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# SYSTEMS ENGINEERING APPROACH TO DETERMINING THE SUITABILITY OF WIRELESS MESH NETWORKS FOR JOINT-FIRES DISTRIBUTED MARITIME OPERATIONS

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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# SYSTEMS ENGINEERING CAPSTONE REPORT

## SYSTEMS ENGINEERING APPROACH TO DETERMINING THE SUITABILITY OF WIRELESS MESH NETWORKS FOR JOINT-FIRES DISTRIBUTED MARITIME OPERATIONS

by

Peter A. Bach, Shawn Brier, and Lauren E. Mcneil

September 2019

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Co-Advisor: Eugene P. Paulo
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Peter A. Bach, Shawn Brier, and Lauren E. Mcneil

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# ABSTRACT

This capstone explored options for two different communications architectures in support of a distributed maritime operation (DMO). Those architectures were the star and wireless mesh networks. The purpose of the scenario models developed for this study was to help give the reader a better understanding of how the tightly coupled data type, data rate, and desired network capabilities impact the network design. This study evaluated each architecture against a variety of assets in the scenarios requiring a combination of video, voice, and data links. It provided insight into the messaging delays inherent to each design and evaluated the reliability of each network. It found that a star and mesh network with a low Earth orbit satellite that utilized onboard routing capabilities provided the lowest timing delay. It also found that network jitter was minimized when a video feed was provided with a dedicated channel. Finally, the reliability of the mesh network was slightly higher than that of the traditional star due to redundancy of data links and a lack of a potentially vulnerable central hub. Therefore, the utilization of an ad hoc wireless mesh communications network will support the deployment of an adaptive force package during a limited offensive joint fires strike in a DMO.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| BDA | battle damage assessment |
| BLOS | beyond line-of-sight |
| BP | bent pipe |
| bps | bits per second |
| Bps | Bytes per second |
| C2 | command and control |
| CCM | combatant craft medium |
| CMS | containerized missile system |
| COMSAT | commercial satellite |
| CNO | Chief of Naval Operations |
| DID | destination identification |
| DL | distributed lethality |
| DMO | distributed maritime operations |
| DOD | Department of Defense |
| EMCON | emission control |
| GEO | geosynchronous Earth orbit |
| HR | hub relay |
| ISR | intelligence, surveillance, and reconnaissance |
| JF | joint fires |
| JP | joint publication |
| kbps | kilobits per second |
| km | kilometer |
| LAN | local area network |
| LCS | littoral combat ship |
| LEO | low Earth orbit |
| LIB | less is better |
| LLC | logical link control |
| LOS | line of sight |

| | |
|---|---|
| LPD | low probability of detection |
| LSV | logistics support vessel |
| MAC | medium access control |
| mbps | megabits per second |
| MIB | more is better |
| MILSAT | military satellite |
| MOE | measure of effectiveness |
| MOP | measure of performance |
| MTBF | mean time between failure |
| MTU | maximum transmission unit |
| NCW | network centric warfare |
| nm | nautical mile |
| NWDC | Naval Warfare Development Command |
| OA | operational activity |
| OODA | observe, orient, decide, act |
| OSI | open system interconnection |
| OTC | officer in tactical command |
| PLI | position location information |
| RBD | reliability block diagram |
| RF | radio frequency |
| RHN | regional hub nodes |
| SATCOM | satellite communications |
| SID | source identification |
| SV | space vehicles |
| VSR | vehicle status report |
| WMN | wireless mesh network |

# EXECUTIVE SUMMARY

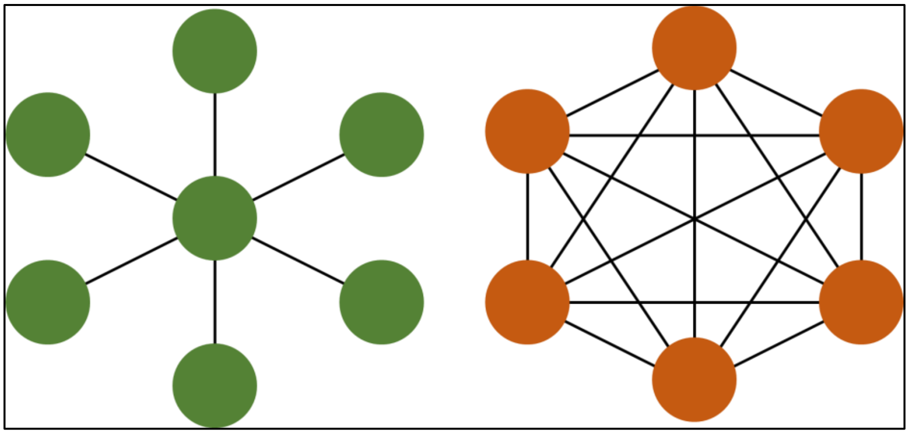
Good communications in any battle-situation are essential to victory. Even in geographic locations that are served by a solid communications infrastructure, confusion can be sown when the field commander does not receive timely reports with the correct information from assets in the field. In maritime battles, especially in the littorals, the communications infrastructure is minimal at best.

Responding to a call from the Secretary of Defense for improving joint fires (JF) operations, this capstone explored options for two different communications architectures in support of a distributed maritime operation (DMO). Those architectures were the star and wireless mesh networks.

The purpose of the scenario models developed for this study was to help give the reader a better understanding of how the tightly coupled data type, data rate, and desired network capabilities impact the network design. This helps highlight the design constraints of the implemented network. The simulation results were used to define a baseline reference and traceable data requirements to support a tactical network designed for a JF DMO.

## A. TACTICAL COMMUNICATION NETWORK TOPOLOGIES

Network setups are often depicted by their topology, which is the physical way in which the nodes within that network are arranged and can communicate (U.S. Army Engineering Division 1984, 7). This research evaluated a traditional star network, shown on the left in Figure 1, with a multilayered mesh communications network shown on the right in Figure 1, and quantified how the arrangement of those links might affect operations.



Sources: ConceptDraw (n.d.) (left), Bordetsky, Benson, and Hughes (2016) (right).

Figure 1. Star Network Topology (left) and Full Mesh Topology (right).

### 1. Star Network

The most widely used topology for a wireless network is that of a star geometric pattern. Star topology consists of a central node through which all information flows. In the star format, all information must be sent and received from each participating asset and routed through the central hub. The central node in this configuration represents a single point of failure. If the central node is taken offline, the entire network will go down.

### 2. Wireless Mesh Network

A multilayered tactical wireless mesh network refers to the process through which information is shared within a network. A mesh network describes a configuration where each node has the capability to communicate and can both send and receive messages to one another. In a mesh, the nodes are self-organizing and automatically established on an as-needed basis through routing algorithms (Shillington and Tong 2011).

## B. CONCLUSIONS

The design requirements for this study focused on the network configuration, the impact on message timing delay, network jitter, and reliability. It found that a star and mesh network with a low earth orbit (LEO) satellite with on-board routing capabilities provided the lowest timing delay. It also found that network jitter was minimized when a video feed was provided with a dedicated channel. Finally, the reliability of the mesh network was slightly higher than that of a traditional star due to redundancy of data links and a lack of a potentially vulnerable central hub. Therefore, the utilization of an ad hoc wireless mesh communications network will support the deployment of an adaptive force package during a limited offensive joint fires strike in a distributed maritime operation.

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# I. INTRODUCTION

## A. BACKGROUND

In the National Defense Strategy of 2018, U.S. Secretary of Defense James Mattis laid out what he viewed as the strategic plan needed to keep the U.S. armed forces competitive. In the strategy, Secretary Mattis specifically called for “a more lethal, resilient, and rapidly innovating joint Force” as one of the key factors needed to improve our military’s advantage (Defense 2018, 1).

The utilization of a joint force is not a novel idea for strategic military planning (Biemer 2000, 203). It is a concept that has been around and employed since the Civil War (Murray 2002). A joint force is defined as two or more services that come together under one mission objective. According to joint publication (JP) 1 Doctrine for the Armed Forces of the United States, “The synergy that results from the operations of joint forces maximizes the capability of the force” (Joint Chiefs of Staff 2017, I-2). This joint operation philosophy allows the individual services to share resources and become a system that operates more effectively together than one of its individual components. With more technologically advanced near-peer adversaries and the increasing complexity of combat environments, the U.S. armed forces will need to continually look for ways to become more efficient and effective at completing their mission.

When looking specifically at the Navy and the evolution of combat, the Navy seeks to modernize the way it operates. The Navy is being challenged to adapt to what it believes the future of naval combat holds (Jensen 2015). In 2015, the concept of distributed lethality was introduced to meet the changing threats we face and to increase our offensive might (Rowden, Gumataotao, and Fanta 2015). Distributed lethality strengthens the Navy’s competitive edge by dispersing our naval assets in a distributed formation forcing our adversaries to split their defenses.

As the distributed maritime operation (DMO) concept continues to evolve, the idea of joint fires (JF) in support of DMO is gaining traction. To illustrate what this entails, this capstone project used a background story to show how the concept of a JF DMO might work in the field. This helped to explore options and concepts for the employment of joint assets in support of maritime operations and enabling maritime calls for fire.

## B. PROJECT STORY

Beginning in 2014, Country Red has been projecting influence and asserting control of a contested region in the Azure Sea through land reclamation and reef enhancement efforts. After reclamation, the enhanced islands and reefs have been militarized and used to extend Country Red sovereignty claims that are disputed by other regional nations, including Country Green, under the United Nations Convention on the Law of the Sea.

Blue Force has been regularly demonstrating freedom of navigation by operating ships and aircraft in the region ignoring warnings and provocations from Red Force that the Blue Force operations are violating Country Red's territorial waters. Additionally, Green Force has been regularly conducting maritime patrols near a disputed island that has been militarized through Country Red's terra forma activity. During one of these Green Force patrols in disputed waters, Red Force fired on and sank a small patrol craft from Green Force.

The Commander-in-Chief of Blue Force has ordered a measured response to this aggression against a partner nation of Country Blue designed to halt the further reclamation of reef islands for military use and to send a clear message to Country Red. Blue Force is to quickly and decisively destroy one or two radar towers on a reef island, thereby rendering them useless and demonstrating the Blue Force capability to conduct a limited, multi-faceted joint precision strike.

## C. RESEARCH OBJECTIVE

In a tactical environment, effective communications and networking drive mission success. The overall mission was to employ a joint fires system that operates in a distributed maritime environment. The Blue objective in this scenario was to quickly and decisively destroy one or two radar tracking stations on Red Island using a limited offensive strike as a show of force.

The focus of this capstone was the network communications aspect of this joint fires problem. The scope consisted of the development of a network communications framework/system architecture that defines and describes the application of a joint force for distributed maritime operations. The research objective explored how communications network architectures like the star and mesh can support a JF operation in a DMO environment.

> *Objective question:* Will the utilization of an ad-hoc wireless mesh communications network support the deployment of an adaptive force package during a limited offensive joint fires strike in a distributed maritime operation?

This study explored how well a small adaptive force composed of the Army, Air Force, Navy, and Marines could synchronize and coordinate a limited strike to destroy key enemy assets and how the utilization of the communications networks affects those operations. The aim was to determine whether a mesh network would help or hinder the speed and accuracy at which the nodes can communicate. This research determined whether there is any benefit in employing either the star or mesh networks and attempted to quantify that benefit to mission success. The mission success for this project was defined as the ability to effectively send and receive the voice, video, and data transmissions necessary to support a joint fires limited strike.

## D. TAILORED SYSTEMS ENGINEERING PROCESS

A tailored systems engineering process was used to address the joint fires problem presented in this study. As is shown in Figure 1, this model served as a guide throughout the system life cycle, allowing team members to view the sequential steps that serve as a baseline reference to coordinate the project process (Blanchard and Fabrycky 2011). The tailored systems engineering process model provided a structured guide to follow while ensuring that the architecture framework being developed met the customer’s requirements.

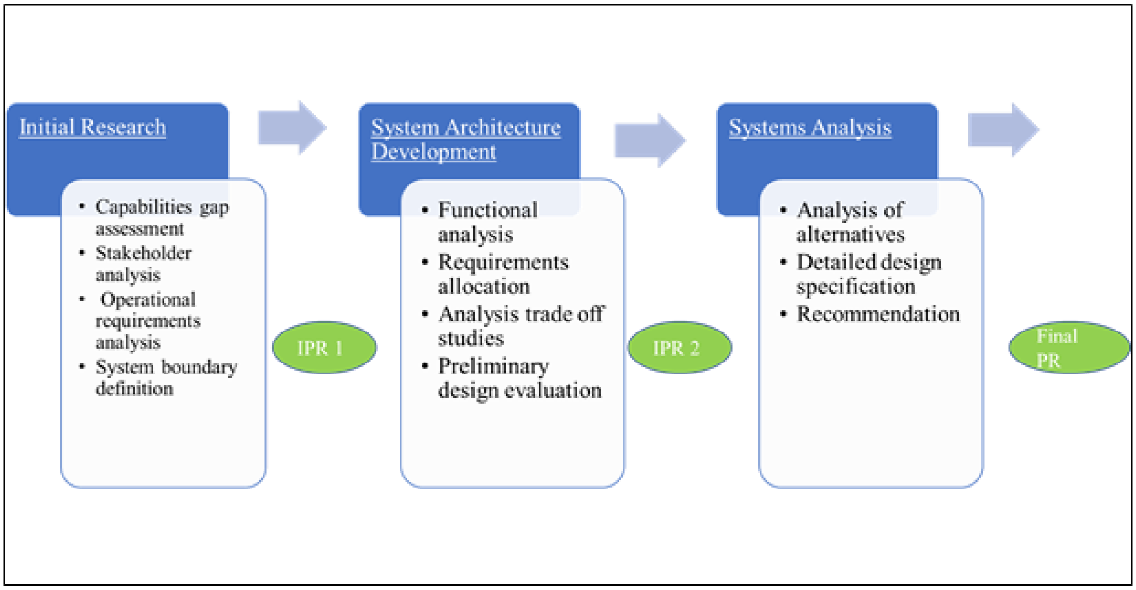


Figure 1. Systems Engineering Process. Adapted from Blanchard and Fabrycky (2011).

The model used for this project consists of three phases. The project began with an initial research phase. The objective of this phase was to thoroughly research the topic and properly constrain and scope the problem. It consisted of a capability gap assessment where the current capability was assessed and gaps that exist were identified. Next was the stakeholder analysis, operational requirements analysis, and the system boundary definition.

At the completion of phase one, the system architecture development phase began. This phase translated needs into functions and functional requirements. It also consisted of the functional analysis, requirements analysis, trade-off study, and preliminary design evaluation. This phase provided the preliminary detailed design criteria for the system architecture.

At the completion of phase two, the system analysis phase began. Here, the final system architecture was refined and evaluated. This phase consisted of the finalization of the detailed design specification, analysis of alternatives, and recommendation of the system architecture. The results of this phase included a final architecture recommendation.

# II. LITERATURE REVIEW

## A. DISTRIBUTED MARITIME OPERATIONS

Distributed maritime operations is a relatively new concept being promoted by the Chief of Naval Operations (CNO). It is a key effort described in the CNO's "Design for Maintaining Maritime Superiority 2.0." In it, the CNO expressed the need to "continue to mature the [DMO] concept and key supporting concepts" (Chief of Naval Operations 2018).

DMO is the "warfighting capabilit[y] necessary to gain and maintain sea-control through the employment of combat power that may be distributed over vast distances, multiple domains, and a wide array of platforms" (Naval Warfare Development Command (NWDC) 2018). It is based on the concept of distributed lethality (DL).

DL has three key features that it uses to gain control of the sea. The first feature is the networking firing capability to increase the firepower of each combatant ship. The second is a distribution of that firing network over a broad geographic area. The third feature is ensuring that each platform has enough resources to accomplish its goal (Popa et al. 2018).

## B. TACTICAL COMMUNICATION ALTERNATIVES

According to the JP6 Joint Communications doctrine:

> All joint functions—command and control (C2), intelligence, fires, movement and maneuver, protection, and sustainment—depend on responsive and available communications systems that tie together all aspects of joint operations and allow the joint force commanders and their staffs to initiate, direct, monitor, question, and react (Joint Chiefs of Staff 2015, vii).

Effective communications and networking are important key parameters that drive mission success. The speed and accuracy of the information that flows between military nodes within a network have a direct effect on the performance of the unit. Gaining the right information at the right time could mean the difference between mission failure and success.

The idea that communications shift towards playing a more integral role in operations was laid out in a network centric warfare (NCW) concept introduced by Admiral Arthur Cebrowski in 1997. Admiral Cebrowski (1998) cited the evolution of information technology in American society as one of the driving forces in the shift of military operations from platform to network centric. Platform centric warfare refers to the concept of relying on the superiority of individual weapon systems or components to maintain operational dominance (Bailey 2004).

The implementation of NCW represents the challenge of "understanding and integration of new operational concepts identified by stakeholders as necessary to meet their operational needs" (Hayes and Paulo 2009). NCW is described as "a concept for conducting warfare more successfully and efficiently through the extensive use of networks to share information and allow for better and more rapid communications and dissemination" (Booz Allen & Hamilton 1999, viii). For NCW to benefit from the information superiority of the networked nodes and shared information, a network communication system capable of connecting these nodes is needed (McElroy 2016).

An ad-hoc wireless mesh network is seen as one solution to providing wireless communications that will enable the benefits of NCW. The research within this project determined how specific types of communication networks used within a tactical environment could affect mission effectiveness. Many different network configurations can be used for a communications network. This research focused on a star and a mesh network.

### 1. Open System Interconnection

One of the fundamental aspects of network communications is the open system interconnection reference model (OSI), shown in Figure 2. Developed by the International Standards Organization in 1984, this graphic depicts how communications within a network are structured. It is a framework that details a set of standardized communication protocols within a computing system (Rouse n.d.). The OSI model consists of seven layers where each layer provides a function and then passes control either up or down to the next layer in the protocol. As described by Margaret Rouse, "Each layer serves the layer above it and in turn is served by the layer below it." (Rouse n.d.). The bottom four layers: physical, data link, network, and transport were the focus of this capstone.

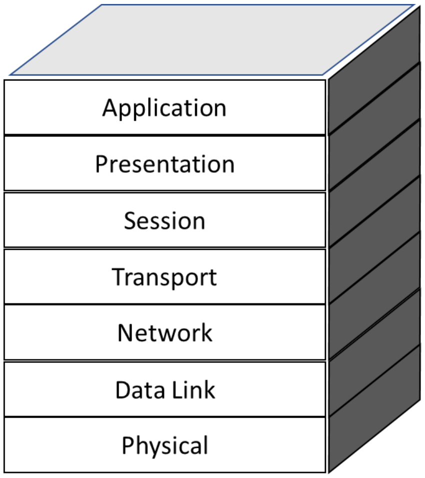


Figure 2. OSI Reference Model. Source: Microsoft (2017).

### *a. Physical Layer*

The physical layer is the physical means for which the communications are transferred from one node to the next. This layer accounts for the protocols that govern the raw data that is passed within the network. This layer also accounts for the equipment and node topology used to pass the communications.

### *b. Data Link Layer*

The data link layer is where transmission errors created in the physical link are found and repaired (National Communications System 1981). This layer "provides the functional and procedural means to establish, maintain, and release data-link-connections" within the network (National Communications System 1981, 81). This layer acts as flow control and establishes the data-link connections. This layer is also where bits of data are grouped and organized into frames. The medium access control (MAC) and logical link control (LLC) are the two layers that comprise the data link layer (Kaing 2004). The MAC layer's function is to manage access to the physical layer, and the LLC layer is responsible for controlling the errors and managing the flow from one layer to the next.

#### *c. Network Layer*

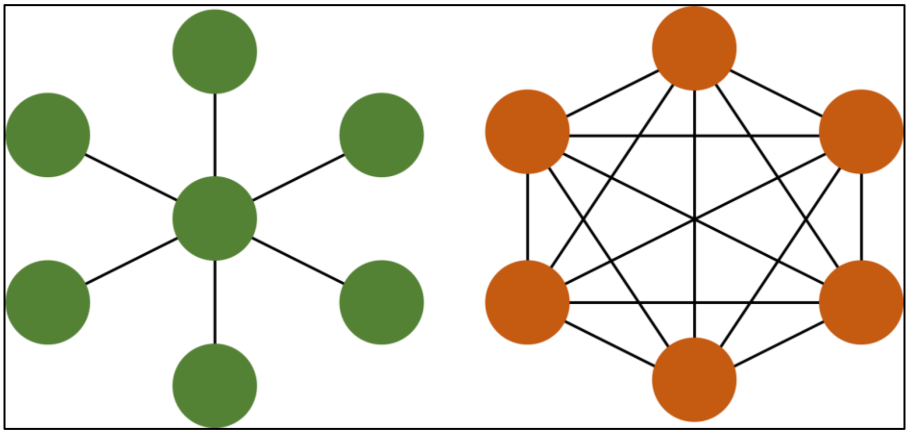
The network layer of the OSI model is where the routing of the data is controlled. The principal function of this layer is to establish communication paths and routing protocols. The network layer "provides the mechanism by which data can be passed from one network to another" (National Communications System 1981, 81). The data in this layer is organized into packets.

#### *d. Transport Layer*

The transport layer of the OSI model governs the transport of the data from one node to the next. Here, the transported data is checked for errors to make sure that the data packet that was sent was received. This layer also provides data flow control through buffering and windowing (OSI model and Network Protocols n.d.).

