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# THESIS

**CONCEPTUALIZATION AND ANALYSIS OF USING UNMANNED AERIAL VEHICLES AS COMMUNICATIONS RELAYS IN A GPS-DENIED ENVIRONMENT**

by

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September 2022

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Many armed forces are becoming network-centric and highly interconnected. This transformation, along with decentralized decision-making, has been enabled by technological advancements in the digital battlefield. As the battlefield evolves and missions require units to be mobile and support numerous tactical capabilities, the current concept of deploying static radio-relay nodes to extend the range of communication may no longer be suitable. Hence, this thesis aims to design an operational concept using unmanned aerial systems such as aerostats and tactical drones to provide beyond line-of-sight communication for tactical forces while overcoming the limitations in a GPS-denied environment. The proposed concept is divided into three phases to assess operational and communication system needs, given Federal Communications Commission regulations that set the maximum effective isotropic radiated power in the industrial, scientific, and medical band at 36 dBm. The maximum communication range between two nodes can be studied using the Friis propagation equation. In addition, Simulink software is used to study the effective application throughput with respect to distance. From the analysis, IEEE 802.11ax can provide a higher data throughput and support both 2.4 GHz and 5.0 GHz frequency bands. Using a simulated environment and operational scenario, the estimated number of aerial systems required to provide communication coverage for a 50 km by 50 km area is determined.

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# ABSTRACT

Many armed forces are becoming network-centric and highly interconnected. This transformation, along with decentralized decision-making, has been enabled by technological advancements in the digital battlefield. As the battlefield evolves and missions require units to be mobile and support numerous tactical capabilities, the current concept of deploying static radio-relay nodes to extend the range of communication may no longer be suitable. Hence, this thesis aims to design an operational concept using unmanned aerial systems such as aerostats and tactical drones to provide beyond line-of-sight communication for tactical forces while overcoming the limitations in a GPS-denied environment. The proposed concept is divided into three phases to assess operational and communication system needs, given Federal Communications Commission regulations that set the maximum effective isotropic radiated power in the industrial, scientific, and medical band at 36 dBm. The maximum communication range between two nodes can be studied using the Friis propagation equation. In addition, Simulink software is used to study the effective application throughput with respect to distance. From the analysis, IEEE 802.11ax can provide a higher data throughput and support both 2.4 GHz and 5.0 GHz frequency bands. Using a simulated environment and operational scenario, the estimated number of aerial systems required to provide communication coverage for a 50 km by 50 km area is determined.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| CSMA/CA | carrier-sense multiple access with collision avoidance |
| CTS | Clear to Send |
| ERP | effective radiated power |
| FCC | Federal Communications Commission |
| GBS | Ground base stations |
| GPS | Global Positioning System |
| IEEE | Institute of Electrical and Electronics Engineers |
| MANET | mobile ad hoc network |
| MCS | modulation coding scheme |
| MIMO-OFDMA | multiple-input, multiple-output orthogonal frequency-division multiplexing |
| OFDMA | orthogonal frequency-division multiple access |
| QOS | quality of service |
| RSSI | received signal strength indicator |
| RTS | Ready to Send |
| Rx-SOP | Receiver Start of Packet |
| UAV | unmanned aerial vehicle (s) |
| WMN | wireless mesh network (s) |

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# EXECUTIVE SUMMARY

With the expansion of the digital battlefield and increasing demand for a highly interconnected force that can conduct multi-domain operations, the current communication concept of employing static relay nodes in the operational theatre may no longer be feasible. Therefore, the aim of this thesis is to design an operational concept that employs unmanned aerial vehicles as communication relay nodes for tactical forces while overcoming the limitation of a Global Positioning System (GPS)-denied environment. Specifically, the primary focus of this research is to determine the maximum communication range for this operational concept and to study the effective data throughput between two aerial relay nodes. In addition, the research seeks to determine the number of aerial relay nodes required to provide communication coverage of 50 km by 50 km or the equivalent. Ultimately, the findings of this thesis aim to further enhance communication effectiveness in a combat operational environment.

The proposed operational communication framework shall adopt a hybrid communication system that employs both aerostat systems and tactical drones as communication relay nodes. Taking advantage of the agility afforded by the tactical drones, it should be possible to increase network data bandwidth conveniently if required. To analyze the operational needs and type of communication system that could be deployed, the proposed operational concept is divided into three different phases.

To study the feasibility of the proposed concept, both IEEE 802.11ax and IEEE 802.11n Wi-Fi standards are used to examine the network's performance and to determine the estimated effective communication range. These IEEE standards are employed because they can operate on both the 2.4 GHz and the 5.0 GHz frequency band.

According to Federal Communications Commission (FCC) regulation, the maximum effective isotropic radiated power (EIRP) in the Industrial, Scientific, and Medical (ISM) band is specified as 36 dBm while operating in the 2.4 GHz frequency band. By limiting the output and effective radiated power, it is possible to determine the theoretically effective communication range while operating in the 2.4 GHz and 5 GHz

frequency bands. Using the Friis propagation equation, the range is calculated to be around 5.5 km and 2.6 km, respectively.

With modification to the existing IEEE 802.11 MAC and application throughput measurement model available on MATLAB Simulink software, the effective application throughput using the IEEE 802.11ax and IEEE 802.11n standards is determined. From the simulation results, it is observed that as the distance increases, the application throughput decreases for both operating frequencies due to several factors, such as latency and the increased number of packets lost. Moreover, the 5 GHz frequency band has a shorter transmission range as compared to 2.4 GHz. Therefore, to compensate for the range limitation and to optimize the data throughput while operating in the 5 GHz frequency band, it is recommended to use a higher channel bandwidth than for operating in the 2.4 GHz frequency band.

From the simulation results, the IEEE 802.11ax Wi-Fi standard shows a higher data throughput as compared to IEEE 802.11n. This is because IEEE 802.11ax uses a more efficient modulation and coding scheme as compared to IEEE 802.11n. Therefore, with IEEE 802.11ax as the recommended Wi-Fi standard, the maximum application throughput when operating on 2.4 GHz and 5 GHz is determined to be around 4.403 Mbps and 4.488 Mbps, respectively.

To estimate the number of aerial relay nodes required to provide a communication coverage for an operational area of 50 km by 50 km, ArcGIS Pro, a map planning tool software, is used to simulate the operational area and to plan for the communication network. With the calculated effective communication range and from the map planning, it is estimated that a total of 23 aerostat systems is required to provide network coverage while operating on the 2.4 GHz frequency band, and an additional 24 tactical drones are required to support a higher data bandwidth network that operates on the 5 GHz frequency band.

It is worth noting that this thesis is limited to analyzing the performance between two aerial relay nodes only and with a simulation model. In the real world, there are several factors that can potentially affect network performance in an outdoor environment, such as attenuation caused by the effects of terrain. Therefore, to have a better understanding of the system's performance, in-depth developmental testing out in the field, with the effects of attenuation and interference caused by the environment, is recommended. The estimated number of aerial relay nodes required to provide communication coverage may differ under such circumstances. In addition, the performance and effective communication range may decrease.

Apart from relaying communication, the height advantage of the aerial relay node can also provide added services such as conducting surveillance and reconnaissance missions. Therefore, to maximize the performance of the system, it is recommended that future researchers study the potential effects of interference caused by the different sensor systems. To minimize the chances of interference, a detailed frequency allocation plan might be necessary to ensure sufficient frequency separation between the different systems.

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# I. INTRODUCTION

## A. BACKGROUND

Many armed forces around the world are moving towards a network-centric and highly interconnected force that can conduct multi-domain operations. With the increasing trend toward data-driven warfare, we can expect a large amount of data and information to flow through the network. The ability to share and acquire real-time information is a key enabler for the success of the mission. However, in times of war, maintaining constant line-of-sight communication throughout the mission is increasingly challenging, especially in complex environments. To extend communication coverage, mobile radio-relay stations (nodes) are being deployed in the theater to form a mobile ad hoc mesh network to exchange a variety of information. Mobile radio-relay stations, however, depend on line-of-sight communication which could be a challenge to operate in an urban environment where obstacles such as buildings may degrade the communication services. The mesh network would then have to rely on other ground-deployed radios to relay the information. This solution may not be ideal as it requires detailed and specific planning to deploy ground radio stations at strategic locations. Often, these strategic locations are easily identified by adversary intelligence, allowing the adversary to conduct espionage or sabotage missions that could jeopardize the mission's outcome and the safety of the crews operating the radio stations. Therefore, to establish a robust mesh communication network beyond the line of sight, many militaries are looking into deploying unmanned aerial vehicles (UAV) as communication relay nodes to support both ground and aerial platforms to extend the network's range even further. Yet, the disadvantage of this approach is UAVs' reliance on the Global Positioning System (GPS) for navigation.

In addition, with the increasing demand for and competition in operating in the radio frequency spectrum. Advances in wireless technology have proven effective to operate across the spectrum of radio frequencies and signal processing by leveraging the wireless channel access protocol to make the wireless channel available to multiple nodes within the network. With the increasing demand for higher bandwidth and the need for wireless mobile ad hoc networks in a combat environment, timing and carrier synchronization among the wireless nodes become essential to ensure that terminals operating in a time-based network are well separated to prevent overlapping of their respective transmission slots. Hence, GPS time has become the basis for providing precise synchronization between distant nodes within the network. The GPS device serves as a reference master clock at a location, providing time synchronization signals to other equipment and the local network. At the same time, the prevalence of GPS jamming technologies, highlights the need to study how to eliminate the reliance on the GPS for navigation and time synchronization.

## B. MILITARY COMMUNICATION NETWORK

One of the key success factors in military operations is information superiority. Tactical radios are commonly employed to provide a reliable and secure communication network, playing a vital role in facilitating command and control and providing commanders with relevant and up-to-date information about the situation during operations to enhance the military decision-making process. The army tactical communication network is divided into different echelons. Each echelon employs a variety of radio-based systems to provide voice and data communication throughout operations and in the most austere environments. A tactical radio network provides the backbone of communication between army and joint forces and supports the horizontal and vertical integration of digital information across the network.

## C. PROBLEM STATEMENT

To gain an advantage on the battlefield, the military today depends on the ability to prevail on the digital battlefield. Edge computing is one of the critical transformations enabling the military to conduct decentralized decision making at the tactical edge, reducing the time needed to gather and process data to drive decisions, while allowing the commanders on the ground to make informed decisions. With edge computing being deployed down to the forward operating bases, combat vehicles, individual warfighters, and small teams conducting an operation in a hostile environment, edge computing has enabled warfighters to gain access to larger databases with processed and analyze data, facilitate information sharing and shortening the sensor shooter loop. The amount of data available is proliferating while processing capabilities are advancing to make data more tenable. Therefore, as the battlefield evolves and the missions require units to be mobile and support numerous tactical capabilities, critical communication infrastructures are becoming more difficult to establish and maintain. Coupled with the increasing demand for and lack of availability in the frequency spectrum, the aim to monitor and cover the pre-assigned area of operations to provide a network quality of service (QOS) continues to pose a challenge.

The continuous advancement in wireless communication and rapid transformation of the digital battlefield to assist in the conduct of multiple concurrent operations has established an increasing need for a more agile mobile communication network that can provide a higher data bandwidth. Therefore, the current concept of deploying physical static radio-relay stations (nodes) in the theatre to extend line-of-sight communication range may no longer be a feasible solution in the long run.

In today's operations, the primary role of radio-relay nodes is to help bridge communication and relay information between higher headquarters (brigade) and the tactical forces (battalions) who are inserted deep into the operating theater. However, the current concept of deploying tactical static radio-relay nodes poses a huge risk to the operators. In operations, the radio-relay nodes are usually deployed a distance away from friendly forces and therefore are seldom under the protection of their own forces. They must rely on themselves against adversarial fires. This can be especially challenging because communication systems emit a high radio signature, making the nodes and their locations easily detectable by the adversary. In addition, the radio-relay node approach does not provide adequate resiliency and redundancy in the event a node is down or no longer operational. Time latency for information to reach from one end to another may also increase, resulting in the delay of information, or in the worst case, the information may become obsolete and adversely affect the commander's decisions. Furthermore, maintaining a rebroadcast node in operation entails a large investment in manpower and maintenance costs.

