Modeling Underwater Communications in Live, Virtual and Constructive Environments

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ABSTRACT

Underwater communication networks (UCN) are enablers of current and future military and commercial applications involving undersea exploration, monitoring, and surveillance. Unmanned Underwater Vehicles (UUVs) hold promise for stealthy low-cost surveillance, particularly in areas where manned undersea platforms cannot be easily deployed, operated, and maintained. Aiming to extend the operational lifetime of UUVs, underwater hubs are being developed for charging UUVs and exfiltrating data from UUVs. As the number and heterogeneity of undersea platforms and infrastructure expected to operate in concert continuous to increase, command, control and coordination of undersea platforms, and timely and secure transfer of data become increasingly important.

UCNs face an inherently disconnected, interrupted and low-bandwidth operational environment and often require specialized protocols for supporting reliable transfer of data. Furthermore, different communication technologies being considered for undersea applications, such as acoustic, optical, and RF communications, have different, yet complementary, characteristics in terms of propagation delay, communication range, and bandwidth. Characterization of the performance of a UCN is critical to avoid unexpected operational disruptions. Yet, in-water experimentation is restrictive and costly, and often cannot be performed in an environment similar to where the UCN deployment is planned. Network modeling and simulation tools offer a low cost alternative for characterizing the performance of a UCN. Unfortunately, most commercially available network simulators designed for modeling wired and RF-based wireless networks are not well suited for modeling UCNs.

This paper describes UCN-X, a scalable UCNs simulator that can be used to investigate real-time underwater command and control, data transfer and exfiltration. UCN-X leverages parallel discrete-event model execution and system-in-the-loop interfaces from EXata, to provide a scalable, live, virtual, constructive (LVC) UCN simulator that can interface with live modems and mission operation and management software applications. UCN-X captures undersea signal propagation effects obtained based on the characteristics of the undersea propagation environment and a diverse set of protocol models at all layers of the communication stack. It additionally includes store-and-forward protocol, data muling, and air/water gateway node models.

To support its use within a system-of-system context, UCN-X can be federated with other simulators including force-force training environments to provide realistic undersea communication modeling. UCN-X can also be interfaced with live and unmodified UUV command-and-control (C2) software. By providing a realistic representation of the dynamic network performance under realistic operating conditions, such a federated model provides a rich and extensible training capability for both military and commercial applications.

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A Modelling and Simulation Framework for Underwater Communication Networks

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INTRODUCTION

Underwater communications and sensor networks, particularly those involving mobile and potentially unmanned assets, are finding increased use in many application domains. Emerging civilian and military applications include unmanned underwater exploration, underwater pollution monitoring, oil extraction, aquaculture, and undersea infrastructure monitoring. Development of advanced undersea wireless communication technologies is, thus, clearly slated as an area for future expansion. In support of sustaining manned and unmanned operations in the underwater domain, researchers have investigated and experimented with many innovative, expeditionary solutions to various operational aspects including communication signal types, networking protocols, and the overall hardware and software infrastructure that would be necessary for supporting extended and autonomous undersea operations (Chitre, Shahabudeen, Freitag, & Stojanovic, 2008) (Pompili & Akyildiz, 2009). Given the complexity of the undersea environment, the challenges associated with undersea experimentation, and the need to interconnect undersea platforms with surface and air platforms, a comprehensive modeling and simulation (M&S) framework can provide significant value for design and analysis of undersea communication networks (UCNs). With the growing range and diversity of applications (Felemban, Shaikh, Qureshi, Sheikh, & Qaisar, 2015) that employ UCNs, particularly those using unmanned assets, there is also a significant need for UCN simulators that can be used for training under realistic operating conditions in both military and civilian contexts.

This paper introduces UCN-X, a novel M&S system for UCNs based on the EXata network simulator (Scalable Network Technologies). UCN-X is a scalable live, virtual, constructive (LVC) UCN simulator that can be used for simulation of end-to-end communications over a network that spans underwater, afloat, ashore, air and space-based assets (Scalable Network Technologies). UCNs face several challenges that can affect the operation of the various communication modalities (Heidemann, Stojanovic, & Zorzi, 2012). For instance, undersea acoustic communications suffer strong signal attenuation, low bandwidth, low propagation speed, multipath, and time varying channel quality. Undersea optical and RF communications cannot support long-range communications at operationally useful data rates. The spatiotemporal variability of the undersea environment, and the sensitivity of acoustic and optical communication technologies to the environment require that UCN-X accurately captures the effects of the environment on the performance of the various modes of communications used in a specific mission. This is particularly important for undersea acoustic communications where depth dependence of temperature, pressure, and salinity define the acoustic sound-speed profile (SSP), thereby dictating the path losses and interference experienced by any acoustic communications system.