### 2. Network Topologies

Network setups are often depicted by their topology, which is the physical way in which the nodes within that network are arranged and can communicate (U.S. Army Engineering Division 1984, 7). This research evaluated a traditional star network, shown on the left in Figure 3, with a multilayered mesh communications network, shown on the right in Figure 3, and quantified how the arrangement of those links affected operations.



Sources: Conceptdraw (n.d.) (left), Bordetsky, Benson, and Hughes (2016) (right).

Figure 3. Star Network Topology (left) and Full Mesh Topology (right).

### *a. Star Network*

The most widely used topology for a wireless network is that of a star geometric pattern. Star topology consists of a central node through which all information flows. In the case of this research, the modeled central node was a Navy littoral combat ship (LCS). Each node within this topology "is connected to the central node with a point-to-point connection" (Sparrow 2011). In the star format, all information must be sent and received, from each participating asset, and routed through the LCS. The central node in this configuration represents a single point of failure (Von Moll and Behbahani 2013). If the central node is taken offline, the entire network will go down.

Benefits of this style of network include efficiency in messaging. This style of communication only sends messages to the intended node eliminating any extraneous communications.

### *b. Mesh Network*

A multilayered tactical wireless mesh network (WMN) refers to the process through which information is shared within a network. A mesh network describes a configuration where each node has the capability to communicate and can both send and receive messages. In a WMN, the nodes are self-organizing and automatically established on an as-needed basis (Shillington and Tong 2011).

The nodes within a WMN form a wireless backhaul network where each node acts as a mesh router (Shillington and Tong 2011). These mesh routers receive data packages and direct the information through multi-hop connectivity until that information is received by the intended node (Jahanshahi and Barmi 2014).

There are three different classifications of routing protocols within a WMN (Chang, Tsai, and Huang, 2017). Proactive routing is one in which the nodes are constantly sending data to each of the connected nodes regardless of the intended recipient (Vijayakumar, Ganeshkumar, and Anandaraj 2012). Routing information is known which reduces the amount of latency associated with finding a route (Mohan and Kasiviswanath 2011, 1). In this protocol, the network topology and location of the receiving node is known before the data packet is sent (Mohan and Kasiviswanath 2011).

Reactive routing, or ad hoc, refers to routes that form in response to a request to send a data packet (Vijayakumar, Ganeshkumar, and Anandaraj 2012). The sending node does not know the location of the receiving node and will try to establish a route. In this routing format, nodes discover their routes using an incremental search method (Mukhija 2011). This routing format introduces timing delays by traversing each link until it reaches its target. Hybrid protocols use a combination of both proactive and reactive routing.

WMN routing introduces redundancies that allow multiple alternative paths for information to flow. If one node goes offline, information is passed through integrated redundant redirections to keep it flowing to its intended target. This style of data flow makes the network more available by reducing information blackout. The benefits of this type of topology include autonomous self-healing links that can form wherever and whenever needed. This ability to self-form allows for scalability of the WMN. Network coverage is scaled based on the number of nodes connected in a mesh network (Held 2005, 17).

## C. JOINT FIRES AND DISTRIBUTED MARITIME OPERATIONS

Synchronizing and coordinating a joint fires strike becomes more complex in a distributed environment. In a system where the nodes are decentralized and separated by some physical distance, a network architecture that seamlessly integrates the components is needed to enable a perfectly timed and effective strike (Bommer 2007). To investigate the effects of network architectures and how they relate to mission success, this project leveraged the research from the thesis, “Joint Fire Support in 2020” (Bartel et al. 2006).

The Joint Fire Support in 2020 study analyzed the effects of fire support requests using a centralized joint fires support network, a distributive joint fires support network, and the status quo plus architecture model. Call for fires support in the status quo plus architecture is the least efficient of the three because of its redundant multi-layer functionality across supporting domains. The distributive joint fires support network architecture has an improved time to support fires requests but comes with a higher risk than the status quo plus and centralized joint fires support network. That risk is related to the required changes imposed on the fire-calls doctrine and the time to implement those changes.

Following the Joint Fire Support in 2020 study recommendations, this capstone research used the centralized joint fires support network architecture and parameters to develop the basic framework for a joint fires mission. Its architecture was expanded and analyzed for network performance using variations of joint intelligence, surveillance, and reconnaissance (ISR) and strike capabilities with a Navy LCS performing the architecture's joint fires coordination cell coordinator functions.

The centralized architecture delegates direct decision making and tasking responsibility of supporting units to the coordinator/officer in tactical command (OTC), referred to henceforth as the commander. As shown in Figure 4, the centralized architecture simplifies the horizontal and vertical command and control functionality for cross-organizational support (Bartel et al. 2006). ISR assets provide the commander with target solutions and mission battle damage assessments. This supports the commander's determination of mission status and success.

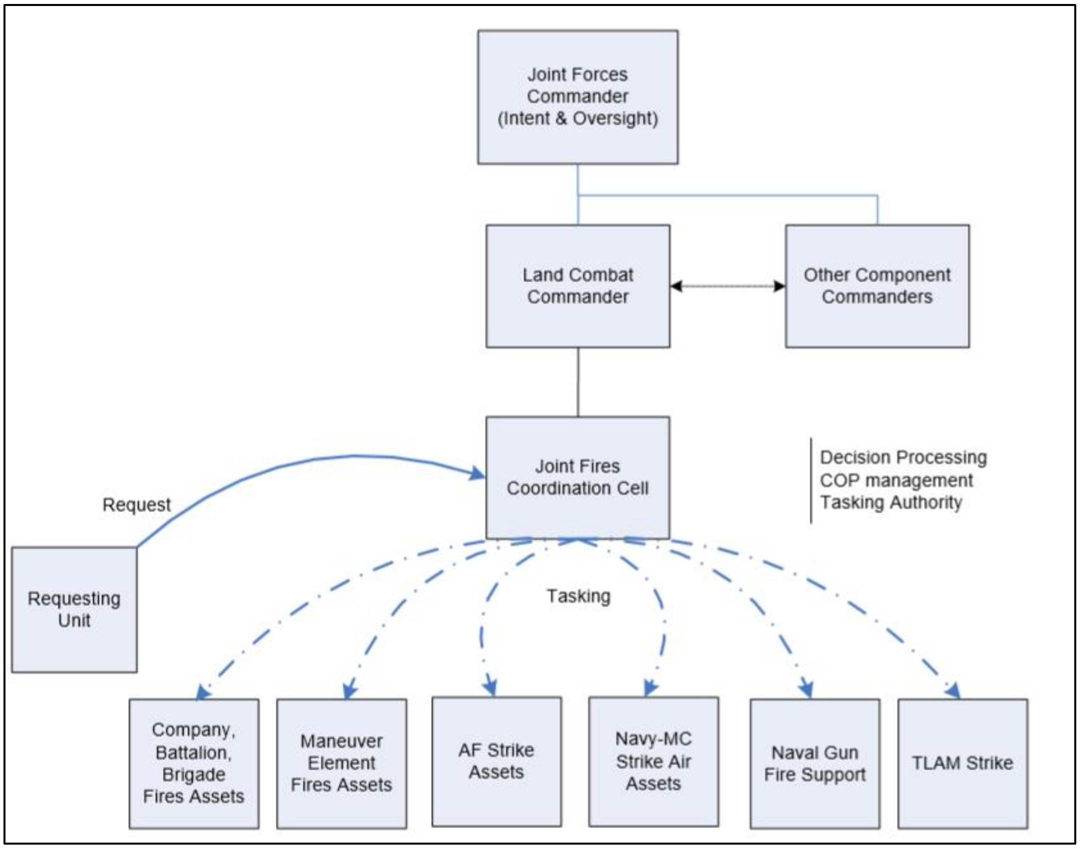


Figure 4. Centralized Joint-Fires Support Network Architecture. Source: Bartel et al. (2006).

Network functions require supporting both digital data and digital voice communications in tactical operating environments. Call for fires responses from the commander/coordinator are also provided through the same voice or data delivery method. This requires higher operational availability of the supporting networks to ensure receipt, acknowledgment, processing, and execution of the fire calls.

## D. MESH NETWORKS IN SUPPORT OF MARITIME OPERATIONS

The maritime domain is described by the Joint Maritime Operations as consisting of “oceans, seas, bays, estuaries, islands coastal areas, and the airspace above these, including littorals” (Joint Chiefs of Staff 2018b, x). The operational environment for this capstone background story was the contested international waters that surround Red Island.

Here, the capstone explored, through modeling and simulation, the effectiveness of a mesh network and how the type of communications network influences mission success.

In an article titled, “Hiding Comms in Plain Sight,” the authors specifically mention the littoral operational environment as one being a challenge due to the physical geography and congested waterways (Bordetsky, Benson, and Hughes 2016b). Operating in a crowded environment or an environment where the geography physically constrains operations adds an increased layer of complexity to the effectiveness of a network. In these types of environments “where defensive and offensive measures are much harder to carry out,” success often relies on an ability to stay mobile and flexible (Bordetsky, Benson, and Hughes 2016b).

Networks that can automatically adapt to dynamic situations and still provide robust capability are critical to mission effectiveness. Mesh networks adapt well to the complexity that exists in the congested maritime environment. The inherent characteristics of a mesh network allow for each node within the network to act as a router. Each node is self-aware and can create a path depending on the message type and the intended target (Herzig 2005). As a result of these self-healing and autonomous links, these “undetectable mesh networks can deliver a significant amount of time-sensitive information while platforms and operators rapidly change locations” (Bordetsky, Benson, and Hughes 2016b).

Another benefit of a mesh versus a star is the mobility of the network. According to Charlie Kawasaki, “command post mobility is one of the capabilities that will enable the Department of Defense (DOD) and warfighters to modernize their tactical networks and maintain overmatch through communication” (Kawasaki 2019).

## E. OODA LOOP

The research in this capstone project focused on a network’s ability to send and receive data and how that might affect a strike on Red Island. Part of this effort deals with the human aspect of receiving those messages and processing that information to make sound decisions in the battlespace.

The observe, orient, decide, and act (OODA) loop, developed by John Boyd in 1976, is a theory that explains how humans make decisions in stressful situations. The concept was first applied in air-to-air combat training to help pilots become more effective in battle (McIntosh 2011). The "OODA loop concept informs decisions and actions and serves as a basis for command and control" (Young 2012, 1). Boyd believed that "by responding quickly to situations and making appropriate decisions, you can get ahead of your opponents" (Mulder 2017).

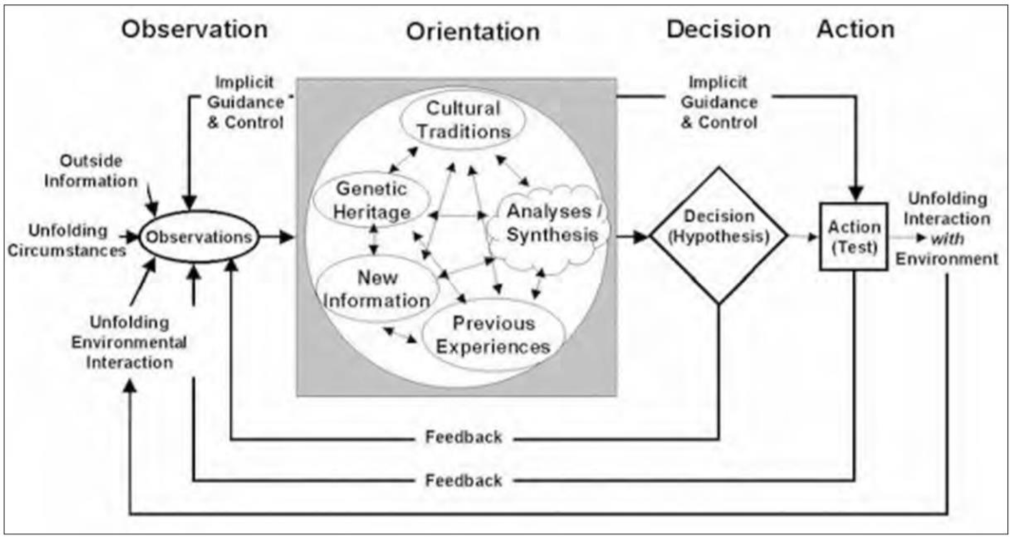


Figure 5. John Boyd's OODA Loop. Source: McIntosh (2011).

The OODA theory is a subsystem of loops within a loop that interact to form the decision cycle (Enck 2012). The OODA loop, shown in Figure 5, starts with observation. The observe cycle is where the decision-maker encounters an outside influence or situation. This is where good communications make a big difference. A battlefield commander with incomplete or incorrect intelligence will make mistakes. Having a reliable stream of position and unit health details combined with video or voice communications will help. The self-healing aspect of mesh networks, where the loss of one node does not bring down the entire network, makes them desirable in these high-risk environments.

The next step in the decision process is the orient loop, the most complex of phases. The orient step is where the person making the decision "interprets this information through an existing framework which creates meaning and provides a range of responses to initiate" (Bousquet 2009). This phase considers certain influences that are caused by cultural traditions, genetic heritage, and previous experiences. "It is here where the creative nature of the individual or organization makes it unpredictable" (Rule 2013).

In the next step, decisions are made based on the orient process. The final step in the theory is the action phase where the decision made will be acted out in the environment. Throughout this process, there are feedback loops from each phase that flow back into the observation step that may change how the environment is observed.

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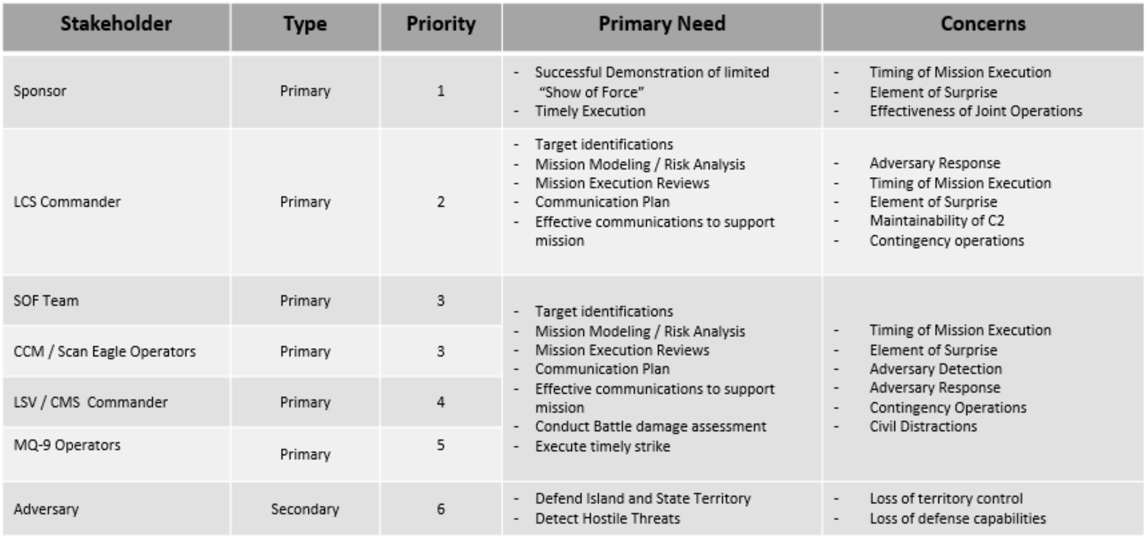
# III. ARCHITECTURE AND SCENARIOS

## A. STAKEHOLDER ANALYSIS

The stakeholder analysis includes seven (7) military system types that were considered in this study to support the mission. The main stakeholders identified are shown in Table 1. They are Country Blue, LCS commander, SEAL Squad, combatant craft medium (CCM) and Scan Eagle operators, logistics support vessel (LSV) and containerized missile system (CMS) commanders, MQ-9 Reaper Operator, and Country Red.

Table 1. Stakeholder Analysis



| Stakeholder | Type | Priority | Primary Need | Concerns |
|---|---|---|---|---|
| Sponsor | Primary | 1 | - Successful Demonstration of limited "Show of Force"<br>- Timely Execution | - Timing of Mission Execution<br>- Element of Surprise<br>- Effectiveness of Joint Operations |
| LCS Commander | Primary | 2 | - Target identifications<br>- Mission Modeling / Risk Analysis<br>- Mission Execution Reviews<br>- Communication Plan<br>- Effective communications to support mission | - Adversary Response<br>- Timing of Mission Execution<br>- Element of Surprise<br>- Maintainability of C2<br>- Contingency operations |
| SOF Team | Primary | 3 | - Target identifications<br>- Mission Modeling / Risk Analysis<br>- Mission Execution Reviews<br>- Communication Plan<br>- Effective communications to support mission<br>- Conduct Battle damage assessment<br>- Execute timely strike | - Timing of Mission Execution<br>- Element of Surprise<br>- Adversary Detection<br>- Adversary Response<br>- Contingency Operations<br>- Civil Distractions |
| CCM / Scan Eagle Operators | Primary | 3 | | |
| LSV / CMS Commander | Primary | 4 | | |
| MQ-9 Operators | Primary | 5 | | |
| Adversary | Secondary | 6 | - Defend Island and State Territory<br>- Detect Hostile Threats | - Loss of territory control<br>- Loss of defense capabilities |

Stakeholder priority was determined by reviewing the anticipated level of human involvement and the capabilities that each asset provides. If the asset involved a human as a primary decision-maker or had the potential for direct contact with the adversary, the priority rating was higher. The LCS commander and the SEAL squad ranked higher than the LSV commander, MQ-9, and CMS operators.

The LSV commander and the CMS operator had equally shared priorities. This was because the two systems were coupled and dependent on each other. The LSV platform was the primary transport means for the CMS to and from the firing coordinates.

Reliable communications, timely executions, and prompt target identifications were all primary needs for each of the stakeholders. The mission scenario played out in a Red occupied area, therefore reliable and low probability of detection (LPD) communications were essential. The communication modes of operation were persistent, emission control (EMCON), and burst. Mission timing was critical to maintaining the element of surprise. That timing included how the assets collectively move from one mode of communication to the next.

Blue forces operate in a location where detection systems are certain to be used, so effective modeling and simulation analysis was another primary need of all Blue stakeholders to determine which approach was the most effective.

Figure 6. Littoral Combat Ship. Source: Wood (2010).

Figure 7. Combatant Craft Medium. Source: SOCOM (2019).

Figure 8. Scan Eagle. Source: United States Navy (2016).

Figure 9. Army Logistics Support Vessel. Source: Xtian06 (2014).

Figure 10. Containerized Missile System. Source: Rosoboronexport (n.d.).

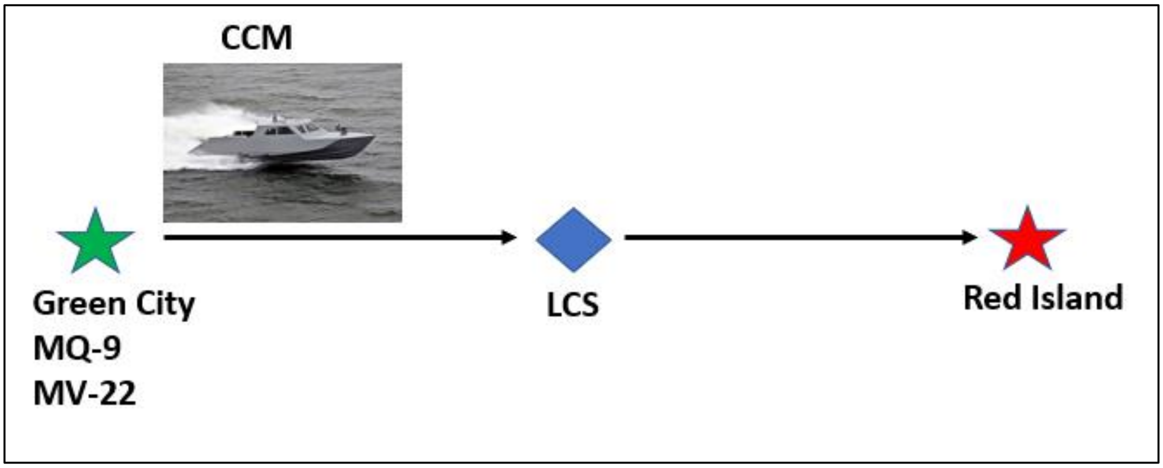
## B. SCENARIOS

Three scenarios were created to evaluate the efficacy of the mesh network under varying conditions. The scope of this capstone project included researching, developing, modeling, and measuring the operational effectiveness of a communication network that supported the performance of three show-of-force or limited-strike scenarios that employed a combination of resources provided by Blue Navy, Army, Air Force, and Marine components. Included in each scenario was a Blue Navy LCS.

The LCS acted as mission C2 and served as the mesh network communications router and hub. It also refueled underway a CCM that delivered a SEAL squad and Scan Eagle to provide direct assault, ISR, and battle damage assessment (BDA).

In two of the scenarios, a Blue Army LSV carrying a CMS provided stand-off strike fires from the sea. A Blue Air Force MQ-9, launched from Green City, was employed for varying purposes, depending on the scenarios. In all scenarios, at least one MQ-9 was used either for ISR or to provide fire support from the air.

In all three scenarios, Blue surface and air assets traversed the area of operations under EMCON to maintain the element of surprise. This capstone evaluated a traditional star network against a multilayer mesh network. In the case of a star configuration, the LCS acted as both a router and a hub. The LCS received the information and decided where it needed to be routed. In the case of the mesh network, each node acted as a "wireless backhaul network" and functioned as a mesh router, receiving information and routing it to its intended node.



