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Design of a Web Based Underwater Acoustic Communication Testbed and Simulation Platform

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Abstract

Underwater Wireless Sensor Networks (UWSNs) are playing a vital role in exploring the unseen underwater (UW) natural resources. However, performance evaluation of UWSNs is still a challenging research problem. Various techniques such as, in-field testing, simulation and emulation have been used for the purpose but they all have limitations. For example, in-field testing is expensive as well as extensive; similarly, a simulation model based on assumptions may not provide precise results. Consequently, it is crucial to have a solution that is reliable, inexpensive and requires less effort to validate the functionality of UWSNs and their components. In this paper, a testbed is proposed that evaluates the UW communication system in a controlled aquatic environment and simulates the UW channel and sound propagation models. The constraint of physical access to the testbed facility is resolved by using a web-based monitoring and controlling graphical user interface. Preliminary results obtained by using the testbed in evaluating the performance of UW communication systems and the simulations done show that the proposed solution is indeed superior to existing solutions as it is cost-effective, requires less effort and is reliable.

Keywords Underwater acoustic communication · Underwater communication simulation · Underwater communication testbed · Underwater web-based testing · Underwater wireless sensor network

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1 Introduction

Nature has bestowed the ocean bed with immense resources that offer a great potential towards the economic growth. Advancement in technology is facilitating the researchers to explore oceans, leading to a breakthrough in industrial and military communication and other applications. To explore marine life, several Underwater Wireless Sensor Networks (UWSNs) have been proposed [1]. Despite the efforts, research in UWSNs is slow due to the challenges posed by undersea communication medium as compared to the Wireless Sensor Networks (WSNs) used in terrestrial communication [2, 3]. Testing of UWSNs and their components in a real environment is still a challenge owing to high deployment cost and time-consumption. Simulators offer an inexpensive solution; due to low setup time and cost but with the trade-off of low accuracy because they use a subset of environmental variables. Another technique is the emulator-based network, deployed using a combination of hardware and software. The test results of emulator-based networks are better as compared to simulator-based setup. However, in order to use emulator based networks, physical access is required [4].

In recent years, several efforts have been made in designing the UW communication testbeds, some of them have been explained in this article. Depending on the requirement, the UW testbeds are designed both for specific as well as general purpose applications. These UW testbeds are categorized based on size i.e., small, medium, and large; and the cost of development and deployment which can be either low, medium or high. The dynamic nature of an underwater channel remains a challenge for the scientific community designing various UW testbeds [4]. The deployment of such networks is not only expensive but requires a lot of time and effort to setup. As a result, the systems deployed at the moment have limitations. Extensive research is being carried out to design a suitable testbed. However, factors such as modeling time, cost, deployment resource and, reliability etc., hinder any major breakthrough.

In this article, UW acoustic communication testbed and simulation platform is proposed and its performance has been evaluated, both as an emulator and a simulator. In emulator mode, the initial testing has been done by using two low-cost UW acoustic modems [5] communicating in a controlled aquatic environment setup in a laboratory. The temperature in °C and salinity in Parts per Thousand (PPT) is acquired using UW sensors and transmitted acoustically using UW modem in the water channel. Data is successfully received by another UW modem and graphically displayed. Similarly, various UW algorithms have been simulated using the proposed simulation platform. The parameters can be configured locally as well as remotely in the beginning or during simulation to get the desired results. Minimum development time and low cost with remote monitoring facility is novelty of the proposed design. It can be easily modified to evaluate various kinds of UW communication systems and algorithms.

The article is organized as follows. In Sect. 2, we provide background information necessary to grasp the paper. Section 3 explains related research work. In Sect. 4 architecture of the proposed underwater acoustic communication testbed is described. Experimental results and discussion are explained in Sect. 5. Finally, Sect. 6 presents concluding remarks.

2 Background

This UWSNs have been an area of interest for researchers for the past few decades. Despite their commercial and military importance, their practical deployment and testing remains an open research area. Due to this reason, several network simulation software have been developed to validate the UW algorithms and protocols [6].

Some simulation tools have been designed specifically to fulfill the requirements of UW scenarios. On the other hand, there are many other tools which were actually developed for terrestrial communication but can be modified to be used in UW applications. Some simulators are open source e.g., Network Simulator (NS-2), Aqua-Sim, etc. [6]. There is another category of licensed software with additional features of simulation and emulation e.g., SUNSET [7], DESERT [8] etc. These simulators evaluate various UW network protocols such as Medium Access Control (MAC) and Multiple Access with Collision Avoidance (MACA) [9]. They can be categorized at different levels, e.g., low-cost platforms are designed for small-scale UW scenarios, while medium to high-cost platforms are used for large-scale testing. To access the experimental facilities remotely, heterogeneous platforms are used which are costly and used for large-scale developments [10].

Underwater acoustic (UWA) modems are the backbone of emulator-based platforms. Commercial modems e.g., LinkQuest [11], Teledyne Benthos [12] and Evologics [13] that are mainly designed for long distance reliable UW communication are being used in the testbeds. Research modems such as Sea Modem [14] and WHOI Micro-modem [15] are economical to be used in the same setup with the tradeoff of Bit Error Rate (BER). UW modems use several modulation schemes such as Frequency Shift Keying (FSK), Orthogonal Frequency Division Multiplexing (OFDM), Direct Sequence Spread Spectrum (DSSS) and Sweep Spread Carrier modulation scheme (S2C) [16] etc. Usually, emulators are used to evaluate actual UW communication systems before deployment in real environments. Compared with simulators, the emulator-based systems are more accurate and require less setup time than real-aquatic environment. They can be used to test various kinds of UW communication systems, Autonomous Surface Vehicle (ASV), Autonomous Underwater Vehicle (AUV), and Remotely Operated Vehicle (ROV) etc.

The proposed testbed software is developed in Laboratory Virtual Instrument Engineering Workbench (LabVIEW) which is a graphical programming language [17]. LabVIEW, with built-in mathematical and analysis functions and graphical front-end controls and indicators, provides a platform that reduces the development time as compared to other software and applications. This helps in quickly creating the required Graphical User Interface (GUI). With the available instrument drivers, it is convenient to connect and acquire data from standard test equipment, sensors and other test devices. LabVIEW uses icons instead of text-based coding. Its front panel is used to create GUI, while the code is written in a block diagram using icons connected by wires. The file format used by LabVIEW is Virtual Instrument (VI). Web server is used to convert a VI into Hypertext Markup Language (HTML) document and embed front panel images to be monitored and controlled using Hyper Text Transfer Protocol (HTTP) in a web browser.

3 State-of-the-Art Underwater Communication Testbeds

Several testbed designs for UW acoustic communication systems have been proposed recently. They are used to evaluate various aspects of UWSNs for UW acoustic communication including hardware, software, protocols, and mathematical models. They are available in different sizes e.g., small, medium and large, and categorized as simulator, emulator or both. These testbeds are deployed in a controlled laboratory as well as in real-world environments. Some existing UW communication system testbeds are discussed in the following section.

