NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EFFECTIVENESS OF A LITTORAL COMBAT SHIP AS A MAJOR NODE IN A WIRELESS MESH NETWORK

by

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March 2017

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704–0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** March 2017	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE EFFECTIVENESS OF A LITTORAL COMBAT SHIP AS A MAJOR NODE IN A WIRELESS MESH NETWORK	**5. FUNDING NUMBERS**
6. AUTHOR(S) Joshua B. Hicks and Ryan L. Seeba	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The Littoral Combat Ship (LCS) is an evolving platform capable of performing missions in a variety of environments worldwide. One theoretical mission area—the performing advanced command, control, communications, computers, intelligence (C4I) with wireless networking technology in a littoral environment—brings new aspects to the level of versatility this platform can provide. The Navy relies heavily upon networks for information sharing between deployed assets; there is therefore a need for a more reliable means of communicating with these systems. The LCS's adaptability makes it a prime candidate for experimentation with wireless networking technology used for communications with multiple assets. Continuous improvements in Wireless Mesh Network (WMN) and Mobile Ad-Hoc Network (MANET) technologies are producing capabilities that satisfy the need for greater bandwidth and reliability between interconnected manned and unmanned systems. This thesis postulates to virtually model and simulate the operation of an LCS equipped with WMN and MANET technologies intended to enable the LCS to manage these networks and to communicate with surrounding assets reliably. Standard thresholds for network reliability are used to determine the network effectiveness. Based on results from network simulation software, the research findings demonstrated the LCS is capable of performing as a major node in a WMN.

14. SUBJECT TERMS mesh networking, littoral operations, network management, simulations	**15. NUMBER OF PAGES** 159
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN NETWORK OPERATIONS AND TECHNOLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 2017

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The Littoral Combat Ship (LCS) is an evolving platform capable of performing missions in a variety of environments worldwide. One theoretical mission area—the performing advanced command, control, communications, computers, intelligence (C4I) with wireless networking technology in a littoral environment—brings new aspects to the level of versatility this platform can provide. The Navy relies heavily upon networks for information sharing between deployed assets; there is therefore a need for a more reliable means of communicating with these systems. The LCS's adaptability makes it a prime candidate for experimentation with wireless networking technology used for communications with multiple assets. Continuous improvements in Wireless Mesh Network (WMN) and Mobile Ad-Hoc Network (MANET) technologies are producing capabilities that satisfy the need for greater bandwidth and reliability between interconnected manned and unmanned systems. This thesis postulates to virtually model and simulate the operation of an LCS equipped with WMN and MANET technologies intended to enable the LCS to manage these networks and to communicate with surrounding assets reliably. Standard thresholds for network reliability are used to determine the network effectiveness. Based on results from network simulation software, the research findings demonstrated the LCS is capable of performing as a major node in a WMN.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

3GPP	3^{rd} Generation Partnership Project
A2/AD	Anti-access/area denial
ADNS	Automated Digital Networking System
AFP	Adaptive Force Package
AGI	Analytical Graphics Incorporated
AO	Area of Operations
API	Application Program Interface
ARAM	Adaptable Radiation Area Monitor
BGP	Border Gateway Protocol
C4I	Command, Control, Communications, Computers, Intelligence
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
C7F	Commander 7^{th} Fleet
CBR	Constant Bit Rate
CBSP	Commercial Broadband Satellite Program
CG	Guided Missile Cruiser
CIG	Commander’s Initiative Group
CLI	Command Line Interface
CN	Core Network
CODA	Common Optical Digital Architecture
CPS	Cyber-Physical Systems
CSBA	Center for Strategic and Budgetary
CSG	Carrier Strike Group
DAMA	Demand Assigned Multiple Access
DDG	Guided Missile Destroyer
DL	Distributed Lethality
DSS	Decision Support System
Eb/No	Energy per Bit to Spectral Noise
eNB	Evolved Node B
EPC	Evolved Packet Core

E-UTRAN	Evolved Universal Terrestrial Radio Access
FAC	Fast Attack Craft
FIAC	Fast Inshore Attack Craft
FTP	File Transfer Protocol
GUI	Graphical User Interface
HD	High Definition
HSMST	High-Speed Maneuvering Surface Target
LAN	Local Area Network
LCS	Littoral Combat Ship
LLC	Logical Link Control
LOC	Littoral Operations Center
LTE	Long Term Evolution
MAC	Media Access Control
MANET	Mobile Ad-Hoc Network
MDB	Manager Database
MEO	Medium Earth Orbit
MIB	Management Information Base
MIMO	Multiple-Input Multiple-Output
MIO	Maritime Interdiction Operation
NAVAIR	Naval Air Systems Command
NCTAMS	Naval Computer Telecommunications Area Master Station
NIPRNET	Non-secure Internet Protocol Routing Network
NMS	Network Management Software
NSO	Network Service Orchestrator
NWC	Naval War College
NWDC	Naval Warfare Development Command
NWDSS	Network Decision Support System
O3b	Other 3 Billion
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
QoL	Quality of Life
QoS	Quality of Service

PDCP	Packet Data Convergence Protocol
RF	Radio Frequency
RHIB	Rigid Hull Inflatable Boat
RLC	Radio Link Control
RRC	Radio Resource Control
RSV	Reed-Solomon/Viterbi
S1AP	S1 Applications Port
SAG	Surface Action Group
SAR	Search and Reconnaissance
SGW-MME	Service Gateway Mobility Management Entity
SHF	Super High Frequency
SIPRNET	Secure Internet Protocol Routing Network
SNMP	Simple Network Management Protocol
SOCOM	Special Operations Command
SPAWAR	Space and Naval Warfare Systems
STK	Systems Tool Kit
TCDL	Tactical Control Data Link
TCP	Transmission Control Protocol
TNT	Tactical Network Testbed
UDP	User Datagram Protocol
UE	User Equipment
VBSS	Visit, Board, Search and Seizure
VOI	Vessel of Interest
VPN	Virtual Private Network
VTC	Video Teleconferencing
WMN	Wireless Mesh Network
WWAN	Wireless Wide Area Network
X2AP	X2 Application Protocol
XML	Extensible Markup Language

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ACKNOWLEDGMENTS

This research was made possible in large part due to the support of Naval Postgraduate School alumni who came before us. We would like to thank U.S. Marine Corps Major Erika Teichert and U.S. Navy Lieutenant Matt Maupin for their assistance in setting us in the right direction with lessons learned, as well as for providing simulation and real-world models for us to build on. The idea of modeling communications systems on naval platforms was fascinating to both of us, but without a framework to begin with, we may have wandered off to other venues of research.

We would also like to thank our supporting Naval Postgraduate School faculty members. First, Brian Woods, for keeping us on track with deliverables and providing much-needed grammatical and spelling oversight. He was a perfect sounding board for ideas and wasn't afraid to tell us when something was just plain nonsensical. Second, Dr. Wayne Porter, whose motivation and drive toward our work is best described as fanatical. A sharp, retired naval intelligence officer who is without a doubt a legend in the Pentagon, his role as a co-advisor was pivotal to the success of this thesis. Lastly, Dr. Bordetsky, the mastermind behind Wireless Mesh Networking experiments in the San Francisco Bay area. He took us under his wing and gave us our marching orders. From there, he gave us much poetic license to figure out what needed to be done and to execute it sharply.

Ryan would like to thank his wife of 11 years, Miae, for following him around the world and remaining understanding of any challenges that came their way, whether it be deployments, homeport shifts or long research hours. He would also like to thank his three children—Edward, Kate and Angela—for always making him smile by just being themselves. Lastly, the United States Navy, for affording him opportunities that most people can only dream of.

Josh would like to thank his wife, Vanessa, and children, Cheyenne, Jasmine and Tatyana, for their love and support during his tour at NPS. Seventeen years ago, he never

would have thought he would have a master's degree, and he is extremely grateful for the opportunities he has been afforded while serving in the world's greatest Navy. This degree represents a significant personal and professional milestone, which could not have been completed without the constant support he received during the last 18 months.

I. INTRODUCTION

> Designed to be a flexible, multirole component in future Navy battle networks, LCS's reconfigurable modular design will be a first among Navy combatants. Indeed, because the ship is so different, much hard work and experimentation still need to be done to unlock its full potential.
>
> —Robert O. Work, 2014

The Littoral Combat Ship (LCS) is an evolving platform capable of performing missions and fulfilling roles in a variety of environments throughout the world. A combination of adaptable, swappable mission packages, as well as the ability to operate within shallow water, enables the LCS to provide support to partner nation and U.S. assets in ways that were once inconceivable. Naval Surface Forces Command has expressed a growing interest in the use of Wireless Mesh Networks (WMN) to perform C2 functions for mission areas as well as intelligence and data collection. The value of a WMN in littoral operations is the ability to have a portable, flexible system capable of being used on aerial, surface, subsurface, manned, and unmanned platforms. For the network to maintain connectivity, a capable platform must be able to dispense signals to the connected nodes reliably. The goal of this research is to discover if an LCS, operating in littoral environments, is capable of fulfilling the role of an Internet Gateway (IGW), hub, router, or network bridge to surrounding connected nodes. The research posits to evaluate data gathered from real-world events, and place it into simulations modeled with equipment and nodes available in the CENETIX Tactical Network Testbed (TNT) located in San Francisco Bay to determine WMN performance. The research seeks to model the findings from observed performance using Systems Tool Kit (STK) and QualNet simulation software. The research culminates in a recommendation for a network structure based on observed performance.

Advances in WMN and Mobile Ad-Hoc Network (MANET) technologies are ringing in an era of improved warfighting capabilities for the naval platforms capable of utilizing them. The idea of Network Centric Warfare, a concept proposed over a decade ago by the late VADM Cebrowski, postulates to use information-sharing as a key enabler to support tactical decision-making across the spectrum of warfighting. Data networks used to support information-sharing are the backbone of any tactical decision maker's arsenal of tools in a littoral environment. Without such networks enabling a constant exchange of information about contacts of interest, mission objectives, and threats, overall situational awareness (SA) becomes stale. As technology improves, the current gap between cyber and physical dimensions in the littorals will eventually be bridged. For this to happen, the network architecture and bandwidth needed to support nodes, in the form of both manned and unmanned systems, will need to be reliable and robust enough to operate in the uncertain conditions of the littorals. The idea of using mesh networks as a means to gain tactical advantages in the cyber-physical domain was introduced in a U.S. Naval Institute article written by Dr. Bordetsky and CAPT (ret.) Wayne P. Hughes in 2016 (Bordetsky, Benson, & Hughes, 2016). The cornerstone of the cyber-physical precept is that mesh networks do more than provide passive information sharing, they are a vital component of tactical decision-making and need to be constantly monitored and managed to support mission functions.

Previous research on tactical wireless networks conducted at the Naval Postgraduate School identified a novel framework for the use of WMN to support C2 functions through the use of network management tools and dynamic node placement. A primary finding that emerged from the research was that Navy commanders might one day need to employ and reposition assets within a wireless mesh network, to strengthen or enable network support to overarching mission tasks (Maupin, 2016). Recent research conducted to demonstrate the benefits of networked systems to support tactical mission areas included work in the TNT as well as testing with commercial satellite services and equipment overseas (United States Seventh Fleet, 2016).

Trident Warrior, a maritime exercise conducted by U.S. 7th Fleet (C7F) Commander's Initiative Group (CIG) in the Pacific in 2015 proved that one readily available platform for the use of C2 enhancing wireless technology is the LCS. Pandarra Net, an experiment conducted during the exercise with the support of Naval Warfare Development Command (NWDC), posited to connect a ship's network to commercially available throughput systems. The goal of the experiment was to test the integration of equipment for use with a high-bandwidth commercial satellite provider, a company known as the Other 3 Billion (O3b), as well as to connect two naval vessels through 4th generation long-term evolution (4G LTE) devices. Also, the experiment tested the effective range of MANET technology integrated with 4G LTE. The results of the experiment demonstrated the ability of USS *Fort Worth (LCS-3)* to take advantage of improved bandwidth through integration with onboard network architecture, via connection with in-line encryption devices used on the ship's unclassified network (C7F CIG). The experiment did not place emphasis on network reliability and instead focused on bringing networking systems online and making them capable of communicating with surrounding assets and shore-side relay stations. The test was short in duration and focused on end-to-end system functionality rather than collecting network metric statistics. Difficulties with obtaining final permission from higher authority to connect commercial devices to the ship's network early in the experiment resulted in less experimental data than anticipated, but overall it did prove that interconnection of a naval network system on an LCS with a commercial satellite provider was possible (United States Seventh Fleet, 2016).

The data available from experiments conducted during Trident Warrior 2015 in the Pacific, as well as annual WMN and MANET experiments performed with the Naval Postgraduate School's TNT in San Francisco Bay, provide a foundation for experimental designs using network simulation software. The goal of such simulations is to create scenarios with an LCS equipped with commercially available wireless technology to observe network performance. Two commercially available software programs capable of modeling WMN and MANET on naval vessels are Systems Tool Kit (STK) and QualNet. QualNet provides protocol and network management within a wireless domain (Scalable Network Technologies, 2016), while STK is interoperable with QualNet and provides real world positional data of satellite orbits and uses a geographic coordinate system for inclusion of models representing network nodes in land, sea, or space (Scalable Network Technologies, 2016). STK contains models of the Freedom and Independence variants of the LCS as well as unmanned systems and other naval platforms. STK is an ideal palette for experiments dealing with satellite and mesh technology on an LCS, while QualNet provides the protocols and network management of the simulated wireless architecture. This research seeks to build on previous studies relating to the reliability and performance of tactical wireless network performance on LCS platforms.

A. MESH NETWORKS IN LITTORAL OPERATIONS

The word "littoral" does not have a precise definition regarding distance from land or depth in the water; it is strictly determined by regional factors such as continental shelf length and high and low tide extremes. The terms naval personnel are most familiar with regarding littorals are "brown-water" and "near-ashore," essentially a region near enough land that a military vessel operating in this area can project mission influence over sea, land and associated airspace domains. The Naval Postgraduate School Littoral Operations Center refers to it as the littoral, or "near shore," is where "hydrography, geography, commerce, fishing, mining, boundaries, maneuver and sustainment issues converge, complicating both the Offense and the Defense, and placing exceptional demands on naval, aerial, and land forces that must operate, fight, and influence events there" (Naval Postgraduate School, n.d.a.). The following is the definition of littoral waters in Naval Warfare College (NWC) terminology, as defined by Dr. Milan Vego: "Littorals, properly speaking, encompass areas bordering the waters of open peripheral seas, vast archipelagoes, and enclosed and semi-enclosed seas. Littorals bordering open oceans, such as the coasts of North and South America, Africa, and India, extend outward to the farthest extent of the continental shelf" (Vego, 2015, p. 13).

Littoral waters are often hallmarked by significant physical features protruding from the ocean floor, such as visible rock formations, extending out from or centering on an island or landmass. These features can affect a friendly vessels radar and line-of-sight RF propagation paths through diffraction or absorption, as well as by concealing smaller, potentially threatening Fast Attack Craft (FAC) or Fast Inshore Attack Craft (FIAC) that may not have posed a threat in open water, but gain an advantage when concealment grants them a more advantageous time and distance vector. The deltas of rivers emptying into the ocean can also be avenues of approach for smaller threat vessels. Near ports in industrialized countries, these waters experience heavy traffic from merchant and freighter traffic that can also inhibit SA. FAC and FIAC capable of posing threats to friendly vessels can make use of radar clutter created by large commercial vessels to conceal their positions. In addition to traditional seaborne threats, a friendly vessel, such as an LCS, has the potential to be targeted by terrestrial anti-ship missile platforms. In the book *Fleet Tactics and Coastal Combat*, the famous quote from Lord Nelson, “A ship is a fool to fight a fort” (Hughes, 2014), is intended to describe the challenges faced by vessels operating in the littorals. In the context of modern day weapons, a “fort” can be anything from mobile launch sites to stationary defenses with sufficient range to target vessels operating in the open-ocean or littorals. There may be little an LCS can do to defend itself against a sudden attack by one of these anti-ship defenses, so it is imperative that SA be shared between allied platforms through C4I enhancing networks to reduce risk. Whenever friendly manned or unmanned platforms are sharing information, they must have a network structure to support it.

Information sharing through network nodes required to mitigate the risk of asymmetric threats forms one of the precepts of Network-Centric Warfare. In Littoral Combat Ship: An Examination of its Possible Concepts of Operation, a study conducted by the Center for Strategic and Budgetary Assessments (CSBA), the precepts that VADM Cebrowski and ADM Clark advocated were rephrased in the following paragraph:

> Engagement on the seaward side of the littoral, however, including the protection of the main battle force and the destruction of enemy coastal naval assets such as mines, submarines, Fast Attack Craft (FACs) and Fast Inshore Attack Craft (FIACs), would be undertaken by small networked combatants. (Murphy, 2014)

Smaller networked combatants include a combination of manned and unmanned systems. The use of the LCS as a sensory platform to help paint the broader contact picture within the littorals is the emphasis. The document also addresses the fact that the LCS does not have long-range air defense capabilities to reduce its vulnerability as an independently operating standalone platform within known hostile environments. As such, an LCS requires the air defense umbrella of a Surface Action Group (SAG) or Carrier Strike Group (CSG) in times of conflict or heightened tensions.

A mesh network is exactly the kind of force multiplier needed to give an edge to Allied tactical decision-makers using the Sense-Decide-Act framework, as well as to offset a potential adversary's decision-making capabilities. In the spirit of Distributed Lethality (DL), the uncertainty of offensive and defensive capabilities presented by friendly manned and unmanned assets utilizing the mesh has the potential to make an adversary expend valuable time and ISR resources in determining false threats from actual ones. This technology affords allies more decision-making time and enables offensive strike capabilities from platforms that an adversary may overlook.

In an article published by Dr. Bordetsky, Steve Benson and Wayne Hughes, on the U.S. Naval Institute Blog in 2016, the concept of using a mesh network in the littorals to improve weapons' reach and information sharing of manned and unmanned assets is espoused. The article further clarifies that in this environment, "The threat of sudden, short-ranged attack is of constant concern" and development of a network that enables us to "Effectively Attack First" is of paramount importance to commanders for the integration of all naval operations and tactics. The framework used to present advantages offered by mesh networks in decision-making is Sense-Decide-Act. The "sense" component refers to visual, electronic, or any other means of discovering and tracking an adversary's whereabouts. The "decide" portion is making the tactical call and beginning to enact it through communications. The "act," in this context, is firing a weapon at the target (Bordetsky et al., 2016).

An LCS is among the primary components of a mesh network employed in this environment. Theoretically, an LCS equipped with a mission module—or other adequately suited communications equipment—capable of allowing it to communicate with nodes within the mesh, then it offers a potential expansion to Command and Control (C2) capabilities within the global littorals. In such a scenario, the LCS could perform many functions. For instance, it may act as a major node between assets within the network, serving as a router, bridge, or hub. Unmanned systems, as well as other remote systems, may need a single platform capable of relaying and translating routing protocols and target information to obtain firing solutions, or at the very least, share SA. Admittedly, not all LCS vessels would be employed as the central C2 platform in a given mesh network, as this would allow adversaries a greater amount of targeting certainty to degrade or eliminate the mesh network.

B. RESEARCH OBJECTIVES

The purpose of this research will be to evaluate the effectiveness of an LCS as a major node in a WMN. Based on analysis of a simulated LCS operating in the cluttered San Francisco Bay environment, a generalized conclusion will be drawn as to this platform's suitability to serve as a critical wireless networking node within a littoral environment. The percentage of network availability time used with USVs and other participating units will be used to observe whether or not the LCS is a platform capable of providing reliable services necessary to maintain a flexible mesh network among various nodes. The research also postulates to identify whether network management software can assist in identifying how an LCS can best serve in a WMN role. The use of network management software and the analysis of LCS WMN interoperability with other nodes in a simulated environment will be the starting point to determine if the vessel can adequately provide the network capabilities needed to support mission areas throughout the U.S. Navy and DOD. The implications of WMN for use in U.S. Navy missions is profound, and the research aims to form one of the initial steps in determining the usefulness of this architecture for sea-going as well as aerial and terrestrial platforms operating in the littorals. The primary questions of this research are:

How well can the LCS platform perform as a WMN node in a littoral environment with Unmanned Surface Vessels (USV) and other nodes?

How can network management software assist in identifying the optimal role of the LCS platform in a WMN?

C. SCOPE AND LIMITATIONS

This thesis research has the potential to demonstrate improved C2 capabilities for LCS platforms as well as the USVs and other nodes connected to it. The research does not seek to make a recommendation for a specific type of commercial satellite equipment to be used on the LCS. An LCS performing as an Internet Gateway (IGW) will be assumed to be equipped with a maritime terminal and subscription or mission package capable of fulfilling this role. Although the research does not analyze the C2 decision-making processes, having the means to communicate over a WMN is a critical enabler.

The simulation portion of this research seeks to model equipment that has been previously used in experiments within the SF TNT as well as the Trident Warrior 2015 exercise. The parameters for the equipment that were used in these exercises will be employed in the simulation software, with the LCS being the primary node in any simulated scenario, whether performing as a gateway, bridge, hub, or router. Simulated packets will be used that closely match real-world throughput in each scenario. The research does not examine how these packets would pass through the long-haul system to Navy Network Operating Centers (NOC) on the shore side, as the network architecture in these sites may have bandwidth limitations imposed by policy and inline equipment.

The final determination on whether an LCS can perform as a major node in a WMN will take into account the network performance and limitations based on the number of connected nodes. The findings, if positive results are observed from simulations, will contribute to further field experimentation on LCS platforms in other networking environments.

D. ORGANIZATION OF THESIS

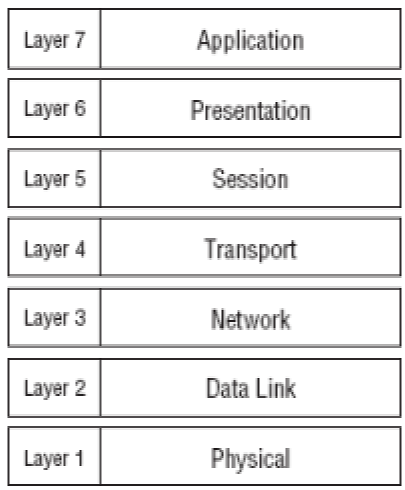
Chapter II provides background and literature review of research and concepts relevant to the objectives. Chapter III covers the research design to be used in QualNet and STK simulation software. Chapter IV is an overview of the simulation results and provides analysis of the data collection. Chapter V summarizes the findings and makes recommendations, as well as future areas of research on the subject matter.

II. LITERATURE REVIEW

A. NETWORK NODE TERMINOLOGY

The basis of any discussion on network nodes and operations invariably begins with the 7-Layer Open System Interconnection (OSI) model. Figure 1 displays the basic OSI model.

Figure 1. OSI Model. Source: Edwards (2009).



The OSI model defines how data packets are managed, translated, and displayed by information systems. In the context of this thesis, the seven layers all pertain to how an LCS can perform as a major node in a wireless network. With this in mind, the layers primarily addressed in this thesis are the Physical through Transport layers. The injection of application software into simulations may be possible but is beyond the scope of this research. A predetermined data bit rate over a prescribed length of time will be used for each of the nodes.

The ability of an LCS to perform as an IGW, router, hub, and bridge will be measured primarily by its performance with connected nodes. A network node, as defined in *Network Management* 2^{nd} Edition, is a component at either end of a network link. The definition of a gateway, router, hub, and bridge are also from *Network Management* 2^{nd}

edition (Subramanian, 2011). The first term, gateway, is a component that connects two independent networks. An LCS performing as an Internet Gateway is serving the gateway function between its internal network and the shore-side Internet architecture. The second term, router, is a component that routes data packets by using definitions in pre-established or learned routing tables. The ability to adapt makes router self-healing, as it can find new routes if a transfer path is lost or added. A router can interface between mediums, in particular, with wired and wireless connections. The LCS will perform as a router between manned and unmanned assets. The third term, hub, is a component used to repeat data or signals in a network. The LCS will perform as a hub when receiving MIO data from the shore side and indiscriminately distributing it to friendly vessels within range. The final term, bridge, is a component that interconnects Local Area Networks (LAN) without transmitting unnecessarily to LANs that do not require specific packet information. It can also be configured as a tool for protocol conversion, due to its ability to store and forward information. The LCS will perform as a bridge by sending data packets on mission critical information to unmanned assets incapable of communicating with one another.

1. LCS Wireless Network Equipment (Theoretical)

In the simulated scenarios, the LCS will serve as the Internet gateway and will require the right network equipment and routing protocols for it to function as such. The shipboard Automated Digital Network System Increment III router (ADNS INC III) will be configured for the ad hoc routing protocols Optimized Link State Routing (OLSR), and Ad Hoc On-Demand Distance Vector (AODV) and a SPAWAR approved wireless access point will be added to the communication suite as well. Research, Development and Test – Navy explains that ADNS INC III has the following features:

- Combines all Navy tactical voice, video, and data requirements into a single IP data stream.
- Operates with higher bandwidth satellites, supporting up to 25 Mbps on unit level ships and up to 50 Mbps on force level ships.
- Incorporates an IPv4/IPv6 dual stack and ciphertext security architecture to align to joint and coalition networks. (RDT&E Navy, 2011, p. 226)

ADNS INC III will serve as an ideal integration point for WMN and MANET technologies.

OLSR is the first routing protocol for which interfaces need to be configured. Thoroughly described in RFC 3626, OLSR has the following features that make it suitable for the scenarios detailed later in the thesis.

- Proactive routing protocol used in MANETs that has routes available when necessary.
- Helps minimize the overhead from flooding of control traffic using multipoint relays (MPR) to retransmit control messages.
- Only requires a partial link state to be flooded to provide shortest path routes.
- Reduces the maximum time interval for periodic control message transmission.
- Maintains routes to all network destinations.
- Designed to work in a distributed manner that does not require control from a central entity.
- Does not require sequenced message delivery, and each control message contains a sequence number for each message. (Clausen & Jacquet, 2003, p. 7–8)

The next protocol used is AODV, which is primarily for mobile nodes in MANETs. As explained in RFC 3561, AODV has the following features:

- Rapid adaptation to dynamic link conditions.
- Low processing and memory overhead.
- Low network utilization.
- Determines unicast routes to destinations within the ad hoc network.
- Use of destination sequence numbers ensures constant loop freedom.
- Requesting nodes select destination with the higher sequence number when choosing between two routes.
- Enables dynamic, self-starting, multi-hop routing between participating mobile nodes attempting to connect to an ad hoc network.

- Nodes can quickly obtain routes to destinations even if they are not actively communicating.
- Notify affected nodes of broken links and will invalidate the routes. (Perkins, Belding-Royer, & Das, 2003, p. 1–2)

The AODV protocol is critical in ensuring network communications paths are always available for participating nodes, and is particularly important if the nodes are mobile.

2. Persistent Systems Wave Relay

To achieve wireless connectivity Persistent Systems Wave Relay (PSWR) radios and Quad Radio Routers will be utilized on both the LCS and participating nodes to form the MANET in the simulated scenarios. PSWR is designed to maintain connectivity between multiple mobile nodes. The technology differs in its ability to scale to a network incorporating high numbers of moving nodes in an any-to-any topology, which allows every node to communicate with each other thus enabling true peer-to-peer connectivity. Forming a MANET including PSWR radios also gives the advantage of maintaining routes, and detecting changes to the network while mobile, which will be the case in the simulations found in this research. The proprietary Wave Relay algorithms excel in an environment utilizing mobile nodes, and maintaining routes in a highly scalable network is the foundation of this technology (Persistent Systems, 2012). The Wave Relay Man Portable Unit Gen 4 (MPU4) is displayed in Figure 2.

Figure 2. Wave Relay Man Portable Unit Gen 4. Source: Persistent Systems (2014c).

In addition to Wave Relay Radios, Quad Radio Routers will be required on certain nodes to form the MANET. Similar to the radios, these routers excel in an environment with mobile nodes. Their ruggedized designs are adaptable for a variety of land and maritime platforms, and they are critical pieces of equipment in these scenarios. Like the Wave Relay radios, the Quad Radio Routers operate at OSI layer 2 using the same proprietary multicast algorithms. The routers are scalable, allowing the creation of peer-to-peer networks providing data, video, and voice in severe environments. For the nodes that utilize the router, there are multiple mounting options available. They can also be used in vehicles for land-based nodes or mounted to the mast of an LCS for coverage over larger geographic areas. When paired with a tracking antenna system kit, the routers are capable of providing long-range, air-to-ground connectivity (Persistent Systems, 2016). The Quad Radio Router is displayed in Figure 3.

Figure 3. Quad Radio Router. Source: Persistent Systems (2016).

Detailed specifications for the Quad Radio Router are found in Figure 4.

Figure 4. Wave Radio and Quad Radio Router Specifications. Source: Wave Relay 5 Integration Unit Technical Specs (2013).

