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THESIS

**DYNAMIC NETWORK MANAGEMENT
THROUGH HYPERNODE DECISION SUPPORT**

by

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June 2020

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**DYNAMIC NETWORK MANAGEMENT THROUGH HYPERNODE
DECISION SUPPORT**

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ABSTRACT

The dynamic nature of the future operating environment requires fast-paced decision-making supported by robust, resilient communication networks. We investigate the concept of hypernodes to perform certain network management functions at the tactical edge of this network. This research advances the hypernode concept by generating and testing an algorithm that continuously calculates successive relay positions to support tactical-unit communication networks. Through a phased approach to experimentation including metric identification, algorithm generation, and lab and field testing, this research answers the question, “How can an autonomous aerial hypernode contribute to information flow optimization in a tactical network?” We demonstrate that a hypernode could calculate a feasible relay position to maintain different levels of quality of service between multiple disparate tactical ground units. The findings support that a hypernode is capable of calculating feasible relay positions for supported network nodes in a tactical environment and recommend that future research pursue automating the hypernode as a mission-control payload aboard an autonomous aerial platform.

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LIST OF ACRONYMS AND ABBREVIATIONS

BLOS	Beyond Line of Sight
BLT	Battalion Landing Team
bps	bits per second
C2	Command and Control
CBR	Case-Based Reasoning
CM	Configuration Management
COC	Combat Operations Center
CP	Command Post
CPG	Commandant's Planning Guidance
dB	Decibel
DBS-PSI	Database Search Parameter Space Investigation
DOD	Department of Defense
EM	Electromagnetic
eTOM	Enhanced Telecommunications Operations Map
FAA	Federal Aviation Administration
FCAPS	Fault management, Configuration management, Accounting management, Performance management, and Security management
FCC	Federal Communications Commission
FCS	Flight Control System
GB	GigaByte
GHz	GigaHertz
GPS	Global Positioning System
HQMC	Headquarters United States Marine Corps
IETF	Internet Engineering Task Force
IP	Internet Protocol
IT	Information Technology
ITIL	Information Technology Infrastructure Library
ITU	International Telecommunication Union
JIFX	Joint Interagency Field Experimentation
JOC	Joint Operations Center

Kbps	Kilobit per second
MANET	Mobile Ad Hoc Network
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MIB	Management Information Base
MOC	Marine Corps Operating Concept
NOC	Network Operations Center
OSI	Open Systems Interconnection
PDU	Protocol Data Unit
PLI	Position Location Information
PSI	Parameter Space Investigation
QOS	Quality of Service
RAM	Random Access Memory
RBR	Rule-Based Reasoning
RFC	Request for Comments
RTT	Round Trip Time
SD	Secure Digital
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SOF	Special Operations Force
TMN	Telecommunications Management Network
TOM	Telecommunications Operations Map
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UnDP	Universal Device Poller
USB	Universal Serial Bus
USMC	United States Marine Corps
VIRT	Valued Information at the Right Time
WMN	Wireless Mesh Network

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I. INTRODUCTION

There is much discussion surrounding the new paradigm of warfare driven by recently developed enemy precision fires and information warfare capabilities. The new operating environment requires fast-paced command and control (C2) decision making supported by network connectivity providing access to vital information (Berger, 2019). The Commandant's Planning Guidance (CPG) (Berger, 2019) requires that C2 systems operate resiliently, especially in contested network environments, to protect the commander's ability to act upon valuable information. This resiliency must be properly aligned with bandwidth availability at the tactical edge of the battlespace and requires a "ruthless prioritization" of information flow in the operating environment (Headquarters United States Marine Corps [HQMC], 2016, p. 17). The adversaries' desire to target our forces in bulk requires that our forces operate in a distributed manner to protect critical assets (Berger, 2019). While the future operating environment is distributed and dynamic, the network architecture must remain interoperable and connected; as such, "preserving the ability to command and control in a contested information network environment is paramount" (Berger, 2019, p. 12). The threats identified also limit the use of manned platforms, meaning an increase in unmanned systems and a corresponding increase in the density of, and our dependence on, proactive network management.

The Marine Corps Network Modernization Primer (Headquarters United States Marine Corps [HQMC], 2019), which stemmed from discussions of the "Objective Network" and is informed by the CPG, discusses a future network designed to support the information flow required by the CPG while streamlining the network from garrison to tactical domains. The Marine Operating Concept (MOC) (HQMC, 2016) called for the development of capable unmanned aerial systems to expand our C2 capabilities throughout an increasingly dynamic operating environment. The CPG (Berger, 2019, p. 9) states that "we must create systems that are resilient and match our warfighting approach in order to protect our ability to make decisions that generate tempo." The operating environment identified in the CPG will necessitate that we employ these unmanned systems in support of C2 and network operations. The accelerated decision-making speed in this environment

requires consistent network connectivity. There is not time to allow a network to lag and fail when a commander needs to communicate with distributed units whose own decision cycles are measured in minutes, not hours. This means that tactical edge networks must be consistently monitored, and dynamically managed to ensure sufficient connectivity—a task current network management tools are not adequately capable of completing.

Tactical Marine Corps networks have historically operated from the Network Operations Center (NOC) under direct human control. Network decisions in these NOCs are informed by decision support tools, such as SolarWinds, which provide insight into network performance status. While these decision support tools provide near real time network performance statistics, human reaction time is delayed by the time required to process, comprehend, and make sense of an anomaly or required change. This often results in reactive network management, vice dynamic network adjustments. In this sense, *reactive* means decision making to adjust once a failure event has already occurred, while *dynamic* means analyzing the environment and making incremental adjustments (or prescheduled changes) to maintain required quality of service or prevent a failure event from occurring. Future NOCs must conduct more dynamic, adaptive and resilient network management than can be accomplished through human inputs alone. If our networks are to remain effective and resilient in distributed, contested environments, they must integrate the capability for network nodes to optimize both network traffic flow and architecture to provide the most effective communications given the specific situation.

A. PROBLEM

The USMC “future network” requires the capability to control communications nodes and links through application and data flow-based adaptation that will enable the network decision-making process to maximize communications capability and create tempo for the force. The MOC (HQMC, 2016) defines a requirement for a network capable of resiliency in austere, contested, tactical environments. This network may span multiple units dispersed across multiple domains, and must remain fully capable while adapting to dynamic conditions, optimizing overall performance, and retaining a low probability of detection (HQMC, 2016). However, existing tactical network controls cannot

automatically adjust communication nodes and links, which degrades network management ability, yielding an advantage to our adversary, and incurring risk to agile C2.

One possible approach to solving this challenge was introduced by Bordetsky and Hayes-Roth (2007) who defined an additional network layer that would extend the Open Systems Interconnection (OSI) model. They proposed the concept of “hyper-nodes” that would evaluate and optimize network productivity in an effort to meet Service Level Agreement (SLA) requirements. The hyper-node concept was refined by Gateau (2007) as nodes that are capable of understanding the network service capabilities of all other nodes in a network. Gateau furthered the idea that hypernodes accessing Management Information Base (MIB) variables could potentially extend network links or direct network changes based on real time knowledge of network connectivity and performance. These hypernodes would provide the NOC the capability to automatically execute selected functions that have normally been accomplished by humans. This would help to achieve network responsiveness consistent with the speed of change in today’s fast-paced operating environments. While multiple examples of research have sought to optimize ad hoc networks using aerial nodes, the concept of optimization using aerial hypernodes employing a combination of SNMP MIBs, RBR, and CBR decision-making tools is yet to be explored. In this thesis, I choose to use Gateau’s (2007) spelling of “hypernode” instead of the original spelling “hyper-node” used by Bordetsky and Hayes-Roth (2007). I advance the concept of hypernodes by applying it to aerial hypernodes to improve capabilities among mobile ground-based network nodes.

B. RESEARCH OBJECTIVE

I advance the study of hypernodes by developing and testing an algorithm by which a hypernode performs a specific NOC management function. By demonstrating a prototype capability to automate the NOC function, I suggest that it is possible for machine teaming with human decision makers to enhance network management processes to optimize connectivity in contested operational environments. This capability could lead to more adaptive and resilient communication networks.

The research questions addressed are:

Central Research Question: How can an autonomous aerial hypernode contribute to information flow optimization in a tactical network?

Supporting Research Questions:

1. What NOC network management functions could a hypernode perform effectively?
2. What metrics are necessary for a hypernode to manage tactical network data flow?

The term optimization in the central research question is defined as allocating limited resources against multiple requirements most efficiently while achieving the best operational results. The solution to that research question will involve developing an algorithm driven by network performance data captured in support of the metrics identified in Supporting Research Question 2. Optimization and the requirement for an optimal solution is further discussed in Chapter III. In order to fully address both of these research questions, it will first be necessary to select from among various potential NOC decision-making criteria, identified through the lens of network management while answering Supporting Research Question 2.

C. SCOPE

This research seeks to provide a proof of concept on a limited scale. I test a network that consists of fewer nodes than might be present in an actual tactical network, but that pursues the Commandant's Planning Guidance regarding focus on distribution at the squad level. This research does not address scalability to larger networks, though this should be explored through future work.

It also focuses on a specific phase of a tactical operation—post amphibious assault when a battalion is dispersing squad-level elements through the land battlespace. Though the Marine Corps typically fights from ship to shore, this research explores optimizing a network for a unit that is established ashore, and conducting distributed operations in rugged terrain.

Finally, I examine the feasibility of one aerial hypernode. Additionally, while I focus on the value and contribution of aerial hypernodes as a fundamental concept, my research is not focused on flying unmanned aircraft (UA), nor does it focus on the direct interaction between the control information produced by the hypernode algorithm and the flight controls of the aerial node. While these control integrations are possible, I leave it to future work to determine the most appropriate integration for the technologies.

D. ORGANIZATION

This thesis is composed of five chapters that outline the research process. The following is a brief overview of each chapter:

Chapter II represents a literature review and the motivation for the research topic. It addresses optimization and its application to network problem sets, and lays the foundation for the use of hypernodes in network optimization and decision support. I will discuss the use of aerial nodes as a means for network extension. Previous use of aerial nodes for interconnection of tactical networks is reviewed. Concepts associated with network management required to optimize appropriate functions are discussed.

Chapter III contains the methodology and experimentation in support of the research objectives. It presents the purpose and method behind each phase of the experimentation process, and resulting observations.

Chapter IV provides the analysis of results gained through experimentation in the context of answering the research questions.

Chapter V provides a summarization of the research, conclusions, and the contributions to theory and application. Additionally, limitations and recommendations for future research that should follow along the lines of my thesis are addressed.

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II. THEORETICAL FOUNDATION / FRAMEWORK

This chapter discusses the foundation of the research and the current background to the theory that is advanced in the experiments. It opens with a tactical vignette to better frame the reader on the intended application of the hypernode concept. It then briefly discusses the definitions and terminology associated with unmanned aircraft systems and autonomous technology, an overview of network theory and network management concepts, and a brief review of previous research along the lines of aerial communication nodes. These topic areas frame the research to determine how information flow might be optimized in tactical networks through the use of aerial (potentially autonomous) hypernodes.

A. VIGNETTE

Opening with a tactical vignette serves two purposes. First, it orients the reader to the practical problem being addressed. Second, it reinforces the scope of the research, and of the supporting review of relevant theory and prior work.

Envision a scenario wherein a Marine Expeditionary Unit (MEU) is conducting an amphibious operation against a force on a contested shore. In this scenario the MEU's mission requires aerial, surface, and land forces to coordinate directly with each other to conduct a successful landing and move inland towards a tactical objective. Once this landing occurs and the Battalion Landing Team transitions command and control from the ship to the forces ashore, control of the inland communications network passes to the ashore battalion Network Operations Center (NOC). This NOC is responsible for ensuring the adaptability, resiliency, and reliability of the battalion commander's network. This network is the direct link between the command elements and other distributed nodes as they move through the contested battlespace and engage with the enemy.

The Battalion Landing Team (BLT) commander applies the CPG to his mission and understands that the most effective way to fight in the current operating environment is through distributed operations. He has experimented with allowing his squads to employ the full level of combined arms under the guidance and coordination of his company

commanders. These squads will disperse throughout their area of operation in an effort to gain an advantage over the enemy force, while reducing the effect of enemy fire and increasing the enemy's uncertainty (Berger, 2019). However, a significant challenge that this dispersion introduces, is the network connectivity required to maintain sufficiently robust C2 channels and to disseminate intelligence to the squads in real time, particularly in rugged terrain.

The BLT communications officer is tasked with establishing a NOC that is capable of monitoring each element's connectivity and ensuring that the battalion commander's higher-priority squads are fully capable of coordinating fires and providing real-time imagery to the combat operations center (COC). The communications officer must simultaneously ensure that the other squads with lower priority are able to maintain less robust, but adequate, C2 capability to accomplish their missions. The terrain in the area of operations is unforgiving both in elevation and density of foliage, which directly impacts the communication capability of each squad as it moves about the area of operation. The result here is that communications links between squads and between the squads and the battalion COC will be unacceptably intermittent without added network capacity. The traditional means to accomplish this task is to deploy one or more man-packed or vehicular retransmission teams to act as network relays in support of the disadvantaged nodes. However, these teams are cumbersome, incur risk to the otherwise unprotected personnel, and are unable to react and reposition quickly in response to changing situations in the operational area.

A link may fail for a variety of reasons ranging from environmental factors such as rain or solar weather, terrain masking, or exceeding effective radio operating range. The communications officer's experience and expertise in NOC operations provide him with the insight that NOC crews typically monitor networks and begin troubleshooting efforts reactively, once a link has failed. With several squads dispersed throughout the area, the NOC will be required to monitor too many links to dynamically manage link status or unit priority changes—especially in the event that a particular squad becomes engaged and the commander immediately shifts priority. Through discussions with counterparts, the communications officer decides to enable a networked device to monitor specific network

performance parameters and recommend decisions in real time to maintain key network connectivity dynamically.

In future contested and distributed environments, a reactive NOC management posture will not provide the network reliability required to support the mission. The implementation of this concept could represent a leap forward in network management and dynamic relay capability for the Marine Corps. The addition of computer aided network optimization could increase future adaptability and reliability of Marine Corps networks, and the lethality and survivability of those Marines who rely on radio networks to complete their tasks in the air and on the ground.

B. OPERATIONAL CONTEXT

The Future Network, as defined by the Marine Corps Network Modernization Primer (2019), demands a focus on network tiers ranging from the tactical edge to garrison areas. This network concept is driven by decreasing bandwidth availability in the tactical fight, as demonstrated by Figure 1.

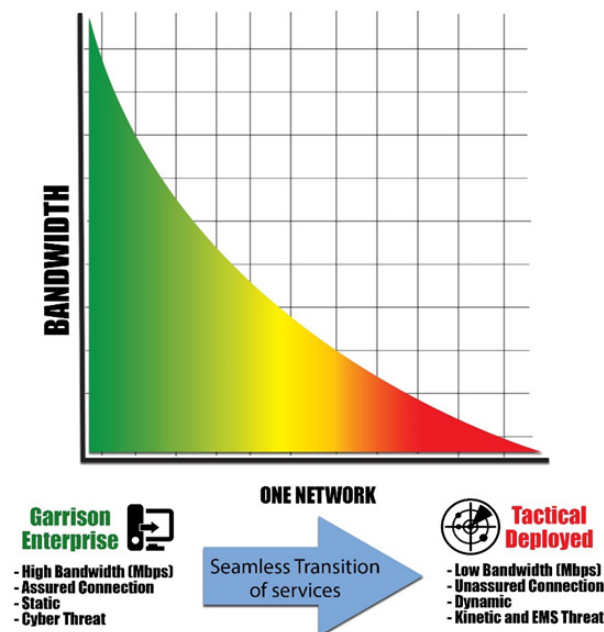


Figure 1. Future Network Tiers. Source: Marine Corps Network Modernization Primer (2019).

As seen in Figure 1, the transition of services through differing levels of bandwidth availability, drive different decision-making processes at each network tier. As an example, the 9th Communication Battalion manages the network for I Marine Expeditionary Force. The network decisions made at this tactical level are driven by network availability and supported through the use of monitoring tools such as SolarWinds. These decisions are made once the network manager recognized that there was a problem, that is, something had already gone wrong.

C. HYPERNODES

Bordetsky and Hayes-Roth (2007) defined an additive eighth layer to the traditional OSI model that allows transfer of some network management responsibility from humans to hyper-nodes. These hyper-nodes would theoretically enable networks to adapt to the speed of dynamic changes in today's contested operations. Though there is complexity in tracking statistics and packet information flow in networks of growing size, the 8th layer concept aims to reduce complexity through the use of multiple levels of analysis and optimization. By introducing the hyper-node concept, Bordetsky and Hayes-Roth (2007) sought to reduce clutter in network performance monitors by focusing only on throughput, packet loss, and response time. They then recommended comparing these performance-based observations with Quality of Service (QOS) requirements enabling hypernodes to ensure network traffic flow met the required demand and priorities. At the upper levels, established SLAs define the flow of traffic through the network. As the network size grows, each hypernode remains responsible for its section of the network with a goal of local optimization. As each hypernode optimizes its cluster, overall network performance should be enhanced.

The above concept of QOS bears further definition with respect to the value it provides to the commander. In the vignette scenario presented, we learned that dispersed squads may have different information flow requirements. From a QOS standpoint, this means there are different loads and capacities on the mobile network. The ability to allocate priorities and provide the level of performance expected from the application or platform is the definition of QOS (Natkaniec et al., 2010). Likewise, QOS is the requirements for

network transport that allow communication from source to destination in acceptable form (Asokan & Natarajan, 2010). From a commander's perspective, QOS means that the service (streaming video, chat, e-mail, etc.) performs in the expected manner when it is required. Put simply, the communication device should work as intended when needed.

The concept of Valued Information at the Right Time (VIRT) addresses concerns that in today's highly complex information networks, users may be overwhelmed due to an overabundance of information. The goal of ideal communication networks is ensuring the receipt of important information and minimizing the transmission of meaningless information (Hayes-Roth, 2006). By optimizing the value of information, one might reduce the demand on the valuable resources of communications bandwidth and processing time. When implementing the VIRT concept with the hypernode concept, it becomes necessary for the network user to understand their information requirements and publish these to the network management system for use by the NOC crew (Bordetsky & Hayes-Roth, 2007). User publication of this requirement allows the hypernodes to account for user requirements as they seek to optimize network traffic.

Gateau (2007) proposed the concept of network service aware hypernodes that understand the appropriate network variables to allow extension of a failing network. The concept he presented involves a special operations force (SOF) team that is moving further from the JOC, and reaching the extent of the range of their radios. As such, the radio link that they rely on for communication is slowly losing the ability to pass the critical traffic they require to continue their mission. Through network service aware hypernodes, the NOC learns that this link is degrading and that there is an unmanned aircraft system (UAS) with available radio in the area that can act as a relay node. The NOC is then able to request support from the UA operators to position the UA in an advantageous location and close the link to the SOF team. Gateau proposed that a better solution would be for some of the human decision making to be elevated to human-on-the-loop and for the UA to process and make some NOC decisions on its own—a true hypernode capable of taking on network management functions in support of improved information flow.

D. AUTONOMOUS UNMANNED AIRCRAFT SYSTEMS

Because my research concept considers utilizing autonomous, UA as network management hypernodes, the following subsections provide context for Unmanned Aerial Vehicles (UAVs), UA, the UAS, and UAS autonomy. This includes definitions and terminology based on doctrinal publications and the current state of autonomous aerial platforms.

1. Unmanned Aircraft Systems

The field of unmanned aircraft systems has been convoluted with redundant terms. UAVs have recently been re-termed UA and UAS. UA and UAS are preferred terms by both the Federal Aviation Administration (FAA) and Department of Defense (DOD). The most recent DOD Dictionary of Military and Related Terms (2020) defines UA and UAS by the following:

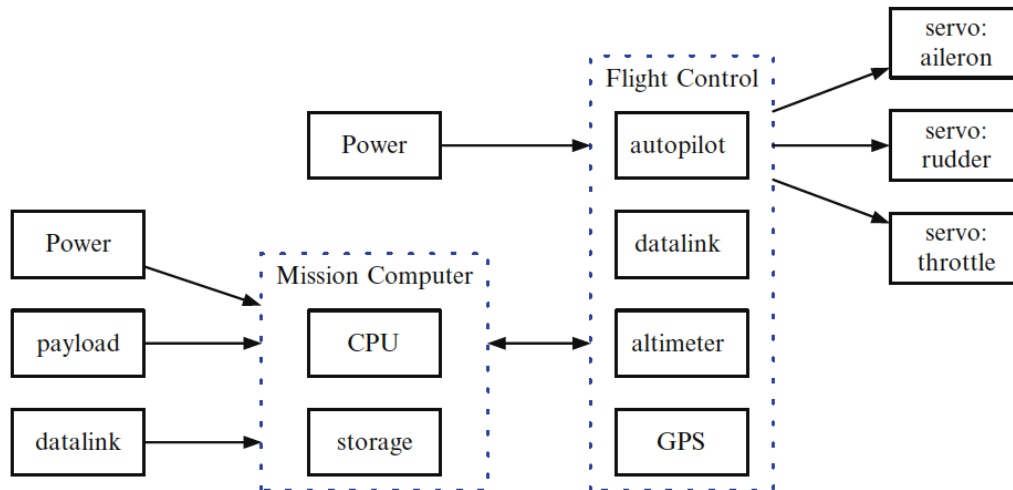
Unmanned Aircraft – An aircraft that does not carry a human operator and is capable of flight with or without human remote control. Also called UA (Office of the Chairman of the Joint Chiefs of Staff, 2020, p. 226).

Unmanned Aircraft System – That system whose components include the necessary equipment, network, and personnel to control an unmanned aircraft. Also called UAS (Office of the Chairman of the Joint Chiefs of Staff, 2020, p. 226).

During the last 20 years, modern unmanned aircraft capabilities have advanced significantly beyond the early UAS. This has happened mostly due to the advancement of enabling technologies. Quadrotors, ducted fans, blimps, and fixed-wing helicopter designs have entered the arena of UAS design (Zaloga & Palmer, 2008). Moreover, as technology has progressed, UASs are becoming increasingly valuable outside of the military domain. Weather, agriculture, and wildlife monitoring; infrastructure inspection; networking and telecommunication; package delivery; space travel; and disaster relief are a few recent non-military applications of UASs. As technology continues to progress, the airworthiness and applicability of unmanned systems will inevitably increase. The potential of unmanned aviation in military and civilian domains cannot be ignored.

2. Theoretical System

While my concept uses aerial nodes to support disadvantaged network nodes, the idea of “full autonomy” does not necessarily apply. I propose a system where the aerial node is able to sense the network devices it is connected to and make self-adjustments based on priority and information parameters presented by a monitoring NOC. In this sense, the aerial node is an extension of human decision making at the NOC and part of the NOC management team. Pippin (2015) recommends a frontseat-backseat systems architecture for supporting autonomous UASs. Essentially, the frontseat driver serves as the Flight Control System (FCS), while the backseat driver serves as the mission controller. This frontseat-backseat systems architecture paradigm disassociates low-level flight control from higher-level autonomous decision making. Because the mission control systems within the frontseat-backseat architecture can be tailored to meet our unique pre-established autonomous network management requirements, we submit it is an ideal architecture for our use case. Figure 2 illustrates the concept of this systems architecture.



The recommended frontseat-backseat system for use in autonomous UASs using separate flight control and autonomous computers. This separation allows logical and physical components to support designed use for the system, where flight control is functional on its own, but can be supported by mission control.

Figure 2. Frontseat-backseat System Architecture for Autonomous UASs.
Source: Pippin (2015).

Here the frontseat, or FCS, handles the autopilot and Global Positioning System (GPS), while the backseat, or mission processor, handles the processing requirements of autonomous behaviors. The key to a frontseat-backseat systems architecture is the separation of vehicle autonomy from vehicle control.

E. NETWORKING CONCEPTS

As networks and internetwork usage became commonplace, the requirement for network management capability developed. Network management is simply the human effort to optimize network performance through observation of network performance. The most simple definition of network management involves monitoring and controlling an operational network while allowing users to do their jobs uninterrupted (Lewis, 2002). This definition does not assume that networks consist only of devices and connections, but fully incorporates the fact that information flow is the reason networks exist. In fact, end users are rarely concerned about the network itself, but merely the information that rides on the network. Multiple methods exist to ensure that networks maintain the capability to pass required information adequately.

1. Structure

Having discussed some metrics for managing networks, we now consider a layered concept for understanding how networks transport information. As seen in Figure 3, the OSI model is the standard, layered representation for computer networking. These interconnected layers become important when we discuss the priorities for network management and the thresholds required to ensure that each layer is able to operate within given constraints observed through the metrics discussed in the previous section.

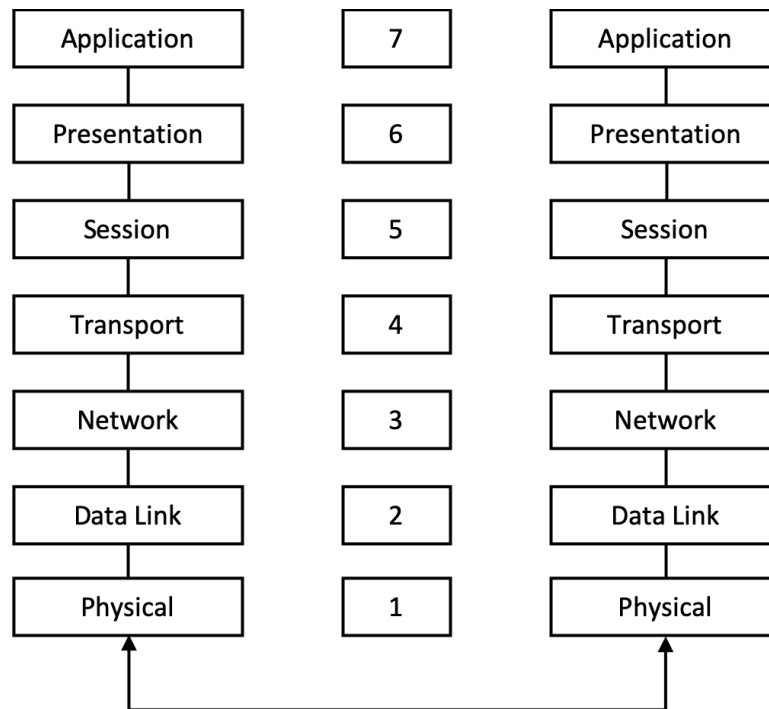


Figure 3. OSI Model Showing Two, Interconnected Devices

This model presents a simple method for discussing how devices connect to each other using internet protocols. It must be understood that in this model, the user exists above the Application layer. As the user decides to transmit information from one node to another, the information moves down the layers until it is encoded physically onto a media for transmission to the second node. At the second node, the reverse happens as the information moves up the model, finally arriving at the user above the 7th layer (Robertazzi, 2012). Each layer plays an important role in this process, namely adding information (known as headers) for use at subsequent nodes during the transmission's journey through the network (Robertazzi, 2012). It is important to note that this model works in what is known as a "peer-layer strategy." This means that source layers are intended to interact with their counterpart layer at the destination; the information they send is specifically crafted for interpretation by the equivalent layer at the distant end (Alani, 2014).