An underwater acoustic testbed is presented in [9] to examine the performance of cross-media networking by combining UW acoustic communication and wireless communication. The testbed consists of a UWA modem based on DSSS modulation and operates in the frequency band of 13–18 kHz. A group of underwater sensor nodes is deployed in a lake to collect environmental data and pass it to a sink node which transmits the data to a terrestrial station. Field trials are conducted in a lake by using six nodes including three sensor nodes, a data generator node, a sink, and an off-shore sink node. Two networking protocols, ALOHA and MACA, have been examined using the testbed. From the experiments, it has been found that the delay between the nodes is very short and some errors in data have been observed during wireless transmission. ALOHA, which does not have any collision avoidance system, works better than MACA in this setup because of simple network topology with minimum load.

Du et al. [18] have designed a UW acoustic testbed to investigate water quality of the Qinghai Lake. The testbed consists of a server and various sensor nodes deployed in water and equipped with an OFDM modem for UW communication. Micro-ANP software is running on each of the nodes to provide an interface between network transport layer and physical layer. The testbed has been used in UW protocol evaluation and aquatic environment monitoring of various parameters such as temperature, salinity, and conductivity. In protocol assessment, throughput of the proposed system becomes steady when payload exceeds 100 bytes. Network performance of the testbed degrades with an increase in the time interval between two packets. Software design of the testbed facilitates researchers to use their own UW network protocols in real underwater environments.

The SUNSET framework, which is a customizable testbed for testing of UWSNs is presented by Petrioli et al. [7]. It is developed using NS-2 for simulation, emulation and in-field testing. The SUNSET core modules include (a) utilities unit that makes framework transparent to the client in simulation and emulation modes, (b) timing unit to introduce delays and overheads usually ignored during simulation, (c) debug unit to log and process debug information based on given precedence and (d) statistics unit that provides a tool to gather readings to investigate protocol performance. Some of the features of SUNSET framework are, (1) it is capable of simulating various UW acoustic channel models, (2) the code can be reused after suitable modifications and (3) it supports five different types of commercial UW acoustic modems and uses different sensors for the measurement of temperature, pressure, salinity, conductivity, etc. The energy efficient SUNSET framework can run on small-size, low-priced hardware platforms such as ARM processors.

DESERT is a customizable platform that has been designed to perform experiments on UW network protocols to promote the experiments in UW networking [8]. Its modular architecture allows researchers to reuse their codes with slight modifications. This research targets the grasp on C language libraries to support UW networking protocols. It can be used as an emulator as well as a simulator. Evologics and WHOI Micro-modem have been tested in emulator configuration using the system running NS-2 Miracle. A similar scenario can be created using simulation. The performance of the system has been successfully tested during single and multiple hop configurations. The DESERT architecture is open source but resource hungry and consumes high energy.

WaterCom is a multi-function testbed designed to perform UW experiments at small, medium, and large scales [19]. The prototype supports UW acoustic and optical communications in three configurations; (a) small-scale UW experiments are performed in a water tank using two modems to test the UW transmission in a reflective environment, (b) medium-scale experiments can be conducted in a dock with one mobile and two stationary nodes to test MAC and Network Protocols and (c) in large-scale configuration, the testbed can be used to evaluate multi-hop UW communication and node movability in the aquatic environment. The testbed is fundamentally designed for small and medium level UW experiments, although, as mentioned above, it can be used in large scale configuration. Currently, point-to-point communication at small-scale configuration is implemented and test results are presented in the paper. The testbed can be accessed online for configuration and UW experiments.

The Porto University testbed has been designed by Martins et al. [20], under SUNRISE project. The main objectives of SUNRISE testbed include UW protocol evaluation such as MAC and routing protocols, UW environment monitoring, ecological data collection, UW localization, and investigation of control algorithms with UW robots. The testbed include; AUVs equipped with UW acoustic modems, UW acoustic localization system, ASVs to be used as mobile UW gateways, ROVs for UW inspection, gateways to support UWSNs, buoys, sensors and shoreline control station. Neptus software toolchain provides complete command and control foundation for all operations. The testbed is compact and versatile with the web enabled clients able to control vehicles and resources through IP suit.

A testbed for UW communication and networking is developed by Alves et al. [21] to evaluate hardware and software of UW communication systems near to conditions as in the real environment. Major blocks of the testbed include (a) the commercial UW acoustic modem placed at the seabed, (b) an acoustic system to generate an arbitrary waveform, (c) some instruments to collect oceanographic data, and (d) command system to provide an interface between other systems and to run experiments. Star topology is used in the test setup equipped with Evologics and WHOI Micro-modems using S2C and FSK modulations respectively. Some observations during test include recording of sound speed at various time periods. Experimental results show a reduction in the transmitter sensitivity by 20 dB due to bio-fouling. The testbed facility can be used by the scientists and is remotely accessible to the collaborating institutions.

A testbed for UWSN based on ARM9 processor is developed by Kim et al. [22]. The authors used and recommended ARM9 processor to be used in UW applications because of its high speed, pipelining feature and energy efficiency. The experimental setup is built in a laboratory using a small water tank and six waterproof UW nodes, one each gateway and sink nodes and four sensor nodes. These are deployed at distances of 30–100 cm to measure the temperature and salinity. Data is transmitted from testbed to the PC using Code Division Multiple Access (CDMA) data transmission scheme. Authors highlighted several challenges during the experiments including power consumption due to long propagation delays, and packet retransmission due to collision.

The UW network testbed Aqua-Lab designed in [23] is used to investigate UW algorithms and protocols in the actual aquatic environment as well as in lab facilities. It consists of (a) a low-power WHOI Micro-modem, (b) water tank filled with around 2000 liters water, (c) hydrophone used to receive acoustic signals, (d) UW speakers to transmit acoustic signals in water, (e) sound mixer that can combine various acoustic signals and ecological noises to mimic real marine environments, and (f) a server to communicate and control the functionality of UW modem. Initial experiences of Aqua-Lab results are encouraging with some constraints e.g., SNR that can be adjusted locally because the sound mixer cannot be accessed by a remote user.

4 Platform Architecture

In this section, the implementation of underwater acoustic communication testbed and simulation platform is presented. The testbed combines the hardware and software techniques to implement state-of-the-art virtual instrumentation. This UW acoustic testbed is cost effective, easy to setup and use as compared to the available platforms [4]. The two main parts of the proposed system include (1) hardware interface, to evaluate the performance of UW acoustic communication systems and (2) software components, based on graphical user interface for testing the functionality and simulation of existing algorithms.

