MArena: SDR-based Testbed for Underwater Wireless Communication and Networking Research

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ABSTRACT

MArena is an open-access underwater wireless testing platform based on the deployment of software-defined underwater modems at a semi-permanent marina location. Each reprogrammable and reconfigurable software-defined underwater modem is connected to a network switch and a mini-PC to enable easy remote access and edge computing capabilities. This setup provides the foundation for conducting experiments and evaluating various communication and networking protocols and algorithms. Additionally, through LTE and Ethernet connectivity, computational power can be further extended over the cloud server for real-time signal processing, where the underwater software-defined modems are synchronized at the symbol level. This paper introduces the architecture, capabilities, and system design choices of MArena while providing in-depth information regarding the software and hardware implementation of its various testbed components. Additionally, the article demonstrates the diverse functionalities of MArena, including its ability to serve as a testbed for synchronized distributed MIMO transmission schemes, real-time wireless underwater video streaming, and PHY/MAC layer optimization.

KEYWORDS

Underwater Wireless Testbed, Underwater Communication, Software-defined Radios, Internet of Things.

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1 INTRODUCTION

The increasing demand for data connectivity creates the need for innovative solutions to extend connectivity beyond terrestrial networks. Considering that the oceans cover two-thirds of the earth's surface, networking technologies for underwater environments is an important and crucial development area for wireless communication systems [14]. Enabling seamless communication underwater unlocks a plethora of applications that were previously inaccessible. Underwater wireless communications are essential for oceanographic research, allowing scientists to gather data from remote marine environments and monitor underwater ecosystems. The concept of the Internet of Underwater Things (IoUT) facilitates the deployment and operation of underwater sensor networks, enabling real-time monitoring of underwater infrastructure, such as oil and gas pipelines or underwater power cables. Furthermore, these technologies are crucial for underwater exploration, providing divers, autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs) with reliable communication links for safety and data transmission. Additionally, underwater wireless communications have military and defense applications, enabling secure and covert communication between submarines and naval vessels. Thus, the advancements in underwater wireless communications have the potential to revolutionize many diverse fields, including research, exploration, industry, and defense.

Despite the progress in the field of underwater wireless communications, there are significant difficulties in deploying and testing devices underwater. Unlike their terrestrial counterparts, underwater deployments face unique challenges that make research and testing particularly complex. One major obstacle is the lack of experimental facilities designed to support rigorous and repeatable underwater wireless networked systems evaluations. As state-of-the-art, research vessels are often employed for experiments, which can be prohibitive in terms of cost, time, and effort [20]. Furthermore, prototyping and deploying sealed communication devices that can withstand the required hydrostatic pressure and waterproof mechanical structures is another challenge by itself. Most importantly, underwater communication is incredibly volatile in real-world settings due to spatial and time-varying communication channels, significant multi-path effects, propagation delay, Doppler spread, and ungovernable motion of both communication devices and surrounding objects. In order to accurately assess the performance and reliability of underwater wireless communication systems in real-world scenarios, a stable, repeatable, and flexible testbed is essential.

To address this need, we established the MArena testbed, in which researchers and developers can conduct experiments at scale, evaluate different protocols and algorithms, and optimize the performance of underwater wireless communication devices, ultimately advancing the field and accelerating the deployment of these technologies in practical applications. MArena is located in Boston, MA. The main contributions of this article are summarized as follows:

- **Real-time experimental underwater channel evaluation platform:** MArena is an open-access platform that can enable real-time underwater channel evaluations with empirical data. With full Internet access, software-defined modems, and edge-computing components, MArena is a platform that supports the experimental characterization and development of underwater wireless communication technologies.
- **Repeatable, flexible, and scalable underwater experiments:** With the semi-permanent testbed location for MArena, evaluation of communication protocols with static nodes can be conducted manually or autonomously without interruption. The number of deployed modems can be increased for network experimentation with multiple nodes. Also by leveraging the LTE connectivity to individual or multiple modems, the deployment layout can be changed within the marina slip grids, enabling flexible deployment settings. Similarly, ROVs or AUVs can also be connected to MArena for mobile node experimentation.
- **Edge processing and cloud computing capabilities:** MArena utilizes reprogrammable and reconfigurable software-defined underwater modems that are linked to a network switch and a mini-PC, allowing remote access and edge computing. Moreover, by leveraging LTE or Internet connections, computational capabilities can be expanded through a remote cloud server for real-time signal processing.