The application layer (Layer 7), as described by Alani (2014), is concerned with specific user interaction and QOS parameters for acceptable performance of each user

required service. Likewise, the presentation layer (Layer 6) prepares data for the application by negotiating the appropriate format. It is also responsible for translation, compression, and encryption, as required (Alani, 2014). Similarly, the session layer (Layer 5) is responsible for organizing connections to multiple end users. Alani also writes that these sessions allow devices to communicate with multiple distant ends at the same time. The transport layer (Layer 4) is the first layer with a defined protocol data unit (PDU) or term for the information grouped together at that layer. At Layer 4, this information is known as a *segment*, which utilizes port information to control where datagrams move (Alani, 2014). The transport layer controls the flow of connections, ensures that segments are arranged in the appropriate sequence, monitors QOS, detects errors, and establishes end-to-end connections (Alani, 2014).

The network layer (Layer 3) utilizes a PDU known as the *packet*. Layer 3 is responsible for moving these packets throughout the network and achieves this through the use of logical addressing assigned to each device on the network. This logical address is used for end-to-end addressing during packet transmission (Alani, 2014). The data link layer (Layer 2) utilizes a PDU known as the *frame*. Alani (2014) contends that Layer 2 is responsible for the control of link connections and identifying appropriate parameters for the exchange of information. The physical layer (Layer 1) utilizes a PDU known as a *bit*. The bit is the basic building block for information exchange, and all transmission are composed of groups of bits organized in a certain sequence to define manner to appropriately describe the intended information. Layer 1 is primarily responsible for ensuring that these bits are translated for the physical medium that will transmit them; that is, they may be voltages for transmission on a wire, lights for transmission over fiber, or modulated radio signals for wireless transmission through space (Alani, 2014). Within the OSI model, all seven layers work together to ensure information is transported from user to user.

2. Management Models

One of the earliest network management models, originally developed by the British government, is the Information Technology Infrastructure Library (ITIL). While

largely focused on supporting Information Technology (IT), ITIL divides network management into five distinct categories that remain focused on providing service level capability to the end user (Greene, 2019). These five categories are Service Strategy, Service Design, Service Transition, Service Operation, and Continual Service Improvement (CSI).

The International Telecommunication Union (ITU) describes a network management system known as the Telecommunications Management Network (TMN) model. This model, shown in Table 1, consists of five logical layers moving from bottom to top as network applications move from technical orientation to business orientation.

Table 1. Telecommunications Management Network (TMN). Adapted from International Telecommunication Union (ITU) (2000).

Business management layer
Service management layer
Network management layer
Element management layer
Network element layer

The ITU further describes the functional areas for network management as fault management, configuration management, accounting management, performance management, and security management. Generally, this grouping of functional areas is referred to by the acronym FCAPS (ITU, 2000). Table 2 describes each functional concern in greater detail.

Table 2. FCAPS Functional Areas. Adapted from Lewis (2002).

Fault Management	- Corrective actions - Network recovery - Routine and preventative maintenance - Self-tests to correct problems
Configuration Management	- Resources applied against changing network demands - Network data collection to provide for network services
Accounting Management	- Process and manipulate records - Tracks service use - Identifies cost of resources
Performance Management	- Ensure efficient utilization of resources - Ensure network meets user requirements - Track network resource behavior - Ensure service content delivered optimally
Security Management	- Access control - Prevent intentional/accidental loss - Provide for range of privileges

Finally, telecommunications operations map (TOM) and enhanced telecommunications operations map (eTOM) were developed to define the information flow between the processes of the TMN. This model captures a much broader perspective than TMN and encompasses additional functions such as billing and revenue that are often not included within typical network management functions. Figure 4 shows the overlay of eTOM.

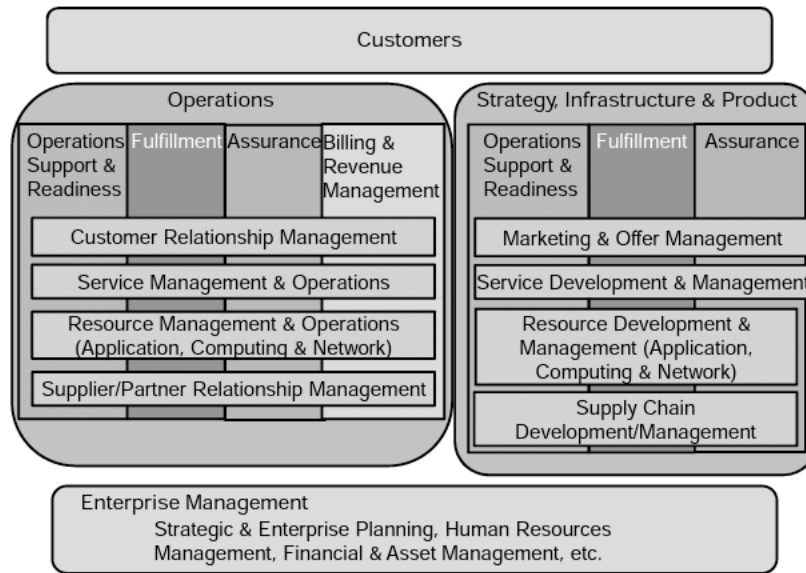


Figure 4. Enhanced Telecommunications Operations Map (eTOM).
Source: Wong (2011).

It is clear from the overview of these network management frameworks that the focus on the manager must be on the information, or service, provided to the end user.

3. Network Operations Center Team Roles

It is critical to assign roles to the members of the team when designing our NOC. In an effort to effectively divide roles, NOC decision support roles are typically scaled along the lines defined by the ITU model of FCAPS.

Fault management is defined as the operations involving the detection and isolation of faults on the network to determine the most probable root cause of problems. A fault is a failure of a network component resulting in the loss of connectivity. Some fault detection activities include polling, traps, and other alarm functions that report information about the network nodes. Fault management also includes the precise identification and reporting of potential fault locations, as well as the determination of most probably root cause and problem resolution (Subramanian, 2011).

Configuration management (CM) refers to the understanding of the topology of the network and the allocation of nodes and resources against our metrics. CM of our tactical

nodes will include maintaining the positioning, pointing, orientation, and bandwidth capacity parameters for all available nodes. CM activities will also include a depiction or mapping of the multi-layered network topology (Subramanian, 2011). These activities will primarily be accomplished by software tools and the associated information made viewable for display at the NOC. Although CM activities will not require a dedicated NOC crew member, the entire NOC crew should have a solid understanding of the network topology, the resources available, and how the operational nodes are physically positioned and connected in the network.

Accounting management, in our concept, is the tracking of the operational status of various nodes within the network. Because our network example involves highly mobile nodes, we cannot always predict when we will expect individual nodes to join the network. Atypical NOC display will show where nodes are located and how they are moving with relation to each other. This information provides details to the NOC crew about potential issues based on node location or speed.

Performance management lends itself to the monitoring of specific performance metrics that define how well the network is supporting the intent of the users (Subramanian, 2011). Pertinent network performance metrics for our mission include node availability, loss and error between each node, measured delays or latency, the instantaneous bandwidth capacity (throughput), and dynamic traffic/routing information. Performance statistics and metrics will inform the NOC crew about any pertinent trends that could negatively impact current or future network operation. The QOS, reliability, response time, error rate, average load, and peak load can all be visually depicted to members of the NOC crew.

The team roles described in the above paragraphs discuss only a few of the myriad of jobs NOC crew members must perform on a daily basis. Incorporating additional computer teaming to help proactively manage the network, will alleviate some of the stress involved with these roles. A hypernode could potentially take over a few of these roles, including parts of configuration management, specifically node positioning and location; parts of performance management such as metric monitoring; and parts of fault management that would allow notification to the NOC when the hypernode was no longer able to improve network performance and required human intervention.

4. Monitoring Tools

There are many network monitoring tools available on the commercial market. The following section will provide a brief review of some current commercial technology in use at the Naval Postgraduate School.

a. SolarWinds

This technology polls connected nodes in order to provide the NOC with updated network information. An added benefit is that Marine Corps NOCs are experienced with using SolarWinds and are familiar with the user interface. This software has the capability of automatically generating user gauges and graphs by combining available MIB information. This makes the output easy to display in the NOC for quick access by the NOC crew. In addition to ease of use, SolarWinds is a valuable tool kit due to its many imbedded features as well as the ability to customize desired metrics. Although it has many MIBs already included, SolarWinds also provides the capability to add additional MIBs. The Universal Device Poller (UnDP) capabilities allow us to define a custom statistic to monitor network performance. The software also gives the NOC the ability to do dynamic network discovery and mapping as well as set customizable alerts. The SolarWinds technology consists of integrated network monitoring tools that aid the user in recognizing network performance issues (SolarWinds Worldwide, LLC, 2020).

b. CodeMettle

CodeMettle has developed a technology toolset that is designed for implementation across distributed networks. It is a solution based on software that provides operators the ability to monitor and asses network status across technologies through a single interface. CodeMettle combines the capability to monitor and troubleshoot network issues through the use of simple dashboards that provide detailed information tailored to the skill level of the user. Its set of Network Operations Center tools allows network managers to view network statuses while simultaneously reviewing performance statistics for management input and situational awareness (CodeMettle, 2019).

5. Management Protocols

The commonality between the management models discussed is the layers incorporated for various management information. In reality, these layers need to communicate with each other to effectively ensure that the health of the overall network meets the requirement of the user. This interlayer communication is accomplished through the use of network management protocols. Bordetsky and Hayes-Roth (2007) stated that the Simple Network Management Protocol (SNMP) is a tool capable of collecting performance information about an operational network that could be useful to control overall performance. The SNMP is composed of the management information base (MIB) that collects information about the network object and a query protocol for retrieving information from the MIB (Lewis, 2002). Wong (2011) stated that the SNMP consists of an architecture of agents and managers utilized solely in internet protocol (IP) networks. Managers use the MIB to maintain detailed data about the objects for which they are responsible. These managers obtain this data through queries of their associated agents. The collected data describes objects referring to specific physical or logical properties of network devices. These properties may include the hostname, connected interfaces, ports, etc. Information provided through MIB data allows a network management system to create a total network map.

6. Performance Metrics

The Network Working Group of the Internet Engineering Task Force (IETF) developed the Framework for IP Performance Metrics in Request for Comments (RFC) 2330 (Paxson et al., 1998). Here, they stated the requirement for a common understanding regarding the measurement of performance and reliability of the internet services provided to users. Essentially, RFC 2330 stated that the term metric should be associated with a specifiable quantity that will assist in capturing information on performance and reliability. These metrics should be: well-defined, repeatably measured, unbiased, and useful to the community. RFC 6390 further refined the definition by stating that an IP performance metric “is a quantitative measure of performance, specific to an IETF-specified protocol or specific to an application transported over an IETF-specified protocol” (Clark & Claise,

2011, p. 6). The implementation of this definition allows the characterization of network traffic in support of monitoring and improving the flow of network services.

Network performance metrics are commonly separated into categories defining like characteristics. A study written by Hanemann et al. (2006) describes four such categories, availability, loss and error, delay, and bandwidth, which tend to capture the majority of available metrics. They contend that *availability* refers to the accessibility of the network and services without error or downtime, though this metric can also apply directly to links and nodes in a network. The same study argues that *loss and error* deal specifically with the amount of data transferred to intended recipient and are measured using the percentage of packets arriving correctly to the destination. Additionally, according to Hanemann et al. (2006), *delay* is an indirect measure of network congestion viewed through the lens of the time it takes for packets to traverse the network. Finally, the study explains, *bandwidth* measures the overall capacity of the network while specifically addressing the amount of correctly transferred data measured over a specific time.

Likewise, Martinovic, Petrisevac, and Zagar (2010) stated that network communication is primarily limited by bandwidth, congestion, and delay. They made it clear that effective and efficient network management is the key to allowing successful transfer of information in intensive, time critical applications. In their discussion of network monitoring and measurement, the key to reducing network congestion is increasing bandwidth or optimizing the use of current available bandwidth.

When the MIB queries certain objects for information, it uses the layers of the OSI model to determine which queries are appropriate. This allows us to determine which layers of the OSI model we are concerned about in this thesis by tying the performance metrics to layers of the OSI model. In our case we are concerned with availability; loss and error; delay; and bandwidth. Availability is the physical connection of the device to the network, which is measured at Layer 1. Loss and error require a unique look at Layer 4 to determine the total loss of packets across the network. Delay can be effectively measured through use of the 'ping' command acting at Layer 3 and providing information on node to node connectivity. Finally, bandwidth is a measure of capable throughput that is measured at Layer 1/Layer 2 by counting the total number of bits and compared to the passage of time.

a. Availability

Availability is a simple measure of whether or not a device is available to act as a network node. Availability can also describe whether or not a link is connected, which directly impacts its ability to pass traffic through the network (Wang et al., 2009).

b. Loss and Error

Loss describes a situation where a packet does not reach its intended destination. Similarly, error describes a situation where a packet reaches the destination but contains an error. In both of these scenarios, Layer 4 must be involved in assessing the packet to ensure all required packets are received and received without error (ITU, 2016).

c. Delay

Delays may consist of delay related to packet construction, medium access, node processing, queuing at an overloaded router, and even delays experienced as signals propagate through the environment (Belhaj & Tagina, 2009). End-to-end delay is a compilation of many types of delay experienced as data traverses a network (Belhaj & Tagina, 2009). End-to-end delay is commonly measured as the total time it takes a packet to move through the network from its source to its destination (ITU, 2016). The nature of IP traffic through large networks dictates that packets may experience different delays as they traverse different paths from source to destination, thus it is common to measure average (or mean) packet transfer delay to gain a greater understanding for the end-to-end delay of a specific network segment (ITU, 2016).

d. Bandwidth

According to Mahanta, Ahmed, and Bora (2013) bandwidth is the measurement of capacity in a computer network. They further state that bandwidth is often measured in terms of traffic flow, typically in bits per second (bps). Bandwidth is a limited network resource that is shared among network nodes (Wang et al., 2009). Bandwidth management, that is, effective allocation of bandwidth to the right nodes and links at the right time, can significantly reduce congestion on the network, therefore increasing capable throughput for valuable applications (Mahanta et al., 2013).

F. DECISION SUPPORT MODELS

Within the discipline of network management, decision support models stem from the concept of event correlation. That is, any report to the network management system is known as an event (Subramanian, 2011). When a manager needs to decide about a subject, they collect the required information, analyze it, and use some means to correlate the information for decision making. Event correlation techniques allow the comparison of different events generated about a network while ensuring all events are considered in concert with each other (Subramanian, 2011). There are multiple event correlation techniques (often described as reasoning models) that may be used to support decision making. Some of the more common event correlation techniques, which will impact this thesis are Rule-Based Reasoning (RBR) and Case-Based Reasoning (CBR).

1. Event Correlation

Rule-Based Reasoning is a system that is based on factual information about the environment and a set of rules that makes decisions based on these facts (Lewis, 2002). The decision model for RBR involves the use of if statements. An example of an RBR scenario is shown in Table 3.

Table 3. RBR Example. Adapted from Lewis (2002).

A	A fact
If A then B	A rule in the rule base
Therefore, B	An inference made by a reasoning algorithm

In the case presented in Table 3, the rule allows the system to use fact A to get to resultant decision B. Another example of this reasoning scheme is color coding for various network states, such as if packet loss is less than 10%, then show node as green (Subramanian, 2011). While chaining these ‘if statements’ together to make a decision model may get tedious, it is a popular method for most vendors (Lewis, 2002). The key to this method is understanding the facts, or metrics, which require measuring, and ensuring simple rules to produce valuable outcomes.

Another approach to decision support is the CBR technique. This method involves capturing historical performance information and information about the environment to create a library of cases for reference (Lewis, 2002). In this vein, the reasoning system should observe its current environment and build a picture of what is going on. It then compares this situation to the case reference library. This allows it to pick the best choice for decision based on past events. Once the decision is made, the success or failure data is captured and the new event becomes another case in the reference library. The CBR model allows the system to continue to build its library as decisions are made.

2. Group Decision-Making

Marakas (1999) described three structures within multiparticipant decision-making, the team, group, and committee. The group structure enables multiple decision makers to collaborate directly in search of a “majority rules” decision. The team structure involves multiple participants, which cannot interact, with only one decision maker. The committee structure has a single decision maker, while, unlike the team construct, the participants are able to collaborate and interact to move towards the best decision. Depictions of these decision structures are located in Figure 5.

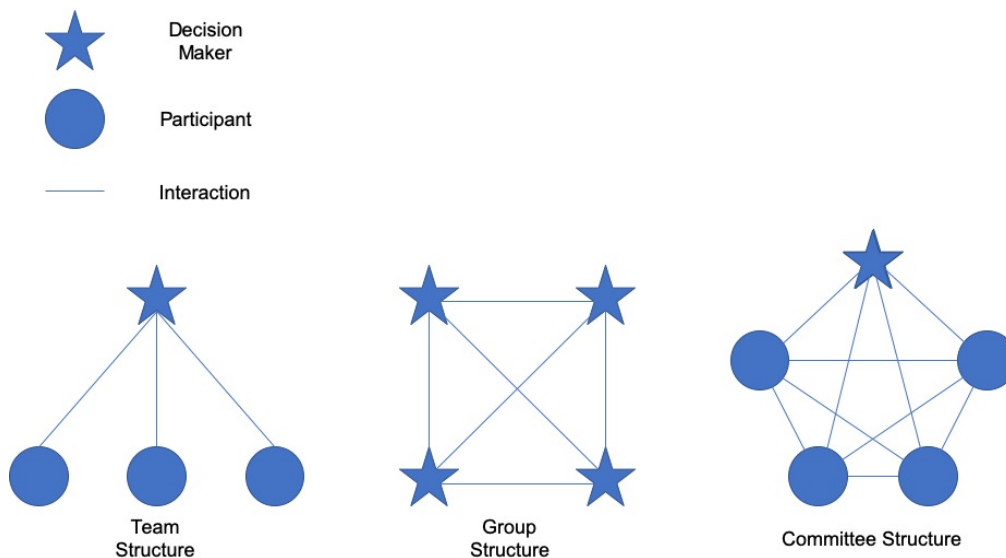


Figure 5. Multiparticipant Decision-Making Structures. Adapted from Bordetsky and Netzer (2010).

3. Optimization

Optimization finds its roots in the operations research techniques developed during World War II (Ibrahim & Alfa, 2017). These techniques sought to allocate limited resources against multiple requirements in the most efficient way possible while achieving the best operational results. As computers progressed, the capability to solve optimization problems increased as operators no longer had to solve them by hand. These problems took both linear and non-linear form. Linear programming optimization problems are solved using continuous variables applied to a linear objective function with linear constraints. Non-linear programming optimization problems similarly use continuous variables, but the objective function and/or at least one of the constraints contains a non-linear function. Ibrahim and Alfa (2017) stated that decision variables such as power, data rate, and bandwidth are able to be modeled using continuous variables for optimization.

Statnikov et al. (2009) present the Parameter Space Investigation (PSI) method as a means of solving multidimensional domain problems through systematic application of the design criteria. Statnikov et al., (2011) introduce pseudo-criteria, whereby the parameters for the criteria, or variable, need not be optimized, but merely achieved. This technique is applicable to the study of hypernodes due to the number of variables that could be used to perform the selected network management functions. This method enables a network manager to identify relevant, additional metrics and apply them within the algorithm. The network manager then applies a threshold, or range, for each criterion that narrows the focus of the hypernode as it seeks a position decision calculation. The application of the DBS-PSI method, introduced by Statnikov et al. (2011), provides an advanced means to sort through the available criteria and pseudo-criteria while providing a workable solution to a relay position problem. The purpose of the algorithm is to ensure that the hypernode supports the required communication protocols. That is, finding the appropriate way to achieve feasible solutions in order to maintain required communication capability.

G. RECENT RESEARCH

This section addresses findings uncovered in previously conducted research. These address concepts that are applied in Chapter III, and inform my experimentation approach.

1. Networks Interconnected by Aerial Nodes

This section provides an overview of tactical communication networks interconnected by aerial nodes.

The concept of using UA to enhance ground-based ad hoc networks through the optimization of network performance has received attention in recent years. Han, Swindlehurst, and Liu (2009) approached analyzing the problem mathematically in an effort to determine the best approach for QOS optimization. They defined four types of connectivity and mathematically determined that adding a UAV with adaptive algorithms improved overall connectivity for the supported MANET (Han et al., 2009). Additional studies focused on employing these optimizing UAVs with multiple antennas while flying at a constant velocity (Jiang & Swindlehurst, 2010). These simulations resulted in improved performance for the supported network, but realized that the constant velocity of the UAV meant that it had to perform loops over the target area instead of having the capability to maintain an optimal, fixed position (Jiang & Swindlehurst, 2010).

Kline (2017) and Murphy (2019) both demonstrated the feasibility of creating bursty, tactical communication networks interconnected by fast-moving aerial nodes. Although both aforementioned proofs-of-concept were conducted within significant constraints, they provide contextual framework in the area of tactical networking, which merits further discussion here. Specifically, the following subsections will provide a brief overview of tactical wireless networking, discuss previous research within tactical networks interconnected by aerial nodes, and propose concepts that both exploit limitations observed by previous research and advance study into networks interconnected by aerial nodes.

Many instances of unmanned aircraft being used as aerial relays exist in modern technology. As early as 2007, the Army began experimenting with attaching radios to unmanned aircraft in Afghanistan to extend communication range (Defense Industry Daily,

2008). The Federal Communications Commission (FCC) also recognized the applicability of aerial communication technology during emergency situations where first responders cannot count on terrestrial communications infrastructure. The FCC study recommends the use of small UA, weather balloon technology, and high-altitude UA as carriers of aerial communication payloads in these emergency situations (Lee & Manner, 2011). The conditions experienced in these emergency scenarios often mirror those of an expeditionary operation in the littorals. In fact, the coverage provided by aerial platforms continues to prove beneficial in the military tactical environment (Lee & Manner, 2011). More recently, Kline (2017) and Murphy (2019) demonstrated proofs of concept in an effort to interconnect distant, dispersed ground nodes using aerial nodes.

2. Mobile Ad Hoc Networks (MANET)

As identified earlier, Mobile Ad Hoc Networks (MANETs) are extremely well suited to the tactical, wireless network environment. MANETs are dynamic networks that do not rely on predetermined infrastructure (Loo et al., 2012). Loo, Khan, and Naser Al-Khwildi further state that these networks are able to communicate with each other without the use of a central administrative device because all nodes act as both routers and hosts. This creates a fully dynamic topology that supports efficient operation in mobile networks (Loo et al., 2012). Another key to use of MANET is its robust self-forming, self-configuring, and self-healing capability, which allows infrastructure changes on the fly (Wang et al., 2009). This benefit is created through the network's ability to utilize multi-hop paths from source to destination.

One drawback of MANET systems is that they are typically smaller and required to be powered from battery sources. It is for this reason, as Wang, Xie, and Agrawal (2009) stated, that they are typically employed in a configuration known as a Wireless Mesh Network (WMN). This configuration allows some of the nodes in the mesh network to be relatively stationary, creating the ability to tie in to more substantial power sources and increasing capacity (Wang et al., 2009). An example of WMN infrastructure can be seen in Figure 6.

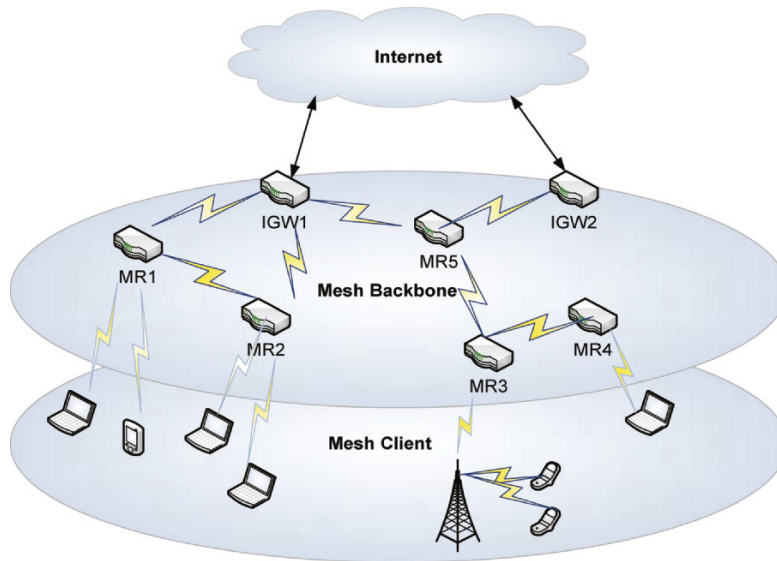


Figure 6. Typical Wireless Mesh Network Architecture. Source: Wang et al. (2009).

Research into the benefits and capabilities of MANET and WMN continues to take place at Naval Postgraduate School. Students such as Kline and Murphy were both able to prove that small nodes were capable of increasing capacity for tactical networks.

3. “Bursty” Tactical Aerial Networks

Kline (2017) observed communication patterns in short-living networks interconnected by projectile-based nodes on a small scale. Kline performed multiple experiments shooting projectiles with embedded mesh communication devices using a launching mechanism similar to a standard M203 grenade launcher. His experiments were designed to determine if command and control data could be relayed between ground users outside communication range, or beyond Line of Sight (BLOS), of one another. With each experiment, Kline created short-living communication network links or “bursty” transmissions. These burst communication links only existed long enough (8-10 seconds) to pass predetermined, mission critical information. Once the critical bits and bytes of data were sent between ground users, the bursty communication link was broken, leaving little trace of electromagnetic (EM) signal. Figure 7 illustrates Kline’s experimental concept for a tactical communication network interconnected by projectile-based aerial nodes. Figure 8 illustrates Kline launching a projectile-based communication device. While

Kline's concept is useful, I extend the concept in a much more persistent context, supporting multiple small units requiring consistent communication.