Most underwater network simulators primarily intended for use in academic research have been developed using open-source simulators (Raj & Sukumaran, 2015). Some widely used undersea network simulators include DESERT (DESERT Underwater) and SUNSET (SUNSET). UCN-X expands on the existing suite of UCN simulators by leveraging a parallel commercially-of-the-shelf (COTS) network simulator, EXata (Scalable Network Technologies), to provide a robust, scalable and easy-to-use M&S capability that can be easily interfaced with existing UUV navigation and operations simulators. In addition to modeling a diverse set of protocol alternatives at the physical, MAC, network, and transport layers, UCN-X also models the relevant set of environmental factors that impact underwater signal propagation. A Mission Operation & Management (MO&M) model - a composable and extensible application layer model is provided to support realistic modeling for various operation and management functions of UCNs, including health-and-status reporting, data storing, and "carry and forward" functionality using data mules.

An important objective for UCN-X is to support its use in a system-of-systems context, where the UCN simulator can be federated with other simulators as well as with unmodified operational software. UCN-X has been interfaced with force-force training environments, which alone assumes perfect communications among platforms. By providing a realistic representation of the time varying and dynamic performance of UCNs under realistic operating conditions, such a federated model provides a rich and extensible training capability for both military and commercial applications. By interfacing with UUV navigation and mobility simulators, and C2 applications, UCN-X can also provide a rich training and analysis framework for operational missions that include a mix of manned and unmanned assets.

UCN-X can interact with external simulators and federations using a variety of standard interoperability solutions that include High-level Architecture (HLA) (Carrera, Tremori, Caamano, Been, Crepso Pereira, & Bruzzone, 2016) and Distributed Interactive Simulation (DIS). UCN-X can also use BSD socket I/O to interface with selected other federations, such as OneSAF (ONESAF).

Networked devices can be directly mapped into a UCN-X simulation, allowing live data to travel through the simulated network, and allowing simulated network data to be sent to live equipment. Software outside of UCN-X can interact with elements inside the simulation via socket or Robot Operating System (ROS) message passing. These features allow for collaborative and iterative system development, where prototype or simulated components of the system are replaced seamlessly with live software modules as they become available.

The rest of the paper is organized as follows. The next section is an overview for the UCN-X simulator. This is followed by a presentation of specific models in UCN-X developed for modeling UCNs. The next section presents some initial simulation results obtained from UCN-X models. The paper concludes with a summary.

UCN-X OVERVIEW

UCN-X is built upon the EXata network simulation framework. The following features of EXata are relevant to underwater communication:

a. Operation in both real-time mode when interfaced with virtual or live systems, and pure constructive mode where the simulation model can run as fast as possible, typically many times faster than real-time.
b. Direct interface with external applications, humans, and live systems.
c. Parallel model execution to support representation of scalable networks operating over large regions with potentially thousands of objects.
d. Dynamic computation of propagation path loss reflecting environmental factors relevant to the communication modality: RF, acoustic, or optical.
e. A modular and extensible set of models of wired and wireless networks and devices for military and commercial networks.
f. Analysis and evaluation of network performance for operational mission threads with comprehensive statistics data collection and report generation.
g. Visualization of the simulation from both operational and network-level perspectives with the ability to interface with third-party visualization tools.
h. GUI-based scenario creation and re-use.
i. Models for dynamic or scripted entity mobility including entity position updates from external federations.
j. Models for battery depletion and recharging.