With the advancement in communication systems and networking, there have been numerous studies and research on establishing a robust mesh communication network beyond the line of sight. In recent years, many researchers have been looking into deploying aerial communication relay nodes to assist in the extension of communication range to support both ground and aerial platforms.

## D. THESIS OBJECTIVES

The purpose of this thesis is to design an operational concept using UAVs as a proposed alternative means of communication relay system to extend the range of communication for tactical forces while overcoming the limitation posed by a GPS-denied environment. The findings of this thesis can be used to further enhance communication effectiveness in a combat operational environment. Considering the agility afforded by the UAVs and the flexibility of the wireless network to integrate and adopt new systems or algorithms to enhance the efficacy of signal of opportunity, this thesis addresses the following questions:

- What is the maximum communication range between two aerial relay nodes?
- How many aerial nodes are required to provide communication coverage for an area of 50 km by 50 km or the equivalent?
- What is the estimated effective data throughput between the aerial relay systems?

# II. LITERATURE REVIEW

## A. WIRELESS AD HOC NETWORKS

In recent years, wireless communication technologies have been undergoing rapid advancements. Unlike infrastructure networking, ad hoc networks are formed on the fly and are decentralized types of networks without any pre-existing infrastructure to support them. Each communication node in an ad-hoc network is responsible for routing data to and from other nodes, forming network communication. The flexibility of the networks allows users to connect from various locations and access points regardless of the distance, establishing a distributed solution that allows users to extend their communication beyond the range of their radio interface.

With reference to the standard mode of operation established by the Institute of Electrical and Electronics Engineers (IEEE) for worldwide interoperability for microwave access, the IEEE 802.11 standard is used to support wireless, local area network communication and typically supports relatively short-range Wi-Fi networks. Hence, it is known for its use in Wi-Fi technology (Ghaboosi 2009). IEEE 802.11 can operate in various frequencies, including 2.4 GHz, 5.0 GHz, 6.0 GHz, and 60 GHz.

The family of the IEEE 802.11 standard consists of a series of half-duplex, over-the-air modulation techniques and uses the carrier-sense multiple access with collision avoidance (CSMA/CA) protocol at the Media Access Control (MAC) layer (Villegas 2007). To avoid collision, nodes within the network leverage the CSMA/CA protocol to sense whether the path of transmission is idle before sending the data packet out. Over the years, the IEEE 802.11 standard has evolved in response to modifications and amendments of service to extend the scope of the standard. Different IEEE 802.11 standards have different specifications. For instance, both IEEE 802.11n and IEEE 802.11ax can operate on both the 2.4 GHz and the 5 GHz frequencies and use multiple-input, multiple-output orthogonal frequency-division multiplexing (MIMO-OFDMA) modulation technique. However, because IEEE 802.11ax is the latest protocol release, it can accommodate a larger channel bandwidth and conduct a more efficient modulation technique as compared to IEEE 802.11n, which results in higher throughput.

Wireless ad-hoc networks can be classified as Mobile Ad-hoc Networks (MANET) and Wireless Mesh Networks (WMN) depending on their application (Ghorale and Bang 2015). Both MANETs and WMNs have been widely used to enhance voice and data transmission. Many military forces around the world are exploiting these networks' advantages, such as low ownership cost, the dynamic nature of the networks, and ease of acquisition as most of the components are commercial off-the-shelf technologies. Both the MANETs and the WMNs can adapt to hostile situations and environments and be deployed rapidly, which attracts military interest to employ them.

### 1. Mobile Ad-hoc Networks

MANET is formed by a class of autonomous mobile nodes that can communicate with one another over a wireless link despite limited bandwidth (Kontogiannis 2012). Each node within the network is capable of detecting and identifying the most efficient route to send and forward messages across the network.

Flexibility, the distinguishing characteristic of MANETs, is very much applicable to military usage. During a military operation, the communication nodes are constantly on the move, resulting in a rapid change in the network topology over time. Therefore, to enhance the network efficiency, MANETs make use of algorithms to organize the network, plan for link scheduling, and conduct information routing.

Despite the flexibility of and advantages provided by MANETs, factors such as link quality, interference, and attenuation resulting in propagation path losses may affect the routing path and delivery of messages across the network (Kontogiannis 2012). In addition, due to the complexity of the military operation, factors such as bandwidth limitation, network latency, power supplies issues, and network security could potentially affect the network design and performance.

### 2. Wireless Mesh Networks

WMNs are commonly used to establish a reliable communication network that spans a protracted distance. A distinct characteristic of WMNs is that they send data across the network through multi-hops across the network (Decastro 2009). WMNs usually consist of clients (computers and wireless devices), routers, and gateways that are arranged in mesh configurations. In a communication network, a WMN consists of multiple radio nodes organized in a mesh topology. Each node is responsible for transmitting and relaying data to other nodes, providing alternate paths to ensure the flow of information through the network. The possibility for communications to take several paths reinforces the reliability of such a network. In the event a node is not able to establish communication with another, the rest of the nodes are still able to establish and retain communication through one or more intermediate nodes, as depicted in Figure 1.

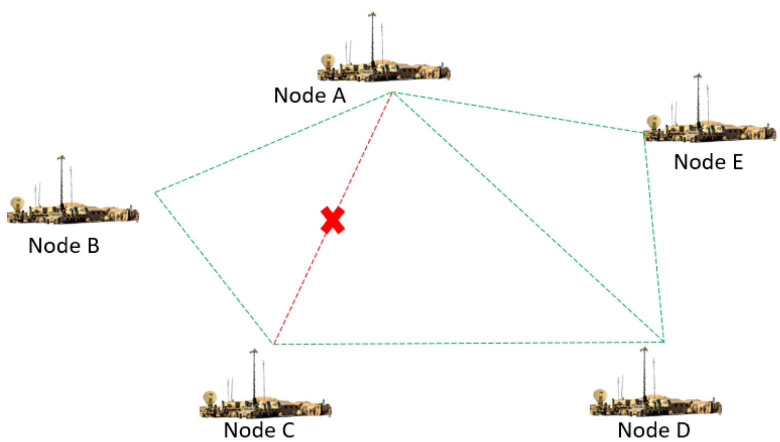


Figure 1. Wireless Mesh Network Reliability

Communication enables the troops to coordinate with one another and to conduct a synchronized operation. Having a reliable network has thus become a critical success factor in the outcome of operations. In addition, to gain the advantage on the battlefield, troops on the ground are transforming into a highly mobile force. Hence, the ability to maintain connections with one or more nodes within the network is essential to provide added redundancy should one or more nodes within the network fail, transverse out of range, or experience propagation path loss due to blockage (Kontogiannis 2012).

Although WMNs are inherently reliable networks and can provide multiple users in a wireless network with high bandwidth access, the frequency spectrum in which WMNs operate are not only tightly controlled but very limited and require detailed spectrum planning allocation.

## B. NETWORK CONNECTED UAVS

In recent years, many research studies and development efforts have been conducted on employing UAVs as a cheap and easily deployable alternative to provide a reliable wireless network and to achieve beyond line-of-sight communication. In these approaches, multiple UAVs can be interconnected to work in cooperation to relay the transmitted data. When forming a multi-hop ad-hoc network, in which each UAV acts as a smart repeater, the effective transmission distance is dependent on several factors, such as the routing protocols used, power management configuration, and type of antenna used on the individual wireless nodes (Kontogiannis 2012).

### 1. Ad-hoc Routing Protocol

To establish a reliable WMN among the communication nodes, a routing protocol is used such that routing information can be exchanged between the nodes. With the routing information, nodes within the network can then decide the shortest and most efficient routing path to send the data packet to the designated node.

The network's performance, in turn, is defined by the ad-hoc routing protocol and the network topology. Among the main challenges presented by an ad-hoc network is the lack of physical infrastructure and the nodes being constantly on the move. There are three families of ad hoc routing protocols for the ad hoc networks, namely the pro-active, reactive, and hybrid algorithm (Mammadov 2013). Each algorithm has its own advantages and disadvantages. For instance, the proactive protocol uses the least time to prepare routes. However, it consumes more power and takes up part of the bandwidth due to periodic routing table updates (Markray 2018). By contrast, the reactive protocol uses less power as the routing table is only updated when required. For reactive protocol, a handshake needs to be established between the transmitting and receiving nodes before data can be transmitted. To establish a route, the transmitting node will send a Ready to Send (RTS) message to the receiving node. Upon reception of the message, the receiving node will send back a Clear to Send (CTS) message with the route information. The transmitting node will then update its routing table. For subsequent transmission, the routing table is used. Only when the route is broken will the protocol find an alternate to the same destination and update the routing table subsequently.

### 2. ISM Bands Regulation

According to the Federal Communications Commission (FCC), under section 15.247 of the Code of Federal Regulations, the output power of systems that use frequency hopping spread spectrum while operating in the 2.4 GHz frequency band is limited to 1 Watt (30 dBm) and a total maximum Effective Radiated Power (ERP) of 36 dBm. The ERP is calculated as follows:

$$ERP = P_{tx}G_{tx} = P_{tx}\,(dBm) + G_{tx}\,(dBm),$$

where $P_{tx}$ is the power level of transmitted signal and $G_{tx}$ is the gain of the transmit antenna. Theoretically, with the identified limitation and by fixing the transmit power, the range within which two nodes can communicate can be derived from the Friis propagation model fundamental equation (Mathuranathan 2013). The received power level $P_r$ is calculated as follows:

$$P_r\,(dBm) = P_{tx}\,G_{tx}\,G_{rx}\left(\frac{\lambda}{4\pi R}\right)^2,$$

where R is the separation between the transmitter and receiver node, $G_{rx}$ is the gain of the receiving antenna, and $\lambda$ is the signal wavelength. Hence, by keeping all variables constant, the received power level is dependent on the wavelength, and hence the frequency, $f$, as the wavelength can be calculated using the following equation,

$$\lambda = \frac{c}{f},$$

where c is the speed of light.

### 3. Free Space Path Lost

Atmospheric attenuation can add to free space path loss. Free space path loss is used to calculate the attenuation of signal strength between the transmitter antenna and the receiver antenna, assuming a direct, straight path line of sight (Vinogradov 2018). Free space path loss can be defined using the following equation,

$$L_p = \left(\frac{4\pi r}{\lambda}\right)^2,$$

where r is the distance between the two antennas and $\lambda$ is the signal wavelength. Hence, the amount of loss is dependent on the carrier frequency.

### 4. Antenna Type and Antenna Gain

With increasing altitude, communication signals transmitted from the aerial communication platforms are more likely to propagate through free space and have a better line of sight with the associated ground base stations (GBS). On the other hand, the signals are more susceptible to uplink/downlink interference from a larger number of non-associated ground base stations (Zhang 2018). Therefore, to minimize link interference, advanced antenna beamforming techniques can be employed at both the UAVs and the GBS. In long-range communication, directional antennas are commonly preferred over omni-directional antennas to reduce interference. With the latter, the transmitted power is dispersed in all directions and is susceptible to higher interference. By contrast, with the directional antenna, the transmitted power is consolidated in a specific direction. To track for moving UAVs, a constant line of sight is required to be maintained for a directional antenna, and it must be precisely pointed at the UAVs due to the narrow signal beam of maximum 10 degrees (Elchin 2013).

In the simulation studies conducted by Park and Jung (2010), where the GBS uses both directional and omni-directional antennas to communicate with a moving UAV, the time in which the GBS antenna is in communication with a moving UAVs is recorded to compare the performance between the two antennas. From the simulation, the results show that with an omni-directional antenna, the moving UAV can maintain communication at least 15% longer as compared to using directional antenna.

Hence, based on a combination of research studies, it can be concluded that at closer range, the omni-directional antenna shows better performance in maintaining communication with mobile UAVs. Moreover, in a mesh network, even when a drone is out of range or has lost communication with the transmitting antenna, data can still be routed through the network to reach the designated nodes via an alternate path. Therefore, having an omni-directional antenna is preferred as it is easier to control and maintains communication with and between the network of UAVs.

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# III. EXPLORATORY RESEARCH

This chapter discusses requirements, identifies the need statement, and explores current technologies that are available that could potentially be employed for aerial communication relay.

## A. CURRENT OPERATIONS COMMUNICATION PLANNING

In today's operations, static relay nodes like the ones shown in Figure 2 are deployed into the theatre to help extend the range of communication. These static relay nodes require operators to be deployed on the ground to set up and man the systems. Often, the operators must rely on themselves against adversarial threats as they are usually deployed a distance away from friendly forces.