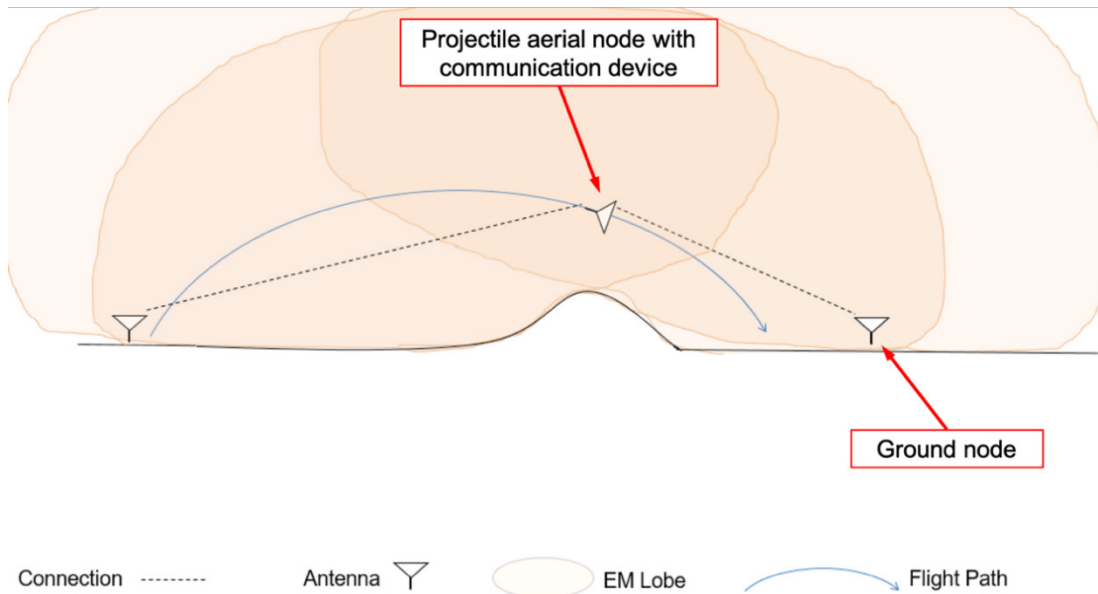


Figure 7. Projectile-based Aerial Node. Adapted from Kline (2017).



Figure 8. Launching Projectile-Based Communication Node. Adapted from Kline (2017).

Expanding on the aforementioned proof-of-concept, Murphy (2019) investigated the feasibility of using fast-moving aerial devices as short-living and bursty tactical networking nodes. Taking advantage of Kline's recommendations for future research, Murphy identified a mesh communication device with advanced routing algorithms and physical characteristics that were suited to his specific use case. He then designed and additively manufactured a mounting system allowing the communication device's attachment to a fast-moving aerial vehicle. Through a series of iterative lab and field experiments Murphy (2019) demonstrated that tactical networks could feasibly be interconnected and extended using fast-moving aerial nodes. Figure 9 illustrates the experimental concept for tactical networks interconnected by fast-moving aerial nodes. Murphy's (2019) research highlights that small UAVs using mesh communication devices show significant potential for exploration as a means to expand communication technologies for ground operators.

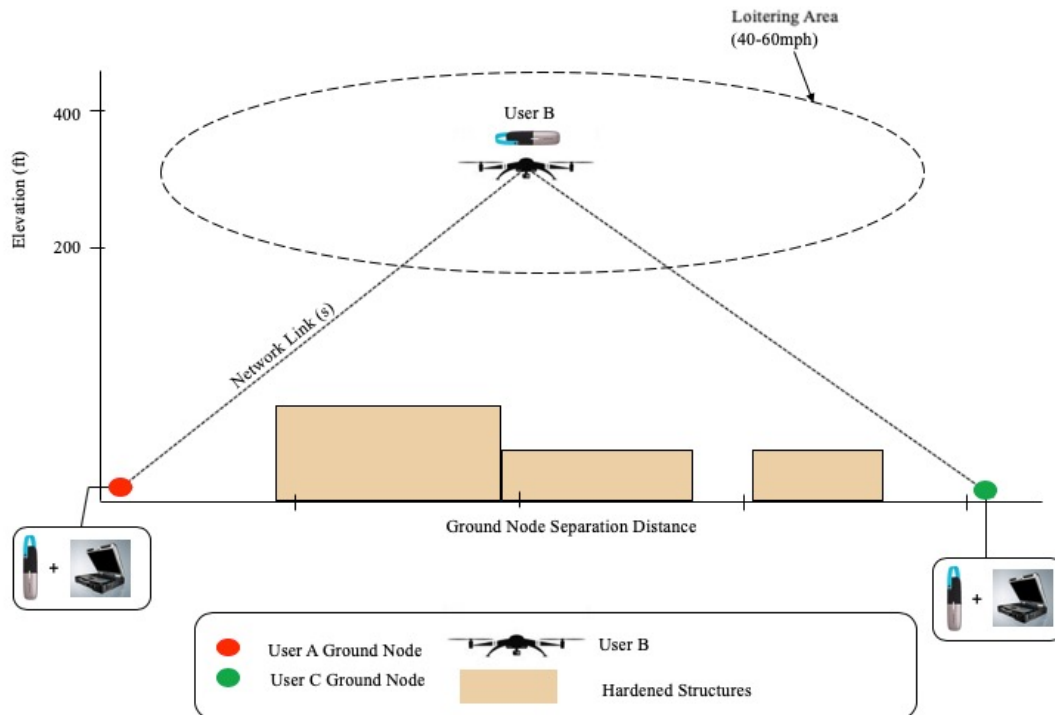


Figure 9. Concept for High-performance Small UAV with Attached goTenna Mesh Radio. Adapted from Murphy (2019).

4. Norway Experiments

During my thesis research I had the opportunity to observe thesis research being conducted by others in Norway. I gained insight on interesting solutions, built upon previous research, which demonstrated potential for the thought process that I undertake in the construct of this thesis.

First, I was able to use an aerial node to extend communication capability from the shore to a Norwegian vessel utilizing a goTenna Mesh radio and a DJI Mavic quadcopter drone. Figure 10 shows the setup of the relay drone.

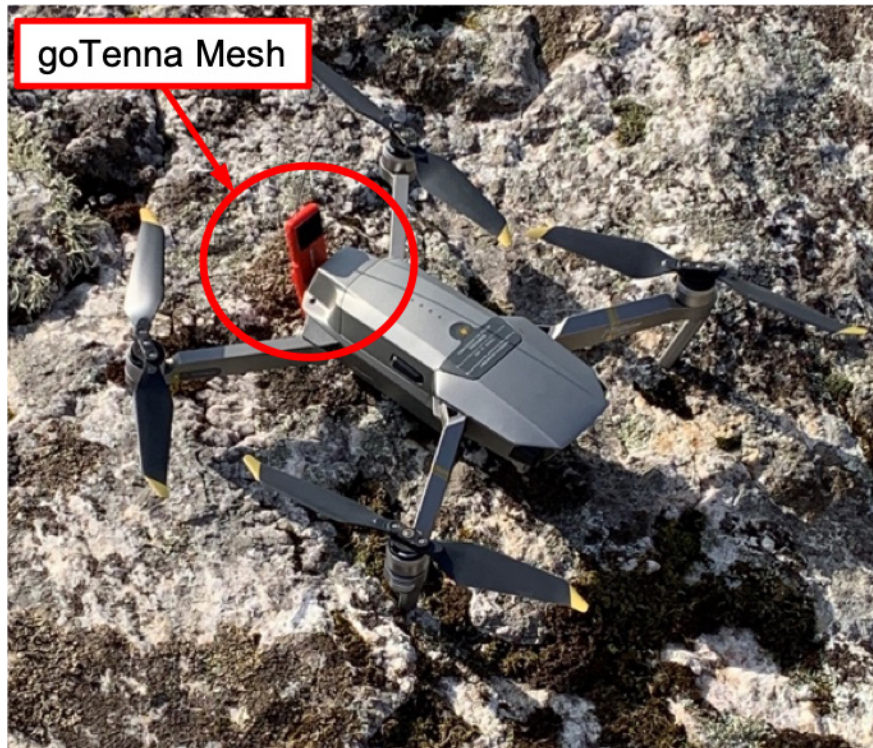
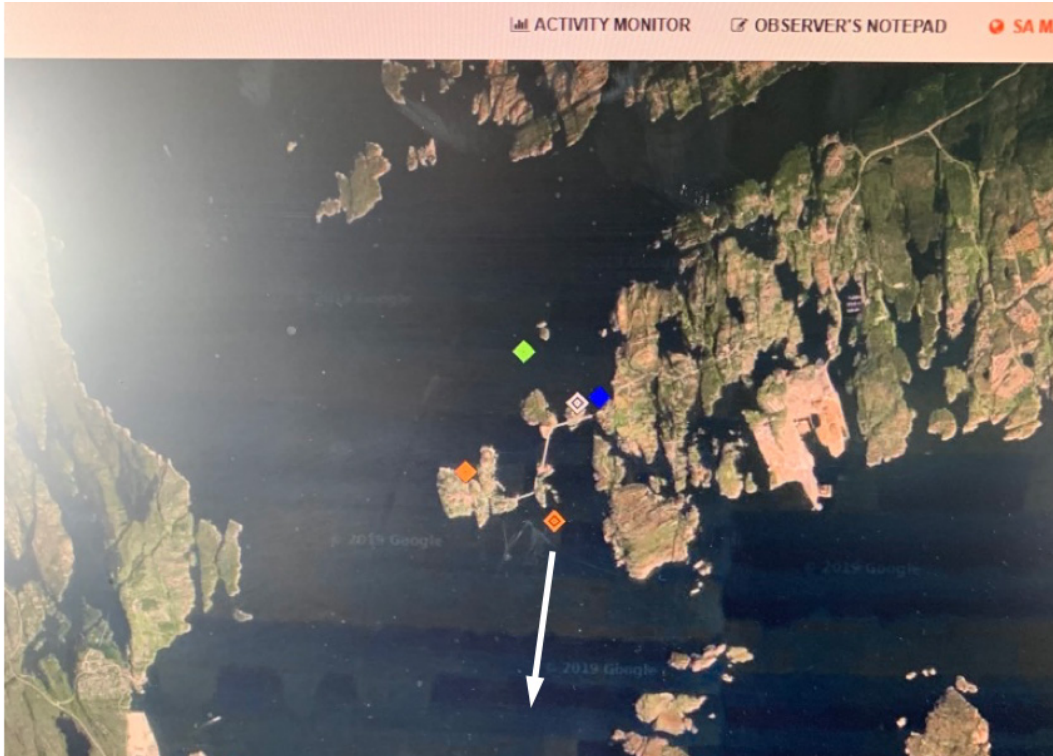


Figure 10. DJI Mavic Carrying goTenna Mesh Relay

Figure 11 shows the location of the simulated Joint Operations Center (JOC), depicted by the white diamond, and the location of the Norwegian vessel, depicted by the orange diamond with black diamond inlay; additionally, it shows the point where the vessel began to move south and connectivity was lost. While we could not establish the link using

a goTenna Mesh-to-goTenna Mesh connection, when the goTenna aerial node relay was elevated, the relayed link was able to pass traffic.



This image shows node locations and connectivity during maritime experimentation in Norway. White arrow indicates direction of vessel movement.

Figure 11. Screenshot from the CENETIX Activity Monitor

At this point, the drone relay was launched and connectivity was reestablished using the aerial node. Figure 12 shows the final locations of the vessel and aerial node.

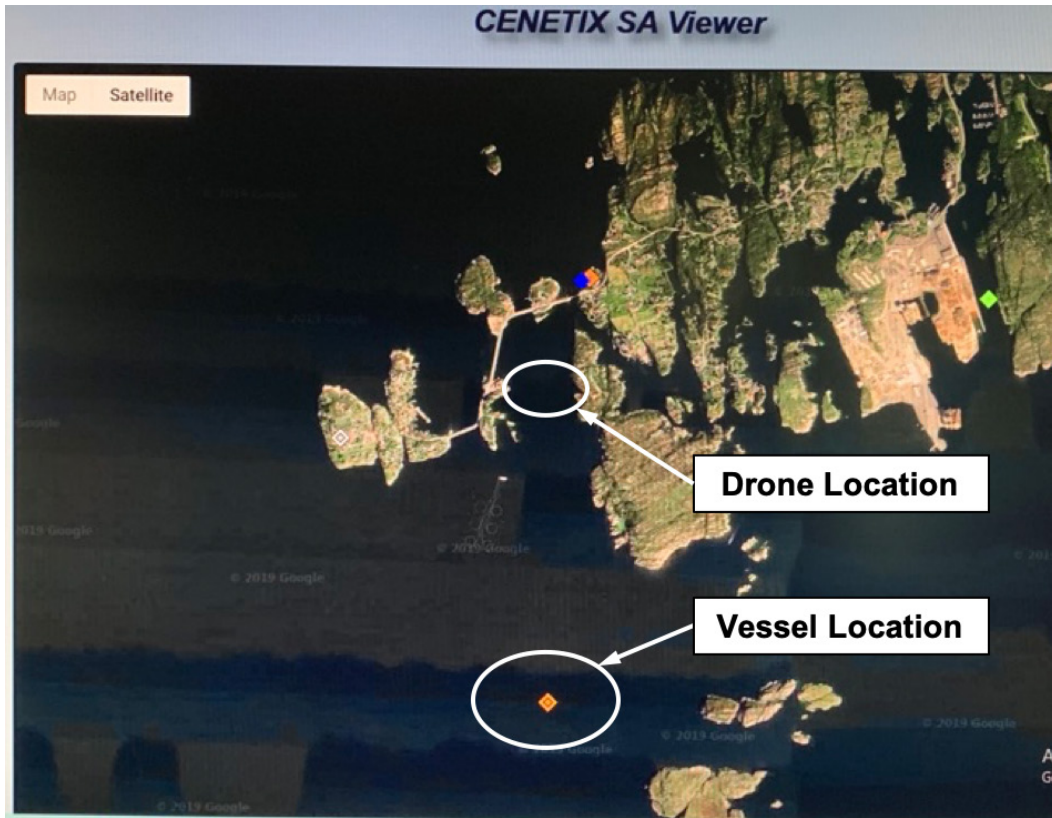


Figure 12. Screenshot from the CENETIX Activity Monitor

Since the goal of this thesis is to allow a hypernode to recognize situations where links will potentially break and act to prevent this issue. If, for example, in our scenario above, the aerial node had been equipped with the same mesh radio in use on the boats, the hypernode could have made the decision to move the aerial node to a mutually advantageous position that would support network extension. The addition of an aerial hypernode would serve to prevent the network disruption.

5. Overcoming Limitations of Previous Studies

Although Kline (2017) and Murphy (2019) demonstrated that tactical communication networks can be interconnected by aerial nodes, both proofs-of-concept identified the following disadvantages: network boundary (range), message payload capacity, bandwidth, network duration, and limited capability/functionality of aerial nodes. Limitations experienced during previous study and Murphy's calls for future research motivated this research, which carries them forward by implementing the following:

- Transition from bursty/short-living to persistent networks
- Create network monitoring/management (decision-making) system
- Make aerial node a hypernode

The proofs of concept by Kline and Murphy, paired with observations of other student thesis work in Norway, provided the motivation to explore aerial node use for persistent networks. Aerial nodes create a path that is reachable from dispersed tactical ground locations, allowing reach-back to a headquarters or NOC. Subsequently, this aerial node might be a hypernode, which will allow it to assume some NOC functions and aid in network optimization by prioritizing network traffic to ensure the most important information flows are routed through the network in the timeliest manner.

When the concept of an aerial relay for communications is paired with the idea of network service aware hypernodes, the solution to the opening vignette is readily apparent—aerial hypernodes that are able to process network support priorities and make network optimization decisions to prevent information loss. These nodes could truly contribute to the adaptability and resiliency of tactical networks. In fact, this concept directly supports the current definition of Artificial Intelligence provided by the Department of Defense (2018, p. 5), which states Artificial Intelligence is “the ability of machines to perform tasks that normally require human intelligence—for example, recognizing patterns, learning from experience, drawing conclusions, making predictions, or taking action—whether digitally or as the smart software behind autonomous physical systems.” The anticipated improvements to the speed of network decision-making have the potential to refine NOC processes and directly impact the way we manage our tactical networks in the future.

III. EXPERIMENT DESIGN AND METHODOLOGY

This chapter discusses the application of the hypernode concept and the design and methodology used to conduct my research by phase, from initial design through field experimentation. The process was divided into six phases: data requirements, initial testing, algorithm development, performance testing, field tests, and advanced field test. Applying this phased approach enabled me to build to an advanced field test of the capability to output hypernode position calculations to a UAS controller. Again, the focus of this research was not flight control integration, but the development of a hypernode algorithm that could effectively calculate relay locations satisfying network connectivity requirements. Table 4 lists the phases and major stages of the experiment.

Table 4. Experiment Phases

Phase 0—Data Requirement Determination
Stage A: Determination of Metrics
Stage B: Hypernode Role Selection
Stage C: NOC Observation
Stage D: Technology Selection
Phase 1—Initial Testing
Stage A: Bench Test #1
Stage B: Bench Test #2
Stage C: Bench Test #3
Stage D: Field Testing
Phase 2—Algorithm Development
Stage A: Hypernode Positioning Algorithm Design
Stage B: Scenario Development
Phase 3—Algorithm Performance Testing
Phase 4—Hypernode Field Test
Phase 5—Advanced Field Tests

A. HYPERNODE CONCEPT

The vignette in Chapter II described a scenario where multiple nodes are moving independently through an area of operations. Each of these nodes has specific communication throughput requirements to accomplish its mission. Additionally, each node (or squad) is assigned a relative priority by the commander. The harsh terrain and continuous movement of the nodes make it nearly impossible for the NOC to make network adjustments in response to degraded links in real time. Building on the concept presented by Bordetsky and Hayes-Roth (2007), we generate a hypernode algorithm that is capable of running aboard an aerial node. This effectively produces an aerial hypernode with the ability to sense the network environment and dynamically adjust its position to improve network connectivity and align it with node information exchange requirements and assigned commander's priorities. The supported ground nodes act only as inputs to the hypernode, they are in no way controlled by the hypernode. I envision a future scenario where an aerial node uses a frontseat-backseat model for control as discussed in Chapter II. The hypernode would act as the mission controller (backseat) and make position recommendations to the flight controller (frontseat).

The effort to achieve this aerial node requires some development of the hypernode concept and process. Our initial step to prove this concept was not to employ the flight control directly on a UA, but to demonstrate that in a simulated environment the hypernode could sense the network and make new position calculations. A separate operator could then relocate the hypernode to the recommended position and verify that the calculated relay position achieves all of the priority and network connectivity requirements according to the algorithm protocols. This hypernode action provides a natural bridge from reactive network management to dynamic network management. In this case, a hypernode is able to assess an active network and make decision recommendations to a NOC operator to adjust the network in real time. The next step would be to employ the hypernode as an aerial node, allowing the flight control system to utilize the position calculations to autonomously adjust the network. A final step would be loading the hypernode with a mission profile that would enable proactive repositioning based on planned unit priority changes, such as shifting the main effort at a specific time during an attack.

The experiment process in this thesis works to achieve the algorithm that will output a position calculation for the hypernode. The hypernode algorithm will be designed to operate continuously to enable the dynamic process of network management. The position changes it calculates will constantly change as the supported network nodes move through the tactical area of operations. While the position may not initially be the optimal relay position, the algorithm is designed to output a relay position that is feasible; that is, it satisfies the specified priorities and network connectivity requirements within established boundaries.

Through the course of experimentation, I was able to discover additional decisions required during the network management process. These decisions apply specifically to managing MANET type radios at the tactical edge. Once I captured these decisions, I set the goal of working to make the tactical edge of the network more dynamic, that is, I wanted the computer to recognize the need for these decisions and act to fix network issues before there was a loss of connectivity identified by the typical network monitoring toolset.

B. PHASE 0—COLLECTION REQUIREMENT DETERMINATION

The purpose of Phase 0 was to determine the specific requirements for collecting data that would contribute to algorithm development. During Phase 0 I identified the network management and optimization metrics to use with hypernodes for network decision-making. This led to the identification of specific NOC roles that hypernodes could perform. Additionally, I visited a Marine Corps NOC to understand the current state of the technology used for network management. Finally, I identified the technology to best enable me to prove the concept.

1. Phase 0A—Determination of Metrics

As discussed in Chapter II, there are specific performance metrics that pertain directly to network management in the context of this research. These performance metrics include availability, loss and error, delay, and bandwidth. All are measurable through various SNMP functions available on networked systems. For example, by capturing the signal to noise ratio (SNR) of our devices we are able to gauge whether or not the device

should be available for connection. Additionally, the signal to noise ratio gives an estimate of the capability of the throughput that a node should be capable.

Carlson and Crilly (2010) stated that the goal of transmitted signals is to overcome the noise inherent in the environment, that is, noise from either other communication signals, known as human interference or from those naturally occurring signals in the environment. They also observe that noise comes from multiple locations to include, electron motion, electrical wires, radio transceivers, etc.

The whole of this observation is defined using what is commonly referred to as the link equation. Since we intend to utilize an aerial node we chose to look at the connectivity calculations, or link equation, from an aerial perspective. The link equation we used for reference is seen below (S. Moore, PowerPoint slides, May 13, 2019):¹

$$\frac{S}{N} = \left(\frac{P_t G_t}{kB} \right) \times \left(\frac{\lambda}{4\pi R} \right)^2 \times \left(\frac{G_r}{T} \right)$$

Where:

P_t equals the power transmitted in Watts

G_t equals the gain of the transmitting antenna

k equals Boltzman's constant 1.38×10^{-23} Joules / Kelvin

B equals the bandwidth of the receiver in Hertz

λ equals the wavelength of the transmitted frequency in meters

R equals the distance between the radios in meters

G_r equals the gain of the receiving antenna

T equals the system temperature in Kelvin

¹ See Singh, Pentaleri, and Price (2011), pages 475-478 for more information on the link equation.

This equation tells us that SNR is a function of the power transmitted, the gain of the transmit and receive antennas, the system noise (Boltzman's constant, system temperature, and bandwidth), and the free space losses as the signal travels between antennas.

For our use of this equation, during network operation we assume that radios will be operated at a constant power, with the same antennas, utilize a constant operating frequency, and a fixed receiver bandwidth. This means that the variable of the link equation that we are able to control in an effort to increase SNR, is the distance between the radios, R . As R is in the denominator of this equation, we need to decrease it to increase SNR. This means that our hypernode algorithm needs to recommend decisions that move it towards disadvantaged nodes. The tradeoff here is that this may move it away from other nodes. We must implement a threshold system for node communication and SNR requirements in addition to accounting for the commander's priorities for which nodes are most important.

a. Signal to Noise Ratio—Availability

I examined *availability* from a Signal to Noise Ratio perspective. From a radio's point of view, there is a minimum SNR required to achieve a connection with a neighbor as discussed in the link equation. In my experiment concept, the central node will seek connectivity with all neighbors. SNR is an appropriate metric to determine availability of each other node in the network.

b. Packet Loss—Loss and Error

I chose to measure the *loss and error* within the network through the measurement of packet loss as information transits the network. This measurement of packet loss enables me to observe the amount of data that is lost based on node connectivity. Observing an increase in packet loss indicates that a node is potentially losing the ability to connect to the network and adequately pass data. This means that the hypernode should respond to this increased loss and work to reduce it.

c. *Round Trip Time—Delay*

Round trip time is a method of measuring the *delay* metric. Round trip time is a measure of the length of time it takes for basic ping packets to travel from one node to another node and back, thus an effective measure of system delay for a particular node. An increase in delay potentially equals a decrease in network quality of service. This must be accounted for in the design of the algorithm at a certain level to ensure delay is minimized to the extent possible.

d. *Throughput—Bandwidth*

The capture of data about network throughput is an indirect measure of available *bandwidth*. However, network bandwidth is the measure of overall capacity; the concept of throughput must be understood in these terms. There are minimum threshold requirements for throughput based on desired traffic flow in a tactical, mobile network. For example, a streaming video feed might use a certain amount of throughput. If this throughput does not exceed the bandwidth of the system that indicates that there is excess capacity available.

e. *Position*

While not specifically defined as a metric in Chapter II, GPS position is an essential, underlying measurement. The hypernode is designed to improve performance by relocating itself to a feasible relay position. This recommended position relies on both the position information of the ground nodes and the aerial hypernode. It is necessary to know where the aerial hypernode is in relation to other nodes in order to change relay position towards improved network performance. During potential autonomous operation, this position information is vital for the frontseat flight controller of the aerial platform.

f. *Link Quality*

During research into the feasibility of calculating the position of a relay node using these metrics, we realized that they could be combined into another metric that better described the connectivity between nodes. Bourakov (personal communication, January 30, 2020) defined a link quality score that combined metrics (which differed in units) to

present information about a specific link between radios resulting in a score between 0 and 100.

Link Quality = $100 * \left(\frac{(snr / \max SNR)}{(1 + rttKcoef * rtt) * (1 + lossKcoef * pktLoss)} \right)$, rounded to the nearest integer.

maxSNR = 70

rttKcoef = 0.005

lossKcoef = 0.1

If the calculated link quality is greater than 100, the link quality displayed is 100, which enables the link quality equation to yield an integer value between 0 and 100.

What we learned as we applied this formula to some of our tests is that the link quality calculation closely mirrored using only the SNR. For this reason, we decided to use SNR as our initial variable of hypernode position at level 1 of the algorithm.

However, the calculation was a useful part of the development process. In fact, the representation of link quality displayed from 0–100 is an easily understandable reference for the NOC crew or the commander as to the current status of connectivity to a node. Combining the overall link quality from the JOC to the individual nodes potentially creates a method for measuring the improvement of the link as the hypernode algorithm repositions the aerial relay.

2. Phase 0B—Hypernode Role Selection

The idea that hypernodes could execute NOC management roles requires defining the roles able to transition into the hypernode management realm. In our design we specifically focus on the configuration management, performance management, and fault management roles of the FCAPS model for network management because their dimensions can easily be transitioned from human control to autonomous functionality. While the accounting management and security management functions are important to the NOC manager, we argue these roles are better served by NOC crew than the hypernode.

In the configuration management role, the hypernode makes decisions regarding the position of relay nodes within the network in an effort to improve network connectivity between the JOC and dispersed ground nodes. For example, if a unit cannot gain connectivity there may be a requirement to establish a relay in support of the communication requirement. This is known as a network configuration change.

In the performance management role, the hypernode takes on the metric monitoring responsibility for nodes that are directly connected to it. It then uses an algorithm to make decisions on these monitored metrics based on commander's priorities and network connectivity and data throughput requirements set by the NOC managers. For example, a node with a SNR lower than required to establish a link may need to move to achieve more effective performance. Thus, performance and configuration management can naturally act as supporting roles in network management.