UCN-X leverages these features from EXata and has developed a set of underwater specific features to support modeling of UCNs in a realistic operational environment for end-to-end network analysis and assessments, and training of network operators and managers.
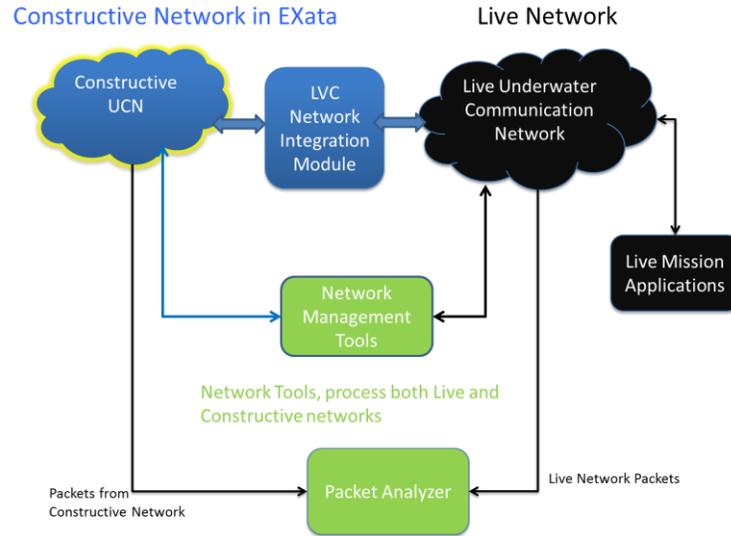
LIVE, VIRTUAL, CONSTRUCTIVE UCN MODELS IN UCN-X

The choice of specific architecture, hardware and software in an underwater system is a domain-dependent application or use-case driven decision. Nevertheless, in the case of the communication paradigm, a network system usually consists of data producers, data transporters, data consumers, and optional data aggregators. The transporter is responsible for transferring data from producers to the consumer. For example, in a marine life monitoring application, an underwater communication network could consist of many sensors installed on the sea basin with adjustable cables serving as data producers. In other cases, UUVs may serve as data transporters that retrieve the collected monitoring data to a "warehouse" data aggregator, which could be another outpost deployed underwater. This outpost may preprocess and repackage the data as needed. Further data transportation could happen between the "warehouse" outpost and the final data consumer (*e.g*., software system operated by a human in a control center) through various means (such as RF, optical fiber, satellite), with the aid from other types of transporters using a variety of technologies (buoys, underwater vessels, surface ferry/ships and airplanes). A network entity may take multiple roles in the system, *e.g.,* a UUV can be a data producer and a data transporter.

To generalize the above supply chain paradigm in UCN-X we postulate a generic UCN as an underwater network of outposts and fixed/limited mobility sensors together with mobile underwater vehicles that include both manned and unmanned objects as well as surface platforms that serve as gateways for communication with aircraft relays or remote command centers using satellite communications. UUVs act as data ferries that collect data from some sensors via acoustic or free-space optical data links (FSO) and deliver them to an outpost or directly to a surface platform. Outposts communicate with each other using fiber links and with nearby sensors using acoustic data links. The outposts act as throw-boxes in charge of aggregating data from nearby acoustic sensors. Data can be transferred from outposts to a command center via UUVs or a gateway node supporting a connection through the air-water interface. Multiple outposts either partially/fully connected or disjoint could also be deployed to expand the service area of the application. For simplicity, we consider the outpost to be fixed in this paper, but it does not exclude the cases of an outpost being maneuvered to adjust its location.

A primary objective of UCN-X was to support the development of scalable LVC models that are suitable for both system analysis and training. The goal with LVC models is to directly interface constructive entities with live and virtual lab-based units to form a "hybrid" network. Along with "at operational scale" deployments, LVC models allow configuration of complex scenarios such as deep sea operations where the constructive domain can be employed to simulate the deep-sea areas and complex network layout, while the live domain can be used to interface operational software and hardware on ashore units and at the control center.

Figure 1 shows a potential use case of the LVC environment for underwater communication system. On the left is the constructive network of UUVs, outposts, sensors, control centers with the underwater communication and networking models. One the right is a live underwater communication network formed by live UUVs, sensors, outposts in a laboratory or field settings. The live and constructive networks are bridged with hardware-in-the-loop interfaces that enable the seamless integration of the constructive and live networks. Industry standard tools including packet sniffers, packet recording and analysis, and network management (*e.g*., Wireshark, Openview, SolarWinds) can be used to transparently monitor data regardless of whether it originated from the constructive or live network.

