Simulation of In-Theater VLF Communications to Unmanned Underwater Vehicles

Terry Whelan, Wei Liu,
Jeff Weaver, Rajive Bagrodia
Scalable Network Technologies
Culver City, CA 90230
{twhelan, wliu, jweaver, rbagrodia}
@scalable-networks.com

Pedro A. Forero, Jose Chavez,
Matthew Capella
Space and Naval Warfare Systems Center Pacific
San Diego, CA 92152
{pedro.a.forero, jose.chavez, matthew.capella}
@navy.mil

ABSTRACT

Autonomous unmanned underwater vehicles (UUVs) are able to perform missions that would be unsafe or impossible for manned submarines. These missions include but are not limited to mine counter measures (MCM) and collection of intelligence, surveillance, and reconnaissance data (ISR). The parameters of these missions occupy an important trade-space between stealth and communications. The operational tasks required of UUVs fall into two general categories: patrolling a region to gather data, and transporting data out of the operational region.

Radio waves are absorbed by sea water - only the lowest frequencies penetrate down to a depth that is useful for UUV operations. Low frequencies require large antennas and high power to transmit efficiently. Radio communications from shore facilities to underwater vehicles are thus restricted to the VLF band (3kHz – 30kHz), or lower, and are not used for underwater to above surface return communications because of these limitations.

Shorter-range, in-theater VLF is a concept that allows communication to submerged UUVs via airborne antennas within a few tens of kilometers of the UUV location. This paper develops the concept of in-theater VLF, including a process to send data back from UUVs to surface assets. This concept is a form of cooperative networking, and to illustrate this networking the following mission is proposed: A swarm of several UUVs simultaneously receive a VLF signal. The vehicles communicate underwater with each other using acoustic or optical signaling and aggregate their response. Finally one of the UUVs travels to a location where it can safely surface to communicate results to mission controllers.

This paper presents simulation results of in-theater VLF communication with UUVs. The simulation integrates several models of communications among vehicles and incorporates all significant propagation and network effects. The simulation results can be used by command staff to investigate the range of mission scenarios over in-theater VLF is practical.

ABOUT THE AUTHORS

Terry Whelan is a Software Engineer at Scalable Network Technologies. He received a BSc degree in Physics from the University of Reading UK. As a graduate student at the University of Iowa he developed distributed particle in cell numerical simulations of auroral processes. At Scalable his interests have included modeling the physics contained in propagation models, multi-antenna (MIMO) systems, and high performance data logging.

Dr. Wei Liu is a Senior Member of Technical Staff at Scalable Network Technologies. He received his Ph.D. degree in Electrical & Computer Engineering from the University of Florida. His research interests include cross layer optimization for mobile ad hoc networks, wireless sensor networks and cellular networks.

Dr. Jeffrey Weaver is Vice-President of Engineering at SCALABLE. He obtained his Ph.D. degree in Electrical Engineering as an NSERC-PGS Scholar from Western University in Ontario, Canada. Dr. Weaver has held key technical and executive engineering roles during his career and has over twenty years of product development experience in hardware and software systems. His research interests include digital communication and propagation modeling using switched stochastic differential equations, signal processing and hybrid analytical-numerical modeling techniques. Dr. Weaver has seven patents in the areas of IP routing, VLAN, QoS, and high-performance hardware design.

Dr. Rajive Bagrodia is the founder of Scalable Network Technologies, Inc. and an Emeritus Professor of Computer Science at UCLA. He obtained his Ph.D. degree in Computer Science from the University of Texas at Austin. Dr. Bagrodia has published over 150 research papers in refereed journals and international conferences on high performance computing and communication. At SCALABLE, Dr. Bagrodia initiated the design and development of the Communication Effects Server (CES) for the Future Combat System Program. The contribution of the CES in advancing the modeling and simulation of DOD communication systems was recognized by an Army M&S Award in the Acquisition category.

Dr. Pedro A. Forero received his Diploma in Electronics Engineering from Pontificia Universidad Javeriana, Bogota, Colombia in 2003, M.Sc. degree in Electrical Engineering from Loyola Marymount University, Los Angeles, in 2006, and Ph.D. degree in Electrical Engineering from the University of Minnesota, Minneapolis, in 2012. His broad research interests lie in the areas of statistical signal processing, machine learning, and underwater networking. His current research focuses on underwater passive acoustic localization and tracking, path planning for autonomous underwater vehicles, multimodal underwater networking, and anomaly detection algorithms. Since Fall 2012, he has been with the Maritime Systems Division at the Space and Naval Warfare (SPAWAR) Systems Center Pacific, San Diego, CA.

Jose Chavez is the Communications Lead for the SPAWAR Systems Center Pacific, San Diego, CA team. He received his BSEE from the University of California at Santa Barbara and his MSEE from the California State University at Northridge. Mr. Chavez' research has been in electrically short antennas, high power Low Frequency/Very Low Frequency antenna systems, and undersea communications.