The details of hardware interface and software components are as under:

4.1 Hardware Interface

Proposed UW testbed as shown in Fig. 1, consists of a tank that can hold around 400 L of water to test the UW communication system. Low-cost UW acoustic modems operating in the range of 30.5–32.5 kHz frequency band with FSK modulation are used in this testbed as a physical layer [5]. Each modem is equipped with UW transducers TX and RX for acoustic transmission and reception in water channel. Temperature and salinity sensors are attached with the Modem A to obtain the real-time data in controlled laboratory environment and transmit acoustically using TX transducer in UW channel. Modem B receives the

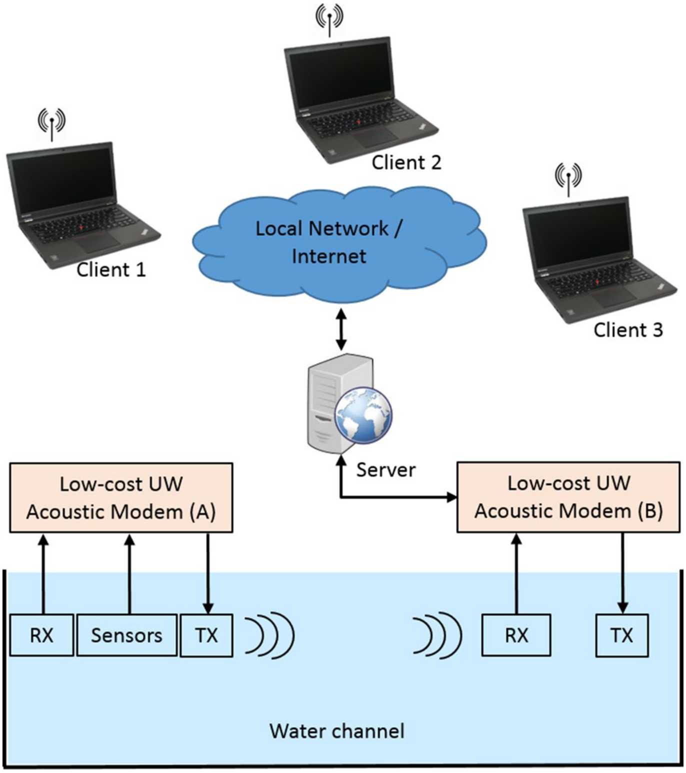

Fig. 1 Proposed UW communication testbed architecture

data from UW channel using RX transducer and pass it to the LabVIEW server running VI for further processing [17]. The LabVIEW server is connected to the local network/Internet to share information with clients.

The sensors connected with Modem A measure the temperature and salinity of water. Modem A transmits the values using acoustic transducer TX in water channel. The values are received by the RX transducer attached with the Modem B which is connected with the LabVIEW server via standard communication port. The LabVIEW server running the VI processes the data and presents it for monitoring and storing at local terminal as well as remote clients. This data is available on the local network/Internet clients via the web browser.

4.2 Software Components

The testbed software is designed in LabVIEW which is a graphical programming language [17]. LabVIEW has built in functions for controlling instruments using General Purpose Interface Bus (GPIB), Universal Serial Bus (USB), Serial, Local Area Network (LAN), Inter-integrated Circuit (I2C), Serial Peripheral Interface (SPI) and Joint Test Action Group (JTAG) etc., interfaces. The available mathematical, statistical and signal processing functions can be used for data and signal analysis. Acquired data can also be displayed using front panel and stored via MS Access and other databases. LabVIEW also provides interface for various Source Code Control applications, data validation systems and other management tools. Test results can also be generated using MS Office and Hypertext Markup Language (HTML) templates and reports. The LabVIEW code can be deployed on target computers by creating standalone executables and installers. LabVIEW applications can also be controlled and monitored remotely.

LabVIEW applications can be created using three sets of programming objects which are tools palette, control palette and indicator, and functions palette. Tools palette is available on both front panel and diagram window while controls are available on front panel and indicator and functions palette are available on diagram window only. The functions and controls are connected to each other based on the datatype. There are debugging tools available in LabVIEW. The VI Analyzer tool help in improving and fault finding the VI’s. Diagram window functions include loops, error handlers and other data structures.

5 Experimental Results and Discussion

5.1 Testbed as an Emulator

To demonstrate the functionality of proposed testbed as an emulator, we use two low-cost UW acoustic modems [5], as has been shown in Fig. 1. The transducers, and temperature and salinity sensors are submerged in an aquatic environment. Modem A collects ecological data using sensors and transmits this data by means of TX transducer in water channel. Modem B receives data using RX transducer from the aquatic environment and transfers it to the Personal Computer (PC) working as a LabVIEW server. Finally, the real-time temperature and salinity values are monitored on a GUI.

Figure 2 shows the front panel indicators displaying instantaneous temperature and salinity values running on LabVIEW server. This is also called local monitoring. The temperature range on the scale is −5 to 35 °C, while the salinity range is between 20 and 40 PPT. On/off switch is used to start and stop the testing process.

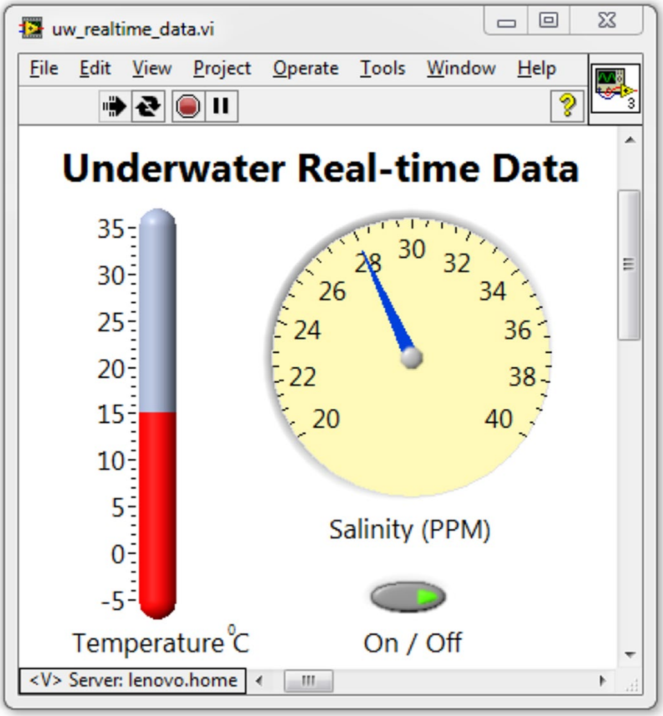

Fig. 2 Underwater real-time data (local monitoring)

Figure 3 shows the front panel indicators displaying instantaneous temperature and salinity values published by LabVIEW web server and monitored by clients in a web browser. The temperature range on the scale is −5 to 35 °C, while the salinity range is between 20 and 40 PPT. A number of clients available on the same network can monitor the temperature and salinity values using the web address.

Figure 4 is the LabVIEW front panel which shows the graphs plotted between temperature (in °C) and salinity (in PPT) vs time (in minutes). The data is collected for a duration of 60 min interval. The initial value of temperature is recorded as 5 °C, that increases up to 17 °C during 60 min. The salinity is recorded from 25 to 29 PPT for the same duration of time.

5.2 Simulation Platform

The proposed UW acoustic simulation platform is based on a graphical development environment LabVIEW [17] commonly used by the scientific community. It is flexible, scalable and requires less programming skills as compared to state-of-the-art simulation platforms [4]. Researchers can easily design, implement, simulate, test and evaluate the performance of UW algorithms. System parameters can be configured in run-time to obtain the desired results. The graphical results of simulations can be monitored and controlled locally as well as remotely using web services. The proposed simulation platform has been tested to evaluate the following UW acoustic algorithms.