3 x 3 MIMO TECHNOLOGY	Extended Range 150 Mbps of throughput Maximal Ratio Combining Spatial Multiplexing Antenna Detection
MODULAR RADIO	RF Modulations: OFDM (64-QAM, 16-QAM, QPSK, BPSK) 6W Transmit Power* Swappable Radio Modules/Radio Boards •RF-1000/RF-1100 - L-Band Frequency Range: 1350 - 1390 MHz* •RF-2000/RF-2100 - S-Band Frequency Range: 2200 - 2500 MHz† •RF-3000/RF-3100 - C-Band Radio in Development Software configurable bandwidths: 2.5 MHz, 5 MHz, 10 MHz, 20 MHz, 40 MHz TX/RX Operating Modes: All modes from SISO to 3x3 MIMO
RoIP	Legacy Radio Tethering Legacy Radio Detection USB Host / RS-232 Serial
VIDEO	HD-BNC Connection 3G-SDI & Composite Input Integrated HD H.264 Video Encoding/Decoding
GPS	3.3V Active Situational Awareness Cursor-on-Target Compliant 1 Second Updates
PTT / EUD	Dual Active PTT Channels End User Device (EUD) Data / Charging USB Host / RS-232 Serial HD Video Output
DATA	USB On-the-Go RS-232 Serial Ethernet HD Video Input
BATTERY	Low Battery Alert Standard Twist-Lock Connector
NETWORKING	Advanced multicast algorithms Seamless Layer 2 network connectivity Integrated serial-to-Ethernet capability Cloud Relay™ DLEP Certified IPv4 and IPv6 compatible Integrated DHCP server USB RNDIS Host and Device
SECURITY	Integrated Hardware Cryptographic Acceleration CTR-AES-256 Encryption HMAC-SHA-256 Authentication & Integrity Utilizes Suite-B Algorithms Cryptographically authenticated Over-the-Air Rekey and Key Zero FIPS 140-2 Level 1 Rechargeable 30 Day Hold-Up for Keys and Configuration Settings
PHYSICAL SPECIFICATIONS	1.5 x 2.6 x 4.7 inches / 38.1mm x 66mm x 119.4mm (NO BATTERY) 1.5 x 2.6 x 7.9 inches / 38.1mm x 66mm x 200.7mm (WITH BATTERY) 17.3 oz / 490.5 grams (NO BATTERY) 29.6 oz / 839.1 grams (WITH BATTERY)
MANUFACTURING & ENVIRONMENTAL	ISO 9001:2008 certified Manufactured to MIL-STD specifications IP68 Coated to meet MIL-C-64159 / MIL-C-53039A(2) standards Operating temperature: -40° to 85° C / -40° to 185° F

The next piece of hardware utilized will be Persistent System Sector Array Antennas, which connect to the Quad Radio Routers. The antennas provide long-range, omnidirectional coverage capable of maintaining maximum throughput for multiple connections. Each Sector Array antenna houses three individual antennas, providing 360-degree coverage and each antenna covers a 120-degree area, directing transmissions in a manner which minimizes interference while providing optimal connectivity for network nodes. Utilizing a vertical beam width, the Sector Array Antenna is ideal for land-based and maritime networks, allowing uninterrupted connections in even the most challenging environments (Persistent Systems, 2014b). This powerful antenna enhances the feature set of the MPU-4 and Quad Radio Router and includes the following features and capabilities.

- Wave Relay MANET routing
- Cursor-on-Target compatible
- Wave Relay over IP (WRoIP)
- Operates on 2.4 and 5 GHz sector arrays
- OFDM with Adaptive Modulation Algorithms
- Variable channel widths of 5, 10, 20 or 40 MHz
- Multiple RF band support
- Peer to peer with other Quad Radio Routers and MPU 4s
- 10-mile range on both the 2.4 and 5 GHz variants (Persistent Systems, 2014b)

Each antenna includes an integrated hardware cryptographic accelerator, is FIPS 140–2 compliant, support AES-CTR-256 with SHA-512 HMAC encryption and over the air rekeying. Configuration management is accomplished using the secure web interface or the network-wide configuration functionality (Persistent Systems, 2014b). The combination of the Quad Radio Router, MPU4s and Sector Array Antennas provide a robust solution to form WMN and MANETs for multiple mission configurations that can be managed from an LCS in multiple configurations that will be simulated in forthcoming sections of the thesis. The Sector Array Antenna is displayed in Figure 5.

Figure 5. Sector Array Antenna. Source: Persistent Systems (2014b).

Utilizing the MPU4s, Quad Radio Routers and Sector Array Antennas allow for the natural formation of a WMN or MANET based around an LCS as a major node and the hardware provides the flexibility required for expansion as necessary. The small hardware footprint makes the Persistent Systems equipment attractive options for both maritime and aerial use. As shown in Figure 7, the Wave Relay technology uses the random-access protocol carrier-sense multi-access with collision avoidance (CSMA/CA) as the basis for wireless networks. Additionally, Wave Relay uses 3x3 multiple-input-multiple-output (MIMO) technology capable of delivering up to 150 Mbps of throughput at varying distances (Pothitos, 2015). Furthermore, the cloud relay serves as a solution to bridge beyond line of sight (BLOS) to line of sight (LOS) networks. Cloud relay technology allows long-range remote access to video, voice, and data to and from all MANETs. It also provides seamless transition via layer 3 networks to other connected MANETs worldwide. Existing infrastructure is used to extend the MANET including LTE, SATCOM, wired Internet and other layer 3 technologies (Persistent Systems, 2014). The configuration allows for easy participation in a MANET from the sea, air or land as shown in Figure 8. Wave relay and cloud relay technologies provide the means to easily maintain a MANET that provides more than adequate throughput for operational purposes. Potential Cloud Relay Group configurations are displayed in Figure 6.

Figure 6. Cloud Relay Groups. Source: Persistent Systems (2014a).

3. Tsunami QB-10100 Series Wireless Network Bridge

The Tsunami QB-10100 series wireless bridge provides near line-of-sight, point-to-point connectivity between networks. The equipment operates in the 5.150-5.925 GHz frequency range and is capable of delivering 600 Mbps throughput. Similar to PSWR, it uses OFDM to enable flexible RF propagation and channels. Proxim Wireless, the company that manufactures the equipment, describes it as having the following key features:

- Suitable for Service Providers, Enterprises, and Governments
- Fully integrates within ProximVision® Advanced Cloud-Based Carrier
- Management System and Controller
- Certified for deployments in the Americas, Europe, and Asia
- The most cost-effective, very high-performance point-to-point solution from Proxim, enabling any deployment to enjoy a quick return on investment (Proxim Wireless, 2016)

B. NETWORK MANAGEMENT AND PERFORMANCE

1. Network QoS and Availability

Two primary factors that determine the performance of a network are the Quality of Service (QoS) and Availability. QoS refers to the ability of a network to run or deliver applications commensurate with a user's or an organization's expected performance. An example of acceptable QoS is when video and audio are streamed without interruption at the resolution desired. The availability of a network refers to the amount of up or down time over a prescribed period. Many organizations use the "five 9s" of availability as a metric, meaning they strive for the highest percentage of network uptime (West, Dean & Andrews, 2016). Table 1 illustrates availability and downtime equivalents and sets a metric for the performance of the LCS as a major node in a wireless network. A variety of commercial network management and performance monitoring tools are available to a network operator to determine the effectiveness of a network. A description of some of these tools is described in upcoming sections.

Table 1. Availability and Downtime Equivalents. Source: West et al. (2016).

Availability	**Downtime/Day**	**Downtime/Month**	**Downtime/Year**
99%	14 minutes, 23 seconds	7 hours, 18 minutes, 17 seconds	87 hours, 39 minutes, 29 seconds
99.9%	1 minute, 26 seconds	43 minutes, 49 seconds	8 hours, 45 minutes, 56 seconds
99.99%	8 seconds	4 minutes, 22 seconds	52 minutes, 35 seconds
99.999%	.4 seconds	26 seconds	5 minutes, 15 seconds

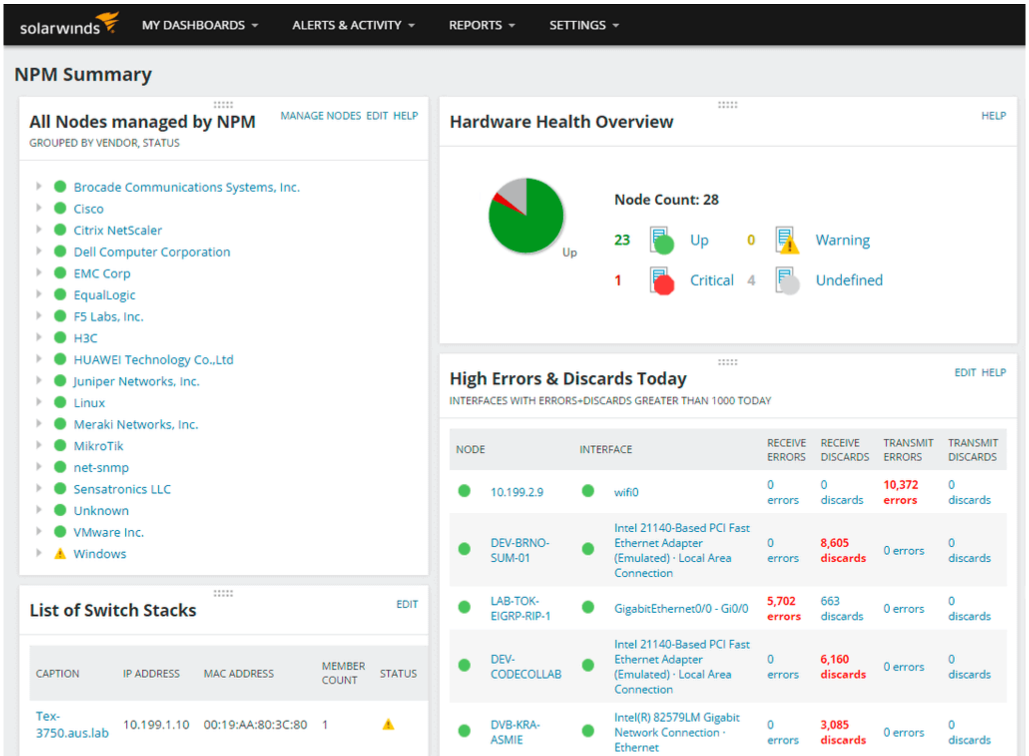
2. Network Management Tools

The proposed software suite for network management is SolarWinds. It is a robust suite of software that will provide proper oversight of the network using the Network Performance Monitor (NPM), Network Configuration Manger (NCM) and IP Address Manager (IPAM). Software of this type is critical to ensure all aspects of the network can be monitored especially network performance of the Internet gateway and connected nodes. In SolarWinds, both of the items above can be checked using the network performance monitor and NetFlow traffic analyzer. Monitoring traffic is critical as bandwidth will likely be limited in most operational environments. The following features will be used from the LCS to manage and monitor the network.

> Network Performance Monitor (NPM): Customizable topology and dependency-aware intelligent alerts, dynamic wired and wireless discovery and mapping, automated capacity forecasting, alerting, and reporting and wireless network monitoring and management. (SolarWinds, n.d.d.)

A screenshot of the Network Performance Monitor dashboard is displayed in Figure 7.

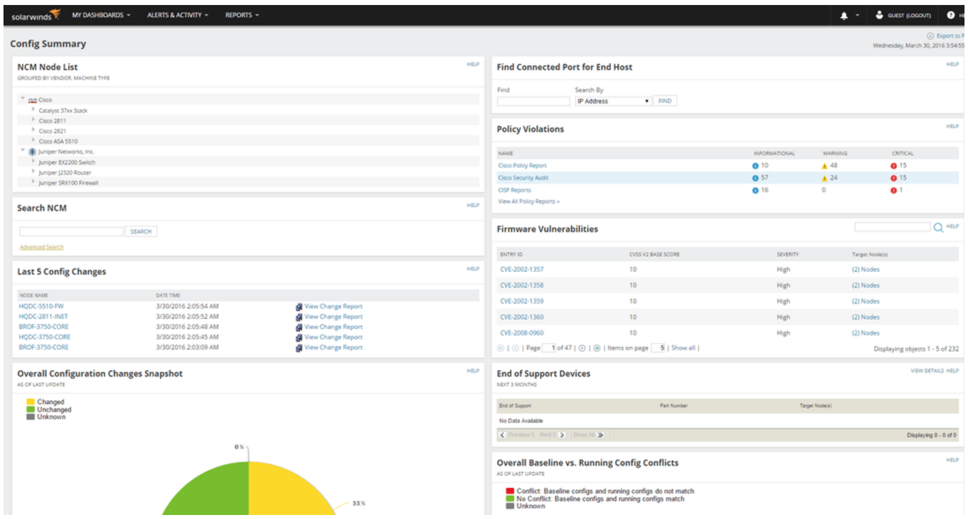
Figure 7. SolarWinds Network Performance Monitor Screenshot. Source: SolarWinds (n.d.d.).



Network Configuration Manager (NCM): Multi-vendor network change and configuration management, real-time configuration change notification, configuration compliance auditing, network change automation, and integration with NPM (SolarWinds, n.d.c.).

A screenshot of the Network Configuration Monitor dashboard is displayed in Figure 8.

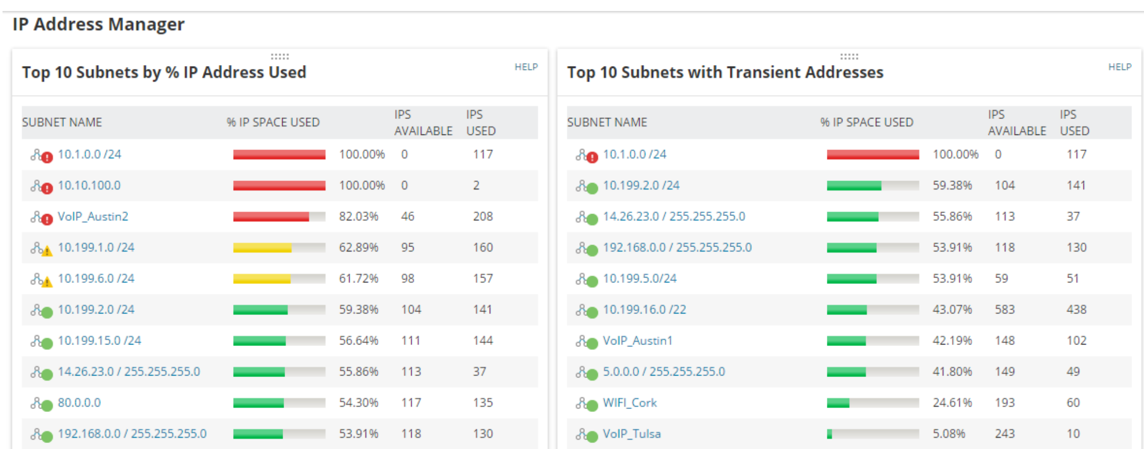
Figure 8. SolarWinds Network Configuration Manager. Source: SolarWinds (n.d.c.).



IP Address Manager (IPAM): Automated IP address management, integrated DHCP and DNS administration, IP alerting, troubleshooting and reporting, delegated administration and IP detail and history tracking (SolarWinds, n.d.a.).

A screenshot of the IP Address Manager is displayed in Figure 9.

Figure 9. SolarWinds IP Address Manager. Source: SolarWinds (n.d.a.).


IP Address Manager

Top 10 Subnets by % IP Address Used

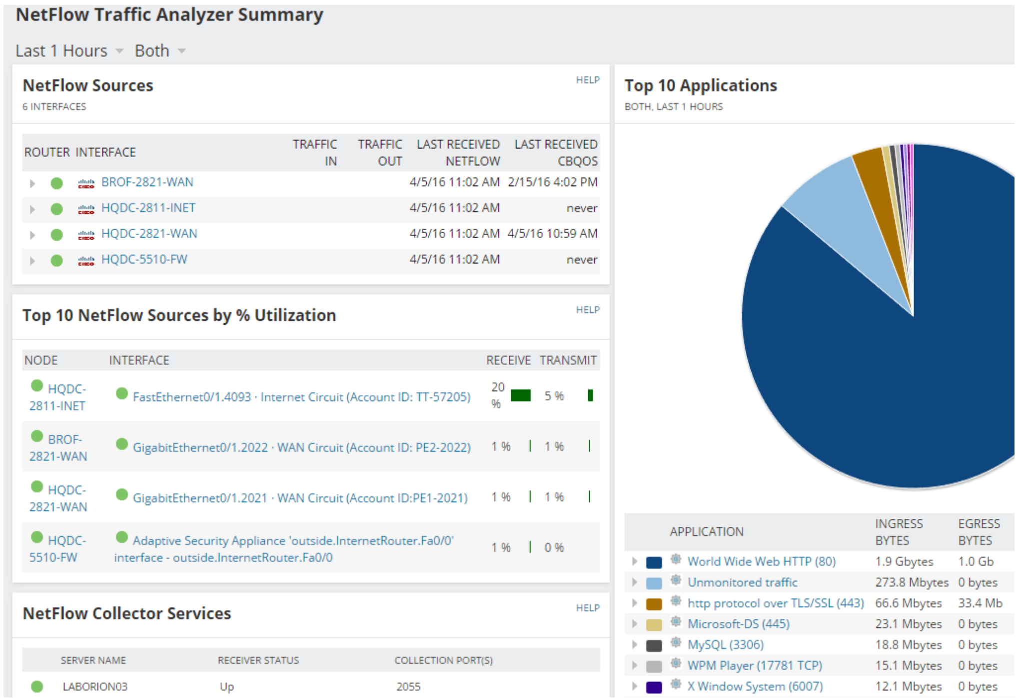
SUBNET NAME	% IP SPACE USED	IPS AVAILABLE	IPS USED
10.1.0.0 /24	100.00%	0	117
10.10.100.0	100.00%	0	2
VoIP_Austin2	82.03%	46	208
10.199.1.0 /24	62.89%	95	160
10.199.6.0 /24	61.72%	98	157
10.199.2.0 /24	59.38%	104	141
10.199.15.0 /24	56.64%	111	144
14.26.23.0 / 255.255.255.0	55.86%	113	37
80.0.0.0	54.30%	117	135
192.168.0.0 / 255.255.255.0	53.91%	118	130

Top 10 Subnets with Transient Addresses

SUBNET NAME	% IP SPACE USED	IPS AVAILABLE	IPS USED
10.1.0.0 /24	100.00%	0	117
10.199.2.0 /24	59.38%	104	141
14.26.23.0 / 255.255.255.0	55.86%	113	37
192.168.0.0 / 255.255.255.0	53.91%	118	130
10.199.5.0/24	53.91%	59	51
10.199.16.0 /22	43.07%	583	438
VoIP_Austin1	42.19%	148	102
5.0.0.0 / 255.255.255.0	41.80%	149	49
WIFI_Cork	24.61%	193	60
VoIP_Tulsa	5.08%	243	10

A screenshot of the NetFlow Traffic Analyzer is displayed in Figure 10.

Figure 10. SolarWinds NetFlow Traffic Analyzer. Source SolarWinds (n.d.b.).



The NetFlow Traffic Analyzer (NTA) provides network traffic analysis and bandwidth monitoring. It is capable of displaying bandwidth use by user, application, protocol or IP address group and can generate customizable network traffic reports. One feature that will be particularly useful in a MANET is the wireless LAN controller traffic monitoring, which shows the applications and nodes utilizing bandwidth on a wireless network. Finally, the program contains network traffic forensics for analyzing traffic patterns over periods of time (SolarWinds, n.d.b.).

These programs provide the tools necessary to effectively monitor a MANET with multiple nodes since the participating units will not always be a fixed number.

C. PANDARRA NET

Pandarra Net took place in two phases. Phase I focused on the installation and end-to-end operation of the network infrastructure on LCS-3 and *USS Warrior (MCM-10)* to transmit data over a 4G LTE Network designed by Oceus. The O3b (Other 3 Billion) long-haul backbone to public Internet services ashore connected to a Wi-Fi network on LCS-3. This connection was a separate network from NIPRNET and operated as an unclassified (UNCLAS) network. The Wi-Fi and 4G LTE network were separate networks that could not communicate with one another. Thus, the Wi-Fi network on LCS-3 was limited to traffic on that ship, and could not function as a repeater to transmit data from MCM-10 to the public Internet.

In Phase II, LCS-3 connected its NIPRNET to O3b's long-haul system. This connection was used in place of its program of record system associated with the Super High Frequency (SHF) Commercial Broadband Satellite Program (CBSP). The throughput of O3B was expected to be much higher, but the results were not indicative of this, which raised other concerns about whether or not the Navy's shore-side network architecture could support a high-speed bandwidth provider. It is an issue of concern but beyond the scope of this research. An overview of both phases and network equipment is shown in Table 2 and Table 3.

Table 2. Phase I and II Overview. Source: United States Seventh Fleet (2016).

	Phase I	**Phase II**
O3b SATCOM Integration with ship's network	None	Passed ship's SIPR and NIPR traffic
Mobile Device integration with ship's network	None	4G LTE connected to FTW Secret network via a file server
O3b SATCOM	UNCLAS only; Connected to public Internet	Replaced ship's existing SHF SATCOM Connected to shore SIPR and NIPR
4G LTE	UNCLAS only	Secret only
Wi-Fi	UNCLAS only	None
CODA-LITE	4G LTE and Wi-Fi	4G LTE
Pacstar & TACLANE	No	Yes
MANET	Yes	No

Table 3. Devices Used during Pandarra Net in Phase I and II. Source: United States Seventh Fleet (2016).

Device	Phase I Quantity	Phase II Quantity
Samsung Note II cell phones	12	5
Dell tablets (Wi-Fi)	4	N/A
Panasonic TouchPads (4G LTE)	N/A	4
HP Laptop supporting LRTV	1	1
HP Laptops for Public Internet Usage (Wi-Fi only)	4	N/A
LRTV (video camera)	1	1

1. O3b

O3b is a commercial satellite company that launched its initial constellation of Medium Earth Orbit (MEO) satellites in March 2014. A technical overview of satellites operated by the company is as follows: they currently maintain 12 satellites, each equipped with 10 steerable beams for customers and 2 beams for IGW ground stations; the channel bandwidth is 216 MHZ; a steerable beam covers a 700 km diameter and uses bent-pipe topology to connect customers with O3b's IGWs; the frequency band for downlink is 17.7–20.2 GHz, and uplink is 27.5–30 GHz (Barnett, 2013). Additional information on standard operating equipment parameters is listed in Appendix A. The advantages of this satellite network is a low latency, high throughput system that has achieved downlink speeds upwards of 400 Mbps in seagoing environments. One of the goals of the company is to provide high-speed data rates to areas of the world where coverage is not currently available. The regions of the world currently covered by O3b's constellation are between +/- 65 degrees latitude; it claims to be capable of servicing over 90% of DOD facilities and AORs with this coverage (D'Ambrosio, 2015). The company has worked closely with DOD agencies, including Space and Naval Warfare Systems command (SPAWAR). O3b's field experiments range from those conducted with U.S. Navy assets as well as those carried out with Special Forces Command (SOCOM) and the United States Marine Corps (USMC) on terrestrial applications. The range of O3b experimentation may be a precursor to eventual DOD acceptance of commercial systems as a viable alternative or supplement to Program-of-Record systems.

O3b envisions it will one day provide data services to U.S. Naval platforms at 50 times the throughput of current Super High Frequency (SHF) systems in use. O3b's satellite constellation utilizes the Ka-Band, and with its lower orbits, company stakeholders claim that it will offer better latency and higher data speeds than geostationary satellites. Improved data transfer is critical to the success of the LCS platform, which is currently equipped with aging SHF terminals, and relies on higher data throughput to push information on the health of onboard equipment to maintenance teams on the shore side to maintain optimal crew manning. Without delving into the many underlying examples of how an LCS requires additional bandwidth when compared to other USN platforms of similar design and mission, it is safe to opine that increased data throughput and availability offers advantages across the spectrum of LCS operations.

Assuming the speeds above are realistic, an LCS would be well-suited to make use of O3b's technology to augment its data needs as well as serve as an IGW to networked nodes in its operating vicinity.

2. Oceus Networks 4G LTE

Oceus, similar to O3b, is a commercial company that has a record of conducting proof-of-concept network and communications experiments with U.S. Navy assets. In an experiment conducted in 2013 with Naval Air Systems Command (NAVAIR), the *USS Kearsarge* and *USS San Antonio* were able to use 4G to integrate data streams between the two ships as well as deployed aircraft (Crowe, 2013). The system used microwave technology to create wireless wide-area network (WWAN) connectivity between nodes (ships and aircraft) and enabled individuals to connect commercial off-the-shelf devices through local access points within the nodes. Transfer speeds between devices were recorded as high as 100Mbps for downlink. For 4G to operate effectively within the hull of a ship, multiple antennas needed to be installed to overcome the detrimental effects on RF propagation from closed hatches and thick bulkheads. An LCS, with limited real estate for antennas on its superstructure as well as interior, may find this restrictive. However, the system has shown its effectiveness at sea and may only need a redesign to make it a viable solution for communications to support various mission areas. The Oceus 4G LTE network used in Pandarra Net 2015 also formed a MANET for small boat operations, demonstrating a practical application for Visit Board Search and Seizure (VBSS) missions (Crowe, 2013).

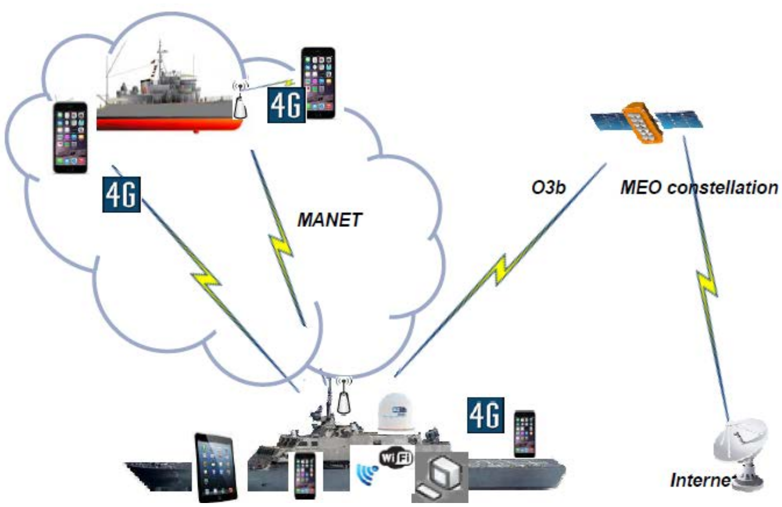
3. Phase I

Pandarra Network in Phase I consisted of three main components: Wi-Fi, Oceus Networks 4G LTE bubble, and O3b Satellite services. The experiment required the installation of specialized equipment to enhance both ships' internal and external network architecture. The installation consisted of a fiber-optic cabling architecture developed by SPAWAR, known as the Common Optical Digital Architecture (CODA) Lite, and wireless node access points that were able to form an UNCLAS network mostly within the skin of the ship. The 4G LTE network was used to connect authorized devices to this network—these devices are listed in Table 2. The external equipment used to connect with O3b's MEO satellites consisted of two 1.2M dishes, displayed in Figure 11, on port and starboard sides of the superstructure. The layout of the entire system is shown in Figure 12. Through this UNCLAS network on the LCS-3, the crew was able to connect to the Internet via approved devices and conduct high bandwidth transactions such as video teleconferencing with family members back home, stream live video, and stream high-definition (HD) subscription services such as Netflix.

Figure 11. 1.2M O3b Radome. Source: D'Ambrosio (2015).

The throughput of the system performed as well as—if not better than—expected by the NWDC team. On the UNCLAS network on LCS-3, the crew was able to connect to quality-of-life (QoL) Internet services without stressing bandwidth limitations. This ability was also because this network did not go through any DOD network architecture on the shore-side, it went through O3B's satellite network which routed it to the public Internet via a ground station in Perth, Australia.

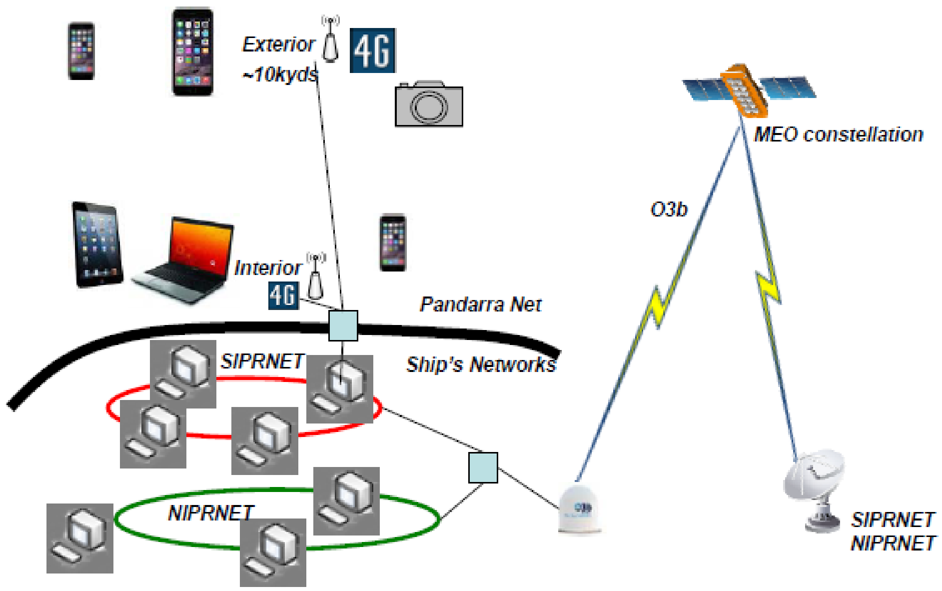
Figure 12. Pandarra Net Configuration in Phase I. Source: United States Seventh Fleet (2016).



4. Phase II

Phase II encompassed the integration of LCS-3's NIPRNET and SIPRNET with the O3b long-haul satellite communications system via connection through Pandarra Net and LC-3's shipboard network. The network configuration is displayed in Figure 13. This phase used the approved 4G LTE bubble—not to be confused with Wi-Fi—to attempt to connect SIPRNET to the shore-side through O3b's backbone. The 4G LTE could have also been configured to connect NIPRNET through O3b's backbone, but it would have required separate routers and equipment to prevent classification spillage. As such, the experiment only connected SIPRNET to 4G LTE during Phase II in light of hardware and time constraints. NIPRNET on the ship's network accomplished via wired connection. The primary finding in this phase was that routers or other intermediate equipment on the shore-side might have been misconfigured because the system had slower speeds than originally anticipated. The findings indicated that the overall throughput was only about twice as fast as the traditional SHF system. The throughput of O3b integrated with SIPRNET was not able to be measured directly due to bit-rate measuring applications being unavailable on the classified network. With this being the case, the experiment team sent a file of a prescribed length to the shore side and measured the length of time for completion to get a rough estimate.