The CCM departed from Green City to rendezvous with the LCS for refueling and crew rest before moving on to the objective at Red Island. An MQ-9 and MV-22 were pre-staged at Green City.

Figure 11. Scenario Pre-Staging. Source: SOCOM (2019).

The scenarios started with the SEAL squad aboard a CCM departing from Green City to rendezvous with the LCS for refueling and crew rest before moving on to the objective at Red Island. An MV-22 and MQ-9 were pre-staged at Green City.

Figure 12. MQ-9 Reaper. Source: Pratt (2008)

Figure 13. MV-22 Osprey. Source: FOX-52 (2014).

Figure 14. SH-60 Seahawk. Source: San Diego Air and Space Museum (2002).

Throughout the mission, the MV-22, SH-60, and a special operations surgical team were on standby to assist in both a medical evacuation capacity and as a quick response team. Those scenarios were considered but were not included in the models and simulation.

### 1. Scenario #1: SEAL Direct Assault

The first scenario, depicted in Figure 15, was a direct assault on the target radar by a SEAL squad. A CCM with the SEAL squad embarked, refueled with the LCS before proceeding about 100 nautical miles (*nm*) to Red Island. An Air Force MQ-9 launched from Green City. The SEALs launched a Scan Eagle from the CCM to provide real-time ISR and went ashore approximately 1 kilometer (*km*) from the target.

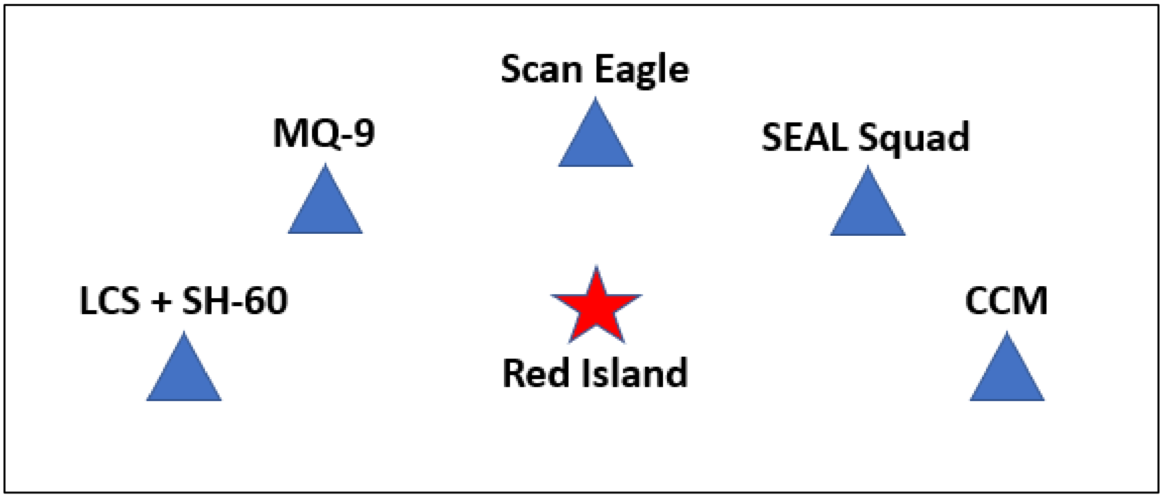


Figure 15. Scenario #1: SEAL Squad Direct Assault

The MQ-9 and Scan Eagle provided ISR. The MQ-9 also provided some air cover for the SEAL squad. Once in place, the SEALs radioed the LCS. On order from the commander, the SEALs destroyed the target radar station. They then conducted link-up procedures with the CCM. The Scan Eagle also returned to the CCM, which then rendezvoused with the LCS approximately 75 *nm* from Red Island. The MQ-9 returned to Green City.

### 2. Scenario #2: SEAL Battle Damage Assessment and Containerized Missile System from the Logistics Support Vessel

The second scenario, shown in Figure 16, included a CMS embarked on an Army LSV. Like Scenario #1, the CCM headed for Red Island with the SEAL squad and Scan Eagle embarked after crew rest and refueling from the LCS approximately 100 *nm* from Red Island. The Scan Eagle was launched when in position for ISR support and the SEAL squad went ashore approximately 1 *km* from the target. Once in position, the SEAL squad identified and marked the target radar stations and radioed the commander on the LCS. The commander then ordered fires from the CMS on the LSV. Following the aerial strike, the SEAL squad conducted BDA and destroyed any remaining infrastructure as needed. The SEALs then egressed through the surf and conducted link up procedures with the CCM. The Scan Eagle also returned to the CCM which will then rendezvoused with the LCS approximately 75 *nm* from Red Island.

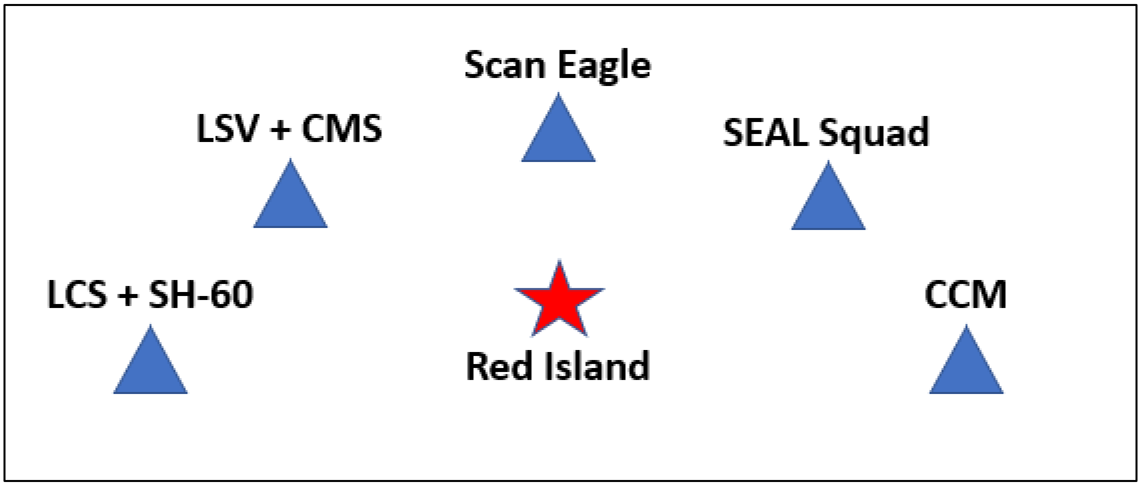


Figure 16. Scenario #2. SEAL BDA and CMS from the LSV

### 3. Scenario #3: SEAL Battle Damage Assessment, MQ-9, and Containerized Missile System from the Logistics Support Vessel

Scenario #3, shown in Figure 17 sought the destruction of two radar stations combining kinetic fires from the CMS and MQ-9. As in Scenarios #1 and #2, the CCM launched with the SEALs and Scan Eagle after crew rest and refueling from the LCS approximately 100 *nm* from Red Island. An MQ-9 launched from Green City and loitered over the target for intelligence collection and later primary fires. Once in position, the SEALs launched the Scan Eagle from the CCM for real-time ISR support. The SEAL squad went ashore approximately 1 *km* from the target. Once the SEAL squad identified and marked the target radar stations, they radioed the commander on the LCS. The commander then ordered fires from both the CMS aboard the LSV and the MQ-9 controlled from the continental United States by satellite communications (SATCOM). The SEAL squad then conducted a BDA after the aerial strike and destroyed remaining infrastructure as needed. The SEALs then egressed through the surf and conducted link up procedures with the CCM. The Scan Eagle also returned to the CCM and the MQ-9 returned to Green City. The CCM then rendezvoused with the LCS approximately 75 *nm* from Red Island.

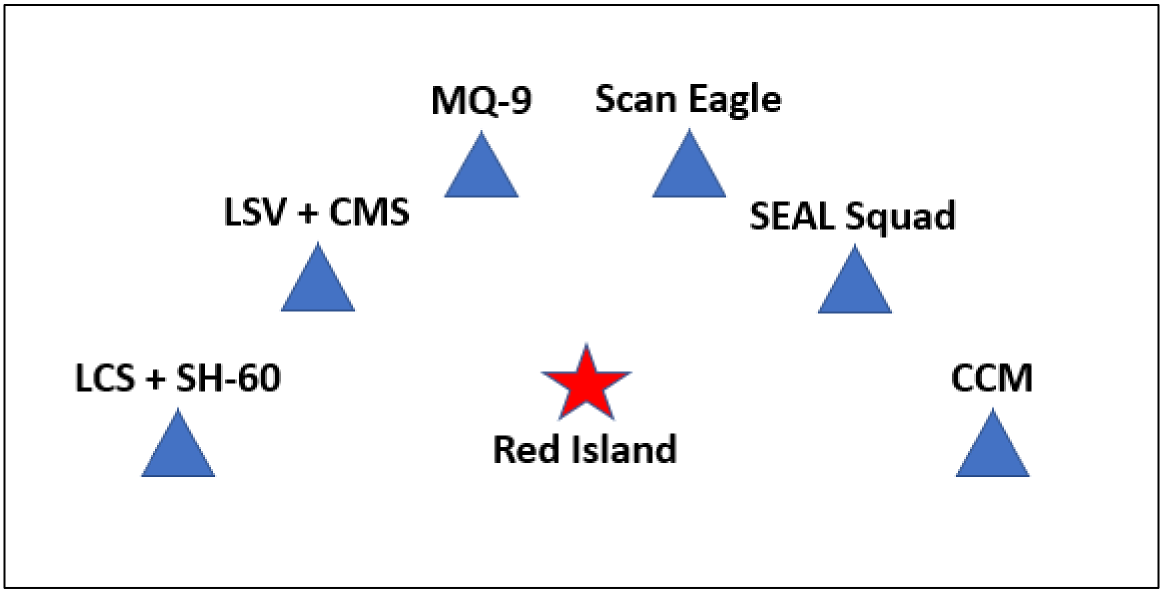


Figure 17. Scenario #3. SEAL BDA, MQ-9, and CMS from LSV

## C. NEEDS ANALYSIS

Three key capabilities were identified for mission success. The JF DMO system design had to support operations that included C2, ISR, and kinetic strike. Figure 18 represents the directionality and message types needed by each asset for Scenario #3.

Scenarios #1 and #2 utilized a subset of the communication needs based on the type of assets assigned to the mission set. The LCS was required in each of the scenarios, providing C2 to the overall mission, and was delegated authority for weapons release in each mission set. The CMS and the MQ-9 strike variants provided fires capability and situational information to dependent assets. The MQ-9, Scan Eagle, and SEAL squad provided targeting solutions and BDA.

Timely and reliable communications to all supporting assets were required to assure mission success while enabling the commander to make informed decisions.

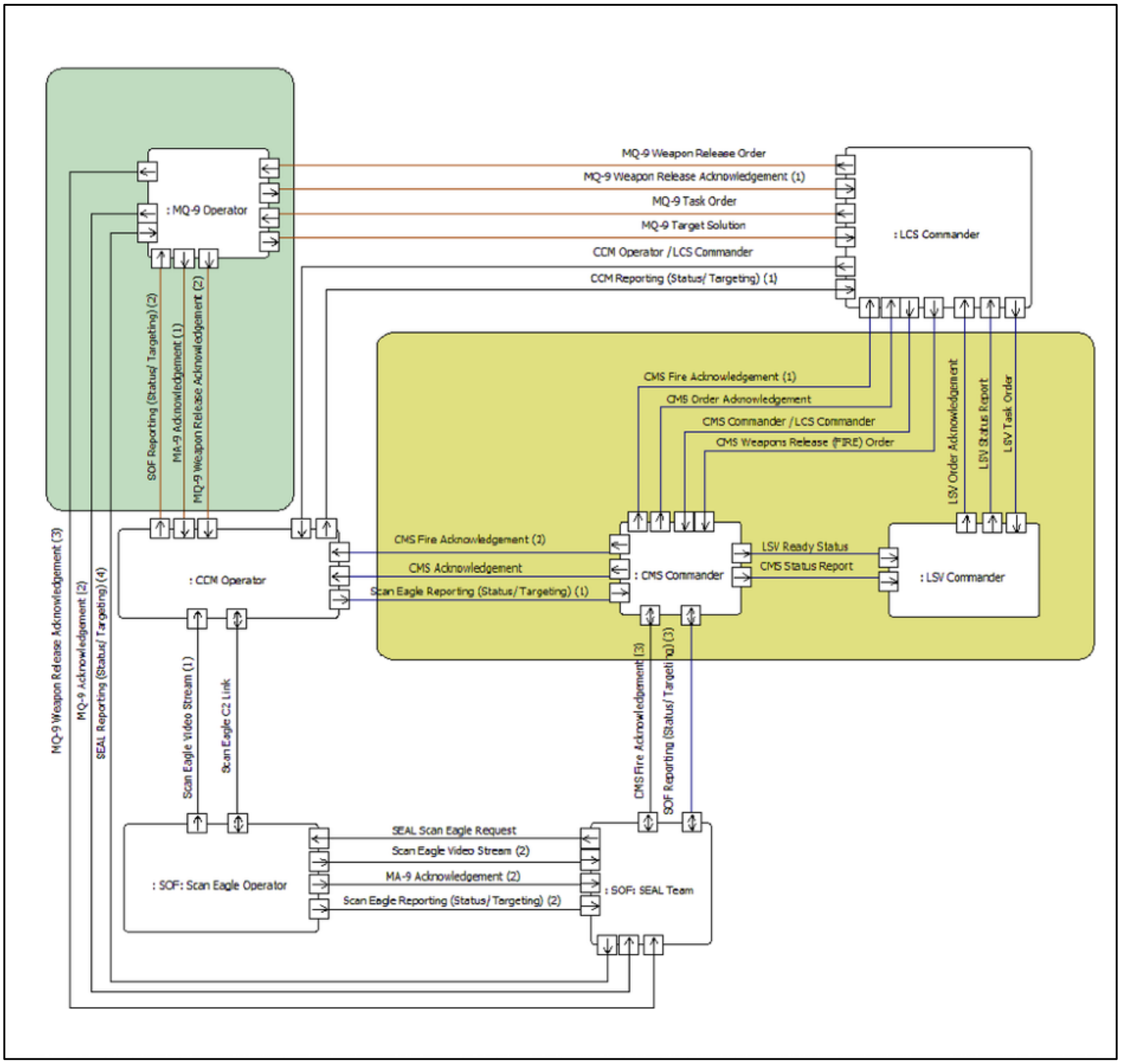


Figure 18. Operational Resource Flow Diagram (OV-2) For Scenario #3

### 1. Command and Control Node

C2 functions for amphibious operations were delegated to Blue Navy command and requires reliable net-centric communications with supporting assets (Joint Chiefs of Staff 2018a). The operational scenarios required a vessel that could support rapid deployment with minimal detection from Red Forces while maintaining an element of surprise. The mission-specific modular nature of the LCS package set made the LCS platform best suited for this purpose.

### 2. Surveillance and Reconnaissance

Surveillance and reconnaissance were capabilities required to assure good target acquisition and to minimize casualties during operations. Depending on the scenario, the surveillance was provided by the MQ-9, SEALs, or Scan Eagle functional elements. These elements needed to report and process mission directives from the commander. Surveillance support was provided throughout the mission to provide real-time target and condition updates to command. This was accomplished through the reporting links for each dependent element. The information provided informed the commander through the decision-making process to authorize a strike on the mission targets. These were indicated through respective dependent task order links.

### 3. Kinetic Strike

The kinetic strike was provided by the MQ-9, SEALs, or CMS. They were all dependent on the commander's authorization to release order. They were also dependent on their support elements. Each supporting element provided concurrent updates to the commander and fires components. Updates included estimated time to firing location, readiness to launch, weapons release, and order acknowledgments to support C2 decisions and limit casualties.

### 4. Key Assumptions

Each of the identified systems operated in support of a maritime operation and had external influences from the systems identified in Figure 19 that could impact the success or failure of the JF DMO system. For instance, the weather influenced how radio frequency (RF) signals propagate in the environment through ducting and multipath. Available commercial satellite (COMSAT) links, another external influence, determined how communications handoff occurs from satellite to satellite. Another external influence, area treaties, influenced staging locations for the assets used in the scenarios.

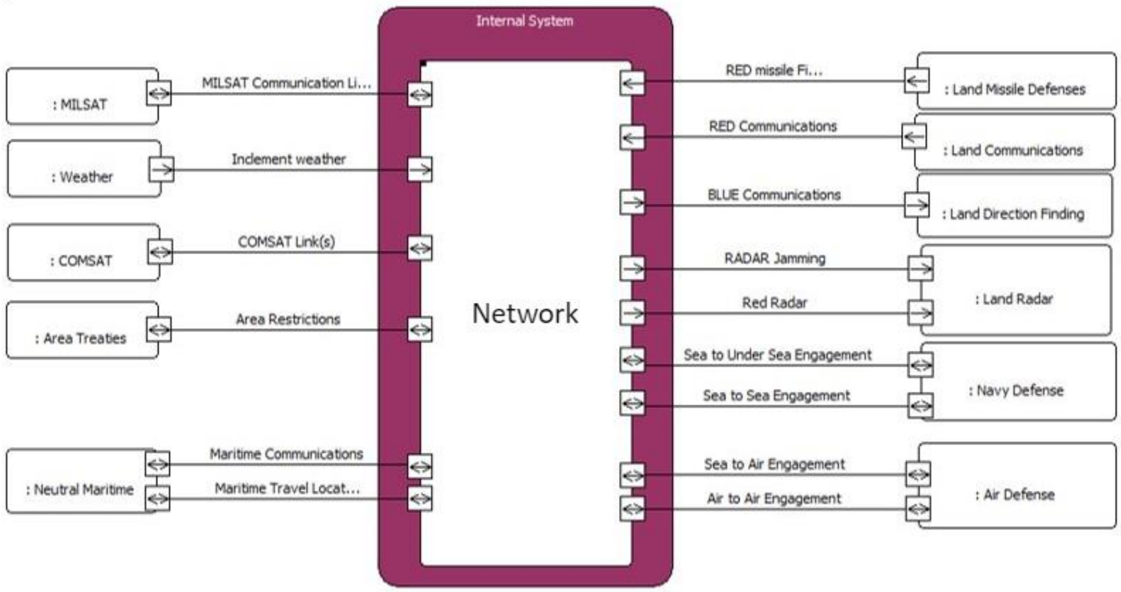


Figure 19. Communications Network System Context

Key assumptions regarding the military satellite (MILSAT) and COMSAT network services include:

- Space vehicles (SV) providing beyond line-of-sight (BLOS) connections were available and uncontested;
- Regional hub nodes (RHN) provided secure network connections to dependent-system C2 stations;
- Cryptographic network solutions supported unidirectional transmissions in support of EMCON operations;
- Assets in each scenario had installed interoperable communication systems that supported ad hoc mesh networks; and,
- Weather conditions were known that could impact RF performance and the safe operations of platforms.

Key assumptions regarding the weather in this study included:

- Operations were performed in ideal weather conditions. Rain, multipath, and ducting conditions had no noticeable impact on link quality;

- Communication systems identified in the architecture were capable of accurately tracking dependent satellites in sea-state 1–2 conditions;

- Neutral maritime operations were considered in the area of operations. The safety of Country Green vessels and commercial/recreational third-party maritime traffic was paramount. Country Blue mission assets did not put white maritime traffic in harm's way; and,

- The target island occupied by Country Red was a surface and air tracking facility. The island had no known defensive surface to air missiles or coastal missile defense systems.

Key assumptions regarding the Country Red occupied island included:

- Red coast guard assets routinely patrolled the area of operations, but larger Red Navy combatants did not;

- Red Army surface to surface or surface to air defenses were not located near the target island, and there was only a small military security detachment on the island; and,

- Red theater and space based ISR sensors were integrated into the Country Red island communication systems.

### 5. Constraints

The following constraints established boundaries for the modeling and simulation of the scenarios: Area of operations, platform specifications, and communication specifications.

System constraints included:

- Transportation and maneuvering of the assets were only by means of sea or air;

- Performance and specifications of targeting and strike capabilities are limited to air and sea platforms or strike teams.

## D. FUNCTIONAL ANALYSIS

"Functional analysis is a fundamental tool of the design process to explore new concepts and define their architectures" (Viola et. al. 2012, 71). It is a process that provides detailed insight into the system functions needed to meet the needs of the stakeholders.

### 1. Functional Hierarchy

The functional hierarchy for the project is shown in Figure 20. F.0 is the top-level function and is "Perform a joint fires limited strike on Red Island."

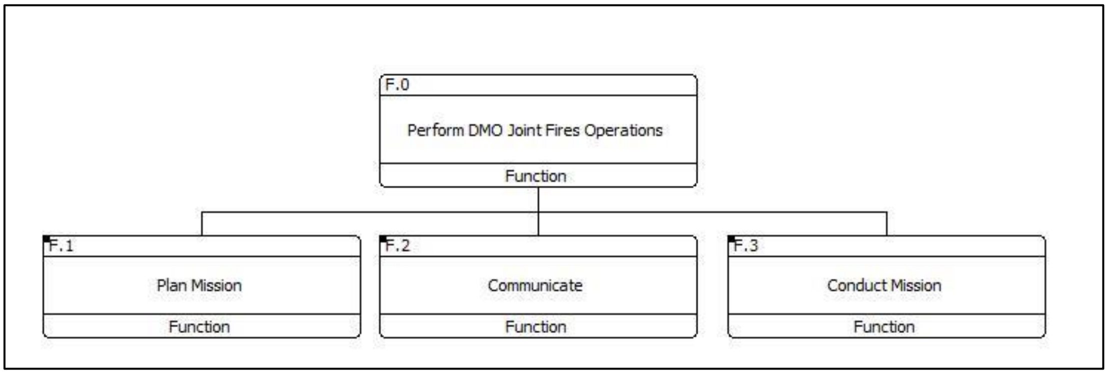


Figure 20. Functional Hierarchy

The top-level function was then decomposed into three sub-functions: plan mission, communicate, and conduct mission. These were then decomposed further into lower-level functions that needed to occur to perform that higher-level function. The decomposed views are shown in the appendix. The functions and sub-functions are described in Table 2.