The rest of the paper is organized as follows. Testbed and the architecture of the platform are described in Section 2. In Section 3, hardware and software components that are required to enable MArena are presented. In Section 4, accessing, basic capabilities, and limitations for the deployment duration are shown. Different experimental capabilities are also shown in Section 5. Finally, a brief literature survey for underwater testbeds is presented in Section 6, and then concluding remarks are given in Section 7.

2 TESTBED DESIGN AND SYSTEM ARCHITECTURE OVERVIEW

MArena serves as a fully softwarized research testbed, enabling real-time experimentation of underwater wireless communication links. Different PHY, MAC, and Network Layer algorithms, deployment settings, and channel effects can be observed and evaluated through this testbed. MArena is comprised of three connection layers of local control station, cloud server, and the software-defined underwater modems (SDUMs) as shown in Fig. 1.

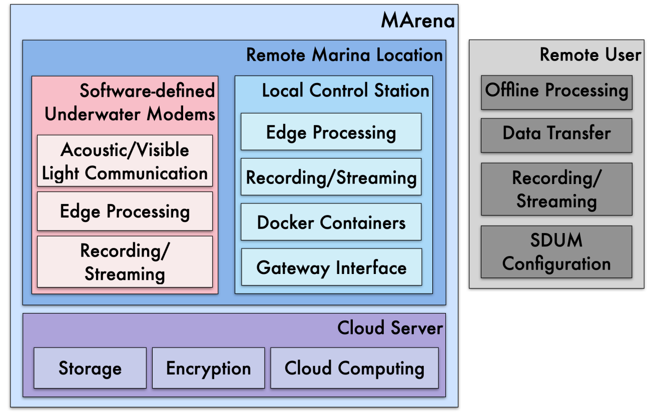

Figure 1: MArena platform block diagram.

Local Control Station. The local control station (LCS) is the main gateway for accessing SDUMs for data streaming, recording, and remote controlling operations. At the same time, the cloud server connection is obtained again through the LCS. LCS is composed of a cable modem that enables Internet access and a mini-PC that acts as both the connection gateway and the edge processing unit. Access to the LCS is maintained through a dynamic DNS (DDNS) setup on the cable modem, which allows easy access to the SDUMs or LCS from anywhere around the world. Each registered user either can have their own user space for private file storage and data processing or shared user spaces can be accessed in the mini-PC. Within these user spaces, Docker containers are readily available for use to run different applications for flexible resource sharing and prototyping different processing applications without disrupting the main operating system within the LCS.

The cable modem can supply Gigabit Ethernet connection with four individual GigE ports. This capability is beneficial for real-time and ultra-low latency control or connection between the remote user and the SDUMs or the LCS. The cable modem within the LCS also employs a network switch for individual connection of SDUMs. Each SDUM is connected to the network switch with unique local IP addresses for a secure shell (SSH) connection. This network switch offers scalability for the MArena platform by enabling the extension of the system with a higher number of SDUMs. Hence, by increasing the number of GigE ports on the network switch, MArena system can be extended to larger underwater networks. Furthermore, with the built-in Wi-Fi Gigabit router capability, smart Wi-Fi outlets are employed to turn off and on the charger units for SDUMs or power cycle the mini-PC if needed.

The Cloud Server. The cloud server is also connected to the LCS for further data processing or access. SSH connection or reverse tunneling can enable communication between the cloud server and the LCS.For data transfer or streaming, port forwarding is used. With port forwarding between the LCS and the cloud server, real-time data transfer and streaming can be accomplished with different protocols, such as; ZeroMQ, TCP or UDP.

Due to the limited computational power of the mini-PC employed at the LCS, the cloud server can be used for computationally heavier tasks, such as; forward-error coding,

(a) (b) (c)

Figure 2: (a) OpenCPN image for the deployment location. Depth values are shown in meters. (b) Satellite image of the deployment location. The exact location is marked. (c) Illustration of the deployment setting.

machine learning, artificial intelligence (A.I.) training data processing, etc. Also, the limited storage capacity of the mini-PC is tackled with the usage of the cloud server. The organization, distribution, encryption, or transfer of these sensitive recordings can also be accomplished with the cloud server.

