting energy besides transferring data by the optical beam and thus reduces the energy requirement. Solar cells are expected to participate effectively in the underwater optical communication, especially after releasing some restrictions on the bandwidth [15].

Miniaturization: The system as a whole requires miniaturizing to allow mounting it to small objects (such as human divers and mid-water sensors). Hence,

it will also help to reduce the power consumption of the whole system.

CONCLUSIONS

In this article, we demonstrated our vision of Aqua-Fi as a novel underwater communication system that facilitates generic Internet-connected applications. Aqua-Fi is a flexible, low cost, and low power underwater network solution that utilizes Raspberry Pis with RF and optical transceivers. We built and tested the Aqual-Fi system to can connect an underwater platform wirelessly to the Internet and transmit real-time voice and video using both LEDs and 520 nm Laser in a static water environment. Our future efforts will focus on providing higher data rates and immunity against mobility by using a high-speed transceiver, highly reactive control system, and improved detection system to fulfill our vision of bringing the Internet underwater.

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