SURVEY OF AQUASIM-NG: A WIRELESS SENSOR NETWORKS SIMULATION FRAMEWORK FOR UNDERWATER APPLICATIONS

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Abstract—Underwater sensor networks (UWSNs) form a central part of monitoring and observing aquatic environments for environmental monitoring, disaster detection, and oil and gas exploration. Underwater sensor networks play a crucial role in data gathering and communication. Underwater sensor networks, however, experience several challenges, including high propagation delay, low bandwidth, high error, and severe energy constraints. Simulation tools are required. But current simulation platforms do not have robust support for UW communication models such as acoustic communication, node mobility, and energy-efficient protocol design. AquaSim-ng is a dedicated simulation platform for UWSNs. It is based on the NS-3 platform. It has the support of acoustic signal simulation, 3D network deployment, and energy-aware protocol design. Aquasim-ng's customizability, flexibility, and adaptability make it a vital tool for Underwater sensor networks, providing a means through which to combat the limitations of simulations as they are currently conceived.

Index Terms—Underwater Wireless Sensor Networks (UWSNs),AquaSim-NG,Network Simulation, Energy-efficient Protocols,3D Node Mobility,MAC and Routing Protocols, Acoustic Communication

I. INTRODUCTION

Underwater sensor networks are wireless sensor nodes in- stalled underwater to collect and transmit data. Underwater sensor networks have applications in Environmental monitoring, Disaster prevention, oil and gas exploration, and military surveillance. Underwater sensor networks are quite different from land networks. Underwater sensor networks must be designed to save marine life and withstand Underwater conditions. Underwater sensor networks are mainly acoustic communication based due to the fact that radio waves are inefficient propagators in water [1]. Underwater sensor networks are also beset with various problems, including high propagation delay, low Bandwidth, high error rates, and stringent energy constraints. It is difficult to design and implement UWSN protocols because the underwater environment possesses unique features. Testing in real underwater conditions is impossible with high expenses and harsh underwater conditions. Simulation, thus, becomes inevitable to test the UWSN protocol prior to implementation. Tools such as NS-2, NS-3, OMNeT++, GloMoSim, QualNet, or OPNET are aimed at simulating Terrestrial networks [2]. These have a number of limitations if used in Underwater Networks owing to the environment of water. Underwater sensor networks use acoustic communication since radio waves travel badly in water. They are affected by high propagation delay, low bandwidth, and Doppler effects.

MAC and Routing protocols of Terrestrial Networks do not work in Underwater owing to high propagation delay and high packet loss. Due to the limitations, researchers developed some extensions to overcome these limitations. AquaSim-ng is an Underwater sensor network simulation tool that is specifically designed to assist an Underwater sensor network based on the NS-3 framework to facilitate the Underwater sensor Network. AquaSim-ng provides acoustic signal simulation and energy-efficient Networking. The major contributions

of AquaSimng are the simulation of acoustic signal communication, energy saving protocol support, and leads in efficient MAC and Routing protocol development [3].AquaSim-ng tries to provide
a tunable and modular simulation of UWSNs. The system also promotes integration of new UWSN applications and 3D Network Deployment. The primary aim of AquaSim-ng is to provide a power-efficient and reliable platform for UWSNs. It
allows testing and optimization of new protocols in real-world before actual application.

II. SIMULATION TOOLS

A. NS-2

NS-2 was one of the first open source discrete event network simulators, which was widely used to simulate wireless and wired networks. [2] NS-2 was written in C++ with an OTcl scripting language, in which the user could configure network simulations easily. NS-2 was then used to simulate UWSNs, employing an acoustic propagation model, energy consumption frameworks, and UWSN-specific protocols. Its two-language architecture made it hard to debug and mod-
ify. Besides, NS-2 is no longer maintained, leading to stale architecture and poor scalability and thus not appropriate for large-scale simulation of underwater networks. This drawback has led to the use of more advanced simulators like NS-3 by researchers.