Figure 1. Live-Virtual-Constructive Environment for Underwater Communication

UCN-X uses the Open System Interconnect (ISO, 1994, revised 1996) conceptual model of a communications network to provide a modular and extensible set of models that span multiple layers of the protocol stack (see Figure 2). Several of the layers of the models are modified to represent the properties of the underwater environment. UCN-X includes a cross layer information sharing module which allows information obtained at one layer can be used by other layers in their network operation decision. For example, the network layer makes routing decisions based on the quality of the channel.
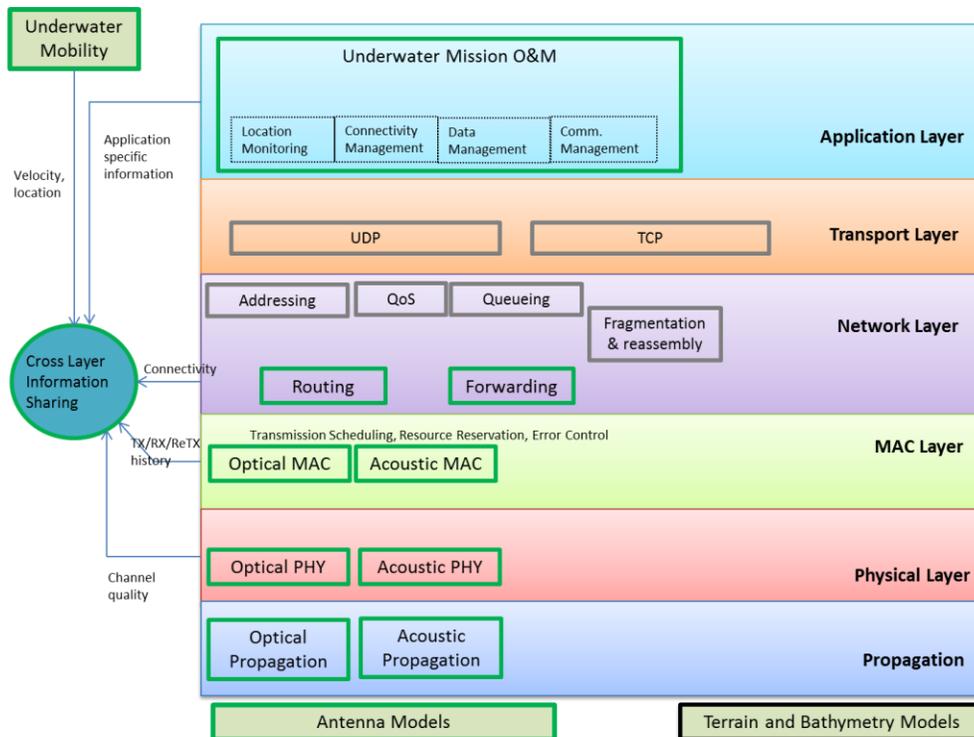
Figure 2. OSI Conceptual Model for UCN

The physical media for OSI are modelled by the propagation equations of the signal energy within the medium. For example the absorption of sound in sea water is a function of the sound frequency. A simulation does not need to be

concerned with pin or cable specifications of the physical layer, however, any impact on the signal within the media must be modeled. The primary concern of a physical layer model is the impact of noise and interference on the signal. This is captured as a signal to interference and noise ratio (SINR), which allows the model to calculate the bit error rate (BER) for the particular modulation and coding scheme.

The data link layer includes media access control (MAC) and logical link control (LLC) components. It is primarily responsible for controlling which devices can transmit on the medium. The long propagation delay of underwater acoustic environment offers unique challenges for the MAC.

A UCN requires network and transport layers that can perform efficiently in a rapidly changing environment. This requires capabilities like disruption and delay tolerant networking (DTN), message store and forward protocols, and dynamic routing.

Signal Propagation Models

Underwater acoustic communications faces several unique challenges (Chitre, Shahabudeen, Freitag, & Stojanovic, 2008) (Pompili & Akyildiz, 2009) (Heidemann, Stojanovic, & Zorzi, 2012). The speed of sound in water is a function of salinity, temperature, and pressure, all of which vary with depth. Hence, sound bends as it propagates through the water. Additionally, multipath fading and ambient acoustic noise sources degrade the acoustic signal quality at receivers. Similarly, underwater optical signals are impacted by both absorption and scattering of the light (Mobley) and ambient light sources can be scattered into the beam.