Finally, the hypernode is able to take on portions of the fault management roles. It should be able to detect when there is a network fault, or potential network fault, through monitoring of performance metrics and comparing against assigned requirements. For example, as performance metrics get worse, the fault manager can predict that a network error is likely to occur. This fault monitoring will help NOC managers control the network situation to develop more resilient networks during operations.

The benefit of offloading certain configuration, performance, and fault management roles to the hypernode is seen in the proactive responses to network change. The hypernode is able to make decisions and adjust to evolving network dynamics in the operating area far more rapidly than could human network managers. Additionally, a hypernode operates at the speed of network change as it is continuously monitoring and adjusting network configurations (relay node position) to ensure required connectivity for all priority nodes.

3. Phase 0C—NOC Observation

In Phase 0C I observed the current state of tactical network management in the United States Marine Corps. I conducted a site visit to 9th Communication Battalion as they supported I Marine Expeditionary Force (MEF) during their Command Post (CP)

Rehearsal exercise. The purpose of this visit was to observe a Marine Corps Network Operations Center to ensure an accurate comprehension, and validate my current working assumption, of how USMC NOCs currently operate. The established network was designed to support the MEF staff and provide services to the Major Subordinate Commands. 9th Communication Battalion uses a distributed network architecture designed to increase resiliency. This architecture pulls in tactical network services via satellite communications and distributes them approximately 13 miles to the MEF CP via tactical fiber and terrestrial multichannel radio. 9th Communication Battalion personnel then monitor and control the distribution of the network using the network management tool SolarWinds. This tool allows the network managers to view the physical laydown of the network nodes and receive near real-time updates on network node status. The network managers can react to network changes using experience, or Case-Based Reasoning. If the personal knowledge about the network change/outage is not adequate to resolve the network issue, the network managers then move on to detailed troubleshooting steps, or Rule-Based Reasoning. These two decision support models enable them to efficiently work their way through network outages.

In the current NOC management process, the human NOC managers follow a process that enables them to troubleshoot network problems. This process is similar to that outlined below:

1. Must recognize that their network management tool is presenting an alert.
2. Must drill down into the alert.
3. Must determine root cause of the problem.
4. Must direct action to fix the identified problem.
5. Must ensure fix action resolved the problem.

If, for example, the alert identified that a distributed node lost connectivity, the root cause of the problem may have been that the node exceeded the effective range of the communication system. In this case, the NOC managers must identify a suitable relay

location and deploy a relay in an effort to regain connectivity with the unit. This process may take from minutes to hours, all valuable when a commander needs to communicate with tactical units.

The observations from this visit reinforce the assessment that NOC management continues to be performed in a reactive manner at the tactical level. It also suggests that there is value in beginning to move towards a proactive network management stance.

4. Phase 0D—Technology Selection

The objective of Phase 0D was to identify technology capable of collecting the desired metrics. During concept development, it became clear that we would need to procure or design some specific tools to examine the concept of hypernodes to achieve the research objectives. We needed a radio system that was capable of measuring the metrics as algorithm inputs and a data capture device that was capable of interacting with our chosen radio system.

a. Radio Selection

Since we plan to use this technology on tactical edge networks where imagery and intelligence information is passed to small units, our networked radio needs to be capable of passing high bandwidth transmissions and operating on a persistent basis. We determined that we needed a communication device (or combination of devices) capable of adequately capturing data points of our metrics. We selected the Persistent Systems Wave Relay MPU5 radio for our experiment as it met our criteria adequately.

The MPU5 can stream high definition video, integrate GPS locations, and communicate with voice technology in one platform (Persistent Systems, 2019). This radio is also capable of operating in a mesh network using the proprietary Wave Relay technology developed and employed by Persistent Systems in their radio technology, allowing efficient use of the radio frequency spectrum while reducing overhead on the network (Persistent Systems, 2019). The MPU5 utilizes a web management interface to provide operators with information about individual radios in the network and the network itself. This management interface is key to our employment of this radio system. The fact

that the radio already consolidates metrics of information which concern us, such as SNR and GPS location information, means we only need to extract it from each networked device and apply it within our algorithm.

Unlike the Virtual Extension (VE) 209S radio used by Kline (2017) and the goTenna mesh radio used by Murphy (2019) the MPU5 is a high bandwidth, long range radio capable of extending the mesh over great distances that approximate the actual range requirements in our tactical context. Its MANET capability is ideal for distributed users who require continuous communication (Persistent Systems, n.d.). In fact, the Wave Relay MANET radio met our requirements because it extends Layer 2 of the network in an effort to be a truly peer to peer network device capable of operating as a transmitter, receiver, and repeater (Persistent Systems, 2016). Finally, the MPU5 is capable of connecting directly to an ethernet network through a 22-pin data connection (Persistent Systems, 2019), which enables the easy extraction of the required experiment data for analysis. Figure 13 and Table 5 illustrate the characteristics of the MPU5.



Figure 13. MPU5 Radio. Adapted from Persistent Systems (2016).

Table 5. Wave Relay Specifications. Adapted from Persistent Systems (2016).

MPU5 Radio Wave Relay Specifications					
Frequency	Throughput	MANET	Network Integration	Radio Management	Security
S-Band - 2200 - 2500 MHz	150 Mbps, 20 MHz bandwidth	Wave Relay Technology No limit on hops No limit on nodes ~ 130 miles between nodes	Layer 2 network extension	Secure web browser interface; Remotely accessible	Cryptographic Acceleration; Suite-B Algorithms; CTR-AES-256 Encryption; SHA-256 HMAC

b. Data capture device

Because the MPU5 outputs to a web portal that is only viewable through a web interface, we also needed to build a device that would capture the SNMP polling data as it is output over time. This enabled us to monitor and track the state of the network in real time as we experimented. It also enabled us to conduct post experiment analysis on aspects of network behavior for trends in performance as we manipulated the hypernode in order to test our algorithm. To capture this information, we chose to use a Raspberry Pi 3 Model B computer similar to Figure 14.

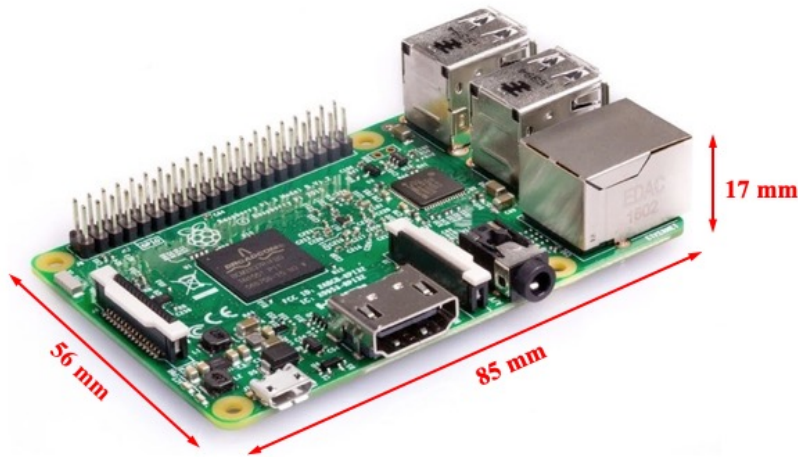


Figure 14. Raspberry Pi 3 Model B. Adapted from Raspberry Pi Foundation (n.d.).

The Raspberry Pi board is a small, capable computer that is able to run the code required to operate as our hypernode when connected to an MPU5. These requirements include processing speed, programming language, and storage. This computer utilizes a quad core, 1.2 GHz central processing unit, is fully capable with 1 GB of RAM, has four USB2 ports, and a direct connection ethernet port (RPi website). Additionally, the Raspberry Pi uses a microSD card to load its operating system and is powered through a 2.5 amp micro USB port (Raspberry Pi Foundation, n.d.). Specifically, useful to us in this experiment are the microUSB power port and the direct ethernet connection. These ports

allow us to connect the programmed Raspberry Pi to the MPU5 radio to act as an SNMP poller.

c. Equipment Configuration

Once we identified the radio and the data capture device, we had to connect the radio to the computer in a manner that would allow us to measure, capture, and transmit the SNMP metric statistics during network operation. The ethernet port of the Raspberry Pi and the MPU5's ability to connect directly to an ethernet connection provided this capability. The MPU5 is capable of connecting to an ethernet connection using the 22-Pin to RJ45 Receptacle (CBL-DATA-2001) cable which allows a direct connection from the radio's data port to an ethernet cable. The MPU5 is also capable of connecting and supplying power to USB devices. We used the 22-Pin to Audio and USB (CBL-AUD-2007) connected directly to the PTT / EUD port to allow power from the MPU5 battery to power the Raspberry Pi. The cables and the radio connections are shown in Figure 15.

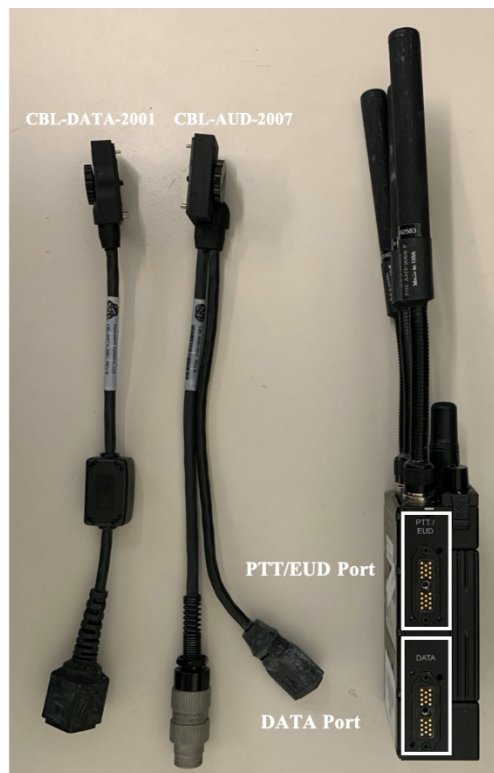


Figure 15. MPU5 Radio Cables and Ports

We also had to design and build a housing for the cables and the Raspberry Pi board. This was achieved using a 3D printer as seen in Figure 16.

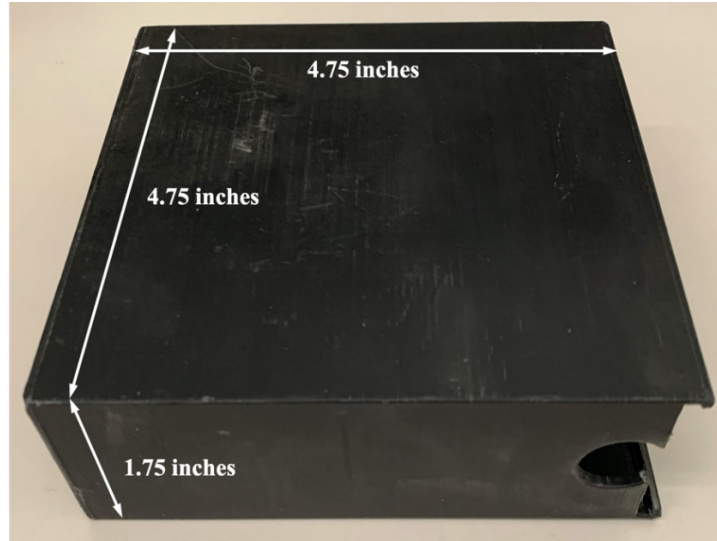


Figure 16. Box Used to House Raspberry Pi

Once this box was printed we assembled a device that was capable of measuring, capturing, and transmitting the SNMP metric statistics during network operation. The steps of assembly of this box and connection to the radio are shown in Figure 17.

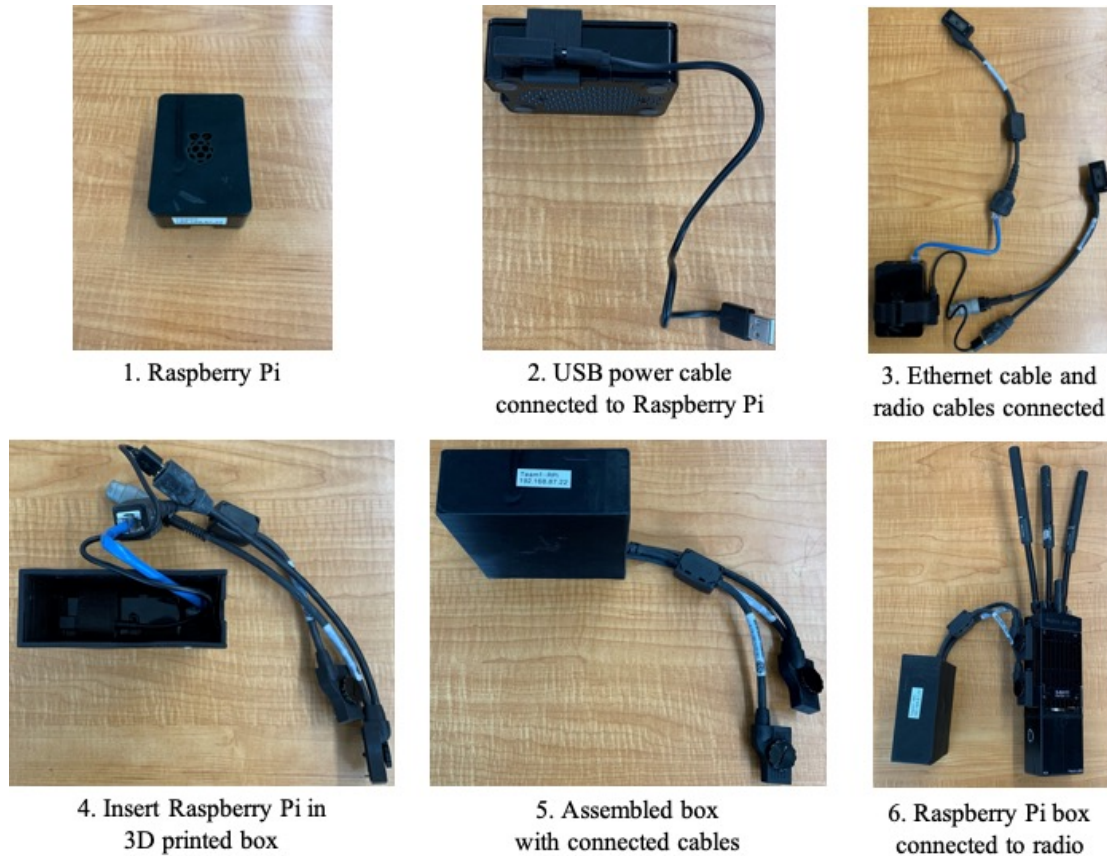


Figure 17. Assembly and Connection of the Raspberry Pi Box

Once assembled, the SNMP box and radio with battery weighed in at 3.2 pounds. We would ultimately use this device as the teams for initial testing with the server and would then convert one of the data collectors into our hypernode for final testing.

d. Unmanned Aerial System

The concept we intend to prove includes using the hypernode on an aerial platform. We determined that this platform should be able to hover in a relay location to provide a relay capability to the supported ground nodes. As such, we required a drone with the capability to loiter in a certain fixed position above the ground while flying at distance from the drone operator comparable to that over which we expect to use the mesh network. Additionally, this drone must be capable of carrying the 3.2 pound payload that we built to serve as the hypernode.

We chose the Matrice 600 drone, made by the DJI, to use as our aerial platform during experimentation. This drone is easily capable of carrying up to 5.5 kg (or approximately 12 pounds) and can fly up to 5 km away from its control station with a flight duration ranging from 18 minutes (max payload) to 40 minutes (no payload) (SZ DJI Technology Co. Ltd., 2020a). This 5 km is enough to confirm hypernode functionality at expected performance ranges during testing. As the DJI Matrice 600 (seen in Figure 18) is a 6-rotor drone, it meets our requirement for hovering. While the available loiter time of the Matrice 600 meets our requirements for testing, it should be noted that 20–40 minutes may not be adequate for use in operational conditions without having to alternate multiple aerial nodes to support ground units.



Figure 18. DJI Matrice 600. Source: SZ DJI Technology Co. Ltd. (2020).

C. PHASE 1—INITIAL TESTING

During the course of our work some opportunities arose to test and validate the equipment we developed for this experiment. Some of these opportunities occurred as local experiments designed to help us gather information that determine metric thresholds while

others allowed us to consider required decisions that would aid in the sequential development of our algorithm.

The networks we built for our bench testing require that the JOC and NOC combined into one facility. While in reality, a JOC and a NOC are separate entities, this combination enabled us to monitor the experiments and collect data from the same workstation. This workstation used a desktop server to collect data about network connectivity from the NOC point of view. Additionally, it enabled us to review the performance in real time as we ensured that our devices were functioning as intended. The ability to verify that we were seeing results and collecting data during our bench tests enhanced our ability to adjust equipment settings and observe required changes during experimentation. The drawback to this experimental set up is that to collect this data in a database, requires connectivity. Once nodes were disconnected from our server we were no longer able to collect data about that node. We overcame this through the use of our data capture device attached to each tactical node. This device acted as a remote monitoring station and collected local data about the device on the Raspberry Pi computer. Once an experiment was complete we downloaded all of the log files to review data from each device.

What we learned through this process is that all of the devices need to be set to the same time prior to an experiment or we would not be able to determine what events on each device happened at the same time. We overcame this challenge by ensuring that the capture devices on each node synched time with GPS each time they were started up. This enabled us to use GPS time to sync the review of our logs during the post experiment data review.

These initial tests provided us the familiarization with our equipment that allowed us to begin our iterative bench testing process.

1. Phase 1A—Bench Test #1

The first experiment was designed to test the equipment and data collection capabilities.

a. Purpose

The purpose of this experiment was equipment familiarization designed to capture data about the network. This captured data would also validate that the chosen technology is capable of delivering the required metric information to the hypernode.

b. Method

In order to verify that the necessary data were being generated and captured, we moved a node in a small network environment within 100 meters range. I achieved this by installing a NOC server which would allow coverage of the immediate vicinity. The NOC is pictured in Figure 19.



Figure 19. JOC Server and Equipment

There was an additional stationary node located approximately 12 meters away. This node served to ensure that there was sufficient local coverage.

I also created a simulated mobile node using a wheeled cart and two MPU5s which were labeled as Team 1 and Team 2. Additionally, I connected a laptop to the Team 1 radio via WiFi to simulate a user on that node as seen in Figure 20.



Figure 20. Simulated Mobile Nodes

I conducted the experiment by walking the simulated mobile node through a building. I then proceeded down the elevator and outside to the breezeway. I moved the node down the length of the building, approximately 150 meters. Once I reached the end,

I returned to the JOC via the reverse route. This movement allowed me to capture available data points in a network environment that was impacted by interference created by distance and obstruction of the mobile nodes.

c. Observations

I observed the data that were collected were satisfactory at this point. For example, in the elevator, the measured SNR dropped to zero, as expected. This resulted in a loss of connectivity between the Team radios and the JOC. The SNR profile for the experiment is in Figure 21, while the correlated actions taking place are available in Table 6. We concluded the bench test when we were confident that we were collecting the necessary data in a useable form.

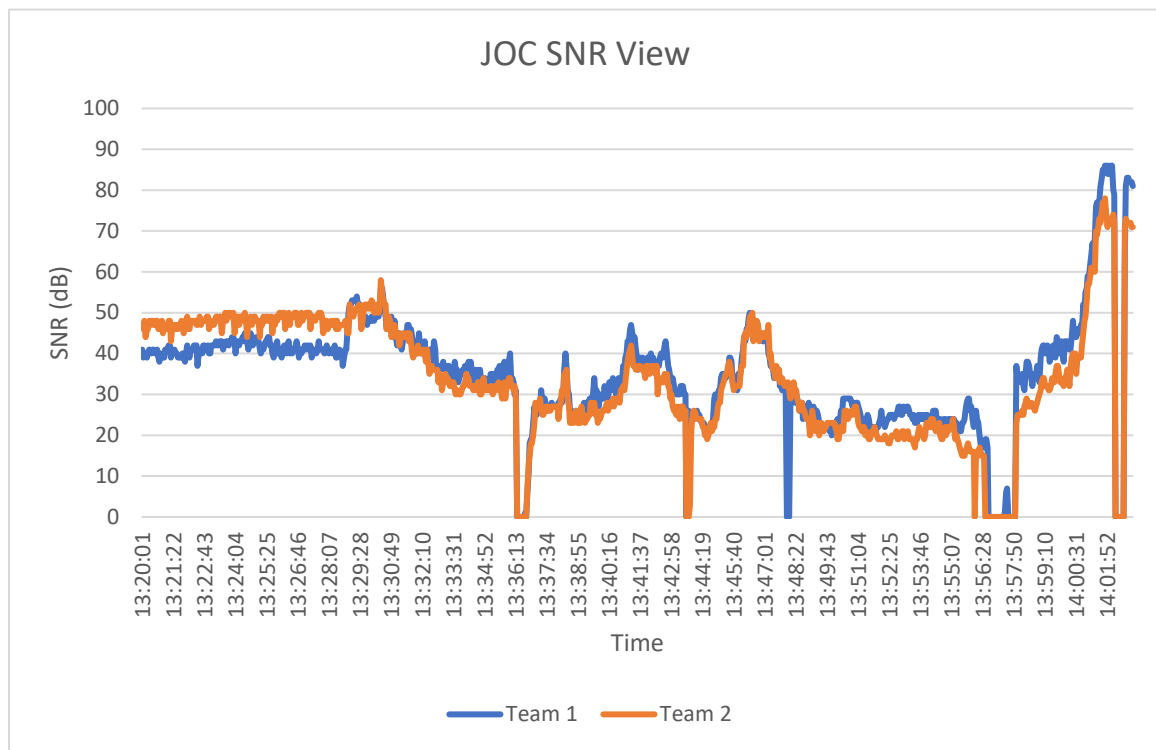


Figure 21. JOC Radio SNR Profile—Bench Test #1

Table 6. Bench Test #1 Key Events

Time	Action of Mobile Node
1320	Experiment start, building 2nd floor
1336	Enter elevator down to ground floor
1338	Exit elevator
1343	Enter distant end of building
1347	Exit distant end of building
1356	Enter elevator back up to 2nd floor
1358	Exit elevator
1401	End test in JOC

This test was useful in enabling understanding of network occurrences as the node moved through the environment. As the experiment began at 1320, it is clear to see in Figure 21 that the SNR was approximately 40–50 dB. This began to decrease as we moved away from the JOC, which is consistent with expectations from the link equation. Upon entering the elevator at 1336 the SNR completely dropped to 0 dB reflecting a broken connection, and upon exiting the elevator at 1338 returned to approximately 28 dB and reestablished the connection, again exactly what we expected. This pattern repeats upon entering the distant end of the building and reentering the elevator for the return trip. This test successfully demonstrated our ability to accurately capture metrics on network in real time and within useful parameters.

2. Phase 1B—Bench Test #2

During the experiment design process, we determined that our focus was too narrow. Since multiple metrics can inform network management decision-making, we needed to conduct another bench test that would capture additional metrics including delay, loss, and throughput.

a. Purpose

This experiment demonstrated that the data collection equipment could capture metrics in addition to Signal to Noise Ratio that aid in managing the network, this required additional traffic traversing the network. I selected streaming video as a good additional

factor and designed a bench test to ensure that the video increased the throughput to a point above the 3–4 Kbps of routine radio network traffic required for mesh connectivity.

b. Method

We built out the rest of the local test network by installing an additional Raspberry Pi board with a camera on the JOC computer, to act as a local video server. Connecting to this video server from a laptop that is connected to a team radio via Raspberry Pi, pulls a much larger amount of data across the link. The intent was to approximate a level of throughput that might be required when passing full motion video between units in a tactical environment, enabling comparison between SNR and network flow. This comparison provides an additional method to analyze network metrics and make NOC decisions. It also enabled the capture of data on delay and loss metrics of network traffic. We needed to ensure we could capture required data before retrying bench test #1 with streaming video. Figure 22 and 23 show the laptop which is receiving streaming video over the network and the throughput monitor on the JOC server.

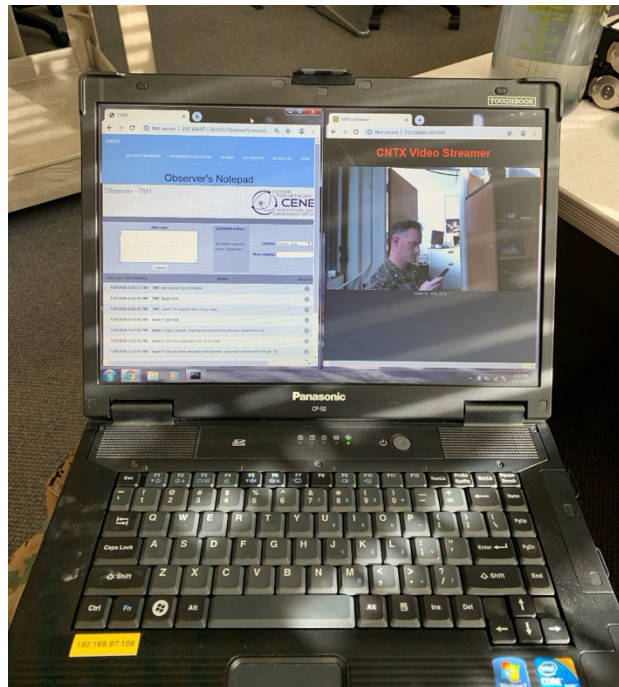


Figure 22. Laptop Viewing CENETIX Video Streamer

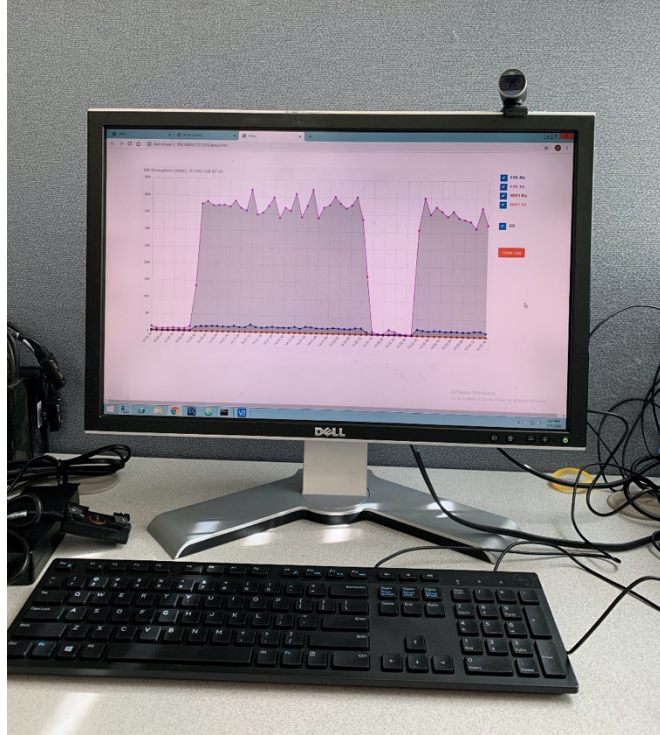


Figure 23. JOC Server View of CENETIX Throughput Monitor

c. Observations

Upon completion of the bench test we downloaded the log files from both the JOC server and the Team 1 SNMP capture device. These log files were then imported to Excel to plot the various metrics over time. The results of this bench test showed the ability to satisfactorily capture data about the following metrics:

Delay, measured in round trip time (RTT) is seen in Figure 24. The RTT readings demonstrate that we are accurately able to capture measurements of delay within the network. These measurements enable future development within our algorithm to adjust network paths which are slower than a required delay threshold. However, the upper limits that will set this threshold must be confirmed through future testing.