Software-defined Underwater Modems. In the MArena platform, any underwater modem that allows Ethernet connectivity with a suitable interface can be used for underwater wireless networking. However, as previously mentioned, software-defined underwater modems are vital for efficient, robust, and adaptive communication for enabling protocol development and mitigating the deteriorating effects of temporal and spatial varying channels. In this work, HydroNet Wideband Modular Modems (WMMs) [19] are selected as the SDUMs, since to the best of our knowledge HydroNet is the only commercial off-the-shelf (COTS) software-defined modem that offers the capabilities that promote the development and experimentation aim of the MArena testbed. In addition to software-defined networking (SDN) capability, with its' modular design HydroNet enables different modalities with acoustical or visible light communication front-ends, which extends the experimental capabilities of the MArena platform. HydroNet WMM is capable of extended deployment times and easily interfaces with a base station via underwater cabling connections. It also hosts a Linux OS, accessible via SSH connection, enabling fully softwarized architecture and allowing for remote developments and re-configurations of the onboard transceivers while the device is deployed. Additionally, HydroNet WMM natively supports open-source development tools, such as GNU Radio, within its framework and Docker containers can be employed to enable faster and more stable prototyping and development for underwater wireless communication protocols. In this testbed, the usage of these SDUMs is vital for experimentation with maximum flexibility and reconfiguration. Underwater communication channels are severely impacted by multipath, delay, and Doppler spread [5, 17, 18]. In order to mitigate these effects, reprogrammability or capability to control transmitted waveforms over the wireless channel enables PHY or MAC layer optimization through different channels [3].

On the other hand, underwater acoustic wireless communication channels are rapidly time-varying. Channel features can change by different deployment settings, ocean tides, waves, weather conditions, limited deployment depth, or oceanic currents. Additionally, since MArena is deployed at a publicly serving marina, ship traffic, location of the parked boats, or setting of the marina slips can also differentiate the multipath effect. Though these uncontrolled variables introduce complexity to the wireless communication channel, using SDUMs is greatly beneficial to mitigate such effects. Thus, optimization over such spatially and temporally varying channels is also vital for robust operation of underwater communication over different environments.

Remote Marina Location. MArena platform is located at a semi-permanent deployment location in Boston, MA. The deployment location is a publicly serving marina that houses seasonal and transient guests. Within the marina, water and metered shore power are supplied for cleaning the bio-fouled underwater devices and powering up the necessary electronics, eliminating the usage of batteries or portable power supplies. Marina slips are positioned over 67500 m^2 area with depth ranging from 4 to 11 meters as shown in Fig. 2 (a). The deepest possible points among the marina slips are selected as the deployment location to mitigate the bottom reflections. Though 11 meters of depth is the maximum that can be achieved within this marina, ocean tides can also affect the actual water column depth. As shown in Fig. 2 (b), this deployment location faces the Boston Inner Harbor, where maritime traffic is present and can be disturbing for the communication signals that are intended to be sent or received by the MArena platform.

3 HARDWARE AND SOFTWARE COMPONENTS

Within this section, we offer a comprehensive explanation of MArena's design decisions, along with its hardware and software setup.

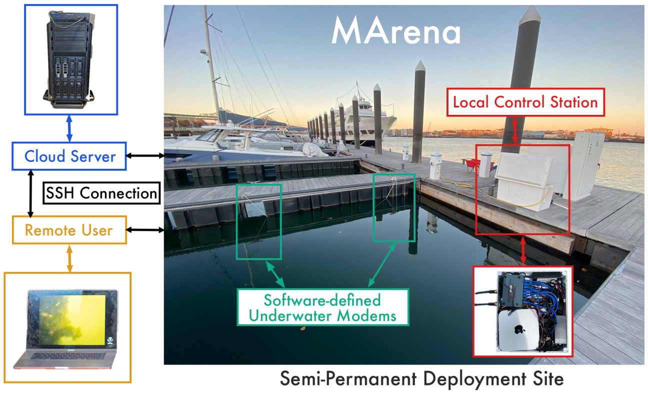

Figure 3: Connection diagram of MArena platform.