Figure 2. Static Relay Communication Nodes. Source: Osborn (2011).

Given the high radio signature emitted by the system, the deployment location of these nodes can be easily detected by the adversary. This poses a huge risk to the life of the operators.

In addition, the static relay nodes require line of sight to bridge communication. Hence, the deployment sites are often limited by the availability of high ground. The static relay nodes are also limited by the communication range of the tactical radios used. Most tactical radios have a communication range of up to 15 km (mobile) and 25 km (static).

This limitation results in the need for the relay nodes to be displaced several times throughout operations as the troops advance into the theatre. The static deployment of the relay nodes also provides limited redundancy during operations, and thus, they are highly susceptible to being sabotage by the adversary's use of jamming devices or damage by firepower.

## B. NEED STATEMENT

To replace manned static relay nodes with a robust network of unmanned aerial relay nodes to reduce the risks to and increase the survivability of the operators being deployed on the ground to bridge communication.

## C. VALUE HIERARCHY

The value model reflects the needs and objectives of the stakeholders, where the foundation of the value modeling effort is a value hierarchy (Hernandez 2018). The value hierarchy shown in Figure 3 reflects the effective needs followed by the critical functions that the system must perform.

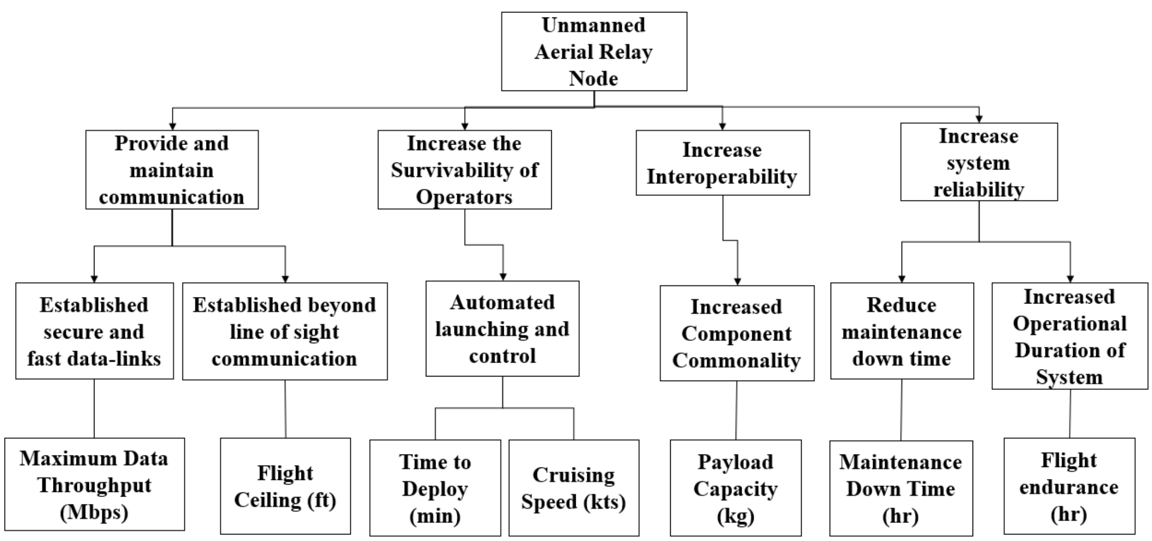


Figure 3. Value Hierarchy

## D. REQUIREMENTS ANALYSIS

The requirements identified for the unmanned aerial relay nodes are listed as follows:

- The relay system shall operate continuously for a minimum of 72 hours.
- The set up and deployment of the relay system shall take no longer than 45 minutes under both day and night conditions.
- The relay system shall be able to relay both voice and video data.
- The relay system shall be deployed autonomously.
- The relay system shall be able to operate in different environmental conditions with temperatures ranging between $15^{o}$ C to $50^{o}$ C.
- The relay system shall be able to carry a payload of at least two kilograms.
- The relay system shall be able to operate on both the 2.4 GHz and the 5 GHz frequency.
- The relay system shall be able to fly by waypoint to its designated location.
- The relay system shall operate in a GPS-denied environment.
- The relay system shall have a latency of less than 30 seconds.

## E. IDENTIFICATION OF POSSIBLE UNMANNED AERIAL SYSTEMS

### 1. Tactical Drones

With the advancement in drone technology, there has been an increase in the application of tactical drones in the military environment, from conducting aerial surveillance to assisting in search and rescue operations. In recent years, drone development has also been shifting towards automated control, which allows multiple drones to operate concurrently. Despite still having several limitations, such as short battery life and small payload capacity, drones now pose a potential alternative means to help extend the range of communication.

#### *a. DJI Matrice 300 RTK*

Figure 4. DJI Matrice 300 RTK. Source: DJI (2022).

The DJI Matrice 300 RTK has a maximum transmission range of 15 km and can operate in harsh environments with temperatures ranging between -20º C and 50 º C. The M300 RTK is equipped with a real-time auto-switching function that allows it to operate on either the 2.4 GHz or the 5.8 GHz frequency band to avoid interference. The M300 RTK is also equipped with hot-swappable batteries and has a maximum flight time of 55 minutes at a maximum speed of 23 m/s. The drone is able withstand a maximum wind speed of 15 m/s and has a service ceiling of up to 7,000 m. Depending on the payload the M300 RTK carries, the drone can conduct multiple actions. The M300 RK can carry a combined payload weighing up to of 2.7 kg. In addition, the drone is equipped with smart pinpoint and tracking functionality to identify and follow moving subjects.

### *b. DeltaQuad Pro VTOL UAV*

Figure 5. DeltaQuad Pro VTOL UAV. Source: DeltaQuad (2022).

The DeltaQuad Pro VTOL UAV is fully autonomous from takeoff to landing, even beyond commercial range. It is equipped with smart technology and has a 50 km radio and video range. In addition, the DeltaQuad can provide a secure mobile network using a virtual private network. With an auxiliary battery, the DeltaQuad is capable of flying up to 150 km or up to 100 km with a payload of 1.2 kg. The DeltaQuad has a cruising speed of 16 m/s and a maximum speed of 13 m/s, providing a flight time of up to 110 minutes and a maximum operating altitude of 13,000 ft (4000m). The DeltaQuad has a wingspan of 235 m and operates at temperatures ranging from -20º C to 45º C. In addition, the DeltaQuad can withstand a maximum wind speed of 14 m/s and operate in a light drizzle environment.

### c. *JTI F160 Inspection and Fighting Drone*

Figure 6. JTI F160 Inspection and Fighting Drone. Source: JTI (2022).

The JTI F160 can perform an array of missions ranging from joint ground surveillance, command and control, electronic information reconnaissance and confrontation to providing comprehensive battlefield situation awareness. These drones can operate in various environmental conditions, ranging from snow to high temperatures, and withstand wind speeds of up to 30 knots. The JTI F160 can operate at a maximum flight altitude of 5,000 m within a 100 m radius. In addition, it can carry a payload of up to 25 kg with a cruising speed ranging from 100 km/h to 140 km/h and has a battery life of 10 hours.

## 2. Aerostats

The disadvantage of employing UAVs as relay nodes is the power limitation which affects their flight endurance. Hence, to overcome the power limitation, one of the proposed solutions is to leverage an aerostat system. In recent years, aerostat systems have been used by the military to conduct surveillance and anti-submarine warfare. Aerostats can operate for an extended period as they are tethered to the ground by a cable that provides the power source. In addition, an aerostat can carry heavier payloads and conduct a greater variety of operations than a UAV depending on the equipment carried onboard. Hence, an aerostat system is one of the potential solutions. Three aerostat systems considered for this research are described in the following paragraphs.

### *a. SKYSTAR 180*

Figure 7. SKYSTAR 180. Source: RT (n.d.).

The SKYSTAR 180 is a small tactical, all-weather aerostat system capable of operating under harsh environmental conditions, making it ideal for military, homeland, and law enforcement security operations. According to the RT Aerostat Systems, Inc. specification manual, the mooring system of the SKYSTAR 180 is based on a towable trailer and can be deployed within 20 minutes with three personnel operating the system. The aerostat has a diameter of 6 m and can withstand wind speeds up to 40 knots. It can operate at an altitude of up to 1,000 ft and has an endurance of up to 72 hours. The aerostat is capable of carrying maximum payload of 18 kg.

#### b. *SKYSTAR 300*

Figure 8. SKYSTAR 330. Source: RT (n.d.).

According to the specification manual provided by RT Aerostat Systems, Inc., the SKYSTAR 330 tactical aerostat system can operate continuously for up to 72 hours while operating at altitudes up to 1,500 ft. The system is compact and can be easily transported using a towable trailer or by container trucks. The system is highly mobile and can be rapidly deployed within 45 minutes with three personnel operating the system. This aerostat has a diameter of 7.7 m and can withstand a wind speed of up to 40 knots. Furthermore, the system can carry any payload up to 50 kg.

#### c. *Desert Star Helikite*


Figure 9. Desert Star Helikite. Source: Allsopp (n.d.).

The Desert Star Helikite is designed to operate in rough environments and withstand sand-blown conditions. The system has been proven to be one of the most durable aerostats in service and has been employed by the U.S. and British Armies in Afghanistan. In addition, the Australian Defence Force (ADF) is also conducting trials to use the Desert Star Helikite as a radio-relay. The helikite comes in different sizes and can carry a variety of payloads. For instance, the 10 $m^3$ Desert Star Helikite can carry a payload up to 5.5 kg while operating at an altitude of up to 1,000 ft and withstand a windspeed of up to 40 knots. The Helikite system consists of a tactical launch pad and can be towed with a trailer. Furthermore, the system can be deployed within 15 minutes and remain in operation up to 5 days.

## F. FUNCTIONAL MAPPING

A functional mapping is required to determine whether the potential alternatives are viable as it is not known how well each alternative will meet the required functions. This process should eliminate any alternatives early if they are not viable options. Therefore, the required system functions are mapped against each alternative to ensure each alternative has at least a chance of meeting the requirements. Table 1 shows the mapping of the top-level functions of the system for each alternative.

Table 1. Functional Mapping

| Top Level Functions | Alternatives | | | | | |
|---|---|---|---|---|---|---|
| | DJI Matrice 300 RTK | DeltaQuad Pro VTOL UAV | JTI F160 | SKYSTAR 180 | SKYSTAR 330 | Desert Star Helikite |
| Establish secure and fast datalink | Yes | Yes | Yes | Yes | Yes | Yes |
| Establish beyond line-of-sight communication | Yes | Yes | Yes | Yes | Yes | Yes |
| Provide automated launching and control | Yes | Yes | Some | No | No | Some |
| Increase component commonality | Some | Yes | Yes | Yes | Yes | Yes |
| Increase operational duration | Yes | Yes | Yes | Yes | Yes | Yes |

In conclusion, the identified drones and aerostat systems meet most of the required functionalities. However, it is necessary to conduct further studies and research to determine the key design drivers and also to conduct a cost analysis to determine which system best fit the operational concept.

# IV. CONCEPTUAL DESIGN

## A. CONCEPTUAL DESIGN

The central idea is to adopt a hybrid communication system that employs both the aerostat system and the tactical drones. Figure 10 shows the operational employment of the systems. As illustrated in Figure 10, the aerostat system can be deployed by the troops as they transverse along preplanned route towards their target location. Depending on the equipment carried, the aerostat system is versatile and can perform a variety of operations such as providing communication and surveillance operations. Given the aerostat system's ability to carry heavier payloads, communication devices such as a long-range radio module and antenna can be mounted on the system to form a wireless communication network to help bridge communication between the troops on the ground and their respective headquarters. In addition, a surveillance camera and sensor can also be mounted to provide added intelligence services.