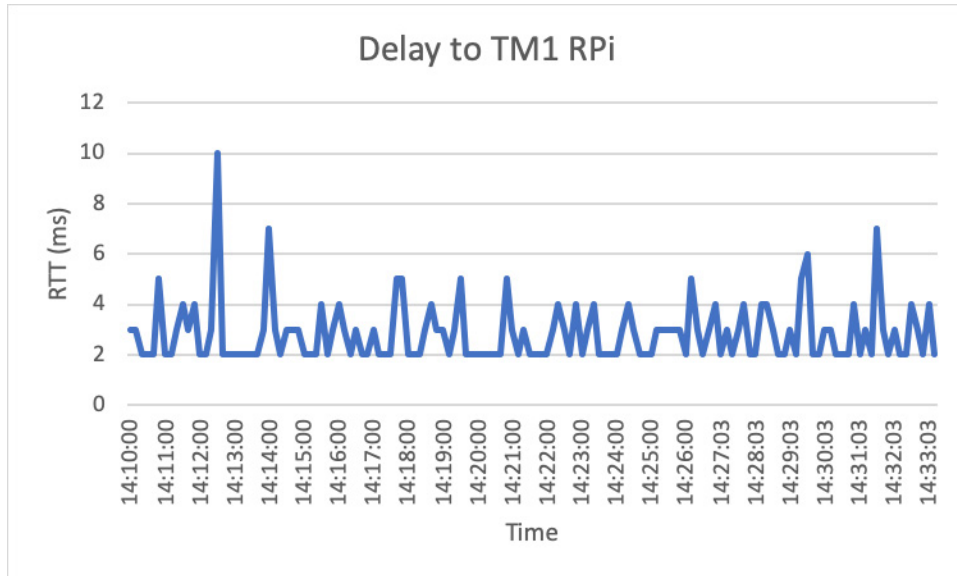


Figure 24. Delay Measured to the Team 1 Raspberry Pi

SNR, seen in Figure 25, demonstrates the correlation between the two ends of the link. The SNR of each node when viewed from the other node follows the same pattern and is within a few dB of being the same. This is seen clearly when both plots show a similar increase in SNR at approximately 1415. At this time, I moved the team 1 radio from a room across the hall into the same room as the JOC resulting in a corresponding increase in SNR. This capture confirms that the devices “see” each other similarly for the duration of the bench test. This is helpful when applying SNR as a metric in algorithm development.

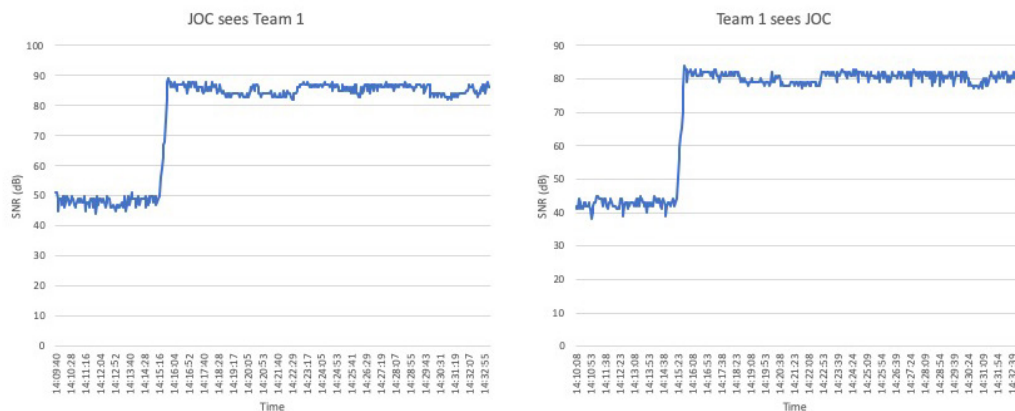


Figure 25. Comparison of SNR JOC to Team 1

Throughput, measured at each device as seen in Figure 26 and Figure 27. In this bench test, the camera was located at the JOC and Team 1 functioned as the distant node receiving the stream. The specific timeframes of interest here are from approximately 1418 to 1423 when I streamed video over the link. The corresponding throughput increases are seen for each node in Figure 26 and 27. Seeing that the input at the JOC radio, matches (roughly) the output at the Team 1 radio confirms that the data was streamed from one to the other over the mesh network. This enables us to view throughput as an adequate metric and conduct testing to determine throughput thresholds required for data traffic over the network.

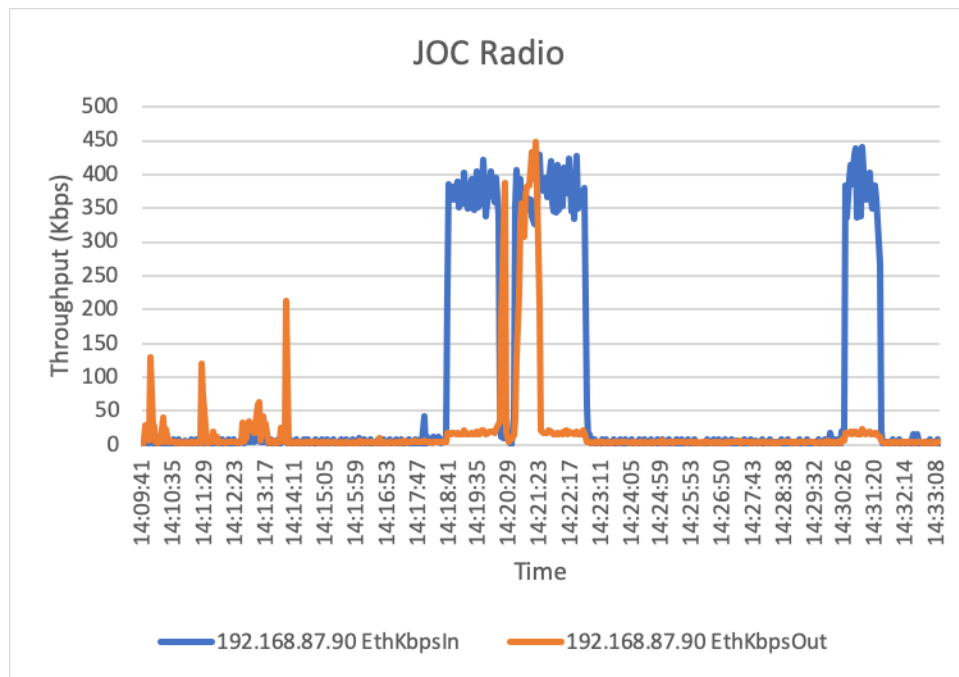


Figure 26. Throughput Measured at the JOC Radio

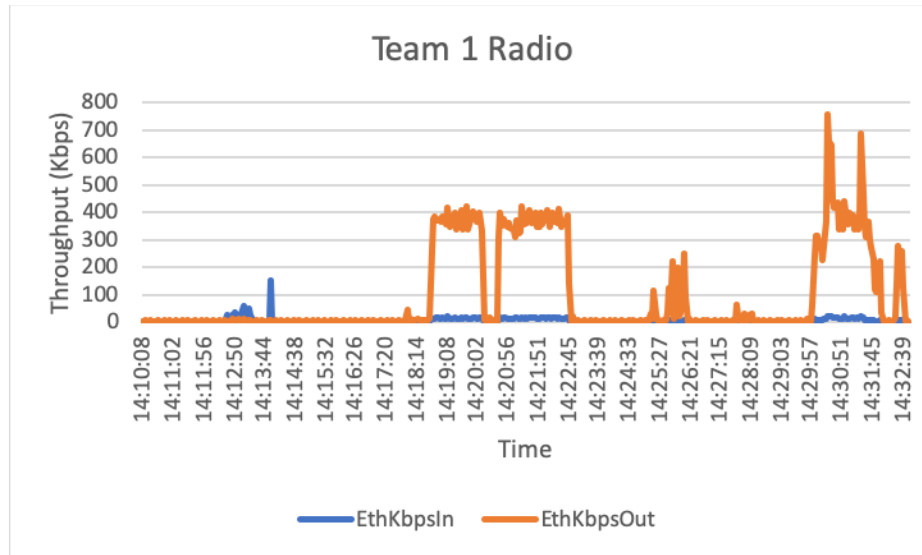


Figure 27. Throughput Measured at the Team 1 Radio

Packet loss, measured at the distant end (Team 1) during this bench test is seen in Figure 28. This capture demonstrates adequately the ability of the hypernode to capture data about packet loss in the network. Of note, capturing packet loss percentage requires a connection to the SNMP device of each node.

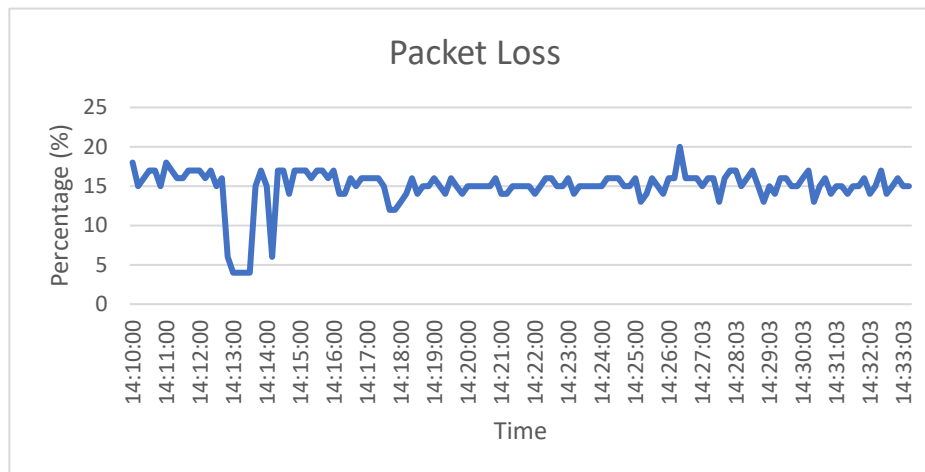


Figure 28. Packet Loss Measured at the Team 1 SNMP Device

3. Phase 1C—Bench Test #3

a. Purpose

After completing bench test #2 with the streaming video set up, we recreated the original data collection scenario from bench test #1. The purpose of bench test #3 was to collect connectivity data to compare it to the additional throughput data. This experiment was designed to determine appropriate thresholds for the SNR metric when working through the hypernode decision-making algorithm.

b. Method

We conducted the experiment by walking the simulated mobile node through the building's upstairs, then proceeded down the elevator, and outside to the breezeway. Eventually, moving the node down the outside length of the building. Upon reaching the end of the building, we returned to the lab via the reverse route. This movement enabled the capture of available data points in a network environment consisting of heavier throughput (streaming video) and with interference created by distance and physical obstruction of the mobile nodes. The timeline of events is available in Table 7.

Table 7. Bench Test #3 Key Events

Time	Action of Mobile Node
1315	Start test
1316	Move from lab to elevator
1322	Enter elevator
1324	Exit elevator, reestablish connection
1330	Reach end of building
1334	Begin return trip
1341	Enter elevator
1344	Exit elevator, connection restored
1349	Reenter lab, stop video stream
1351	End test

c. Observations

The key result from this test was the recognition that certain throughput levels appear directly tied to the SNR. This enabled me to anticipate the requirement to establish proper threshold levels in the algorithm. These thresholds would be required for the hypernode algorithm to understand throughput requirements of a node and ensure a minimum threshold of SNR is achieved for the node in an effort to pass data.

Figure 29 compares SNR during the video stream test and the captured throughput at the Team 1 radio.

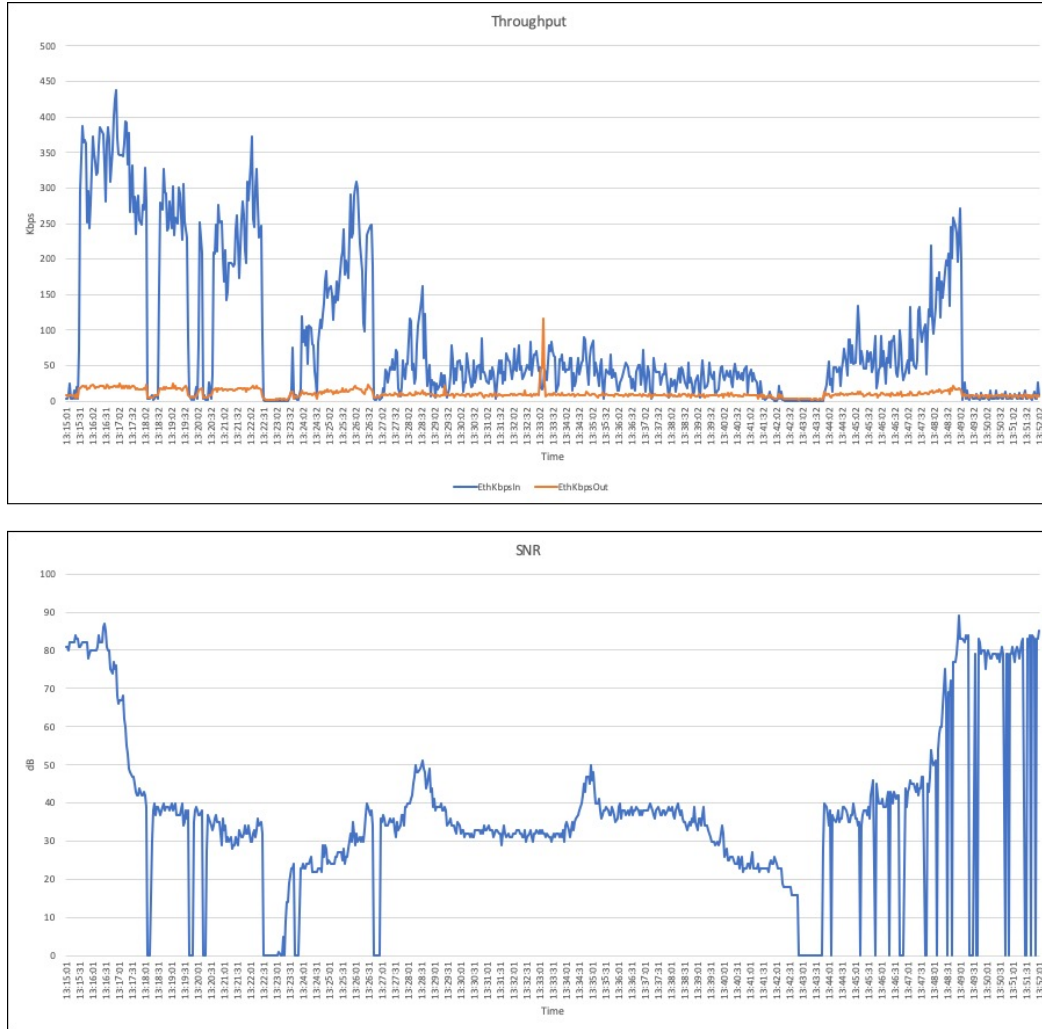


Figure 29. Streaming Video Throughput Compared to SNR

During the course of this test, there was no change to the streaming video being pushed over the network. It is clear from Figure 29 that the decrease in SNR as the node moved down the length of the building, corresponds to a decrease in throughput to the mobile node. The decrease in throughput, combined with observations of the video quality during the conduct of the experiment, demonstrated the requirement for the use of SNR thresholds in algorithm development. This means that there are certain thresholds of SNR that are required for streaming video to achieve the required throughput for adequate viewing, that is, a frame rate that updates sufficiently for the video to appear coherently. The results we assess from this experiment are that streaming video requires a threshold of approximately 30 - 40 dB for efficient use.

4. Phase 1D—Field Testing

a. Purpose

In November of 2019 I conducted initial experimentation at the Joint Interagency Field Experimentation (JIFX) exercise 20–1. The purpose of this experiment was to gather data associated with mesh network connectivity in a more realistic environment prior to repeating the process later during the iterative approach. During this experiment I formulated a tentative data capture process, including collecting network usage and radio connectivity data. Additionally, we would observe decisions made by simulated NOC personnel to maintain communications in the testing environment. I also refined the design and test scenarios that represent the network employment vignette presented in Chapter II.

The objective was to capture data that support physical decisions associated with tactical network management. The site provided the separation and distances required to simulate distributed squad operations, enabling testing of mesh radio connectivity that would require dynamic NOC decisions to maintain required connectivity among several mobile, tactical nodes in the network.

b. Method

During this experiment I established a small mesh network using MPU5 radios. Data were collected by Raspberry Pi devices directly connected to the radio data port.

Additionally, we used vehicles to move through a simulated tactical area, increasing the range of our network environment. I observed NOC functions as network nodes moved throughout a large, simulated tactical operating environment. We also estimated the actual decisions NOC managers would have to make and execute in order to maintain prioritized network connectivity when nodes move through the terrain as simulated, individual tactical units. The chosen patrol route is depicted in Figure 30.

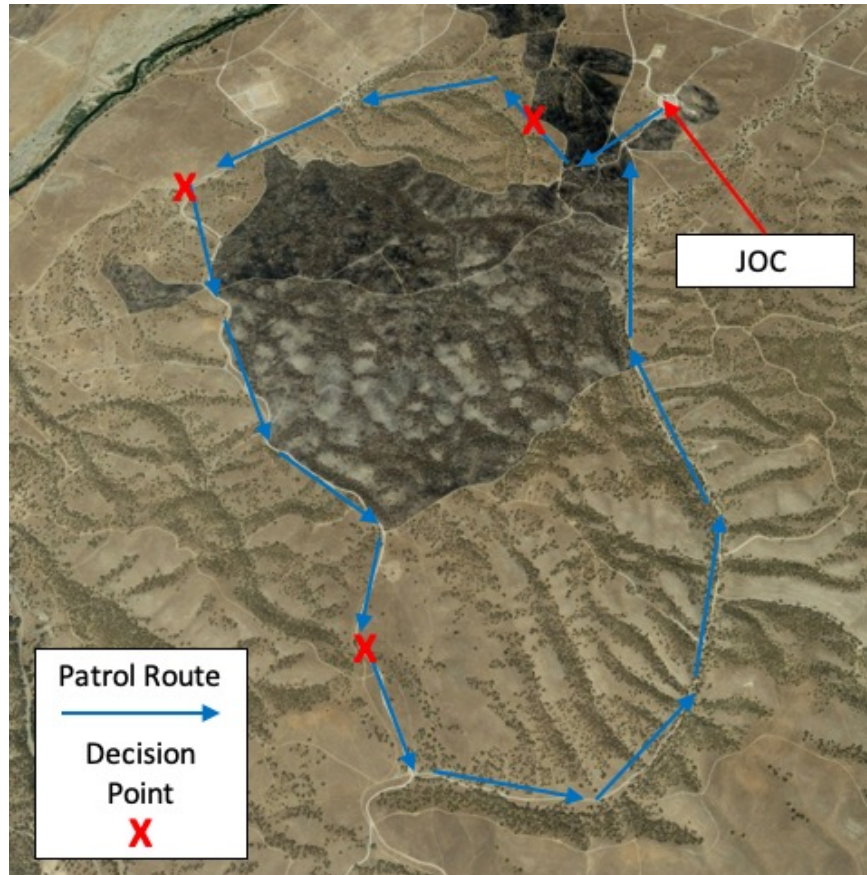


Figure 30. First Field Test. Adapted from Google (2020a).

While monitoring network connectivity from the JOC we moved a mobile node along the patrol route in Figure 30. We monitored link quality along designated routes to observe when we lost connectivity with the JOC radio (via time out delay monitor). Finding these dead spaces prepared us for the next step of the experiment where we captured NOC decision points. We then recorded the required NOC decisions when connectivity between

any node and the JOC was lost. The observed decisions were: continue mission and regain connectivity further along route, halt mission while dropping a relay to ensure connection to JOC, or re-task a tactical unit to provide relay capability for the priority node.

We configured an unmanned ground vehicle (UGV) to act as a mobile relay during the experiment by attaching the Team 4 radio to the mast of the robot. Although this UGV is programmed to receive waypoints remotely which we opine would work in support of autonomous ground relays, the propulsion system was not working during our experiment timeframe. Therefore, we simulated the ground mobile relay using the UGV's pedestal (dismounted from the UGV) and placed it by hand in locations that would benefit a disadvantaged node. This pedestal configuration for ground nodes is seen in Figure 31.



Figure 31. Ground-based, Pedestal Relay

c. Observations

We observed that our radio and Raspberry Pi device configuration was adequate for our data collection purposes during this field test. The devices captured the data required about the network connectivity metrics and we demonstrated that we could provide that data to a hypernode for implementation in an algorithm. We also learned the decision sequence and options that would enable our hypernode algorithm to determine feasible relay locations. Of note, the relays we used during the conduct of this test were all ground-based relays. This means that we had to observe and use higher terrain to ensure adequate area coverage for our mesh network extensions. An aerial relay that could relocate autonomously based upon network changes and support disadvantaged nodes based on commander's priorities would greatly help to maintain connectivity along the route. Ideally, this aerial relay would be a UA that is capable of hovering in the feasible relay location.

The decisions we observed during this experiment led us to three main decisions the NOC crew had to make during the execution of the simulated tactical maneuver. All of these decisions stemmed from scenarios where the maneuvering teams lost the ability to communicate with the JOC. The available decisions for the NOC to regain connectivity to the node were:

- Continue along route to see if connection is regained
- Place relay to regain communication
- Maneuver another unit to act as a relay (taking unit off task)

These tests were ultimately successful, enabling us to determine key decision points for a hypernode and ensuring that we could capture available metric data about the network during operation. These observed key decision points enabled us to begin development of our decision rules for the algorithm.

D. PHASE 2—ALGORITHM DEVELOPMENT

In Phase 2 we used an iterative approach to develop the algorithm used to position the hypernode as it makes network performance-based positioning decisions. This phase includes both the development and initial bench and lab testing of the algorithm as we prepared it for our initial field testing. Concurrently, we develop a testing scenario that allows us to simulate performance in an environment similar to that of our vignette.

1. Phase 2A—Hypernode Positioning Algorithm Design

a. Purpose

The initial development of the algorithm was to design specific controls for hypernode positioning utilizing the metrics defined earlier. The criteria that were included created a rough formula of position calculation. We iteratively generated several algorithms, each of which improved how performance criteria would be incorporated. Below are the initial position calculation theories.

Feasible Relay Position = ($Latitude_{relay}$, $Longitude_{relay}$), where

$$Latitude_{relay} = \left\{ \frac{\sum_{i=1}^n (lat_i \times weight_i)}{\sum_{i=1}^n weight_i} \right\}$$

and

$$Longitude_{relay} = \left\{ \frac{\sum_{i=1}^n (long_i \times weight_i)}{\sum_{i=1}^n weight_i} \right\}$$

$$\text{Weight Factor} = \left\{ (Priority) \left(\frac{1}{SNR} \right) \left(\frac{1}{Throughput} \right) (Delay_{RTT}) (PacketLoss) \right\}$$

This representative formula for feasible relay position uses a simple weighted average calculation. In this case, the requirement uses the relative position of the ground nodes from GPS to calculate the average position between all of the participating ground nodes. The hypernode would then move to the calculated average. In an effort to include

all of the required metrics, we created the weight factor as a combination of the metrics with the assigned commander's priority. This weight factor is designed to ensure that the average position is weighted in the favor of the most disadvantaged node. Therefore, values that decrease as connectivity worsens are placed in the denominator (such as SNR and throughput), while values that increase as connectivity worsens are placed in the numerator. This results in a larger weight factor for more disadvantaged nodes. Finally, we apply the commander's priority which ensures the higher priority nodes are weighted appropriately. This version of the formula assumes higher priority nodes are assigned larger number for priority, for example, the highest priority node out of four nodes is four.

While this rough formula allows us to describe the intention of the hypernode and demonstrate desired behavior, we chose to program our aerial hypernode through rule based reasoning algorithm composed of multiple levels designed to implement metrics individually based on network requirements instead of all implementing all metrics at the same point in the algorithm.

From here, we shifted to designing and programming an algorithm using rule and case based reasoning. This method would allow us to use a more elegant programming capability which flowed from case to case while logically searching through each case using rule based reasoning. This allowed us to use specific variables and assign rules to the measured (or assigned) variable. For example, in a simple decision scenario, we might use rain as a metric for decision-making. If someone wants go outside, they may check if it is raining. The answer to this question determines if they go outside with an umbrella. Figure 32 presents a simplified example of this technique.