3.1 Local Control Station Configuration

The MArena platform is an open-access platform that is available to both academic and industry researchers upon account registration. LCS stands as the main gateway to access the MArena platform and correspondingly controls the software-defined underwater modems deployed at the testbed. The LCS is composed of a gateway, cable modem, and switch. Connection to LCS is accommodated through SSH connection with the dynamic DNS configuration within the cable modem connected at the LCS. As the cable modem, Motorola MG7700 DOCSIS 3.0 modem with built-in AC1900 dual-band Wi-Fi router combo is used. Wi-Fi functionality of the modem is used for remote control over the Kasa HS103P2 smart plugs for turning off or on the battery chargers of the SDUMs and also rebooting the mini-PC that acts as the gateway in the LCS in case of an error or remote interruption required. Gigabit Ethernet connection is distributed through TP-Link TL-SG108 8 port gigabit Ethernet switch to the SDUMs. Each gigabit port can be employed by the SDUMs and connection to each individual SDUM can be provided through SSH connection with a proxy jump over the gateway as shown in Fig. 3. The gateway is implemented on an Apple Mac Mini running MacOS Ventura, Apple M2 chip with 8-core CPU, 10-core GPU, 256 GB storage, and 8 GB unified memory. This machine enables remote connectivity and Internet access to SDUMs, further edge processing capability through data streams from or to SDUMs, immediate data storage, and cloud server connection.

To power all these components in the LCS, metered shore power connected to APC BX1500M uninterruptible power supply (UPS) is used to protect the LCS and the SDUMs from power surges or outages. Similarly, the Internet connection is supplied through a cable provider available at the marina location. However, for remote operations or for locations, where cable Internet is not available, LCS can also obtain Internet connection through NETGEAR LM1200 4G/LTE broadband modem as an alternative option. The same gateway structure can be implemented with this LTE modem and a portable power supply to tackle power or cable shortages or to use on operations that require remote or mobile deployments. The LCS consumes 24 Watts with the cable modem, while the same system with LTE modem consumes 18 Watts of power. Finally, all the electronic components are placed in a ABS plastic IP65 junction box for protective housing and then the junction box is placed in a fiberglass dock box for protection from harsh weather conditions and salt water.

3.2 Cloud Server Configuration

The cloud server is used at a remote location with a Dell PowerEdge T440 machine running Fedora 32 Linux kernel. This cloud server acts as an improved processing power for further computation or signal processing blocks and also as robust and encrypted data storage. Specifically, the cloud server has a 32-core (64-threads) Intel Xeon Silver 4208 processor with 2.10 GHz base frequency, 4 TB SSD storage, and two 16 GB DDR4-3200 RAM with 3200 MT/s speed. Similarly to the LCS, the cloud server is powered through UPS for possible power surges or outages.

As described in Section 2, the cloud server is beneficial for the computationally expensive processing of data or recordings. Encryption, generation, storage, and processing of datasets can be accomplished with this cloud server. Training datasets for machine learning or artificial intelligence applications can also be conducted with MArena testbed [21]. SDUMs can employ the cloud server for additional processing of the received communication signals or sensor data, such as demodulation, forward error correction (FEC), or decompression.

Remote connection of the cloud server to the SDUMs can be accomplished through either SSH connection with proxy jumps, port forwarding, or reverse tunneling as shown in Fig. 3. Web servers can be implemented in the cloud server, which can be used to access and control SDUMs to reprogram and adapt PHY or MAC layer settings/parameters using XML-RPC protocol. With this feature, the software-defined functionality of the underwater modems can be fully exploited remotely.

3.3 Deployment Configuration

Although the number of SDUMs can be extended, in this work, only 4 HydroNet SDUMs are used within the MArena testbed. Two of the modems are deployed through the dock cleats with their transducers facing towards the ocean surface and the other two are deployed with their transducers facing the ocean bottom. In this way, total of six reciprocal links forming vertical, horizontal, and diagonal channels are obtained with four different modems as shown in Fig. 2 (c). Such settings are useful for minimal movement or alterations on the deployment setup while having maximum flexibility and variance over channel link experimentation.

With the help of the dock cleats, SDUMs are fastened to the marina slip for static node operation. Though within the pier, ocean waves are dampened compared to open ocean environments, due to movements of ships, weather conditions, or ocean waves, slips can vibrate or move with the ocean surface, which will lead to Doppler spread. Although these slight movements can be negligible for low-frequency operation, at higher frequencies Doppler spread can be more disruptive over effective wireless communication [17]. Similarly, with the help of pulleys, semi-mobile node operations can be accomplished within the MArena platform. Remotely operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs), or unmanned surface vessels (USVs) can be useful for conducting mobile node analysis for underwater communications. These vehicles can be either tethered to the local control station or have wireless connectivity through a local area network within the vicinity of the MArena platform. With such operation capabilities, a full range of underwater wireless communication experimentation can be accomplished without the need of a research vessel.