Figure 13. Pandarra Net Configuration in Phase II. Source: United States Seventh Fleet (2016).



5. Pandarra Net Design and Implementation Challenges

The case for computer simulation as a supplement to real world C4I experiments can be made based on the policy and technical challenges faced during the Pandarra Net experiment. DON IT governing policy and administrative issues are not a primary theme of this thesis, but it is important to note that these can influence real-world experiment objectives and outcomes. One method to overcome these hurdles is to rely more heavily on simulation before conducting exercises. The parameters of equipment and devices selected for Pandarra Net can be modeled into commercially available simulation software tools, described later in this chapter. Once a basic model is developed, it can be adjusted and reused accordingly. An underlying notion of this thesis is that innovative C4I experiments should be modeled in simulation software before Fleet experimentation to compare and contrast with real world performance.

The research design of this thesis, in part, models different simulation experiments based on the observed equipment capabilities and performance of the LCS as a wireless node during Pandarra Net 2015. Additionally, a recommendation for network management software can be made based on the data gathered from these experiments.

D. QUALNET

1. Overview

QualNet was designed and is regularly updated by the company Scalable Networks. It is a flexible software application that can model wireless and wired network nodes. The primary advantage of this software is its compatibility with other simulation programs, allowing it to be the driving engine behind the operation of protocols and applications within the 7 OSI Layers. Alternatively, Systems Tool Kit (STK) software simulates the physical positioning of nodes as they move about between predetermined points on a plot in San Francisco Bay. Layer 4 (Transport) and lower will be the layers examined for the purpose of this research. The data packets used in the simulation will be injected, using size and characteristics of those observed from previous field experiments.

An advanced version of QualNet, EXata, allows users to emulate networks. This functionality allows real-world network nodes to interact with a simulated network. Also, network management applications can interface with a simulated network via plug-ins.

The software version used to simulate the network is QualNet 7.3 and contains device libraries obtained through an educational license between the researchers and Naval Postgraduate School Information Sciences Department. The libraries define parameters for frequencies, protocols, and packet routing information for wireless and wired equipment to be used in the experiment. The educational license models utilized for this thesis are the wireless and developer's library. While this non-commercial license provided the necessary libraries to conduct the experiment, it limited the number of nodes to 50 that could be simultaneously simulated. While building the scenarios, the limited number of nodes did not place any additional constraints on the experiment.

2. LTE Library

The Long-Term Evolution (LTE) library, purchased to supplement experimentation involving MANET, was used to expand the data collection of simulations in QualNet and STK. In QualNet, the LTE library provides an accurate simulation of 4G cellular networks, based on the 3GPP release 9 standards. The software consists of three models. The PHY model, Layer 2 model, and Evolved Packet Core

(EPC) model. First, the LTE PHY models are based on the 3GPP 36.3XX architecture, which specifies Evolved Universal Terrestrial Radio Access (E-UTRAN), physical models. The main functions of this model follow.

- Downlink transmission/reception using OFDMA
- Uplink transmission/reception using SC-FDMA
- Coding/decoding, modulation/demodulation
- Multi-antenna operation (MIMO)
- CQI/RI/PMI reporting
- Power control
- Cell selection
- Random access
- Measurements (Scalable Network Technologies, 2014c)

Next is the Layer 2 model, which is also based on the 3GPP 36.3XX architecture that specifies E-UTRAN MAC and higher layer models. The Layer 2 model consists of following three sub-layers.

- Packet Data Convergence Protocol (PDCP): Handles ciphering, header compression and packet forwarding upon handover.
- Radio Link Control (RLC): AM data transfer, concatenation, segmentation and reassembly, re-segmentation and reordering of data PDUs.
- Media Access Control (MAC): Multiplexing/demultiplexing of SDUs into/from transport blocks, radio resource scheduling, and buffer status report.

Additionally, this layer includes the Radio Resource Control (RRC) that is responsible for connection management, handover control and measurement control (Scalable Network Technologies, 2014c).

The final layer in the LTE model library is the LTE Evolved Core Packet (EPC), Model. The EPC model is based on the 3GPP 36.423 and 3GPP 36.413 architecture which specifies X2 Application Protocol (X2AP) and S1 Application Part (S1AP). In the

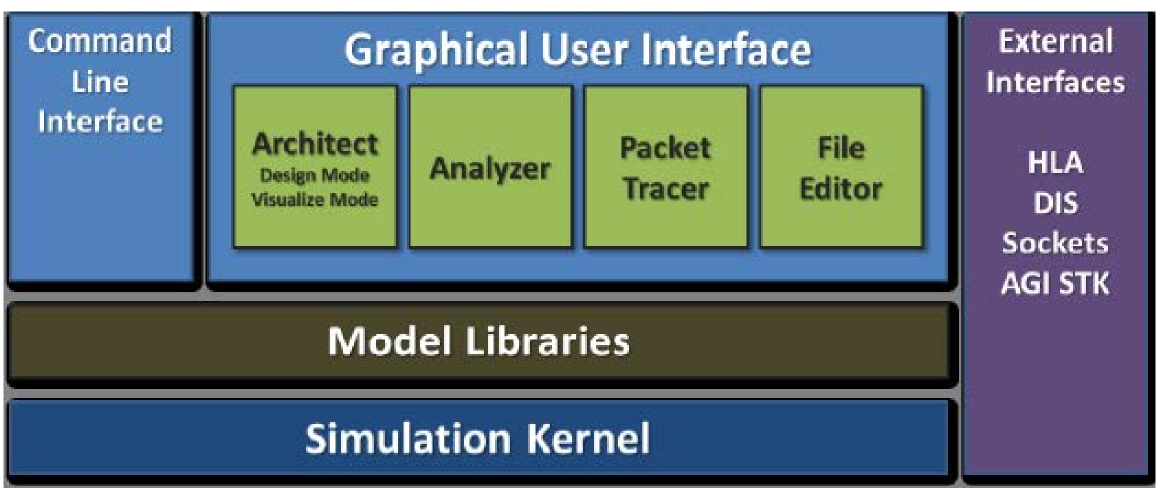
LTE library, EPC is a framework for providing converged voice and date on a 4G LTE network. The primary functions of the EPC are:

- Handover decision
- Admission control
- Management downlink data path
- X2AP: Messages exchanged on the X2 interface
- S1AP: Messages exchanged on the S1 interface (Scalable Network Technologies, 2014d)

The use of the QualNet LTE Model Library will further enhance the four scenarios created to test the LCS as a major node and is a valuable addition to the research in this thesis.

Scenarios, (i.e., network topologies), are created by using a Graphical User Interface (GUI) or Command Line Interface (CLI) for node placement and general parameters are used throughout each scenario. The architecture of QualNet and its interfaces are shown in Figure 14.

Figure 14. QualNet Architecture. Source: Scalable Network Technologies (2014f).



3. QualNet Statistics

Upon completion of a simulation run, QualNet generates a statistics file based on the 7-layer OSI model configuration for nodes and applications run between them. The data collected in this report is in an aggregate format, displaying packets sent, received, or lost over the total run time of a simulation. The statistics and descriptions primarily used for determining the effectiveness of an LCS as a major node are illustrated in Table 4. The statistics file can be displayed in the STK/QualNet GUI, allowing the option of toggling unwanted statistical data on or off. Also, the .stat file can be imported to a Microsoft Excel Workbook. The Excel Workbook displays all data in raw format, including null values of statistics not collected. Additional useful statistics are listed in Appendix C.

Table 4. QualNet Statistics and Descriptions. Source: Scalable Network Technologies (2014f).

Model/Layer	**Statistic**	**Description**
Satellite-RSV PHY	Signals transmitted	Number of signals transmitted by this physical layer process.
Satellite-RSV PHY	Signals received and forwarded to MAC	Number of signals received by this physical layer process and subsequently forwarded to the MAC layer for further processing.
Satellite-RSV PHY	Signals locked on by PHY	Number of signals that triggered logic to lock the transceiver onto an incoming signal.

Model/Layer	Statistic	Description
Satellite-RSV PHY	Signals received but with errors	Number of signals received that were successfully received by the MAC but had errors due to interference or noise corruption.
Satellite-RSV PHY	Average Eb/No (dB)	Average EB/No of the channel
Satellite-RSV MAC	UNICAST packets sent to the channel	Number of unicast packets sent to the channel
Satellite-RSV MAC	BROADCAST packets sent to the channel	Number of broadcast packets sent to the channel
Satellite-RSV MAC	UNICAST packets received from channel	Number of unicast packets received from the channel
Satellite-RSV MAC	BROADCAST packets received from channel	Number of broadcast packets received from the channel
802.11 a/g PHY	Signals transmitted (signals)	Number of signals transmitted
802.11 a/g PHY	Signals detected (signals)	Number of signals detected by PHY
802.11 a/g PHY	Average path loss (dB)	Average path loss
LTE PHY	Signals transmitted by the node.	Total number of signals transmitted

Model/Layer	**Statistic**	**Description**
LTE PHY	Transport blocks received and forwarded to MAC	Total number of transport blocks received and forwarded to MAC for the node.
802.11 MAC	Packets from network	Total number of packets received from the network layer.
802.11 MAC	Unicast packets sent to channel	Total number of unicast packets send to the channel
802.11 MAC	Broadcast packets sent to channel	Total number of broadcast packets send to the channel
802.11 MAC	Unicast packets received clearly	Total number of unicast packets received form the channel
802.11 MAC	Broadcast packets received clearly	Total number of broadcast packets received from the channel
802.11 MAC	Unicasts sent	Total number of successful unicast packets sent to the channel
802.11 MAC	Broadcasts sent	Total number of successful broadcast packets sent to the channel
802.11 MAC	Unicasts received	Total number of successful unicast packets received from the channel

Model/Layer	**Statistic**	**Description**
802.11 MAC	Broadcasts received	Total number of successful broadcast packets received from the channel
LTE MAC	Number of packets from Upper Layer.	The number of PDCP SDUs received from the upper layer
LTE MAC	Number of packets from Upper Layer but discard	The number of PDCP SDUs received from the upper layer, but can be discarded for the following reasons: Not connected. Broadcast packet (not supported).
LTE MAC	Number of packets to Lower Layer	The number of PDCP PDUs transmitted to the lower layer
LTE MAC	Number of packets from Lower Layer	The number of PDCP PDUs received from the lower layer
LTE MAC	Number of packets to Upper Layer	The number of PDCP PDUs transmitted to the upper layer.
AODV Network	Number of Data packets sent as Source	Number of data packets sent as the source of the data
AODV Network	Number of Data	Number of data packets

Model/Layer	Statistic	Description
	Packets Forwarded	forwarded
AODV Network	Number of Data Packets Received	Number of data packets received as the destination of the data
AODV Network	Number of Data Packets Dropped for no route	Number of data packets dropped due to lack of route.
LTE Network	Number of handover request sent	The number of Handover Requests sent. This statistic is collected only for eNB nodes
LTE Network	Number of handover request received	The number of Handover Requests received. This statistic is collected only for eNB nodes
LTE Network	Number of handover request acknowledgment sent	The number of Handover Requests Ack sent. This statistic is collected only for eNB nodes
LTE Network	Number of handover request acknowledgment received	The number of Handover Requests Ack received. This statistic is collected only for eNB nodes
OLSR Application	Hello Messages Received	Total number of Hello Messages Received by the node

Model/Layer	**Statistic**	**Description**
OLSR Application	Hello Messages Sent	Total number of Hello Messages Sent by the node
CBR Application	First Unicast Fragment Sent (seconds)	Time in seconds, when first unicast fragment was sent
CBR Application	Last Unicast Fragment Sent (seconds	Time in seconds, when last unicast fragment was sent
CBR Application	Total Unicast Fragments Sent (fragments)	Total number of unicast fragments sent
CBR Application	First Unicast Message Received (seconds)	Time in seconds, when first unicast message was received
CBR Application	Last Unicast Message Received (seconds)	Time in seconds, when last unicast message was received
CBR Application	Total Unicast Messages Received (messages)	Total number of unicast messages received
CBR Application	Unicast Received Throughput (bits/second)	Unicast throughput at the server (bits/second)

4. QualNet Application Layer Models

QualNet 7.3's simulated applications consist of models that can be added to nodes and customized with parameters that can be tailored to observe various aspects of network performance. The majority of applications allow the user to set the application start time, stop time, the size of data bytes, and the interval between transmitting items. The applications oriented toward the research on an LCS performing as a major node are listed in this section; additional applications are listed under Appendix A.

5. Constant Bit Rate (CBR)

The Constant Bit Rate (CBR) traffic generator creates items, or UDP segments, and transmits them at a steady rate within a set interval. The application can be configured to start or end at any time during a scenario. The CBR item size can be adjusted within QualNet defined upper and lower limits but is not necessarily meant to stress or test the limits of a network. In most experiments, it is useful for adding background traffic while testing other applications. In MANET and WMN settings, it is useful for testing routes, as unicast packets sent and received can be used as a metric for determining availability through UDP at the Transport Layer. Also, unicast throughput is measured in bits/second (Scalable Network Technologies, 2014e).

6. File Transfer Protocol/Generic (FTP)

The File Transfer Protocol (FTP) Generic is a traffic generator useful for simulating the exchange of established file sizes between a client and server. The number of files sent is set to a maximum number over a user-defined period. The application will terminate at the end of the prescribed length even if all files are not successfully transferred. If desired, the start and end time can be set to a value that will allow the FTP application to run throughout the entirety of a simulation, terminating when all files are sent. This application is capable of measuring unicast throughput from the client to the server like the CBR application, but using TCP/IP at the Transport Layer instead of UDP.

7. Super Application Traffic Generator

The Super Application Traffic Generator is capable of modeling different multimedia formats based on user input. The supported encoding schemes are listed in Table 5.

Table 5. Super Application Encoding Schemes. Source: Scalable Network Technologies (2014f).

Codec	Default Packet Size (Bytes)	Default Packet Interval (ms)
H.261	160	20
H.263	160	20
MPEG1.M	2500	20
MPEG1.H	7500	20
MPEG2.M	12500	20
MPEG2.H	37500	20
G.711	160	20
G.729	20	20
G.723.lar6.3	23	30
G.726ar32	80	20
G.726ar24	60	20
G.728ar16	40	30
CELP	18	30
MELP	8	22.5

This traffic generator is useful for testing the limits of a network's performance and is well-suited for simulating some of the applications that would be used in a real-world environment with the LCS performing as a major node.

E. EXATA

EXata is a network emulation program which has a GUI layout nearly identical to QualNet's. EXata differs from QualNet in its capabilities and features, including its enhanced capability to create an emulated network testbed on a server or workstation. For the purpose of experiment design, it will be used to enhance STK/QualNet scenarios built around the LCS and associated nodes through a proof-of-concept experiment proposal demonstrating the capability to interconnect network management software (NMS) with an emulated LCS node. EXata uses a Connection Manager Application, separate from the EXata application itself, to connect real-world devices to its emulated network. The devices connected to the network as emulated nodes can run a NMS or any other installed third-party application to inject network metrics into the testbed. The model libraries for nodes and interfaces in EXata, similar to QualNet, are comprised of devices that represent the following network elements according to the EXata 5.3 User's Guide:

- Routers
- Switches
- Access points
- Ground stations
- Satellites
- Cell phones
- Radios
- Sensors
- PCs
- Servers
- Firewalls

- Other security apparatus
- Communications links that interconnect the nodes (Scalable Network Technollgies, 2014a)

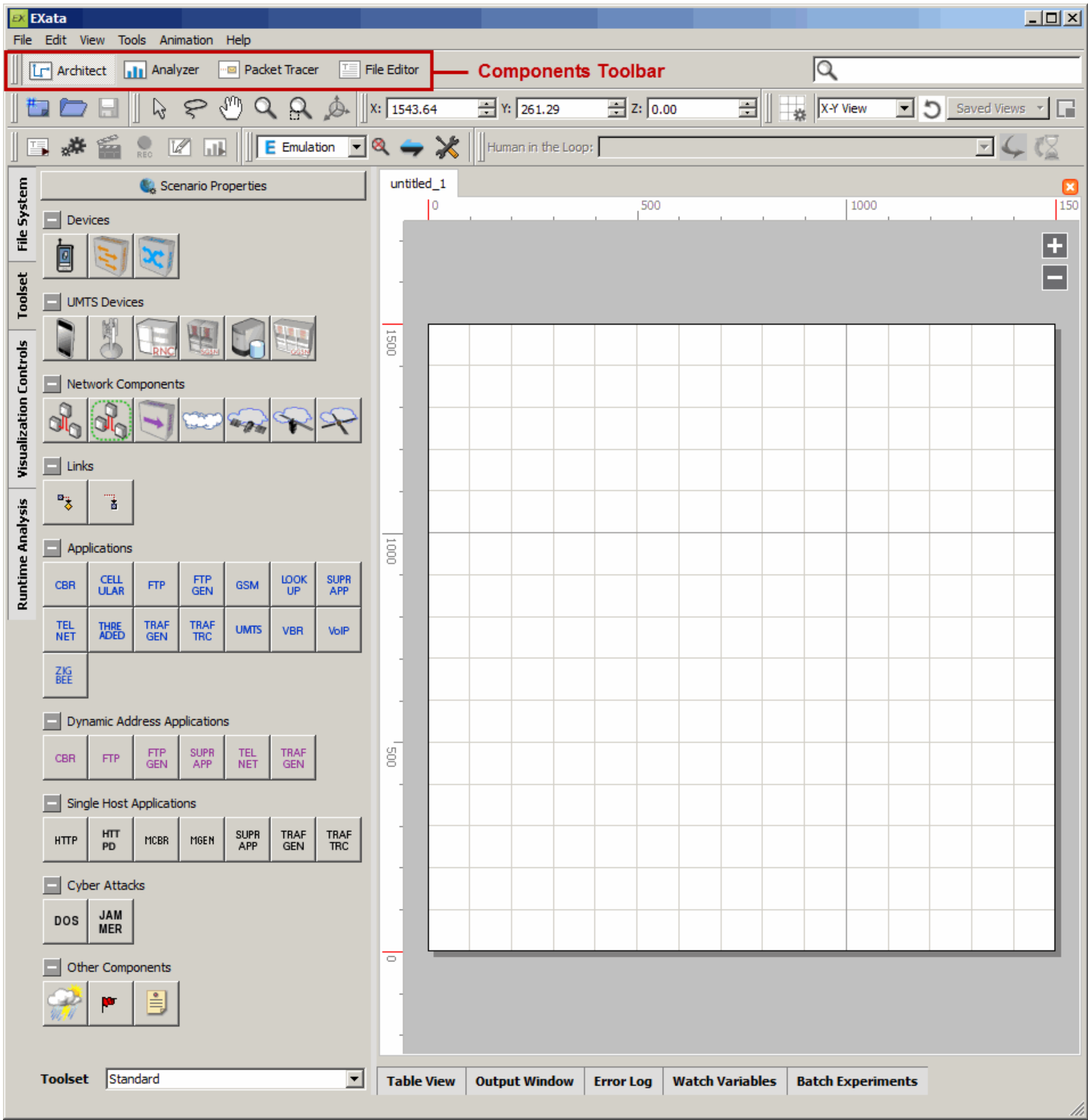
EXata can also be used for network design and architecture optimization, capacity prediction, RF interference and propagation modeling, mission planning, hardware and software development, communications problem identification and equipment scalability evaluation (Scalable Network Technologies, 2014a). Using this program will mimic the functionality of a real network, and provides a “high-quality reproduction of external behavior so that the emulation is indistinguishable from the actual system” (Scalable Network Technologies, 2014a). The use of emulation provides an environment which quickly shows the impact of design decisions, and how applications will perform in the real world (Scalable Network Technologies, 2014a).

Simple Network Management Protocol (SNMP) capability is an additional feature EXata provides which QualNet does not. The software can enable the addition of SNMP agents and the upload of SNMP configuration files on both simulated and emulated nodes. The SNMP functionality enables NMS, such as SolarWinds, the ability to detect these nodes and add them to a Manager Database (MDB).

EXata offers many benefits over QualNet. However, Scalable Networks does not offer an educational license version of it. Research using EXata was limited in scope to what could be accomplished with a two-week trial version provided by the company.

A screenshot of EXata is displayed in Figure 15.

Figure 15. EXata Screenshot. Source: Scalable Network Technologies (2014b).



Other key program features and capabilities follow:

- Develop simulation models for network technologies.
- Develop communications protocol models using the OSI-style architecture of the EXata protocol stack.
- Develop wireless networks of real-world size.
- Perform what-if analyses: Analyze the performance of networks and perform 'what-if' analyses to optimize them.

- Connect real networks, applications, and devices with EXata emulated network.
- Manage an emulated network with the SNMP agent, which enables the use of standard SNMP managers to view, monitor and control emulated networks. (Scalable Network Technologies, 2014a, p. 2-4)

Scenarios can be built from scratch or from the libraries in EXata which contain a variety of real-world and network components. EXata comes with a default set of libraries, including the Network Management, Wireless, Cellular and LTE libraries that were used in the four scenarios designed for this thesis (Scalable Network Technologies, 2014a).

Due to restrictions on the Naval Postgraduate School network, EXata will not be used for this research but should be considered for future work.

F. SYSTEMS TOOL KIT

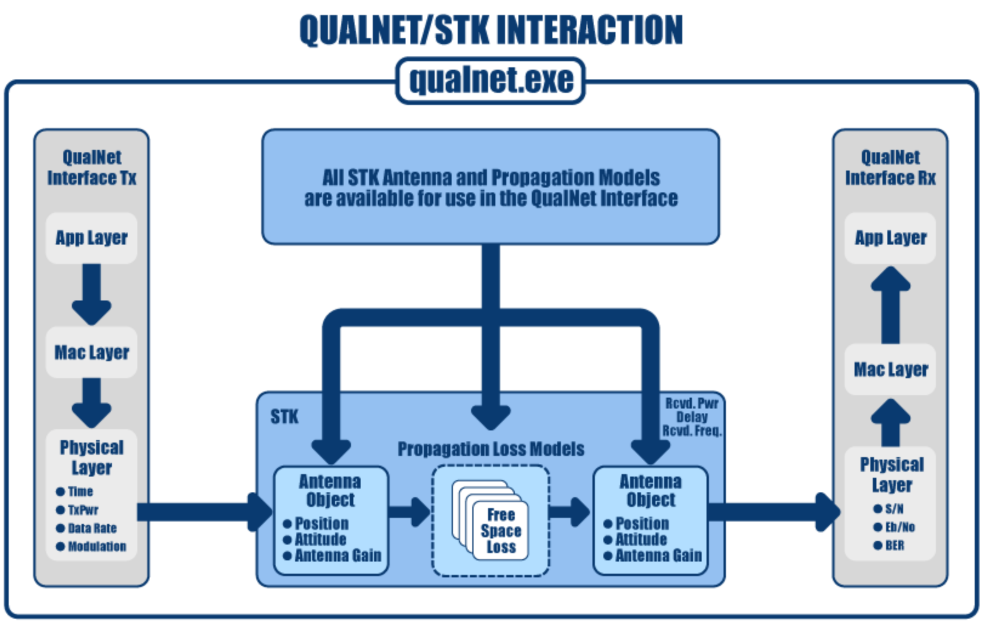
Systems Tool Kit (STK) is a modeling software developed and periodically updated by Analytical Graphics Incorporated (AGI). The software's primary use is for the modeling of communication satellite performance with ground stations, but it has since grown into a robust palette capable of modeling communications between a combination of ground, air, sea and space communication nodes. STK 11.1, the most current version at the time of this study, allows a user to interface many software applications with STK, including unlicensed third-party programs. The robust capabilities of the software suite create opportunities for integrating network management software overlays. Also, STK's output feeds into servers that can translate XML, such as the CENETIX SA Server. This capability allows for the merging of actual network nodes used in field experimentation with simulated network nodes.

STK uses object-oriented software to enable a user to place objects, in the form of locations or vehicles, on a geodetic representation of the Earth. Models are viewed as scalar representations in either two-dimensions (2D) or three-dimensions (3D). Objects can also be placed on other objects, such as antenna objects on a ship object, tying the positional characteristics of antenna objects to their hosting platforms. For example, if a mobile parent object moves throughout the simulation, the child object attached to it is carried with and is affected by the same weather conditions, terrain or signal reception.

STK has a database of ship and vehicle models that can be downloaded to a software library for inclusion in scenarios. The online database contains models of both the Freedom and Independence class variants of the LCS, as well as other manned and unmanned U.S. Navy platforms. The extensive library of military platforms available for simulation enables testing a broad range of routing protocols and data rates.

A primary reason for choosing STK is its compatibility with QualNet, which allows for a more in-depth analysis of nodal performance between the LCS and connected assets. The interaction between QualNet and STK is shown in Figure 16.

Figure 16. QualNet/STK Interaction. Source: Scalable Network Technologies (2014f).

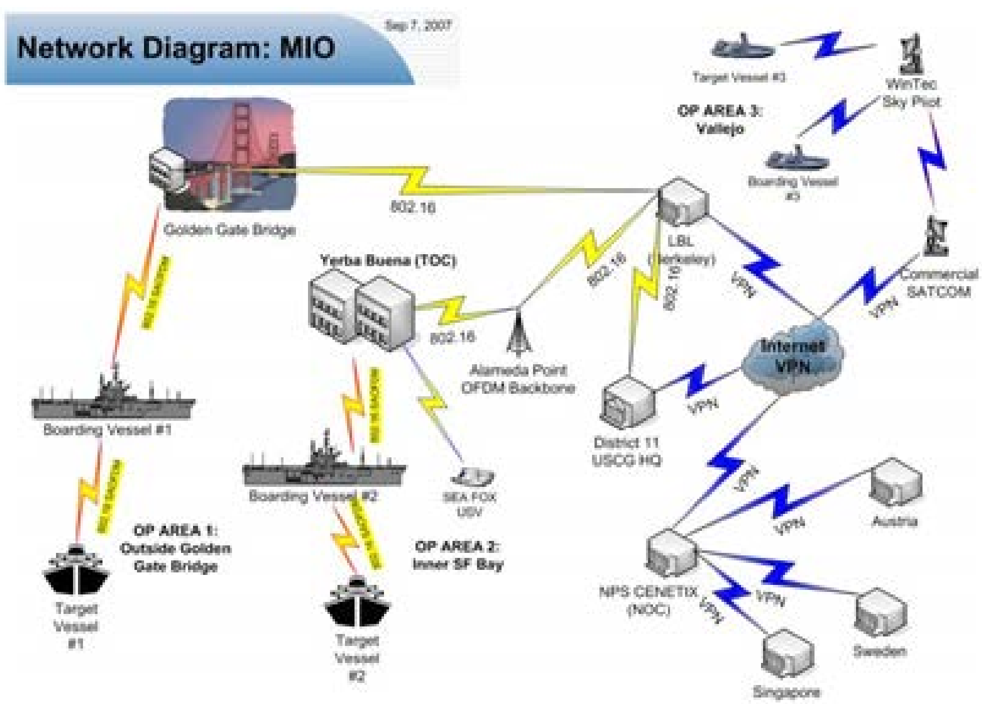


G. CENETIX TACTICAL NETWORK TESTBED

1. Tactical Networking Testbed (TNT)

The purpose of integrating data from previous experiments in the TNT is to determine the effectiveness of the Littoral Combat Ship (LCS) platform as a major node with interconnected vessels, both manned and unmanned, that would perform operations in the littorals. Simulated network configurations are used to obtain data on performance at the optimal bandwidth levels. Navy ships rely heavily on satellite communications, which will be utilized in modeled networking configurations to provide off-ship communications in addition to the more flexible mesh networks used by the LCS and other vessels that make up the simulated testbed environment. In this thesis, the feasibility of using a current LCS architecture and platform as an Internet gateway for multiple vessels will be examined as a possibility of particular interest use during operations in the littorals. While there will be multiple benefits to the proposed configuration, the main advantage is improved and uninterrupted command and control of multiple vessels. Simulations of these settings will be based on the tactical networking testbed (TNT) environment. The TNT has several benefits including the integration of people, networks, sensors and unmanned systems and also the ability to incorporate plug-and-play, tactical and unmanned systems networking capabilities with global reach back (Bordetsky & Netzer, 2010). The simulated scenarios in this thesis will take advantage of the San Francisco Bay environment to include manned and unmanned vessels and several land-based sensors. While the configurations may vary, the TNT environment can be configured for a wide variety of scenarios, and a typical test configuration will include data exchange in the forms of video, audio and text files. During these tests, the primary metrics will focus on network performance with moving nodes and determining whether or not the wireless mesh network is properly healing itself should a node drop offline. The main goal is to determine the effectiveness of the LCS as a major node with a variety of network configurations, utilizing the capability and flexibility of the platform to test available communications paths in a wireless mesh network configuration. There are tremendous tactical and operational advantages to always being connected. Using previous experimentation in the TNT as a stepping stone to test traditional and novel communication configurations is one of the major drivers of this research. The work in this thesis will primarily focus on the maritime portion of the TNT, particularly maritime interdiction operations (MIO). The following network diagram (Figure 17) is an example of a configuration that will be simulated in the research (Bordetsky & Netzer, 2010).

Figure 17. Sample MIO Network Diagram. Source: International C2 Journal (2010).



The TNT also allows for the monitoring of network performance, the identification of downed nodes and notification of new nodes in the network. Accessing the TNT can be accomplished by the following methods.