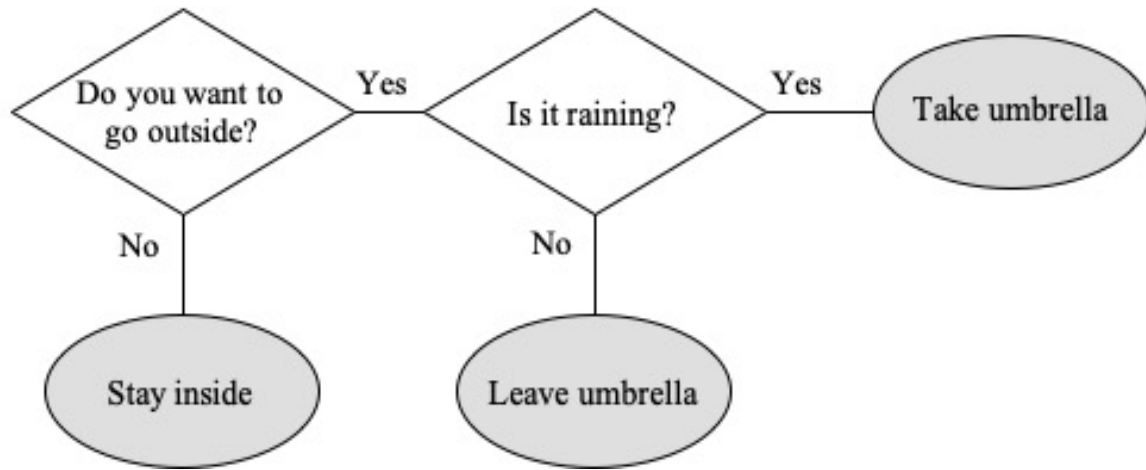
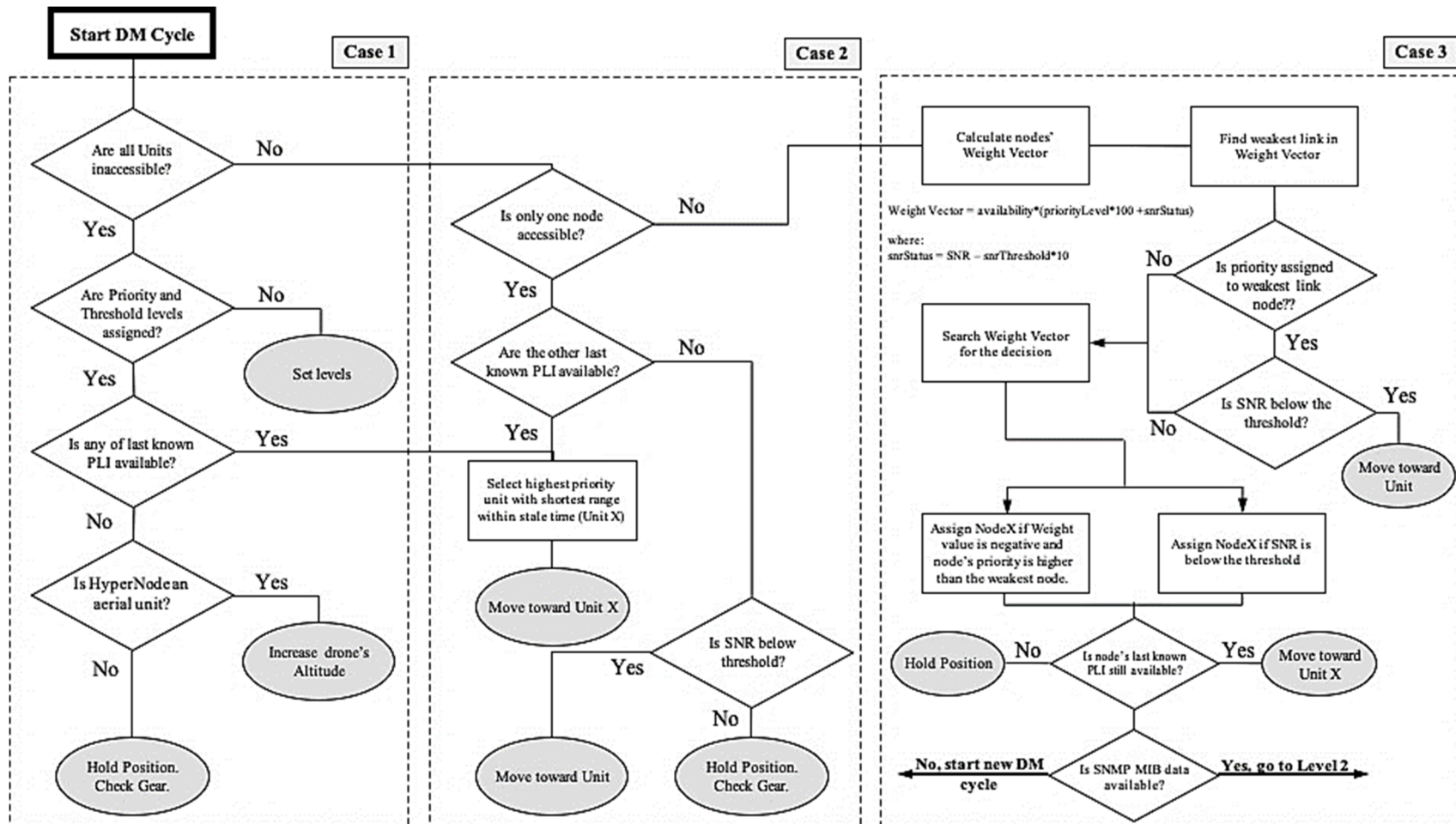


Figure 32. Simple Decision-Making Algorithm

Our algorithm includes multiple cases that work through rule based decision trees similar to Figure 32. We began our design by working through the initial layers of metric which we wanted to use for decision-making. As discussed in Chapter II, the metrics we chose are associated with selected layers of the OSI model. We used different algorithm levels to ensure we managed the metrics at the appropriate level through the design process. The first algorithm level focused on the use of SNR to measure availability, which acts at Layer 1 of the OSI model. We also chose to measure node position during this level of the algorithm as moving the node is the basic function of the hypernode decision process that sustains continued connectivity.

We began with a basic design for the algorithm, as shown in Figure 33. The algorithm is intended to enable an aerial hypernode to autonomously reposition itself according to the protocols that prioritize the required QOS for each ground node in order to act as a relay to maintain communication pathways.



Level 1 Focus – Accessibility, Priority, SNR Threshold, Location Range

Figure 33. Hypernode Decision-Making Algorithm, Version 1

This algorithm used “If-Then-Else” statements to ensure that there were ground nodes connected to the network which might need the hypernode to act as a relay between the ground node and the unit’s JOC. Once it verified that one or more nodes are connected to the network the algorithm used the assigned priorities and measured metric of SNR to calculate a vector for each node. This *weight vector* enables the hypernode to assess the relative connectivity of each node with respect to its current priority. The hypernode would then output a decision to the hypernode display interface. This interface is shown in Figure 34.

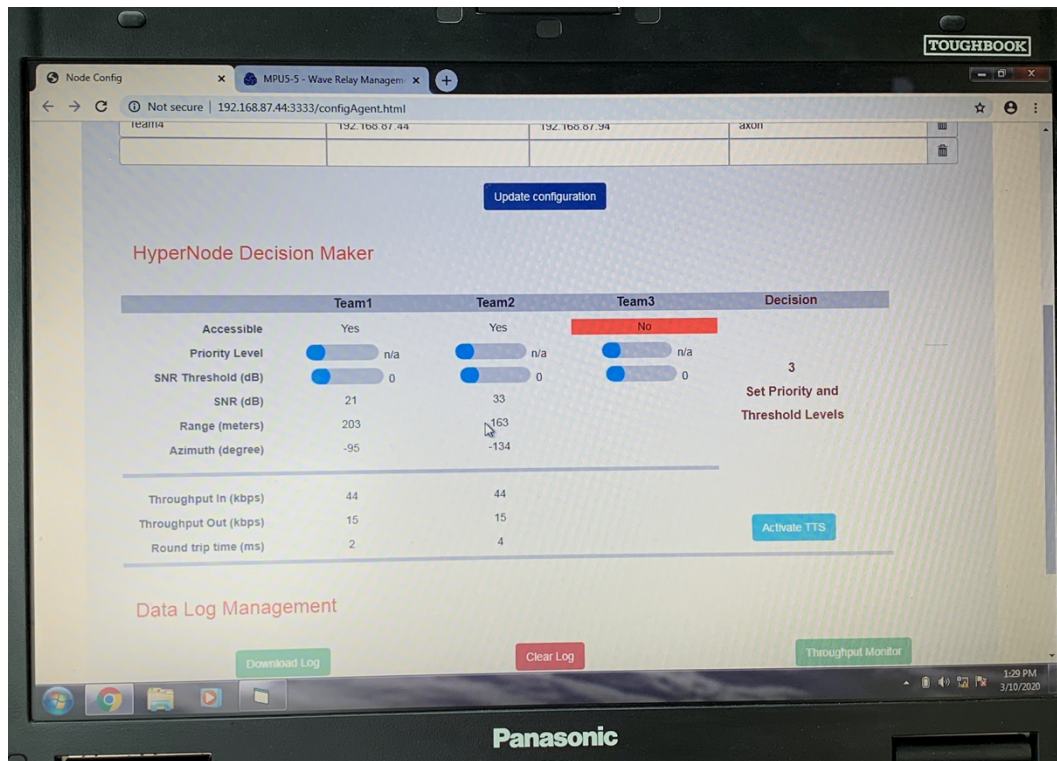


Figure 34. Hypernode Decision-Making Interface

b. Method

We began a series of bench tests using Version 1 of the algorithm. We tested our algorithm with the goal of ensuring that the decision-making software output the desired decision in scenario situations. For example, in one of our tests we placed two ground

nodes near the hypernode with decreased radio power settings (simulating increased distance). We then adjusted the priority settings on the interface to reflect the assignment of relative QOS priorities for each node. Additionally, we varied the SNR threshold to ensure that the hypernode was adjusting accordingly.

c. Observations

During this initial testing we observed various issues that would require refinements in Version 2 of the algorithm. These issues pertained to mesh network connections and relative priority formatting.

The first issue we experienced related to the mesh nature of the MPU5 radios and the requirement for a direct (non-mesh) connection to the hypernode. This means that while nodes may be connected to the network, they may not be directly connected to the hypernode. In other words, any node could be connecting through another one or more nodes, and not be connected directly with the hypernode. In such a case, it would be impossible to use SNR as a valid metric for hypernode connectivity, since nodes that are not directly connected do not have an SNR measured between them in the Persistent Systems interface. This issue directly impacted Version 1 of the algorithm because of the simple “ping” test used to verify availability of the nodes. However, just because a node was available, did not mean that it had a valid SNR measurement to the hypernode that could be used for Weight Vector calculation. We need to account for this lack of direct connection in future iterations of the algorithm.

The other issue we noticed with the algorithm during initial testing is more intuitive. We initially set priorities so that the highest priority number related to the highest priority node(s). As we discussed what “priority” means to a commander we changed this visually in the interface. For example, a commander’s highest priority unit is typically the FIRST priority; therefore, in future iterations of the algorithm and its display interface, we will use 1 as the highest priority, 2 as the next priority, and so on.

Finally, we recognized the need to change some of the calculations themselves, specifically the weight vector. The weight vector is a vector calculated for each node that enables the algorithm to compare it to the other nodes. Once the vector is calculated, the

hypernode algorithm uses the values in the weight vector to search for a decision. In our case, the node with the lowest weight vector is the most disadvantaged node.

Version 1, weight vector calculations:

$$\text{Weight Vector} = \text{availability} * (\text{priorityLevel} * 100 + \text{snrStatus})$$

where:

$$\text{snrStatus} = \text{SNR} - \text{snrThreshold} * 10$$

and

$$\text{availability} = 1 \text{ (if available) or } 0 \text{ (if unavailable)}$$

Version 2, weight vector calculations

$$\text{Weight Vector} = \text{availability} * (\text{snrStatus} * \text{priorityStatus})$$

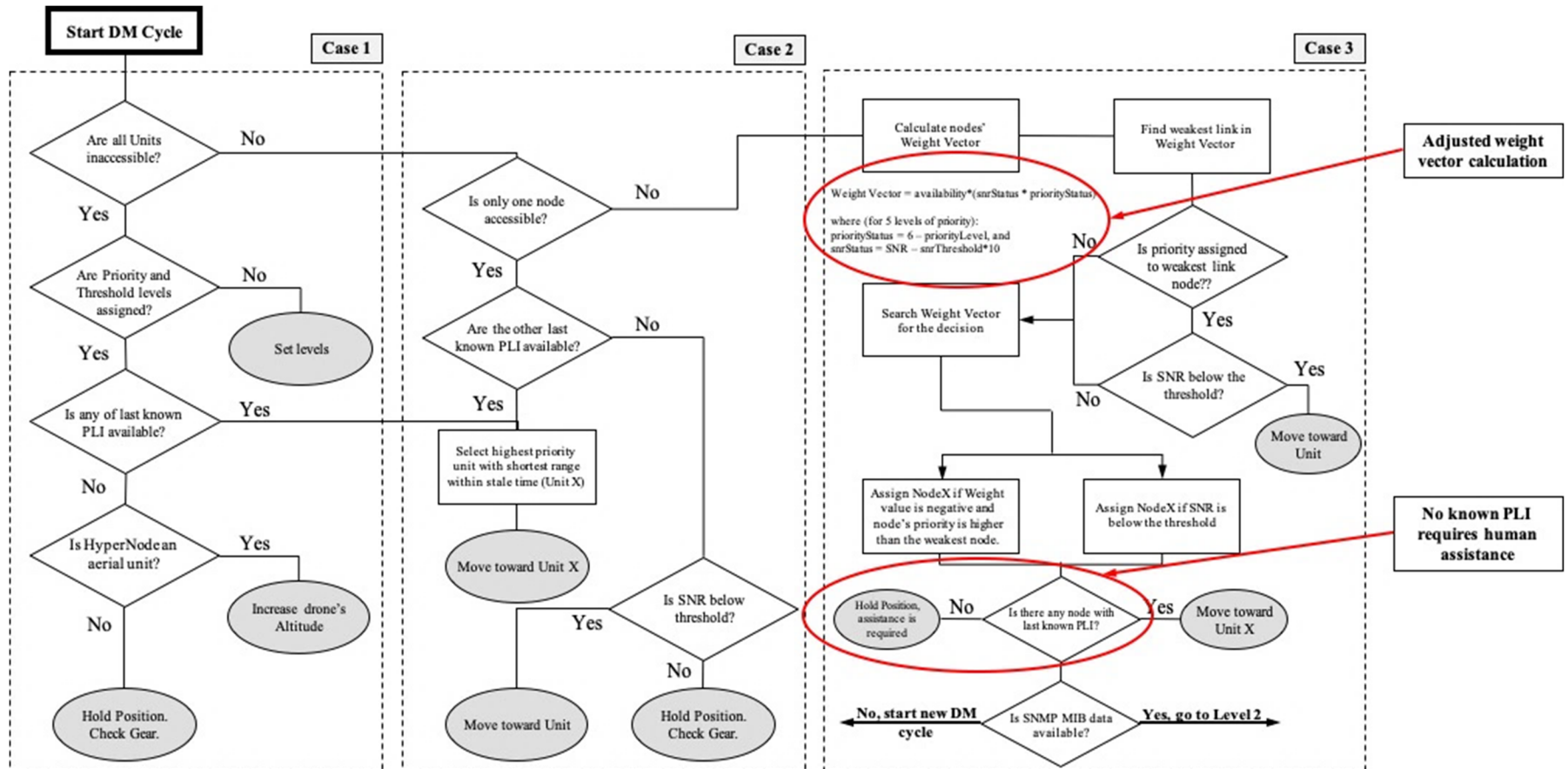
where (for 5 priority levels):

$$\text{priorityStatus} = 6 - \text{priorityLevel},$$

and

$$\text{snrStatus} = \text{SNR} - \text{snrThreshold} * 10$$

These changes to the weight vector enabled us to more accurately calculate the weight vector for each node as it accounts for priority set by the commander. The results of our bench testing resulted in Version 2 of the algorithm, which is presented in Figure 35. This version of the algorithm met our initial expectations for algorithm performance and was ready for implementation in larger testing scenarios.



Level 1 Focus – Accessibility, Priority, SNR Threshold, Location Range

Figure 35. Hypernode Decision-Making Algorithm, Version 2

2. Phase 2B—Scenario Development

Much of our scenario development focused on the general concept for what tasks that we assessed were feasible for the hypernode to perform in a simulated tactical environment. The opening vignette imagines squads moving through a battle space with requirements to maintain links to higher headquarters. I envisioned this as I designed experimental scenarios for the employment of the hypernode. With the equipment available we were able to incorporate five total nodes. These comprised a NOC, three mobile teams, and one hypernode relay. We ran many scenarios using this configuration, with the understanding that the mobile nodes would have their priority set by the commander, and the threshold for SNR would be determined according to the communication requirements of the unit. For example, if a unit required full motion video to complete its mission, it may require a minimum SNR threshold of 40 dB. A lower priority node may be relegated to only a chat function, which would warrant a threshold of 10 dB. This combination of priorities and thresholds would enable the units to maneuver freely while the hypernode made dynamic relay position recommendations to the NOC.

Our original scenario design envisioned an aerial hypernode as shown in Figure 36.

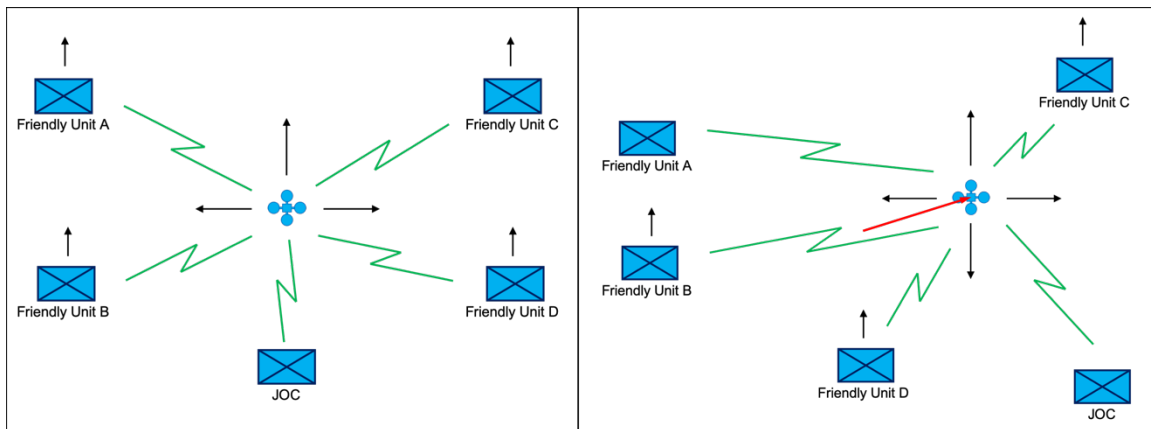


Figure 36. Initial Hypernode Relay Scenario Design

The left side of Figure 36 depicts the initial state of the ground nodes and the aerial relay hypernode. On the right side of Figure 36, the ground node positions have changed

and the red arrow depicts the movement of the hypernode relay to continue support for the ground nodes. In this scenario, the hypernode repositions based on network performance feedback as it tracks units moving through the operational environment.

However, we were limited in the execution of our scenario by the withdrawal of an exception to policy in the Department of the Navy which allowed use of Office of Secretary of Defense banned drones. As such, we were unable to use the drone we had planned for aerial testing. However, we were able to modify scenarios where we move the hypernode at ground level, either by foot or by vehicle, enabling interaction with the other nodes for testing. These other nodes will be stationary for initial testing of the hypernode performance and mobile for advanced testing scenarios.

E. PHASE 3—ALGORITHM PERFORMANCE TESTING

While the algorithm was tested during development, once we refined it to the point that we were comfortable with how it was working, we decided to do a few bench tests to confirm expected operation.

1. Purpose

The purpose of this bench test was to confirm algorithm operations and processing. We specifically needed to verify that the issue with indirect node connections, that is, connections via mesh, was resolved.

2. Method

In the previous phase, the hypernode processing happened on a desktop computer allowing ease of software design. The first step in this phase was moving this software onto the Raspberry Pi computer board of our hypernode. Once we loaded the software on the hypernode computer, we placed the hypernode on the roof of a six-story building to increase its coverage area. We then moved nodes around in the coverage area to increase and decrease SNR to the hypernode while adjusting required threshold levels at the hypernode control interface. This enabled us to verify that the hypernode made correct decisions and recommendations in given scenarios. Additionally, we decreased the power at the nodes and allowed them to only connect to the hypernode via the mesh radio

capability. This was done in order to verify that the hypernode recognized that the individual nodes were not directly connected. This endeavor was successful.

3. Observations

The hypernode functioned as desired during this bench test. The issues identified during the initial algorithm development and testing were resolved and the hypernode is ready to conduct initial field testing in a more distributed environment. We ended Phase 3 upon determination that we resolved the identified issues.

F. PHASE 4—HYPERNODE FIELD TEST

1. Purpose

The purpose of this phase was to verify hypernode performance on small scale in a field environment. Specifically, we wanted to test whether the hypernode would recognize different input parameters and recommend a feasible relay opportunity accordingly. We also wanted to test performance while the hypernode was physically moving. For the purposes of this test, the supported nodes remained stationary. This allowed us to eliminate potential impacts from multiple nodes moving simultaneously.

2. Method

We established two elevated, stationary nodes that would act as the supported units during this test. These nodes were placed in locations such that they would be obstructed at times to allow robust testing of the algorithm design and ensure that the algorithm generated appropriate recommendations. Additionally, we designed an interface by which we could monitor the hypernode during operation. This interface was accessible through a web portal configured on the hypernode which we accessed through a connected computer. With the understanding that the hypernode is intended to move and reposition itself, we did not want to connect another computer directly to the hypernode. We decided to use an additional radio to connect to the hypernode mesh enabling connectivity through a laptop. A diagram of this experiment configuration can be seen in Figure 37.

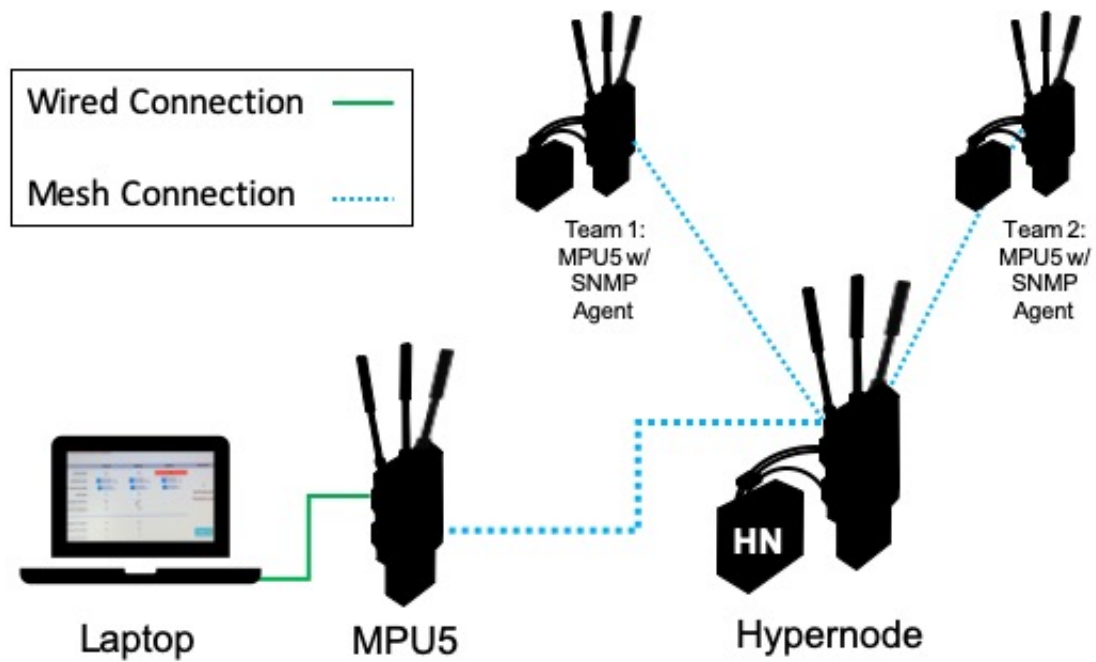


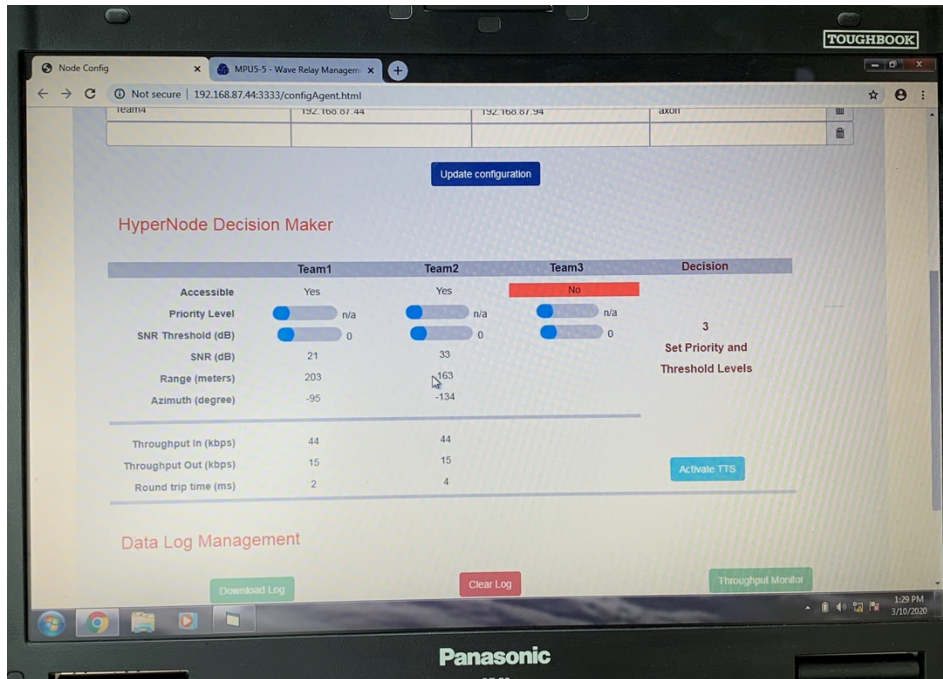
Figure 37. Logical Hypernode Test Configuration

For the purposes of this test, we used a vehicle to create a mobile hypernode. We attached the hypernode to the roof of the vehicle, as seen in Figure 38, and placed the monitoring interface computer and attached radio inside the vehicle.