Matthew Capella is currently the Networks M&S IPT Lead for the SPAWAR Systems Center Pacific, San Diego, CA team. He received his BSEE from the University of California, San Diego. His research has included nuclear fusion, parametric modeling and optimization, machine learning, underwater acoustics, signal processing, and computer networks.

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1 INTRODUCTION

Autonomous unmanned underwater vehicles (UUVs) are able to perform missions that would be unsafe or impossible for manned submarines. These missions include but are not limited to mine counter measures (MCM) and collection of intelligence, surveillance, and reconnaissance data (ISR). The parameters of these missions occupy an important trade-space between stealth and communications. The operational tasks required of UUVs fall into two general categories: patrolling a region to gather data, and transporting data out of the operational region.

Communications in an undersea environment possess significantly different characteristics than in the atmosphere. Radio waves are rapidly absorbed by sea water - only those with the lowest frequencies penetrate down to a depth that is useful for UUV communication. Low frequency transmission requires large antennas and high power for efficient operation at large ranges. Radio communications from shore facilities to underwater vehicles are thus restricted to the VLF band (3kHz – 30kHz), or lower. Radio communications from underwater locations to other underwater, or above surface locations are not practical with any current technologies.

In-theater VLF communication is a concept that allows communication to submerged UUVs via airborne antennas within a few tens of kilometers of the UUV location. This paper develops the concept of in-theater VLF, including a process to send data back from UUVs to surface assets. The concept is a form of cooperative networking. Instead of relying on the VLF stations deployed thousands of kilometers away to emit the signal, the mission controller conducts in-theater operations through a local VLF transmitter installed on an airplane or ship a few tens of kilometers from the operation area. The concept is studied in a typical underwater operational setting: A swarm of several UUVs simultaneously receive a VLF signal from the mission controller; the vehicles communicate underwater with each other using acoustic or optical signaling and aggregate their response as results; finally, one of the UUVs travels to a location where it can safely surface to communicate results to the mission controller.

This paper is organized into several sections: This introduction is section 1. Section 2 presents the background of VLF communications including propagation characteristics, along with a description of large scale VLF systems to provide contrast to the smaller in-theater VLF. A description of the in-theater communication activities is provided in section 3. Section 4 describes the simulation experiments performed using in-theater VLF communications, depicting a potential use of this technology. The paper ends in section 5 with conclusions and future directions.

2 BACKGROUND

In the early 20^{th} century rotating oscillators generated the first commercial transatlantic and transcontinental radio transmissions (Grimeton; Yosami). Mechanical factors limited the signal frequency to below about 20kHz. These systems were used through World War II to supplement easily cut transoceanic cables.

During the cold war era VLF signals were used for both strategic submarine communications and for the OMEGA navigation system (Kasper & Huchinson, 1978). OMEGA used eight coastal VLF transmitters spread around the globe. It relied on the planet spanning range, and good phase stability of propagation of VLF waves to provide signals that could be used to determine position with an accuracy of about 2km. Various command and control ships (England), along with the TACAMO strategic force communications aircraft (Boeing, 2018) have included VLF transmitters as part of their collection of communications capabilities. The VLF band is important today due to its global reach as well as its resistance to jamming and other disruptions. It is used to send messages to remote bases and airborne, surface and underwater strategic assets.

The US Navy, and others, have conducted detailed studies of VLF behavior (Naval Electronic Systems Command, 1972; Gebhard, 1979; Hammond, 2001). A key feature of VLF communication is that it provides a one way, broadcast communications path from a central command and control location to a distributed collection of receivers. Acknowledgement of the reception of a message will have to travel through a different path and may be greatly delayed.

2.1 Antennas

Efficient transmission and reception of any radio communications requires antenna sizes on the order of the wavelength. The VLF frequency band corresponds to wavelengths of several tens of kilometers. Building antennas on this scale is often impractical, so they are made as large as possible. A VLF antenna will therefore be short relative to the wavelength which reduces the efficiency of the power transfer from the amplifier to the surrounding environment.

Examples of VLF antennas include those installed at the Cutler Naval Radio Station, in Maine, which has a pair of antennas each nearly 2km across and 300m high. The top of each antenna consists of a hexagonal array of horizontal wires. Another example is the Jim Creek Naval Radio Station, in Washington, which uses wires up to 2.5km long spanning across a valley between two mountains to provide the upper plane.