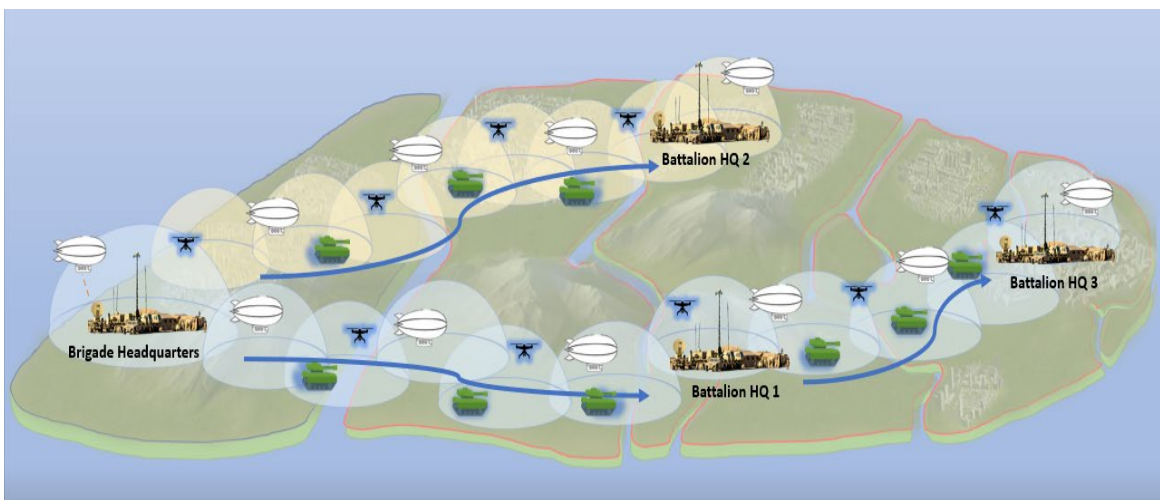


Figure 10. Operational View (OV-1)

Even though the aerostat system has relatively long flight endurance, there are several factors that could potentially affect other aspects of the aerostat's operation. Such factors include unforeseen weather conditions such as drastic wind speed, which can potentially deter the aerostat from launching off the ground. Therefore, to enhance the overall reliability of the communication network, tactical drones can be deployed to help bridge communication in the event that the aerostat system is down or when there is a need for larger bandwidth communication. Based on the predetermined route of the advancing troops and the deployment site of the aerostat system, the communication officer can plan the flight path of the tactical drones. With the current technology and algorithms that are available, the drones can be autonomously deployed and fly based on predetermined way points to their designated deployment site.

## B. OPERATIONAL SCENARIO AND ASSUMPTIONS

Based on the current operation plan, the brigade will receive its orders from the higher headquarters. From the orders, the area of operation, taskings, and key areas of interest will be made known to the brigade. The brigade will then plan its operations with three battalions under its command. During the pre-operation phase, the brigade will develop an operation plan and assign taskings to the respective battalions. From the taskings given by the brigade, the respective battalions will then conduct their own mission planning, which includes their movement routes and direction of attack. Therefore, to determine the type of communication relay system and bandwidth required, the operation scenario is divided into three different phases.

### 1. Phase 1: Advancement of Troops along Pre-planned Route

Operation Requirements: During the movement phase, the commanders at the brigade headquarters will want to know the whereabouts of and receive movement updates from the respective battalions. During the planning phases, the troops will determine their movement route and mark it with codewords to be used as the report line to inform the commanders on their location as they advance into the operational area. These codewords are usually sent in the form of voice messages back to the higher headquarters. In addition, as the troops advance into the theatre, it would help to be aware of the situation forward through real-time intelligence updates that would enhance the overall operational safety of the troops.

Possible Solutions: As the troops are traversing along the pre-planned route, the aerostat system can be dropped off and deployed at intervals to establish a wireless communication network. With the aerostat deployed, the troops on the ground can draw video feed from the surveillance camera on board the aerostat while using the aerostat system as relay nodes to transmit voice messages back to the brigade headquarters.

### 2. Phase 2: Conduct of Battle and Securing Key Area of Interest

Operation Requirements: In a close combat operation, the brigade is responsible for the synchronization and integration of the battalions' operation through command and control. Therefore, the brigade will constantly require eyes on the ground to monitor the battle. At the same time, intelligence updates from the higher headquarters will also assist the soldiers on the ground in countering the adversary and enhancing their own survivability. This calls for communication requiring larger data bandwidth. In addition, to swiftly secure and take control of a key tactical area, the battalions will have to work closely with one another through tight coordination. Therefore, having a reliable communication network is critical for the soldiers in close combat operations.

Even after securing the key tactical area, troops on the ground will continue to conduct civil-military operations to minimize further civil interference within the area, requiring constant intelligence updates from the higher headquarters. In addition, intelligence data gathered on the ground will be sent back to the higher headquarters.

Possible Solutions: The aerostat systems that were deployed during phase 1 of the operation will continue to relay data between the brigade and the troops on the ground. However, to accommodate higher data requirements, tactical drones can be deployed into the operational area and integrated with the aerostat system to form a wireless communication network that supports a larger data bandwidth. The deployment of the tactical drones can be centralized and initiated by the brigade headquarters. With the current technology, algorithms can be written to control and set the drones to fly by waypoint to their respective pre-determined deployment locations.

### 3. Phase 3: Conduct Battle Damage Assessment

Operation Requirements: Once the troops on the ground have successfully secured the key tactical area, the brigade headquarters will then order the battalions on the ground to conduct a battle damage assessment and provide an update on their respective manpower and logistics status. This allows the brigade headquarters to plan for resupply missions to support and get the troops ready for next mission, if necessary. In current operations, these updates can be in the form of voice messages using tactical radios or via text messages sent from the battle management system that the soldiers are equipped with.

Possible Solutions: Since only a small amount of data is being exchanged between the brigade headquarters and the battalions, the tactical drones that were deployed to support larger data bandwidth are no longer required. The battalions shall continue to rely on the aerostat system to relay messages back to the brigade headquarters.

### 4. Data Exchange and Average Bit Rate

In a combat operation, voice and text messages are the most common types of data exchanged among the troops. Yet, with the increased demand for real-time situation awareness, intelligence data is expected to proliferate and be shared across different echelons. Given the advancements in sensor technology and systems, larger amounts of data such as real-time video feeds and sensor imagery are expected to flow through the communication network. Table 2 provides an estimated bit rate for the different types of data expected to pass through the network. With the estimated bit rate, it is possible to determine the maximum number of channels required.

Table 2. Data Types and Their Average Bit Rates. Source: CISCO (2021).

| Data Exchange | Bits Rate |
|---|---|
| Voice Message | 64 kbps |
| Video Feed | 2 Mbps |
| Text Messaging | 0.224 kbps |
| Text Messages with Images | 1 Mbps |

# V. FEASIBILITY ANALYSIS

To analyze the feasibility of the proposed concept described in the previous chapter, the Friis propagation equation is used to determine the theoretical communication range between two nodes. In addition, to measure the performance of the network, the maximum data throughput is also analyzed with respect to distance. Given the effective communication range, it is possible to determine the number of assets required to support an operational area of 50 km by 50 km.

## A. MAXIMUM COMMUNICATION RANGE

Receiver Start of Packet Detection Threshold (Rx-SOP) is a fine-tuning network design tool under radio frequency profiles. Rx-SOP determines the Wi-Fi signal level at which an access point's radio demodulates and decodes a packet by introducing the minimum received signal strength indicator (RSSI) threshold (CISCO 2017). As distance increases, the signal strength and wireless data rate decrease, leading to a lower overall data throughput. According to the *Cisco Wireless Controller Configuration Guide*, Release 8.5, the permitted ranges for the Rx-SOP detection threshold for the 5GHz band and the 2.4 GHz band are shown in Table 3.

Table 3. RSSI Signal Level. Source: CISCO (2017).

| **IEEE 802.11 Band** | **High Threshold** | **Medium Threshold** | **Low Threshold** |
|---|---|---|---|
| 5 GHz | -76 dBm | -78 dBm | -80 dBm |
| 2.4 GHz | -79 dBm | -82 dBm | -85 dBm |

Therefore, by setting the maximum ERP in accordance with the FCC ISM band regulation and setting the minimum RSSI threshold at -80dBm, it is possible to determine the maximum communication range between two nodes transmitting at 2.4 GHz and 5 GHz, respectively, using the Friis transmission equation and keeping the transmit power,

$P_{tx}$, and transmit antenna gain, $G_{tx}$, at a constant of 30 dBm and 6 dBi, respectively. Figure 11 shows the plot of the received signal strength as a function of distance for both operational frequencies.

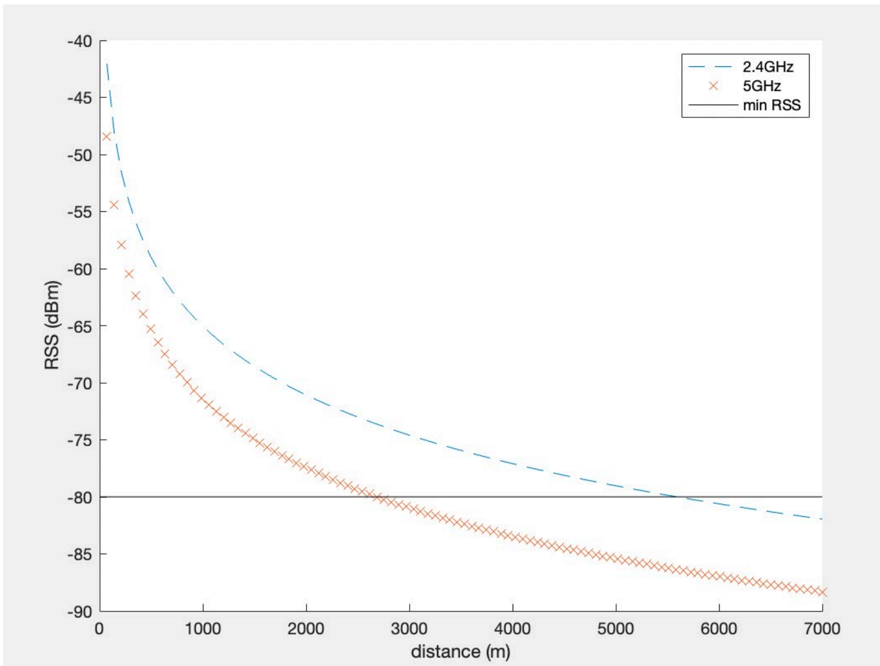


Figure 11. Received Signal Strength as a Function of Distance when Operating at 2.4 GHz and 5GHz.

From the graph, it is evident that the maximum communication range when operating at 2.4 GHz and 5GHz is determined to be around 5.5 km and 2.6 km, respectively.

## B. EFFECTIVE APPLICATION THROUGHPUT

To study the effective application throughput with respect to distance, we modify the existing IEEE 802.11 MAC and application throughput measurement model available on MATLAB Simulink software, to simulate a WLAN network (see Appendix). The model is used to simulate and calculate the application throughput when 500-byte packets are sent between two nodes at 0.001 seconds packet interval. Throughput is defined as the rate of successful transmission over a communication channel and can be calculated using the following equation,

$$Effective\ Throughput = \frac{Total\ number\ of\ bits}{Time\ taken\ to\ send\ and\ receive\ a\ file\ (seconds)}.$$

Based on the example and model in MathWorks, the model allows for the configuration of several applications such as setting the priority of traffic at the application layer and selecting various IEEE wireless standard waveform generation and decoding formats (MathWorks, Inc. n.d.). In addition, the model has also implemented the CSMA/CA protocol to avoid collision, using physical carrier and virtual carrier sensing to determine whether the medium is busy before starting transmission and to establish a Ready to Send/Clear to Send handshake to prevent hidden nodes (MathWorks, Inc. n.d). For this simulation, the channel bandwidth is set at 20 MHz, and the model is modified with the parameters as shown in Table 4.

Table 4. Parameters Used to Measure Application Throughput between Two Nodes.

| **Parameters** | **Values/Settings** |
|---|---|
| PHY Tx Format | HT (IEEE 802.11n) and HE-Ext-SU (IEEE 802.11ax) |
| RTS Threshold | 2347 |
| Tx Power (dBm) | 30 |
| Tx Gain (dB) | 6 |
| Rx Gain (dB) | 0 |
| Rx Noise Figure (dB) | 5 |

The application throughput for both IEEE 802.11n and IEEE 802.11ax standards is analyzed using the model. Both IEEE 802.11n and IEEE 802.11ax can operate on the 2.4 GHz and 5 GHz frequency bands. From the simulation, it is possible to compare the throughput measurements obtained for the respective IEEE standards and analyze their performance.