- Combining sensors and mesh networking elements in the closed IP space of the TNT testbed with fixed IPv4 or IPv6 addresses
- Connection via remote local area network (LAN), including command or operations centers through VPN
- Sensor and unmanned vessel/vehicle integration via the application layer interoperability interface
- Access via a collaborative portal or peer-to-peer collaborative clients and VTC (Bordetsky & Netzer, 2010)

Nodes equipped with Wave Relay devices use Orthogonal Frequency Division Multiplexing (OFDM) for participation in the WMN or MANET. In Ka Ki Yeung's thesis, *Detailed OFDM Modeling in Network Simulation of Mobile Ad Hoc Networks,* he explains that one benefit of OFDM is that it converts a wideband signal into a series of independent narrowband signals and places them side-by-side in the frequency spectrum. Using OFDM is also beneficial since the subcarriers in a particular frequency band can overlap (Yueng, 2003). Used on the physical layer, OFDM is an encoding technology for transmitting signals via RF (Abdullah, Ahmed, & Mandal, 2012). Additionally, OFDM eliminates the problem of multipath propagation due to its low date rate per subcarrier, which is a fraction of a conventional single carrier system with similar throughput and is a major advantage of OFDM modulation (Yeung, 2003). Other studies showed the use of adaptive OFDM in ad hoc networks improves the energy performance of mobile nodes. The performance gains were noted when adaptive OFDM was used on the physical layer (Abdullah et al., 2012).

These means of access allow for a variety of monitoring to not only view video feeds but network performance as well. The TNT remains a solid platform that will be used to determine the optimal configuration for wireless mesh networks with littoral combat ships serving as the primary Internet gateways.

2. San Francisco Fleet Week

Fleet Week is an annual event that occurs in San Francisco Bay during the month of October. Since its inception in 1981, select U.S. and foreign naval vessels arrive to participate in maneuvers at sea in the surrounding waters with a follow-on public affair gathering ashore (Zamora, 2014). In recent years various LCS hull numbers have taken part in this event. This point is notable because, with proper coordination between NPS research associates and LCS program stakeholders, a visiting LCS may be involved in a CENETIX TNT experiment to gather real world data on the vessel's performance as a major node. A CODA-Lite system as well as fly-away kits, similar to what was used during the Trident Warrior experiment, could provide valuable data if installed on Fleet Week vessels and interfaced with the TNT.

The design for the STK simulation is based on such a theoretical real world experiment. The vessels and platforms chosen to interface with the LCS as a major node in the simulation are those that, wherever possible, would normally participate in Fleet Week in addition to platforms that have been used in past TNT experiments.

H. UNMANNED VESSELS AND TACTICAL CONTROL DATALINK (TCDL)

To expand the WMN/MANET beyond the LCS and traditional manned ships or aircraft, unmanned vessels are employed to serve as additional network nodes. The two platforms utilized in the simulations are the RQ-8 Fire Scout unmanned aerial vehicle, and the Seafox, an unmanned surface vessel. In real-world situations, either can be equipped with the network equipment required to operate in an existing WMN or MANET. With the addition of the Tactical Control Datalink, either platform can relay various types of data back to an afloat operations center, which in simulations is the LCS.

The Navy's RQ/MQ-8B Fire Scout is the first unmanned vehicle of its kind and possesses the ability to perform vertical takeoffs and landings on any aviation-capable ship. It can also monitor targets up to 150 nautical miles out and report time-critical data (Cubic, 2013). Additional capabilities, to include communications relay capability, make the Fire Scout a platform that can easily be integrated into an existing MANET (Cubic, 2013).

The Seafox is an unmanned surface vessel, built on a 17-foot, aluminum rigid hull inflatable boat (RHIB) platform. In the current configuration, they deploy with communications hardware allowing for remote control and wireless networking capabilities (Naval Postgraduate School, n.d.b.).

Utilizing a TCDL, either platform is capable of not only communicating with an LCS or land-based operating center but also imagery collection, intelligence gathering, and precision targeting. Detailed specifications for TCDL are shown in Figure 18.

Figure 18. TCDL Terminal Specifications. Source: Cubic (2013).

AIR DATA TERMINAL (ADT)

Key Features

- Ku-band CDL transceiver
- 200 kbps to 44.73 Mbps
- CDL specification 7681990-compliance
- Internal encryption
- Omnidirectional and directional antennas
- Ethernet, serial, and analog Interfaces (commercial standard, nonproprietary)
- Integrated video encoding (MPEG-2)
- Tested Interoperable with CDL terminals from other vendors

Performance Characteristics

Frequency	Ku-band (transmit & receive)
Data rate	200 kbps – 44.73 Mbps
Transmit RF power	10 Watts
Operations mode	Full-duplex
Interfaces	RS-170 analog video (input to ADT) Ethernet Analog audio (input & output)
Video	Analog NTSC
Encryption	Type 1

Physical Characteristics

Transceiver

Size	22.5" x 14.25" x 8.5"
Weight	37.8 lbs.
Power Consumption	260 W maximum
Primary Power	28 VDC
Vibration & Shock	MIL-STD-810F
EMI/EMC	MIL-STD-461E
Temperature	-40° C to +55° C

Directional Antenna

Size	8.0" dia. x 9" high (excluding connectors)
Weight	7.0 lbs.
Power Consumption	10 W maximum
Primary Power	28 VDC
Vibration & Shock	MIL-STD-810F
EMI/EMC	MIL-STD-461E
Temperature	-40° C to +55° C

Omni Antenna

Weight	0.33 lbs.

GROUND DATA TERMINAL (GDT)

Key Features

- Ku-band CDL transceiver
- 200 kbps to 44.73 Mbps
- CDL specification 7681990-compliance
- Internal encryption
- Omnidirectional and directional antennas
- Ethernet, serial, and analog interfaces (commercial standard, nonproprietary)
- Video decoding (MPEG-2)
- Interoperable with CDL Terminals from all vendors
- Optional ruggedized laptop display with control software

Performance Characteristics

Frequency	Ku-band (transmit & receive)
Data Rate	200 kbps – 44.73 Mbps
Transmit Power	10 Watts
Antenna Gain	39.6 dBi (directional), 0 dBi (omni)
Operating Mode	Full-duplex
Interfaces	RS-170 analog video (output from GDT) Ethernet Analog audio (input & output)
Video	Analog NTSC output
Encryption	Type 1

Physical Characteristics

Remote Antenna

Size	60" high x 56" diameter tripod foot circle
Weight	147 lbs.

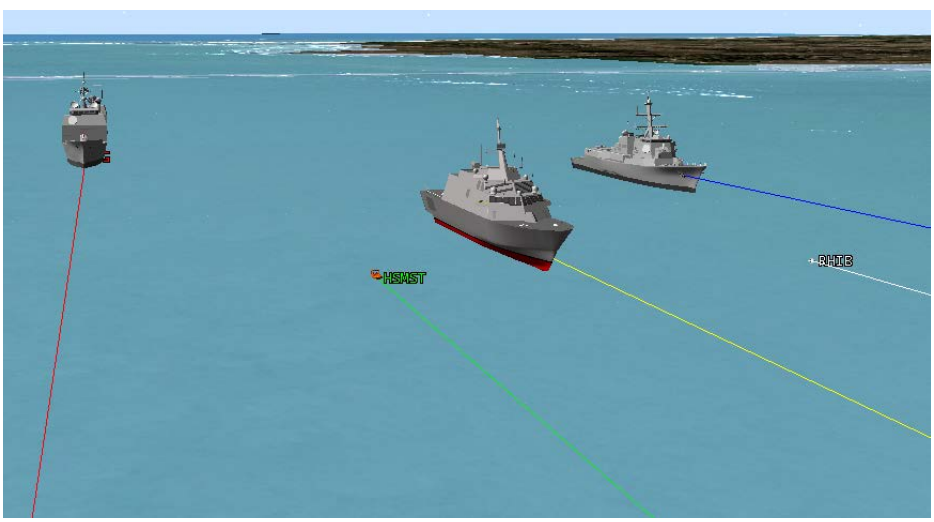
Modem Assembly

Size	22.5" x 23.5" x 6"
Weight	29.7 lbs.
Power Consumption	35 W (supplied by power supply)
Power	28 VDC
Vibration & Shock	MIL-STD-810F
EMI/EMC	MIL-STD-461E
Temperature	-40° C to +55° C

III. RESEARCH DESIGN

The simulation is designed around concepts from the two experiments described in Chapter II; Pandarra Net and the San Francisco Bay MIO/TNT event. Naval platforms typically participating in a Fleet Week were also utilized in the experiment. Four scenarios were designed to test LCS performance as a major node. Individual scenarios were created for the LCS to perform as a gateway, router, hub, and bridge. Each scenario used antennas and equipment identical or similar to those used in previous real-world experiments. Three U.S. Navy platforms were used in two of the four scenarios; a Freedom Class LCS, a Ticonderoga Class cruiser, and an Arleigh Burke-class destroyer. Depending on the scenario type, smaller unmanned and manned assets were used in addition to these baseline platforms. Figure 19 is a screen capture of some of the STK 3D models used in the SF Bay scenarios.

Figure 19. STK 3D Models Used in the SF Bay Scenario

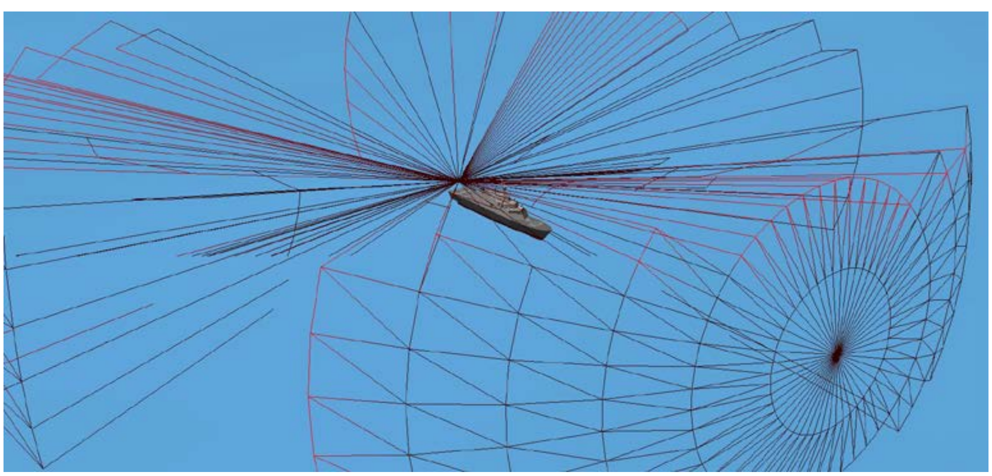


In the 2015 MIO experiment, the Coast Guard Station on Yerba Buena Island served as a NOC and was used as a surrogate LCS (Maupin, 2016). For simulation purposes, Yerba Buena Island will not be used as a NOC or surrogate LCS but can act as an additional node as necessary.

A. WMN

The mesh network in the simulation was comprised of antenna objects with characteristics as described in Chapter II. The STK simulation of Wave Relay's directional antennas consisted of three rectangular pattern antenna objects mounted on the stern of equipped vessels and hand-held isotropic radios for smaller, manned assets. Persistent System's Wave Relay over Internet Protocol (WRoIP), used on radios and devices in the mesh, is proprietary and not available for modeling via STK/QualNet. Due to this limitation, AODV is substituted for Wave Relay as the routing protocol at the MAC layer of WMN nodes in the STK/QualNet simulation. The Wave Relay nodes in the mesh, including the antenna on the LCS, formed their own subnet—this was the first autonomous system added to the scenario. In practice, ship ADNS networks also form autonomous systems when routed through long-haul RF paths back to a shore NOC in the same AOR. In the scenario, the LCS and connected nodes in the mesh formed an autonomous system at the operational front using the LCS as a NOC. Lastly, the LCS served as a gateway by bridging the mesh to another autonomous system, O3b's satellite constellation, and long-haul throughput. The LCS performing as a gateway is an important aspect of the research design due to its tactical and QoL implications. A wire frame displaying the propagation of the simulated Wave Relay Sector Antenna mounted on the deck of the LCS is displayed in Figure 20.

Figure 20. Wave Relay Sector Antenna Mounted on LCS



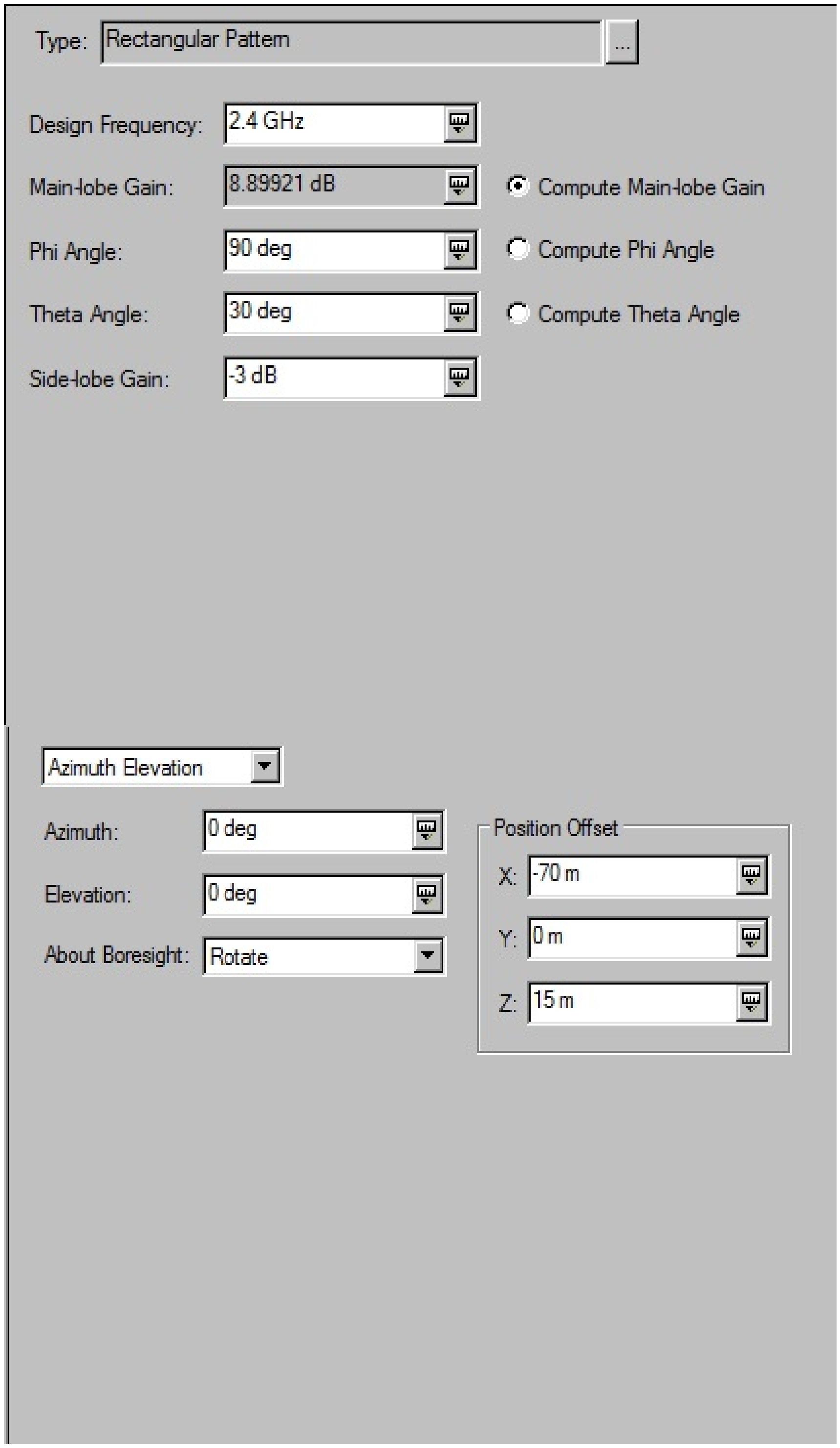
B. MANET

The MANET in the applicable scenarios was formed using 4G LTE technology. The LCS, equipped with a ZDA 1.5M Band 17 antenna and LTE core server, created an LTE bubble for data sharing among participating nodes. Devices connected to the bubble consisted of Samsung Galaxy Note II devices, band 4 antennas, and LTE enabled cameras and imaging devices. The STK/QualNet interface, through a purchased QualNet license, is capable of modeling LTE elements in a scenario.

C. SCENARIO 1: LCS PERFORMING AS A GATEWAY

The LCS in the simulation was equipped with two 1.2M satellite terminals as well as a Wave Relay Sector Antenna Array, containing three separate 120-degree directional antennas within its housing unit. In the simulation, the 1.2M satellite terminals are mounted on port and starboard side of the LCS on its upper level, and the Antenna Array is physically fitted to the flight deck. Although this may not have been the best location for efficient RF propagation paths, it is a realistic location based on the premise that the device would be set up ad-hoc in a real-world experiment. The maritime Wave Relay antenna in the scenario can easily be relocated to a mast yard arm or other location if needed. The physical mounting of attached antenna objects on models in STK is accomplished using a Cartesian coordinate system in relation to the model. The STK parameters of a mounted Wave Relay Sector Antenna are displayed in Figure 21.

Figure 21. Wave Relay Sector Antenna Propogation and Orientation Parameters onboard the LCS. Source: Scalable Network Technologies (2016).



The STK mounting parameters of the 1.2-meter KA-band terminals are displayed in Figure 22 and their respective locations on the 3D model in Figure 23.

Figure 22. O3b Ka-Band Terminal Mounting Parameters. Source: Scalable Network Technologies (2016).

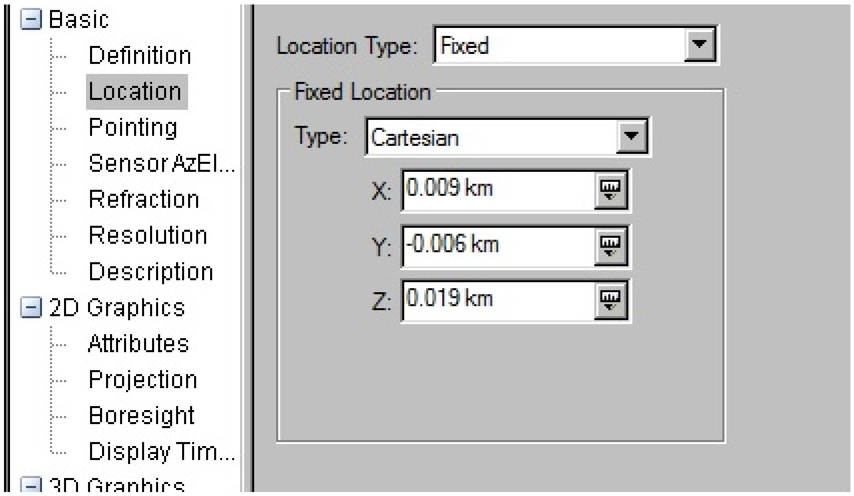
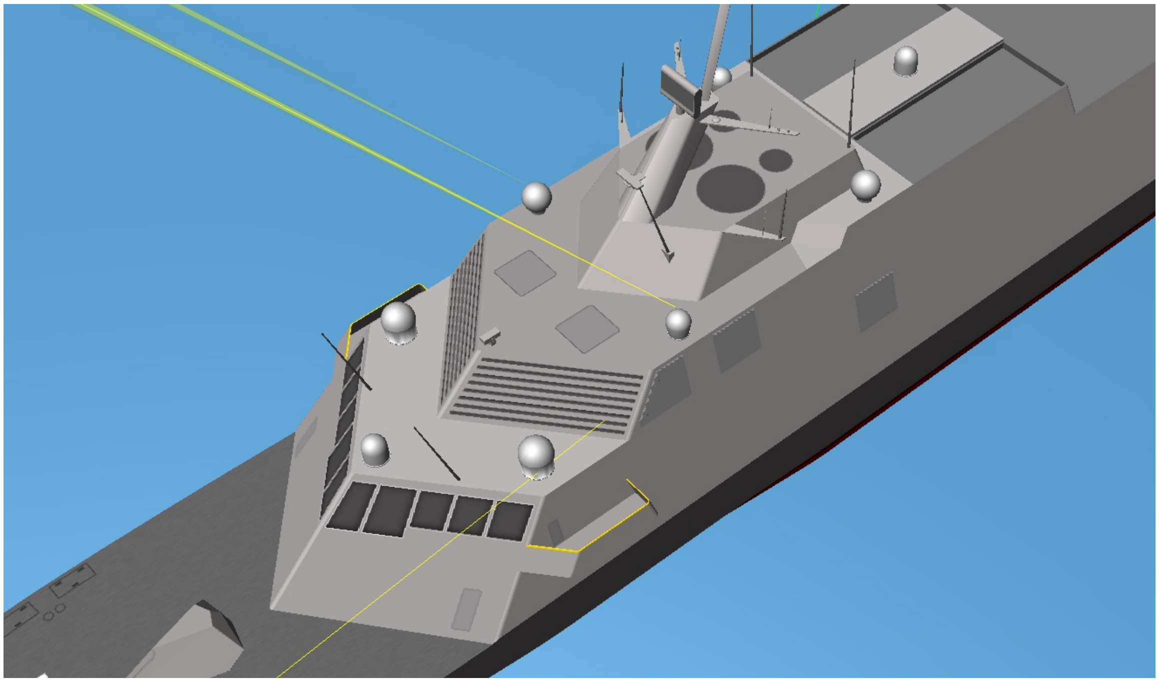
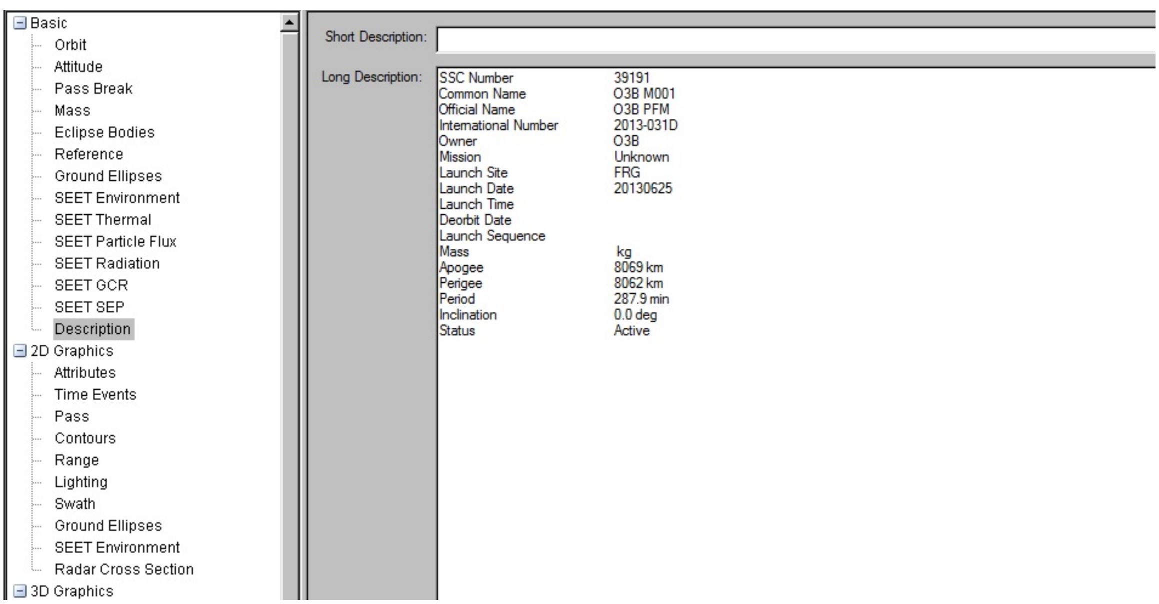


Figure 23. O3b Ka-Band Terminals Mounted on Simulated LCS. Source: Scalable Network Technologies (2016).



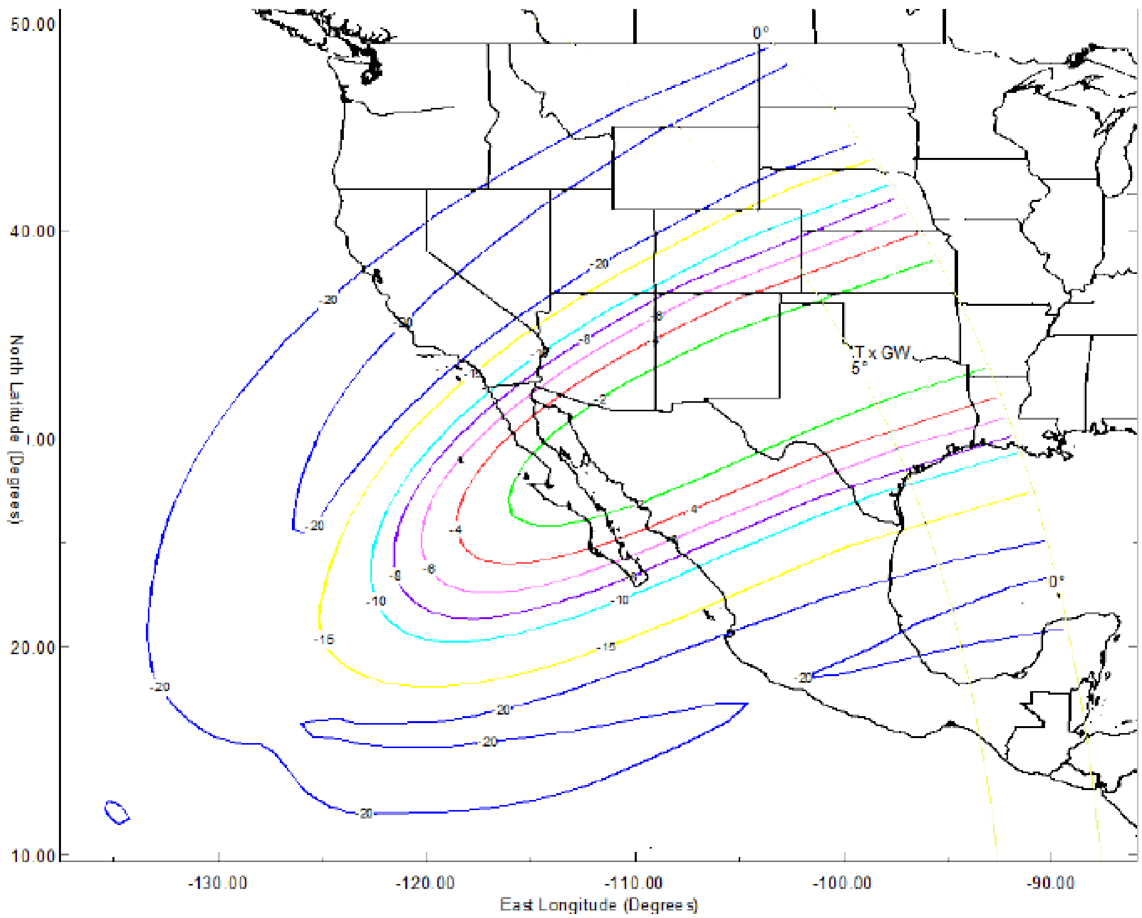
The terminals established links with the O3b MEO constellation over wireless subnets between the ground stations and satellites. As illustrated in chapter II, O3b maintains a constellation of 12 satellites, with an orbital period of 6 hours, positioned above the equator. In the simulation, 4 of these satellites were selected to communicate with the LCS. The satellites use steerable beams to effectively cover regions +/- 45 degrees from the equator; any area located above or below the 45-degree margin experience major degradations in service. The latitude of SF Bay is approximately 37.7 N and is within a serviceable region. The LCS in the scenario relays communications off-ship to the O3b satellite, which in turn relays it to an O3b-owned ground station through a bent-pipe architecture. The STK orbital parameters of an O3b satellite are illustrated in Figure 24.

Figure 24. O3b Orbital Parameters. Source: Scalable Network Technologies (2016).



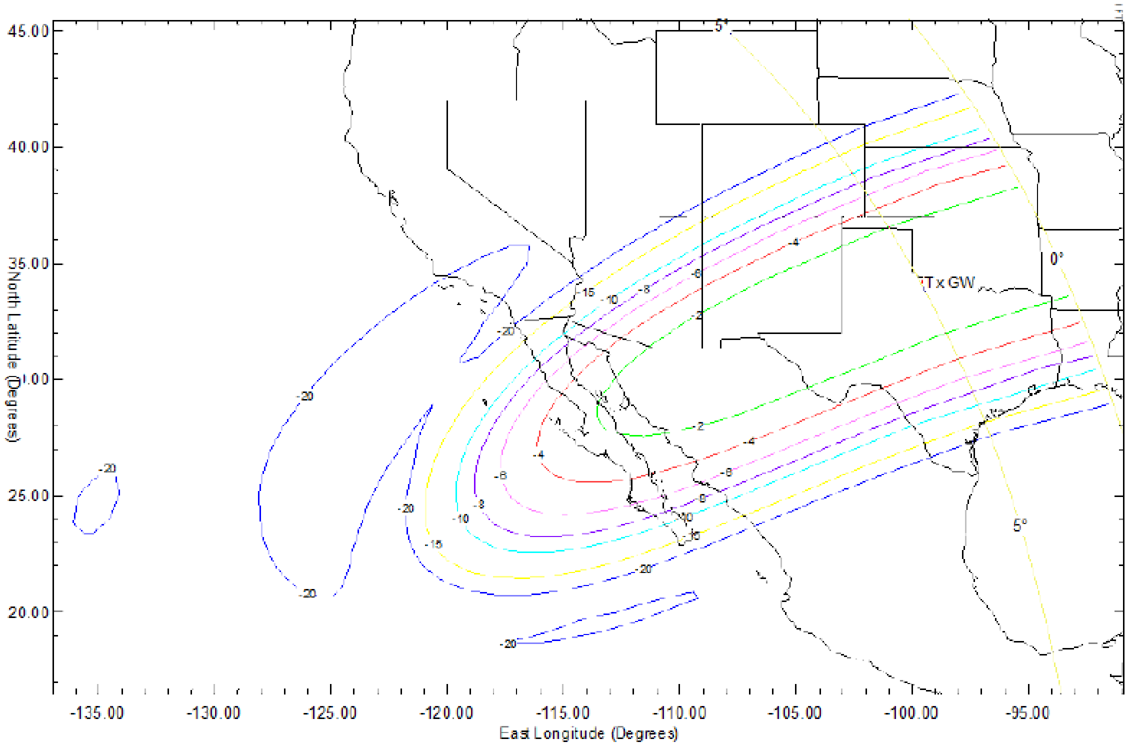
In the future, the Ka-band transponder may be used by O3b satellites to be reconfigured to direct a signal to government-owned facilities such as a Naval Computer Telecommunications Area Master Station (NCTAMS). For simplicity, and based on data from Pandarra Net 2015, the simulated scenario used O3b earth stations. The company currently owns two earth stations in the United States: one in Vernon, Texas and the other in Haleiwa, Hawaii. According to a technical paper on O3b's services, the Haleiwa and Vernon earth stations have very similar link budgets (D'Ambrosio, 2015). The simulation used the Vernon, Texas ground station as the relay for Scenario 1. The simulation did not model the path from the ground station to the nearest NCTAMS facility. Figure 25 displays the transmit gains and losses of O3b satellites operating at 5 degrees elevation in the West as viewed from the O3b station in Vernon, Texas.