4 LIFE-CYCLE OF AN EXPERIMENT

In this section, we describe the user access, scheduling, and network speed characterization of the MArena testbed along with the challenges and limitations introduced with the testbed.

4.1 System Access

User Access. In order to access MArena, the user should have a registered user space at the LCS or the cloud server through the Network File System (NFS). After logging in to the LCS or the cloud server, connection to the SDUMs can be established through SSH sessions. Being able to connect to the SDUMs through SSH enables easy access to the kernel, control, and governance of the operation of wireless communication and reprogrammability. Although the number of accessible SDUMs in the MArena is governed by the number of gigabit ports of the network switch included in the LCS, the number of network nodes can be extended by network switches with higher number of gigabit ports or replicating the LCS. Since DDNS is used for LCS connection, each SDUM can be accessed through multiple local control stations by only modifying the proxy jump address at the SSH configuration file.

User Scheduling. User access to the SDUMs needs to be coordinated to establish fair use and to avoid interference and collisions during experiments. To implement this functionality, an automation platform such as StackStorm can grant access to a restricted set of users according to a schedule. The scheduling can be determined with a web-based reservation front end. Each user can obtain access to the SDUMs with unique SSH keys enabling privatized control over the SDUMs and processes that will be run through the SDUMs. This access scheme can be controlled over LCS, which will utilize the automation platform for individual user requests. Although the unregulated acoustic communication channel and limited bandwidth of transducers can limit the usage of MArena, depending on the deployment setting, utilized bandwidth, or the load of the individual processes, the automation platform can utilize the channel concurrently and efficiently by employing frequency division or time division multiple access schemes, at the expense of increased interference.

Connection Speed & Latency. MArena platform is mostly limited by the waterproof cables and the connectors that need to be connected to the SDUMs in terms of connection speed and latency. The connection speed between LCS and the cloud server can go up to 800 Mbps, which is limited by the cable modem in the LCS. However, the lack of proper twisted pair cabling and standard Ethernet cable wiring on the waterproof cables available at the MArena limits the link speed between LCS and SDUM to 100 Base-T. SSH speed and latency measurements for each connection link are given in Table 1. Although cables determine the upper limit, internet service providers (ISP) can also limit the internet speed. Internet speed at the LCS is limited to 600 Mbps for download and upload is 20 Mbps by the ISP at the MArena.

Table 1: SSH upload, download speed, and average latency are given for each connection link in the MArena platform respectively.

	Cloud Server	LCS	SDUM
Remote User	112.27 MB/s 111.53 MB/s 0.215 ms	49.34 MB/s 1.45 MB/s 13.3 ms	11.27 MB/s 1.44 MB/s 14.0 ms
Cloud Server	-	88.57 MB/s 2.66 MB/s 12.0 ms	11.34 MB/s 2.47 MB/s 14.4 ms
LCS	-	-	11.41 MB/s 11.34 MB/s 0.403 ms

4.2 Deployment Limitations

Biofouling & Corrosion. One of the major limiting factors for the deployment duration of the SDUMs is biofouling and corrosion that occurs on the water-tight enclosure. In Figure 4, SDUM that is deployed for 34 days, before and after biofouling is shown. Biofouling refers to the accumulation of bio-matter on an underwater surface. Endemic life, most notably mussels and seaweeds, grow on SDUMs, underwater cables, and deployment ropes, making the cleaning process much more intensive. One solution to this challenge is to employ anti-biofouling paint on key metal failure points on the modem. This has yielded decreased rates of biofouling, however, it is necessary to apply such paint materials over all surfaces of the SDUMs to completely alleviate this problem.

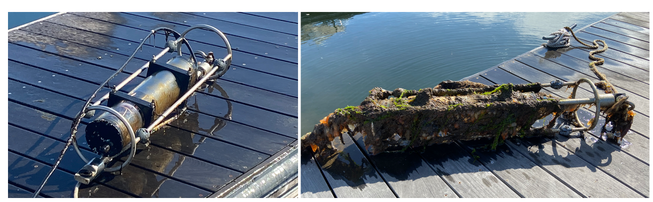

Figure 4: Images of the SDUM, that is deployed for 34 days, before (left) and after (right) biofouling.