Table 2. Functional Description

| Function | Description |
|---|---|
| F.0 | Perform limited show-of-force strike on Red Island. Blue force was to quickly and decisively destroy a radar tower on Red Island. |
| F.1 | Plan mission. This function included conducting ISR and scenario determination. It was in this step that analysis and wargaming were conducted and a scenario was chosen. |
| F.2 | Communicate. This function included the router, internet gateway functions, and communication modes. |
| F.3 | Conduct mission. This function included the synchronization and coordination of the land, air, and sea kinetic fires strikes. |

### 2. Enhanced Functional Flow Block Diagram

Figure 21 shows the enhanced functional flow block diagram for Scenario #3, which combines elements from Scenarios #1 and #2. This diagram shows the flow of communication functions needed to perform the mission. Each gate represents the performer of that function. The white boxes identify the functions performed. The green boxes are the triggers that are needed to start a certain event and grey boxes are constant outputs.

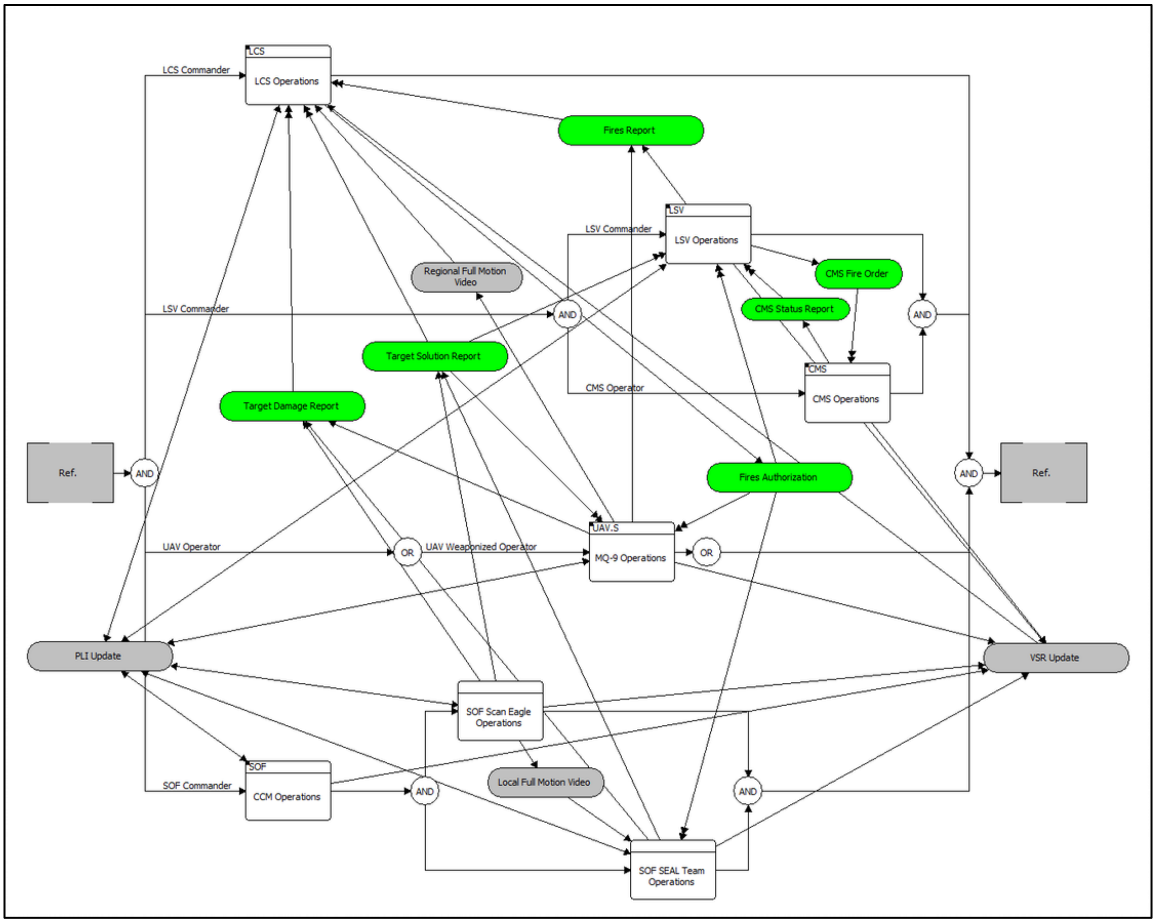


Figure 21. Enhanced Functional Flow Block Diagram

Joint fires were coordinated through the commander, serving as OTC, using the target solutions reported by the SEAL squad. The Scan Eagle provided real-time ISR throughout the mission, which required a direct line of sight (LOS) communications link with the CCM. Once the Scan Eagle was in flight, the system provided the SEAL squad full-motion video to support strike solutions.

SEAL squad communications were operated in short burst mode providing target solutions and BDA. The LCS, MQ-9, and LSV/CMS received the target solution provided by the SEALs. Once the LSV/CMS team received the target solutions and the order to fire, the missiles were launched, and its tracking information was continuously reported to the LSV throughout the flight. When the MQ-9 was in the airspace near the target, the commander gave the order to fire and the inbound missile tracking relied on visual detections rather than network messaging. Once the target objective was destroyed or reported as a hit, the SEAL squad reported their BDA.

Throughout the SEAL presence ashore, full-motion video was provided by the Scan Eagle to assist with situational awareness and BDA. Throughout the conduct mission phase, both unit status and platform health status were automatically reported at constant rates. The unit status information was shared with all nodes in the network using a broadcast distribution. Platform health information was provided to the commander for situational awareness and to adjust mission plans when an unexpected platform failure occurred.

# IV. REQUIREMENTS

## A. REQUIREMENTS ANALYSIS

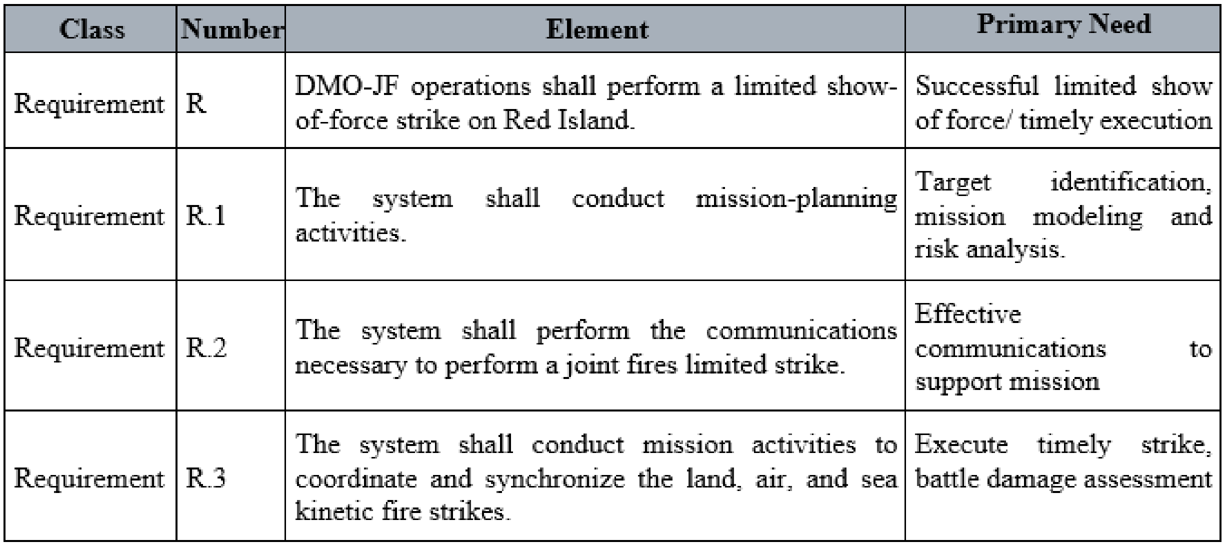
The system requirements analysis combined refinement of the stakeholder needs with derived operational requirements. These were traced through to the functional analysis and requirement allocation discussed later in the report.

## B. REQUIREMENT ALLOCATION

The stakeholder analysis of Table 1 was performed to establish the top-level system requirements shown in Table 3. Each system requirement was directly traced to a primary need identified in the stakeholder analysis.

The requirement identification numbers are shown in the second column, each beginning with the letter ‘R’. Requirement R.0 was traced to the capability need identified by the sponsor, which was to successfully demonstrate a limited “show of force.”

Table 3. Top Level Requirements



| Class | Number | Element | Primary Need |
|---|---|---|---|
| Requirement | R | DMO-JF operations shall perform a limited show-of-force strike on Red Island. | Successful limited show of force/ timely execution |
| Requirement | R.1 | The system shall conduct mission-planning activities. | Target identification, mission modeling and risk analysis. |
| Requirement | R.2 | The system shall perform the communications necessary to perform a joint fires limited strike. | Effective communications to support mission |
| Requirement | R.3 | The system shall conduct mission activities to coordinate and synchronize the land, air, and sea kinetic fire strikes. | Execute timely strike, battle damage assessment |

Focusing on R.2, network communications were further decomposed focusing on the network’s ability to support minimal delay, message reliability, and transport reliability measures.

Table 4. R.2 Requirement Breakdown.

| Requirement | Sub-Requirement | |
|---|---|---|
| **R.2** | **R.2.1** | The communications system needs to be able to handle the maximum amount of information with the least delay |
| | **R.2.2** | Network reliability is defined as the ability to get a message sent to and received by the intended recipient at the correct reporting rate |
| | **R.2.3** | Architectural reliability is defined as the ability of the communications system to withstand disruption (for instance, a node is physically destroyed) and still be functional |

## C. SYSTEM MEASURES

This capstone focused on requirements R.2 in Table 4 which were all related to the communications aspect of the JF DMO. The key measure of any communications network is its ability to effectively transmit and receive information in a timely manner. This capstone modeled and measured the system's ability to send and receive the voice, video, and the data transmissions necessary to perform a joint fires limited strike. The speed and accuracy of the information that flows between military nodes within a network have a direct effect on the performance of each unit. Gaining the right information at the right time could mean the difference between mission failure and success.

The measures of effectiveness (MOE) and measures of performance (MOP) used to measure the degree to which the system objectives were successful are shown in Table 4 and Table 5 and are traced to the system requirements.

### 1. Measures of Effectiveness

In each scenario, mission success was dependent upon the ability to effectively send and receive the communications necessary to perform a joint fires strike on Red Island. The reliability of each communications network configuration was a metric used to evaluate its effectiveness. The top-level effectiveness measures that were used to measure the communications network are shown in Table 5.

*Reporting Time:* (Table 5) measured the network's effectiveness in supporting timely message delivery to the intended receiver. Factors that define how effectively a network transports a message depends on how well the network is tuned according to its throughput, MTU, data message size, and message rates.

*Message Rate*: (Table 5) measured the effectiveness of the network to support the transmission of messages with minimal jitter. Jitter is the variance between message receive rate and transmission rate. For instance, if a series of message packets are transmitted exactly every second, the recipient should receive the packets exactly every second. Any deviation from that one-second cadence is jitter.

*Network Availability:* (Table 5) measured the effectiveness of the network's availability. A network's unavailability may be caused by hardware failure or some form of interference in the link.

Table 5. System Measures of Effectiveness

| Requirement | MOE | | | | MOP |
|---|---|---|---|---|---|
| | Index | Name | Description | Measure | |
| **R.2.1** | **MOE1** | **Reporting Time (LIB)** | Message delay between transmit and receive data | LIB | Message Delay |
| **R.2.2** | **MOE2** | **Message Rate (LIB)** | Communications Network Jitter | LIB | Network Reliablity |
| **R.2.3** | **MOE 3** | **Network Availability (MIB)** | Operational Availability of the network | MIB | Communication Reliablity |

Note: more is better (MIB); less is better (LIB).

## 2. Measures of Performance

The MOPs that directly relate to the MOEs are shown in Table 6. The message delay and network jitter are performance measures dependent on the communications network configuration. The communications reliability depends on the physical topology of the connect links and nodes.

*Message Delay:* (Table 6) measured the message delay based on the network configuration and number of user nodes. The performance measure was a factor of time, representing the time for a message to transverse the network. Factors that define how much time delay is experienced in the delivery of the message depends on how well the network is tuned according to its throughput, MTU, data message size, and message rates.

*Network Jitter:* (Table 6) measured the message received rate deviation based on predetermined message rates at the time of transmission. For instance, if a series of message packets are transmitted exactly every second, the recipient should receive the packets exactly every second. The performance measure was a factor of time, representing the deviation time from the defined message rate of transmission. Factors that define how much message jitter is introduced depends on how well the network is tuned according to its throughput, MTU, data message size, and message rates.

*Communication Reliability:* (Table 6) measured the network operational availability based on the system architecture. An unavailable network may be caused by hardware failure or some form of interference in the link. The performance measure was a factor of reliability (percent), representing the number of network nodes and network paths available for both the star and mesh network architectures. Factors that define reliability depended on the failure rate (λ) of each network node in the network and the mission timing (τ) in minutes.

Table 6. System Measures of Performance

| **MOE** | **MOP** | | | |
|---|---|---|---|---|
| | **Index** | **Name** | **Description** | **Measure** |
| MOE1 | **MOP1** | **Message Delay** | **The time for a message to transverse the communication network.** | **LIB** |
| MOE2 | **MOP2** | **Network Jitter** | **The amount of deviation in the received message rate based on the intended transmitted reporting rate** | **LIB** |
| MOE 3 | **MOP3** | **Communication Reliablity** | **The operational reliablitiy of the communication network based on network elements in the architecutre** | **MIB** |

Note: more is better (MIB); less is better (LIB).

### 3. System Variables

The configuration of a network is determined from the following:

- *Message Size*: Number of bits required to transmit a message. It is determined by the user application based on the message type (Table 7). The performance measure for message size is less is better (LIB) to support increased reporting rates and reduced time to transmit.

- *Maximum Transmission Unit (MTU)*: The largest size of information packet sent (Table 8). The performance measure for message size is LIB to support minimal message fragmentation.

- *Throughput*: The amount of data that can be transferred without information loss. (Derived from Table 9). The performance measure for message size is MIB to support increases in reporting rate and message size transmissions. While throughput is generally a communication network system output and not a variable, this study varied the network throughput to determine which network configuration provides the best performance to minimize delay and jitter (variation) in predetermined message transmission rates.

- *Message Rates*: The frequency of a message being transmitted (Table 7 and derived from Section V.F.1). The measure of the message rate is MIB to improve the accuracy of machine and human decisions based on sensor reporting updates.

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# V. MODELING, SIMULATION, AND RESULTS

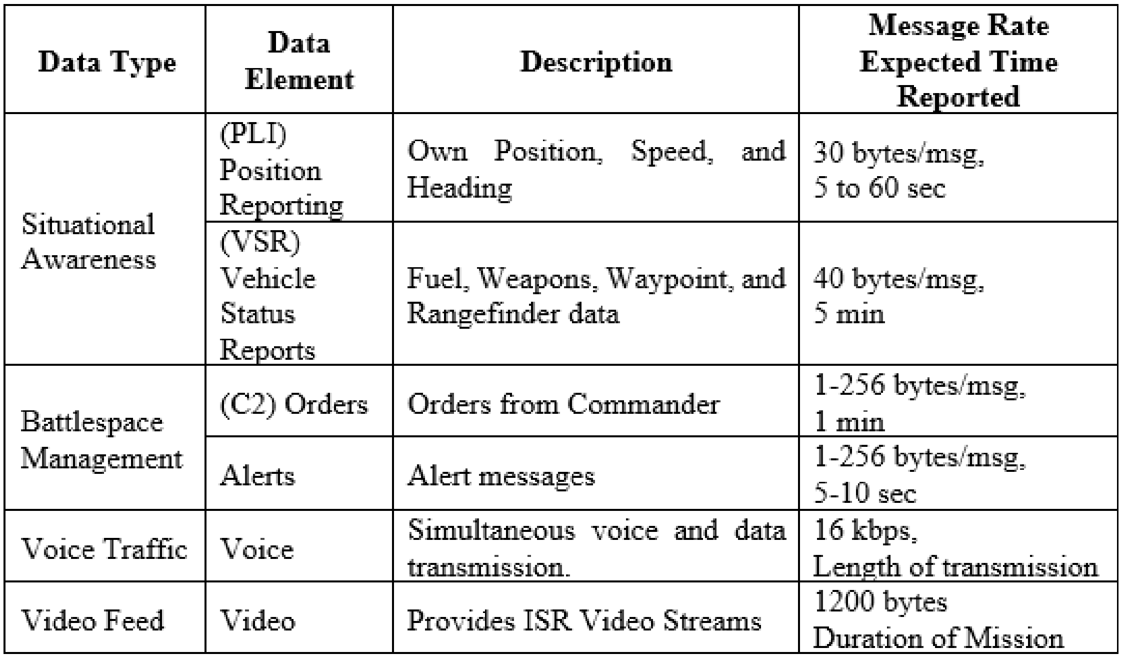
## A. MODEL AND SIMULATION APPROACH

The simulation approach of this study was designed to model how different communications network configurations could impact the reliability and the effectiveness of a joint strike operation. The information exchanges defined in Figure 18 were simulated and analyzed for performance message delays and network reliability. The results of this study addressed the partial mission modeling defined in the stakeholder analysis (Table 1) with a focus on the communication network.

The models and simulations were created to determine how well each network configuration could support similar data types. The model data types were created and classified by tactical relevance at specific moments in the mission timeline. For instance, if a message was sent between the SEAL squad and the commander, it may have been for situational awareness. Likewise, messages from the commander to other assets may be for battlespace management.

In this study, message structure and protocols were captured as constant variables that account for the network response. Additionally, each message element type in Table 7 was considered part of the network demand. The basis of messaging services required during the mission was established to understand the demands on the communications networks.

Table 7. Data Elements and Attributes Determining Message Size and Rate. Adapted from Nakamura (2008).



| Data Type | Data Element | Description | Message Rate Expected Time Reported |
|---|---|---|---|
| Situational Awareness | (PLI) Position Reporting | Own Position, Speed, and Heading | 30 bytes/msg,<br>5 to 60 sec |
| | (VSR) Vehicle Status Reports | Fuel, Weapons, Waypoint, and Rangefinder data | 40 bytes/msg,<br>5 min |
| Battlespace Management | (C2) Orders | Orders from Commander | 1-256 bytes/msg,<br>1 min |
| | Alerts | Alert messages | 1-256 bytes/msg,<br>5-10 sec |
| Voice Traffic | Voice | Simultaneous voice and data transmission. | 16 kbps,<br>Length of transmission |
| Video Feed | Video | Provides ISR Video Streams | 1200 bytes<br>Duration of Mission |

Note: PLI = position location information, VSR = vehicle status report

Position location information (PLI) messages consist of geolocation, a heading vector, and the rate of speed of the platform, and are defined in the tactical message format standard, MIL-STD-6017 (DOD 2017). The PLI allowed joint assets to display Red Force and Blue Force assets in a common operational picture to visually represent the dynamic battlespace environment. Vehicle/vessel status report (VSR) is another standard message that provides the health, fuel, ammunition, and subsystem status of a platform. C2 data exchange is a text message transmission also defined in MIL-STD-6017.

Communications architectures generally fall into two categories: LOS and BLOS. To be LOS, there must be little to no obstruction between the transmitter and the receiver. Geographic features like mountains and the curvature of the Earth along with natural features like islands that block the transmission path necessitate a connection type that is called BLOS.

BLOS architectures are used for over the horizon communications and have the advantage of poor detectability by near-peer LOS detection systems. Two types of BLOS communications architectures were modeled using bent pipe (BP) or hub-relay (HR) structures. Both architectures were represented in the model to account for the time delay inherent in each for a message to reach its intended target node or hub.

BLOS-BP is a satellite architecture that enables two or more network nodes to connect. The satellite acts as a reflector or relay point for the OSI physical layer. This is shown in Figure 22 where the lines of communication (black lines) require the satellite to connect to other nodes.

In the simulations of this study, the time delay for BP operations was set to 0.5 *s* for geosynchronous Earth orbit (GEO) satellite operations. This number was based on the round-trip time of travel from the Earth's surface to the satellite and back. In a BP architecture, each platform is equipped with a modem capable of direct communication with other nodes in the network without the use of a hub router.