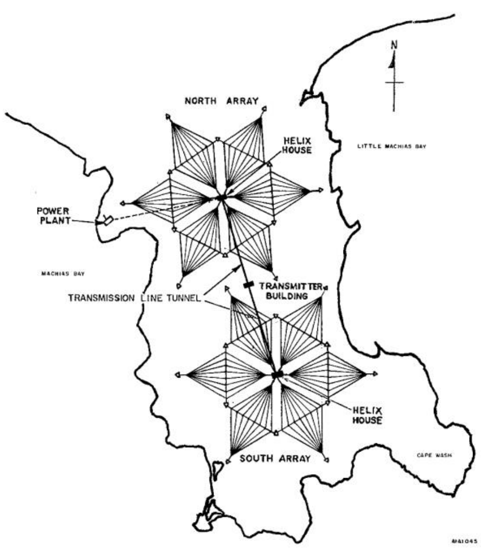

Figure 1 Cutler Naval Radio Station

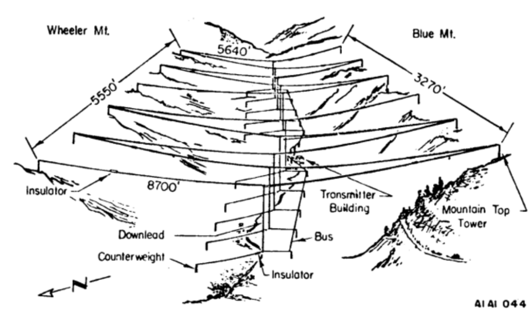

Figure 2 Jim Creek Antenna Array

These large-scale antennas are driven by transmitters producing between 1-2megawatts. Due to the high efficiency of these antennas 80% of this energy is radiated as useful signal. The large physical scale and high-power requirements of VLF transmitters is a major reason why VLF communication is a one-way process. Other on shore VLF transmitters use vertical masts that are several hundreds of meters high. Such impressive, and expensive, antenna structures are valuable for communicating with strategic resources, but cannot be replicated in theater. Receiving antennas can be much smaller than those of the transmitter and are usually either electric dipoles or magnetic loops.

2.2 Atmospheric Propagation

There are three modes for propagation from any radio transmitter to a receiver: the surface wave, the direct wave, and the sky wave. As radio waves propagate from the transmitter they tend to follow the curvature of the earth, especially over a good conductor like sea water, which yields propagation in the form of a surface wave. The direct wave is prevalent during line of sight propagation. Lastly, the sky wave consists of wave energy reflected from the ionosphere. These are illustrated in Figure 3 and Figure 4 (Poole, RF Propagation, 2016)

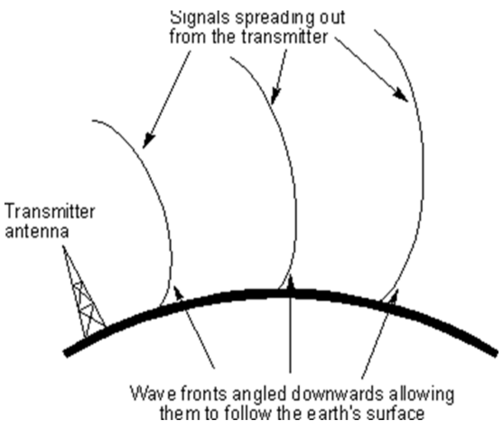

Figure 3 Surface Wave

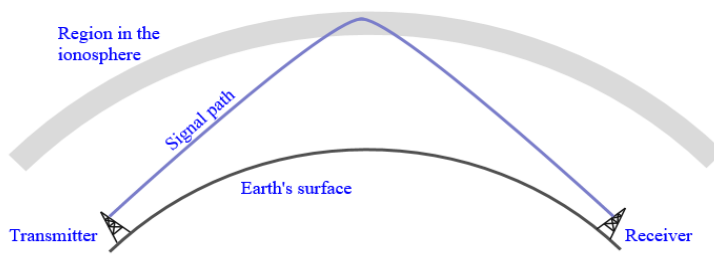

Figure 4 Sky Wave

Radio waves will be reflected by an ionized medium if the wave frequency is less than the electron plasma frequency (Wieseman, 2012), given by equation 1:

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{ne^2}{m_e\varepsilon_0}} \sim 8.9\sqrt{n} \qquad (1)$$

In this equation, f_{pe} is the plasma frequency in Hz, n is the electron density, m_e is the mass of the electron, e is the charge on an electron, ε_0 is the permittivity of free space, all variables in SI units. The innermost component of the ionosphere is the D layer at an altitude of 60km to 90km. The electron density in the D layer varies between about $10^9/m^3$ at night and $10^{10}/m^3$ during the day, the plasma frequency is at least 300kHz, 3 octaves above the VLF band At VLF frequencies the D layer is a good conductor, so the waves are reflected, however, higher frequencies are attenuated by this layer.

High levels of ionospheric and ocean reflection result in a very large transmission range, in some cases, a single transmitter can cover the whole globe. It is common to model the long-range propagation of VLF between these two conductors as a wave guide. Multipath is not a significant effect for VLF communication.