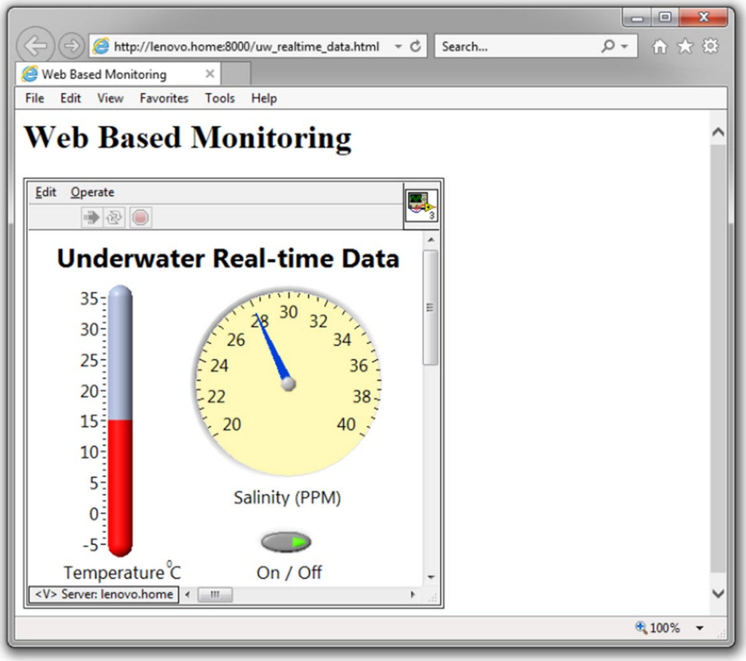

Fig. 3 Underwater real-time data (web based monitoring)

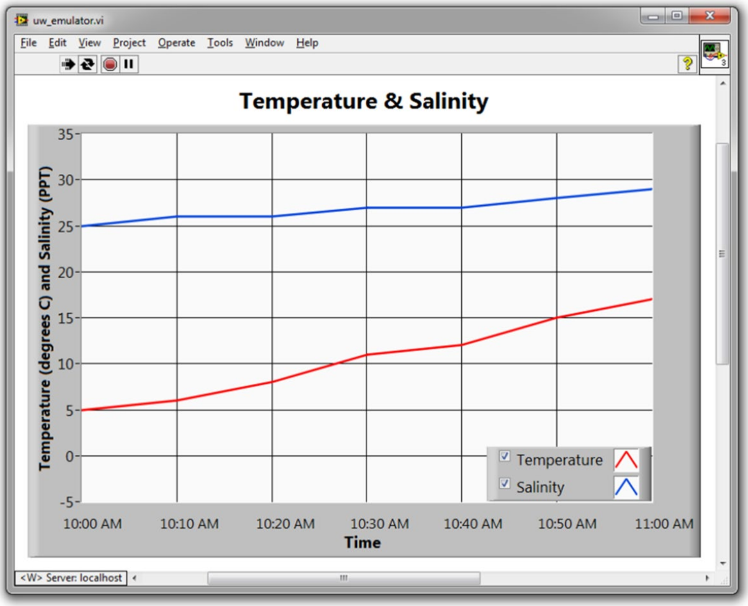

Fig. 4 UW temperature and salinity measurements versus time (LabVIEW front panel)

(a) UW Sound Propagation.

To calculate the underwater sound propagation, several mathematical relationships have been formulated by real-world experiments as well as in controlled laboratory conditions. Mackenzie used following simple nine-term equation to determine the sound speed in UW environments with the typical error of 0.07 m/s [24, 25].

$$\begin{aligned} c =& 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\ &+ 1.340(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \end{aligned} \tag{1}$$

where c is speed of sound in m/s, T is temperature in °C in the range of $-2 \leq T \leq 30$ °C, S is salinity in parts per thousand (PPT) in the range of $25 \leq S \leq 40$, and D is depth in meters from $1 \leq D \leq 8000$ m.

Speed of sound in UW is a function of temperature, salinity and depth. Figure 5 shows the relationship between UW speed of sound in m/s and depth in meters. The four graphs are plotted for salinity values of 25, 30, 35, and 40 PPT for a temperature of 4 °C that can be seen on the thermometer. The temperature value can be adjusted any time before or during the simulation within the range of −5 to 30 °C using the control knob available at

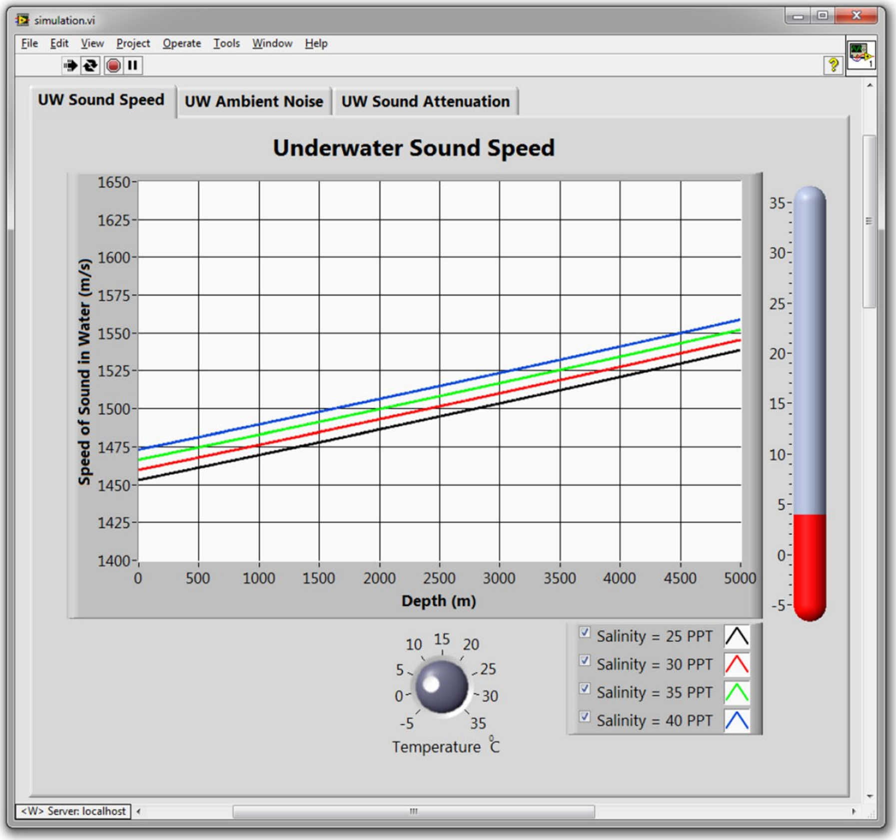

Fig. 5 Underwater sound speed versus depth (LabVIEW front panel)

bottom of the graph. The simulation allows to hide one or more graphs to improve visibility and the user may choose suitable values to get desired results.

Figure 6 shows the diagram window of LabVIEW VI. This is implementation of the Equation used by Bjørnø [24]. The VI consists of two for loops. The outer loop is executed four times to generate salinity values that are offset by 5 to bring salinity values within the range of 25–40 PPT. The inner nested for loop runs 5000 times to generate depth values in meter. Each time the loop executes, the depth value is incremented by 1 m. The constant temperature value is used as an input inside the inner loop.

(b) UW Ambient Noise.