Ultimately, communication range depends on the signal to interference and noise ratio (SINR) at the receiver, the demodulation scheme, and the acceptable error rate. The propagation layer models of UCN-X provide the ability to model all the previous characteristics as they affect underwater signal attenuation.

Physical Layer Models

UCN-X provides the following features in both Acoustic Physical Layer Model and Optical Physical Layer Model.
- Signal transmission process with indicated coding and modulation scheme by the host
- Signal reception process with SINR calculation and packet error checking

Acoustic Physical Layer Model can be readily extended to support any other modulation and coding schemes used in typical COTS acoustic modems.

The Optical Physical Layer Model support the following modulation used in FSO communications: OOK, M-ary PPM, and M-ary PAM.

MAC Layer Protocol Models

The data link layer models the MAC, packet synchronization, flow control and error checking protocols. Several MAC layer models are currently available, *e.g.*, slotted Aloha, CSMA and others.

Application Layer Models

In addition to directly interfacing with external applications, UCN-X provides the ability to model realistic control and payload data traffic for UCNs. A generic mission operation and management (MO&M) application model has been developed to provide an extensible and scalable application framework for UCN operations. The MO&M models the offered load for a variety of functions that include payload generation, store–carry-forward and store-forward type of payload transfer. The MO&M model was designed to model multi-modal communications with platforms equipped with the corresponding modems and communication interfaces. The model has been designed such that the most suitable communication interface (either acoustic, optical or fiber optical) is used based on the current communication context (*e.g.*, location and traffic types). The model has been designed to be extensible, and new modules or features can be easily added for new use cases or applications.

EXAMPLE UCN-X USE CASE

A simple underwater mission scenario is used to demonstrate the M&S capabilities provided by UCN-X. In this scenario, oceanographic data collected by a UUV from a designated region is transmitted to an aircraft via a buoy.

After collecting the data, the UUV moves within communication range of the buoy. Depending on the environmental conditions, the UUV transmits the data to the buoy over acoustic or optical links. The buoy, in turn, transmits the data to the aircraft over a microwave link. The entities in the scenario operate in a three-dimensional environment. Figure 3 represents a 2-dimensional view of the simulation region where only the horizontal position and depth are shown.
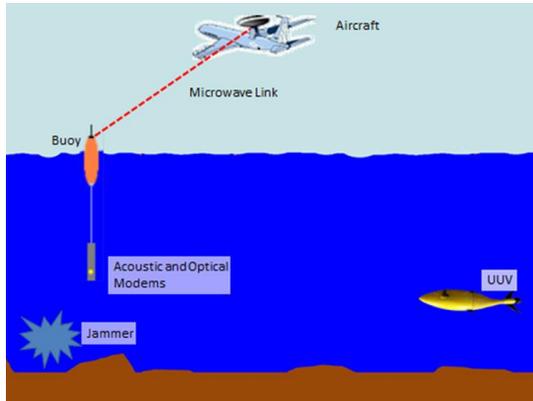

Figure 3. 2D View of Scenario Region
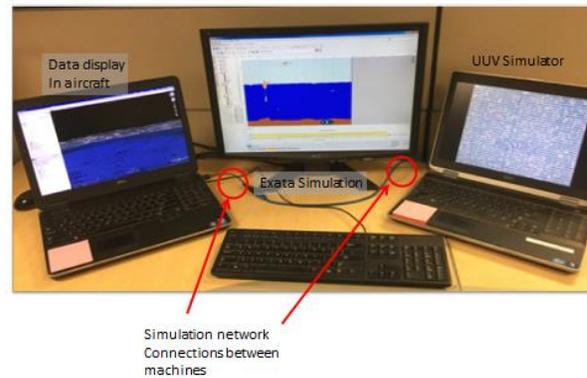
Figure 4. LVC Environment Setup

To demonstrate the LVC capabilities of UCN-X, two live applications interacting with the network simulated in UCN-X were used. The first application is a UUV simulator running on an external host which injects real oceanographic data into the representation of the UUV in UCN-X. This data is eventually transmitted by the UUV to the aircraft within the UCN-X simulation. The second application is an oceanographic data processing and display tool running on another host which is also connected to the UCN-X simulation. The representation of the aircraft in UCN-X forwards the data received from the UUV to the live oceanographic data processing tool. Figure 4 shows the LVC setup with the machine running UCN-X (in the middle) connected to the two live hosts via Ethernet cables.