2.3 Underwater Propagation

At VLF frequencies the skin depth for the absorption of radio waves in a conducting, non-magnetic medium, such as sea-water, can be approximated by the formula in equation 2 (EM GeoSci, 2015-2017)

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \sim 503\sqrt{\frac{1}{f\sigma}} \quad (2)$$

In equation 2, δ is the skin depth in m, f is the frequency in Hz, μ_0 is the permeability of free space ($4\pi \times 10^{-7} H/m$) and σ is the electrical conductivity in Siemens/m. For typical ocean conditions σ is approximately 4.0 Siemens/m, and if, f is around 20,000Hz, then δ is calculated as around 1.8m. At VLF frequencies, the electric field decays by about 5dB/m of depth into the ocean. In comparison, microwave frequencies that have skin depths on the order of a few millimeters and decay at hundreds of dB/m, therefore they are not suited for use in air-to-water communications.

With suitably sensitive receivers VLF signals can be received at a depth of a few tens of meters, thus it is useful for submarine communications. This operational depth depends on the conductivity of the water which in turn depends on the salinity, a quantity that varies depending on the location of the body of water. The polarization of the wave is rotated by nearly 90° in the water compared to above the surface, thus vertically polarized transmissions can be received by either horizontal electric antennas, or vertical magnetic loops.

2.4 Ambient Noise

The primary source of noise in VLF communications is distant lightning strikes. Lightning can be considered an electromagnetic impulse, producing an instantaneous perturbation across a large range of frequencies. The same mechanisms that control signal propagation allow lightning from many parts of the globe to reach the detector. In addition to the ionospheric wave guide within the atmosphere lightning at high latitudes can also excite the magnetospheric whistler mode (Stanford VLF Group, 2018). Whistler waves propagate along magnetic field lines and are reflected by the strengthening magnetic field near the polar cusps. The propagation is dispersive - lower frequencies travel slower resulting in the characteristic high to low pitch of these waves. The power spectrum of this noise varies with time of day, month of year, latitude, and geo-magnetic activity. There are no significant sources of VLF under the water surface, and the noise at the surface is attenuated in the same manner as signal. It follows that the signal to noise ratio at any depth is the same as the ratio at the surface.

Lightning is a random event, in which each strike is independent of all others. It is therefore best described by a Poisson distribution. The Poisson distribution tends towards the Gaussian in the limit of a high probability of occurrence. There are tens of lightning strikes per second occurring on the surface of the globe, any of which can send VLF energy that can be detected by a sensitive receiver. For this study we will assume a Gaussian noise model as it is adequate to demonstrate in-theater VLF feasibility.

3 IN-THEATER VLF

Autonomous unmanned underwater vehicles (UUVs) offer unique capabilities to military missions. Their low probability of detection coupled with their ability to act independently of human operators allows for missions that would otherwise be too risky for routine execution. On the other hand, the same features that make the vehicles stealthy make communications difficult. As the battery and autonomy technologies improve the duration of missions can prolong, thus the need to be able to modify the mission by sending command and control instructions increases.

Acoustic communications have limited range and can be potentially detected. While the range can be increased through the use of a narrow beam transmission this may not be feasible if the UUV’s location cannot be ascertained, such as in the case of a high degree of autonomy. Underwater acoustic networks have been proposed, based on mobile ad hoc network (MANET) technologies (Sozer, M.Stajanovic, & Proakis, 2000; Lal, Petroccia, & Conti, 2016; Casari & Zorzi, 2011). Such networks can allow a swarm of UUVs to communicate between each other. Adding surface buoys, with radio transmission capability, as part of the ad hoc network, can extend the network above the surface of the ocean.

This paper considers the possibility of using a VLF transmitter on a ship a few tens of kilometers from the operational region of a collection of UUVs as an alternative to data transfer via acoustic communications. The antenna on the ship will either be held aloft by a balloon or by a helicopter. Since VLF communication is one way from the ship to the UUVs, mechanisms must be in place to send an acknowledgement message back to the ship. A buoy at a fixed location in the operational region will provide this return path. The buoy is defined to have an acoustic communications device along with a satellite communications facility. The UUVs can send messages via an acoustic signal towards the buoy, which are relayed by the buoy via the satellite back to the ship. Several buoys can be used to provide redundant paths for the messages.

The concept relies on the fact that a low power transmitter close to the receiver can have similar received signal strength to a more powerful transmitter a long distance away. Specifically, when we consider the impact of the ionospheric wave guide, a 1MW transmitter at a distance of 1,000 km will have about the same received power as a 10kW transmitter at 10km. A 1.5km antenna supported by a balloon can have a gain of about 0.1 at 20kHz (Koons, 1982; Hagaman, 1993), this is within about 3dB of values reported for a large scale transmitter e.g. (Hansen, Chavez, & R.Olsen, 1997).