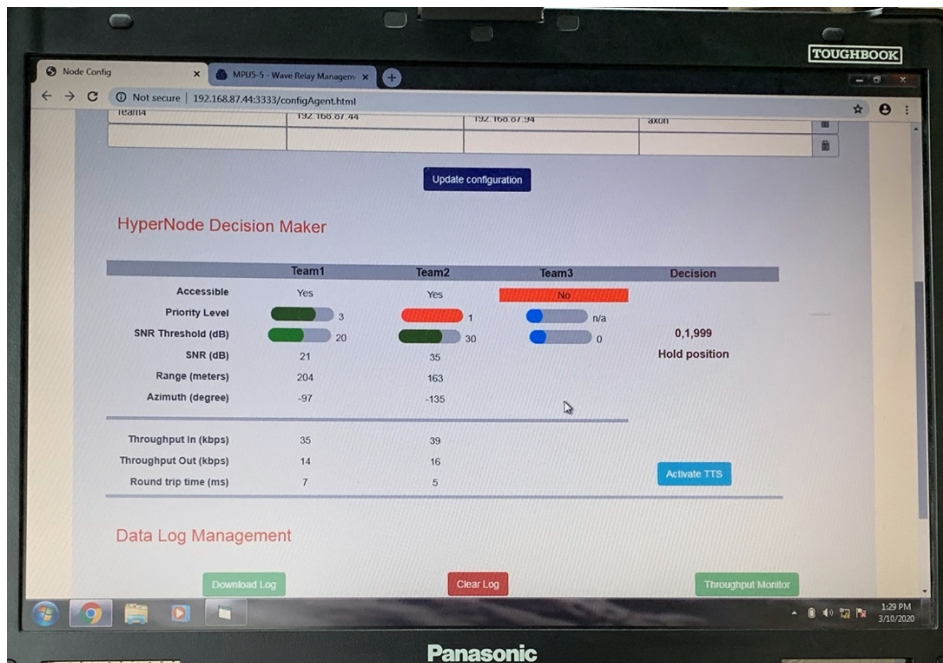
Figure 38. Hypernode Mounted to Roof of Author's Truck

Once the nodes were in place and the hypernode was turned on we began to work our way through the algorithm. The first step was to assign priorities and SNR thresholds to the nodes as seen in Figures 39 and 40.



No priorities or thresholds applied to the nodes for Team 1 and 2.

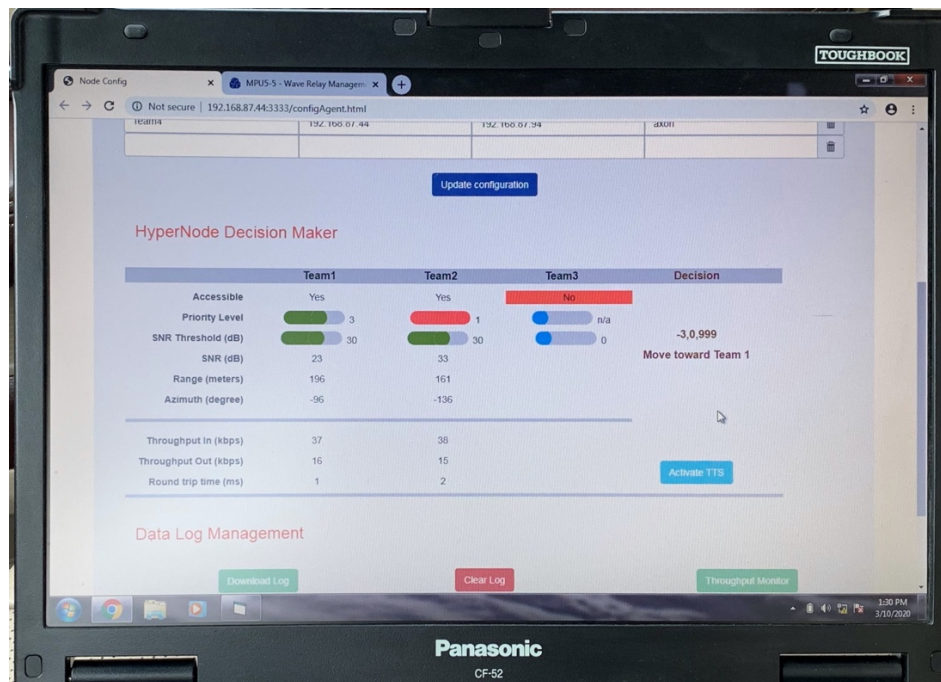
Figure 39. Priority and SNR Threshold Assignment



Team 1 and Team 2 have assigned priorities and thresholds. Of note, both nodes meet connectivity requirement so algorithm calculates relay should hold position.

Figure 40. Priorities and SNR Threshold Assigned

Once we had assigned initial priorities and thresholds the first position recommendation was for the hypernode to remain in position. This means the SNR thresholds were met for each of the two supported nodes. The next step was to test the hypernode algorithm by assigning an SNR to a node that was clearly above the current SNR level, indicating that its connection to the hypernode relay was insufficient. To do this, we assigned Team1 an SNR threshold of 30 dB, which is higher than the current SNR of 21 dB, and can be seen in Figure 41. We expect the hypernode to recommend moving towards Team1 in an effort to strengthen the link.



Team 1 threshold increased to 30 dB (this is higher than current 23 dB SNR). This results in calculated decision to move towards Team 1.

Figure 41. Adjusted SNR Threshold

The hypernode made the recommendation to move towards Team1. The initial and new position node locations are depicted in Figure 42.

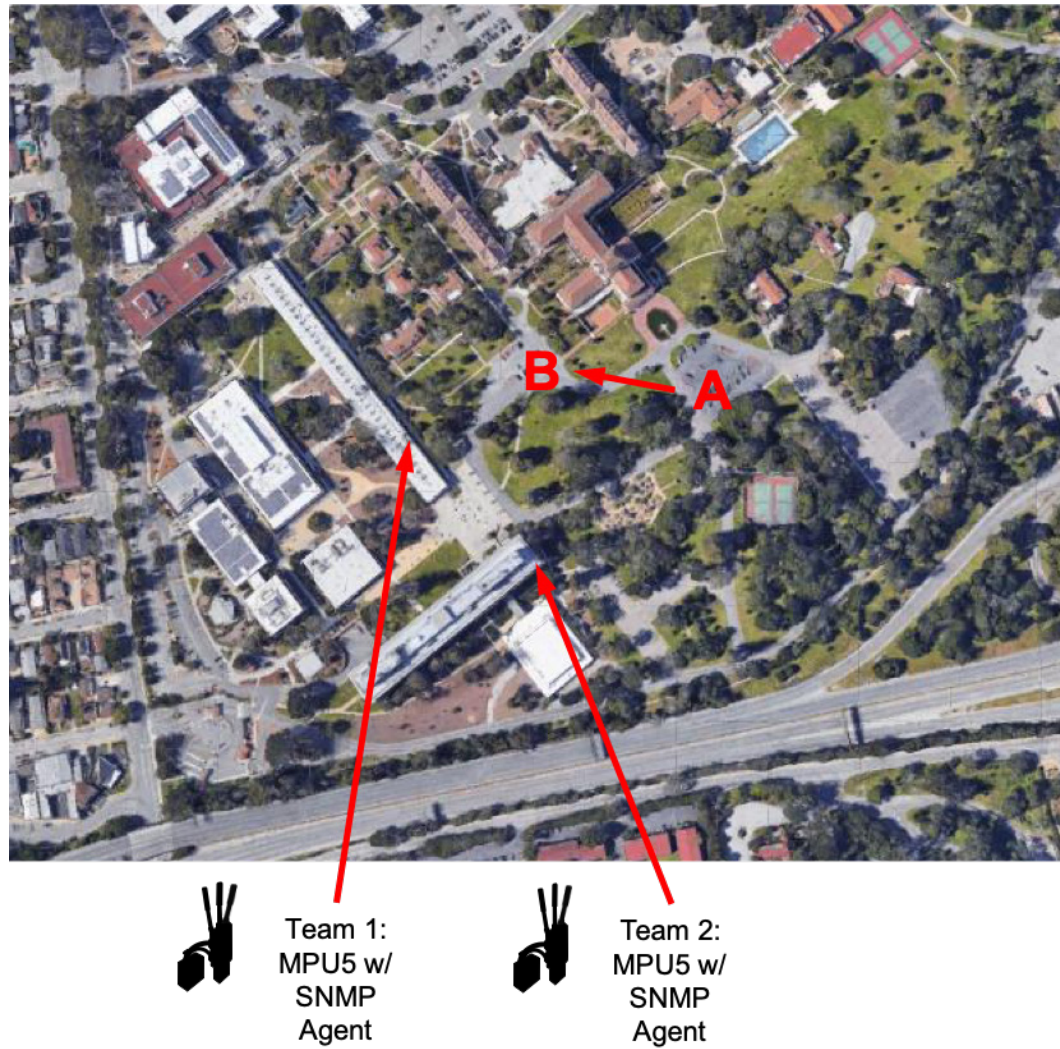
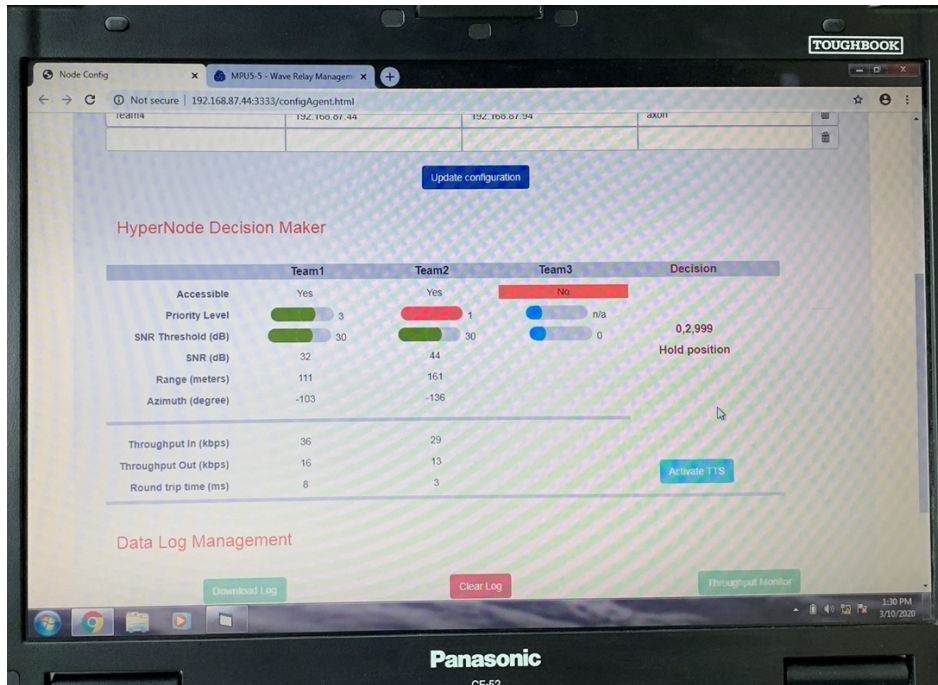


Figure 42. Node Position Overview for Hypernode Field Test. Adapted from Google (2020b).

In Figure 42, position A indicates the starting position for the hypernode, while position B indicates the first calculated feasible relay position for the hypernode. Moving toward Team1 increased the SNR between Team1 and the hypernode to an acceptable level while maintaining the required SNR threshold for Team2 as seen in Figure 43.



Hypernode recommends “Hold Position” once all connectivity requirements are achieved.

Figure 43. Successful Hypernode Position Recommendation

Once we observed this successful test of hypernode functionality, we also tested the other portions of the algorithm. For example, we tested the function that recommends moving to last known node position when functionality is lost. This worked successfully. Additionally, once the node PLI went stale (we set this threshold at one minute), the hypernode recommended holding position and having human input to continue troubleshooting the network disconnection.

3. Observations

Hypernode performed as designed. It adjusted to the inputs of threshold adequately and accurately. Additionally, it was fairly responsive to changes. The disconnected node functions performed as designed. We ended Phase 4, once we made these observations and determined that the hypernode performed as desired in a field environment.

As the hypernode was vehicle mounted, we observed significantly more interference than we predict we would if the node was on an aerial platform. This is due to the numerous trees and buildings in the vicinity of the local experiment. If the node were

mounted on an aerial platform it would overcome these barriers to line of sight communications and more readily support the ground nodes. Additionally, an aerial node increases the freedom of movement for the ground nodes. For example, in an urban scenario, mobile nodes may be obstructed by buildings as they move through a city. If the relay is at ground level the potential for obstruction is increased, as in Figure 44. If the relay is elevated (aerial) there is less potential for obstruction meaning that the hypernode is better able to adjust to all of the supported nodes, as in Figure 45.

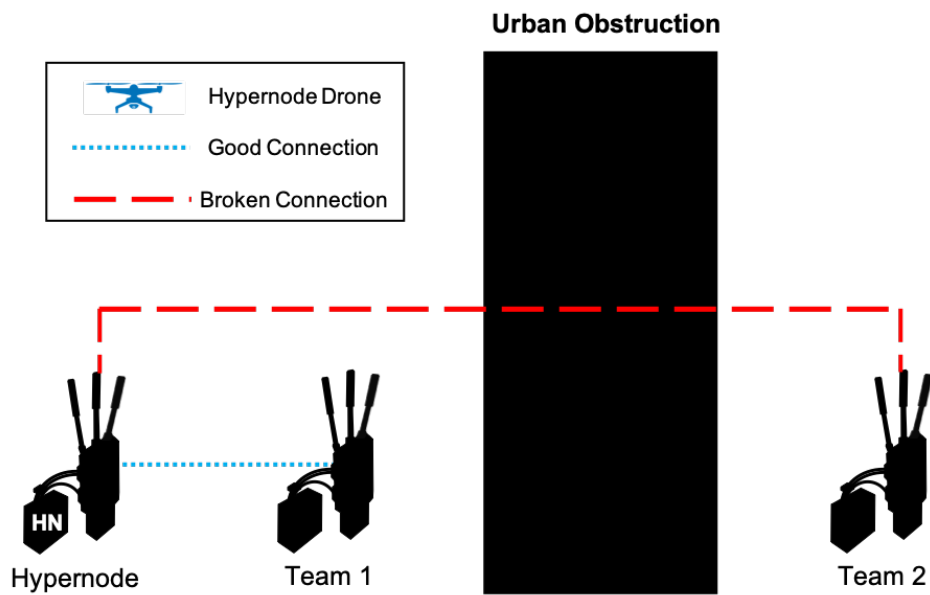


Figure 44. Urban Obstructed Ground Hypernode Scenario

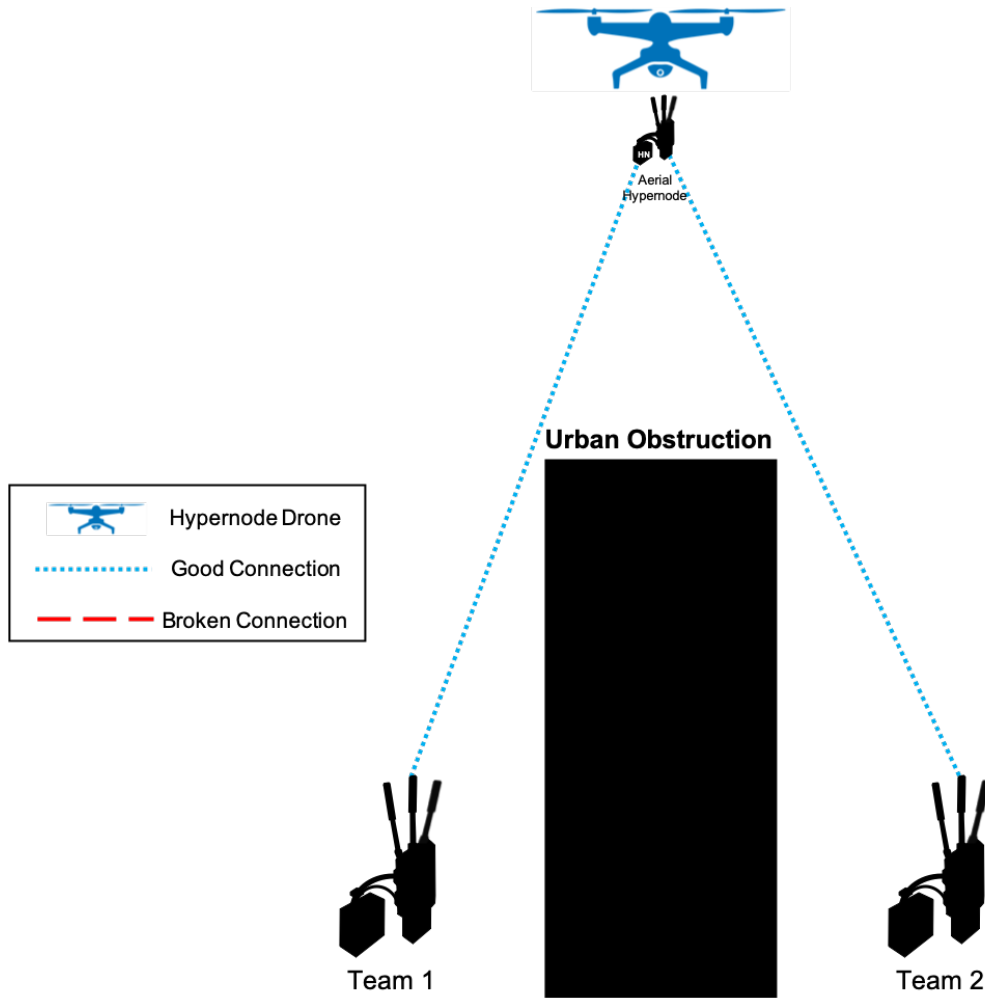


Figure 45. Urban Aerial Hypernode Scenario

G. PHASE 5—ADVANCED FIELD TESTS

The previous five phases enabled us to demonstrate that the hypernode algorithm is able to calculate a feasible position for the relay node. The advanced field tests are the next step to examine the aerial hypernode concept for semi-autonomous network management.

1. Purpose

The purpose of Phase 5 is to measure improvement in data flows in the supported network as the hypernode repositions based on algorithm calculations. We expect to observe data flows across all nodes that meet dynamically set protocols as the hypernode

implements position changes using its algorithm. This phase requires monitoring by the hypernode, the JOC, and the SNMP collection devices at each node in an effort to put the hypernode concept together end-to-end while measuring performance in a challenging field environment.

2. Method

This phase requires the use of the hypernode, at least three mobile ground nodes, and a NOC server for data collection. The NOC will implement the commander's priorities and apply SNR thresholds in order to meet or exceed minimum requirements for QOS, while streaming video and sending chat messages to the distributed nodes. CENETIX software tools will capture the data.

The teams would be represented by the nodes consisting of a radio and an SNMP capture device. We would then tactically disperse the nodes in the experiment area. The nodes will be assigned priorities based on commander's guidance and SNR thresholds based on established requirements for communication. Upon initial network establishment it is necessary to ensure that the nodes are using the hypernode as a relay to the NOC server and that the nodes are each at or above their assigned thresholds. Once we establish that the nodes are at assigned thresholds we will move one node at a time further away from the NOC and the hypernode. The expected result here is that the hypernode calculates and recommends a new relay position. For the purposes of this advanced field test the design calls for the hypernode to be elevated by a drone. The decisions would then be relayed to a hypernode interface monitor and passed to the drone controller who would maneuver the drone based on the hypernode calculated feasible position.

Once a node moves out of range of the hypernode such that the SNR drops below the threshold, three things are expected to happen. First, the hypernode would register that the SNR and communication throughput are no longer operationally adequate. This would be verified at the network node by the experiment team. Second, the NOC receives the calculation of a more feasible new position for the hypernode relay as calculated by the algorithm. Third, a recommended new position for the hypernode would be relayed to the drone operator via voice from the NOC. As the hypernode moves to the new position, it

would continuously calculate new position recommendations until it achieves priority and threshold requirements relative to all nodal links.

The next step in this phase is to allow the ground nodes to move freely and capture data about how well the overall network was maintained during the simulated operation. We believe that the aerial hypernode will improve capability during the operation as the relay maneuvers to support the disadvantaged nodes. It will also ensure that all nodes remain within threshold based on the commander's priorities and communication requirements.

We plan to capture the data about connectivity through the SNMP capture devices at each node, through the NOC server, and through observer observation at the NOC and each node. These observations will be compiled and analyzed to provide final analysis on the employment of the aerial hypernode concept. While the hypernode will receive and make calculations using data from each node, we will also capture this information on local log files at each node for post experiment analysis. These captures will enable us to graphically depict the network activity and changes over time as the hypernode acts on the network. It will also enable us to verify the decisions the hypernode made while calculating new relay positions during experimentation.

3. Observations

Due to circumstances beyond our control we were not able to execute this portion of our experiment. During our planned experiment time we were not able to access our lab equipment in a fashion that would provide us the ability to conduct the required observations and data capture for this phase. The requirements to operate within close proximity to the rest of the experiment team and share equipment and workspace prevented us from executing the final phase of our proof of concept. However, the results produced in Phase 4 indicate that the hypernode algorithm would perform as expected during aerial employment.

IV. ANALYSIS

This chapter provides analysis of the experimentation results as they apply to the central and supporting research questions. It addresses the capabilities gained from the employment of a hypernode in a tactical communications network architecture.

A. RESEARCH OBJECTIVE

The research goal was to improve tactical network management by exploring the feasibility of an aerial hypernode to perform selected network management functions, through the employment of an algorithm. The research advances the hypernode concept by generating and testing an algorithm that dynamically calculates successive relay positions based on network node metrics collected through SNMP feedback. It answers the central research question: How can autonomous aerial hypernodes contribute to information flow optimization in tactical networks?

In order to optimize information flows it was first necessary to determine the criteria that govern data flow through tactical communication networks, and to measure them. It was then possible to examine ways to optimize the geographic positioning of a hypernode to act as a network relay. This led to two supporting research questions: What NOC network management functions could a hypernode perform effectively? What performance metrics are necessary for a hypernode to manage tactical network data flow? I focused initial efforts on down-selecting and assembling the hypernode components and generating the hypernode algorithm. We conducted an iterative experiment process to answer our research questions. The research culminated with the hypernode dynamically calculating feasible relay positions.

In order to build the analysis in a logical sequence, Supporting Research Question 1 will be discussed first to explain the network management function that was selected as the experimental exemplar. It will be followed by discussion of Supporting Research Question 2 as analysis of the associated metrics upon which the algorithm operates. The answers to these supporting research questions provide context for discussion of the main research question.

B. HYPERNODE NETWORK MANAGEMENT FUNCTION

This section addresses the supporting question: What NOC network management functions could a hypernode perform effectively? Observing both decision-making processes and network management functions enabled this analysis.

During the field tests in Phase 1, we generated tentative required decisions for NOC crews that are important to maintaining tactical network communication to achieve specified protocols. These decisions were observed in a realistic environment. While two of the three decisions involved establishing a relay, we suggest a role for the hypernode to fill is to position itself as a relay to aid in regaining and maintaining network communication. The two decisions we ruled out involved taking a unit off task to act as a relay or continuing mission with the hopes of regaining communication. We ruled these two decisions out due to potential adverse impacts to the mission. The hypernode positioning itself as a relay to improve network connectivity does not impact the ground units' ability to move within the environment.

The positioning of a relay is a decision that falls to the NOC crew, and is within the NOC functional area of Configuration Management. Configuration Management is a challenging process for NOC crews. Changing configuration on an active network requires detailed documentation and understanding throughout the NOC, as small changes may have larger, unintended impacts across the network. As the NOC crew determines what challenges the operational environment presents, it is their recommendation to the commander that drives the positioning of a relay to enhance the battlefield network.

In the case of our scaled-down, experimental, tactical network, we suggest that it may be possible to delegate some control over configuration management to the hypernode. The hypernode could autonomously enact physical position changes to support the network. These changes in relay position support increased network performance by simultaneously and continuously calculating the links between the hypernode relay itself and each ground node. This means that the relay position decision is a pivotal, functional role for the hypernode to perform. Once we analyzed the decisions we observed during this

field test, it was clear that an algorithm was needed to support this configuration management role for the hypernode.

During Phase 4, we observed this configuration process from the perspective of the hypernode. Repositioning of the hypernode relay to maintain network performance using the assigned protocols. Keeping performance metrics within the boundaries of these protocols enabled improved network connectivity among nodes. The MPU5 radio system enabled dynamic movement of the relay. The hypernode calculated a relay position for itself in real time which improved SNR and maintained connectivity for each node within required limits. This required a dynamic network capability, such as MANET technology, which allowed dynamic changes to network configuration, and ensured effective links between nodes.

C. NETWORK PERFORMANCE METRICS

This section addresses the supporting question: What performance metrics are necessary for a hypernode to manage tactical network data flow? Various metrics were tested in order to determine which were necessary as baseline inputs to calculate successive relay positions. Data on additional metrics were collected for subsequent refinements to strengthen the hypernode's relay location selection.

The developed algorithm enabled the hypernode to make sense of the network performance data it collected and used that data to adjust its position to act as an effective relay. The algorithm employed the metrics of SNR and GPS position to calculate a subsequent, feasible location. The hypernode interface output from the initial and subsequent relay location are shown in Figure 46.