### 1. Received Signal Strength as a Function of Distance

In free space, as the distance increases, the received signal strength decreases due to attenuation. With reference to the inverse square law of electromagnetic propagation, as a radio wave leaves its source, it spreads out covering the surface of an ever-expanding sphere, while traveling in straight lines, as shown in Figure 12. The spread area increases proportionally to the square of the distance the radio waves have travelled (Hyperphysics 2016).

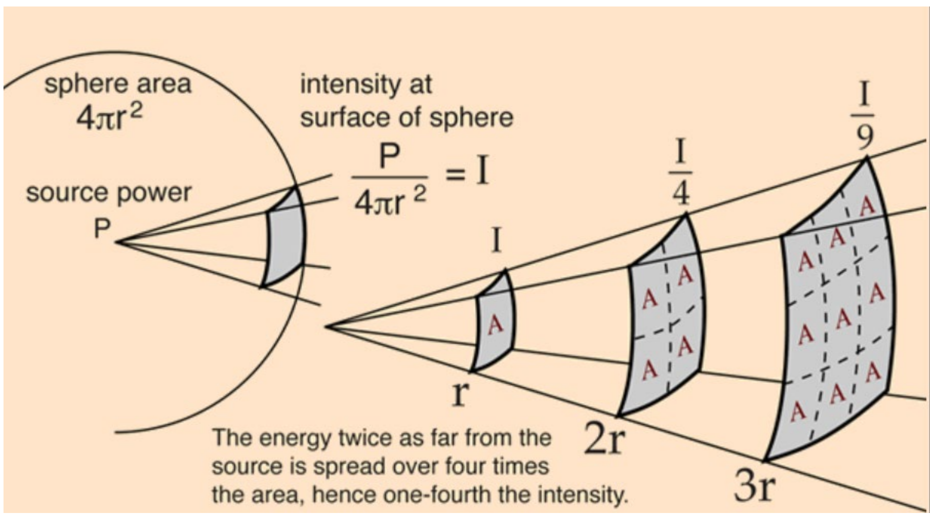


Figure 12. Inverse Square Law of Electromagnetic Propagation. Source: Hyperphysics (2016).

The intensity of the radio waves can be calculated using the following equation,

$$I = \frac{P}{4\pi r^2},$$

where P is the power transmitted from the source and r is the distance the radio waves have travelled (Hyperphysics 2016). From the simulation model, the received signal strength is being recorded as the distance between the two relay nodes increases. It can be observed from Figure 13 that the received signal strength is inversely proportional to distance. As distance increases, the received signal strength decreases. In addition, the higher frequency is more susceptible to atmospheric attenuation as the radio waves transverse the air, resulting in a greater loss of signal strength as distance increases, as can be observed from Figure 13 that compares the received signal strength of the network when operating at 2.4 GHz and 5.0 GHz.

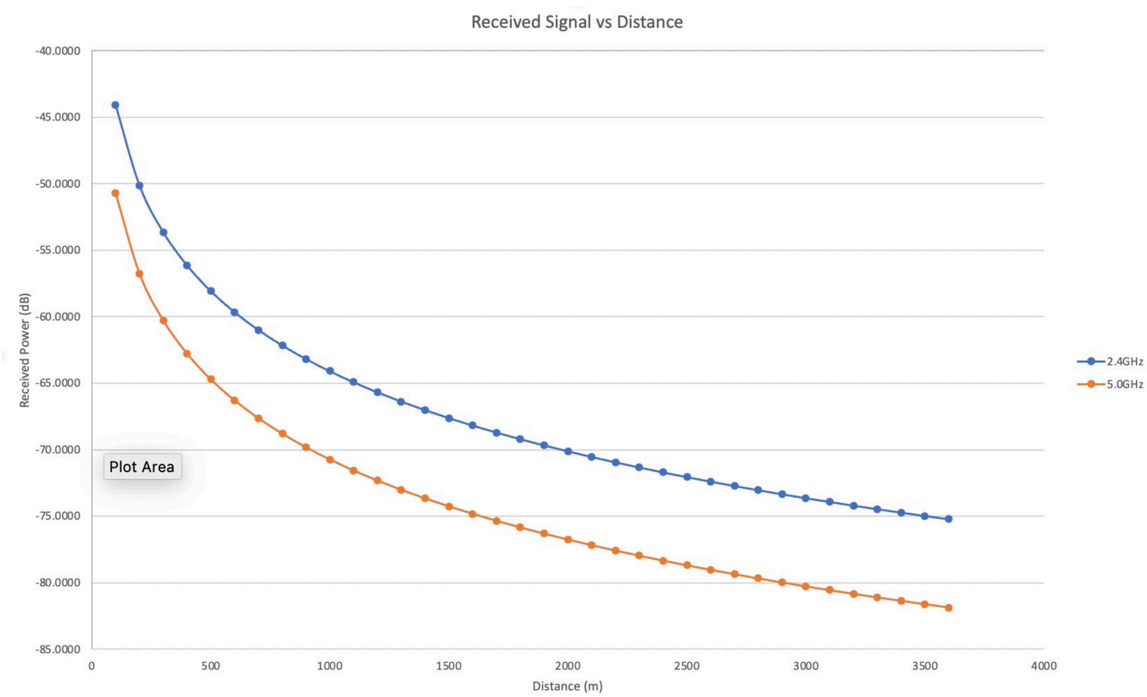


Figure 13. Comparing 2.4 GHz and 5GHz Received Signal Strength to Distance

### 2. Analysis of IEEE 802.11ax Standard

With the channel bandwidth remaining at a constant of 20 MHz, the simulation model is used to compare the performance of the application throughput by varying the operating frequency between the two nodes while operating on the IEEE 802.11ax standard. Figure 14 plots the application throughput against distance while operating at the 2.4 GHz and the 5 GHz frequency band, respectively.

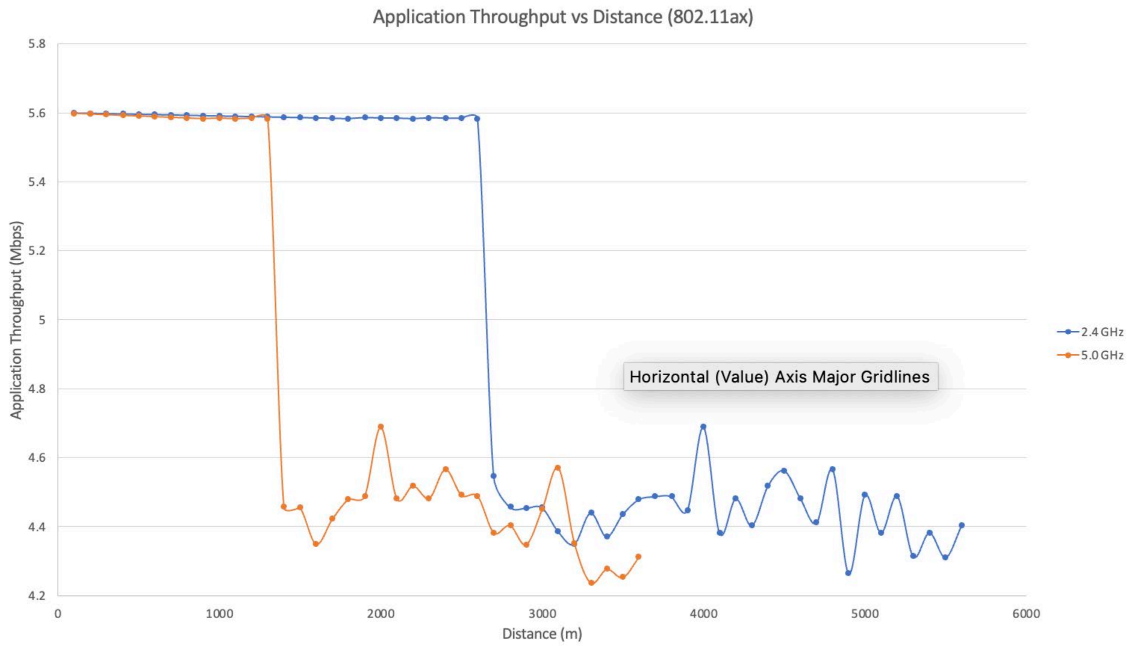


Figure 14. Application Throughput Measured against Distance, Using IEEE 802.11ax Standard.

It can be observed from the plot that when operating on the 5 GHz band, the effective communication range is shorter as compared to 2.4 GHz due to the susceptibility of attenuation at higher frequencies. In addition, when operating at 5.0 GHz, the application throughput decreases drastically as the distance separating the two nodes increases more than 1,350 m. Similarly, the application throughput decreases drastically when the distance between the two nodes increases more than 2,650 m when operating at 2.4 GHz.

Application throughput is expected to decrease as distance increases due to several factors, such as packet loss, network congestion, and latency. Packet loss is one of the main factors that results in the decrease of application throughput. The probability of packet loss or packets being damaged is likely to increase with distance, resulting in the need to retransmit the packet and hence reduce the average throughput between the communicating devices. From Figure 15, it can be seen that the network statistics obtained from the simulation show an increase in the number of data packets dropped (highlighted in the red circle) as the separation distance increases to more than 1,350 m while operating on 5.0 GHz frequency, which explains the drastic decrease in application throughput from around

5.5822 Mbps to about 4.4569 Mbps. In addition, latency is the amount of time it takes for a packet to travel from the source to its designated destination. Therefore, as distance increases, the amount of latency increases, which is also known as propagation delay.

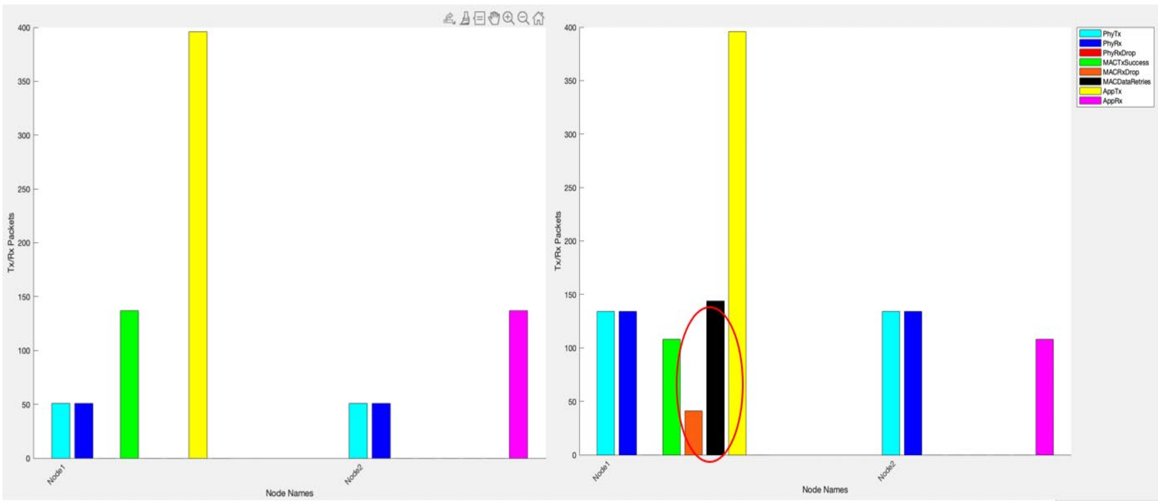


Figure 15. Comparing the Network Statistics at 1,340 m (left) and 1,350 m (right).

Despite the limited transmission range operating on the 5 GHz frequency band, it has the advantage of having more non-overlapping channels, which reduces the chances of interference, and it provides faster upload and download speeds (Zomaya 2019). Even though the IEEE 802.11ax standard can operate at higher channel bandwidths such as 40 MHz, 80 MHz, and 160 MHz, using different modulation technique and varying guard interval to accommodate for a higher data throughput, it is not recommended to increase the channel bandwidth from 20 MHz while operating on the 2.4 GHz frequency band due to the limited number of non-overlapping frequency channels. Increasing the channel bandwidth will reduce the number of non-overlapping channels and thus increase the chances of interference. By contrast, with 5 GHz, to optimize the data throughput while minimizing interference, it is recommended to use the 40 MHz channel bandwidth instead.