4 ANALYSIS AND RESULTS

The in-theater VLF concept was developed and evaluated in the UCN-X (Whelan, et al., 2017) simulator. The UCN-X is an underwater communications network simulator based upon the EXata (Scalable Network Technologies, 2008-2017) simulation platform, with extensions to include acoustic, free space optical and VLF underwater communications. The acoustic communications model is fully capable of exploiting underwater terrain data (bathymetry) and hydrodynamic properties in the propagation model. The VLF propagation model provides support for transmitters both inside and far outside the operation region. For the case of a transmitter outside the region the field strength is constant, varying only with depth under water. A transmitter within the operation region has a field strength dependent on both horizontal distance and depth. The network models in EXata seamlessly include wired and wireless communications with high fidelity. The EXata simulation platform can be extended with the Military Radio Library to provide tactical communications models such as Link 11 and Link 16 libraries. Qualified customers can access the JNE library (Scalable Network Techologies, 2008-2018) to include a collection of models for more advanced battlefield communication.

In order to model a scenario several parameters must be specified. These include the transmission power and efficiency of both the transmitting and receiving antennas, whose values are provided by the works cited above. The VLF signal is modulated with a MSK scheme (Poole, What is MSK, 2016), a typical modulation scheme for VLF. We define only one transmitter, therefore the medium is always available - no MAC protocol is required.

The acoustic propagation model assumes a uniform absorbing medium. Since propagation distances are generally large a cylindrical spreading model is used. High shipping noise but low wind noise is assumed in the operation area. The UUVs, the buoy and ferry can all transmit acoustic messages. To regulate the access to the acoustic channels among them, CSMA MAC protocol is used.

In-theater VLF uses several communications modalities. To allow UCN-X to move data from VLF to acoustic and satellite communications static IP routes are configured between the various nodes and messages are passed as UDP datagrams.

Once these low-level communications parameters are configured, the scenario is further configured with networked applications and node mobility to simulate the information flow and movement taken place in the mission.

To demonstrate the utility of the VLF model in UCN-X we consider a simple two-node scenario. The first node is a ship with a VLF 100kW transmitter, attached to a 1,000m antenna held aloft by a balloon. The ship's transmissions are received by the second node, a UUV with an antenna pointing in the direction of maximum gain. Two cases were studied:

- Variation of distance from the transmitter to the receiver: fixed depth of the UUV to 10m while changing the distance from 1km to 30km.
- Variation of depth of the UUV: fixed distance from the transmitter to the receiver of 1km while varying the depth of the receiver from 5m to 50m.

The received signal strength in each case is shown in Figure 5 and Figure 6 respectively.

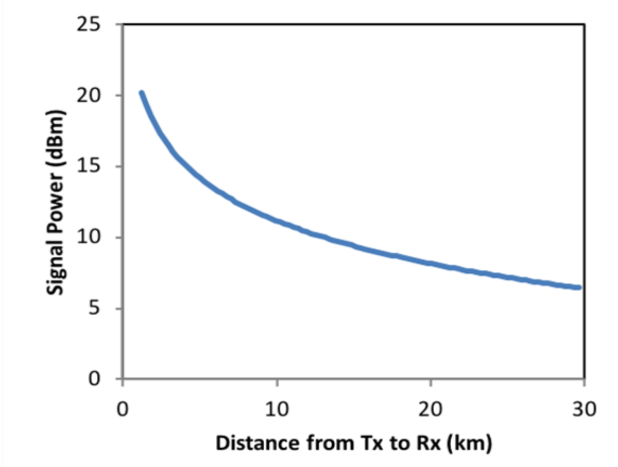

Figure 5 Recieved Power vs Distance

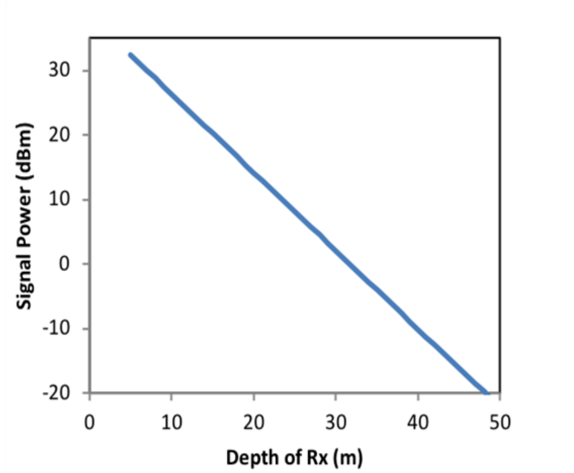

Figure 6 Received Power vs Depth

The thermal noise floor depends greatly on the characteristics of the receiver; in this case it is about 0dBm. Assuming a 3dB reception margin these graphs show that the signal power is sufficient for transmission out beyond 30km, at depths to at least 30m.