Ambient noise is an undesirable sound in aquatic environment that causes interference during acoustic communication. To model the ambient noise in UW environment we use Eqs. 2a–2e in the frequency range from few Hz to several kHz [25, 26].

$$10\log N_t(f) = 17 - 30\log f \tag{2a}$$

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f - 60log(f + 0.03) \tag{2b}$$

$$10\log N_w(f) = 50 + 7.5w^{0.5} + 20\text{log}f - 40\log(f + 0.4) \tag{2c}$$

$$10\log N_{th}(f) = -15 + 20\log f \tag{2d}$$

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{2e}$$

where N_t is the noise due to turbulence and is less than 10 Hz. Ns represents the noise generated by shipping activity. The range of shipping factor is from 0 to 1, i.e., 0 for no shipping, 0.5 as moderate shipping, and 1.0 as high shipping activity from 10 to 100 Hz. Waves play a major role to the noise in the wide region of 100 Hz–100 kHz. Finally, thermal noise is beyond 100 kHz. The overall effect is presented in Eq. 2e.

The relationship between UW ambient noises in dB vs frequencies in kHz is shown in Fig. 7. The four graphs show the behavior of turbulence, waves, shipping and thermal noise

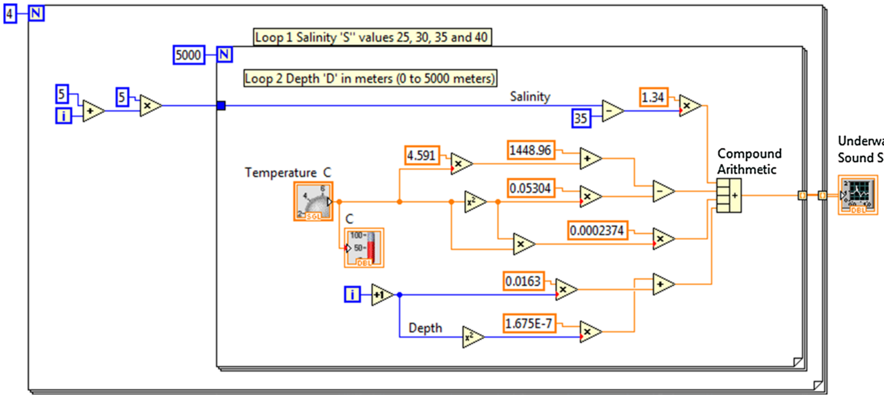

Fig. 6 Underwater sound speed versus depth (LabVIEW block diagram)

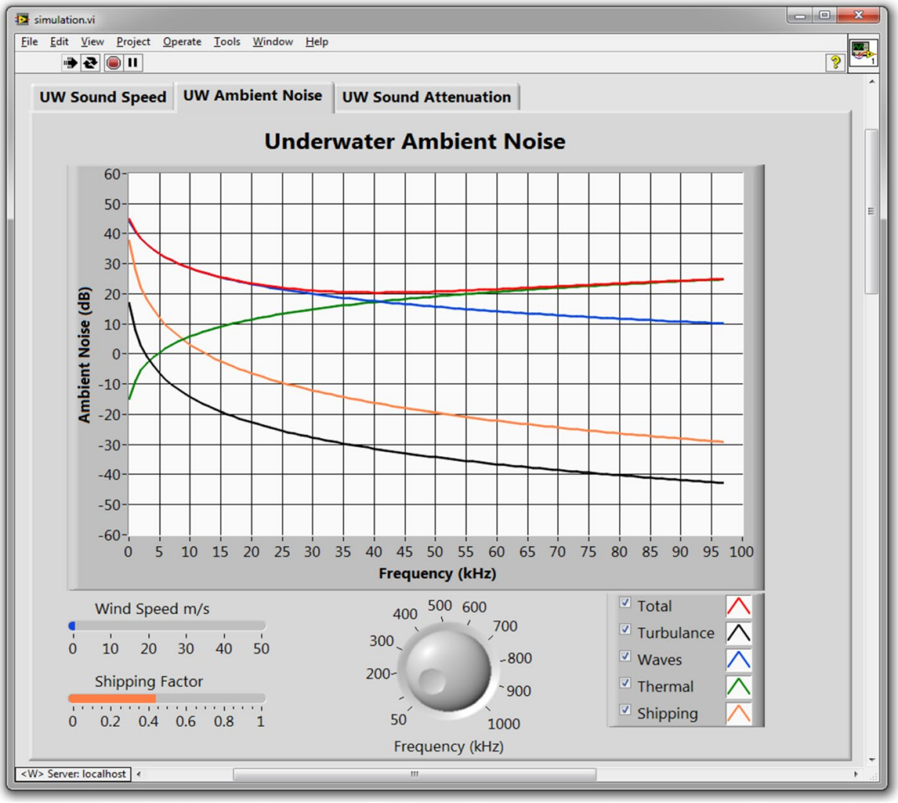

Fig. 7 Underwater ambient noise versus frequency (LabVIEW front panel)

as a function of frequency. The total ambient noise shown in the Fig. 7 is obtained by adding all the four types of noise. For simulation, the frequency range can be selected from the control using LabVIEW. The shipping factor can also be set between 0 and 1. Similarly, the wind speed can be set in the range of 0–50 m/s.

Figure 8 represents the diagram window designed in LabVIEW. This is basically the implementation of the four noise Eqs. 2a–2d and their combined effect 2e, mentioned above. The code is inside a “for loop” which generates the frequency values selected by the knob. The loop is incremented by 1 kHz within the range of 50–1000 kHz. The four noise values are plotted individually as a function of frequency. All the four noise values are also combined to plot the fifth graph which is the ambient noise in dB. The number of times the for loop is executed is based on the frequency knob setting. While generating the Waves noise the value of the Wind speed is taken into account and similarly shipping factor value is used for shipping noise. The values of Frequency, Wind speed and Shipping factor can be set before or during the simulation.

(c) UW Sound Attenuation.

The attenuation in underwater acoustic channel is a function of distance l for a signal of frequency f and is given by Eq. 3a. The first term is spreading loss and second term is absorption loss.

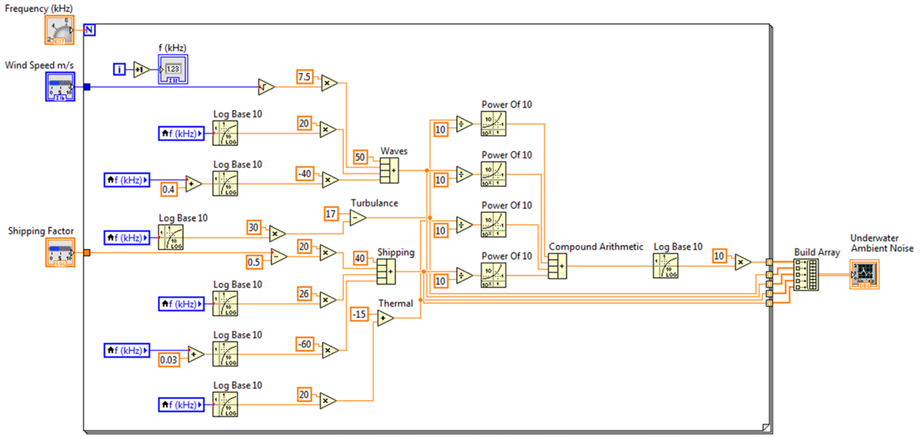

Fig. 8 Underwater ambient noise versus frequency (LabVIEW block diagram)

$$10\log A(l,f) = k.10\log l + l.10\log a(f) \tag{3a}$$

where the spreading factor k depicts the propagation geometry. For spherical spreading, the value of k = 1, for cylindrical spreading k = 2, while k = 1.5 for practical spreading [25, 27].