Another aspect associated with the deterioration of the SDUMs over their deployment lifespan is the galvanic corrosion of exposed metal components. Galvanic corrosion occurs when two different metals form an anode and cathode when submerged in seawater [4]. The SDUMs have sections exposed to seawater made out of anodized aluminum; this material is designed to be exceptionally durable and corrosion-resistant. However, it is secured via structures that are not made from the same anodized aluminum (e.g., stainless steel, brass, etc.), allowing for galvanic corrosion to occur. Excessive corrosion can potentially breach the sealed enclosure of the SDUM and destroy it. A technique used to reduce the effects of galvanic corrosion is to utilize a sacrificial anode; which serves as a way to "soak up" the corrosion without damaging the metal components of the SDUM. These sacrificial anodes are regularly replaced as they deteriorate. Overall, an underwater deployment environment can be very hostile for a testbed such as MArena and must be considered for any extended experimentation. However, by leveraging the aforementioned mitigation techniques, the physical deterioration of the deployed testbed can be limited.

Interference & Noise. MArena testbed provides more realistic experimental settings compared to traditional water tanks or pools, commonly used for controlled experiments in underwater wireless communication research. However, the MArena testbed is subject to dynamic variations in the acoustic communication channel caused by constant tide changes and shipping activities. Moreover, man-made or natural noise sources such as echo sounders, SONARs, velocity profilers, or marine animals might appear in the unregulated underwater acoustic spectrum [5]. The underwater acoustic spectrogram received at the MArena platform is shown in Fig. 5, depicting the power of different interference and noise sources. As a result, the MArena testbed experiences temporally and spatially varying noise, interference, and multipath conditions, which can significantly impact the communication link conditions. However, thanks to the SDUMs employed in the testbed, MArena is capable of implementing, studying, and evaluating communication protocols under these constantly varying conditions.

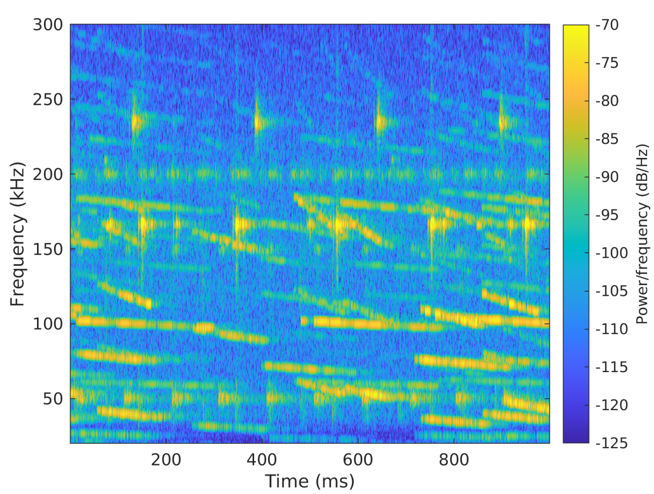

Figure 5: Acoustic spectrogram at the MArena platform receiving the interference and noise between $10-300$ kHz **spectrum.**

Power. As in every remote and battery-powered testbed deployment, power consumption and recharging capabilities are also critical for the MArena testbed. Specifically, for the current deployment location, the components of the MArena testbed (including the LCS and SDUMs) are powered with the shore power provided through the marina structure. However, the MArena testbed is capable of getting replicated in remote locations where no shore power lines are available. For such deployment cases, MArena's components offer battery-powered operations and charging capabilities through solar panels [7]. Overall, MArena can adequately address the power requirements for extended deployments without constant on-site maintenance in different deployment settings and locations.

5 EXPERIMENTAL CAPABILITIES

MArena platform can be used as an underwater acoustic or visible light communication experimentation testbed and also an enabler for a wide range of diverse application prototyping and development. Within this section, we explore various experimental use case scenarios and evaluate some published work on the MArena platform.