5 POTENTIAL MISSION APPLICATIONS

5.1 Concept of Operations

UUVs can be dispatched by various means, such as directly from a ship or from a large displacement UUV that is itself launched from the ship. In the simulations that follow the UUVs are already located in the operational region. The UUVs can be programmed to select one of several routes to efficiently gather mission data. Along with the mission-specific sensors, the UUVs are equipped with a VLF receiver, acoustic communications equipment, and short range optical communications. Once the UUVs have completed their scanning task they return to a specified location and upload their data, via the optical device, to a single UUV data ferry. Once all the scanning data are uploaded the data ferry travels back to the ship, from there the data can be forwarded by tactical radios or satellite communications.

While the mission is progressing, requirements may change. The UUVs may need to be informed of the presence of an adversary's ship, the need to scan a different region, or a change of the location of the data ferry. The commands to execute these changes will be transmitted via in-theater VLF to the UUVs.

5.2 Specific Mission Vignette

Four UUVs are covertly scanning a contested ocean route. The mission for the UUVs is to gather data on the nature and location of underwater devices deposited by an adversary, while also gathering current bathymetry data for the region. The adversary has demonstrated a willingness to capture friendly UUVs that stray too close to the surface near one of their ships.

A friendly ship lies in international waters a few tens of kilometers away from the scanning region. A data ferry is located near the edge of the operational region, and a relay buoy in the middle. Two hours into the mission the ship transmits a message to all UUVs telling them to return their data, the message is repeated every 5 minutes for an hour. As a UUV receives the message it transmits an acknowledgement to the buoy via acoustic communication (ACOMM), and travels to the ferry, where data are uploaded. Once all data are uploaded to the ferry the data ferry returns to the ship.

The scenario layout as it appears in the UCN-X designer is show in Figure 7. This is a two-dimensional representation of the operational region that is 30km X 30km in size, the small boxes in the figure are 2km X 2km. The red flags represent the waypoints that the UUVs travel to perform their mission, using a 'lawnmower pattern' with a 4km separation between passes. The vehicles will not complete the trajectory as once they receive the VLF message from the ship to return their data, they will start moving towards the ferry. The purple lines represent the logical links between a satellite LEO constellation (*e.g*. Iridium) and the above the surface assets.

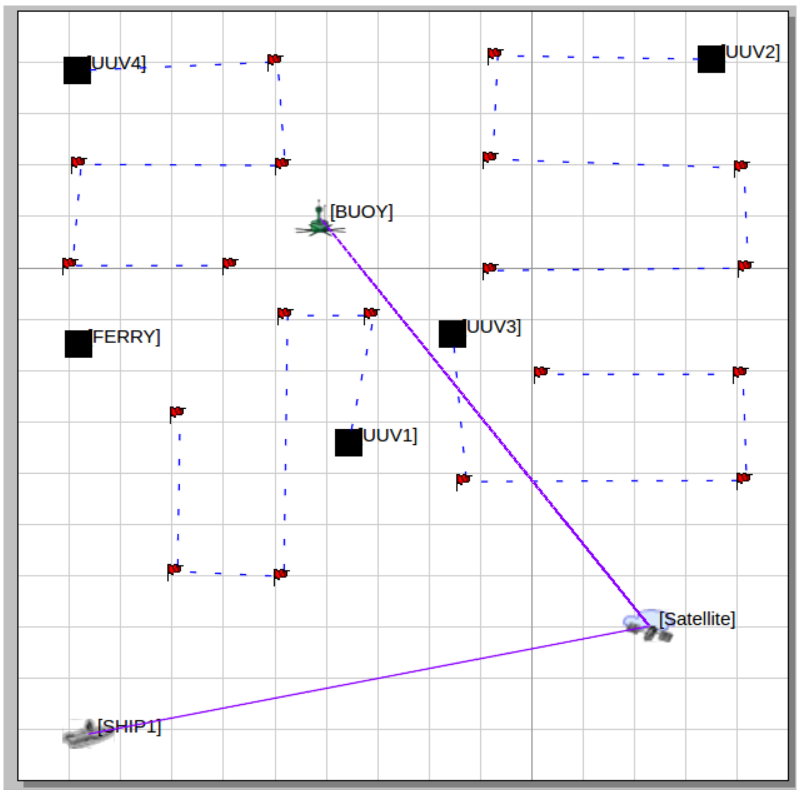

Figure 7 Scenario Layout

Figure 8 shows the distance of the various UUVs from the ship when acoustic or VLF communication events happen. This distance is critical to the processes that are being modeled. UUVs that are far from the ship will not receive the VLF signal, or the signal may be unreliable.