The absorption coefficient $\alpha(f)$ can be calculated by Thorp's formula given below.

$$10\log \alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f} + 2.75\times 10^{-4}f^2 + 0.003 \tag{3b}$$

The UW sound attenuation based on spreading loss and absorption loss is illustrated in Fig. 9 using Eqs. 3a, and 3b. The total attenuation in dB/km is plotted against a frequency range of 0–1000 kHz and is shown using red color, while the individual losses i.e., spreading loss and absorption loss are shown by green and dotted blue colors respectively. The transmission range can be controlled from 0 to 10 km, while the spreading coefficient *k* can be adjusted in the range of 1–2.

The diagram window of UW sound attenuation designed in LabVIEW is shown in Fig. 10. This is the implementation of Eqs. 3a and 3b using for loop running in the frequency range of 0–1000 kHz, with the increment of 1 kHz. The individual values of spreading loss, absorption loss and their combined effect is calculated inside the loop. The array function outside the loop is used to display all values on the same graph. Transmission range in km and spreading coefficient k in the range of 0–2 can be adjusted before or during the simulation to get the desired graph.

5.3 Web Interface Platform

LabVIEW is used as the platform to implement web interface. Web publishing tool enables the LabVIEW VI's to be controlled and monitored using a webpage. The remote client can change parameters to generate required results. Multiple clients can monitor the simulation at the same time. If control is required then a client can request control of the VI to change parameters. To monitor or control data, the client first establishes a connection with

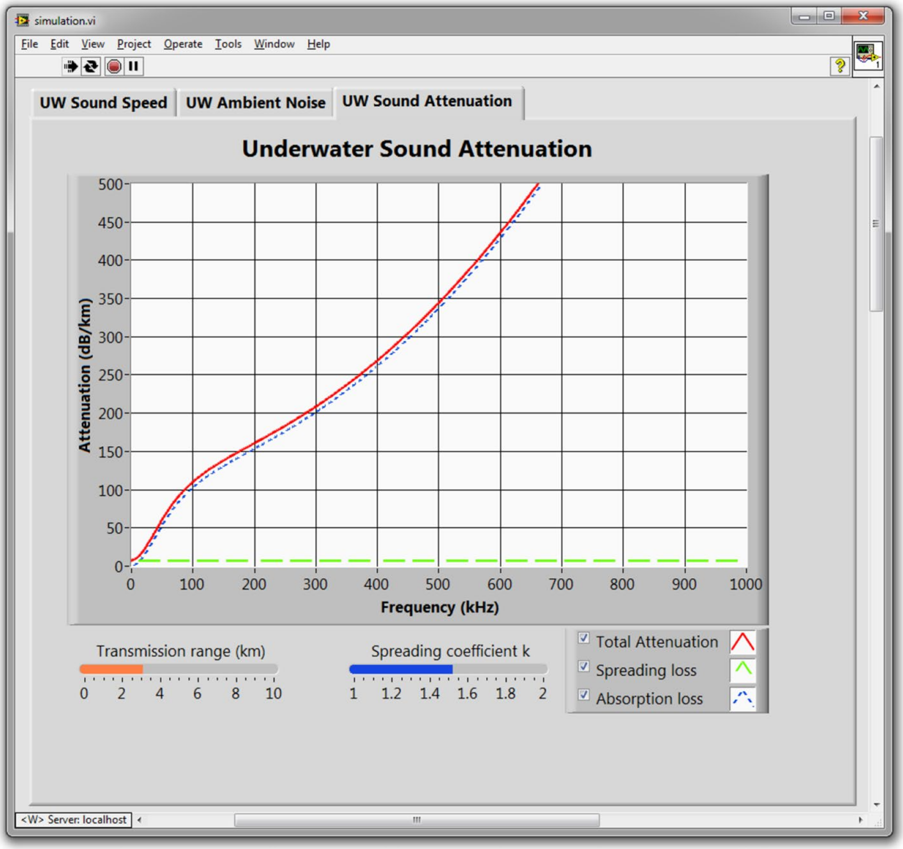

Fig. 9 Underwater sound attenuation versus frequency (LabVIEW front panel)

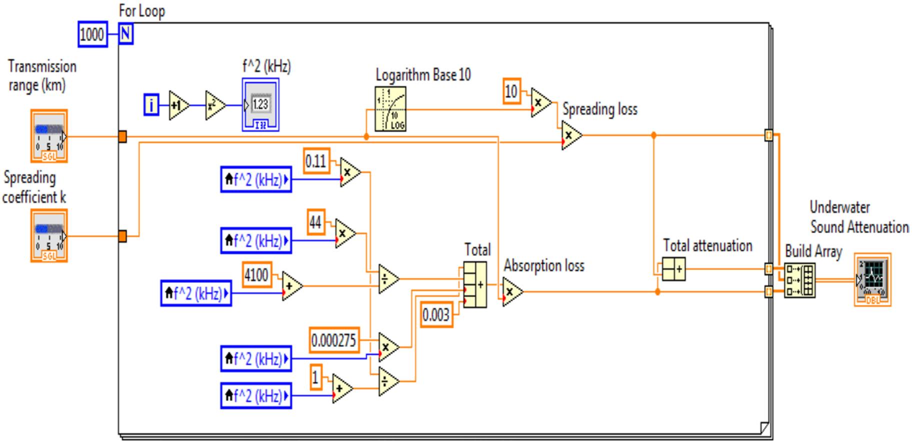

Fig. 10 Underwater sound attenuation versus frequency (LabVIEW block diagram)

the web server through webpage. In monitor mode, the webpage is refreshed automatically when the VI is updated. The LabVIEW web server generates a URL for the VI to control or monitor remotely. An example of a LabVIEW web server generated URL is given below.

$$\text{http://\{IP\_address or name\} : \{port number\}/\{VI\_name.html\}} \quad (4)$$

Remote user can access the VI through webpage by either using the server name or IP address. Depending on the requirement, a secure connection (https) can be established instead of normal (http) protocol. Server name or IP address is followed by a unique port number which is used by LabVIEW web server. Port number can be changed if it is engaged by another application. Different port number can also be used if the port is not available or busy with another application.

(a) Web Based Monitoring of UW Sound Speed.