Figure 25. O3b Satellite Transmit Gains as Viewed from Vernon, Texas, with a Satellite at 151 Degrees West. Source: O3b Non-Geostationary Satellite System (Barnett, 2013).



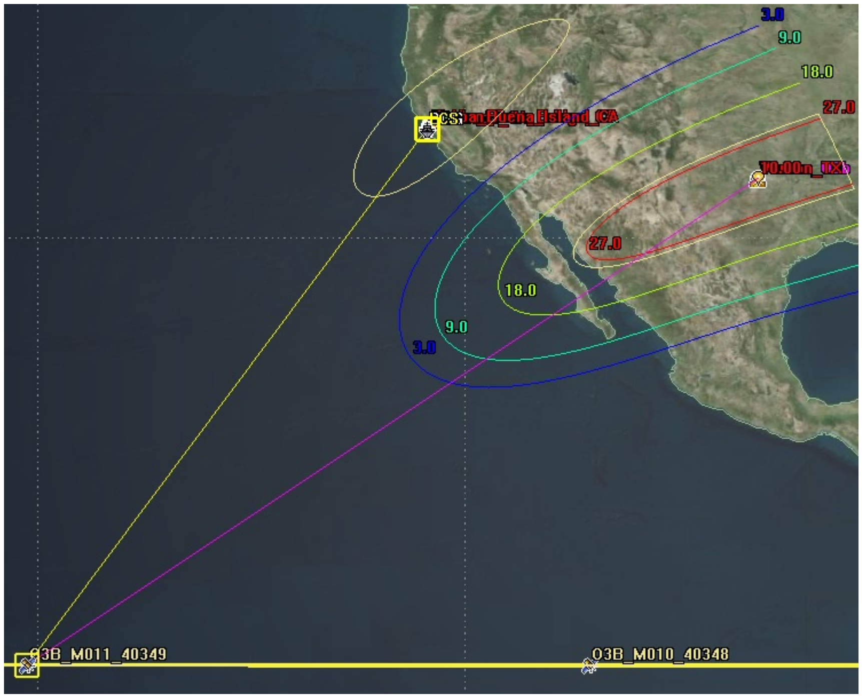
O3b satellite receive gains from Vernon, Texas are displayed in Figure 26.

Figure 26. O3b Satellite Receive Gains as Viewed from Vernon, Texas, with a Satellite at 151 Degrees West. Source: O3b Non-Geostationary Satellite System (Barnett, 2013).



O3b satellite gains from the STK simulation are shown in Figure 27.

Figure 27. O3b Satellite Gains from STK Simulation as Viewed from Vernon, Texas, with a Satellite at 151 Degrees West



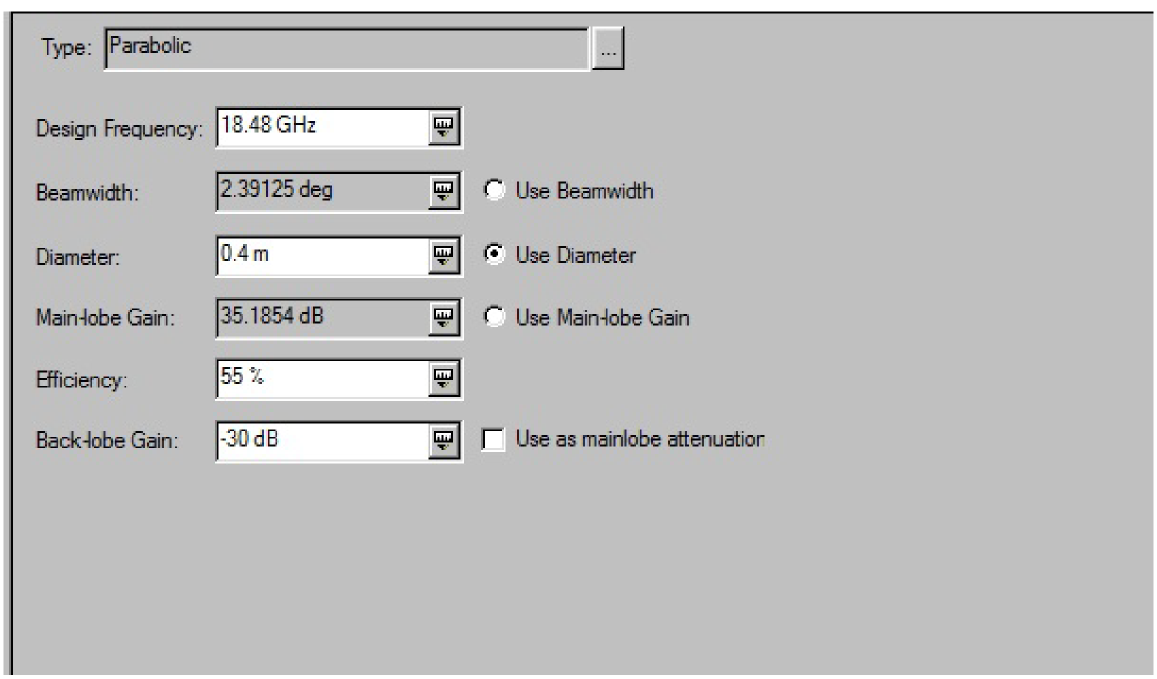
The Cruiser and Destroyer conducting operations with the LCS were also equipped with Wave Relay Sector Antenna Arrays. The Wave Relay devices were mounted to the flight decks of these vessels like that of the LCS enabling the vessels to send data and connect through the LCS' IGW.

The duration of the scenario was six hours. The length was selected based on the six-hour orbital period of an O3b satellite. In the scenario, the three vessels were assigned screen sectors in the form of approximated 3-by-3 kilometer (KM) operational boxes outside the mouth of San Francisco Harbor. The LCS took a position in the center operational box with the cruiser and destroyer operating north and south, respectively. The waypoints for each vessel are randomly chosen within each operational box.

The waypoints of the ship object models were the first items built into the simulation. The process for determining object positions throughout the scenario involved the use of STK's smooth rate calculations. The LCS and DDG transited throughout their operational boxes with a speed of 10 knots, while the CG transited at a slightly slower speed of 5 knots. With the smooth rate option selected in each ship's object window, STK automatically calculated waypoint arrival times based on these constant speed settings and a variable distance covered—this in turn automatically calculated total scenario time. Waypoints for each object were randomly selected and added until the elapsed scenario time had reached a 6 hour period or greater. Once the desired scenario time had been reached, the STK analysis period, which collects statistics, was modified in the scenario window to encompass 1900 on August 10th to 0100 on August 11th.

Next, O3b satellite objects were loaded into the scenario. The ephemeris data for these objects was obtained from previous research completed by an NPS student on the use of O3b to enhance throughput for Marine Corps missions (Teichert, 2016). The antenna parameters of one of these objects are displayed in Figure 28.

Figure 28. Antenna Parameters of O3b Satellite. Source: Scalable Network Technologies (2016).



M003, M007, M009, and M011 were the O3b satellites selected to provide coverage over the San Francisco Bay Area. In reality, these satellites may or may not have spot beams positioned to cover this region. The assumption is that with a subscription service to the network, O3b will align spot beams within its constellation to provide the best coverage of a region. The satellite objects, equipped with parabolic dishes, were modeled with sensors that enabled their spot beams to point directly at the LCS as well as at the Vernon ground station. In a real-world environment, the LCS may not have the luxury of consistently being at the center of a spot beam. Consequently, the simulated LCS experienced higher antenna gains when compared to real-world measurements; this was indicated by comparing Figure 25 and Figure 26. Each satellite, with two attached sensors and antennas, was able to point at Vernon and the LCS during access windows simultaneously. There was a sufficient overlap of spot beams for handovers to occur between satellites. In the QualNet portion of the simulation, a satellite object was modeled with two STK antennas with an attached interface on each. The two interfaces are configured for the uplink and downlink frequencies of the LCS and Vernon gateway, respectively.

As described in Chapter II, STK handles the antenna and propagation models, while QualNet handles protocols and packets in the OSI layers. Understanding the relationship between the two programs was critical in configuring the ground station and satellite connections. The benefit of the STK/QualNet interface is a layout that simultaneously displays objects from STK and nodes from QualNet. Although QualNet configuration files can be built independently and loaded into STK, it is not a recommended method due to positional misalignments between nodes and interfaces that can occur. The recommended method, according to the QualNet documentation, is to build entire STK/QualNet scenarios within the STK VDF (Scalable Network Technologies, 2016). The STK/QualNet interface, while intuitive in design to users familiar with each separate program, does not offer the same level of support and functionality when compared to each program used separately. For example, QualNet offers several different types of wireless subnets to model satellites, but not all will run within the STK/QualNet environment.

Initially, the Abstract Network Equation (ANE) satellite model was built into the STK/QualNet scenario to create communications between the LCS, O3b Constellation, and O3b ground station. The QualNet wireless library documentation defines ANE as a model that provides an advanced set of tools that simplifies modeling spot-beam satellites and multiple upstream systems (Scalable Network Technologies, 2016). Despite various attempts to integrate it into the STK/QualNet scenario, the ANE model did not function properly. Despite extensive troubleshooting, the issue was not resolved, and the ANE model is deemed incompatible with the STK/QualNet interface due to software issues. The STK/QualNet interface contains a running log for viewing script changes and error messages in QualNet processes. Normally when running a scenario containing design errors, the simulation will automatically cancel and fault descriptions will be displayed here. However, this was not the case when running ANE model scenarios. The scenario would remain in initialize mode indefinitely, preventing the simulation from running and providing no details in the QualNet log. As such, it was impossible to determine whether or not the ANE satellite model was interoperable with STK.

In light of poor success with the ANE model, a different approach was used in creating satellite links between the LCS, O3b Satellites, and the ground station. Rather than create subnets for the objects to pass traffic, a more direct method was used by establishing wireless links. The STK/QualNet interface supports and recognizes point-to-point links between nodes and interfaces. These links use QualNet's Abstract Link MAC Model, which can be configured for wired, wireless, or microwave mediums (Scalable Network Technologies, 2016). As with ANE, there were limitations in the performance of these links. First, a point-to-point link only connects one interface on a node to one interface on another throughout the entire simulation. This one-to-one limitation did not necessarily prevent scenario one from running but created the need for many more interfaces than intended. For example, the LCS Ka-band terminal was required to point at multiple O3b nodes to maintain availability, but this was not possible with a single interface on the antenna. A single STK object, such as an antenna, can have multiple QualNet interfaces (or "instances") assigned to it. Multiple interfaces are required to link the LCS or ground station to each satellite as it gained access. Scenario one was capable of executing and collecting statistics with this configuration, but it led to concerns that the additional interfaces may introduce errors. Also, having too many interfaces made it very time-consuming to make the slightest of changes to the overall model. As such, the approach reverted to using wireless subnets to link satellite and ground nodes together.

Further research into STK/QualNet interactions revealed that the QualNet Satellite-RSV model, one of multiple models available, is recognized in the program's operating environment with STK version 10.1.3 (Scalable Network Technologies, 2016). The Satellite-RSV model is unique when compared to other wireless models insofar as QualNet defines it as "multilayer"—meaning multiple OSI layers require specific settings for it to function properly. The basic capabilities of the Satellite-RSV model are defined in QualNet documentation as, "The Aloha Satellite Model with Reed-Solomon/Viterbi (RSV) support is a Demand Assignment Multiple Access (DAMA) scheme based on the Aloha protocol. The model operates either as a bent-pipe satellite or as a satellite with an onboard processor-payload" (Scalable Network Technologies, 2016). The Aloha Protocol is used on older generations of satellite terminals and offers simple routing at the MAC layer by broadcasting data when data is received. The data source will continue to retransmit at random intervals if an acknowledgment is not received. With STK/QualNet interoperability and the bent-pipe architecture of O3b's constellation in mind, the satellite RSV-model was best suited for simulating and forwarding data received by the LCS to the Vernon ground station.

Implementing the Satellite-RSV model in STK/QualNet required adjusting settings on two OSI layers. First, the radio type at the physical layer of a nodal interface—whether ground or satellite—was set to Satellite-RSV, and the listenable channels (uplink and downlink) configured according to transmit and receive frequencies of the antenna objects. Next, the routing protocol of the MAC layer is set to Satellite-RSV, and the protocol role was designated as a ground station or satellite. The uplink and downlink channels of the interface are also established in this submenu as well as optional parameters such as cross channel interference, noise and more. Although it is possible to configure a QualNet nodal interface to be satellite-RSV at the physical layer, with a different routing protocol at the data/MAC layer, the configuration is not recommended. The QualNet documentation states that the satellite-RSV model at the physical layer should only be used in conjunction with the same model at the data/MAC layer for optimal performance. The configuration of the scenario channels is displayed in Figure 29.

Figure 29. Scenario 1 Channel Configuration

Number of Channels	5
Channel Name [0]	**CGDDGLCSWireless**
Channel Frequency [0]	2.4 GHz
Enable Inter-channel Interfernce [0]	No
Signal Propagation Speed (m/s) [0]	300000000
Propagation Limit (dBm) [0]	-1000
Channel Name [1]	**LCSuplink**
Channel Frequency [1]	**27.6 GHz**
Enable Inter-channel Interfernce [1]	No
Signal Propagation Speed (m/s) [1]	300000000
Propagation Limit (dBm) [1]	-1000
Channel Name [2]	**LCSdownlink**
Channel Frequency [2]	**19 GHz**
Enable Inter-channel Interfernce [2]	No
Signal Propagation Speed (m/s) [2]	300000000
Propagation Limit (dBm) [2]	-1000
Channel Name [3]	**VernonUplink**
Channel Frequency [3]	**28 GHz**
Enable Inter-channel Interfernce [3]	No
Signal Propagation Speed (m/s) [3]	300000000
Propagation Limit (dBm) [3]	-1000
Channel Name [4]	**VernonDownlink**
Channel Frequency [4]	**19.5 GHz**
Enable Inter-channel Interfernce [4]	No
Signal Propagation Speed (m/s) [4]	300000000
Propagation Limit (dBm) [4]	-1000
Rain Outage Percent	0.1

The configuration steps at the physical and MAC layers are completed for each ground station and satellite object interface. Two satellite-RSV wireless subnets, one for the LCS Ka-band terminal and one for the Vernon ground station, were configured with the RSV-satellite model at the physical layer and MAC sublayer once all interfaces are established. The two subnets linked all IGW objects and interfaces within the scenario and prevented them from overlapping on downlink and uplink frequencies. One observation noted with an RSV-satellite wireless subnet was that it did not retroactively enact global updates to interfaces under its hierarchy if changes are made to any setting. It is uncertain whether this was an intentional design of QualNet or oversight. In any case, minor modifications made to properties in the Satellite-RSV subnet required the user to go back and manually change all interfaces in the hierarchy to match. Discrepancies in uplink and downlink channels between the subnet properties and nodal interfaces sometimes caused the STK/QualNet program to crash or the scenario to initialize indefinitely. As with the ANE satellite model, the crashes, and endless initialization prevent the QualNet log from updating, making in-depth troubleshooting difficult if not impossible.

Next generation satellite terminals, such as those used by O3b, typically use TDMA or CDMA protocols on coding/decoding devices connected to the terminal. It was possible, but not practical, to mix the satellite-RSV physical model with a TDMA routing protocol at the MAC layer. However, to achieve the best interoperability with STK and QualNet, the satellite-RSV model was used on the first two layers on every satellite interface and subnet. This configuration appeared to be the closest match to O3b's bent-pipe architecture that could be designed in the simulation. An additional benefit was the relative simplicity of the model when compared to the previous attempts. The STK antenna objects on each node required one QualNet interface vice the many of a point-to-point configuration providing concise statistics output and narrowed down troubleshooting paths when issues arose.

The scenario is concluded after statistics are gathered for one orbital period of O3b's satellites.

D. SCENARIO 2: LCS PERFORMING AS A ROUTER

The LCS performing as a router was designed in the STK/QualNet interface with simulation models available in the QualNet LTE Library. The premise of the scenario is that an LCS, using organic assets, is tasked with conducting a compliant VBSS boarding in the littorals. The nodes used in this scenario are the LCS, two Rigid Hull Inflatable Boats (RHIBS), and an RQ-8A Fire Scout. All nodes are connected via a self-contained 4G LTE bubble generated by external antennas mounted on the LCS. The Fire Scout is equipped with a commercially available 4G LTE video camera used to stream video back to the LCS and boarding teams. The networking equipment on the LCS is an LTE core server that can theoretically share data with the ship's ADNS network to complete back-haul to the shore side. The modeling of the long-haul throughput with 4G LTE was beyond the scope of this scenario. The focus was on the performance of the LCS as a major node using the LTE networking technology to form a MANET in the local environment. The total scenario time was approximately three hours.

In LTE terminology, the LCS and connected nodes formed an Evolved Packet Core (EPC) subnet. The LCS was configured as the evolved Node B (eNB) or base station. The other nodes were set up as User Equipment (UE). As there was only one base station, the availability metric in this scenario was the number of packets received and sent—handovers between base stations was excluded.

The premise of the scenario is that a cargo vessel, designated as a Vessel-of-Interest (VOI), is transiting through the littoral regions near Yerba Buena Island. The LCS is given permission to search the vessel by the MIO commander. To conduct surveillance and reconnaissance (SAR) of the vessel before boarding, the LCS launches its RQ-8A. The airborne platform performs a sweep of the area and discovers the cargo vessel transiting due North. Once it locates the cargo ship, the RQ-8A trails it and begins to stream live video back to the LCS through the LTE bubble. The camera selected for use on the RQ-8A was an LG LTE Action Camera; this device does not require tethering to a handheld device to function in the bubble. The following are the camera's specifications, and Figure 30 shows the compact form factor of the device.

- Camera: 1/2.3-inch 12.3MP (150-degree wide angle lens) / 1.55 x 1.55㎛ pixels
- Video Recording: UHD 30fps / Full HD 30, 60fps / HD 30, 60, 120fps
- Video Live Streaming: HD (up to 30fps)
- Chipset: Qualcomm® Snapdragon™ 650 Processor
- Memory: 2GB RAM / 4GB ROM (OS only) / microSD (up to 2TB)
- Size: 35 x 35 x 79.7mm
- Weight: 99g
- Others: IP67 / GPS / Accelerometer / Gyroscope (LG Newsroom, 2016)

Figure 30. LG Action Camera. Source: LG Newsroom (2016).

In the scenario, once the RQ-8A detects the cargo vessel, the LCS repositions to launch the RHIBs and conduct the boarding. While the VBSS team members are preparing for launch, they can view images and live video of the VOI through LTE enabled handheld devices. After the RHIBs are launched and approach the VOI, the teams can maintain SA via the RQ-8A streaming video back to the LCS. The device used by the VBSS team members was the Samsung Galaxy Note II LTE. The following are some of the specifications of this device:

- Display: 16M Color HD SUPER AMOLED, 16:9 Full Touch Display
- Size 5.55," Resolution 1280 x 720pixel
- Dimension (WxHxD) 80.5 x 151.1 x 9.45mm
- Weight 182g
- Band FDD-LTE (800/900/1800/2600MHz) + WCDMA (850/900/2100MHz) + GSM (850/900/1800/1900MHz)
- Processor 1.6GHz Quad-Core Processor
- Data Transfer LTE 100Mbps / HSDPA+ 42Mbps / HSUPA 5.76Mbps
- Video Play Format H.263 / H.264 / WMV / MPEG4 / DivX / AVI / FLV
- Video Recording 1280 x 720 pixels (30fps)
- Recording Mode: Slow Motion and Fast Motion
- Camera Resolution 8.0 Megapixel Auto Focus Camera
- Front Camera 1.9 Megapixel (Samsung, n.d.)

The Samsung Galaxy Note II used by VBSS members is displayed in Figure 31.

Figure 31. Samsung Galaxy Note II. Source: Samsung (n.d.).

The RQ-8A remains on station until its fuel is nearly expended, at which point it returns to the LCS. Once the RHIBs detach from the cargo vessel, the scenario ends.

E. SCENARIO 3: LCS PERFORMING AS A HUB

The LCS performing as a hub in this scenario used network nodes with the same radio and satellite equipment as Scenario 1. The goal in this scenario was to observe LCS network performance when receiving and distributing data originating from the shore side. In essence, the data flow shifted to nodes receiving the majority of traffic rather than sending it. The metric used to determine the effectiveness was once again availability over a six hour period. The availability can be viewed from an end-to-end perspective, comparing total broadcast packets sent from Vernon with the number received at each node.

In addition to the nodes in Scenario 1, the CG and DDG each launched a RHIB to conduct picket boat operations on the outskirts of the operational boxes. The RHIBs were equipped with handheld isotropic 2.4 GHz Wave Relay radios. Cargo vessels were modeled into the scenario transiting on a traffic separation scheme into and out of the SF Bay near the operational area. The LCS in the scenario broadcasts information regarding the traffic of vessels and VOIs to all nodes within the mesh, as received from the Vernon Ground Station.

A broadcast IP address was assigned to one of the RHIBs to make the LCS forward packets to all nodes on the Wave Relay subnet.

F. SCENARIO 4: LCS PERFORMING AS A BRIDGE

The LCS in this scenario performed as a bridge between two networks through multiple point-to-point microwave links. The scenario consisted of three LCS platforms; one behaving as the major node and the other two serving as control stations for unmanned assets. The first of the LCS control stations launched two RQ-8As and received data collected from their organic sensors; this data was fed to the organic ship's network. The next LCS control station performed the same function, but with USVs. Ideally, a Sea Fox USV would have been used if the model was available through STK downloadable resources. At the time of this thesis, the USV model available in STK that closely resembled the Sea Fox was the High-Speed Maneuvering Surface Target (HSMST). This vessel is capable of being manned or remotely operated and is typically used for force protection and gunnery exercises. For simulation purposes, it was remotely operated.

Tsunami QB-10100 Point-to-Point Wireless Bridge Bundles were modeled into the simulation to create a network bridge between the LCS subnets containing the unmanned nodes via the major node LCS. In total, four Tsunami QB-10100 were modeled into the scenario; two on the major node LCS, and one on each control station LCS. The scenario duration was three hours. Unlike previous scenarios, the nodes remained close together and on logical paths and trajectories throughout; this design reflected the need to have nodes pointing in specific directions to bridge the networks. Aside from the USVs, all nodes used directional microwave antennas. The measure of availability was observed by sending a constant bit rate from an unmanned asset on one subnet to the LCS on a different subnet. The parameters of the TCDL links used for the Fire Scouts are displayed in Figure 32 and Figure 33.

Figure 32. Fire Scout STK TCDL Antenna Parameters. Source: Scalable Network Technologies (2016).

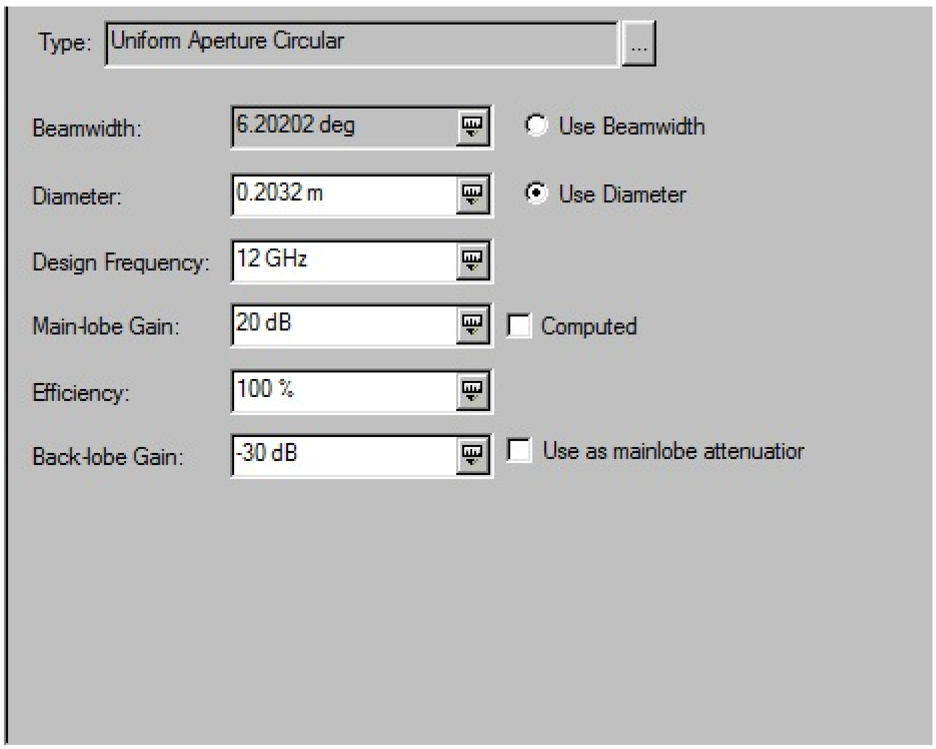
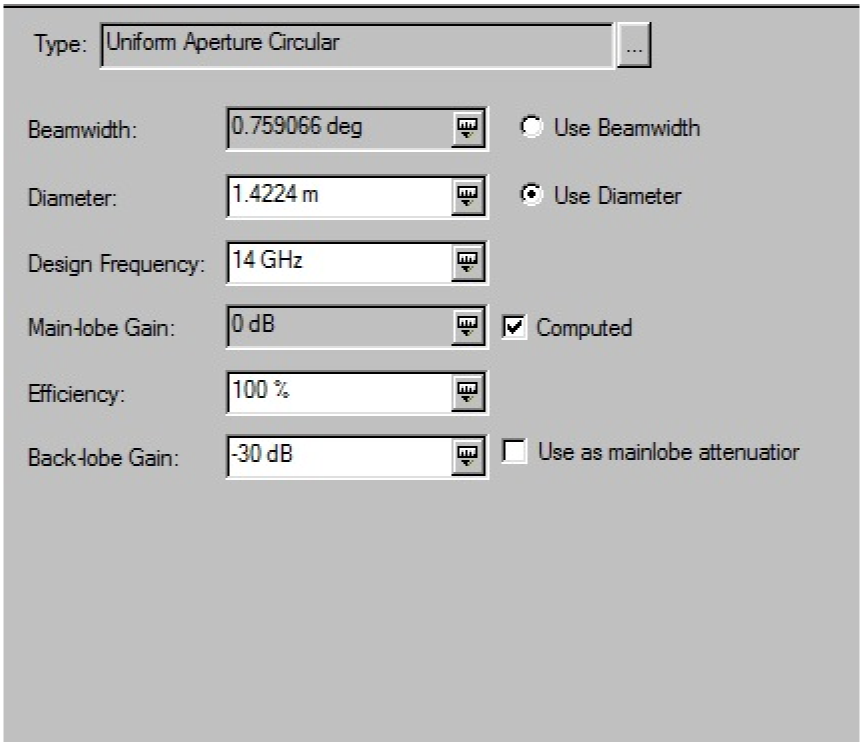
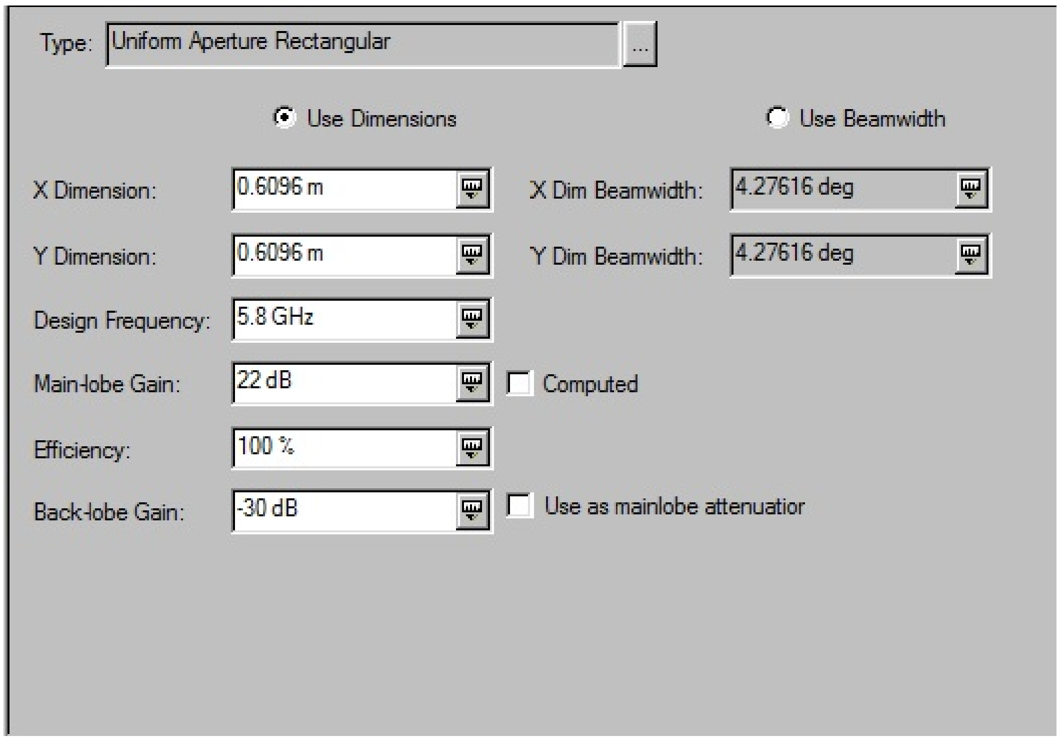


Figure 33. LCS Control Station STK TCDL Antenna Parameters. Source: Scalable Network Technologies (2016).