Initially the UUVs are moving in various directions, at distances from 27km to 3km from the ship. The time when the UUVs receive the first VLF message is shown as a red dot on the UUV trajectory. At 2 hours UUV1, UUV3, and UUV4 receive the VLF message, UUV2, which is the furthest from the ship, only gets the 10th re-transmission of the message 45 minutes after the first transmission. The green dots show the time that messages from the UUVs acknowledging the VLF command are received by the buoy. UUV1, which has a trajectory near the buoy sends a message that is immediately received by the buoy. The acknowledgment from UUV2 or UUV4 does not get to the buoy until their trajectory takes them close to the buoy on the way to the ferry. The path of UUV3 is furthest from the buoy, thus, no acknowledgment of the VLF is received. The command staff on the ship would not be aware that UUV3 was travelling to the ferry until the data was unloaded from the ferry.

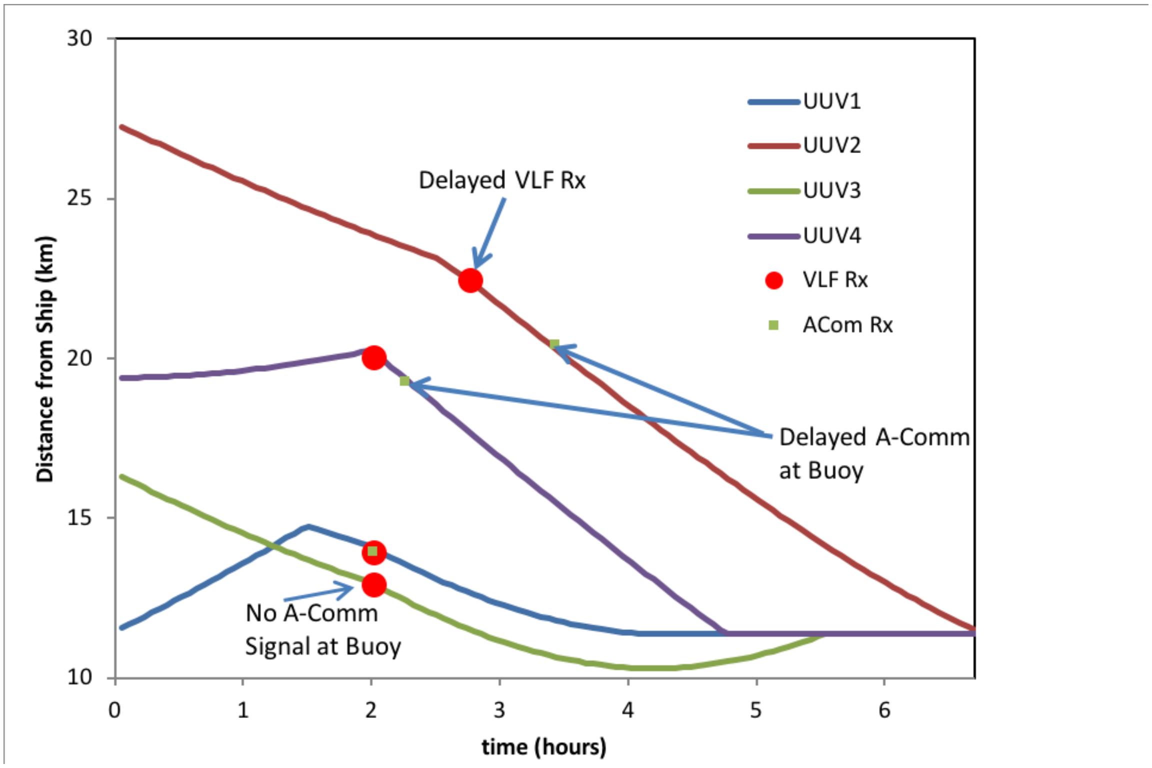

Figure 8 Distance of UUVs from Ship

These results demonstrate problems that are common to all communications that use an unreliable medium. Messages must be repeated and it is generally impossible to know if a message arrived at its destination.

Different from the previous case in which the first VLF signal is sent at 2 hours into the simulation, an additional experiment was repeated with the first VLF signal to the UUVs being sent 10 hours into the mission. In this case the vehicles are near the ends of their trajectories. The resulting metrics are presented inTable 1, which shows, for each UUV, the simulation time, in decimal fractions of an hour, when the VLF signal is received by the UUV, when its ACOMM acknowledgement is received at the buoy, and the time when the UUV arrives at the ferry.

Table 1 Timestamp of the UUV Events (signal sent at 10 hours)

Event	UUV1	UUV2	UUV3	UUV4
First VLF Rx	10.00	10.17	10.42	10.00
First ACOMM Rx	10.25	10.17	11.92	10.00
Arrive at Ferry	10.26	13.58	15.00	11.68

These results reflect the changed distance of the UUVs from the ship and buoy from the earlier case. UUV2 is now much closer to the ship than in the 2 hour signal case, so the VLF signal is received on the 2nd VLF transmission. UUV2's trajectory takes it close to the buoy therefore the ACOMM signal is received immediately after. UUV3's path takes it away from both the ship and the buoy, which leads to the increase of the required number of transmissions and consequentially the delay before signals are received.