B. NS-3

Network Simulator 3 (NS-3) was created as a more scalable, modular, and debuggable replacement for NS-2. As opposed to NS-2, NS-3 is written entirely in C++ with Python bindings, making it a more versatile simulation platform. To model underwater networks, NS-3 offered the Underwater Acoustic Network (UAN) framework, such as underwater channel models, PHY and MAC layers, and AUV mobility.

The platform can execute several acoustic propagation models, some of which include the Ideal Channel Model (zero path loss assumption), the Thorp Model (executing Thorp's empirical formula for acoustic attenuation), and the Bellhop Model (executing ray tracing techniques to accurately model underwater propagation) [2]. NS-3 also supports sophisticated visualization tools like NetAnim and packet capture (.pcap) file generation to be run using tools like Wireshark. NS-3 is more computationally intensive and harder to learn than NS-2 but is also more scalable and accurate.

C. Aqua-Sim (NS-2 Extension)

Aqua-Sim, which is an added module to NS-2, was developed by the UWSN Lab to especially simulate underwater sensor networks. Aqua-Sim featured all the upgrades of NS-2, [4] including acoustic signal models of attenuation, packet resolution collision, and support node placement in three dimensions. NS-2's single package for wireless simulations, unlike Aqua-Sim, is executed as a stand-alone module to allow for changes without affecting terrestrial network simulations.

The simulator consists of four components: uw-common (manages sensor nodes and water traffic), uw-mac (offers MAC protocols and acoustic channels), uw-routing (offers underwater routing protocols), and uw-tcl (executes OTcl test scripts for testing). Aqua-Sim includes Underwater Node (a model of an underwater sensor node) and Underwater Channel (a model of an acoustic channel). But since AquaSim is built over NS-2, it also inherited its limitations, such as poor scalability, outdated architecture, and inadequate debugging support. For these reasons, researchers now have better alternatives with NS-3 for underwater network simulation on a grand scale.

D. AUVNetSim

AUVNetSim is an open-source Python simulator dedicated to underwater acoustic networks, particularly autonomous underwater vehicles (AUVs). Unlike NS-2 and NS-3 general purpose simulators, AUVNet Sim is dedicated to acoustic networking protocols and AUV communications. AUVNet Sim provides pre-configured networking protocols as well as environmental scenario conditions and provides researchers with an opportunity to experiment and test different underwater networking scenarios. However, AUVNetSim suffers because
of Thorp's propagation model that it uses for the simulations. That limits the potentialities to modeling only the water environments where there are varying levels of temperature, salinity, and varying pressures. It has become restricted thereby through resulting variations by simulated environments when compared with

field applications. Although limited, AUVNet-Sim is still used to a great extent since it is easy, convenient, and extremely flexible for quick prototyping, and is suitable for researchers who require an easy-to-use environment for underwater simulations.

E. UWSim

UWSim is an underwater simulation tool for robotics and visualization and not for network simulations. It is developed using C++ with the assistance of OpenScene Graph and os-gOcean libraries. UWSim provides a very flexible interface to simulate underwater robotic systems. It can incorporate sensors, actuators, external software, and AUVs and hence is very suitable for AUV research in marine robotics. One of the good points about UWSim is that it can simulate a number of AUVs in one simulation session, which researchers utilize to see cooperative underwater vehicle behavior. Dynamic rigid-body motion simulation using a state-space dynamic model is also provided by UWSim, which can effectively simulate AUV motion, environmental noise, and object collision. However, UWSim lacks native support for networking simulation, and therefore researchers must integrate it with other external packages like NS-3 for networking simulations. In spite of this limitation, UWSim remains one of the best tools for underwater robotics visualization.

III. AQUASIM-NG OVERVIEW

Aqua-Sim-NG is a high-performance simulator for under- water networks that is built as an extension of NS-3 to address the limitations of its earlier version, Aqua-Sim for NS-2. Aqua-Sim-NG provides a very efficient, scalable, and modular simulation platform for UWSNs. It leverages the strong simulation engine, improved event scheduling, and more sophisticated debugging facilities of NS-3 to provide better performance, realistic modeling of underwater communication, and support for large-scale networks. Underwater communications are beset with problems such as high delay propagation, low bandwidth, and severe energy depletion. Aqua-Sim-NG overcomes such problems by employing advanced acoustic channel models, energy-saving protocols, and 3D mobility for underwater nodes [5]. This makes it a robust tool for underwater monitoring, surveillance, and oceanographic data gathering.