In their journal article "A Performance Analysis of IEEE 802.11ax Networks," Natkaniec et al. (2019) describe a simulation they conducted while operating on the 2.4 GHz frequency band. Using the lowest modulation and coding scheme and largest guard interval value of 800 ns, they compared the performance of the transmission range by varying the channel bandwidth. From the result shown in Figure 16, it is evident that as the channel bandwidth increases from 20 MHz to 80 MHz, the effective throughput is about four times higher. On the other hand, the effective network coverage decreases by half the distance.

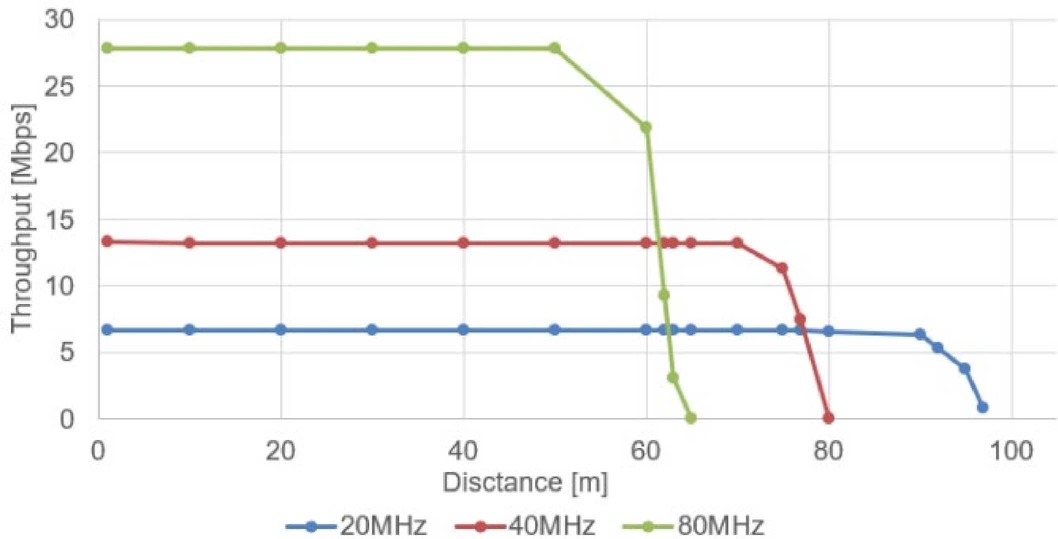


Figure 16. Throughput Measured against Distance, Using IEEE 802.11ax Format. Source: Natkaniec et al. (2019).

Hence, to maximize the data throughput and overcome the range limitation, the proposed communication relay concept can consider varying the channel bandwidth depending on the operating frequency used.

#### a. *Comparing the Performance between 2.4 GHz and 5.0 GHz*

Depending on the type of modulation used and several variables, the maximum data rate of a network can be calculated using the following equation,

$$Data\ Rate = \frac{N_{SD} \times N_{BPSCS} \times R \times N_{SS}}{T_{DFT} + T_{GI}},$$

where $N_{SD}$ is the number of data subcarriers, $N_{BPSCS}$ is the number of coded bits per subcarrier per stream, $R$ is the coding, $N_{SS}$ is the number of spatial streams, $T_{DFT}$ is the OFDM symbol duration, and $T_{GI}$ is the guard interval duration (Verges 2019). Given that the simulation model in this thesis uses orthogonal frequency-division multiple access (OFDMA) modulation scheme, Figure 17 shows the IEEE 802.11ax MCS table with reference to the SemFio network (Verges 2019).

| | | | | OFDM (802.11ax) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MCS Index | Spatial Stream | Modulation | Coding | 20MHz | | | 40MHz | | | 80MHz | | | 160MHz | | |
| | | | | 0.8μs GI | 1.6μs GI | 3.2μs GI | 0.8μs GI | 1.6μs GI | 3.2μs GI | 0.8μs GI | 1.6μs GI | 3.2μs GI | 0.8μs GI | 1.6μs GI | 3.2μs GI |
| 0 | 1 | BPSQ | 1/2 | 8.6 | 8.1 | 7.3 | 17.2 | 16.3 | 14.6 | 36.0 | 34.0 | 30.6 | 72.1 | 68.1 | 61.3 |
| 1 | 1 | QPSK | 1/2 | 17.2 | 16.3 | 14.6 | 34.4 | 32.5 | 29.3 | 72.1 | 68.1 | 61.3 | 144.1 | 136.1 | 122.5 |
| 2 | 1 | QPSK | 3/4 | 25.8 | 24.4 | 21.9 | 51.6 | 48.8 | 43.9 | 108.1 | 102.1 | 91.9 | 216.2 | 204.2 | 183.8 |
| 3 | 1 | 16-QAM | 1/2 | 34.4 | 32.5 | 29.3 | 68.8 | 65.0 | 58.5 | 144.1 | 136.1 | 122.5 | 288.2 | 272.2 | 245.0 |
| 4 | 1 | 16-QAM | 3/4 | 51.6 | 48.8 | 43.9 | 103.2 | 97.5 | 87.8 | 216.2 | 204.2 | 183.8 | 432.4 | 408.3 | 367.5 |
| 5 | 1 | 64-QAM | 2/3 | 68.8 | 65.0 | 58.5 | 137.6 | 130.0 | 117.0 | 288.2 | 272.2 | 245.0 | 576.5 | 544.4 | 490.0 |
| 6 | 1 | 64-QAM | 3/4 | 77.4 | 73.1 | 65.8 | 154.9 | 146.3 | 131.6 | 324.3 | 306.3 | 275.6 | 648.5 | 612.5 | 551.3 |
| 7 | 1 | 64-QAM | 5/6 | 86.0 | 81.3 | 73.1 | 172.1 | 162.5 | 146.3 | 360.3 | 340.3 | 306.3 | 720.6 | 680.6 | 612.5 |
| 8 | 1 | 256-QAM | 3/4 | 103.2 | 97.5 | 87.8 | 206.5 | 195.0 | 175.5 | 432.4 | 408.3 | 367.5 | 864.7 | 816.7 | 735.0 |
| 9 | 1 | 256-QAM | 5/6 | 114.7 | 108.3 | 97.5 | 229.4 | 216.7 | 195.0 | 480.4 | 453.7 | 408.3 | 960.8 | 907.4 | 816.7 |
| 10 | 1 | 1024-QAM | 3/4 | 129.0 | 121.9 | 109.7 | 258.1 | 243.8 | 219.4 | 540.4 | 510.4 | 459.4 | 1080.9 | 1020.8 | 918.8 |
| 11 | 1 | 1024-QAM | 5/6 | 143.4 | 135.4 | 121.9 | 286.8 | 270.8 | 243.8 | 600.5 | 567.1 | 510.4 | 1201.0 | 1134.3 | 1020.8 |
| 0 | 2 | BPSQ | 1/2 | 17.2 | 16.3 | 14.6 | 34.4 | 32.5 | 29.3 | 72.1 | 68.1 | 61.3 | 144.1 | 136.1 | 122.5 |
| 1 | 2 | QPSK | 1/2 | 34.4 | 32.5 | 29.3 | 68.8 | 65.0 | 58.5 | 144.1 | 136.1 | 122.5 | 288.2 | 272.2 | 245.0 |
| 2 | 2 | QPSK | 3/4 | 51.6 | 48.8 | 43.9 | 103.2 | 97.5 | 87.8 | 216.2 | 204.2 | 183.8 | 432.4 | 408.3 | 367.5 |
| 3 | 2 | 16-QAM | 1/2 | 68.8 | 65.0 | 58.5 | 137.6 | 130.0 | 117.0 | 288.2 | 272.2 | 245.0 | 576.5 | 544.4 | 490.0 |
| 4 | 2 | 16-QAM | 3/4 | 103.2 | 97.5 | 87.8 | 206.5 | 195.0 | 175.5 | 432.4 | 408.3 | 367.5 | 864.7 | 816.7 | 735.0 |
| 5 | 2 | 64-QAM | 2/3 | 137.6 | 130.0 | 117.0 | 275.3 | 260.0 | 234.0 | 576.5 | 544.4 | 490.0 | 1152.9 | 1088.9 | 980.0 |
| 6 | 2 | 64-QAM | 3/4 | 154.9 | 146.3 | 131.6 | 309.7 | 292.5 | 263.3 | 648.5 | 612.5 | 551.3 | 1297.1 | 1225.0 | 1102.5 |
| 7 | 2 | 64-QAM | 5/6 | 172.1 | 162.5 | 146.3 | 344.1 | 325.0 | 292.5 | 720.6 | 680.6 | 612.5 | 1441.2 | 1361.1 | 1225.0 |
| 8 | 2 | 256-QAM | 3/4 | 206.5 | 195.0 | 175.5 | 412.9 | 390.0 | 351.0 | 864.7 | 816.7 | 735.0 | 1729.4 | 1633.3 | 1470.0 |
| 9 | 2 | 256-QAM | 5/6 | 229.4 | 216.7 | 195.0 | 458.8 | 433.3 | 390.0 | 960.8 | 907.4 | 816.7 | 1921.6 | 1814.8 | 1633.3 |
| 10 | 2 | 1024-QAM | 3/4 | 258.1 | 243.8 | 219.4 | 516.2 | 487.5 | 438.8 | 1080.9 | 1020.8 | 918.8 | 2161.8 | 2041.7 | 1837.5 |
| 11 | 2 | 1024-QAM | 5/6 | 286.8 | 270.8 | 243.8 | 573.5 | 541.7 | 487.5 | 1201.0 | 1134.3 | 1020.8 | 2402.0 | 2268.5 | 2041.7 |

Figure 17. IEEE 802.11ax MCS Table. Source: Verges (2019).

With reference to the MCS table, the maximum data rate based on BPSK modulation with a guard interval of 800 ns, is used to compare the performance between 2.4 GHz and 5GHz while operating on IEEE 802.11ax, as shown in Table 5. Hence, from the summary table, it is seen that the 5.0 GHz frequency band can provide a higher data bandwidth and hence is able to provide a faster data rate as compared to 2.4 GHz.

Table 5. Summary of IEEE 802.11ax Performance.

| IEEE 802.11ax | | |
|---|---|---|
| **Frequency** | **2.4 GHz** | **5.0 GHz** |
| **Distance** | Further | Shorter |
| **Bandwidth (MHz)** | 20, 40 | 20, 40, 80, 160 |
| **Max Data Throughput based on BPSK Modulation at GI of 800 ns** | 17.2 | 72.1 |

### 3. Analysis of IEEE 802.11n Standard

Figure 18 compares the plot of the application throughput against distance while operating on the 2.4 GHz and the 5.0 GHz frequency, respectively, using the IEEE 802.11n standard. Both Figures 14 and 18 show similar results. The application throughput decreases with distance for both operating frequencies. In addition, 5 GHz has a shorter transmission range as compared to 2.4 GHz. The drastic decrease in throughput can also be observed in both frequency bands.

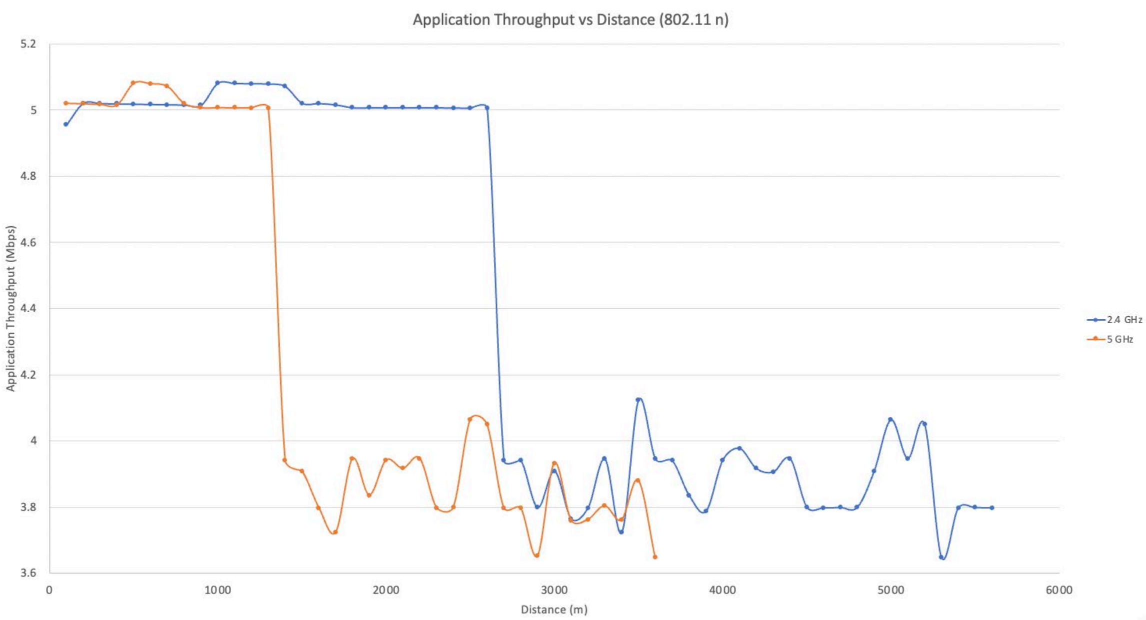


Figure 18. Application Throughput Measured against Distance, Using IEEE 802.11n Standard.