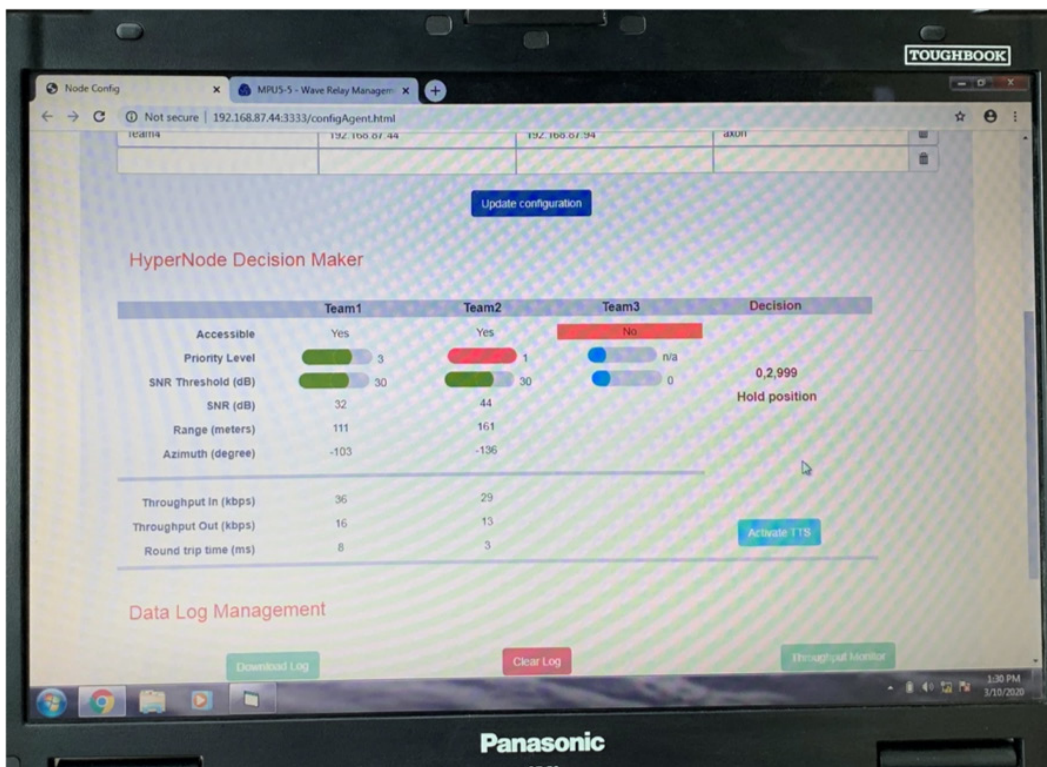
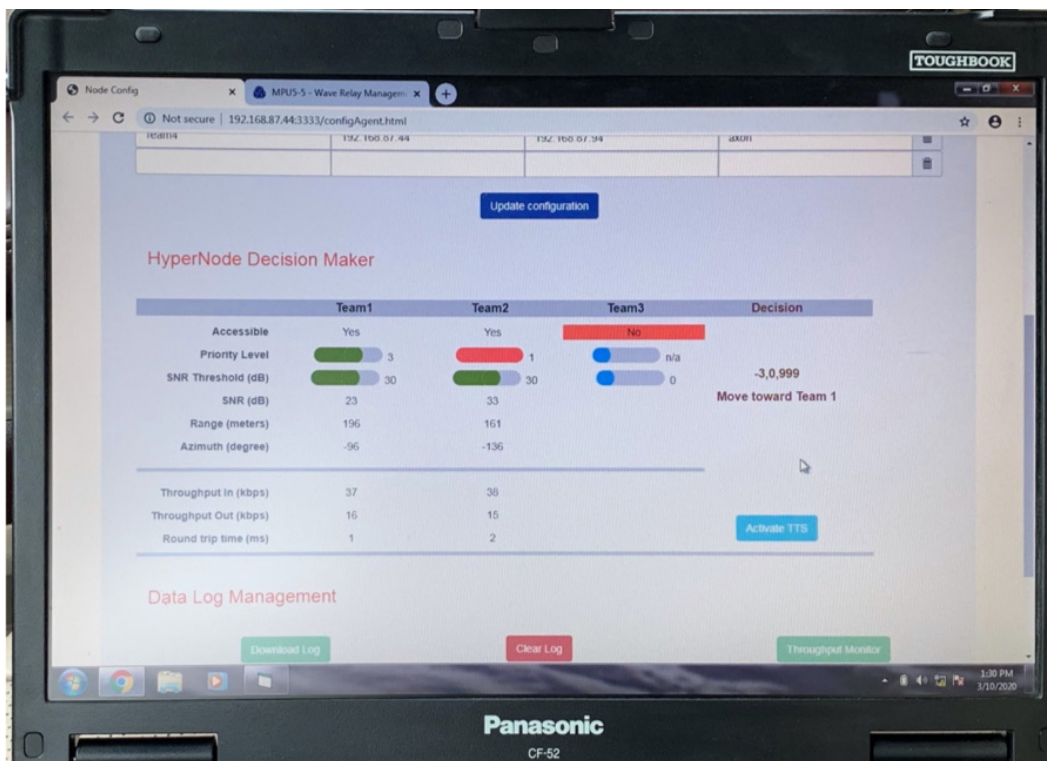


Figure 46. Hypernode Decision-Making Interface Comparison

In Figure 46, the image on the top shows the metrics for Team1 and Team2 as well as the hypernode calculation that movement towards Team1 is required. The image on the bottom shows the metrics for Team1 and Team2 with the calculation that the hypernode can now hold position.

The subsequent feasible location resulted in an SNR improvement of 9 dB for Team1 and 11 dB for Team2. Additionally, as is visible in Figure 46, the impacts to the other metrics are shown. While we collected data about the other metrics, we did not employ them in the hypernode algorithm; they were beyond the scope of the first level of algorithm position calculation. This simplification provided the baseline metric required to achieve a nominal feasible relay location. Though this initial solution set was not optimal, it served to satisfy all of the specified network priority and connectivity requirements within the established boundaries. We assess that the metrics of SNR and GPS position are the minimum necessary for feasible management of tactical data flow. While additional performance metrics are important to maintain multiple levels of QOS, they were not necessary to calculate a nominally feasible relay position.

1. Additional Metrics

The additional metrics that could enhance the algorithm include packet loss, round trip time, and throughput. These would enhance the accuracy of the relay position further limiting nominal feasibility. We demonstrated the ability to measure each of the suggested metrics in Chapter III. The additional metrics could be employed to strengthen successively more detailed levels within the algorithm. In Chapter II we compared our suggested metrics to the OSI model, providing a starting point for the levels we suggest. For example, the basic level of our algorithm calculated a feasible relay position using only the metrics of position and SNR. Once this initial feasible relay is achieved, the algorithm could move on to process the next level. We suggest that processing at separate algorithm levels decreases the time to achieve a feasible relay position while allowing additional position refinement over time.

Processing at level two could calculate additional refinements by applying throughput levels. Adding the throughput metric would improve performance by directly

correlating achieved throughput to protocol requirements. Once a new feasible position is achieved using throughput, further position refinement at level three uses the delay metric. Adding this metric serves to reduce overall system delay. We would then use the loss and error metric at level four of the algorithm. These proposed, additional algorithm levels correspond directly to the layers of the OSI model we associate with each metric in Chapter II.

We suggest that the implementation of these algorithm levels should improve the network management function of the hypernode by consistently refining the inputs to the algorithm and the relay position calculation. The additional performance metrics will allow the hypernode to make more finely tuned adjustments to the initial feasible position in an effort to achieve a more optimized network flow solution. Using the OSI model as a reference for our algorithm levels will directly align the hypernode with current IP traffic flow protocols in use across tactical networks.

2. Multi-variable Optimization

Additional metrics and variables could enhance the network management function. These variables are also pseudo-criteria, in that they should be considered when planning to optimize network performance, but do not necessarily need to be optimized themselves. However, these would be more challenging to implement. When considering variables that impact network connectivity, it is necessary to design networks to support forces operating in hostile and austere environments. One must consider enemy capabilities, the weather, friendly force posture, etc., when developing future network management criteria and pseudo-criteria (M. Akin, personal communication, March 3, 2020). Adding this level of complexity makes it more challenging to determine a feasible solution set.

A potential solution to this more challenging problem involves the use of optimization techniques used to solve complex, multi-variable problem sets. In our hypernode algorithm, uses two of the five network management metrics we selected in Phase 0. Implementing all five metrics in the algorithm would increase the hypernode's calculation requirement. This would need to employ an additional method for identifying both the feasible and optimal solution sets to the relay positioning problem.

For example, in the baseline algorithm, in addition to the SNR threshold, a network manager could set parameters concerning the delay between the ground node and the NOC. This means that as the delay between nodes reaches an unacceptable level, the hypernode must reposition to decrease this delay. Once this pseudo-criterion is included in the position calculation, the hypernode would apply it as it calculates a new relay position. Applying the PSI method to our algorithm could result in more efficient use of multiple variable inputs to the hypernode algorithm

D. AUTONOMOUS AERIAL NODES

This section provides analysis that directly contributes to answering the central question: How can an autonomous aerial hypernode contribute to information flow optimization in a tactical network? It addresses the impact that an aerial hypernode could have on information flow within tactical networks through the lens of our experimentation.

During the conduct of Phase 1 we did not have access to UAS for testing. In this phase, the relays we placed to ensure connectivity with the ground patrols required that we identify suitable terrain to employ a relay. This meant searching for elevated positions that would provide radio connectivity to large portions of the patrol area. Through the use of ground nodes, we learned that an aerial node could be impactful in rugged environments because it needs not address terrain issues to perform relay function. Ensuring that an aerial node remains at, say 400 feet altitude, will improve its line of sight. This should enable unencumbered connectivity to the majority of ground nodes with potentially less direct interference from buildings, terrain, and foliage. If we had access to a UAS for the aerial node relay, it would already be elevated.

During Phase 4, we again observed the potential value of an aerial node. As the testing occurred using a vehicle-based ground hypernode, it experienced significant interference from obstructions as the hypernode vehicle moved through the testing area. As demonstrated in the observations from Phase 4, elevating the hypernode would help to overcome these connectivity challenges and increase network resiliency.

We were not able to execute Phase 5 of our research. However, the concept envisioned a UA autonomously repositioning itself within designated altitude limits. For

experimentation purposes, a UA controlled by a human operator would have served as a surrogate to autonomous flight. While Phase 1 and Phase 4 suggested that using an aerial node is preferable for the employment of this hypernode concept, our design and planning for Phase 5, supported the idea of a hypernode operating as a payload on a drone with the capability to reposition itself throughout the operational area.

E. TACTICAL EMPLOYMENT

The opening vignette of Chapter II discussed the requirement for Marine Corps squads to operate in challenging environments while dispersed. We suggest that providing the battalion communications officer with an aerial hypernode capability would increase the NOC's ability to dynamically manage the network as the squads move through the operating area. If each squad leader used a mesh capable radio an aerial hypernode would have the capability to dynamically reposition itself to improve information flow as a performance and configuration management function. This would free the battalion communications officer to more proactively observe the network configuration changes implemented by the hypernode's autonomous repositioning. Adding a hypernode to his network does not relieve the battalion communications officer of the requirement to monitor the network; but it provides him a valuable tool to prevent network outages.

F. IMPLICATIONS

The analysis brings to light some implications regarding the use of hypernodes and the impact on network management. The potential impact of aerial autonomy and the application of multiple hypernodes to larger networks is discussed in this section.

1. Aerial Hypernode Autonomy

Our algorithm applied SNMP enabled measurement of network performance to calculate the best location for an aerial hypernode relay to support a tactical network based on required performance protocols. It was not within the research scope to investigate automated UAS flight based on guidance calculated from performance metrics. However, by leveraging the frontseat-backseat systems architecture, we conceptualize the systems architecture seen in Figure 47.

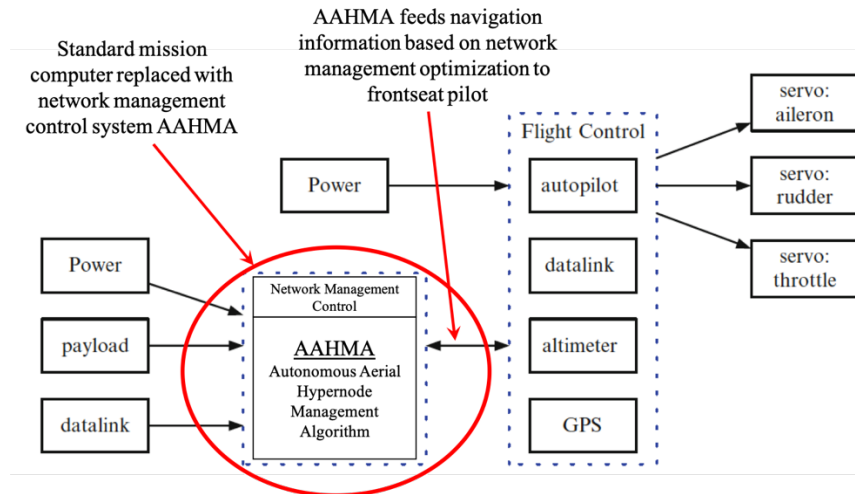


Figure 47. Conceptualized Frontseat-Backseat Hypernode Implementation. Adapted from Pippin (2015).

In Figure 47, we replace the mission control system with the network management algorithm, termed Autonomous Aerial Hypernode Management Algorithm (AAHMA), which was developed as part of this research. Because we use a frontseat-backseat systems architecture, the hypernode design can be substituted as the mission control system (the backseat). Of note, this does not implement changes to the frontseat controller, we merely use hypernode feedback to provide guidance to the FCS from the backseat. Backseat guidance will be developed purely based on network monitoring information sensed by the hypernode and calculated by the algorithm. The NOC could dynamically modify the communications priorities and parameters on the hypernode, as required. This configuration would enable a network to be optimized by an autonomous aerial hypernode.

2. Addressing Networks at Scale

Networks vary in physical space and quantity. It is likely that multiple hypernodes would be needed to maintain acceptable network connectivity in larger operating areas. This problem of scaling might potentially be solved by a committee. The approach would be to add additional hypernodes to the network that would coordinate directly with one another for increased network management, what we call the “hypernode committee.”

a. Hypernode Committee

Identifying the appropriate method for coordination among multiple hypernodes is more challenging. The potential solution to this second approach involves group decision-making theory. During the research we identified decision support models that allow the hypernode to make decisions about network performance and configuration management. We considered RBR and CBR, because those methods were directly applicable to the algorithm. However, increasing the number of hypernodes (participants) in the network, introduces the requirement to calculate how the hypernodes coordinate. The hypernode algorithm in our research follows along the lines of the team structure (Figure 48).

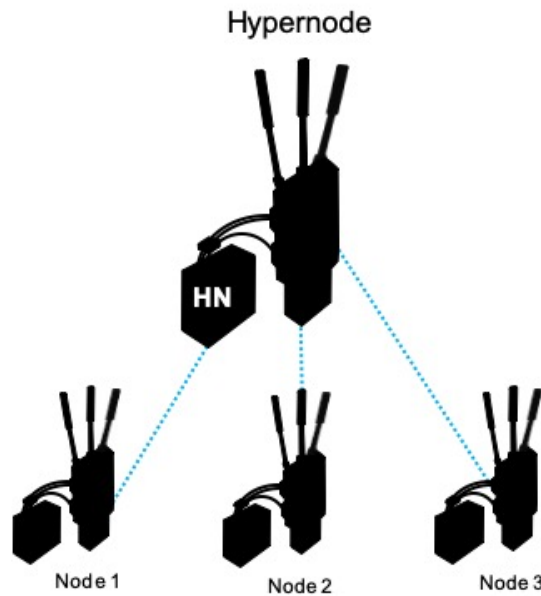


Figure 48. Team Hypernode Management Structure

The hypernode acts as the decision maker and the ground nodes are participants in the network. As discussed in Chapter III, the ground nodes are not controlled by the hypernode, they merely provide the network performance metrics to the hypernode enabling it to calculate and reposition itself to better support the ground nodes. In fact, they do not have any direct interaction other than to provide data to the hypernode for position calculation.

Introducing additional hypernodes to the network creates a group structure within the network. The group structure consists of a group of team hypernode management structures, with hypernodes each working to manage their respective supported ground nodes, as seen in Figure 49.

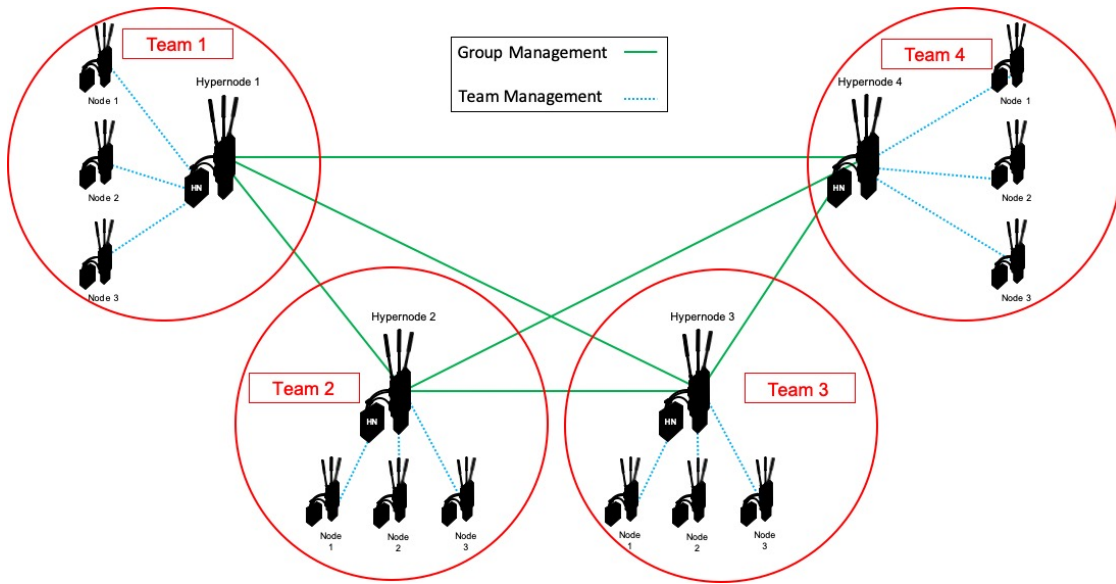


Figure 49. Group Hypernode Management Structure

This structure incorporates multiple decision makers, and creates a potentially unstable network as each hypernode makes decisions for its own team. Bordetsky (2001) proposed a committee structure would enable more collaborative work between agents, hypernodes in our case, during decision-making, while still allowing one decision maker for an entire network. Implementing a committee decision structure enables each hypernode to run its own algorithm and determine a feasible relay position to support its designated nodes. The committee model also enables the hypernodes to work together to mutually determine the most feasible positions to support the entire network. This committee structure requires either an additional “Primary Hypernode,” as depicted in Figure 50, or the designation of one of the hypernodes in the network as the primary decision maker for all of the hypernodes.

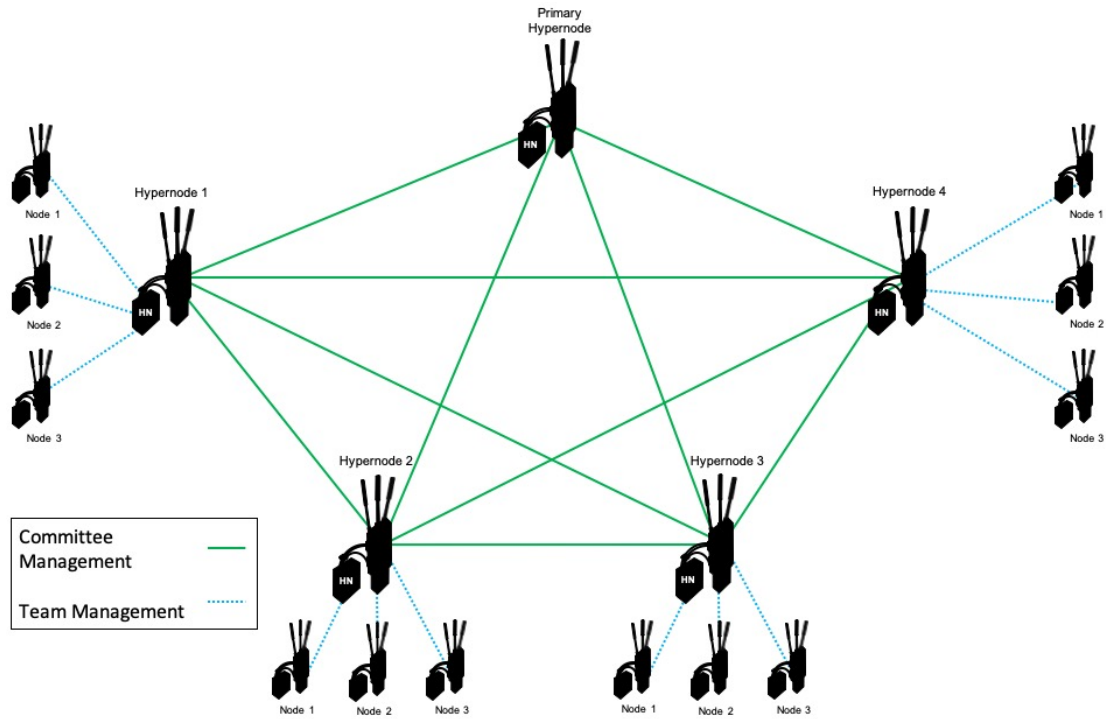


Figure 50. Proposed “Hypernode Committee”

This committee decision-making model for multiple hypernode interaction was not tested in this research. However, the interaction between nodes must support the whole of network management. The individual hypernodes must still be able to support disadvantaged nodes to improve network information flow within their own team. Additionally, they must also be able to support the rest of the hypernodes in the mesh network.

A further step would be to enable the hypernodes to exchange supported ground nodes through interactive decision-making. For example, if a node from the team of Hypernode 1 moved too far outside of its supportable range but to within the range of Hypernode 2, Hypernode 1 could exchange control information with Hypernode 2 and transfer support of that ground node to Hypernode 2. This information exchange is similar to a cellular phone handoff between stationary cell towers, with the exception that ground nodes in our tactical example are all in constant motion; each ground node and each hypernode always has the capability to move.

b. Committee Optimization

The combination of the two techniques discussed above yields multiple hypernodes able to effectively process multicriteria datasets in an efficient manner. This application would advance the hypernode tested in this research to a more robust optimization technique for large scaled mesh networks.

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V. CONCLUSION

This thesis demonstrated how an autonomous aerial hypernode contributed to information flow optimization in a simulated tactical mesh network, through an iterative experimentation process. The research shows, on a small scale, the capability of a hypernode to perform a network management function. This is an important step in an age where distributed forces will operate in challenging and contested environments, C2 functions require information superiority, and communication networks require assured resiliency. This chapter offers a summary of the research results, their theoretical and practical contribution, limitations, and suggestions for future research.

A. SUMMARY

Advancing the hypernode concept involved generating and refining an algorithm to enable a hypernode to perform a selected network management function. It addresses an existing gap in relay capability by introducing a new potential technology for a NOC manager. The hypernode collected network data and the algorithm calculated a new relay position that enabled improved support to disadvantaged network nodes, while maintaining nominal connectivity according to dynamic protocols. While the initial time on station for aerial drones would be limited (as discussed in Chapter III), this is an initial step, motivated by emerging USMC doctrine and illustrating the tactical employment concept in the opening vignette of Chapter II.

We generated an algorithm that calculated a feasible location for an aerial relay node, based on sensed performance metrics within a tactical mesh network. In our case, feasible meant that the calculated relay position satisfied the priorities and network connectivity requirements within established boundaries. We chose the “feasible” location instead of the “optimal” location in an effort to decrease requirements to calculate a useable solution and get a working relay in place more expediently. It enabled continued flow of C2 information in disadvantaged situations and provided the answer to the question: How can an autonomous aerial hypernode contribute to information flow optimization in a tactical network? The hypernode algorithm and device successfully ingested SNMP data

and continuously calculated subsequent relay positions, serving as a proof of concept that a hypernode could improve information flow.

Though unable to test the hypernode algorithm on an aerial platform due to circumstances beyond our control, the results of the field tests confirm the potential value of a hypernode and suggest increased value when mounted on a tactical UAV. Phase 1 revealed the NOC decisions required to manage a dynamic tactical network in a test environment while employing simulated tactical units and a hypernode on ground platforms. Phase 4 demonstrated the capability of the hypernode to improve information flow by calculating feasible relay positions to support network nodes. During this phase we physically moved the hypernode to the calculated position instead of using an aerial platform. The vehicle mounted hypernode demonstrated the direct communications impact of having a relay at ground level in an urban environment. Understanding the impact of employing the hypernode at ground level leads, by extension, to the conclusion that elevating the hypernode on an aerial platform would improve ability to optimize information flow.

In order to advance the hypernode concept to the point where it sensed the network environment and calculated feasible relay positions it was necessary to address the research questions about network management function performance and network performance metrics. The answers to these questions informed the development of the hypernode algorithm, which enabled relay position calculation. This is a network management task that often falls to NOC personnel who are neither able to be proactive nor to react quickly enough to prevent network outages at the tactical edge. In the future operating environment, network configurations must change at the increasingly rapid pace of tactical operations.

The conceptual scenario required network connectivity that enabled high fidelity streaming video and chat services between the tactical units and the headquarters. Through initial research we chose the performance metrics of SNR, packet loss, round trip time, and throughput to test during experimentation. We also added the metric of position as it was required to understand where to move the hypernode to support the other nodes. During algorithm development we focused on hypernode position and the SNR between the hypernode and the supported nodes in order to establish a baseline functionality. While

only incorporating those two of the selected five metrics, we demonstrated the ability to capture the other three metrics in order to suggest methods to implement them in future algorithm versions. Established network parameters (notionally derived from commander's guidance) ensured SNR threshold levels enabled the network to exist within performance constraints. As we observed network change, we verified that our network was maintained successfully through hypernode support.

There is experimental evidence to indicate that a hypernode could perform a configuration and performance management function within a NOC hierarchy in order to alleviate some tasks from human operators. The observed decisions involved placing relays that would enable the tactical units to continue their mission as they moved through the operational area. When compared to the FCAPS network management model, relay-position-based decisions fall in the category of configuration and performance management. As such, a hypernode could calculate successive relay positions and move itself about the battlefield in support of disadvantaged nodes. This thesis demonstrates that it can be possible for a hypernode to conduct the network management function of maintaining network performance through configuration management, thus increasing network resiliency through improved information flow in dynamic tactical environments.

This research highlights the potential for use of the hypernode concept in tactical networks to support communications within the dynamic and distributed operating environment. We believe that in the future network environment, efforts to utilize the speeds of computer processing to aid human decision-making will significantly enhance network connectivity and resiliency efforts. Networks that move at the speed of future wars require the capability to integrate network feedback with real-time network reconfiguration—the hypernode concept provides just that capability.

B. LIMITATIONS

Two significant and unforeseen events impacted the extent and robustness of my research and findings.

1. Aerial Testing

The DOD grounding of all DJI drones forced the cancellation of the test phase in which we planned to analyze the performance of the hypernode as a payload on an aerial platform. This required adaptation by conducting experiments on the ground instead of flying at the anticipated altitude of approximately 400 feet above ground level. The ground mobile configuration proved sufficient to validate the hypernode relay concept. At this point, it is only possible to tentatively extrapolate the research results to the air.

2. COVID-19

Restrictions on social distancing across the DOD and the educational community directly impacted completion of the research. It was not possible to conduct the culminating phase of the experiment series. This prevented fully field testing the hypernode relay functionality using all of the metrics and in a larger scale network. Advanced field experimentation would have afforded the opportunity to collect more robust data to strengthen the proof of concept.

C. FUTURE WORK

As a result of this research, I suggest three specific research paths that could directly contribute to further advancement of the hypernode concept and increase the resiliency and reliability of tactical networks.

The first path would be to integrate the hypernode algorithm as the mission control computer in a UAS. This would enable the hypernode to provide movement direction to the drone, creating an autonomous relay. Exploring this UAS integration could be paired with implementation of the hypernode device on a smaller platform. For example, Persistent Systems makes a smaller Wave Relay module that might be integrated into the UAS to save on weight and power. This scaled integration is a logical step towards autonomous system integration from the larger MPU5 we tested.

The second path would be to create the additional algorithm levels based on performance metrics at each layer of the OSI model. As discussed in Chapter IV, these

levels add increasing refinement to the hypernode algorithm with the goal of improving the calculated relay position for increased network performance.

The third path would be to scale the concept to use multiple hypernodes working together to manage larger networks. This “hypernode committee” concept, as discussed in Chapter IV, entails developing additional algorithms to integrate feedback from multiple hypernodes and using a group decision model to determine best relay locations for the group.

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