The parameters for the Tsunami Point-to-Point wireless network bridge are displayed in Figure 34.

Figure 34. Tsunami Point-to-Point Wireless Network Bridge STK Parameters. Source: Scalable Network Technologies (2016).

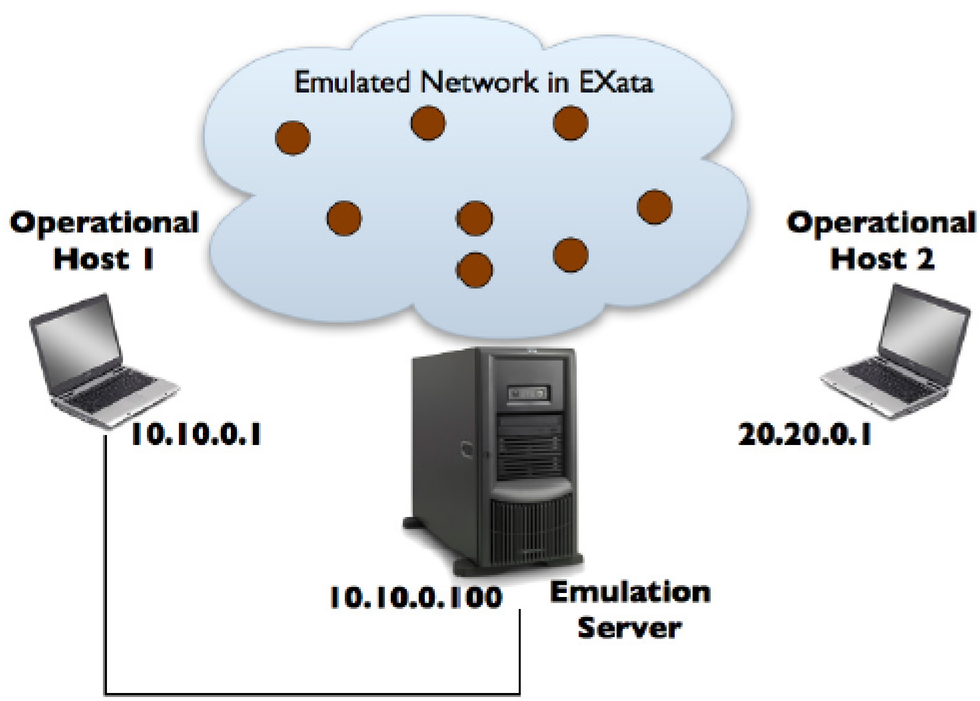


G. XATA 5.3 CONCEPTUAL EXPERIMENT

The experiment for testing network management software on the LCS was designed to use two workstations, IT140321 and IT140717, available in the CENETIX Lab at NPS. The software tools used were EXata 5.3, QualNet 7.3, and STK 10.1.3. The network management tools acquired were SolarWinds Network Performance Monitor (NPM) and Network Configuration Manager (NCM). The biggest challenge in setting up the experiment was overcoming licensing hurdles. The SolarWinds tools offered a 30-day free trial, while Scalable Networks offered a two-week trial version of EXata 5.3. The license files for QualNet 7.3 and STK 10.1.3 did not cause any issues since they are maintained through an educational agreement with NPS.

As illustrated in Chapter II, the primary benefit of EXata over QualNet is its ability to run an emulated network testbed indefinitely. Also, it allows a user to create both emulated nodes and simulated nodes within the testbed. An emulated node is a device, real or virtual, which can connect and interact with simulated nodes. The simulated nodes are the same as those found in QualNet 7.3. The applications that can be run on an emulated node are constrained only by the capabilities of the system performing this role. To connect an emulated node to the testbed, a Scalable Networks application called Connection Manager is installed on IT140321; this enabled it to perform as an operational host on the network. EXata 5.3 was installed on IT140717, and a Connection Manager internal to this application was used to identify devices capable of serving as an operational host. An overview of an emulated testbed is illustrated in Figure 35.

Figure 35. Conceptual Emulated Testbed with Operational Hosts. Source: Scalable Network Technologies (2014a).



By design, the machine running EXata 5.3 was unable to run other applications as emulated nodes within the testbed while running an emulated scenario. This point was important to keep in mind because any software or application to be run on an emulated node needed to be installed on a machine separate from the EXata machine. Therefore, the SolarWinds tools were installed on IT140321. To inject a simulated LCS into the emulated testbed, a separate scenario had to be built and saved by using the STK/QualNet interface on either machine. When a scenario is made using STK/QualNet, a separate application and configuration file for STK and QualNet is created, respectively. The QualNet configuration file created from the STK/QualNet mapping can then be loaded into EXata. The configuration file carries over the majority of parameters from STK/QualNet to EXata, in particular, the location of the nodes.

For the conceptual experiment, to test the network management capabilities of the LCS, the QualNet configuration files from scenarios 1 through 4 can be loaded into the EXata environment. The simulated node designated as the LCS in the STK/QualNet interface can then be changed to an emulated node. The simulated nodes in the testbed can be given SNMP agents that allow network management. SolarWinds network management tools, connected to the LCS' emulated node via operational host IT140321, can be used to monitor and configure the simulated nodes with the SNMP capability set. The simulated nodes with SNMP capability can also be loaded with network management configuration files to define Management Information Base (MIB) structure and entities. EXata 5.3 offers compatibility with most variants of SNMPv1 through SNMPv3. With the LCS emulated node performing as the manager, it is possible for it to identify and manage nodes using third-party network management tools such as SolarWinds.

IV. STK DATA COLLECTION AND ANALYSIS

A. SCENARIO 1 DATA: LCS PERFORMING AS A GATEWAY

Initially, a major shortfall in the LCS as Gateway scenario was the inability to realistically model the Wave Relay devices in the STK/QualNet environment (Figure 35). Table 6 shows the nodes used in this scenario. The majority of 802.11 signals transmitted by the destroyer and cruiser were detected by the LCS, but few of the signals were locked on. The inability to lock on caused the AODV routing protocol to search for new routes and to eventually drop packets due to a perceived lack of viable route. Nodes were able to maintain connection and transfer data only at very close ranges, approximately half a kilometer. The scenario 1 overview is displayed in Figure 36 and participating nodes are listed in Table 6.

Figure 36. Scenario 1 Overview. Source: Scalable Network Technologies (2016).

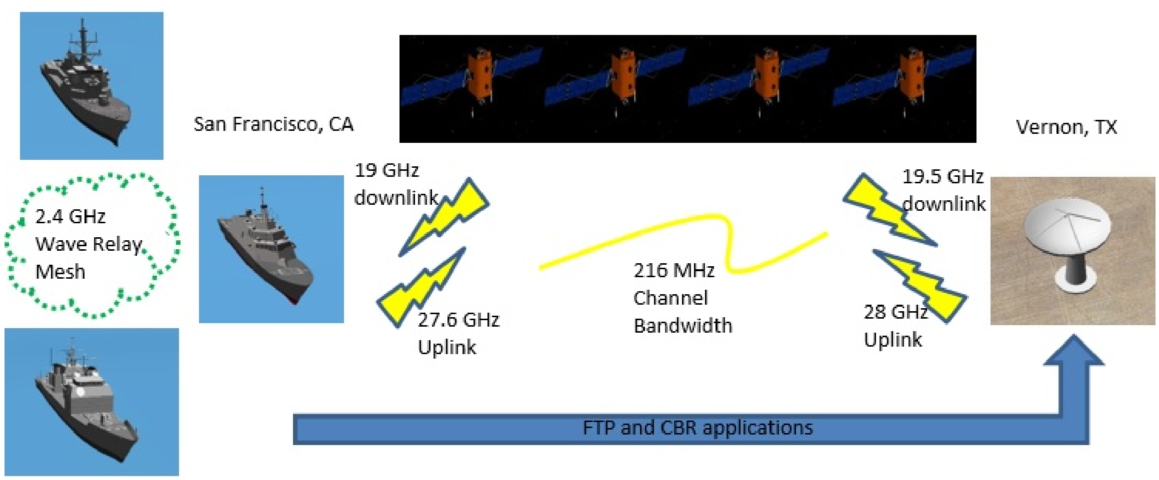


Table 6. Scenario 1 Nodes

QualNet Node ID	STK Platform Type/Model/Description	STK Antenna/Sensor	QualNet PHY Model	QualNet Subnet
5	Ship/CG 3D Model/Ticonderoga Class CG	Rectangular Pattern	802.11a/g	192.168.86.0
6	Ship/DDG 3D Model/Arleigh Burke Class DDG	Rectangular Pattern	802.11a/g	192.168.86.0
7	Ship/LCS 3D Model/Freedom Class LCS	Rectangular Pattern, Parabolic, Fixed Target Sensor	802.11a/g, Satellite-RSV	192.168.86.0, 190.0.3.0
23	Place/Facility/O3b Ground Station	Parabolic	Satellite-RSV	190.0.2.0
11	Satellite/M003/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
15	Satellite/M007/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
17	Satellite/M009/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
19	Satellite/M011/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0

The solution was to change some of the default parameters within the OSI layer options of QualNet to improve performance. The two most notable improvements were achieved by enabling Logical Link Control (LLC) and adjusting the MAC Propagation Delay parameter in STK/QualNet from the default setting of 1 microsecond to 100 microseconds. LLC enables error and flow control at the Data Layer while changing the propagation delay was assumed to decrease the saturation of the established data links. Based on manufacturer's specifications of the Sector Array Antennas and radio devices, as well as previous field experimentation conducted by the NPS CENETIX team, the Wave Relay devices in the simulation performed realistically when all factors were considered. With the simulation parameters as described, the Wave Relay devices on the ships were able to transmit and receive unicast packets at ranges of over 3 kilometers. The same equipment parameters, when placed on stationary land devices in the simulation, were able to achieve unicast packet reception at ranges of over 10 kilometers —near the ranges listed in the manufacturer's specifications (Persistent Systems, 2015). The success using land devices demonstrated the impact environmental factors such as sea state and mobility had on the nodes. As such, it was determined that the observed operating ranges were accurate for the purpose of this research. The effective ranges were measured by having a node traverse in a straight path away from the LCS while running a wireless CBR application. The CBR application was set to transmit an item at 1-second intervals throughout the analysis period. The distance between the location of the transmitting node and the LCS was measured at the recorded time that the last unicast packet was received.

The mounting parameters of the Wave Relay antennas had only a slight effect on the overall performance. As described in Chapter III, the antennas were mounted on the flight decks of the vessel to simulate an ad-hoc experiment. The ship nodes were able to communicate with one another when within range, and also use other nodes as hops when a node was out of range.

Data collection centered on the availability and throughput of the mesh network by observing how the nodes in the Wave Relay and O3b subnets performed. First, to observe availability, a CBR application at low data rates was set to run throughout the duration of the analysis period. For this scenario, it was configured to send 56 bytes of data at 1-second intervals, for a total duration of 21,600 seconds (6 hours, the length of the STK analysis and satellite orbital period). To calculate the percentage of availability, the total number of unicast packets sent from the originating node(s) was compared to the total number of unicast packets received at the end node.

The FTP application was set to run from the start of the scenario to the end. By selecting 1 second as the start time and 21,600 seconds as the end time, it sent files of a prescribed size (20 MB) at random time intervals. The maximum number of files to be sent can be specified, but this does not guarantee that exact number will be sent. By adjusting the number of items to be sent to 0, the simulation will send a random number of items throughout the iteration. This methodology was used in this scenario, but not for every following scenario.

The first CBR application measured availability from each node in the mesh to the LCS. The second CBR application, run in a separate iteration, measured the availability of the LCS to the O3b ground station. The third CBR application measured the availability of the DDG and CG, using the LCS as an IGW to the O3b ground station. The STK/QualNet stat output file measures simulation results in an aggregate format. The output for the DDG sending unicast segments to the LCS is displayed in Figures 37 and 38. The remaining simulation data will be placed in tables that are addressed later in this section.

Figure 37. Total Unicast Messages Sent from CG and DDG to LCS

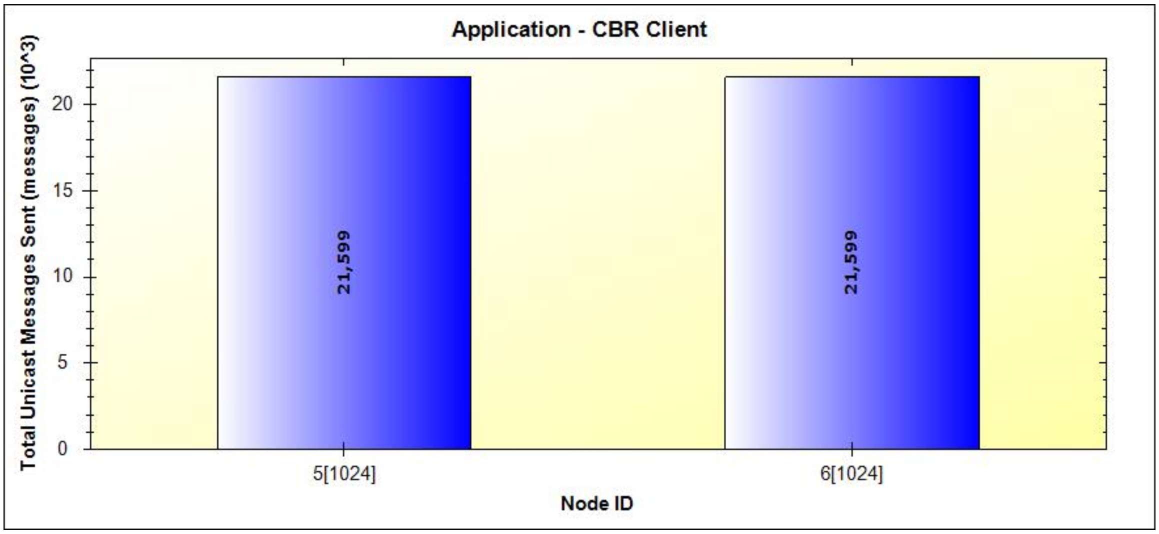
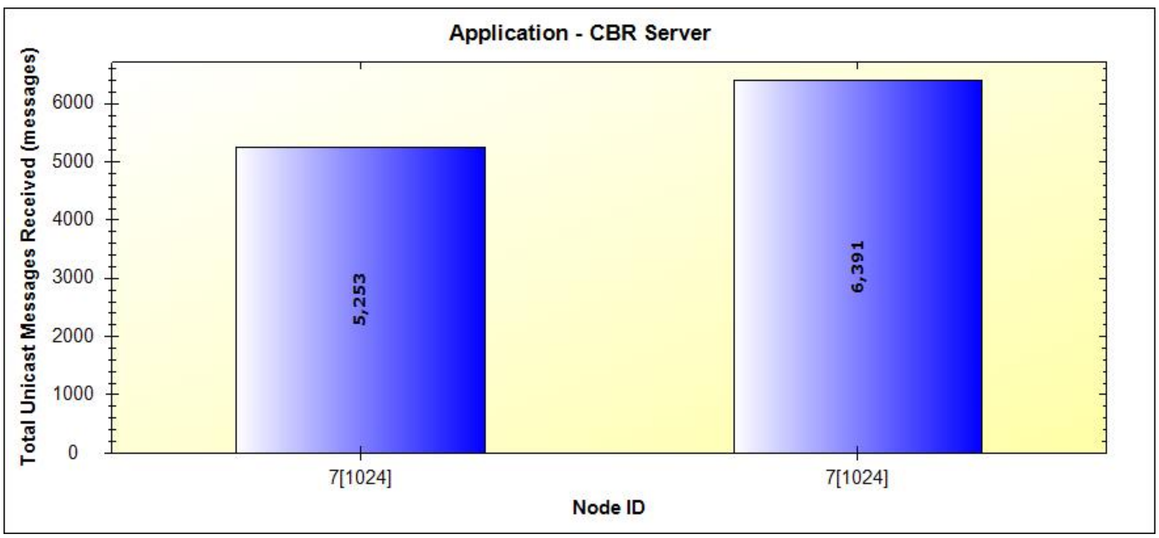


Figure 38. Total Unicast Messages Received by LCS from CG and DDG



The LCS to the O3b ground station used the satellite nomenclatures described in Chapter III. Many challenges were faced in establishing end-to-end connectivity with the satellite links and supporting nodes. The experiment design posited to use OLSR routing protocols among all O3b satellite and ground interfaces, while ship nodes in the mesh routed with AODV. No packets were received at the ground station when running this configuration. Further examination revealed that in order to enable communications between different protocols, a Border Gateway Protocol (BGP) was needed. A BGP and multiple network hierarchies (Autonomous Systems) can be established in the standalone version of QualNet, but a method for doing this in the STK/QualNet interface was not discovered, and it was assumed to be a limitation. That being said, for the remaining scenarios it was assumed that STK/QualNet only allowed for a single network hierarchy and hence the nodes were assigned the same routing protocols.

To create end-to-end connectivity between nodes and the ground station, AODV is enabled on every node. A duplicate scenario was run using the OLSR network protocol on all nodes and the results were compared to the original scenario to test the impact of this. The difference was slight; the AODV-enabled ground station received about ten more total unicast packets than OLSR over the course of the entire scenario.

The last limitation identified was that the LCS could only use one of its Ka-band terminals to connect to the satellite constellation. A suitable method for creating a handover between the Ka-band terminals as they locked onto satellites was not found. The additional terminal caused issues with the LCS satellite uplink and downlink channels. As such, the additional terminal was left in the STK portion of the scenario for visual purposes but was not mapped to a QualNet interface.

In addition to the Wave Relay subnet, the final working configuration of the LCS communications path to the ground station used two subnets: one for the LCS Ka-Band terminal to the O3b satellite interfaces, and one for the Vernon, Texas ground station to O3b satellite interfaces. The simulation results are displayed in Table 7, Table 8, and Table 9.

Table 7. Scenario 1 Availability

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Availability
CBR	7 (LCS)	23 (Vernon)	21,599 Unicast Segments	16,624 Unicast Segments	76.9%
CBR	5 (CG)	7 (LCS)	21,599 Unicast Segments	5,253 Unicast Segments	24.3%
CBR	6 (DDG)	7 (LCS)	21,599 Unicast Segments	6,391 Unicast Segments	29.6%
CBR	5 (CG)	23 (Vernon)	21,599 Unicast Segments	4,050 Unicast Segments	18.8%
CBR	6 (DDG)	23 (Vernon)	21,599 Unicast Segments	4,460 Unicast Segments	20.6%

Table 8. Scenario 1 FTP Throughput

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Throughput Tx	Throughput Rx
FTP	5 (CG)	23 (Vernon)	60 MB	40MB	2.8 KB/s	1.85 KB/s
FTP	6 (DDG)	23 (Vernon)	140 MB	120MB	6.48 KB/s	5.56 KB/s

Table 9. Scenario 1 Network IP Carried Load (Bytes/Second)

Node ID	5	6	7	11	15	17	19	23
Carried Load	2,277	6,086	65,848	484	7,834	668	21,257	738

The super application, as described in Chapter II, would have been useful in testing throughput capabilities of the network by injecting video and voice data streams into the mesh. Unfortunately, this application would not run without crashing the scenario. The scenario would cancel upon running, and the QualNet log file would generate a list of parameters needed to be set for the application to run successfully. Even when the application parameters were set accordingly, the STK/QualNet environment would not detect them.

As a result, the CBR and FTP-generic applications were used exclusively for the remainder of the research. These applications had the highest level of stability in the STK/QualNet environment. Even so, the FTP-generic application would sometimes crash the simulation when a large number of files, sizes ranging from 2 MB to 20 MB, were sent. These findings made it appear that certain limits existed on the amount of network data that could be simulated and collected. The bounds of these limits were not known, and it was beyond the scope of the research to identify them.

From the data collected with FTP and CBR, the availability and throughput during the period of analysis were unacceptably low from a customer or warfighter standpoint. However, this was somewhat expected as the nodes were set to move randomly within their operational boxes to observe data links breaking and reforming. For the Wave Relay devices, if the nodes moved in an established formation to maintain effective ranges then the results would likely improve. The superstructure of the ships in the simulation appeared to have a large effect on RF reception as well -- placing an antenna too close to the skin of a node resulted in degraded performance, if not blocking it completely. As such, experiments mounting Wave Relay antennas on high points of the node enabled better 360-degree coverage. Lastly, the CBR applications were sent from the DDG and CG simultaneously, which resulted in slightly degraded performance compared to each node sending them at individual times.

The satellite communications may have experienced degraded availability for several reasons. Fortunately, the QualNet statistics file generates network information specific to satellite performance. The Satellite-RSV bent-pipe model displays information about packets utilizing uplink and downlink channels, as well as average Eb/No for each satellite interface. In scenario 1, the LCS sent 21,599 unicast packets to the ground station. Of these packets, only 18,125 made it off the ship through the uplink channel between the LCS Ka-band terminal and the O3b constellation. Furthermore, only 16,624 were received at Vernon, Texas. The frequencies and parameters of the satellite links may have been partly to blame. Also, the single Ka-band terminal needed to switch to a new satellite without a seamless handover. This error was also replicated at the Vernon ground station whenever it needed to lock on to a new satellite. If this was the case, the availability could be improved by finding a method to enable handovers to occur.

The second area to examine, the average Eb/No for each satellite, can be measured by observing the performance of the LCS during a satellite's access window. The Eb/No graphic displays information on the LCS and Vernon interface of each satellite. On interface 17(0), the O3b antenna linking to the LCS 1.2M terminal, an average Eb/No of -38.9 dB was recorded. During the access window, it was suspected that the Ka-band terminal on the LCS was transmitting into the hull of the LCS. The QualNet average Eb/No and STK access window are displayed in Figure 39 and Figure 40.

Figure 39. Scenario 1 O3b Ground Station and Satellite QualNet Eb/No

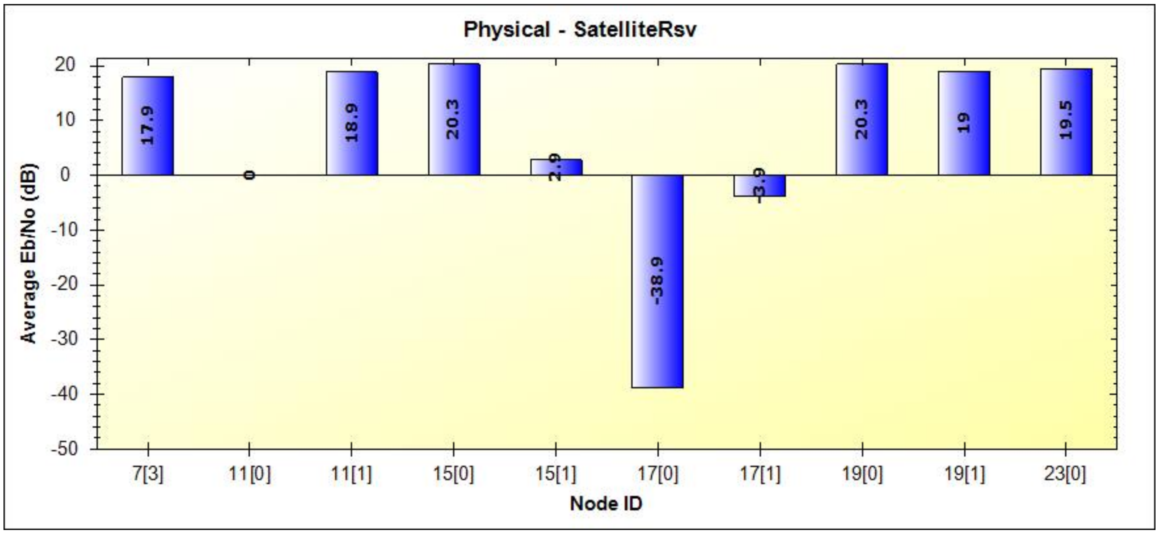


Figure 40. Satellite M009 (Node 17) STK Access Window

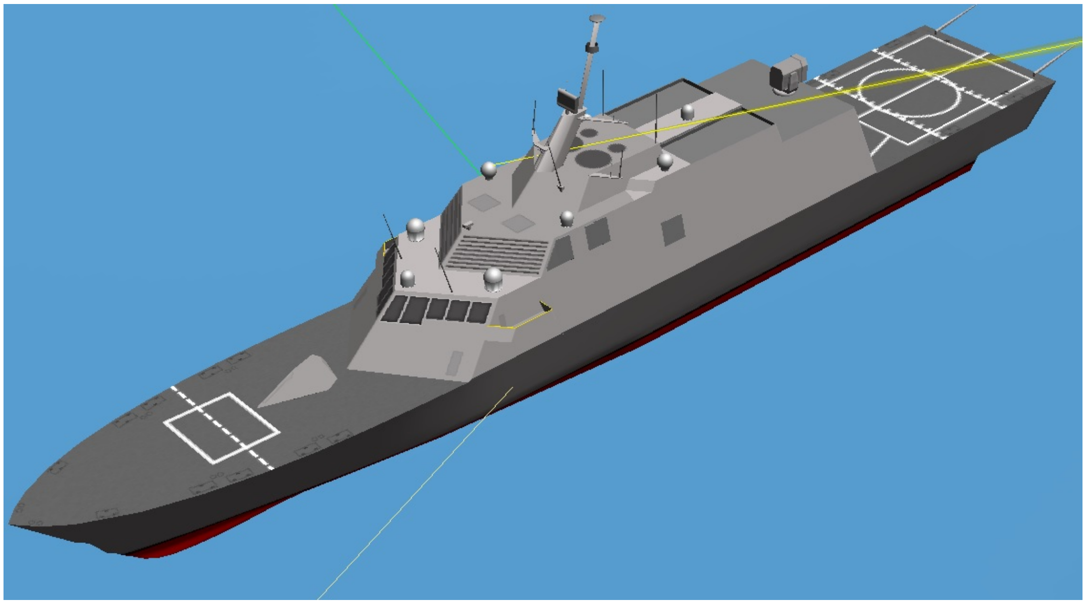
```
                                                                               28 Jan 2017 10:03:03
 AGI Educational Alliance Partner
Satellite-O3B_M009_40351-To-Ship-LCS:  Access Summary Report


O3B_M009_40351-To-LCS
---------------------
                  Access       Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------   ------------------------   --------------
                       1    10 Aug 2016 19:57:15.421   10 Aug 2016 21:49:24.310         6728.889

Global Statistics
-----------------
Min Duration           1    10 Aug 2016 19:57:15.421   10 Aug 2016 21:49:24.310         6728.889
Max Duration           1    10 Aug 2016 19:57:15.421   10 Aug 2016 21:49:24.310         6728.889
Mean Duration                                                                           6728.889
Total Duration                                                                          6728.889
```

The access summary report shows the period in the scenario where the LCS uses satellite M009 as its network link to the ground station. In STK, skipping to the timeframe of interest reveals that the Ka-band terminal may have experienced blockage due to the LCS superstructure. This is displayed in Figure 41.