Channel Sounding and PHY/MAC Layer Optimization. As discussed previously, underwater wireless communication channel spatially and temporally varies rapidly. In Fig. 6, synchronized recordings of channel impulse responses of three distinct SDUMs that are deployed in close proximity are shown [6]. Even marginal spatial or temporal deviations can result in completely different results, which immediately affects the quality of communication links for wireless acoustic networks. With MArena, assessment of these spatial and temporal changes, and correspondingly developing efficient, robust, and adaptive physical (PHY) or medium-access control (MAC) layers, channel sounding and optimization algorithms can be implemented [3, 5, 17].

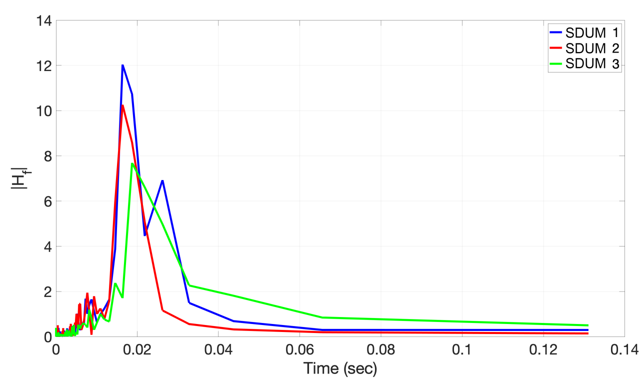

Figure 6: Channel impulse response of three SDUMs deployed in close proximity.

Dataset generation for AI and ML. The MArena testbed holds immense potential for generating datasets crucial for training artificial intelligence (AI) and machine learning (ML) algorithms in the context of underwater wireless communication systems. Leveraging underwater AI enables the implementation of techniques like adaptive modulation and coding, spectrum sensing, and complex receiver architectures such as polymorphic receivers to enhance spectrum utilization. However, creating datasets for AI and ML in this domain poses significant challenges due to the unique characteristics of underwater channels and the complexities involved in underwater deployments. To create highly accurate and generalizable ML models for underwater channels, it is essential to capture a substantial volume of real-world data. This necessity arises from both the limited bandwidth of acoustic systems and the temporal variability of the channel, and the recordings take an order of magnitude longer than RF datasets for ML. Traditionally, simulation-based approaches have been used, but they often fail to capture the nuances of real-world scenarios, leading to discrepancies in performance. However, MArena overcomes these challenges by providing a realistic and controllable environment for dataset generation. The testbed's deployment of software-defined underwater modems, coupled with the flexibility of reprogrammability and reconfigurability, enables researchers to simulate and evaluate diverse communication protocols and algorithms [21].

Distributed SIMO. Preliminary experimentation on the feasibility of distributed SIMO systems is presented in [6] using the MArena platform. With a single transmitting SDUM, maximal-ratio combining (MRC) algorithm is implemented to improve channel capacity with the same bandwidth and transmission power by employing three individual receiving SDUM nodes. Bit-error-rate (BER) improvement at the same signal-to-noise ratio (SNR) level by increasing the number of receiver nodes is shown in Fig. 7. Signal processing such as packet detection, Doppler/CFO compensation, and channel equalization is conducted by SDUMs. Equalized received signals are streamed to the cloud server for symbol synchronization and MRC. MArena platform enabled extensive experimentation capability also flexibility by facilitating further processing at the cloud server. Simultaneous, remote, and synchronized processing of incoming streams from different SDUMs at the cloud server within the MArena platform, enables real-time implementation of distributed SIMO systems.

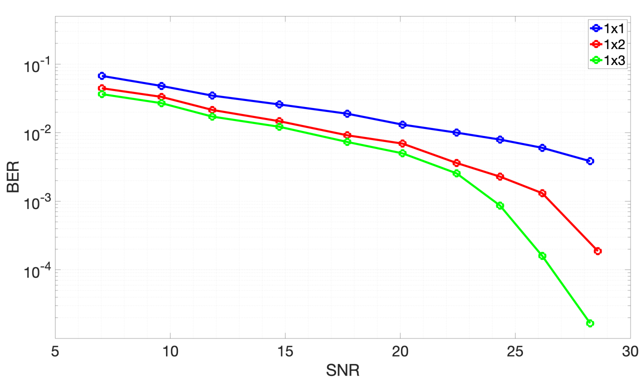

Figure 7: Average BER at different SNR levels with 1x1, 1x2, and 1x3 distributed SIMO settings.