To further investigate the probability of signal reception the simulation was repeated with VLF signals transmitted every 5 minutes from the ship to each UUV. The UUVs then routed the messages from VLF reception to the buoy via ACOMM. The purpose of these messages is to probe the quality of the two hop communications path, no mission data were included in the message. The UUVs remained on their "lawn-mower" trajectories following receipt of this message. A separate message was sent to the UUVs at simulation time 10 hours, and every 5 minutes for the next hour, to instruct the UUVs to change direction and head to the ferry. The simulation records events that occur at each layer of the network stack, including the transmission of each VLF message by the ship, reception of VLF by the UUV, and reception of acoustic messages by the buoy. The results of this study for UUV2 and UUV3 are presented in Figure 9 and Figure 10, in each of which the blue line represents the percentage of VLF messages from the ship received by the UUV and the green line represents the percentage of these messages received by the buoy. The vertical axis in each plot corresponds to the percentage of successfully received messages during each hour of simulated time. Since only messages received by the UUV can be forwarded to the buoy the value of the green line cannot exceed the blue.

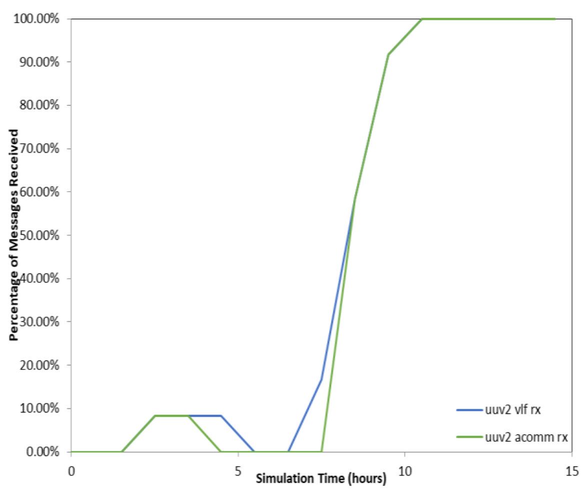

Figure 9 Probability of Message Reception for UUV2

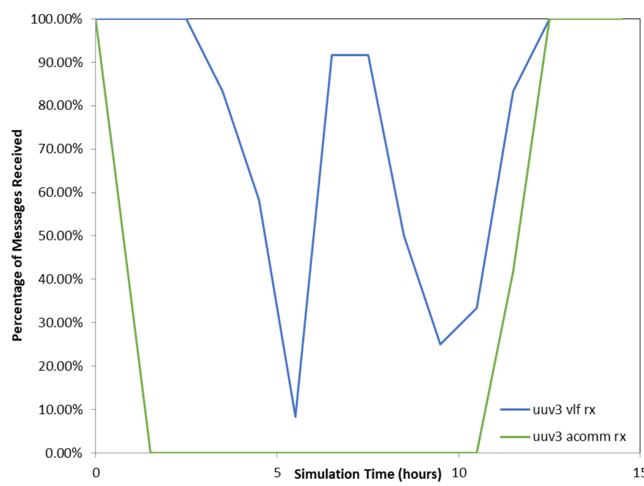

Figure 10 Probability of Message Reception for UUV3

These results show that once the UUVs move close to the ferry both VLF message and ACOMMs message are delivered to their destination with 100% reliability. During the middle phase of the mission, the UUVs are both near the western edge of the simulation region. The probability of both VLF and acoustic message reception during this time is low.

6 CONCLUSIONS AND FUTURE DIRECTIONS

This paper discussed some of the benefits and challenges associated with in-theater VLF communication. Traditionally VLF communication is used for point-to-point or point-to-multipoint communication from on shore to at sea assets. Through simulation studies, we have shown that deployment of at sea transmitters is a compelling use of VLF technology and, through the use of cooperative undersea protocols using other communication modalities, such as free space optics or acoustic communications, VLF can be used to reliably communicate with a multitude of at sea assets and coordinate activities in disadvantaged environments (*e.g.* rough seas, high ambient noise due to lightning strikes, *etc*.). Due to the low transmission power the range of the transmitter is finite, using reasonable assumptions about the characteristics of the transmitter and receiver signals can be received underwater tens of km from the transmitter.

We plan to continue to develop the concepts identified in this paper to include specific protocols designed to function in a disrupted, disconnected intermittent and limited bandwidth (D-DIL) environment. By integrating these protocols into the complete network architecture we can investigate issues related to timeliness and reliability of message reception.

A simulation platform that includes multiple communications modalities and protocols allows a system designer to identify and solve problems in the complete end to end command and control chain. If a concept like in-theater VLF is chosen for deployment then simulation tools can be used to aid in training operational staff in the use of the technology.

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