Aqua-Sim-NG is layered and modular in design, enabling flexibility and scalability for simulating underwater networks.

The simulator consists of a number of core modules, each responsible for handling one layer of the network stack.

Modularity in Aqua-Sim-NG gives researchers the ability to construct and experimentally verify new underwater communication protocols without affecting other components of the system. The NS-3 integration enhances simulation speed and real-time event handling along with multi-layer communication support, i.e., application, transport, routing, MAC, and physical. Mobility module and energy management introduce realistic underwater node behavior by taking ocean currents into account as well as power constraints. Tracing and visualization functions provide real-time glimpses of network performance, and thus Aqua-Sim-NG is a valuable research environment for underwater networks.

Aqua-Sim-NG is constructed on top of modular and layered architecture, supporting flexibility and scalability when simulating underwater networks. Each core entity manages a specific network layer such that researchers are able to augment or modify functions without affecting the whole system.

The systematic aspect allows for improved implementation and verification of new underwater communication protocols with greater ease without sacrificing simulation accuracy and performance.

A. features

1) Acoustic Channel and Propagation Models: Aqua-Sim- NG's greatest strength lies in its acoustic channel model, which simulates the realistic underwater communication with consideration to major issues including signal attenuation, propagation delay, and noise interference. In comparison to wireless networks on land, underwater communication exploits acoustic signals that are plagued with common problems of high delay and energy loss. Aqua-Sim-NG features a number of propagation models, including the Ideal Model (no signal loss is simulated), the Thorp Model (from Thorp's empirical frequency-dependent attenuation equation) [2], and the Bell- hop Model (a ray-tracing-based model with multipath effects and refraction of signals).

These models enable researchers to contrast different underwater scenarios, ranging from controlled laboratory environments to highly dynamic oceanic environments.

2) Medium Access Control (MAC) Layer: MAC layer of Aqua-Sim-NG is an energy low channel access mechanism that is power-aware in nature, making it minimize power consumption as well as reduce the collision rates. Long propagation delay of underwater communications and the restricted bandwidth of it make the MAC protocols used on the ground classical. Aqua-Sim-NG offers multiple MAC protocols developed specifically for underwater networks, [5] like Carrier Sense Multiple Access (CSMA), Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Slotted ALOHA. It also supports hybrid MAC techniques that switch automatically between various MAC techniques based on network conditions. These mechanisms enhance network efficiency by reducing packet collisions, ensuring maximum bandwidth utilization, and extending node battery life.

3) Routing Protocols: Routing is essential to ensure energy-efficient and stable data transmission for underwater networks.Aqua-Sim-NG implements multiple routing protocols in view of underwater constraints like node mobility, depth variation, and dynamic topology variation. Among the most important protocols used are Vector-Based Forwarding (VBF) to minimize redundant transmissions by a given forwarding vector, Depth-Based Routing (DBR) using depth information to choose forwarding nodes to minimize transmission paths, and Cluster-Based Routing, where nodes are organized into clusters to minimize communication overhead as well as network lifetime. These delay-tolerant and power-efficient routing protocols promote data transmission reliability with reduced power usage, and therefore, Aqua-Sim-NG is applicable for large-scale underwater sensor networks.

4) Transport Layer Mechanisms: Established transport protocols like TCP will not function in oceanic environments because they will not be able to tolerate huge latencies or huge packet loss rates. Aqua-Sim-NG has proprietary transport layer functionality that enhances reliability and efficiency further. UDP support as an option is also provided, best suited for scenarios which need to make real-time deliveries and are willing to compromise on guaranteed delivery but not excessive latency. It is also designed with error recovery capability to limit packet loss and adaptive transmission control for dynamically regulating the data rates in relation to channel condition to achieve maximum throughput. All these transport layer features enable efficient communication for undersea applications like remote sensing, real-time monitoring, and oceanographic data acquisition.