Real-time Underwater Video/Sensor Data Streaming. MArena platform is beneficial for developing different applications that involve underwater wireless communication. With this platform, real-time streaming of any underwater sensor data can be implemented. Among different sensor data, real-time video streaming is one of the most *"data-rate hungry"* applications. As shown in Fig. 8, SDUMs and the MArena platform can be fully exploited for streaming high data-rate video information wirelessly. This application is greatly important for enabling remote or tetherless operation of underwater vehicles or underwater visual surveillance/observation purposes. Again in Fig. 8 (right), a frame of streamed video through wireless acoustic channel is shown, where a lumpfish is present in close proximity to the camera and the transmitting SDUM.

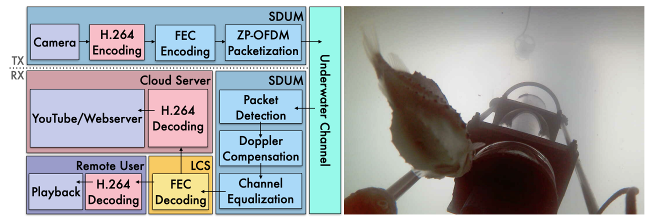

Figure 8: Block diagram (left) and a frame (right) from the real-time video streaming application.

Mesh Networking Development. The unique capabilities afforded by the MArena have allowed ongoing development exploring dynamic mesh routing networking capable of overcoming the volatility of the underwater channel. With the high propagation delay associated with the underwater channel, timing optimization is critical for ensuring an efficient MAC. Specifically, MAC schemes in the ALOHA family have been experimented upon using the unique deployment setting granted by the MArena. In a system with floating or otherwise non-static nodes, it is very difficult to perform network layer experimentation due to a constantly changing distance between nodes. MArena does not have this issue due to the static positioning of the deployed SDUMs. With the ease of altering deployment configurations, MArena can be adapted for optimal experimentation with the behavior of control packets and the construction of the dynamic routing table with different orientations. The software development of this system has required remote access, reliability, and availability, all of which are provided by MArena.

6 RELATED WORK

While the breadth of developments into underwater communication testbeds is currently relatively limited, a few testbeds have been proposed, simulated, and deployed for various use cases. Notable works in this field include [1, 2, 8–10, 12, 15, 16, 22], where some researchers focused on having controlled testbeds that can be accessed remotely. Luo et al. [11] developed a software-defined networking (SDN) based testbed for performing experiments on underwater sensor networks. The system proposed consists of nodes capable of accessing the underwater acoustic channel. Nodes communicate with each other via LoRaWAN, allowing for nodes to be deployed in a much wider range than a wired system would be capable of. A drawback of this system is the decreased data rate associated with the utilization of LoRa RF for interfacing with the nodes as opposed to the wired interface of MArena. Another potential limitation is the non-static nature of the buoys utilized in the SDN-based testbed. While the movement of nodes is inevitable due to oceanic currents, MArena provides a more controlled environment due to the static deployment methods.

Another scalable underwater testbed, WaterCom [13], is presented where three testbeds are proposed: a tank setup, a marina setup, and an open water setup. Each testbed is designed to be remotely accessible with scheduling for jobs and experiments. MArena is similar to the static marina setup proposed in WaterCom, however, MArena has gone beyond the simulation space and explored the real-world limitations of extended deployment of static underwater nodes. In conclusion, MArena breaks new ground as an underwater communications testbed due to its ease of access, versatility, reliability, and high data-rate capabilities proven through real-world deployments.

7 CONCLUSIONS

In conclusion, the development of MArena has addressed the limitations and challenges in underwater wireless communication research by providing an open-access testing platform. By deploying reprogrammable and reconfigurable software-defined underwater modems at a marina location, MArena offers a robust foundation for conducting experiments and evaluating communication protocols and algorithms in a real-world setting. The integration of network switches, mini-PCs, LTE, and Ethernet connectivity enhances the testbed's capabilities, enabling remote access and edge computing, as well as real-time signal processing through cloud servers. The three-tier design of MArena, with submerged modems, ensures flexibility, scalability, and reproducibility in evaluating and developing wireless underwater communication links and networks.

Overall, MArena's establishment fills a crucial gap in the field of underwater wireless communication by providing a stable and flexible testbed that bridges the gap between simulation-based development and real-world scenarios. The platform offers researchers and industry professionals an invaluable tool for advancing the understanding and development of underwater wireless communication systems.

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