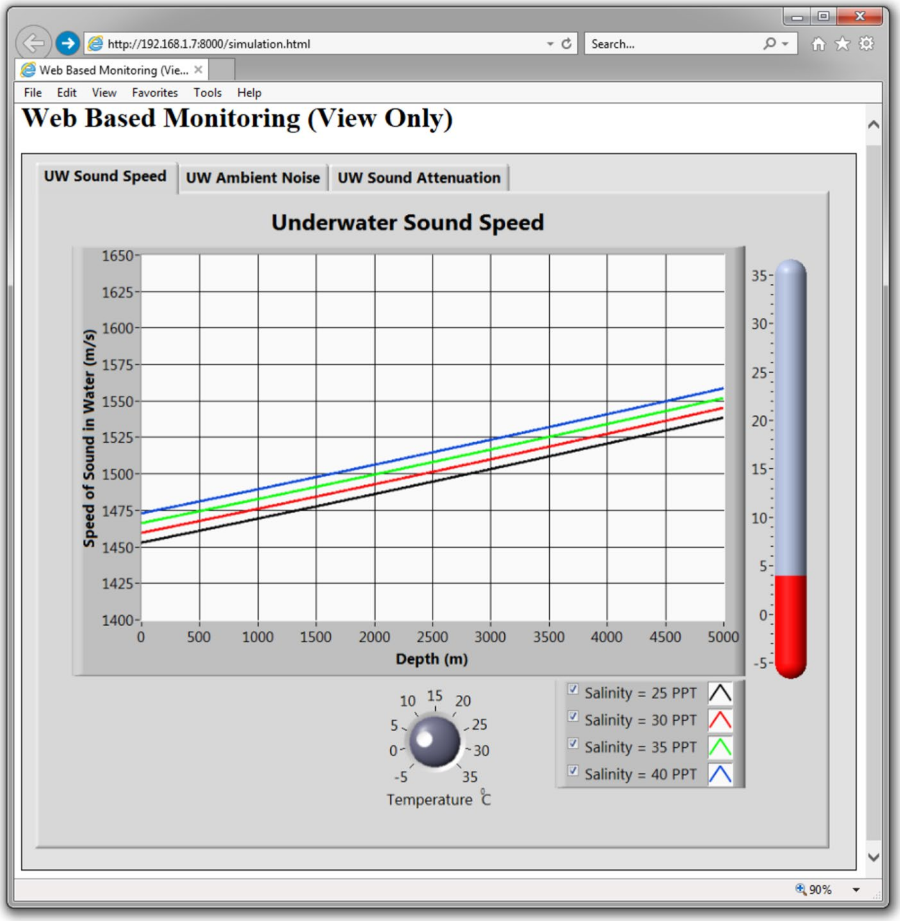

Fig. 11 Underwater sound speed versus depth (Web based monitoring)

Web based monitoring of UW sound speed simulation is shown in Fig. 11. The four graphs are plotted for salinity values of 25, 30, 35, and 40 PPT for the temperature 4 °C to obtain sound speed in m/s versus depth in meters. The temperature value can be adjusted any time before or during the simulation within the range of −5 to 30 °C using the control knob available at bottom of the graph. The temperature can be varied from LabVIEW server and the response can be observed on clients accessing the VI in their browser using URL:

$$\text{http://192.168.1.7 : 8000/simulation.html.} \tag{5}$$

(b) Web Based Controlling of Ambient Noise.

Web based controlling of UW ambient noise simulation in client browser is shown in Fig. 12. The four graphs show the relationship between Turbulence, Waves, Shipping and

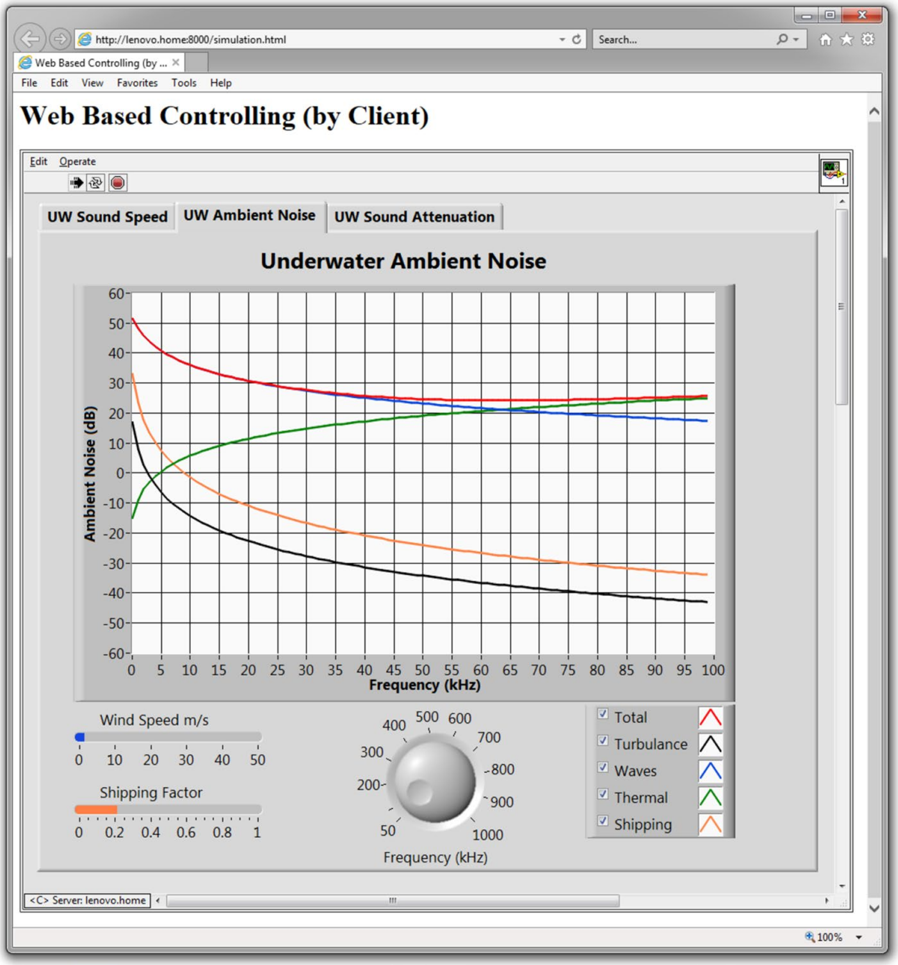

Fig. 12 Underwater ambient noise versus frequency (Web based controlling)

Thermal noise responses in dB vs frequencies in kHz. The total ambient noise graph combines the effect of each factor and displays on the same graph. A remote client can change the frequency range, wind speed from 0 to 50 m/s and shipping factor in the range of 0–1 in real-time to obtain desired results. The parameters can be adjusted by the client and the VI can be observed and controlled by the client in its browser using URL.

$$\text{http://lenovo.home:8000/simulation.html.} \tag{6}$$

5.4 Discussion

A qualitative comparison of proposed design and state-of-the-art UW communication testbeds is presented in Table 1. From the scalability point of view, the testbeds are divided into three groups and arranged according to the testing environment and scalability. The first group includes two large-scale testbeds, i.e., SUNRISE project [20] and SUNSET framework [7]. Both are deployed and evaluated in a real aquatic environment, however, they can also be used in laboratory testing and have simulation facilities. The second medium-scale group comprises of three UW communication testbeds i.e., cross-media network [9], ecological monitoring [18] and UW communication and networking [21]. These are also tested in real aquatic environment i.e., a Lake and harbor, but as compared to the above two they have limited features. The third group of four testbeds DESERT [8], UW-ASN [22], Aqua-Lab [23], and WaterCom [19] are listed along with the proposed testbed, classified as small-scale. Details of the testing environment i.e., real-aquatic environment or laboratory testing and simulation facilities of each group are described below. Table 1, also provides information related to commercial and research UW modems used as part of these testbeds. Finally, the remote accessibility feature of the testbeds for monitoring and controlling is also compared.