5) Mobility and Energy Management: Mobility and Energy Management Aqua-Sim-NG facilitates true 3D mobility models, and Autonomous Underwater Vehicles (AUVs), floating nodes, and static underwater sensors are simulatable. Because underwater nodes are influenced by ocean currents and environmental factors, ocean current models impacting network connectivity and topology are facilitated by the simulator.

Energy efficiency is also an important part of underwater sensor networks since the replacement or charging of batteries is usually not feasible. Aqua-Sim-NG prefers energy management techniques that aim to maximize network lifetime.

These are sleep scheduling, in which nodes can change to low-power states when inactive, adaptive power control, where transmission power changes dynamically based on distance and channel conditions, and energy-efficient MAC and routing protocols that conserve the battery. These features enable Aqua-Sim-NG to simulate real underwater networks where power saving is critical.

6) Simulation Control and Visualization: Simulation Visualization and Control Aqua-Sim-NG offers real-time debugging and performance analysis facilities, which help researchers track and analyze network behavior more conveniently. Unlike previous simulators that supported static trace files, Aqua-Sim-NG offers real-time visualization, under which packet transmission, network traffic patterns, node mobility, and energy consumption can be tracked in real-time. Moreover, Aqua-Sim-NG offers third-party data export to environments like Wireshark, MATLAB, and Python environments for thorough analysis of performance. Visualization and monitoring capabilities greatly add to usability and accuracy in simulation of underwater networks.

Aqua-Sim-NG offers a powerful platform for researchers to deploy, test, and simulate underwater network protocols in a realistic and scalable environment by integrating good control of simulation, real-time monitoring, and powerful analysis tools.

B. Advantages

Aqua-Sim-NG brings about several improvements over Aqua-Sim for NS-2, such as improved scalability, efficiency, and realism of simulated underwater networks. Aqua-Sim-NG, built atop NS-3, enjoys improved memory management, scheduler improvements, and bigger debugging capabilities, making the simulation more stable and scalable. It also supports several acoustic propagation models in addition to the standard Thorp model, with the addition of Bellhop and fading models that make it even more realistic. In contrast to AquaSim for NS-2 that supported only selective MAC and routing protocol features, Aqua-Sim-NG provides a wider energy- saving MAC and routing protocols feature to researchers for more accurate emulation of next-generation underwater environments. Additionally, realistic 3D mobility and so- phisticated energy-conserving mechanisms improve network lifetime and performance, eliminating major challenges in UWSNs. The NS-3 integration also has the ability to perform real-time debugging, external support for visualization tools, and hardware-in-the-loop (HIL) testing, and so Aqua-Sim-NG is a more realistic relevent solution for underwater network research.

IV. SIMULATION FEATURES

Aqua Sim-NG is an underwater sensor network simulation platform in the form of a wireless sensor network simulation platform that can emulate UWSNs in the NS-3 framework [3].

There is no other network simulator capable of dealing with the complexity of communication underwater, i.e., large prop-

agation delay, low bandwidth, and power limitation. It is superior to current simulators since it offers an increased scalable and flexible platform to test the protocols. Another aspect of AquaSim-NG is the modeling of underwater commu- nication. RF waves and light signals do not travel well under- water. Thus, UWSNs use acoustic waves for communication.

AquaSim-NG models these acoustics like signal delay, multipathing, and Doppler shift to model real-world conditions underwater. It facilitates the study of how the mobility of nodes and the environment impact data transmission.