Figure 41. LCS during Satellite M009's Access Window



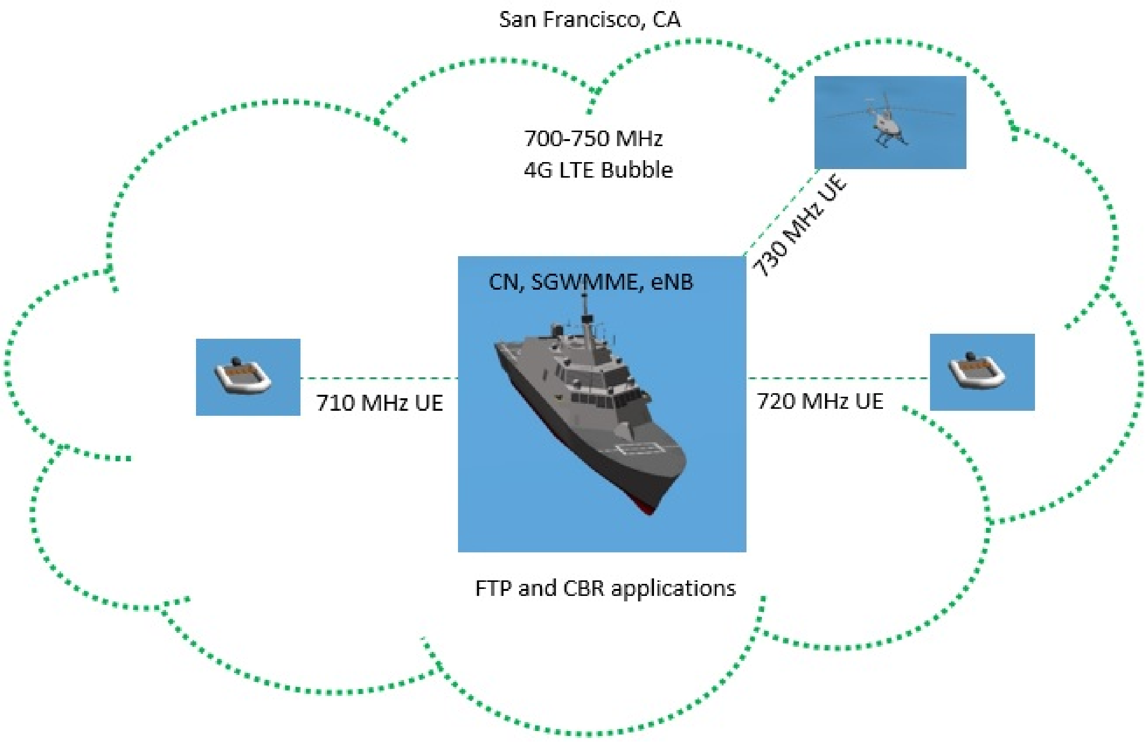
The main observations from scenario 1 were that for the LCS to be an effective IGW, the connected nodes in the mesh must be aware of the effective ranges of the Wave Relay equipment and reposition themselves accordingly. The lower than expected satellite availability appears to be a function of limitations imposed by the manner in which the scenario was designed, as well as a lack of handover capability between ground terminals in STK/QualNet.

B. SCENARIO 2 DATA: LCS PERFORMING AS A ROUTER

The original design of LCS as Router scenario posited to employ the QualNet LTE Physical and MAC layer models to create a 4G LTE bubble around the LCS that allowed nodes within to communicate with one another (Figure 42). Table 10 shows the nodes used in the scenario. It was discovered after much trial and error that the LTE portion of

QualNet was not compatible with the STK/QualNet environment. The reason an EPC network could not be established is that a Core Network (CN) must be connected to an 802.3 wired network and a SGWMME (in the form of a hub or router). This requirement cannot be modeled in STK/QualNet, as only wireless subnets, links, and wired links can be modeled. The model in Figure 42 displays the components necessary for LTE to function in QualNet 7.3.

Figure 42. Scenario 2 Overview. Scalable Network Technologies (2016).



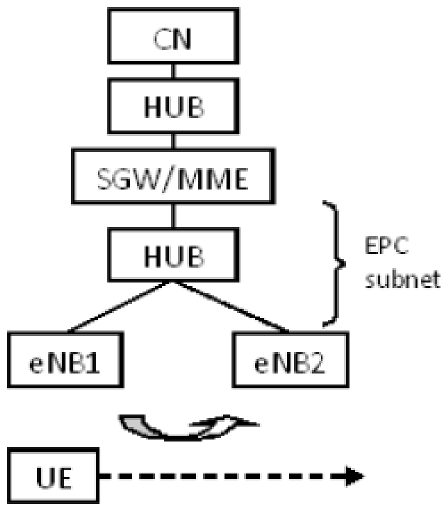
Scenario 2 nodes and additional information about the nodes is displayed in Table 10.

Table 10. Scenario 2 Nodes

QualNet Node ID	STK Platform Type/Model/Description	STK Antenna/Sensor	QualNet PHY Model	QualNet Subnet
7	Ship/LCS 3D Model/Freedom Class LCS	Isotropic	802.11b	190.0.x.x
9	Ship/Rubber Boat 3D Model/RHIB 1	3cm Dipole	802.11b	190.0.1.0
5	Ship/Rubber Boat 3D Model/RHIB 2	3cm Dipole	802.11b	190.0.2.0
8	Aircraft/RQ-8A 3D Model/Fire Scout	3cm Dipole	802.11b	190.0.3.0

The LTE EPC model is displayed in Figure 43.

Figure 43. LTE EPC Model. Source: Scalable Network Technologies (2016).



In STK/QualNet, simulation errors occur when running applications in an LTE user equipment (UE) wireless subnet with an evolved node B (eNB) interface and UE interface attached to nodes. The scenario will not initialize with this configuration. If all interfaces are changed to UEs within a UE wireless subnet, the simulation will run, but LTE packets will never be received.

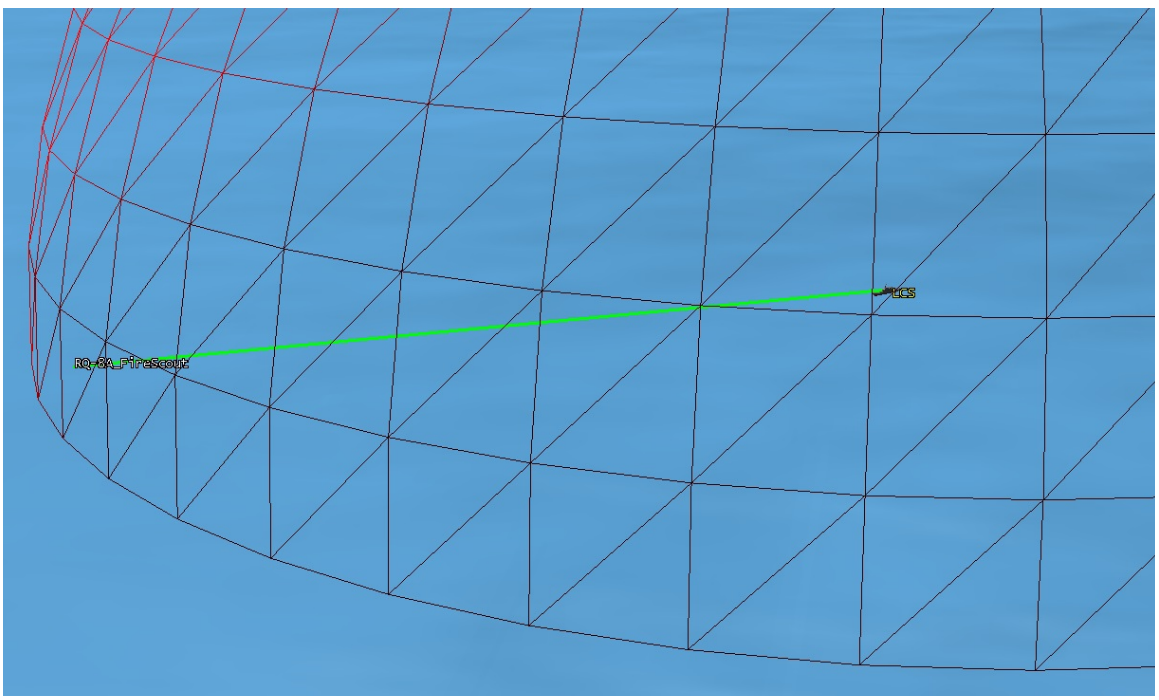
To collect data on the LCS as a router, the experiment design needed to be adjusted due to these limitations. Rather than create an LTE bubble, an 802.11b "network bubble" was modeled into the scenario using parameters for devices that mimicked those of the LTE devices described in Chapter III. The eNB antenna was mounted on the upper levels of the LCS vice the flight deck as in the previous scenario.

For each 802.11b UE, a separate 10 MHz data link was created under the channel configuration menu. The UEs were connected to the LCS eNB antenna through these individual links. The UE links to eNB each formed individual subnets so that the devices could not communicate with one another unless within the network bubble. A test scenario was created to make sure the network bubble functioned properly; in the test scenario, the two LCS RHIBs traveled in a straight line away from the vessel while transmitting a CBR application to one another. As expected, once the RHIBs reached the outer edge of the LCS network bubble they lost all connectivity with one another – despite the short distance separating them.

As such, the redesign of the scenario was in line with the original concept of testing the LCS' performance as a router. The Fire Scout was modeled with a channel to support the camera equipment in a similar manner.

The start of the scenario is displayed in Figure 44, where the Fire Scout is screening the area ahead of the LCS and sending back FTP applications through the network bubble. The effective range was approximately 4.7 kilometers.

Figure 44. Scenario 2. Fire Scout Sending FTP Application to LCS



The LCS and Fire Scout transited into San Francisco Bay. The Fire Scout approached the VOI as it headed due north on the opposite side of Yerba Buena Island, sending images back to the LCS. Based on the information, the LCS changes course to launch both RHIBs to conduct the boarding as displayed in Figure 45.

Figure 45. Scenario 2. RHIB 2 Approaching the VOI

Once the RHIBs were launched, the Fire Scout began to transmit a CBR application of 56 bytes/second. The start time for the RHIB 2 application was 4,680 seconds into the simulation, sending 5,000 items at 1-second intervals. The start time for the RHIB 1 application was 5,280 seconds into the simulation, sending the same number of items. The total scenario time was 10,800 seconds (3 hours), any items scheduled to be sent beyond the end time were truncated. The results from the CBR application are displayed in Table 11.

Table 11. Scenario 2 Availability

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Availability
CBR	8 (Fire Scout)	5 (RHIB 2)	5,000 Unicast Segments	5,000 Unicast Segments	100%
CBR	8 (Fire Scout)	7 (LCS)	10,799 Unicast Segments	10,799 Unicast Segments	100%
CBR	8 (Fire Scout)	9 (RHIB 1)	5,000 Unicast Segments	5,000 Unicast Segments	100%

The availability was high in this scenario due to the fact the nodes remained within the network bubble throughout the scenario duration. At altitude, the Fire Scout had clear LOS to the LCS eNB antenna, which in turn routed the packets to the RHIBs. The 3cm dipole antennas on the handheld devices on the RHIBs were oriented to a 90-degree elevation, essentially giving them a vertical radiating pattern. They were also placed at the height of an observer, approximately 2 M above the deck. The separate channels and subnets assigned to each device connecting to the eNB antenna likely improved performance as well.

The Fire Scout sent the FTP applications at different start times for each node. Each file size was 1 MB, with a maximum of 20 files sent. The start time was 1 second with an end time of 4,000 seconds for the LCS, 5,280 seconds with and end time of 10,800 seconds for RHIB1, and 4,680 seconds with an end time of 10,800 seconds for RHIB 2. The results of the FTP application for scenario 2 are illustrated in Table 12.

Table 12. Scenario 2 FTP Throughput

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Throughput Tx	Throughput Rx
FTP	8 (Fire Scout)	5 (RHIB 2)	20 MB	20 MB	1.85 KB/s	1.85 KB/s
FTP	8 (Fire Scout)	7 (LCS)	20 MB	20 MB	1.85 KB/s	1.85 KB/s
FTP	8 (Fire Scout)	9 (RHIB 1)	20 MB	20 MB	1.85 KB/s	1.85 KB/s

Lastly, the Network IP carried load demonstrated the Fire Scout is generating the most traffic with the LCS receiving some of it, and forwarding packets as needed to the RHIBs. The Network IP carried load for Scenario 2 is illustrated in Table 13.

Table 13. Scenario 2 Network IP Carried Load (Bytes/Second)

Node ID	5	7	8	9
Carried Load	818	21,901	29,168	821

In summary, Scenario 2 demonstrated the LCS's ability to route packets to nodes within a network bubble. The 4G LTE design would not function as originally planned, but an 802.11b network bubble sufficed. The nodes in the scenario experienced high availability. This was a function of consistent distances of nodes from the LCS while following planned routes—if the nodes had strayed from the bubble, there would have been losses. Also, each network interface connection had a dedicated subnet and 10 MHz bandwidth channel. This prevented nodes from battling for resources. Overall, a functioning LTE model would have been ideal, as it is much more complex in its utilization of multiple-input-multiple-output (MIMO) antennas on UE and in modeling the way in which the core network (CN) deals with the assignment of resource blocks. The functionality of the 802.11b network bubble cannot be directly compared to LTE, but it did demonstrate the effectiveness of some of the Physical Layer properties that could be designed into an LTE network bubble used by a primary node LCS.

C. SCENARIO 3 DATA: LCS PERFORMING AS A HUB

Scenario 3 modeled the LCS as a hub broadcasting data packets to all connected nodes in the mesh network. In this scenario, data originates from the Vernon, Texas ground station as well as LCS. This was simulated in two ways; the LCS sending a Constant Bit Rate (CBR) and Vernon, Texas sending application files to all nodes. The overview of the experiment is illustrated in Figure 46 and Table 14.

Figure 46. Scenario 3 Overview. Source: Scalable Network Technologies (2016).

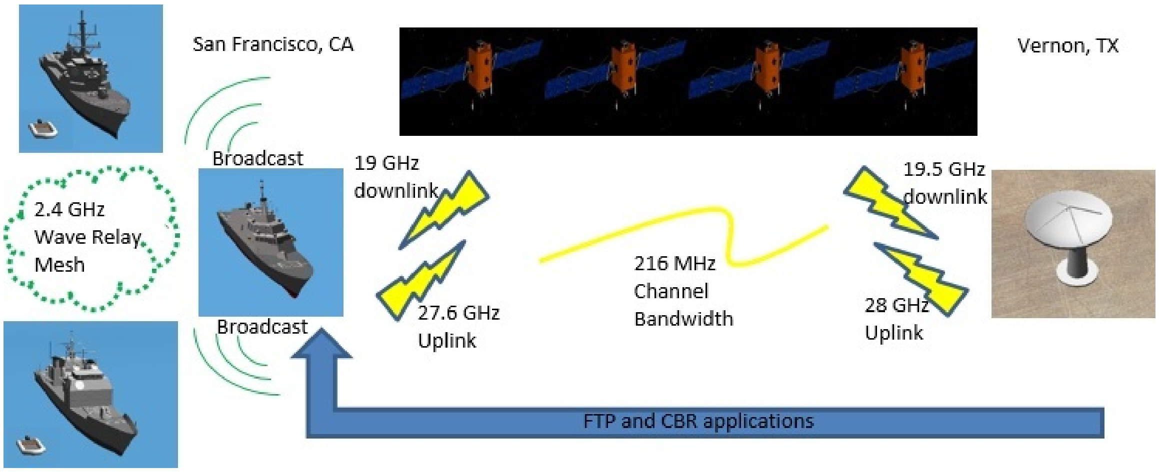
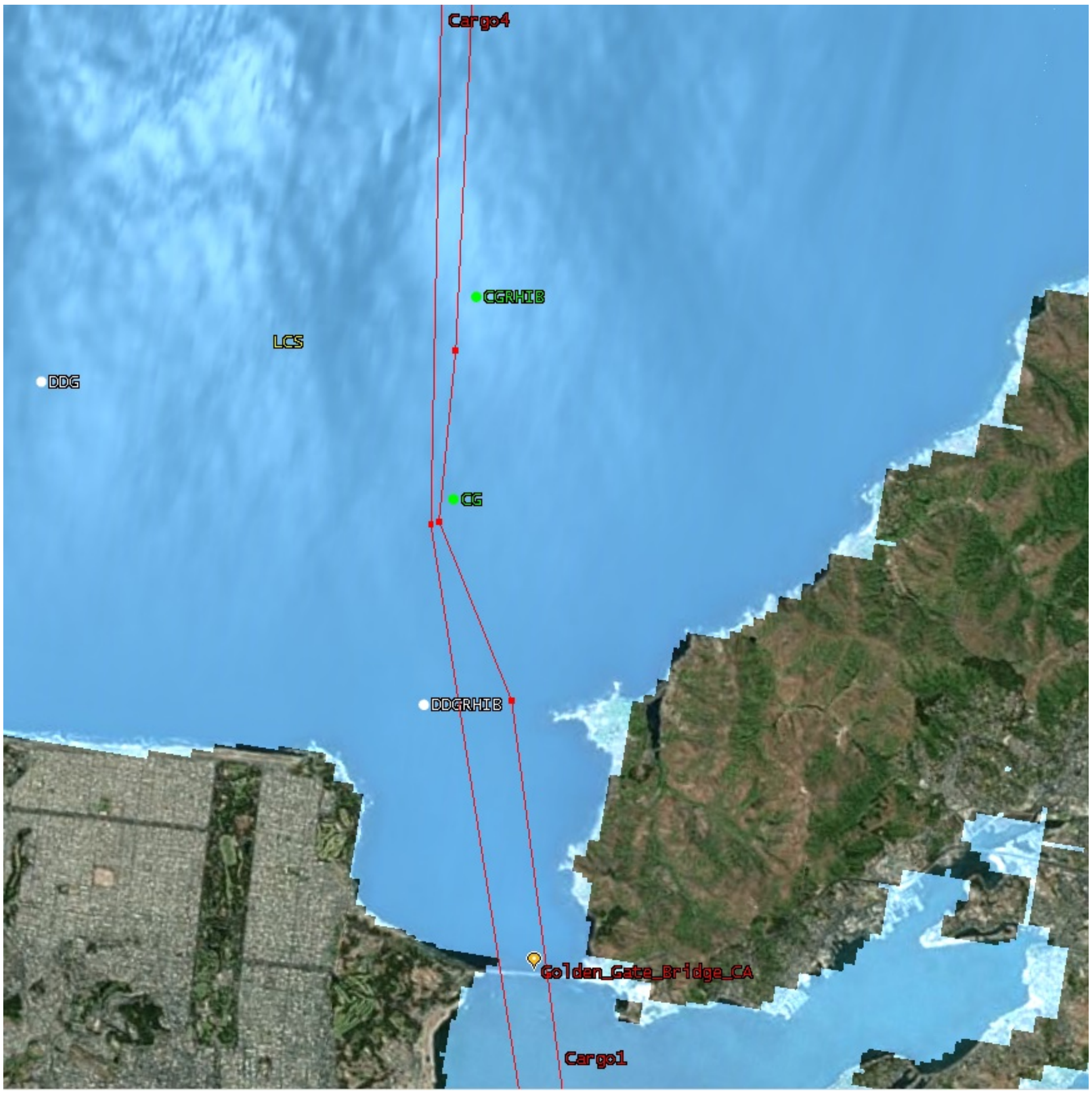


Table 14. Scenario 3 Nodes

QualNet Node ID	STK Platform Type/Model/Description	STK Antenna/Sensor	QualNet PHY Model	QualNet Subnet
5	Ship/CG 3D Model/Ticonderoga Class CG	Rectangular Pattern	802.11a/g	192.168.1.0
6	Ship/DDG 3D Model/Arleigh Burke Class DDG	Rectangular Pattern	802.11a/g	192.168.1.0
7	Ship/LCS 3D Model/Freedom Class LCS	Rectangular Pattern, Parabolic, Fixed Target Sensor	802.11a/g, Satellite-RSV	192.168.1.0, 190.0.3.0
23	Place/Facility/O3b Ground Station	Parabolic	Satellite-RSV	190.0.2.0
11	Satellite/M003/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
15	Satellite/M007/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
17	Satellite/M009/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
19	Satellite/M011/O3b MEO	Parabolic, Fixed Target Sensor	Satellite-RSV	190.0.2.0, 190.0.3.0
8	Ship/Rubber Boat 3D Model/CG RHIB	Isotropic	802.11a/g	192.168.1.0
22	Ship/Rubber Boat 3D Model/DDG RHIB	Isotropic	802.11a/g	192.168.1.0

In addition to the nodes used in Scenario 1, the cruiser and destroyer each launched a RHIB to conduct picket boat operations. The scenario run time was 6 hours for the same reason as scenario 1. A bird's eye view of node placement is displayed in Figure 47.

Figure 47. Scenario 3 Nodes in San Francisco Bay



The network design of the scenario consisted of the subnets in Table 14 and manual assignment of a broadcast IP address to the DDG RHIB. The Wave Relay subnet mask was 255.255.255.224, and the broadcast IP address of the RHIB was 192.168.1.31. The results of the simulation were the same regardless of which node in the Wave Relay subnet was assigned the broadcast address. The CBR application was sent from the LCS to the DDG RHIB, which broadcast the application to all nodes in the subnet. The results are illustrated in Table 15.

Table 15. Scenario 3 Availability

Application	**Originating Node**	**Receiving Node**	**Data Tx**	**Data Rx**	**Availability**
CBR	7 (LCS)	5 (CG)	21,599 UDP Broadcast Segments	9,742 UDP Broadcast Segments	45.1%
CBR	7 (LCS)	6 (DDG)	21,599 UDP Broadcast Segments	13,416 UDP Broadcast Segments	62.1%
CBR	7 (LCS)	8 (CG RHIB)	21,599 UDP Broadcast Segments	2,886 UDP Broadcast Segments	13.4%
CBR	7 (LCS)	22(DDG RHIB)	21,599 UDP Broadcast Segments	445 UDP Broadcast Segments	2.06%

Reception of broadcast packets was low on the RHIBs; this can be attributed to the fact that the RHIBs were modeled with 2.4 GHz isotropic antennas, giving them a lower effective range—approximately 1.4 KM - in the mesh when compared to sector array antennas. The broadcast packets do not hop across other nodes to create more efficient routes; they simply radiate from the LCS and are received by all nodes in range. The RHIBs remained in relatively static picket positions at the edge of the ships' operational boxes, so when the LCS moved from one end of its box to the other, there was no reception. As in scenario 1, increased distance induced high availability losses.

Next, the same CBR application was sent from the Vernon ground station to the RHIB. The application did not broadcast, however. The broadcast IP address was reassigned to the Wave Relay device on the LCS, but the results were the same. This was simply because the originating interface and the broadcast interface were on different subnets.

To work around the issue, a multicast domain was established to send packets from Vernon directly to the LCS Wave Relay interface with the broadcast address, but this did not solve the issue. It was assumed the application would not broadcast due to different broadcast domains between the two subnets, and a workaround was not found.

As described in Scenario 1, the super application did not function in STK/QualNet. This application would have been very helpful in testing UDP broadcast. Due to the limitations, an FTP experiment was designed to test throughput. FTP uses TCP at the Transport Layer and therefore cannot broadcast on a subnet like UDP. However, to complete the experiment using the LCS as a hub or node to distribute data, it was tailored to suit the need.

Instead of the LCS broadcasting a single application, the Vernon ground station simultaneously transmitted an FTP application to each node -- this was more intensive on satellite bandwidth. The FTP application was configured to send a maximum of 20 items with a file size of 2 MB each at random intervals throughout the scenario to every node (excluding the LCS). The results are displayed in Table 16.

Table 16. Scenario 3 FTP Throughput

Application	**Originating Node**	**Receiving Node**	**Data Tx**	**Data Rx**	**Throughput Tx**	**Throughput Rx**
FTP	23 (Vernon)	5 (CG)	40 MB	40MB	1.85 KB/s	1.85 KB/s
FTP	23 (Vernon)	6 (DDG)	40 MB	2 MB	1.85 KB/s	.093KB/s
FTP	23 (Vernon)	8 (CG RHIB)	0 MB	0 MB	-	-
FTP	23 (Vernon)	22 (DDG RHIB)	8 MB	2 MB	.37KB/s	.093KB/s

Due to the randomization in the number of files to be sent, the simulation did not send anything to node 8. The CG experienced the highest throughput despite having lower availability in the CBR experiment. The lower availability may have been due to longer periods of stable connectivity vice data links breaking and reforming with the DDG. With FTP, the TCP/IP protocol used at the Transport Layer must handshake and confirm delivery of packets. If the link breaks, this protocol must reestablish the three-way connection. Compared to the CBR application, which uses a connectionless approach by streaming UDP segments, this makes data transfer more difficult under less than ideal conditions. There are advantages and disadvantages to each, depending on the overall purpose of the mission (streaming video, sending image files).

The Network IP carried load for scenario 3 is displayed in Table 17.

Table 17. Scenario 3 Network IP Carried Load (Bytes/Second)

Node ID	5	6	7	8	11	15	17	19	22	23
Carried Load	141	64	4,729	.09	2.7	1.9	2.31	4733	217	4415

From this data, the nodes with the largest amount of network traffic are the LCS, the ground station, and O3b satellite M011. M011 is the satellite that has access to the LCS Ka-band terminal at initialization of the scenario. It appears most files sent through the FTP application were delivered during this access window. The CG, receiving the most files, had an FTP session start time of 1 second which ended at 724 seconds. During this time, the CG had stable connectivity with the LCS through the Wave Relay subnet due to its proximity. The DDG, receiving the least number of files sent, started an FTP session at 1 second and ended at 7,572 seconds. TCP packets were received only during the first few minutes. The DDG experienced lower connectivity due to its increasing range from the LCS as the scenario progressed. At the outset of the Scenario, the DDG and LCS were close to one another, but they immediately went off in different directions, with the LCS on a heading closing the distance to the CG. This maneuver once again demonstrated the effect of distance and mobility of nodes on availability and throughput.

A summary of findings in Scenario 3 is as follows: broadcasting packets from the LCS as a primary node requires the other nodes to be within proximity to be of use. Broadcast data packets will not hop across nodes in the mesh to reach their destination. A method to get around broadcast domains between the O3b and Wave Relay subnets would have improved data collection during the scenario. Using the FTP application, the LCS could distribute files 2 MB in size originating from the Vernon ground station to nodes within the mesh. Performance varied based on mobility, distance, and whether antennas were sector array or isotropic.

D. SCENARIO 4 DATA: LCS PERFORMING AS A BRIDGE

Scenario 4 consisted of unmanned systems sending information through LOS point-to-point wireless links and mesh to their respective controlling platforms, and in turn linking this information to one another through a central LCS performing as a network bridge. This is illustrated in Figure 48 and Table 18.

Figure 48. Scenario 4 Overview. Source: Scalable Network Technologies (2016).

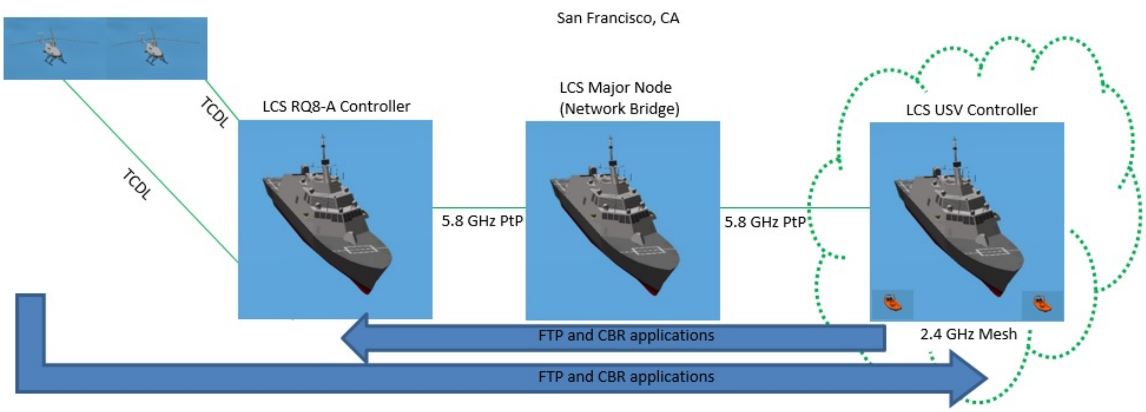
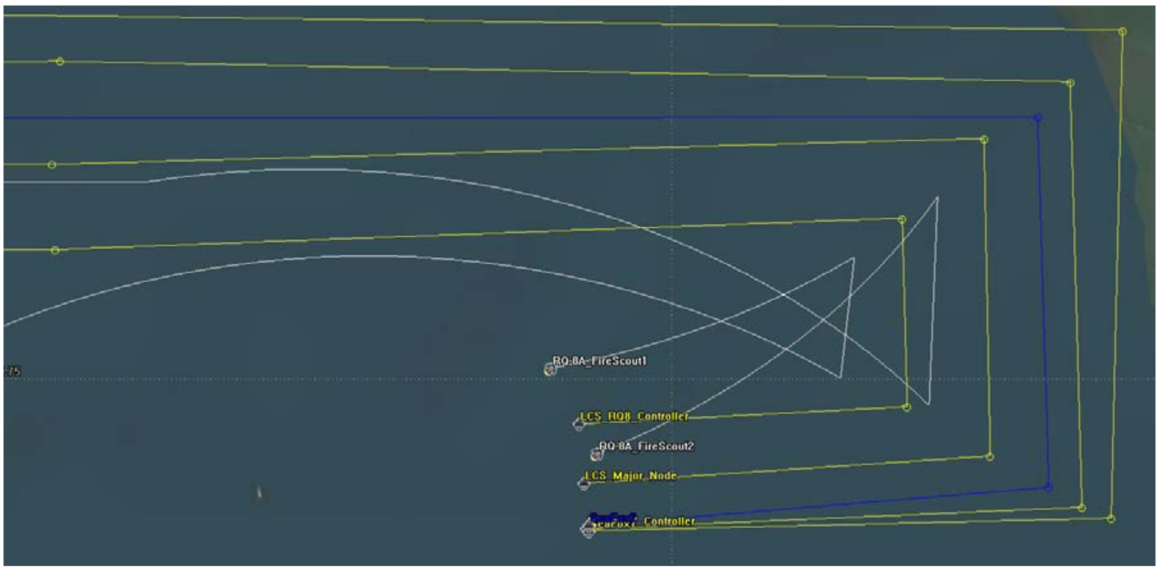


Table 18. Scenario 4 Nodes

QualNet Node ID	**STK Platform Type**	**STK Antenna/Sensor**	**QualNet PHY Model**	**QualNet Subnet**
7	Ship/LCS 3D Model/Freedom Class LCS functioning as network bridge	Uniform Aperture Rectangular	Abstract	190.0.6.0, 190.0.7.0
5	Ship/LCS 3D Model/Freedom Class LCS with RQ-8A control station	Uniform Aperture Circular, Uniform Aperture Rectangular	Abstract	190.0.4.0, 190.0.5.0, 190.0.6.0
6	Ship/LCS 3D Model/Freedom Class LCS with USV control station	Isotropic, Uniform Aperture Rectangular	Abstract, 802.11b	190.0.9.0, 190.0.7.0
9	Aircraft/RQ-8A 3D Model/Fire Scout	Uniform Aperture Circular	Abstract	190.0.4.0
10	Aircraft/RQ-8A 3D Model/Fire Scout	Uniform Aperture Circular	Abstract	190.0.5.0
13	Ship/HSMST 3D Model	Isotropic	802.11b	190.0.9.0
14	Ship/HSMST 3D Model	Isotropic	802.11b	190.0.9.0

The total length of the Scenario was 3 hours; it initiated with all nodes near one another and on a course approaching the mouth of San Francisco Bay. The speed of the nodes remained relatively constant, approximately 10 knots unless it was necessary for a node to increase speed to catch up with the formation following a turn. The 2D overview in Figure 49 displays the nodes and routes taken during the first leg of the scenario.