However, based on the results, it is evident that IEEE 802.11ax has a higher data throughput as compared to IEEE 802.11n. This is because IEEE 802.11ax offers better efficiency, network capacity, and performance while reducing latency as it uses a more efficient modulation and coding scheme as compared to IEEE 802.11n. Therefore, to increase the application throughput, the proposed concept can consider leveraging on the benefits of the IEEE 802.11ax standard to maximize the overall performance of the network.

In conclusion, with the theoretical communication range determined in the previous section and the recommended Wi-Fi standards, it can be determined that the maximum application throughput when operating at 2.4 GHz and 5 GHz is around 4.403 Mbps and 4.488 Mbps, respectively. Given the estimated throughput, the number of channels available to send different types of data are summarized in Table 6. In comparison, the number of channels increases as the channel bandwidth increases. Hence, to increase the data throughput of the network, it is recommended to operate using the 5 GHz frequency band as it can operate in higher channel bandwidths, which increases the data rate and number of non-overlapping channels.

Table 6. Estimated Number of Channels Required to Send Different Types of Data.

| Frequency | | 2.4 GHz | | 5.0 GHz | |
|---|---|---|---|---|---|
| | | Simulation Result (@ 20 MHz Bandwidth) | MCS table (@ 40 MHz bandwidth) | Simulation Result (@ 20 MHz Bandwidth) | MCS Table (@ 160 MHz bandwidth) |
| Data throughput for IEEE 802.11ax (Mbps) | | 4.403 | 17.2 | 4.488 | 72.1 |
| | | | | | |
| Data Exchange | Bit Rate | Number of Channels | | | |
| Voice Messages | 64 kbps | 68 | 268 | 70 | 1,126 |
| Video feed | 2 Mbps | 2 | 8 | 2 | 36 |
| Text Messages | 0.224 kbps | 19,656 | 76,785 | 20,035 | 321,875 |
| Text Messages with Images | 1 Mbps | 4 | 17 | 4 | 72 |

## C. PROPOSED NUMBER OF ASSETS REQUIRED

With the theoretical communication range between two nodes determined to be around 5.5 km and 2.6 km when operating on the 2.4 GHz and 5GHz frequency bands, respectively, it is possible to determine the number of aerial relay nodes required to provide communication coverage for an operational area of 50 km by 50 km.

### 1. Simulation of Operational Environment

To determine the number of assets required to support an operational area of 50 km by 50 km, the ArcGIS Pro software is used as a map planning tool to plan for the communication coverage within the operational area. As shown in Figure 19, an area around the town of Barstow, California, is used to simulate the operational area. For this scenario, the brigade is to conduct a swift and deceive operation to secure Barstow with three battalions under the brigade's command. Based on the initial planning, the battalions will take two different advancement routes towards their target location.

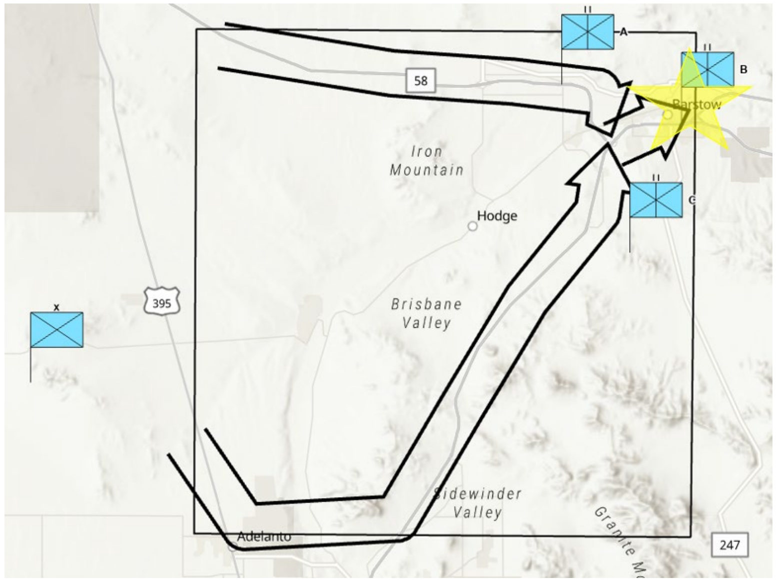


Figure 19. Simulated Operational Area Marked Out by ArcGIS Pro Software

With the movement route of the battalions, the maximum communication range is determined as 5.5 km and 2.6 km while operating at 2.4 GHz and 5 GHz, respectively. The number of assets needed to provide communication coverage within the area of operation can then be determined.

### 2. Communication Coverage

Based on the proposed operational concept, as the battalions advance along the pre-determined route, they are tasked to drop off and deploy the aerostat systems to provide communication coverage along the route of advancement. Hence, using ArcGIS software, the communication coverage while operating on 2.4 GHz frequency band is plotted as shown in Figure 20.

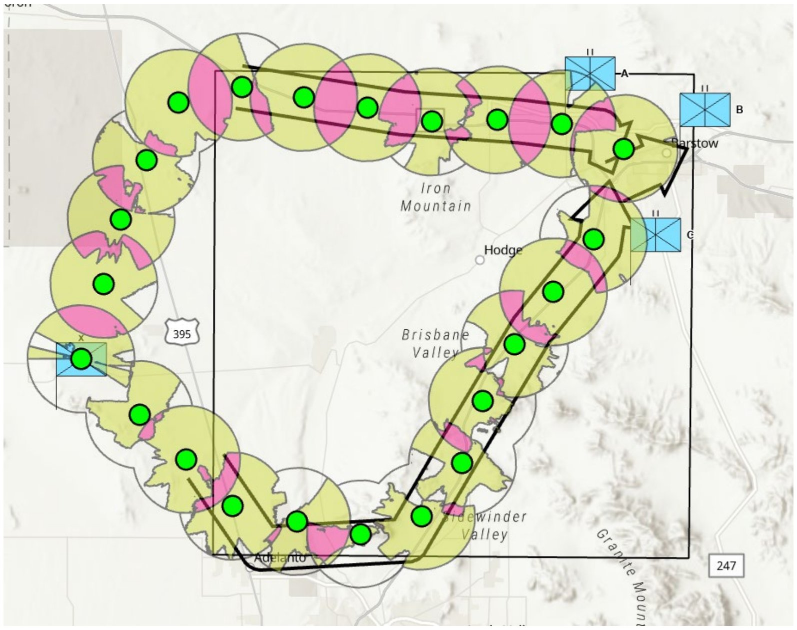


Figure 20. Communication Coverage for Network Operating on 2.4 GHz, with Aerostat Deployed at 300 ft

For this scenario, the aerostat is assumed to be deployed at 300 ft. Despite deploying the relay nodes at a higher elevation, it is observed that due to the presence of mountainous terrain, especially for the southern route, not all aerostats can achieve line of sight with one another. In addition, they have a very narrow and directed azimuth to achieve a line-of-sight angle with the adjacent node.

To accommodate a larger data bandwidth to support phase 2 of the operation, where troops are involved in a heated combat environment, real-time intelligence and situational updates are crucial for the survival of the soldiers on the ground. As the bandwidth increases, the communication range decreases. Therefore, tactical drones can be deployed into the theatre to form a communication network with the pre-deployed aerostat system. Similarly, the tactical drones are assumed to hover around 300 ft while operating as relay nodes. Figure 21 shows the communication coverage provided by both the aerostat and tactical drones when operating at 5.0 GHz.

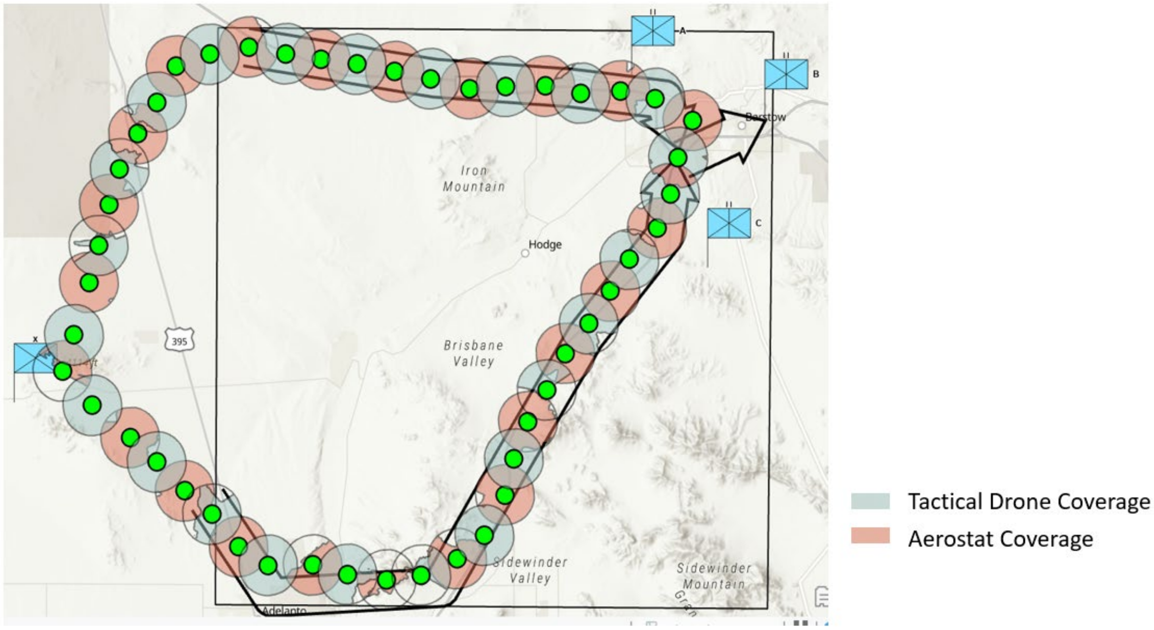


Figure 21. Communication Coverage for Network Operating on 5 GHz, with Aerostats and Tactical Drones Deployed at 300 ft

Despite elevating the altitude to 300 ft, both the communication coverage provided by the aerostats and tactical drones are obstructed by the mountainous terrain in the area. Therefore, to improve the communication coverage, it is recommended to increase the operating altitude of the relay systems, such that the system components can achieve a clear line of sight with one another. Based on map planning from the ArcGIS Pro software, the communication coverage improves as the altitude of the systems is adjusted to 500 ft and 1000 ft, as shown in Figures 22 and 23, respectively.