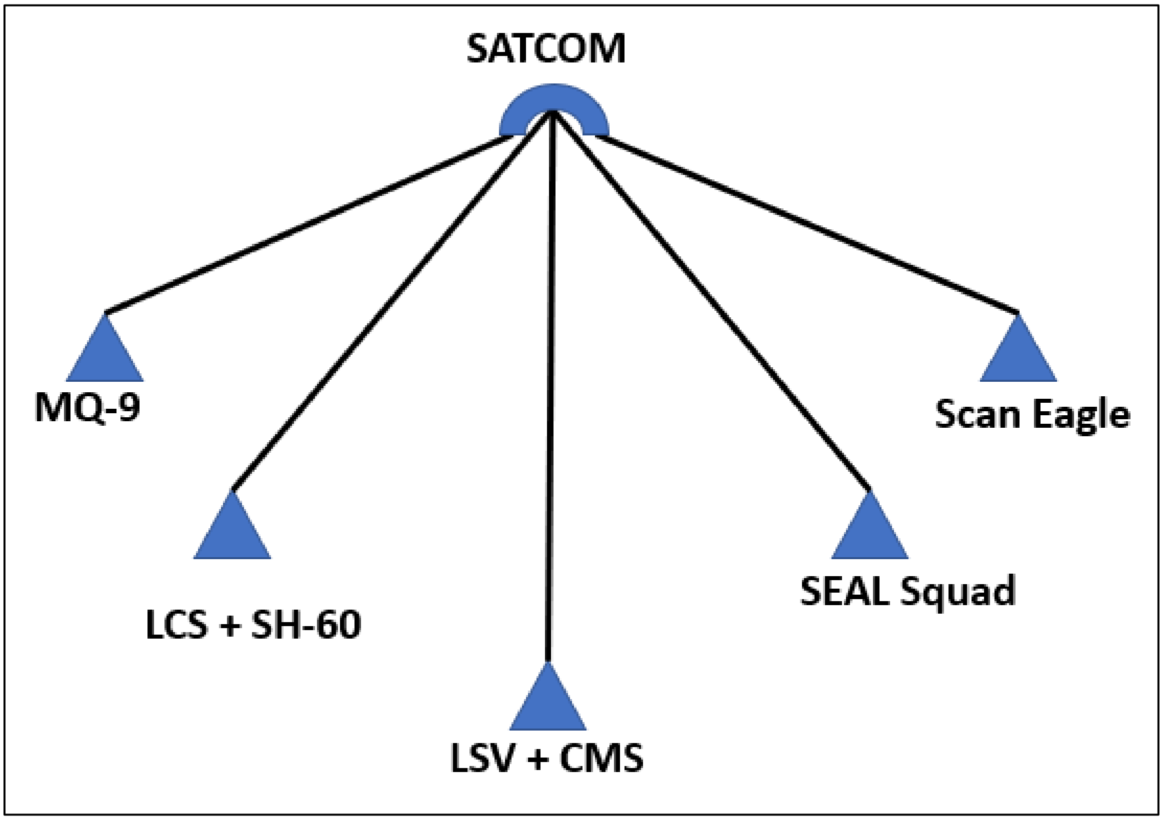


Figure 22. BLOS-BP Communication Architecture

BLOS-HR delays are incurred when the network system requires a hub located somewhere in the vicinity of the satellite of operations to process all return link signals. Return link signals, shown in Figure 23 as blue lines, are classified by the transmission from a distant user station to the satellite back down to the hub station. Forward links, shown in Figure 23 as green lines, are the signal paths between the hub station and the satellite to the distant user station. Since BLOS-HR operations require the hub to process signals for rebroadcasting, an additional 0.5 *s* are required for the forward path transmission, incurring a total minimum delay of 1 *s*.

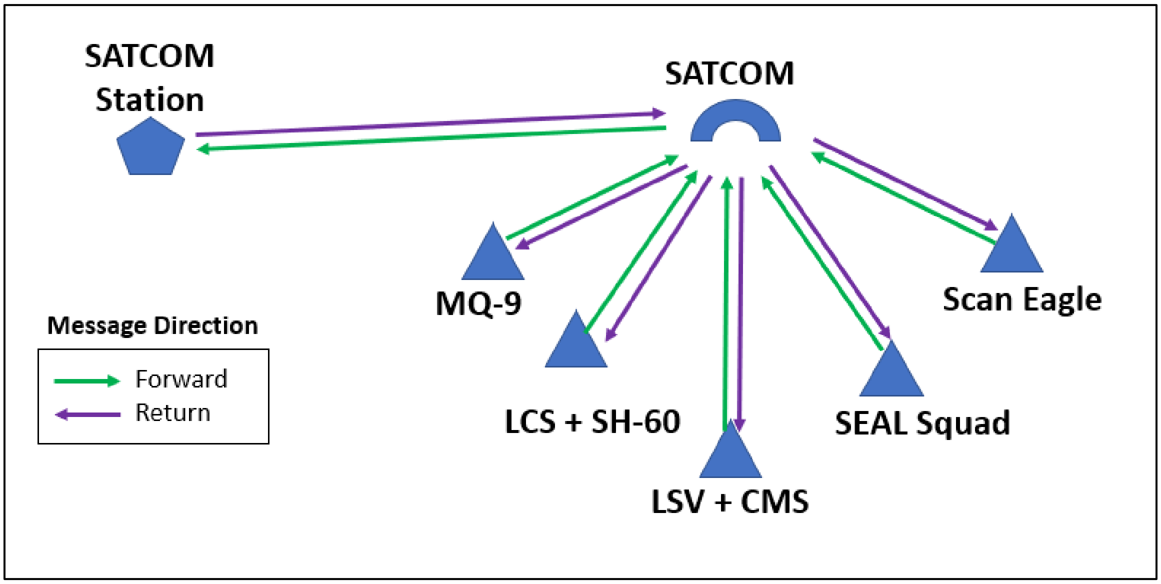
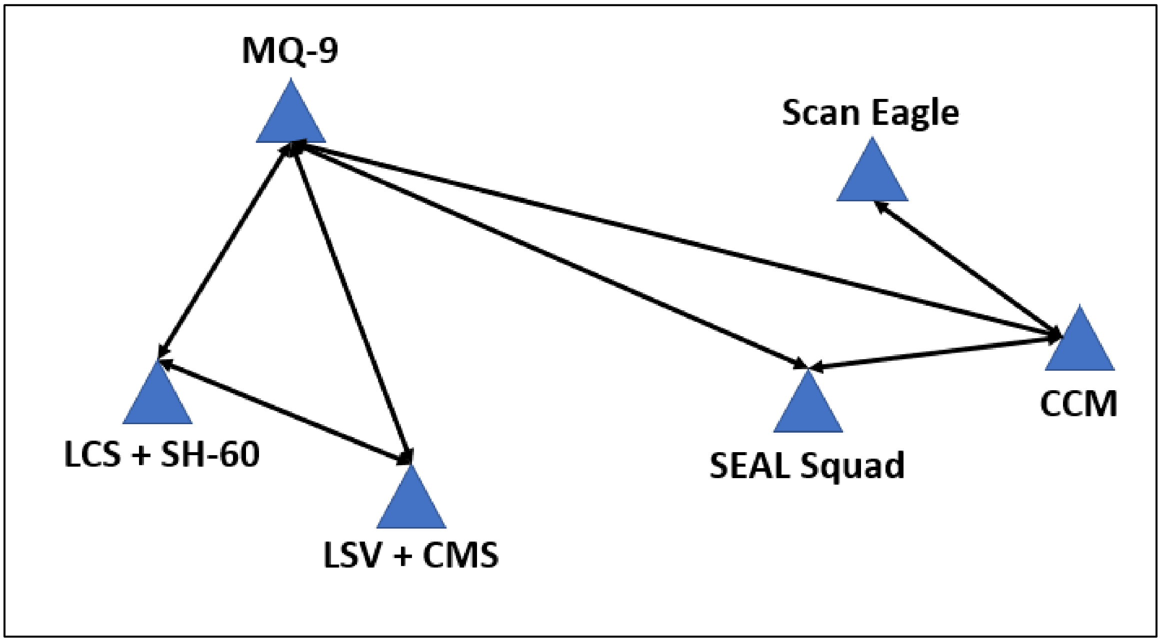


Figure 23. BLOS-HR Communication Architecture

In LOS networks, each node performs dynamic routing of the data elements. The elements change as each network node dynamically moves through the area of operations. Figure 24 illustrates with solid black lines the available network links between each node. As network nodes maneuver through the area, direct links may fail causing data to route between multiple nodes. Time of delivery is dependent on the configuration of the network and includes latency, message size, and throughput.



Note that while LOS is available to the MQ-9, in practice, it has no direct communications with any of the assets shown. Likewise, the LCS and LSV would only have LOS if geographically close enough.

Figure 24. LOS Communication Architecture

## B. PURPOSE OF THE MODELS

The purpose of the scenario models developed for this study was to help the reader better understand how network latency is impacted by message size, MTU, and throughput. This highlights the design constraints of the implemented network. The simulation results were used to define a baseline reference and traceable data requirements to support a tactical network designed for a JF DMO.

## C. TOOL SELECTION

### 1. Microsoft Excel Modeling

For evaluation, both LOS and BLOS threshold models were created in Microsoft Excel. The simulation results were then used to determine speed and network parameters for the ExtendSim simulations. The completion rate values were set to objective mission network timing for C2 and real-time decision making. Note: While more frequent message reporting updates make for a more complete picture of the mission status, higher reporting rates may increase unit detectability by Red Forces. Adjusting the reporting times of various data elements may be a way to adjust acceptable mission risk.

Excel modeling was also used to estimate and determine position reporting rates based on the type of platforms used in the mission scenarios. Fast-moving platforms required a higher rate of position reporting. This was due to the need from the commander for increased accuracy and tracking information to maintain battlespace awareness.

### 2. ExtendSim Simulations

ExtendSim was used to model discrete network performance and to evaluate the user demands introduced by changing networks and parameters. ExtendSim models enabled the use of queues to evaluate and determine network design constraints from changing communication path characteristics. These characteristics included changes in data rate, MTU size, and transmission delays per network segment.

### 3. MATLAB

MATLAB was used for post-processing and analysis of the data-logs generated by the ExtendSim simulations.

## D. MODELING ASSUMPTIONS

Modeling assumptions were made to effectively represent and simulate the performance of the network including the data transmission overhead incurred as data was generated by one application or user node to another in the same network.

The layers of the OSI model, as initially described in Chapter 2, range from the layer 1 (physical) connections to the layer 7 (application) which processes and generates the type of data identified in Figure 25. The graphic displays all seven layers in a high-level view that enables two computing systems to communicate. This model was applied and analyzed for wireless network operations.

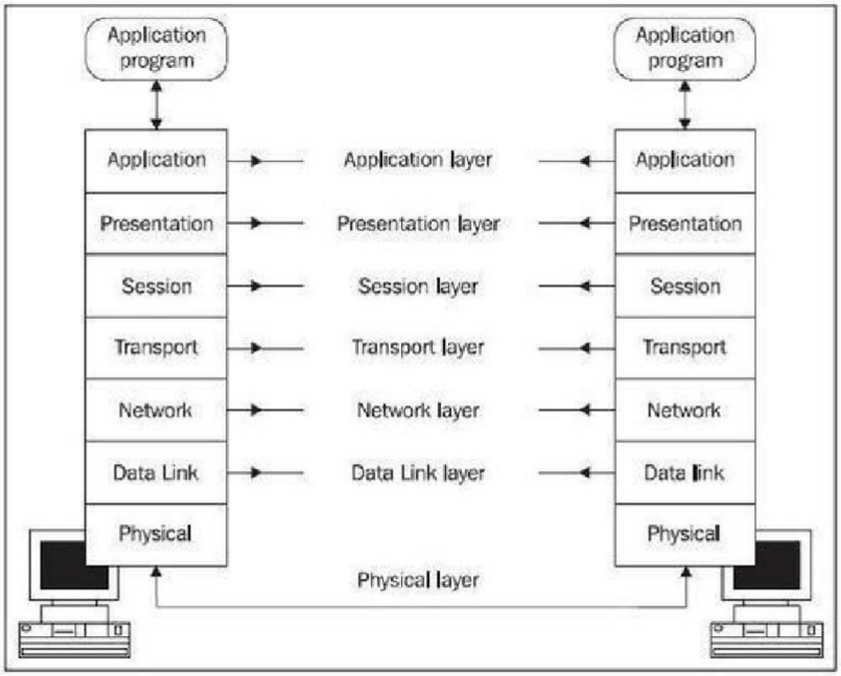


Figure 25. Seven-Layer OSI Model. Source: Dostalek and Kabelova (2006).

The application data size, known as the payload, and message rates directly impact the demands within each layer of the OSI model. Focusing on mission success, a higher demand for user data may increase the probability of detection. To counter the increased detectability in the electromagnet spectrum, the characteristics of the physical layer should be considered but were not in the scope of this study. Physical layer specifications for a wireless network relates to power, spectrum, and the duty cycle each transmitter uses in the network.

The data link layer consists of three parts that are needed to communicate between wireless nodes: Data link header, payload, and a checksum. The data link header consists of link parameters which aid in link control and the access of roaming nodes. Depending on the protocols used for wireless connections, the header can range in size from one or more 8-bit words. To represent the data link control requirements, the variable "Data-Link Overhead" in Table 8 was used to capture the data requirements for transmission.

The network layer is used to determine the data routing needs. If a single network was used, then there was no need for routing data between disparate network topologies and architectures. But, if the mission scenario included multiple assets without data sharing-provisioned interoperable hardware, the need for additional routers and system delays must be considered. In the scenarios of this capstone, the data requirements for both transport and network requirements were captured as "Network/Transport Overhead" in Table 8. This enabled data dissemination between the different networks.

Table 8. Variable Definitions

| **Variable** | **Value** | **Unit** |
|---|---|---|
| MTU Size | 128 | bytes |
| Encryption | 20 | bytes |
| Network/Transport Overhead | 20 | bytes |
| Data Link Overhead | 1 | bytes |
| Physical Link Overhead | 0 | bytes |
| LOS Threshold | 1 | second |
| LOS Delay | 0.05 | seconds |
| BLOS Threshold | 1 | second |
| BLOS (Bent Pipe) | 0.5 | second |
| BLOS (Hub Relay) | 1 | second |

Table 8 reflects a snapshot of the network variables and type of network time requirements and limitations.

The MTU size variable was used to determine how the network was optimized for the intended operating environment. It set a limit on how much payload and user-data could be transmitted in one network frame. When it comes to wireless communications, the MTU size can improve network performance when set lower than the MTU size for wired terrestrial communications. The reason for this relates to the total transmission time required to complete a message transmission. If a frame fails to be received, the entire frame would need to be retransmitted.

The Encryption variable accounted for the additional bytes of data required when the original data is encrypted. There are several key types that are certified for government or commercial use. In both cases, the original data size will increase based on the type of cryptographic solution set used. In this study, the Encryption variable was initially set to 20 Bytes, increasing the original data required for transmission.

## E. MODELING DESCRIPTION

Figure 26 shows the high-level operational activities (OA) that the system needed to perform. The activities started with a received call for fires, OA.0.1, in response to an event. Once received, a target analysis was conducted in OA.0.2. In this phase, intelligence was collected on the targets to prioritize them. Once the high value targets were identified, the appropriate level of response was determined in OA.0.3, the mission requirements phase. After the mission requirements have been established, the assets maneuvered into location in OA.0.4. This capstone focused on modeling OA.0.5, the communications needed to support a limited strike on Red Island. The final operational activity, OA.6, is where the SEAL squad and asset extraction occurred after mission success.

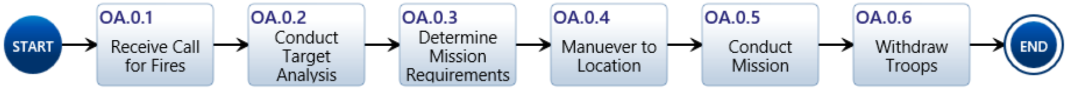


Figure 26. JF DMO Notional Operational Activities

The mission timeline shown in Figure 27 spanned a notional 12-hour period where the risk for loss-of-life elevated to high during the strike period. The green areas represent persistent communication operations during the maneuver-to and extraction-from the strike zone phase for all assets. As the ground strike teams neared the strike locations, they entered EMCON to minimize detection as the risk increased to moderate levels. This phase of the operation primarily affected the SEAL squad and CCM operators and is indicated in yellow. The highest risk is represented in red and shows the time of strike execution. Communications of forward operating units transition from EMCON to short burst operations to communicate target solutions, acknowledge orders, and perform BDA.

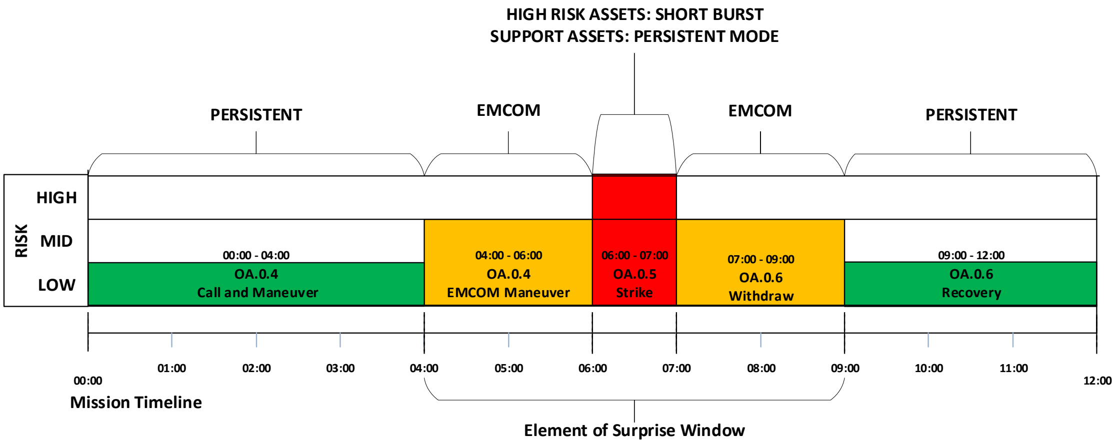


Figure 27. Risk Relative to a Notional Mission Timeline

The communication operating states shown in Figure 28 were defined by the operational phases of the mission as shown in Figure 27. Persistent operations included transmitting and receiving unit status, platform health status, C2 data exchange, voice, and full-motion video.

As the SEALs maneuvered to the strike zone on the CCM, transmissions from communications systems were silenced for EMCON. This mode is receive-only, capable of receiving supporting asset messages. Message types identified earlier are received but not acknowledged. Once the team enters the strike zone, they exit EMCON and utilize a short burst mode of operations. This only affected the SEALs' and CCM operator's ability to automatically report position, vehicle status, voice communications, their ability to call in strikes, perform BDA, or request extraction. During normal extraction, forward units re-entered EMCON until they were safe in non-hostile waters. Then they returned to a persistent mode of operations.

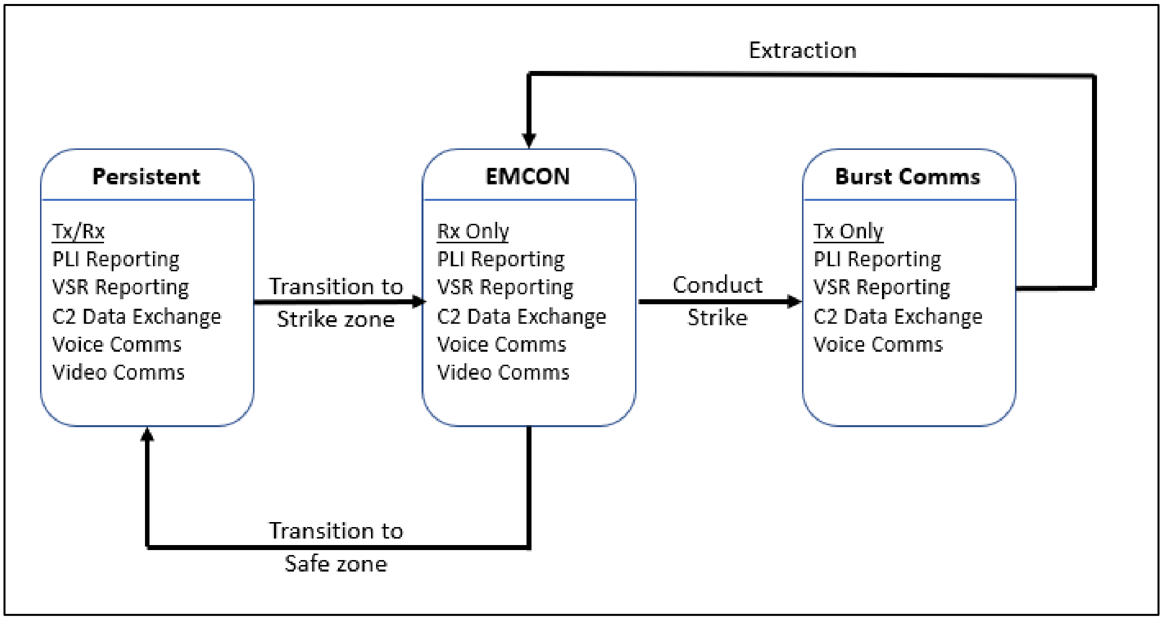


Figure 28. Communications Operating States

Each platform was modeled to transmit and receive the messages defined in Figure 28 “Burst Comms” operational state. Video from the Scan Eagle was only provided to the CCM where the Scan Eagle operator provided intelligence and target solutions through the C2 data exchange. Video from the MQ-9 was provided to the commander through a SATCOM hub. C2 data exchanged was randomly transmitted to supporting nodes to emulate cross-sharing of information and requests to provide direct support to forward users.

## F. MODEL AND SIMULATION OUTPUT AND FINDINGS

The model and simulation results were executed such that the results from earlier model analyses drove the criteria for later simulations. First, an analysis was performed to provide a better understanding of the impact of network delays on position accuracy. Then a network model was created to determine the desired data rates and network parameters. Those parameters were then integrated into the ExtendSim model and recorded.