Energy efficiency is another central aspect of UWSNs because of the limited capacity batteries in underwater sensor nodes. AquaSim-NG supports power control operations to different transmission power against node distance and emulates battery drain over time. It also supports sleep cycles

as well as packet forwarding efficiency and helps in designing energy-efficient communication protocols to ensure maximum network life. AquaSim-NG emulates mobility challenges in underwater networks. Underwater nodes are not stationary like ground nodes; they are transported by ocean currents, waves, and tides. The simulator accommodates three-dimensional

(3D) mobility models emulating realistic underwater node mobility to assist researchers in examining the impact of topology change on data delivery and routing. Underwater communications are plagued by channel noise, signal attenuation, and propagation delay. AquaSim-NG com-

putes acoustic signal propagation time, frequency-dependent loss, and environmental noise interference from human activity and marine animals based on models. All these facilitate more precise measurement of network performance in the real world. In analysis, AquaSim-NG offers logging as well as visualization. It generates comprehensive logs of transmission, energy consumption, and packet delivery. It further accom- modates packet tracing, with the help of which researchers are capable of watching data flow and identifying congestion spots. AquaSim-NG further includes NS-3 visualization functionalities to facilitate real-time and after-simulation investigation of such significant performance metrics like end-to-end delay, packet delivery ratio, and network throughput. In totality, [5] AquaSim-NG is a comprehensive and realistic UWSNs simulation tool. With the features of acoustic communication emulation, power-saving mechanisms, mobility support, and performance analysis tools, it allows researchers to design and test innovative underwater network protocols. Its capability of simulating realistic underwater environments

makes it an essential tool to drive underwater wireless communication technologies.

V. APPLICATION

Aqua Sim-NG is a Handy tool to simulate underwater wireless sensor networks (UWSNs) that possess numerous real-world applications. By providing a real-world simulation setup, AquaSim-NG allows researchers to implement and test novel network protocols for underwater communication.

Certain key areas where AquaSim-NG is helpful are described below [3]. One of the principal uses is environment monitoring and forecasting disasters. UWSNs are used extensively to monitor oceanic conditions, water conditions, and climate patterns. Ocean sensors are used to monitor parameters like temperature, salinity, and levels of pollutants, enabling scientists to research climate patterns and identify deleterious changes like oil spills or toxic algal blooms. Moreover, underwater networks have a vital role to play in the earthquake and tsunami early warning systems, capable of providing timely warnings that can save lives and reduce damage. Underwater surveillance and exploration is one of the largest applications.

Research institutions and governments employ UWSNs for security, naval defense, and oceanic life studies. Sensor net- works can be deployed to identify submarines, underwater mines, and illegal entry in banned waters. Sensor networks aid in monitoring marine life, fish migration patterns, and deep-sea ecosystems without causing any disturbance in the natural habitat in marine biology [6]. AquaSim-NG can be used in oil pipeline and infrastructure monitoring. Submarine pipelines, oil platforms, and sea-based wind farms must be continuously monitored to prevent leaks, structural collapse, and corrosion. UWSNs provide real-time feedback regarding the condition of these structures, reducing the possibility of environmental disasters and improving maintenance effectiveness. For offshore drilling, underwater sensor networks can help identify pressure fluctuations, gas leaks, and equipment faults, ensuring operations are safer. Overall, AquaSim-NG facilitates the design of robust and effective UWSN protocols, thus it is a critical tool for underwater technological advancement. By simulating real-world issues such as signal fading, mobility, and limited energy, AquaSim-NG enables researchers to conceive solutions to enhance underwater communication and monitoring systems.

property	AquaSimng	AquaSimNs2	Ns2	Ns3	AUVNetSim	UWSim
Framework	Ns3	Ns2	Standalone	Standalone	MATLAB	ROS
PrimaryPurpose	UWSNsimulation	UWSNsimulation	GeneralNetwork simulation	GeneralNetwork simulation	AUVbasedUWSN research	UnderwaterRobotics visualisation
Modularity	High	Limited	Low	High	Moderate	High
Scalability	High	Limited	Limited	HIgh	Moderate	Low
Easeofuse	Moderate	Complexsetup	Moderate	Complexsetup	Moderate	UserfriendlyGUI