In a training context, the scenario can be used so that operational staff gain experience in programming and instructing the UUV, *e.g.,* in response to the presence or absence of an adversary. The ocean conditions can be varied to demonstrate variation in the communications channel, and how this reflects on probability of mission success. Mission data can be prioritized with high priority data sent first, so that the metric of success value degrades gracefully rather than failing completely as the situation gets more difficult. To demonstrate the usefulness of UCN-X for training, the scenario can be enhanced by altering the network conditions in real time via Human-In-The-Loop (HITL) commands and studying the impact of these changes. For instance, we used the HITL feature of UCN-X to launch an acoustic jamming attack during the scenario, which results in the switching of communication between the UUV and buoy from acoustic mode to optical mode.

The scenario begins with the UUV moving towards the buoy from a position several kilometers away. Once the UUV is within communication range, it starts communicating with the buoy over the acoustic channel. When the adversary detects the communication between the UUV and buoy, it initiates a jamming attack, thereby degrading the acoustic channel. The UUV responds to this by moving closer to the buoy and switching to the optical link. This behavior is illustrated by the throughput graph (Figure 5). Initially, the throughput over the acoustic link is a few 1000 bits per second. Once the jammer starts, the throughput falls off to zero. As soon as the UUV gets within optical range of the buoy, the optical channel is used to transmit data at a much higher data rate.

For reliable optical communications between the UUV and buoy, good pointing accuracy needs to be maintained between them. Rough water can cause the beam to move off target, causing loss of signal and poor communication. We ran the scenario with various values of water turbulence, resulting in different pointing accuracies. The results due to the jitter of pointing angle are shown in Figure 6. As the graph illustrates, even for very small changes in pointing accuracy the optical throughput decreases by a factor of 10.
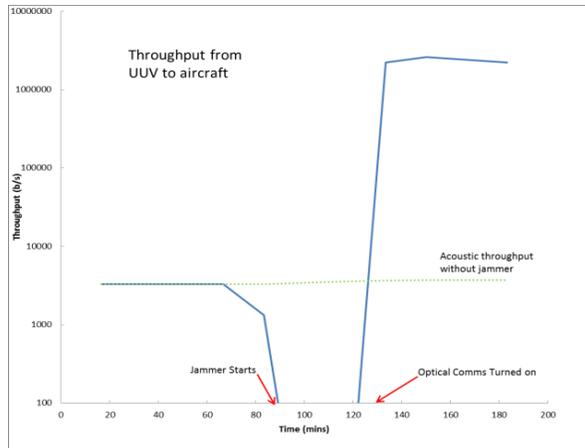
Figure 5. Data Throughput vs. Time
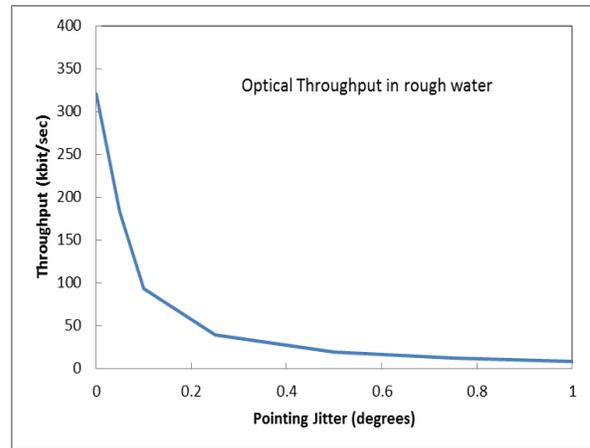
Figure 6. Optical Communication Throughput vs. Pointing Jitter

In addition to changing network conditions or operational parameters through HITL commands (*e.g.*, launching jammer attack or changing the transmission power), changes in network conditions can also be introduced by other tools in the LVC environment. For example, the mobility of any vehicle in the UCN-X simulation can be controlled by an external simulation tool that specializes in movement of that class of vehicle, perhaps one tool for aircraft and another for underwater vehicles. These tools can be federated with UCN-X in the LVC environment. The motion and directional jitter provided by the federated simulation tools can be injected into the UCN-X simulation, and their impact on system performance can be studied, possibly in real time. The tester may operate the live software (*e.g.*, the navigation software) in response to the observed changes in system performance. This operation, in turn, will update the network configuration in UCN-X. In the scenario described above, when the tester observes the degradation of the acoustic channel because of jamming, the tester can move the UUV closer to the buoy to use the optical communication capability.