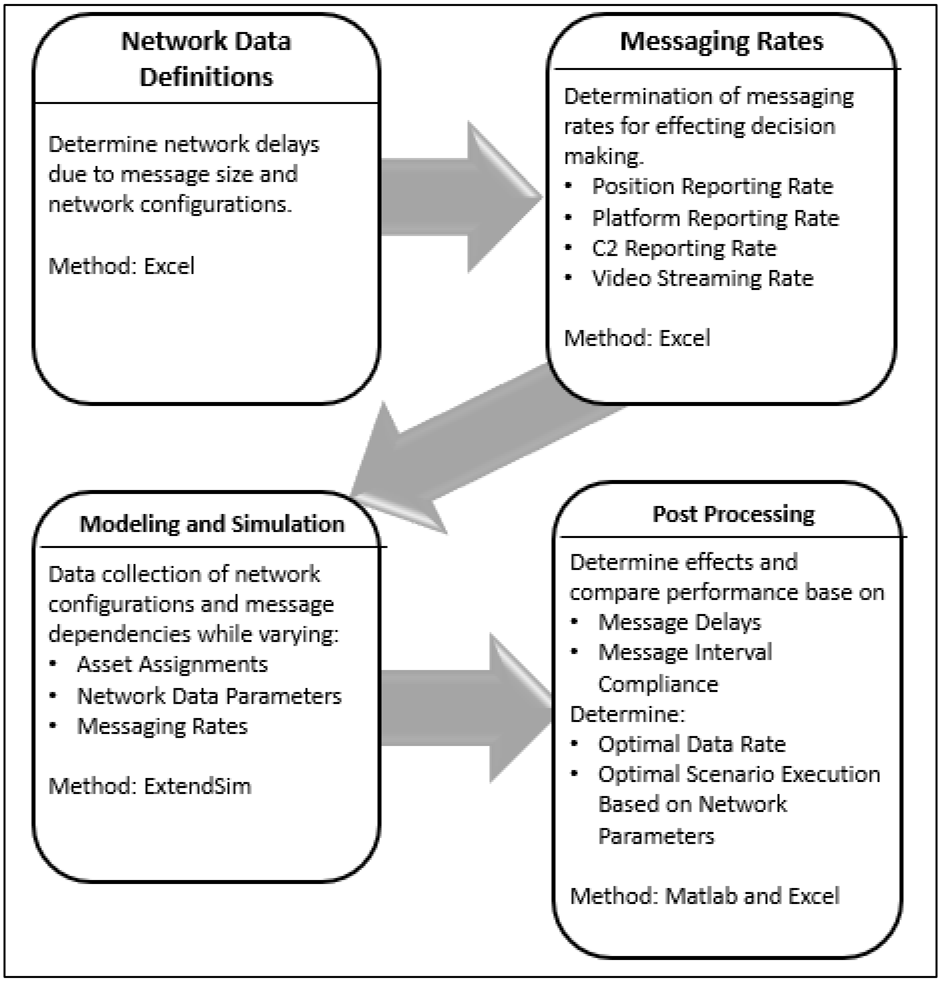


Figure 29. Data Processing Flowchart

### 1. Position Reporting Rates versus Position Accuracy

In Table 7, Nakamura referenced position reporting rates for ground platforms of the U.S. Army of one every five to sixty seconds. Figure 30 shows position accuracy trends based on a platform's speed of travel and how often the position information was transmitted.

Fast movers like aircraft with higher travel speeds have a higher degree of inaccuracy of position relative to the time the message is received by the remote user. Assuming no time loss between transmission of the message and the message being received, the error is related only to the time passed since the previous position was reported.

For example, if a platform is traveling at 275 *knots* (142 *m/s*), the platform will have traveled over 128 *m* for every second of position. For slow movers like an LCS traveling at 13 *knots* (4 *m/s*), the vessel will only have traveled 4 *m* in one second's time.

For this study, the assets in the network were assumed to be transmitting at a constant rate of 1 message/second. If any delays to position reporting were introduced by later defined network parameters, the accuracy of the position reporting may introduce error in the observations and orientation stages of the OODA loop and decrease the probability of successfully making a mission-critical decision.

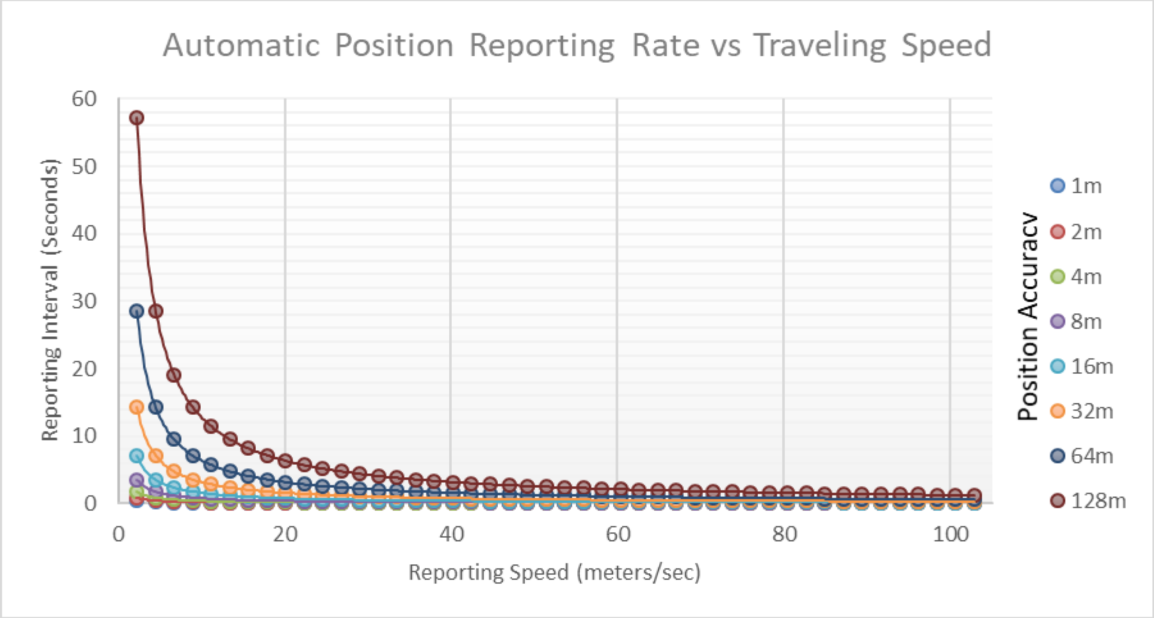


Figure 30. Position Reporting versus Traveling Speed

See the appendix for the data table and chart.

### 2. Network Baseline Model

Modeling assumptions were used for each layer of the OSI model that impacted the total data transmission requirements. The following equations were used to determine the latency estimations based on communication network overhead and payload size.

The total data for each single, non-streaming message element required to be transmitted was represented by the following variables and equation:

$NT_{Bytes}$ = Network transportation overhead (Bytes)
$E_{Bytes}$ = Encryption overhead (Bytes)
$D_{Bytes}$ = Data element (Bytes)
$P_{Bytes}$ = Physical layer overhead (Bytes)
$DL_{Bytes}$ = Data link overhead (Bytes)

$$Data_{BytesTotal} = D_{Bytes} + E_{Bytes} + NT_{Bytes} + DL_{Bytes} + P_{Bytes}$$

Equation 1. Single Message Total Data Requirement (Bytes)

From the data requirements, constraints, and determination of data rates, the estimated time of delivery of the message was calculated by the following equations.

$MTU_{Bytes}$ = Message transmission unit size (Bytes)
TTU = Total transmission units (Seconds)
$D_{Path}$ = Delay of signal path (Seconds)
$Time_{TD}$ = Total time transmitting message (Seconds)

To determine the total number of frames needed for data element transmission:

$$MTU_{TTU} = \left\lceil \frac{Data_{Bytes-Total}}{MTU_{Bytes}} \right\rceil$$

Equation 2. Message MTU Requirement

To determine the time required to transmit the data element:

$$Time_{TD} = \left\lceil \frac{(MTU_{TTU} \times MTU_{Bytes})}{Datarate_{Bytes}} \right\rceil + D_{path}$$

Equation 3. Single Message Time of Delivery

Applying the criteria of Table 8 to the calculations, Table 9 displays the estimated delays expected for each network type: LOS, BLOS-BP, and BLOS-HR. Based on the results, the network transport should be configured to between 2 *kilobits/second* (*kbps*) and 4 *kbps* data rates with a payload size of fewer than 188 *Bytes* (1504 *bits*) per message to achieve a 1 *s* network delay.

Table 9. Throughput Delays for Each Network Type

| Throughput | | | Payload Size | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 24 | 47 | 94 | 188 | 375 | 750 | 1500 | <- Bytes | MTU/sec |
| bps | Mbps | Path | 192 | 376 | 752 | 1504 | 3000 | 6000 | 12000 | <- bits | |
| 128 | 0.0001 | LOS | 8.05 s | 8.05 s | 16.05 s | 16.05 s | 32.05 s | 56.05 s | 104.05 s | LOS | 0.125 |
| | | BLOS-BP | 8.5 s | 8.5 s | 16.5 s | 16.5 s | 32.5 s | 56.5 s | 104.5 s | BLOS-BP | |
| | | BLOS-HR | 9 s | 9 s | 17 s | 17 s | 33 s | 57 s | 105 s | BLOS-HR | |
| 256 | 0.0003 | LOS | 4.05 s | 4.05 s | 8.05 s | 8.05 s | 16.05 s | 28.05 s | 52.05 s | LOS | 0.250 |
| | | BLOS-BP | 4.5 s | 4.5 s | 8.5 s | 8.5 s | 16.5 s | 28.5 s | 52.5 s | BLOS-BP | |
| | | BLOS-HR | 5 s | 5 s | 9 s | 9 s | 17 s | 29 s | 53 s | BLOS-HR | |
| 512 | 0.0005 | LOS | 2.05 s | 2.05 s | 4.05 s | 4.05 s | 8.05 s | 14.05 s | 26.05 s | LOS | 0.500 |
| | | BLOS-BP | 2.5 s | 2.5 s | 4.5 s | 4.5 s | 8.5 s | 14.5 s | 26.5 s | BLOS-BP | |
| | | BLOS-HR | 3 s | 3 s | 5 s | 5 s | 9 s | 15 s | 27 s | BLOS-HR | |
| 1,024 | 0.0010 | LOS | 1.05 s | 1.05 s | 2.05 s | 2.05 s | 4.05 s | 7.05 s | 13.05 s | LOS | 1.000 |
| | | BLOS-BP | 1.5 s | 1.5 s | 2.5 s | 2.5 s | 4.5 s | 7.5 s | 13.5 s | BLOS-BP | |
| | | BLOS-HR | 2 s | 2 s | 3 s | 3 s | 5 s | 8 s | 14 s | BLOS-HR | |
| 2,048 | 0.0020 | LOS | 0.55 s | 0.55 s | 1.05 s | 1.05 s | 2.05 s | 3.55 s | 6.55 s | LOS | 2.000 |
| | | BLOS-BP | 1 s | 1 s | 1.5 s | 1.5 s | 2.5 s | 4 s | 7 s | BLOS-BP | |
| | | BLOS-HR | 1.5 s | 1.5 s | 2 s | 2 s | 3 s | 4.5 s | 7.5 s | BLOS-HR | |
| 4,096 | 0.0041 | LOS | 0.3 s | 0.3 s | 0.55 s | 0.55 s | 1.05 s | 1.8 s | 3.3 s | LOS | 4.000 |
| | | BLOS-BP | 0.75 s | 0.75 s | 1 s | 1 s | 1.5 s | 2.25 s | 3.75 s | BLOS-BP | |
| | | BLOS-HR | 1.25 s | 1.25 s | 1.5 s | 1.5 s | 2 s | 2.75 s | 4.25 s | BLOS-HR | |
| 8,192 | 0.0082 | LOS | 0.175 s | 0.175 s | 0.3 s | 0.3 s | 0.55 s | 0.925 s | 1.675 s | LOS | 8.000 |
| | | BLOS-BP | 0.625 s | 0.625 s | 0.75 s | 0.75 s | 1 s | 1.375 s | 2.125 s | BLOS-BP | |
| | | BLOS-HR | 1.125 s | 1.125 s | 1.25 s | 1.25 s | 1.5 s | 1.875 s | 2.625 s | BLOS-HR | |
| 16,384 | 0.0164 | LOS | 0.113 s | 0.113 s | 0.175 s | 0.175 s | 0.3 s | 0.488 s | 0.863 s | LOS | 16.000 |
| | | BLOS-BP | 0.563 s | 0.563 s | 0.625 s | 0.625 s | 0.75 s | 0.938 s | 1.313 s | BLOS-BP | |
| | | BLOS-HR | 1.063 s | 1.063 s | 1.125 s | 1.125 s | 1.25 s | 1.438 s | 1.813 s | BLOS-HR | |
| 32,768 | 0.0328 | LOS | 0.081 s | 0.081 s | 0.113 s | 0.113 s | 0.175 s | 0.269 s | 0.456 s | LOS | 32.000 |
| | | BLOS-BP | 0.531 s | 0.531 s | 0.563 s | 0.563 s | 0.625 s | 0.719 s | 0.906 s | BLOS-BP | |
| | | BLOS-HR | 1.031 s | 1.031 s | 1.063 s | 1.063 s | 1.125 s | 1.219 s | 1.406 s | BLOS-HR | |
| 65,536 | 0.0655 | LOS | 0.066 s | 0.066 s | 0.081 s | 0.081 s | 0.113 s | 0.159 s | 0.253 s | LOS | 64.000 |
| | | BLOS-BP | 0.516 s | 0.516 s | 0.531 s | 0.531 s | 0.563 s | 0.609 s | 0.703 s | BLOS-BP | |
| | | BLOS-HR | 1.016 s | 1.016 s | 1.031 s | 1.031 s | 1.063 s | 1.109 s | 1.203 s | BLOS-HR | |
| 131,072 | 0.1311 | LOS | 0.058 s | 0.058 s | 0.066 s | 0.066 s | 0.081 s | 0.105 s | 0.152 s | LOS | 128.000 |
| | | BLOS-BP | 0.508 s | 0.508 s | 0.516 s | 0.516 s | 0.531 s | 0.555 s | 0.602 s | BLOS-BP | |
| | | BLOS-HR | 1.008 s | 1.008 s | 1.016 s | 1.016 s | 1.031 s | 1.055 s | 1.102 s | BLOS-HR | |
| 262,144 | 0.2621 | LOS | 0.054 s | 0.054 s | 0.058 s | 0.058 s | 0.066 s | 0.077 s | 0.101 s | LOS | 256.000 |
| | | BLOS-BP | 0.504 s | 0.504 s | 0.508 s | 0.508 s | 0.516 s | 0.527 s | 0.551 s | BLOS-BP | |
| | | BLOS-HR | 1.004 s | 1.004 s | 1.008 s | 1.008 s | 1.016 s | 1.027 s | 1.051 s | BLOS-HR | |
| 524,288 | 0.5243 | LOS | 0.052 s | 0.052 s | 0.054 s | 0.054 s | 0.058 s | 0.064 s | 0.075 s | LOS | 512.000 |
| | | BLOS-BP | 0.502 s | 0.502 s | 0.504 s | 0.504 s | 0.508 s | 0.514 s | 0.525 s | BLOS-BP | |
| | | BLOS-HR | 1.002 s | 1.002 s | 1.004 s | 1.004 s | 1.008 s | 1.014 s | 1.025 s | BLOS-HR | |
| 1,048,576 | 1.0486 | LOS | 0.051 s | 0.051 s | 0.052 s | 0.052 s | 0.054 s | 0.057 s | 0.063 s | LOS | 1024.000 |
| | | BLOS-BP | 0.501 s | 0.501 s | 0.502 s | 0.502 s | 0.504 s | 0.507 s | 0.513 s | BLOS-BP | |
| | | BLOS-HR | 1.001 s | 1.001 s | 1.002 s | 1.002 s | 1.004 s | 1.007 s | 1.013 s | BLOS-HR | |
| 2,097,152 | 2.0972 | LOS | 0.05 s | 0.05 s | 0.051 s | 0.051 s | 0.052 s | 0.053 s | 0.056 s | LOS | 2048.000 |
| | | BLOS-BP | 0.5 s | 0.5 s | 0.501 s | 0.501 s | 0.502 s | 0.503 s | 0.506 s | BLOS-BP | |
| | | BLOS-HR | 1 s | 1 s | 1.001 s | 1.001 s | 1.002 s | 1.003 s | 1.006 s | BLOS-HR | |

Note: results shown in a measure of seconds (s) represent the estimated calculated message delay.

Table 9 results provide network operators an estimate on required data rates and supportable message sizes based on the defined network parameters for the scenarios in this capstone. Considerations for network configurations are dependent on the bandwidth required by a BLOS solution, the number of users, and the reusability of bandwidth for other missions in the serving area.

### 3. ExtendSim Modeling Results

ExtendSim was used to determine the network performance over the notional one-hour time span of the strike and support the analysis of message flow from the source identification (SID) to the destination identification (DID) network nodes. Real-time calculations were performed for each network segment of the communications network. Packet inspections were performed at each segment to find the latency effect for the transition between key network nodes. Packet delays were calculated based on the birth (origination) time and arrival time meta-data, which were impacted by the network configuration and congestion points of the architecture.

In the simulation, each modeled asset (LCS, LSV, etc.) independently generated data based on their messaging requirements. Independent variable values for each simulation included variations in:

*Scenario assets*: Each scenario leveraged assets that were varied through logical switches that enabled and disabled message traffic to them.

- Scenario #1 included 5 assets
- Scenario# 2 included 6 assets
- Scenario #3 included 7 assets

*SATCOM delays*: SATCOM link delays were varied to simulate the effects of various orbiting planes and different onboard satellite capabilities. Modeling of the GEO and LEO constellations with and without onboard hub processing was simulated.

- LCS integrated SATCOM Hub using GEO satellite constellation. (1 second)
- SATCOM with an integrated hub in GEO orbit. (0.5 seconds)
- LCS integrated SATCOM hub using LEO satellite constellation. (0.60 second)
- SATCOM satellite with integrated hub in GEO orbit. (0.3 seconds)

*Forward and Return Data Rates*: Most satellites use asynchronous data rates to improve the performance of the overall network. This resulted in variable data rates based on the initial analysis results summarized in Table 9. For this project, the forward and return data rates were independently varied. Mission performance was evaluated using 256 *Bps*, 512 *Bps*, and 1024 *Bps* data rates.

*Maximum Transmission Unit (MTU)*: The MTU was optimized for the type of message traffic being transmitted and was determined through the analysis summarized in Table 9. It was applied only to the SATCOM links. For both RF terrestrial links and physical communication links, the MTU size defaulted to 1500 *Bytes*.

*RF LOS terrestrial data rates*: Simulated at 4800 *Bps*.

*Physical Communication links*: Simulated at 125 *mbps* for standard Gbps local area network (LAN) effects.

*Video Enabled*: Only for the Scenario #2 simulation which included the MQ-9 asset.

*Video Channel*: Dedicated (not sharing the same network as C2) or Shared (combining both Video and C2 messaging on the same transport layer).

Numerous simulations were run to cover the variations in the scenario models. Each simulation evaluated a network configuration that changed according to the independent variables listed in Table 10. These in combination with the controlled variables impact the system architecture MOEs. They are based on the scenario constraints and the network SATCOM configuration. The control variables for each configuration are also listed.

Table 10. Extendsim Model Fixed and Variable Inputs

| Fixed Inputs | Value | Unit | Rate |
|---|---|---|---|
| PLI Message Size | 30 | byte/msg | 1 s |
| VSR Message Size | 40 | byte/msg | 5 m |
| C2 Message Size | 256 | byte/msg | 1 m |
| Video Message Size | 1200 | byte/frame | continuous |
| Voice Message Size | 16 | bit/msg | short burst |
| SATCOM MTU Size | 128 | byte | n/a |
| LOS MTU Size | 1500 | byte | n/a |
| LOS Data rate | 4800 | Bps | n/a |
| **Variable Inputs** | **Value** | **Unit** | **Rate** |
| Number of Assets | [5,6,7] | n/a | n/a |
| SATCOM Architecture Delays | [0.5,0.25,0.30,0.15] | seconds | n/a |
| SATCOM Data rates (Forward and Return Link) | [256,512,1024] | Bps | n/a |
| Video Enabled | [enabled, disabled] | n/a | n/a |
| Video Channel | [shared, dedicated] | n/a | n/a |

The overall network performance was reviewed for inherent configuration delays and how the configuration supported the inclusion of video on the network, whether through a shared or dedicated channel. Message performance was analyzed by looking at the difference between broadcast and unicast messages.

Unicast messages target a specific user on the network and include vehicle status reports and C2-type messages. Broadcast messages were sent to all users on the network to provide necessary information updates including video sharing from the MQ-9 and position reporting from each network node.

The ExtendSim model applied to both the mesh and the star analysis of the SATCOM links. At the physical layer, the SATCOM architecture is the same for both the mesh and star implementations. The SATCOM satellite itself is where the aggregation of the physical layer connections for both architectures is consolidated. The difference in the implementation between mesh and star is based on the network layer of the link which relies on the same connected satellite.

If a commercial SATCOM service that offers either mesh or star transport services is used, the required encryption for DOD transmissions still requires a dedicated gateway for processing and routing data for supported users, if true IP header information is masked or unavailable. To simulate this feature, the message traffic was modeled with predetermined delays based on the transport architectures.