TABLE I
COMPARISON OF SIMULATORS

VI. COMPARISON

AquaSim-NG (NS-3) is the most suitable simulator for simulating underwater wireless sensor networks (UWSNs). It has scalability, energy-efficient modeling, and realistic acoustic communication, which are most suitable for underwater network studies. AquaSim-NG is more flexible and precise compared to its earlier versions. AquaSim (NS-2) continues to be applied in UWSN research but is outdated and sub-standard currently. NS-2 is another network simulator that can be utilized for general-purpose simulation without anyunderwater communication facility and therefore continues to be substandard in underwater research. NS-3 is a newer, more generic network simulator than NS-2. However, it lacks native support for underwater networks. UWSN researchers need to incorporate extensions such as AquaSim-NG in order to make it useful for their study. AUVNetSim, which is MATLAB-based, aims to simulate AUV motion and network simulation but isn't protocol-specific. UWSim is principally for underwater AUV visualization and robotics and thus more suited to robotic applications than network simulation. For underwater network studies, AquaSim-NG would be ideal. To simulate general networks, NS-3 would be ideal. If one wants to study the

movement and action of AUVs, both AUVNetSim and UWSim are ideal I.

VII. CHALLENGES

AquaSim-NG is a strong simulation tool for underwater wireless sensor networks (UWSNs) but is also not without certain limitations that impact its Functionality and Coverage. Overcoming such limitations can further enhance its capabilities and extend its use to underwater communication research. One of the main concerns is the support of specific protocols. Though AquaSim-NG is capable of supporting diverse underwater routing and MAC protocols, it is not able to support all current and new UWSN protocols. Researchers who want to try and apply new protocols should have to tweak the simulator, which is time-consuming. Adding more routing, MAC, and transport layer protocols to the protocol library would make AquaSim-NG more flexible and decrease development effort. Another disadvantage is the installment and setup complexity. AquaSim-NG is developed on NS-3, which is a challenging platform to master. Simulator installation involves manual dependencies, compiling, and environment setup, which is weary for newcomers. Documentation improvement, pre-installed package installments, and incorporating a GUI for simplified configuration would enhance usability. Subsequent studies in AquaSim-NG can involve the inclusion of energy-aware, machine-learning-based, and security-oriented UWSN protocols into libraries of protocols.

Researchers can then implement the latest improvements with- out the need for extensive customizations. Another potential

enhancement is incorporating real-world hardware support.

As it stands, AquaSim-NG has simulations alone, and a gap between simulation and real deployment would be valuable.

Including underwater modem support, AUV support, and IoT-based underwater sensors would allow AquaSim-NG to perform hybrid experiments combining both simulation and

real-world testing. Lastly, it is important to enhance AquaSimNG to handle simulations of large scales. As UWSNs become larger and more complex, it may be costly computationally to run large-scale simulations with numerous nodes. Parallel processing, cloud computing simulations, and memory management efficiently would enhance performance and make possible the simulation of thousands of underwater nodes without much delay. Finally, though AquaSim-NG is a solid ground to conduct UWSN research, solving these problems can also make it further enabled. Based on the progress of protocol support, installation ease, hardware support, and optimization of large-scale simulation, AquaSim-NG can still remain a useful tool in promoting underwater communication technology.

VIII. CONCLUSION

AquaSim-NG Plays a Critical role in promoting underwater wireless sensor network (UWSN) research through providing a realistic and effective simulation platform. Its support for underwater acoustic communication, energy-efficient mechanisms, and sophisticated mobility models makes it a critical tool for UWSN protocol and network performance evaluation. In comparison to previous simulation platforms, AquaSimNG provides better scalability, flexibility, and accuracy, allowing researchers to investigate novel solutions to underwater communication issues. By incorporating prominent features

like acoustic propagation modeling, energy-awareness, and three-dimensional mobility support, AquaSim-NG is greatly contributing to underwater network research. Its compatibility with NS-3 makes it more realizable, allowing researchers to design next-generation UWSN protocols based on it. Its scope and possibility for growth make Aqua Sim-NG a resource from which the UWSN community can gain. Promoting its use will make developments in underwater networks efficient and more efficient communication systems are generated for deployment in applications including environmental monitoring, underwater exploration, and disaster warning.

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