CONCLUSION

Because of the widespread use of UCNs, the need for training and experimentation in realistic operational conditions is becoming a necessity. This requires both specific training methodologies and the tools to portray realistic and comprehensive scenarios with which the trainee can interact. The training method might change from a government application to a commercial one; however, the concepts and challenges in deploying and managing a UCN and successfully utilizing it to collect and distribute information remain. These challenges include disrupted communications that contribute to long delays, in the order of tens of minutes and even hours. Information transfers would often be characterized by bursty transmissions of large amounts of data, *e.g.*, when UUV or ship is able to establish an optical connection, or when an underwater system is able to deploy a buoy system capable of high-speed communication back to the command center.

Whatever the method, the intermittent and inconsistent nature of information flows poses substantial challenges for the operator, the software developer, and the C2 structure. By combining the effects of many devices, and allowing the efficient programming of devices using an applet model, UCN-X has been developed to portray undersea communications in a learning environment and can be rapidly modified to meet any training need. This is particularly important when the nature of the information flow itself is rapidly changing. In a field such as undersea communications in which the technology, the software, the devices and the system-control algorithms are changing quickly to meet the demands for future undersea operations, the ability to train and re-train people, to develop and re-develop software, and deploy and re-deploy systems is a key capability whose development will be impacted by advances and technologies put forward by the M&S community.

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REFERENCES

Carrera, A., Tremori, A., Caamano, P., Been, R., Crepso Pereira, D., & Bruzzone, A. G. (2016). HLA Interoperability for ROS-Based Autonomous Systems. *International Workshop on Modelling and Simulation for Autonomous Systems.* Springer.

Chitre, M., Shahabudeen, S., Freitag, L., & Stojanovic, M. (2008). Recent advances in underwater acoustic communications & networking. Proceedings of OCEANS.

DESERT Underwater: An NS-Miracle extension to DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols. (n.d.). Retrieved from http://nautilus.dei.unipd.it/desert-underwater

Distributed Interactive Simulation. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Distributed_Interactive_Simulation

Felemban, E., Shaikh, F. K., Qureshi, U. M., Sheikh, A. A., & Qaisar, S. B. (2015). Underwater Sensor Network Applications: A Comprehensive Survey. International Journal of Distributed Sensor Networks.

Heidemann, J., Stojanovic, M., & Zorzi, M. (2012). Underwater sensor networks: applications, advances and challenges. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1958), 158-175.

High-level architecture. (n.d.). Retrieved from https://en.wikipedia.org/wiki/High-level_architecture

ISO. (1994, revised 1996). ISO/IEC 7498-1 "Information technology – Open Systems Interconnection – Basic Reference Model: The Basic Model.

Mobley. (n.d.). Ocean Optics Web Book. Retrieved from http://www.oceanopticsbook.info

One Semi-Automated Forces (ONESAF). (n.d.). Retrieved from http://asc.army.mil/web/portfolio-item/peo-stri-one-semi-automated-forces-pdm-onesaf/

Pompili, D., & Akyildiz, F. (2009, January). Overview of Networking Protocols for Underwater Wireless Communications. IEEE Communications Magazine.

Raj, C., & Sukumaran, R. (2015). Modelling UWSN Simulators. International Journal of Computer, Electrical, Automation, Control and Information Engineering, 9(2), 585-591.

Robot Operating System. (n.d.). Retrieved from https://www.ros.org

Scalable Network Technologies. (n.d.). EXata - Network Emulation. Retrieved from http://web.scalable-networks.com/exata

SUNSET: Sapienza University Networking framework for underwater Simulation, Emulation and real-life Testing. (n.d.). Retrieved from http://reti.dsi.uniroma1.it/UWSN_Group/index.php?page=sunset