#### *a. Overall Network Performance*

This section provides a summary of the results from the ExtendSim communications simulations that are required to support a joint fires strike on Red Island. Hundreds of runs were performed, the most successful of which are highlighted below. The data was first categorized by scenario and then ranked based on timing delays of messaging. In Scenarios #1 and #3, the data were further parsed based on whether the messaging had shared or dedicated-video to determine if these variables had any effect on timing delays. To determine the relationship between messaging transmission method and timing delays, data was then categorized by broadcast or unicast message transmission type. The results were separated by scenario and ranked. The overall results for all three scenarios are shown in Table 17. *The most compelling takeaway is that the best timing performance corresponded to a broadcast message type*. The fastest broadcast message had a timing delay of 0.813 *s* with a standard deviation of 0.045 *s*.

Overall network performance was analyzed by combining all unicast and broadcast message traffic together, along with any effects from the addition of a dedicated or shared video network channel. Video transmissions were injected at the hub location and broadcast over the forward link to all assets. Using a dedicated network transport layer enabled the mission command messaging (PLI, VSR, C2) to be transmitted over one network transport while the video was transmitted over another. A shared network transport would combine the mission command messaging with the video stream.

Scenario #1 included five assets all using the same network configurations based on the permutation of the simulation. There were 108 configurations simulated varying the network configuration variables identified in Table 10. Of the 108 configurations, the best performance for messaging delays, where less delay is better, required the network to support a forward and return link data rate of 1024 *Bps* and a 128 *Byte* MTU and terrestrial RF communications supported by 4800 *Bps* with a 1500 *Byte* MTU. The performance variation between a dedicated or shared video link in this scenario resulted in a similar delay performance with a 0.01 *s* standard deviation. Messages were all received in an average of 1.61 *s* from transmission with a standard deviation of 0.15 *s* making this architecture acceptable for further analysis. See Table 11 for the overall network simulation results of Scenario #1.

## Table 11. Scenario #1 Overall Network Performance Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| **SCENARIO 1** | **Overall** | **1 (Best Performance)** | **1** | **.15** | **[1024/1024]** | **Yes / Dedicated** | **1.610** | **0.149** | **0.021** | **0.226** |
| | | 2 | 2 | .15 | [1024/1024] | Yes/Shared | 1.611 | 0.045 | 0.000 | 0.056 |
| | | 3 | 5 | .15 | [1024/1024] | Not Enabled | 1.614 | 0.045 | 0.000 | 0.056 |
| | | 4 | 8 | .15 | [512/1024] | Not Enabled | 1.860 | 0.143 | 0.000 | 0.212 |
| | | 5 | 9 | .25 | [1024/1024] | Yes / Dedicated | 2.010 | 0.183 | 0.033 | 0.264 |
| | | | | | | | MOE -1 | | MOE -2 | |
| | | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | **Dedicated Video** | **1 (Best Performance)** | **1** | **.15** | **[1024/1024]** | **Yes / Dedicated** | **1.610** | **0.149** | **0.021** | **0.226** |
| | | 2 | 9 | .25 | [1024/1024] | Yes / Dedicated | 2.010 | 0.183 | 0.033 | 0.264 |
| | | 3 | 15 | .30 | [1024/1024] | Yes / Dedicated | 2.210 | 0.169 | 0.000 | 0.249 |
| | | 4 | 20 | .15 | [512/1024] | Yes / Dedicated | 2.360 | 0.217 | 0.000 | 0.337 |
| | | 5 | 22 | .15 | [1024/512] | Yes / Dedicated | 2.360 | 0.239 | 0.036 | 0.335 |
| | | | | | | | MOE -1 | | MOE -2 | |
| | | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | **Shared Video** | **1 (Best Performance)** | **2** | **.15** | **[1024/1024]** | **Yes/Shared** | **1.611** | **0.045** | **0.000** | **0.056** |
| | | 2 | 11 | .25 | [1024/1024] | Yes/Shared | 2.011 | 0.123 | 0.026 | 0.089 |
| | | 3 | 18 | .30 | [1024/1024] | Yes/Shared | 2.213 | 0.146 | 0.001 | 0.267 |
| | | 4 | 23 | .15 | [1024/512] | Yes/Shared | 2.360 | 0.255 | 0.000 | 0.427 |
| | | 5 | 24 | .15 | [512/1024] | Yes/Shared | 2.361 | 0.213 | 0.000 | 0.343 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

Scenario #2 included six platforms all using the same network configurations based on the permutation of the simulation. Here, there were 36 configurations simulated using the network configuration variables identified in Table 10. Unique to this scenario, there was no video streaming shared over the network. Mission execution was performed based on mission command traffic (PLI, VSR, C2) only. Of the 36 configurations, the best performance for messaging delays required the network to support a forward and return link data rate of 1024 *Bps* with a 128 *Byte* MTU and terrestrial RF communications supported by 4800 *Bps* with a 1500 *Byte* MTU. Messages were all received in an average of 1.61 *s* from transmission with a standard deviation of 0.16 *s*, making this architecture also acceptable for further analysis. In comparison with Scenario #1, there was no impact or improvement noticed. This is due to the network configurations. See Table 12 for the overall network simulation results of Scenario #2.

Table 12. Scenario #2 Overall Network Performance Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| **SCENARIO 2** | **Overall** | **1 (Best Performance)** | **3** | **.15** | **[1024/1024]** | **Not Enabled** | **1.612** | **0.157** | **0.000** | **0.211** |
| | | 2 | 13 | .25 | [1024/1024] | Not Enabled | 2.012 | 0.118 | 0.028 | 0.176 |
| | | 3 | 14 | .15 | [512/1024] | Not Enabled | 2.110 | 0.123 | 0.001 | 0.201 |
| | | 4 | 17 | .30 | [1024/1024] | Not Enabled | 2.212 | 0.136 | 0.011 | 0.155 |
| | | 5 | 21 | .15 | [1024/512] | Not Enabled | 2.360 | 0.225 | 0.001 | 0.248 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s)*

Scenario #3 included seven platforms all transmitting with the same network configurations based on the permutation of the simulation. Like Scenario #1, there were also 108 configurations simulated using the network configuration variables identified in Table 10. Of the 108 configurations, the best performance for messaging delays required the network to support a forward and return link data rate of 1024 *Bps* with a 128 *Byte* MTU and a terrestrial RF communication supported by 4800 *Bps* with a 1500 *Byte* MTU. The performance variation between a dedicated or shared video link in this scenario resulted in similar delay performances and a 0.02 *s* deviation. Messages were received in 1.61 *s* with video not enabled; 1.82 *s* when the video was enabled over a dedicated link. In both configurations, the standard deviation was approximately 0.1 *s*, making both configurations acceptable for further analysis. The increase in delays was expected due to the increased number of user nodes and loading of the network. See Table 13 for the overall network simulation of Scenario #3.

Table 13. Scenario #3 Overall Network Performance Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 3** | **Overall** | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **4** | **.15** | **[1024/1024]** | **Not Enabled** | **1.613** | **0.118** | **0.000** | **0.142** |
| | | 2 | 6 | .15 | [1024/1024] | Yes / Dedicated | 1.821 | 0.131 | 0.000 | 0.203 |
| | | 3 | 7 | .15 | [1024/1024] | Yes/Shared | 1.821 | 0.154 | 0.002 | 0.236 |
| | | 4 | 12 | .25 | [1024/1024] | Not Enabled | 2.012 | 0.168 | 0.018 | 0.213 |
| | | 5 | 19 | .30 | [1024/1024] | Not Enabled | 2.214 | 0.157 | 0.006 | 0.248 |

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 3** | **Dedicated Video** | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **6** | **.15** | **[1024/1024]** | **Yes / Dedicated** | **1.821** | **0.131** | **0.000** | **0.203** |
| | | 2 | 28 | .15 | [1024/512] | Yes / Dedicated | 2.460 | 0.192 | 0.041 | 0.255 |
| | | 3 | 31 | .25 | [1024/1024] | Yes / Dedicated | 2.510 | 0.152 | 0.037 | 0.211 |
| | | 4 | 42 | .30 | [1024/1024] | Yes / Dedicated | 2.760 | 0.118 | 0.000 | 0.176 |
| | | 5 | 57 | .25 | [1024/512] | Yes / Dedicated | 3.010 | 0.223 | 0.049 | 0.261 |

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 3** | **Shared Video** | Scenario Performance Ranking | Overall Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **7** | **.15** | **[1024/1024]** | **Yes/Shared** | **1.821** | **0.154** | **0.002** | **0.236** |
| | | 2 | 29 | .15 | [1024/512] | Yes/Shared | 2.460 | 0.228 | 0.000 | 0.352 |
| | | 3 | 32 | .25 | [1024/1024] | Yes/Shared | 2.512 | 0.157 | 0.028 | 0.248 |
| | | 4 | 44 | .30 | [1024/1024] | Yes/Shared | 2.761 | 0.182 | 0.000 | 0.317 |
| | | 5 | 66 | .25 | [1024/512] | Yes/Shared | 3.014 | 0.272 | 0.045 | 0.323 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

#### ***b. Message Method Type Performance (Broadcast versus Unicast)***

Further analysis of Scenario #1 investigated the difference in performance between broadcast and unicast traffic. Broadcast traffic was intended to be received by all users supporting the scenario. Unicast traffic was a direct interaction between only two of the user nodes.

Reviewing the 108 data subsets for Scenario #1 revealed the architecture that provided the best performance based on traffic type. For both broadcast and unicast messaging with and without video, the architecture using a LEO satellite with onboard routing capabilities provided the best performance. A dedicated video channel from the hub provided the lowest delay in message delivery. Broadcast messaging resulted in an average of 0.81 *s* delay due to the video injection at the hub. Unicast messaging resulted in an average of 1.61 *s* delay. See Table 14 for Scenario #1 message delivery method simulation results.

Table 14. Scenario #1 Message Delivery Method Performance Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 1** | **BROADCAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data Rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Yes / Dedicated** | **Broadcast** | **0.813** | **0.045** | **0.000** | **0.029** |
| | | 2 | .15 | [1024/1024] | Not Enabled | Broadcast | 0.813 | 0.045 | 0.000 | 0.030 |
| | | 3 | .15 | [1024/1024] | Yes/Shared | Broadcast | 0.813 | 0.045 | 0.000 | 0.031 |
| | | 4 | .25 | [1024/1024] | Yes/Shared | Broadcast | 1.015 | 0.062 | 0.000 | 0.039 |
| | | 5 | .25 | [1024/1024] | Yes / Dedicated | Broadcast | 1.015 | 0.062 | 0.000 | 0.040 |
| | **UNICAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Yes / Dedicated** | **Unicast** | **1.610** | **0.149** | **0.021** | **0.025** |
| | | 2 | .15 | [1024/1024] | Yes/Shared | Unicast | 1.611 | 0.008 | 0.000 | 0.004 |
| | | 3 | .15 | [1024/1024] | Not Enabled | Unicast | 1.614 | 0.005 | 0.000 | 0.003 |
| | | 4 | .15 | [512/1024] | Not Enabled | Unicast | 1.860 | 0.143 | 0.000 | 0.025 |
| | | 5 | .25 | [1024/1024] | Yes / Dedicated | Unicast | 2.010 | 0.183 | 0.033 | 0.029 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

Further analysis of Scenario #2 investigated the performance difference between the broadcast and unicast traffic when there was no video traffic shared in the mission set. There were 36 data subsets in this scenario which, like the results for Scenario #1, also showed that using an LEO satellite with onboard routing capabilities provided the best performance. Broadcast messaging resulted in an average of 1.18 *s* delay while unicast messaging resulted in average of 1.61 *s* delay. See Table 15 for Scenario #2 message delivery method simulation results.

Table 15. Scenario #2 Message Delivery Method Performance Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 2** | **BROADCAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Not Enabled** | **Broadcast** | **1.184** | **0.025** | **0.000** | **0.025** |
| | | 2 | .25 | [1024/1024] | Not Enabled | Broadcast | 1.386 | 0.039 | 0.000 | 0.035 |
| | | 3 | .15 | [512/1024] | Not Enabled | Broadcast | 1.435 | 0.044 | 0.000 | 0.035 |
| | | 4 | .15 | [1024/512] | Not Enabled | Broadcast | 1.440 | 0.073 | 0.000 | 0.046 |
| | | 5 | .30 | [1024/1024] | Not Enabled | Broadcast | 1.487 | 0.048 | 0.000 | 0.038 |
| | **UNICAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Not Enabled** | **Unicast** | **1.612** | **0.157** | **0.000** | **0.036** |
| | | 2 | .25 | [1024/1024] | Not Enabled | Unicast | 2.012 | 0.118 | 0.028 | 0.031 |
| | | 3 | .15 | [512/1024] | Not Enabled | Unicast | 2.110 | 0.123 | 0.001 | 0.036 |
| | | 4 | .30 | [1024/1024] | Not Enabled | Unicast | 2.212 | 0.136 | 0.011 | 0.027 |
| | | 5 | .15 | [1024/512] | Not Enabled | Unicast | 2.360 | 0.225 | 0.001 | 0.044 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

Analysis of Scenario #3 included 108 network configurations, which included all assets from Scenarios #1 and #2. Performance between the broadcast and unicast traffic was the best when video traffic was not enabled. With video services not provided, the average delay of broadcast messages was 1.18 *s* and unicast messaging was 1.61 *s*.

With video services enabled, broadcast messaging was best performed with a shared channel using an LEO satellite-based network routing architecture. These results were unexpected and further analysis would be needed to provide a deeper understanding of that performance. The expected result was that the network configuration for Scenario #3 should have ranked third. This would correlate with the findings from the first two scenarios, justifying the need for a dedicated video broadcast channel.

It was also noticed that unicast messaging increased time delays. This was due to the hub routing. Once video traffic was injected at the hub, it was processed to route the feeds to a dedicated network channel, creating a 0.1 *s* broadcast and 0.2 *s* unicast delay increase.

For Scenario #3, using an LEO based satellite network routing architecture is recommended with a dedicated video channel. See Table 16 for Scenario #3 message delivery method simulation results.

Table 16. Scenario #3 Message Delivery Method Performance Summary

|  |  |  |  |  |  |  | MOE -1 |  | MOE -2 |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 3** | **BROADCAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
|  |  | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Not Enabled** | **Broadcast** | **1.184** | **0.045** | **0.000** | **0.030** |
|  |  | 2 | .15 | [1024/1024] | Yes/Shared | Broadcast | 1.212 | 0.045 | 0.000 | 0.031 |
|  |  | 3 | .15 | [1024/1024] | Yes / Dedicated | Broadcast | 1.212 | 0.045 | 0.000 | 0.031 |
|  |  | 4 | .25 | [1024/1024] | Not Enabled | Broadcast | 1.386 | 0.062 | 0.000 | 0.039 |
|  |  | 5 | .15 | [512/1024] | Not Enabled | Broadcast | 1.436 | 0.096 | 0.000 | 0.044 |
|  | **UNICAST MESSAGING** | Performance Ranking | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Type (Broadcast or Unicast) | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
|  |  | **1 (Best Performance)** | **.15** | **[1024/1024]** | **Not Enabled** | **Unicast** | **1.613** | **0.118** | **0.000** | **0.022** |
|  |  | 2 | .15 | [1024/1024] | Yes / Dedicated | Unicast | 1.821 | 0.131 | 0.000 | 0.029 |
|  |  | 3 | .15 | [1024/1024] | Yes/Shared | Unicast | 1.821 | 0.154 | 0.002 | 0.033 |
|  |  | 4 | .25 | [1024/1024] | Not Enabled | Unicast | 2.012 | 0.168 | 0.018 | 0.032 |
|  |  | 5 | .30 | [1024/1024] | Not Enabled | Unicast | 2.214 | 0.157 | 0.006 | 0.038 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

### *c. ExtendSim Results (Overall)*

Reviewing all three scenarios and the number of network configuration permutations, each case resulted in a LEO-based network routing architecture using a dedicated video channel. As network nodes are added to the architecture, delays are increased. In the model used for this capstone, the traffic delays increased an average of 0.21 *s* when adding two user nodes.

Based on initial calculations, the expected delays for a message size of fewer than 47 *Bytes* would result in a 1.6 *s* delay for a SATCOM with onboard network routing services versus 2.0 *s* when using a bent pipe requiring an LCS relay.

Should encryption be required for data traffic that is not implementable on the SATCOM payload, additional traffic delays would be expected. In addition, if the encryption algorithm changes, the result is an increase of payload size due to the encryption and an expected increase in message delivery delays.

It is recommended that interfacing systems use efficient, low data messaging to reduce overall data payload size to accommodate increasing encryption and future network control overhead. By reducing data demands and overhead, stakeholders will be able to diversify their communication options. In the case where higher frequency spectrum services are available, the performance would be greatly improved over the base. Likewise, performance would be expected to be better if the SATCOM transport exceeds the minimum bandwidth requirements. Though more bandwidth seems attractive, the overall number of users supported on the transport services should be considered. Neither supportability of scaled users nor encryption effects were analyzed in this report.

See Table 17 for the modeling and simulation results summary.

## Table 17. Modeling and Simulation Results Summary

| | | | | | | | MOE -1 | | MOE -2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **SCENARIO 1** | **Overall** | Scenario Performance Ranking | Number of Platforms in Scenario | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | 1 | 5 | .15 | [1024/1024] | Yes / Dedicated | 1.610 | 0.149 | 0.021 | 0.226 |
| | | **2 (Best Performance)** | | **.15** | **[1024/1024]** | **Yes/Shared** | **1.611** | **0.045** | **0.000** | **0.056** |
| | | 3 | | .15 | [1024/1024] | Not Enabled | 1.614 | 0.045 | 0.000 | 0.056 |
| | | 4 | | .15 | [512/1024] | Not Enabled | 1.860 | 0.143 | 0.000 | 0.212 |
| | | 5 | | .25 | [1024/1024] | Yes / Dedicated | 2.010 | 0.183 | 0.033 | 0.264 |
| | | | | | | | MOE -1 | | MOE -2 | |
| **SCENARIO 2** | **Overall** | Scenario Performance Ranking | Number of Platforms in Scenario | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | 6 | **.15** | **[1024/1024]** | **Not Enabled** | **1.612** | **0.157** | **0.000** | **0.211** |
| | | 2 | | .25 | [1024/1024] | **Not Enabled** | 2.012 | 0.118 | 0.028 | 0.176 |
| | | 3 | | .15 | [512/1024] | Not Enabled | 2.110 | 0.123 | 0.001 | 0.201 |
| | | 4 | | .30 | [1024/1024] | Not Enabled | 2.212 | 0.136 | 0.011 | 0.155 |
| | | 5 | | .15 | [1024/512] | Not Enabled | 2.360 | 0.225 | 0.001 | 0.248 |
| | | | | | | | MOE -1 | | MOE -2 | |
| **SCENARIO 3** | **Overall** | Scenario Performance Ranking | Number of Platforms in Scenario | SATCOM Delay (Second) | SATCOM Data rate [FWD Link / RTN Link] (Bytes/Second) | Video Channel [Yes or No/ Dedicated or Shared] | Message Delay (Seconds) [Average] | Message Delay (Seconds) [Standard deviation] | Message Interval (Seconds) [Average] | Message Interval (Seconds) [Standard Deviation] |
| | | **1 (Best Performance)** | 7 | **.15** | **[1024/1024]** | **Yes / Dedicated** | **1.821** | **0.131** | **0.000** | **0.203** |
| | | 2 | | .15 | [1024/1024] | Yes/Shared | 1.821 | 0.154 | 0.002 | 0.236 |
| | | 3 | | .15 | [1024/512] | Yes / Dedicated | 2.460 | 0.192 | 0.041 | 0.255 |
| | | 4 | | .15 | [1024/512] | Yes/Shared | 2.460 | 0.228 | 0.000 | 0.352 |
| | | 5 | | .25 | [1024/1024] | Yes / Dedicated | 2.510 | 0.152 | 0.037 | 0.211 |

Note: SATCOM Delay represents: LCS Hub w/GEO Satellite (0.5 *s*), GEO Satellite w/ integrated Hub (0.25 *s*), LCS Hub w/LEO Satellite (0.30 *s*), and LEO Satellite w/ integrated Hub (0.25 *s*)

## G. NETWORK RELIABILITY

The physical layer reliability of both the wireless mesh and star networks were calculated using reliability block diagrams (RBDs). RBDs are models that display the networks in a series-parallel block configuration that helps to assign reliability at the component level. (Blanchard and Fabrycky 2011).

### 1. Star Network Calculations

The RBD for the star topology is shown in Figure 31.