Figure 49. Scenario 4 Nodes and Routes



CBR applications were established to test availability as prescribed in the research design. The characteristics of the applications and associated availability are illustrated in Table 19.

Table 19. Scenario 4 Availability

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Availability
CBR	9 (Fire Scout 1)	6 (LCS Controlling USVs)	10,799 Unicast Segments	10,799 Unicast Segments	100%
CBR	10 (Fire Scout 2)	6 (LCS Controlling USVs)	10,799 Unicast Segments	10,799 Unicast Segments	100%
CBR	13 (Sea Fox 1)	5 (LCS Controlling Fire Scouts)	10,799 Unicast Segments	6,810 Unicast Segments	63%
CBR	14 (Sea Fox 2)	5 (LCS Controlling Fire Scouts)	10,799 Unicast Segments	6,810 Unicast Segments	63%

The availability of the Fire Scouts to the LCS USV controller was high for many reasons: they were airborne, their directional antennas had higher gains, and the TCDL link was established as point-to-point microwave links in STK/QualNet. The point-to-point abstract links in QualNet typically enable full access as long there is LOS between transmitting and receiving interfaces. The same can be said of the Tsunami wireless point-to-point links connecting the LCS platforms to one another. The Sea Fox USVs, connected to their corresponding LCS with 2.4 GHz isotropic antennas, experienced degraded availability for the same reasons as outlined in previous scenarios. As with previous experiments, the FTP application was set to start at 0 seconds and transmit files of 2 MB in size until the scenario ended. The point-to-point links worked well for the same reasons as described in the CBR section. Scenario 4 FTP throughput is displayed in Table 20 and the carried load over Network IP is displayed in Table 21.

Table 20. Scenario 4 FTP Throughput

Application	Originating Node	Receiving Node	Data Tx	Data Rx	Throughput Tx	Throughput Rx
FTP	9 (Fire Scout 1)	6 (LCS Controlling USVs)	458 MB	456 MB	42.4 KB/s	42.2 KB/s
FTP	10 (Fire Scout 2)	6 (LCS Controlling USVs)	460 MB	456 MB	42.5 KB/s	42.2 KB/s
FTP	13 (Sea Fox 1)	5 (LCS Controlling Fire Scouts)	42 MB	40 MB	3.9 KB/s	3.7 KB/s
FTP	14 (Sea Fox 2)	5 (LCS Controlling Fire Scouts)	42 MB	40 MB	3.9 KB/s	3.7 KB/s

Table 21. Scenario 4 Network IP carried load (bytes/second)

Node ID	5	6	7	9	10	13	14
Carried Load	1,267,815	199,647	1,374,030	587,992	587,905	54,049	53,347

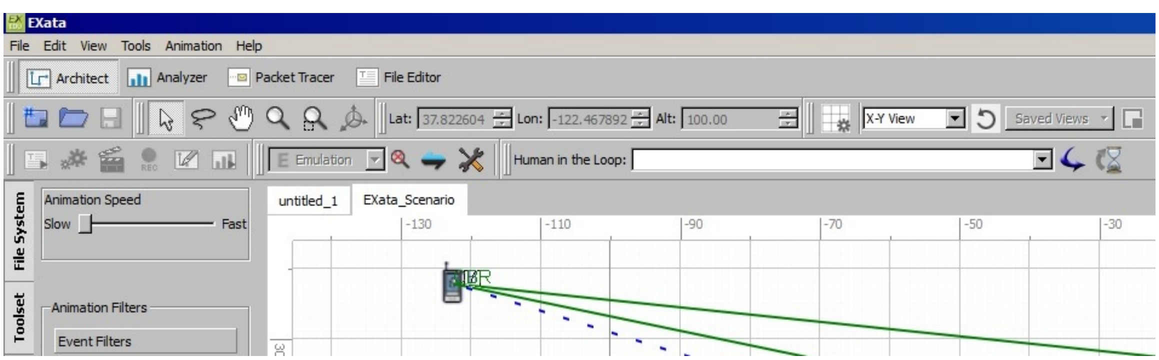
Node 7, the LCS performing as the major node, carried approximately 1.37 MB/s (Table 21) throughout the duration of the scenario. This factors into the IP traffic traversing the wireless network bridge from both LCS nodes controlling the unmanned systems.

In summary, Scenario 4 showed that point-to-point links creating a network bridge are effective at relatively close ranges with the LCS acting as a major node. Also, the nodes moved along predetermined routes to support this connectivity, and that improved availability.

E. EXATA 5.3 CONCEPTUAL EXPERIMENT

The EXata application functioned as anticipated in many respects. The QualNet configuration file created from the STK/QualNet interface maintained latitude/longitude positional data and network properties when loaded into EXata. However, the positional data was only inherited for the nodes' starting points—mobility was not. This was overcome with relative ease by creating waypoints within the EXata palette. Also, when emulation is initiated, nodes can be placed or removed to observe the effect on network performance. Figure 50 illustrates that positional data from San Francisco Bay was inherited from the STK/QualNet scenarios for the LCS.

Figure 50. LCS (Node 7) Positional Data. Source: Scalable Network Technologies (2016).



Two aspects of the experiment were not accomplished due to technical challenges. First, the SolarWinds application was not able to install on IT140321 due to lack of administrative privileges. The application required the installation of MySQL Express to store and maintain a network management database, which would not install on NPS machines even with local administrative privileges—additional administrative rights were required and not available. Also, the machine running EXata was not able to identify IT140321 as an operational host. This, however, was not a major issue as other machines in the CENETIX lab, detected on the network, can use the EXata Connection Manager and function as operational hosts.

The trial version of EXata 5.3 was operable for less than two weeks. If a fully licensed copy was available, more experimentation could have been performed, and the issues resolved. Hence, to design an experiment with observable network management metrics, a fully licensed copy of the software is needed.

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V. FINDINGS AND FUTURE RESEARCH

Once a year, Navy Fleet Week provides a window for a variety of Navy and Coast Guard platforms to conduct C4I experimentation in San Francisco Bay with the CENETIX TNT. This exercise provides an opportunity for system stakeholders to test the use of fly-away kits and mobile communications equipment as well as other C4I concepts on a variety of platforms, including the LCS. Other venues for Fleet experimentation would also serve this purpose. The simulated scenarios using only waterborne assets would not be exceedingly difficult to be carried out as field experiments.

The simulation results of our research demonstrated wireless network capabilities by equipping the LCS with commercially available wireless mesh and MANET equipment, as well as integrating levels of military equipment. One of the initial findings that was, perhaps, intuitive, is that distance and mobility of nodes played a large part in the effectiveness of the LCS as a major node. Units operating in a mesh network created by the LCS must remain constantly aware of the effective ranges of the equipment in use if they hope to take full advantage of it.

A challenge encountered in this research was acquiring software educational license agreements for versions of STK and QualNet that were compatible with one another. The newest version of QualNet at the time of this thesis (QualNet 7.4) was only compatible with the latest version of STK (STK 11). Only the 32-bit version of QualNet (QualNet version 7.3) was compatible with the STK version available at NPS (STK 10.1.3) during the period of research. QualNet software agreements are node-locked, meaning that only individual Naval Postgraduate School student researchers can access the most up-to-date versions of the software. The Scalable Networks QualNet agreements had to be brokered between student researchers, a faculty member, and the software companies.

The learning curve for self-taught skills in creating STK/QualNet scenarios was steep—many scenarios needed to be created to gain an understanding of the intricate relationship between the STK/QualNet interfaces. STK and QualNet maintain a plethora of documentation describing each as a standalone program, but there is little documentation to tie the two together. Hence, many of the limitations and incompatibilities of STK/QualNet had to be discovered through trial and error.

The designed STK/QualNet scenarios successfully ran and collected data, but the interaction between STK objects and QualNet interfaces often did not occur as expected. For example, QualNet interfaces could link to STK antenna objects and sensors, but not transmitters and receivers. STK antenna objects linked with QualNet interfaces could be assigned as parent objects of STK transmitters and receivers, but this had no impact on simulation runs even when extreme setting changes were made. This configuration was tested by performing the same simulation runs with and without the transmitter and receiver objects attached to antennas. The detriment of this was that antennas without attached transmitters and receivers had less experimental capability; properties such as polarization, additional gains, and data throughput based on propagation models could not be customized.

The simulation model was not able to fully test throughput limitations of the mesh. The Super Application for doing this would not run in the STK/QualNet interface even when configured with recommended parameters. The best throughput measure that could be achieved was sending large files with the FTP application in the scenarios. QualNet trace files, generated upon completion of a simulation run, were recorded as taking up anywhere from 2 GB to 8 GB on the local hard disk when running this type of iteration. These files needed to be periodically removed to free up system resources. Hence, the observation was that testing throughput caused issues with resources on the local machine running the simulation. It is uncertain whether the Super Application, had it been able to run, would have overburdened system resources to the same extent or greater.

The EXata 5.3 emulation testbed showed promising capabilities. However, the short period it was made available was not enough to set up complex network management experiments with the LCS.

Additional follow-on research may include:

- Modeling LCS ADNS networks connected to commercial satellite providers to test throughput limitations
- Effectiveness of the LCS as a network manager in a mesh network using an emulation testbed
- Modeling a 4G LTE EPC network on the LCS if compatible with STK/QualNet in future versions
- Field experimentation with vessels participating in fleet week using Wave Relay devices and fly-away kits for other wireless networking experiments
- Modeling optimized formation and placement of nodes for availability around an LCS performing as a major node in a mesh network
- Feasibility of an LCS C4I mission package utilizing mesh and high-bandwidth satellite technology
- Simulations evaluating the LCS with other tactical network communication devices

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VI. CONCLUSION AND RECOMMENDATIONS

This thesis research answered the question, “How well the LCS platform can perform as a Wireless Mesh Network node in a littoral environment” with Unmanned Surface Vessels (USV) and other nodes. This was accomplished by modeling the platform as an Internet Gateway, router, hub, and network bridge in simulation. The results demonstrated favorable and unfavorable capabilities depending on equipment used and movement of nodes.

The research partially answered the question of how network management software can assist in identifying the optimal role of the LCS platform in a WMN, and presented a baseline model to be used with EXata 5.3 emulation software to test network management capabilities of the LCS. It is recommended that NPS acquire rights to this software, or a comparable tool, to establish an emulation testbed for projects on network management using the LCS.

A recommendation for improving network simulation research opportunities for NPS students is for the campus to aquire server-license agreements for STK/QualNet. This would smooth out logistical issues and allow for students to experiment without the need for node-locked license agreements. Furthermore, students in the Network Operations and Technology (NWOT) curriculum are not required to take courses giving them hands-on experience with these simulation programs. QualNet and STK are capable of performing simulations with a substantial number of DOD platforms and associated communications equipment. The in-depth analysis of networking protocols and DOD network architecture that this software can provide closely parallels learning objectives of the NWOT curriculum. It is further recommended that a required course be offered that instructs NWOT students the basics of using network modeling software as it pertains to DOD systems, which may in turn garner interest in research like that conducted in this thesis.

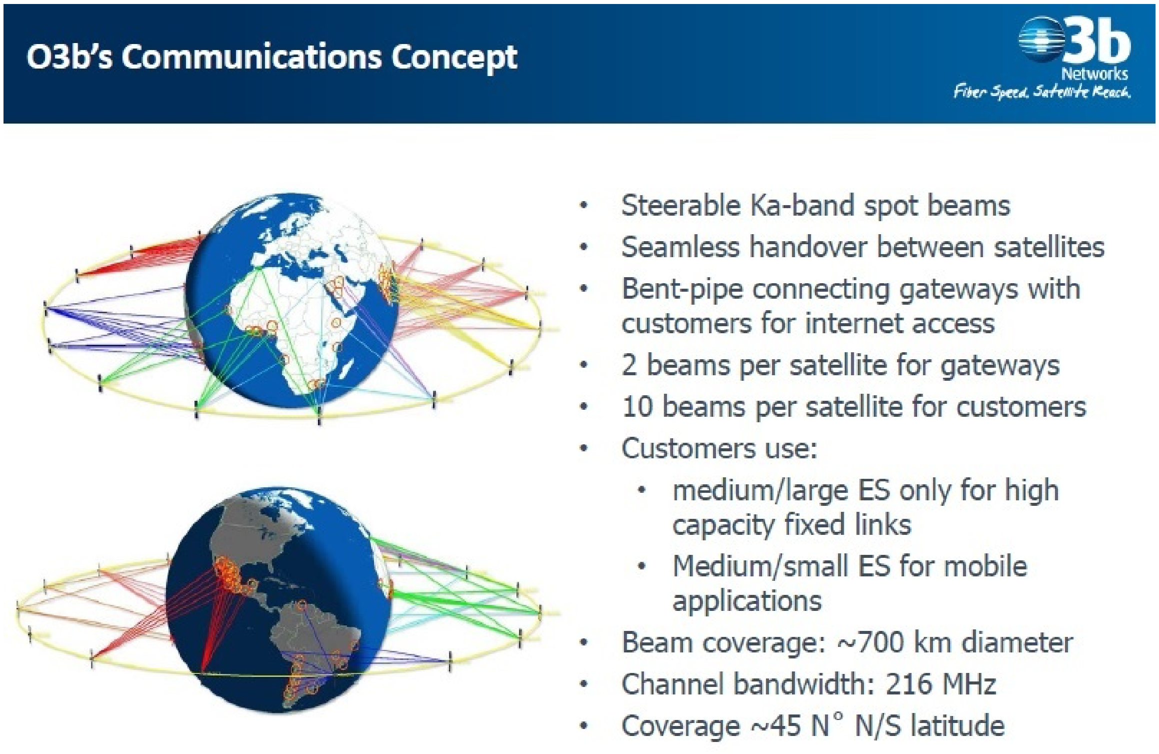
The STK/QualNet simulation of the LCS performing as a major node in a wireless mesh network—under the vignette of a multi-vessel San Francisco Fleet Week

C4ISR field experiment—demonstrated the platform's potential to execute network-centric warfare roles. Bearing all modeling constraints of STK/QualNet in mind, the LCS proved capable of fulfilling networking roles as an Internet gateway, router, hub, and bridge to varying degrees of performance and reliability in a mesh. The research demonstrated a macroscopic view of the effectiveness of communications links—mainly those offered by tactical wireless devices and satellite equipment commercially available—connecting manned and unmanned nodes in a mesh network to a theoretical core tactical network on the LCS. The simulation did not model internal network interactions between LCS mission modules and ADNS combat systems architecture. The intricacies of LCS internal networks may be well be beyond the scope and capabilities of the developed model. As such, a recommendation is to conduct Fleet field experiments with tactical wireless networking equipment connected to an ADNS network on an LCS and other nodes. Furthermore, it would be useful to model any tactical wireless field experiments beforehand to observe effective ranges of proposed equipment and configuration, as well as the impact of node mobility on performance. The model developed for this research offers reusability for various equipment and networking parameters that can be continuously adjusted or improved to serve the needs of Fleet experiment designers. The vignette of the LCS performing as a major node by modeling it as an Internet gateway, router, hub, and bridge is merely a springboard for future network-centric warfare research and experimentation.

The CONOPS for LCS is continuously undergoing redefinition and improvements. Only through further simulation and field experimentation can the true network warfare and Distributed Lethality potential of this platform be evaluated. As such, it is fitting to conclude with a quote from Mr. Work.

"Future variants of the LCS may evolve in ways not now anticipated or foreseen, just as happened with torpedo boats. The only thing standing in the way of success for LCS would be a lack of imagination and hard work." (Work, 2014)

APPENDIX A. O3B OPERATIONS AND DATASHEETS



Source: Barnett (2013)

7.3 Meter Ka-Band Antenna
Broadband Gateway Earth Station

The 7.3 meter Ka-band gateway is an integral part of the broadband system delivering high-speed WiFi connections for residential, commercial and government services. The antenna is efficiently designed to receive and transmit data from high capacity satellites to make full use of their high data rate capabilities.

Site Information	**VERNON, TX**
Venue Name	
Latitude (NAD 83)	34° 13' 4.7" N
Longitude (NAD 83)	99° 23' 46.5" W
Climate Zone	A
Rain Zone	2
Ground Elevation (AMSL)	390.47 m / 1281.1 ft

Link Information	
Satellite Type	Low Earth Orbit
Mode	TR - Transmit-Receive
Modulation	Digital
Minimum Elevation Angle	3.0°
Azimuth Range	0.0° to 360°
Antenna Centerline (AGL)	3.66 m / 12.0 ft

Antenna Information		**Receive - FCC32**		**Transmit - FCC32**	
Manufacturer		ViaSat		ViaSat	
Model		8073		8073	
Gain / Diameter		61.2 dBi / 7.3 m		65.0 dBi / 7.3 m	
3-dB / 15-dB Beamwidth		0.02° / 0.04°		0.01° / 0.02°	
Max Available RF Power	(dBW/4 kHz)			15.7	
	(dBW/MHz)			39.7	
Maximum EIRP	(dBW/4 kHz)			80.7	
	(dBW/MHz)			104.7	
Interference Objectives:	Long Term	-156.0 dBW/MHz	20%	-151.0 dBW/4 kHz	20%
	Short Term	-146.0 dBW/MHz	0.01%	-128.0 dBW/4 kHz	0.0025%
Frequency Information		**Receive 18.0 GHz**		**Transmit 28.0 GHz**	

Source: VIAsat (2012)

O3b Maritime

Technical Specifications

Antenna Type:	Dual offset Gregorian
Antenna size:	1.15m (45'')
Radome Size:	D: 1.55m (61")
	H: 1.69m (67")
ADE Weight (Exc BUC):	185Kg (408 lb)
Configuration:	A quadruple-axis polarization-over- elevation-over-tilt-over-azimuth
Range of Dynamic Motion:	Full hemispherical coverage, down to satellite elevation view angle as low as 10° at all sea conditions. With no "keyholes" at zenith or horizon
Range of Mechanical Pedestal Axes:	
	Azimuth: Continuous
	Elevation: -30° to +120°
	Cross Elevation: -75° to +75°
Ship Gyro Interface:	NMEA 0183, Step by Step, Synchro
Operating Frequency – (Range via 2 selectable bands):	
Rx	17.8 GHZ to 19.3 GHz
Tx	27.6 GHz to 29.1 GHZ
System G/T (dB/°K, Typical includes all losses):	
	≥19dB/°K @ mid-range at 20° Elevation

Source: O3b Networks (2013)

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APPENDIX B. 4G LTE SPECIFICATIONS

Model	ZDAQJ700-6	ZDAQJ700-8	ZDAQJ700-10
Frequency Range	698-755 MHz	698-755 MHz	698-755 MHz
Gain	6dBi	8dBi	10dBi
Polarization	Vertical	Vertical	Vertical
Horizontal Beam Width	360 °	360 °	360°
Vertical Beam Width	30 °	25°	16°
VSWR	<1.5	<1.5	<1.5
Input Impedance	50 ohm	50 ohm	50 ohm
Input Maximum Power	200 W	200 W	200 W
Lightning Protection	DC Ground	DC Ground	DC Ground
Connector	N female or customized	N female or customized	N female or customized
Size	39.37in.(1000 mm)	61in.(1550 mm)	110in.(2800 mm)
Radiating Electrical Material	Cu Ag	Cu Ag	Cu Ag
Radome Material	Fiberglass	Fiberglass	Fiberglass
Operating Temperature	-40° C to 85° C (-40° F to 185° F)	-40° C to 85° C (-40° F to 185° F)	-40° C to 85° C (-40° F to 185° F)
Diameter of Installation Pole	1.2-2.3in. (30-60 mm)	1.2-2.3in. (30-60 mm)	1.2-2.3in. (30-60 mm)
Weight	3.3 Lbs (1.5 Kg)	4.4 Lbs (2 Kg)	9.4 Lbs (3.5 Kg)

Source: ZDA Communications (2014).

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APPENDIX C. TSUNAMI QB-10100 SERIES NETWORK BRIDGE

Specifications: Tsunami® QB-10100 Series

PRODUCT MODELS		PART NUMBERS	
QB-10100-LNK	Tsunami® QB 10100 Link, single radio, 866 Mbps, MIMO 2x2, Type-N Connectors	902-00769 QB-10100-LNK-US	902-00771 QB-10100-LNK-WD
QB-10150-LNK	Tsunami® QB 10150 Link, single radio, 866 Mbps, MIMO 2x2, 22 dBi integrated antenna	902-00773 QB-10150-LNK-US	902-00775 QB-10150-LNK-WD
QB-10150-LKL	Tsunami® QB 10150 Link Long-range, single radio, 866 Mbps, MIMO 2x2, 28 dBi integrated antenna	902-00779 QB-10150-LKL-US	902-00780 QB-10150-LKL-WD

INTERFACES	
WIRED ETHERNET	Two auto MDI-X RJ45 10/100/1000Mbps Ethernet (Port #1 with PoE in & Data, Port #2 with PoE out & Data)
WIRELESS PROTOCOL	WORP® (Wireless Outdoor Router Protocol)

RADIO & TX SPECS			
MIMO	2x2:2		
MODULATION	OFDM with BPSK, QPSK, QAM16, QAM64, QAM256		
FREQUENCY	5.150 – 5.925 GHz (Subject to Country Regulations)		
CHANNEL SIZE	80 MHz, 40 MHz and 20 MHz		
DATA RATE	MCS 0 to 9 with Dynamic Data Rate Selection		
TX POWER	Up to 28 dBm (dual chain)		
TX POWER CONTROL	0 - 27 dB, in 1 dB steps. Automatic TPC with configurable EIRP limit		
	80 MHz	40 MHz	20 MHz
TX POWER	MCS0: 28	MCS0: 28	MCS0: 29
	MCS9: 21	MCS9: 22	MCS8: 25
RX SENSITIVITY (Per=10%)	MCS0: -89	MCS0: -93	MCS0: -94
	MCS9: -68	MCS9: -71	MCS8: -74
THROUGHPUT	Up to 633 Mbps	Up to 324 Mbps	Up to 137 Mbps
OTHER	Dynamic Channel Selection (DCS) based on interference detection. Dynamic Frequency Selection (DFS) based on radar signature . Automatic Transmit Power Control (ATPC) with EIRP limit support		

ANTENNA	
QB-10100-EPA	Two N-type Connectors with built-in Surge Protection
QB-10150-EPR	Integrated 2x2 MIMO 22dBi Dual Polarized 1 foot Panel Antenna
QB-10150-EPL	Integrated 2x2 MIMO 28dBi Dual Polarized 2 feet Panel Antenna

MANAGEMENT	
REMOTE	Telnet and SSH, Web GUI and SSL/TLS, TFTP, SNMPv3
SNMP	SNMP v1-v2c-v3, RFC-1213, RFC-1215, RFC-2790, RFC-2571, RFC-3412, RFC-3414, Private MIB
OTHER	Syslog, sFlow™ agent, SNTP and local time, Spectrum analyzer

Source: Proxim Wireless (2016).

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APPENDIX D. SUPPLEMENTARY QUALNET APPLICATIONS

The File Transfer Protocol (FTP) application uses network traces to determine the size of the file sent between a client and server. It is based on the RFC 959 standard. It differs from the FTP Generic model used in the scenarios due to its randomization. The size and number of files sent can be randomly determined by the tcplib.

The Hypertext Transfer Protocol (HTTP) application simulates single TCP connections between web servers and clients. The application can model the client-server functionality between nodes and can also simulate an FQDN through the specific configuration of the server node in the QualNet application file. Nodes can be automatically configured in the simulation by designating them as HTTP servers.

The Lookup Traffic Generator simulates ping commands and DNS lookups from one node or IP address to another. It can be configured with predetermined start and stop times or left to run throughout the entire scenario, similar to the CBR application.

The Multicast Constant Bit Rate (MCBR) Generator is useful for testing the network's capability to run applications reliant upon steady time synchronization, such as on-demand services -- i.e., streaming video or VoIP. The application is typically configured to send items to a multicast address.

The Variable Bit Rate (VBR) application is similar to the CBR application. It is useful for injecting background traffic over a specified time interval. The user determines a fixed item size to send from one node to another at random intervals between the start and stop time of the simulation.

Source: Scalable Network Technologies (2014f)

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APPENDIX E. SUPPLEMENTARY QUALNET STATISTICS

802.11 a/g PHY	Signals locked (signals)	Number of signals locked on by PHY
802.11 a/g PHY	Signals received with errors (signals)	Number of signals received with errors
802.11 a/g PHY	Signals received with interference (signals)	Number of signals received with interference
802.11 a/g PHY	Signals sent to mac (signals)	Number of signals sent to MAC
802.11 a/g PHY	Time spent transmitting (seconds)	Time spent in transmitting signal
802.11 a/g PHY	Time spent receiving (seconds)	Time spent in receiving signal
802.11 a/g PHY	Average transmission delay (seconds)	Average transmission delay
802.11 a/g PHY	Utilization (percent/100)	Total utilization
802.11 a/g PHY	Average signal power (dBm)	Average signal power
802.11 a/g PHY	Average interference (dBm)	Average interference
802.11 MAC	CTS packets sent	Total number of CTS packets send to the channel.
802.11 MAC	RTS packets sent	Total number of RTS

		packets send to the channel
802.11 MAC	ACK packets sent	Total number of ACK packets sent.
802.11 MAC	RTS retransmissions due to timeout	Total number of RTS retransmissions due to timeout
802.11 MAC	Packet retransmissions due to ACK timeout	Total number of data retransmissions due to no ACK received
802.11 MAC	Packet drops due to retransmission limit	Total number of packets dropped due to retry limit exceeds
AODV Network	Number of RREQ Packets Initiated	Number of route request messages initiated
AODV Network	Number of RREQ Packets Retried	Number of route requests resent because node did not receive a route reply
AODV Network	Number of RREQ Packets Forwarded	Number of route request messages forwarded by intermediate nodes
AODV Network	Number of RREQ Packets Initiated for local repair	Number of route requests initiated for local repair
AODV Network	Number of RREQ Packets sent for alternate route	Number of route requests initiated for finding alternate routes
AODV Network	Number of RREQ	Number of route requests

	Packets received	received
AODV Network	Number of Duplicate RREQ Packets received	Number of duplicate route requests received
AODV Network	Number of RREQ Packets dropped due to TTL expiry	Number of route requests dropped due to TTL expiration
AODV Network	Number of RREQ Packets discarded for blacklist	Number of route request dropped due to the previous hop been in blacklist table
AODV Network	Number of RREQ Packets received by Destination	Number of route requests received by the destination
AODV Network	Number of RREP Packets Initiated as Destination	Number of route replies initiated from the destination
AODV Network	Number of RREP Packets Initiated as intermediate node	Number of route replies initiated as an intermediate hop
AODV Network	Number of RREP Packets Forwarded	Number of route replies forwarded by intermediate hops
AODV Network	Number of Gratuitous RREP Packets sent	Number of gratuitous route replies sent
AODV Network	Number of RREP Packets Received	Number of route replies received by the node

AODV Network	Number of RREP Packets Received for local repair	Number of route replies received for local repair
AODV Network	Number of RREP Packets Received as Source	Number of route replies received as data source
AODV Network	Number of Hello message sent	Number of hello messages sent
AODV Network	Number of Hello message received	Number of hello message received
AODV Network	Number of RERR Packets Initiated	Number of route error packets initiated

Source: Scalable Network Technologies (2014f).

APPENDIX F. UNMANNED SYSTEM SPECIFICATIONS

Seafox Unmanned Surface Vessel

Source: Naval Postgraduate School (n.d.b.)

Communications

- 440MHz command and control link
- 2.4GHz wireless mesh network

Sensors

- Dual BlueView obstacle avoidance sonar (2D)
- Horizontal plane and vertical plane
- Independent, computer-controlled pan/tilt actuators
- Remote or computer-controlled actuation (deploy/retract)
- Dual HoodTech Stabilized Pan/Tilt/Zoom video camera turrets
- Elector-optic camera
- Infrared camera
- Six fixed wide angle video navigation cameras
    - (3) Daylight (color)
    - (3) Low Light (black & white, lowlight (3)

RQ/MQ-8 Fire Scout Unmanned Aerial Vessel

Source: Parsch (2009)

Technical Specifications

- Length Folded 30.03 ft (9.2 m)
- Rotor Diameter 27.50 ft (8.4 m)
- Height 9.42 ft (2.9 m)
- Gross Weight 3,150 lbs (1,428.8 kg)
- Engine Rolls-Royce, Model 250-C20W
- Speed 125+ knots
- Ceiling 20,000 ft (6.1 km)
- Total Flight Time with Baseline Payload 8+ hours
- Total Flight Time with 500 lb Payload 5+ hours
- Payloads 600 lbs capacity
    - EO / IR / LD BRITE Star II
    - UHF / VHF Comm Relay
    - COBRA Mine Detector
    - Airborne Comm Package (Pineda, 2009)

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