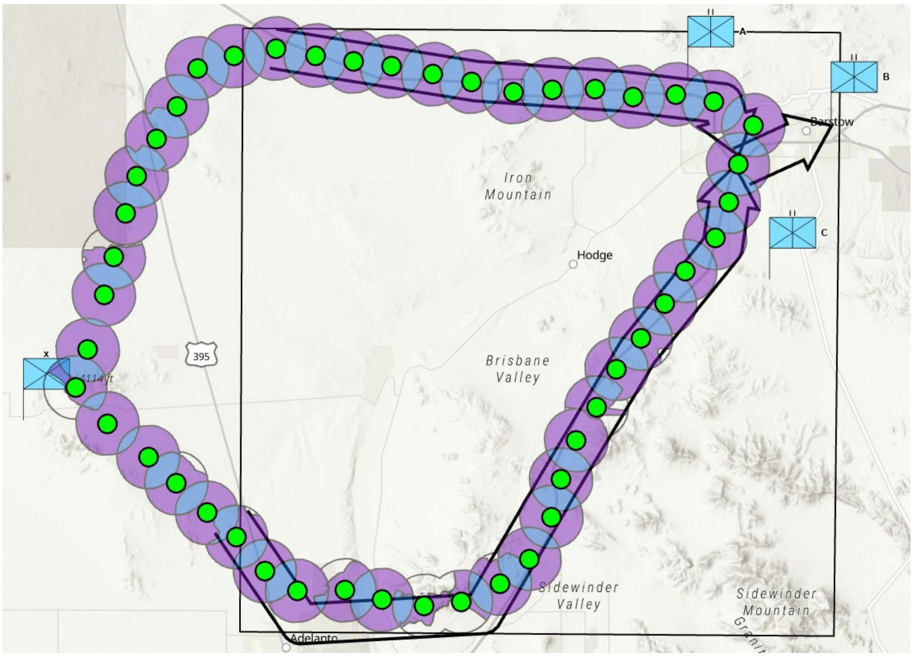

Figure 22. Communication Coverage for Network Operating on 5 GHz, with Aerostats and Tactical Drones Deployed at 500 ft

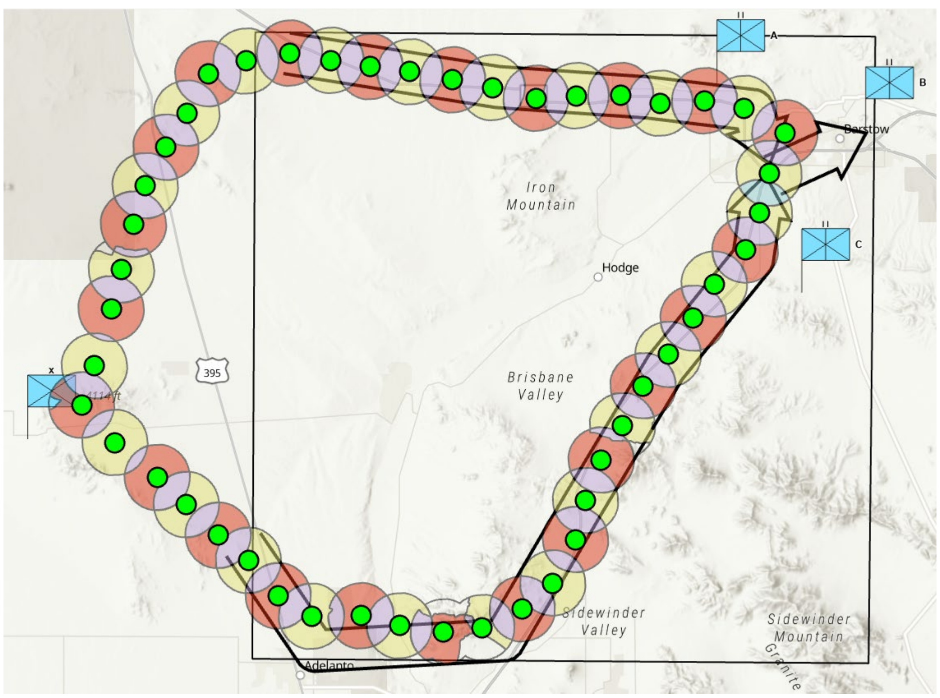

Figure 23. Communication Coverage for Network Operating on 5 GHz, with Aerostats and Tactical Drones Deployed at 1000 ft

### 3. Number of Assets Required

The total number of assets required to provide communication between the brigade and the battalions during the different phases of operations is summarized in Table 7.

Table 7. Number of Assets Required

| Phases of Operation | Type of System | Frequency Band | Number of Assets |
|---|---|---|---|
| Phase 1: | Aerostat Communication Relay | 2.4 GHz | 23 |
| Phase 2: | Aerostat Communication Relay | 5.0 GHz | 23 |
| | Tactical Drone Communication Relay | | 24 |
| Phase 3: | Aerostat Communication Relay | 2.4 GHz | 23 |

## D. SUMMARY

Theoretically, for 5.0 GHz network, the maximum communication range between two relay nodes is determined to be around 2.6 km with a maximum application throughput of 4.488 Mbps. While operating at 2.4 GHz, the theoretical communication range is determined to be around 5.5 km with a maximum application throughput of 4.403 Mbps. Based on the communication range, a total of 23 aerostat systems and 24 tactical drones is required to provide communication coverage for an operational area of 50 km by 50 km.

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# VI. CONCLUSION

With the technological advancements in the digital battlefield and increasing demand for a highly interconnected force that can conduct multi-domain operations, the current communication concept of employing static relay nodes in the operational theatre may not be an ideal solution in the long run. Therefore, the main goal of this thesis has been to design an operational concept by employing UAVs—specifically, aerostats and tactical drones—as relay nodes to extend the range of communication for tactical forces while overcoming the limitations in a GPS-denied environment. The findings of this thesis can be used to further enhance communication effectiveness in a combat operational environment.

## A. THESIS CONTRIBUTIONS AND ACHIEVEMENTS

This thesis introduces an operational communication framework that adopts a hybrid communication system by enabling both aerostat systems and tactical drones as communication relay nodes. The proposed framework takes advantage of the agility afforded by the UAVs and the flexibility of the wireless network to integrate and adopt new systems. In addition, to accommodate the increasing demand for a higher data bandwidth, the solution presented uses both the 2.4 GHz and the 5.0 GHz frequency band to examine the network performance and analyze the feasibility of the proposed concept.

First, the operational concept is divided into different phases to examine the needs and type of system that could be deployed. To assess the feasibility of the proposed communication network, the research examines the effective communication range and data throughput between two aerial relay nodes. By limiting the output power and ERP in accordance with the FCC ISM regulation, it is determined that the effective communication range of the proposed concept while operating in the 2.4 GHz and 5 GHz frequency bands is around 5.5 km and 2.6 km, respectively.

To study the effective application throughput with respect to distance, the existing IEEE 802.11 MAC and application throughput measurement model available on MATLAB Simulink software were modified to simulate a WLAN network. The model was used to determine the application throughput for both the IEEE 802.11ax and IEEE 802.11n standard. From the simulation results, it was observed that as distance increased, the application throughput decreased due to several factors such as latency and the increased number of packets lost. In addition, the 5 GHz frequency band also provided a shorter transmission range as compared to the 2.4 GHz band. Therefore, to optimize the data throughput while minimizing interference, it is recommended to use the 40 MHz channel bandwidth while operating on the 5 GHz frequency band. From the simulation results, it was evident that IEEE 802.11ax showed a higher data throughput as compared to IEEE 802.11n, undoubtedly because IEEE 802.11ax uses a more efficient modulation and coding scheme as compared to IEEE 802.11n. Therefore, with IEEE 802.11ax as the recommended Wi-Fi standard, the maximum application throughput when operating at 2.4 GHz and 5 GHz is around 4.403 Mbps and 4.488 Mbps, respectively.

Having established the effective communication range, it was possible to determine the estimated number of communication system components required to support an operational area of 50 km by 50 km. ArcGIS Pro, a map planning tool, enabled us to simulate an operational area and to plan the communication coverage. It was determined that a total of 23 aerostat systems and 24 tactical drones would be required.

## B. FUTURE WORK

This thesis has focused primarily on the conceptual design of a network architecture that employs both aerostat systems and tactical drones. To assess the feasibility of the designed concept, the analysis focused solely on the performance between two aerial relay nodes in a simulated environment. Therefore, there is a need to further research and study the effects on overall network efficiency caused by having multiple transmitting stations within the network. To that end, following are some of the recommendations for future research.

Real-life Flight Testing. There are several factors that can affect the efficiency of the communication network. One of those factors is the effect of attenuation on the radio signal caused by the environment. For instance, rain, fog, and clouds could result in the perturbation of the radio waves. Humidity in the air can result in a different throughput value as the water vapor in the air can cause part of the signal wave energy to be absorbed or scattered. Thus, this can result in lower throughput. To have a better understanding and more accurate estimation of the effective throughput of the aerial relay network, it would be most helpful to conduct a live test in an environment similar to the one in which the relay nodes are expected to operate.

Power Consumption. The flight duration of the drone systems is limited by their battery life. Other than providing power to sustain the drone in the air, the batteries installed on the drone system are required to provide power to the payload, which greatly reduces the airtime of the drone. Given the limited amount of payload that the drone is capable to carry, there is a need to explore alternatives such as integrating a solar power system with the drones to prolong their flight duration and to power up the payload.

Integration with Other Surveillance Systems. Apart from relaying communications, the aerial relay nodes theoretically could provide additional services such as conducting surveillance and reconnaissance missions if sensors and camera systems were installed on the relay nodes. To confirm this, it would first be necessary to determine whether the different systems integrated on the aerial relay nodes would cause interference. These systems may operate in similar frequency bands that could potentially interfere with one another; therefore, a detailed frequency allocation plan might be necessary to ensure that there is enough frequency separation between the different systems to minimize interference.

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# APPENDIX. SIMULATION MODEL

## A. MODEL LAYOUT BETWEEN TWO WLAN NODES

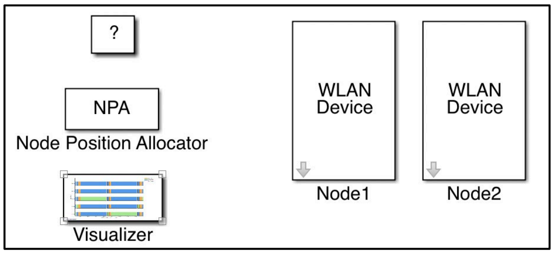


Figure 24. WLAN Simulation Model between Two Nodes. Adapted from MathWorks Inc. (n.d.).

## B. MODEL LAYOUT WITHIN A WLAN NODE

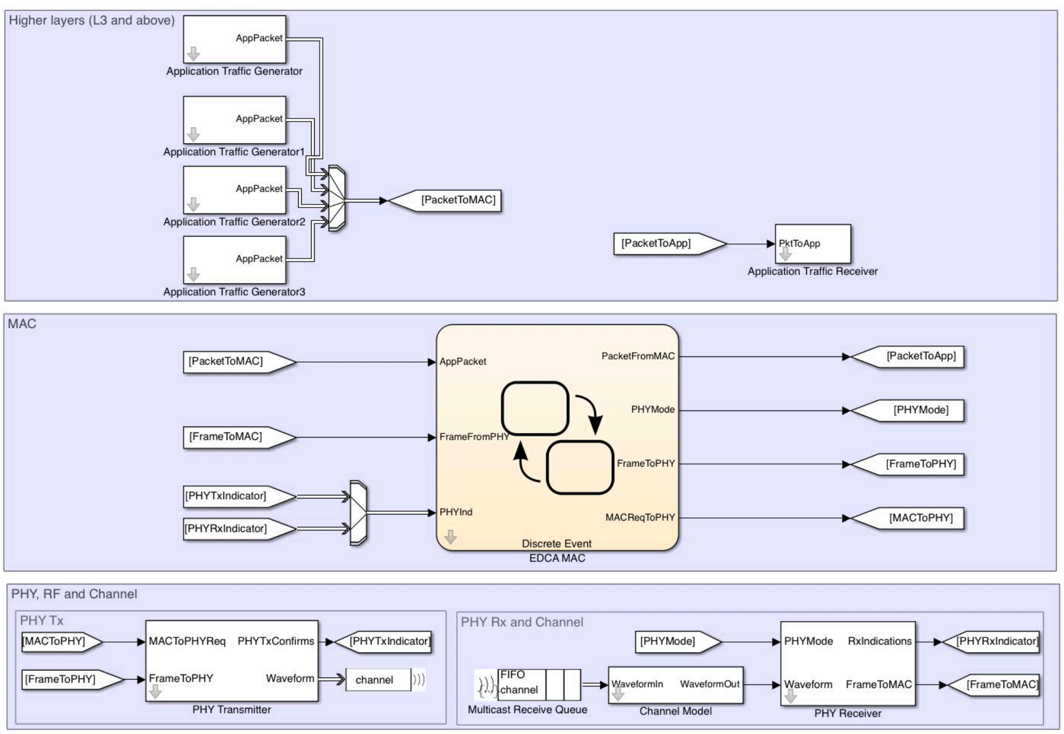


Figure 25. Simulation Model within a Node. Adapted from MathWorks, Inc. (n.d.).

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