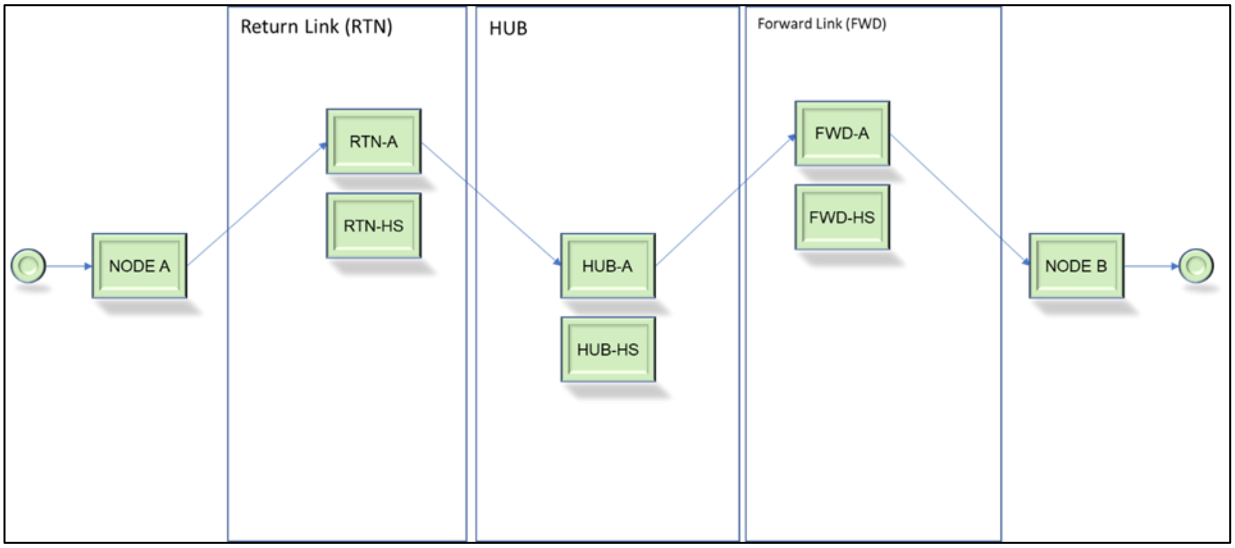


Figure 31. Reliability Block Diagram for Star Configurations

Data packets in a star network traveling from node (A) to node (B) would take the path shown. The reliability for this message configuration was calculated using a series component relationship shown in Equation 4.

$$P_{HubRelay} = P_{NodeA} \times P_{RTN} \times P_{HUB} \times P_{FWD} \times P_{NodeB}$$

Equation 4. SATCOM Star Network Reliability

This series network was divided into five separate nodes. As depicted in Figure 31, the return link, hub, and forward link all have standby redundancy. If the node were to fail, there would be a spare available to take its place to keep the data packages flowing. The equation for nodes: RTN, HUB, FWD are shown in Equation 5, which calculates the reliability of that node with one standby spare.

$$P_{STANDBY} = e^{-\lambda\tau} + \lambda\tau e^{-\lambda\tau}$$

Equation 5. Reliability Calculation of Network Nodes with One Standby Spare

The reliability was calculated using the Poisson distribution where ($\lambda$) is the failure rate, and ($\tau$) is the mission timing in minutes. Nodes (A) and (B) do not have any redundancy and the reliabilities can be found using Equation 6. If nodes (A) and (B) fail, there would be no back-up to replace them and the message link would fail.

$$P_{A,B} = e^{-\lambda\tau}$$

Equation 6. Reliability Calculation of User Nodes

### 2. Mesh Network Calculations

The RBD for the WMN topology is shown in Figure 32. Nodes (A) and (B) are capable of tracking three LEO satellites at any given time. Calculations for the mesh network assumes that the primary communications will be provided by one of the satellites and an alternate in view. The primary satellite transporting the network has communication coverage that would enable network bridging between nodes (A) and (B). The cross links between satellites are used for transitioning network sessions to the incoming satellite on the same orbiting plain.

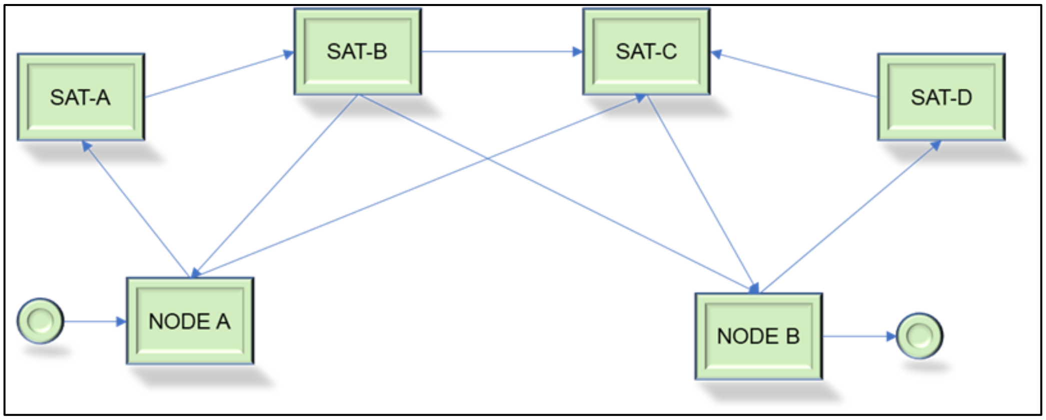


Figure 32. RBD for a Wireless Mesh Network

A data packet moving from node (A) to node (B) could follow the path shown in Figure 32. In the scenarios described in this study, the geographic separation of supporting assets was connected by the same satellite as the forward operating units. The reliability of this network configuration is calculated using Equation 7. The primary satellite will failover to the alternate as it transitions to the mission area, therefore $P_{SAT}$ is calculated using the same equation as $P_{STANDBY}$, shown in Equation 5 in the previous section.

$$P_{Mesh} = P_{NodeA} \times P_{NodeB} \times P_{SAT}$$

Equation 7: Reliability Calculation of a Mesh Network

This equation shows a network that utilizes a combination of both series and parallel components. Nodes (A) and (B) are in series with a total of two satellite nodes in parallel, SAT-B and SAT-C, where one of the satellites is in standby for redundancy. The details of each node calculation are further explained below.

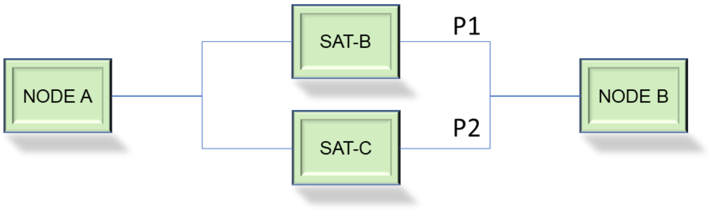


Figure 33. Mesh Network Node Breakdown

The mesh reliability was calculated by dividing the entire network into different path links. In this case, nodes (A) and (B) have no redundancy and the reliability was calculated using Equation 3 in the previous section. Figure 33 shows a calculation example for a mesh path link that supports the scenarios within this study. This figure depicts a data packet that leaves node (A) and travels from SAT-B to node (B) in a series component configuration.

### 3. Results

The reliability results for both the star and mesh are shown in Figure 34.

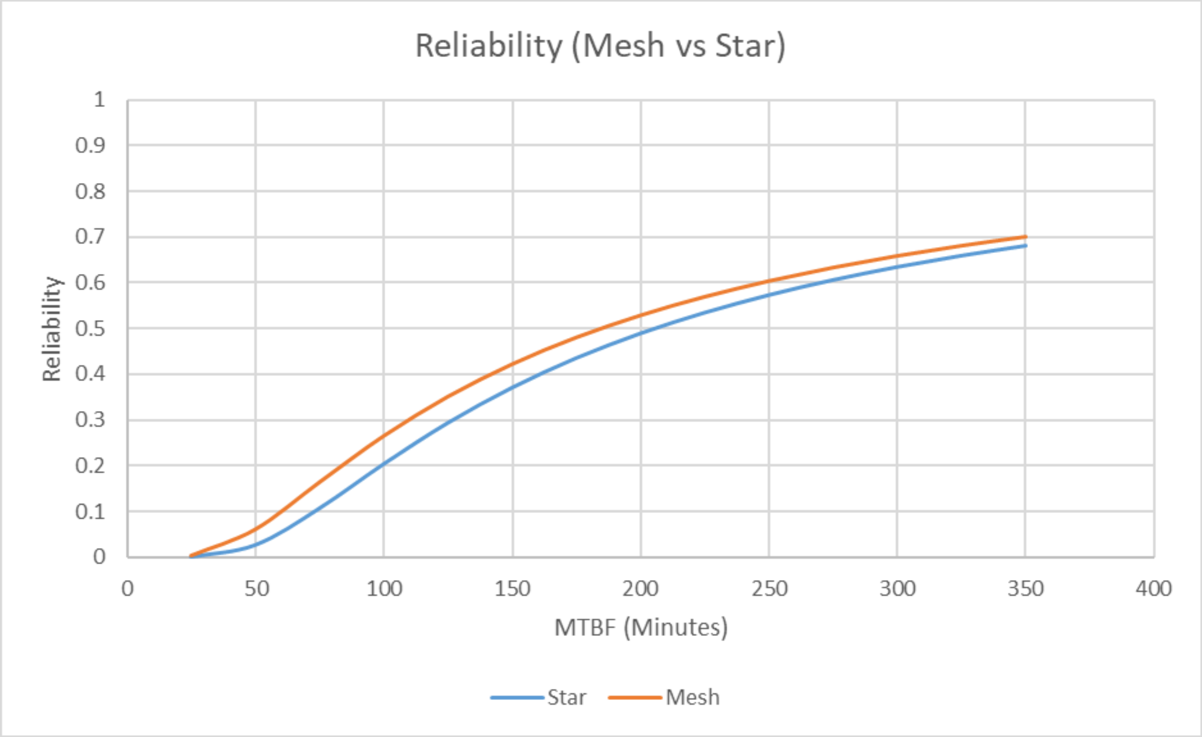


Figure 34. Reliability Results for Star and Mesh Networks

This chart shows the reliability for both a star and mesh network as a function of the mean time between failure (MTBF). In this calculation, a 60-*minute* mission timing was used and the MTBF was increased at a constant rate of 25 *minutes* from 25-350 *minutes*. The results show that the mesh network maintained higher reliability than the star network. The reliability difference between the two network types was at its greatest when MTBF approached 100 *minutes*. At 100 *minutes* MTBF, the reliabilities were found to be 0.20 for the star network and 0.26 for the mesh network.

# VI. CONCLUSIONS AND RECOMMENDATIONS

## A. STUDY PURPOSE

The purpose of this study was to determine which network architecture, star or mesh, would more effectively support a JF DMO offensive strike. In a review of the operational mission objectives and the variations of joint assets supporting each scenario, this study focused on the interfaces between assets and the communications network.

## B. CONCLUSIONS

The ExtendSim model applied to both the mesh and the star analysis of the SATCOM links and did not discriminate between the two network architectures. The design requirements for this study focused on the network configuration, the impact to message latency, network jitter, and architectural reliability. For network communications to be effective, the architecture design at both the physical and network layer was important to correlate. Focusing on SATCOM communication, the physical layer reliability for both star and mesh networks had similar trends and resulted in comparable performance with an estimated 3% difference in reliability.

Network configurations had the most impact on the overall performance based on the application data requirements for interfacing with dependent joint assets. Delay and network reliability for both unicast and broadcast traffic were performances measured in the network configurations. Critical design factors that impacted the system performance were related to the data transition requirement, message transmission unit sizing, messaging overhead for network control, encryption, and emission control.

Network design considerations need to support the data requirement and exchanges for application and services to be effective. To enhance JF DMO, strong consideration should be given to the messaging between assets to optimize the amount of data that needs to be transmitted. The message size directly impacted network configuration performance. Network responses were based on how each network handled messaging transmission, data rates, location of network controllers, and how external data was injected and distributed over the network.

### 1. Timing Delay

For both Scenarios #1 and #2, the network architecture that provided the lowest timing delays included an LEO satellite service with on-board routing capabilities. Utilizing this network configuration, broadcast messages had an average delay time of 0.81 *s* while a unicast message had an average delay of 1.61 *s*. The main cause of delays in this scenario was related to the network data rates and whether video broadcasts were on a dedicated network.

For Scenario #3, the best configuration with video-enabled was also an LEO satellite-based network routing architecture. Without video-enabled, broadcast messages had an average delay time of 1.81 *s* while a unicast message had an average delay of 1.61 *s*. Further work should be done to determine why the modeling and simulation showed that a shared video channel for this scenario was more efficient than a dedicated channel.

### 2. Network Jitter

Network jitter measures the message reporting timing arrival rate. It describes how effective the network is at synchronizing the messages sent and received by a communications system. In all three scenarios, the network jitter was measured by sending out the data packets at a rate of 1 per second and measuring the variation in the arrival time.

The variable that had the largest effect on message time arrival was the messaging type. This is related to whether the message was sent through a unicast or broadcast transmission. In Scenario #1, the lowest measured variation was 0 *s* with a standard deviation of 0.029 *s*. In Scenario #2, where there was no video capability, the lowest measured message inter-arrival variation was measured at 0 *s* with a standard deviation of 0.025 *s*. In Scenario #3, the lowest measured variation was 0 *s* with a standard deviation of 0.03 *s*.

### 3. Reliability

Reliability is generally defined in terms of the probability in which a system successfully completes its mission for some time duration (Blanchard and Fabrycky 2011).

The operational reliability of a star network was compared to a mesh network. Here, reliability as a MOP was dependent upon many factors including the number of networked nodes, MTBF, and any availability of redundancy.

This analysis assessed the probability that one data packet would successfully flow from node (A) to node (B), its intended target. In the case of the star, the data packet needed to traverse five links using a point-to-point flow. The FWD link, HUB, and RTN link all possessed standby redundancy, so a spare was available if that link failed. If node (A) or (B) were to fail, the message would fail and not reach its intended target.

For the mesh network, the data packet was assessed for successful flow from node (A) to node (B). The data packet was sent by node (A) as a broadcast message type through eight different paths in order to be received by node (B). The eight identified message paths were each configured in a parallel configuration with an operational redundancy. All eight paths were utilized at the same time in order to get the message to node (B). If anyone of the paths were to fail, the message would just flow through one of the other seven paths.

The results from the analysis showed that the mesh network was more reliable at sending data packets than the star. For a 60-*minute* mission, the peak reliability difference was found when the MTBF approaches 100 *minutes*, which corresponds to a failure rate of 0.01 per *minute*. The mesh network maintained a slightly improved reliability for the 60-*minut*e mission.

## C. RECOMMENDATIONS FOR FUTURE WORK

- Determine optimal battlefield reporting for higher confidence in human decision making based on situational awareness.
- Research scalable SATCOM networks to support larger user bases into the thousands.
- Research predictive algorithms to predict position reporting with minimal data reporting from users.

- Research benefits of moving network routing capabilities from RF communication systems into warfighting computing devices using software-defines networking technologies.

- Research how evolving encryption solutions impact the effectiveness of the tactical network system, using commercial supplied mesh network services

- Research and enhance joint messaging standards (i.e. MIL-STD-6017) and how it impacts network design and transport architectures

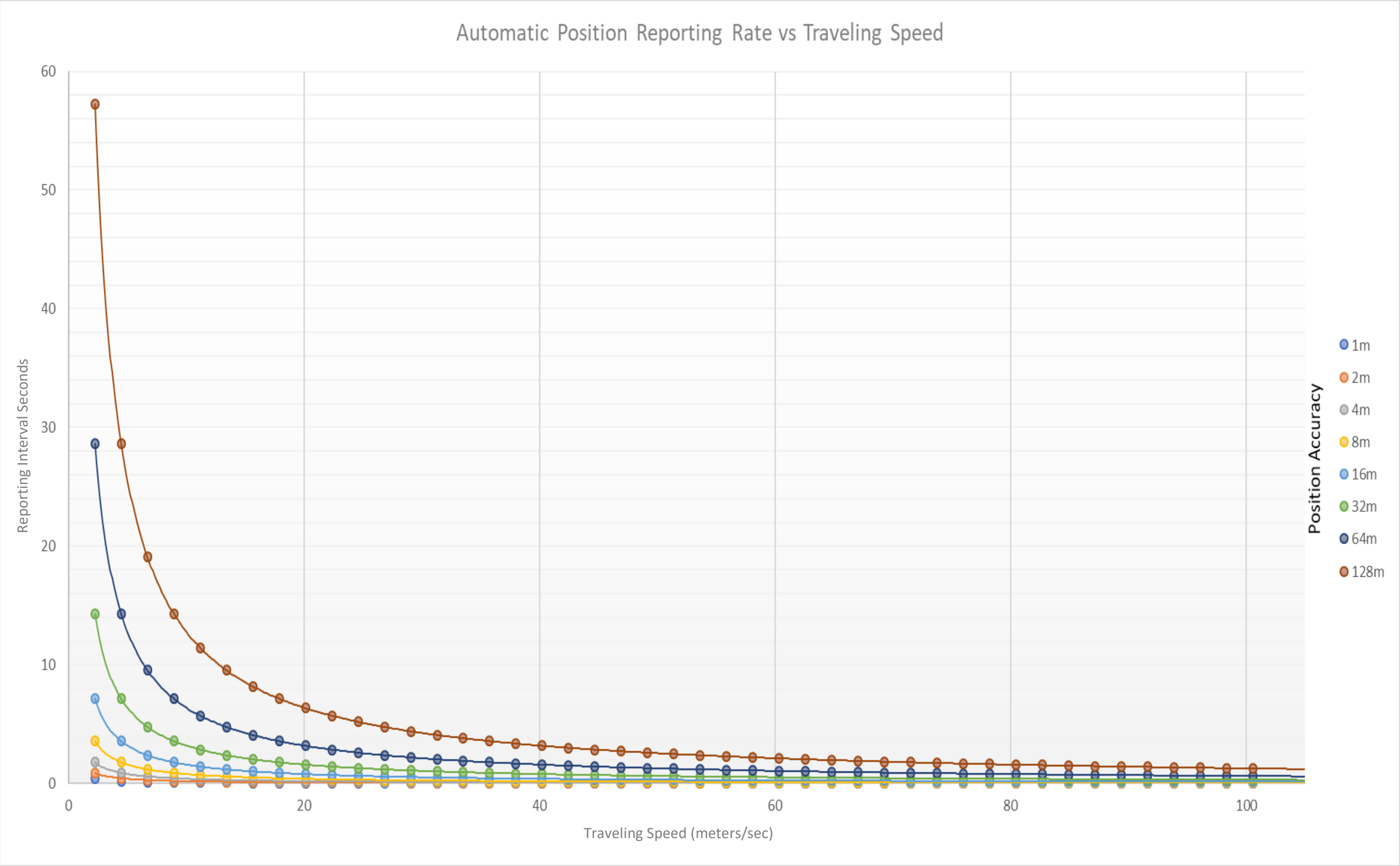
- Research the benefits of using broadcast service protocols (IP and Non-IP) and architecture recommendations to enhance mix mode transmissions for enhancing voice and video content dissemination in tactical environments.

# APPENDIX: POSITION REPORTING VERSUS POSITION ACCURACY DATA

Calculated time of reporting is based on the position accuracy (Columns 1-128m) and the speed of travel (Rows 2-142 *meters/second*).

*Table: Automatic Position Reporting Rate based on distance traveled*

| ***Velocity*** | | | | ***Position Accuracy (m)*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***mph*** | ***kpm*** | ***Knots*** | ***meters/sec*** | ***1*** | ***2*** | ***4*** | 8 | ***16*** | ***32*** | ***64*** | ***128*** |
| 5 | 8 | 4 | 2 | 0 | 1 | 2 | 4 | 7 | 14 | 29 | 57 |
| 10 | 16 | 9 | 4 | 0 | 0 | 1 | 2 | 4 | 7 | 14 | 29 |
| 15 | 24 | 13 | 7 | 0 | 0 | 1 | 1 | 2 | 5 | 10 | 19 |
| 20 | 32 | 17 | 9 | 0 | 0 | 0 | 1 | 2 | 4 | 7 | 14 |
| 25 | 40 | 22 | 11 | 0 | 0 | 0 | 1 | 1 | 3 | 6 | 11 |
| 30 | 48 | 26 | 13 | 0 | 0 | 0 | 1 | 1 | 2 | 5 | 10 |
| 35 | 56 | 30 | 16 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 8 |
| 40 | 64 | 35 | 18 | 0 | 0 | 0 | 0 | 1 | 2 | 4 | 7 |
| 45 | 72 | 39 | 20 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 6 |
| 50 | 80 | 43 | 22 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 6 |
| 55 | 89 | 48 | 25 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 5 |
| 60 | 97 | 52 | 27 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 5 |
| 65 | 105 | 56 | 29 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 |
| 70 | 113 | 61 | 31 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 |
| 75 | 121 | 65 | 34 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 4 |
| 80 | 129 | 70 | 36 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 4 |
| 85 | 137 | 74 | 38 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 |
| 90 | 145 | 78 | 40 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 |
| 95 | 153 | 83 | 42 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 |
| 100 | 161 | 87 | 45 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| 105 | 169 | 91 | 47 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| 110 | 177 | 96 | 49 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| 115 | 185 | 100 | 51 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 120 | 193 | 104 | 54 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 125 | 201 | 109 | 56 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 130 | 209 | 113 | 58 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 135 | 217 | 117 | 60 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 140 | 225 | 122 | 63 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| 145 | 233 | 126 | 65 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 150 | 241 | 130 | 67 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 155 | 249 | 135 | 69 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 160 | 257 | 139 | 72 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 165 | 266 | 143 | 74 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 170 | 274 | 148 | 76 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 175 | 282 | 152 | 78 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 180 | 290 | 156 | 80 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 185 | 298 | 161 | 83 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 190 | 306 | 165 | 85 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 195 | 314 | 169 | 87 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 200 | 322 | 174 | 89 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 205 | 330 | 178 | 92 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 210 | 338 | 182 | 94 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 215 | 346 | 187 | 96 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 220 | 354 | 191 | 98 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 225 | 362 | 196 | 101 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 317 | 510 | 275 | 142 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |


Automatic Position Reporting Rate vs Traveling Speed
Reporting Interval Seconds
60
50
40
30
20
10
0
0
20
40
60
80
100
Traveling Speed (meters/sec)
Position Accuracy
1m
2m
4m
8m
16m
32m
64m
128m

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