The first group consists of two testbeds, SUNRISE project [20] and SUNSET framework [7] used in large-scale scenarios. Both testbeds are deployed in a real-aquatic environment to collect ecological data, and testing of UW networking protocols such as MAC, routing, and cross-layer protocols etc. The testbed hardware supports commercial modems e.g., Evologics using S2C modulation, and research modem such as Micro-modem with FSK and PSK modulations for UW acoustic communication. The SUNSET framework also supports other commercial modems e.g., Kongsberg and Teledyne Benthos. Laboratory testing in a controlled environment i.e., emulation and simulation of UW acoustic channel model and other empirical formulae are the common features of SUNRISE project, SUNSET framework and the proposed testbed. The performance of proposed testbed has been successfully evaluated during environmental data collection e.g. temperature and salinity as an emulator in a laboratory environment using two low-cost UW acoustic modems [5]. We used inexpensive modems that we designed ourselves but other types of modems can also be interfaced with the proposed testbed via standard communication ports. SUNRISE project [20] and SUNSET framework [7] provide a number of features and consists of AUVs, ASVs, ROVs, Buoys, sensor, commercial and research modems and coastal control station, almost a complete solution, available in huge cost. In contrast, our proposed solution which is a subset of above-mentioned facilities is an inexpensive and reliable tool for the research community. Our design is based on LabVIEW which can be used to test UWSNs components, communication systems and UW acoustic modems in a laboratory environment. However, it can be used in real environment with suitable modifications. Simulation of UW

Table 1 Comparison of UW communication testbeds

References	Testbed name	Testing environment	Modems used/tested	Simulation facility	Remote accessibility
[20]	SUNRISE	In field and laboratory	Evologics, Micro-modem	Yes	Monitoring and controlling
[7]	SUNSET	In field and laboratory	Micro-modems, Evologics, Kongsberg, Teledyne Benthos	Yes	Monitoring and controlling
[9]	Cross-media networking	Lake	DSSS modem	N/A	N/A
[18]	Ecological monitoring	Lake	OFDM modem	N/A	Monitoring
[21]	UW comm. and networking	Harbor	Evologics, Micro-modem	Yes	Monitoring and controlling
[8]	DESERT	Laboratory	Evologics, Micro-modem	Yes	N/A
[22]	UW-ASN	Laboratory	UW modem based on ARM9 Processor	N/A	N/A
[23]	Aqua-Lab	Laboratory	Micro-modem	N/A	Monitoring
[19]	WaterCom	Laboratory	AquaSeNT OFDM modem	N/A	Monitoring and controlling
–	Proposed testbed	Laboratory	Low-cost UW acoustic modem	Yes	Monitoring and controlling

empirical formulae and remote accessibility for monitoring and controlling are common features of above-mentioned testbeds and our proposed design.

The second medium-scale group has three testbeds. i.e., cross-media network [9], ecological monitoring [18] and UW communication and networking [21]. The UW acoustic network testbed [9] is used to evaluate cross-media networking and to examine UW networking protocols ALOHA and MACA using DSSS UW acoustic modem. The testbed in [18] collects ecological data such as temperature, salinity, and electrical conductivity using sensors. An OFDM acoustic modem is used for UW communication. Remote access feature is used to present online results. The UW communication and networking testbed [21] is used to evaluate the hardware and software of UW communication systems in conditions similar to a real aquatic environment. Evologics modem using S2C modulation and an FSK version of Micro-modem are used in the testbed for UW communication. It has a simulation facility and can be accessed remotely for monitoring and controlling from the collaborating institutions. Performance of the first two testbeds has been evaluated in a Lake, while the third one has been tested in a harbor. Compared with these testbeds, the performance of proposed testbed has been examined by obtaining UW ecological parameters i.e., temperature and salinity using two low-cost UW acoustic modems [5] in a controlled laboratory environment. The aforesaid testbeds have been used in field testing and no details are available in the research work to use them in a controlled laboratory environment. The proposed testbed has a feature of simulation of UW algorithms and empirical formulae which is not available in these medium scale testbeds excluding the UW communication and networking [21]. Another additional feature of our design is its remote accessibility that enables several clients to monitor and selected clients to control the emulation and simulation in real-time. Only the UW communication and networking testbed has similar features [21]. However, the testbed used for ecological monitoring [18] offers clients to monitor the work and in cross-media network [9] remote accessibility is unavailable.

Finally, the third group of four UW testbeds DESERT [8], UW-ASN [22], Aqua-Lab [23] and WaterCom [19] are classified as small-scale scenarios. The common feature in all designs is the testing procedure using a small water tank inside a laboratory. Among the four testbeds, DESERT [8] uses Evologics and Micro-modem for UW communication, while our testbed uses low-cost UW acoustic modem [5] to obtain the UW ecological data. Another common feature of DESERT and proposed testbed is the simulation of UW algorithms. However, the additional feature of remote accessibility during monitoring and controlling as an emulator and a simulator makes our design superior to DESERT. Another design UW-ASN [22] uses ARM9 processor-based sensor nodes to deploy UWSN testbed in water tank along with temperature and salinity sensors. Our testbed setup and testing procedures are similar to UW-ASN except for the number of nodes, which are more in UW-ASN, while we use two low-cost UW acoustic modems [5]. Our design is superior due to two features namely, simulation and remote accessibility. None of these is present in UW-ASN architecture. In the end, Aqua-Lab [23] uses Micro-modem and WaterCom [19] uses AquaSeNT OFDM modem for UW communication. Similar to our case, the performance of both testbeds has been evaluated in a laboratory environment using a water tank. WaterCom is designed to operate at different levels, but preliminary results are provided using a small-scale configuration. Again our proposed UW acoustic communication testbed offers an edge over the two designs due to the simulation facility which is not available in these testbeds. WaterCom offers the remote accessibility similar to our design for both monitoring and controlling but this is restricted in case of Aqua-Lab in which only monitoring is allowed and no control is available. In addition, development of software-defined networking (SDN) based experimental testbed [27] and simulation software [28] are at their preliminary stages for evaluating the performance of UWSN.

6 Conclusion and Future Work

An underwater acoustic communication testbed is designed. The implementation includes both the simulation and emulation options. An important feature include remote connectivity for the user to run various tests as required. The simulation option is useful in evaluating the system performance and its limitation, while emulation provides real hardware-software test facility in a controlled laboratory environment. As compared to the state-of-the-art underwater acoustic communication testbeds that are usually implemented using high level programming languages, the proposed solution uses GUI designed in LabVIEW. The main features include less development time, low cost and remote monitoring facility. This design can be easily modified and reused to test various types of UW communication systems and algorithms. The remote users can monitor and evaluate the performance of the low-cost UW acoustic modems in real-time using the LabVIEW server based testbed. The platform is used to analyze various UW algorithms. The real-time data and results can be published locally as well as remotely using web browser. The simulation parameters can also be adjusted both locally as well as remotely by authorized users for a given period of time.

In this work, we implemented the testbed as a small-scale configuration. In future, we would like to extend its capacity to evaluate different types of UWSN components, UW acoustic communication systems and UW modems. We would like to include more libraries of UW algorithms for simulation.

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