Ad-Hawk Aerial Connectivity Network: An Integrated and Empirical System Evaluation

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Wildfires in the United States have been increasing significantly in both frequency and size in recent decades, requiring unprecedented resource and communication efficiency on the part of wildfire management organizations. However, while the methodology and technology to combat wildfires have improved, the connectivity infrastructure in rural regions of the country is either incompatible with newer technology or altogether non-existent. Due to this, many modern communication methods are rendered useless in areas where a connection is needed most, complicating the overall fire management procedure. To improve communication and logistics between responders on the front lines and headquarters, a team of NASA research associates has developed the schematic for a rapidly deployable mobile ad-hoc internet-enabled Wi-Fi network that can bring stable internet access to any desired area.

Disclaimer: NASA does not endorse the products and services detailed in this report. They were simply selected as examples of existing technologies and offerings to validate the proposed concepts of the Ad-Hawk Network.

I. Nomenclature

Ad-Hawk = Play-on-Words for ad-hoc network
AP = Access Point
*AP*I = Application Programming Interface
C2 = Command and Control
CG = Center of Gravity
COLT = Cell on Light Truck
COTS = Commercial Off-The-Shelf
COW = Cell on Wheels
EMF = Electro-Magnetic Frequencies
FCC = Federal Communications Commission
Flying COW = Cell on Wings g
GCS = Ground Control Station
IMU = Internal Measurement Unit
IoT = Internet of Things
ISM = Industrial, Scientific, and Medical
LaRC = Langley Research Center
LEO = Low-Earth Orbit
M/R = Modem/Router
NEST = Network Enabled Source Technologies
NTIA = National Telecommunications and Information Administration
PDF = Portable Document Format
PoE = Power over Ethernet
RC = Remote Control
SIM = Subscriber Identity Module
SPOT = Satellite Picocell on Trailer
THOR = Tactical Humanitarian Operations Response
UAS = Uncrewed Aerial System
WDS = Wireless Distribution System

II. Introduction

Fighting wildland fires requires a sizeable labor force of firefighters working in various crews spread out over vast distances. Though there are many methods currently implemented in wildfire suppression, such as aerial drops of water or fire retardant, the most reliable and widely practiced technique is crews of people on the ground cutting fire lines (i.e., removing potential fuels with heavy machinery and/or hand tools) to guide the fire towards existing choke points such as rivers, ridges, or roads [1][2]. Quick and clear communication between frontline crews and basecamp/logistics is essential to coordinating effective fire lines.

However, in more rural areas, cellular signals can be weak or nonexistent, drastically inhibiting communication lines. The primary form of communication between wildfire first responders in these scenarios is the handheld radio, which is only capable of vocal data transmission, leading to bottlenecks and data generalization [3]. Ideally, ground crews will use digital tablets only capable of connectivity via an internet-enabled Wi-Fi channel to upload/download time-sensitive information, operate apps, run wildfire simulation software, or generally communicate with operation leadership [4]. Without Wi-Fi, they are forced to relay information via clogged radio channels instead of directly updating common operating pictures.

Remote areas of the United States—particularly on the West coast—simply do not have the cellular or Wi-Fi infrastructure required to support the communication networks desperately needed by first responders to combat increasingly massive and devastating wildfires [5]. Broadcasting a stable internet-enabled Wi-Fi signal in remote areas would allow ground crews to use the tools provided to them to their fullest potential and effectively relay information as necessitated by these chaotic situations.

This paper presents the conceptualization, testing procedures, and data analysis of an aerial, ad-hoc Wi-Fi network intended to increase connectivity in remote areas for first-responder use. With access to a mobile network capable of achieving sufficient bandwidth, firefighting crews could send and receive mission-critical information in a timely manner. Using a concept validated by previous research, the team designed a pair of unmanned aircraft system (UAS) payloads capable of achieving this Wi-Fi mobility and carried out both ground and flight testing at NASA Langley Research Center. By gaining empirical data on the interconnected aerial system, the research team explored and validated its efficacy.

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III. Similar Research

This report is a re-summarization and continuation of work completed in [6], where the Ad-Hawk system was conceptualized, researched, and a basic proof-of-concept test was completed. This paper builds upon the research conducted in 2022 to present a quantitative study of the efficacy of an integrated and fundamentally comprehensive Ad-Hawk system. While the 2022 research team posed multiple possible configurations and use cases for such a system, this paper will focus on a particular hardware configuration with associated testing conducted both on the ground and as a set of payloads aboard two UAS.

The Ad-Hawk research also references and builds upon [7], in which Yixin Gu of the University of North Texas explores airborne Wi-Fi networks through directional antennas. Gu validated the notion of affixing network establishing and point-to-point bridging hardware to a pair of UAS. Additionally, this study confirmed that emitting 2.4 GHz signals would not interfere with the 2.4 GHz connection between the UAS and its remote control.

Further, a network of UAS providing ad-hoc Wi-Fi coverage in disaster relief scenarios is proposed theoretically by Indrakshi Dey in [8], however, details of said proposal do not include any empirical data or hardware configurations. Dey proposed the UAS network be used in tandem with a network of “smart buoys” to primarily aid in early warning detection of tsunami, flood, and chemical spill disasters. Unlike Ad-Hawk, Dey's proposed UAS ad-hoc network is not intended for providing usable Wi-Fi to first responders but rather as a medium for the intermittent transmission of data between the "smart-buoys" and data conglomeration centers.

An ad-hoc wireless mesh network for disaster relief scenarios proposed in [9] utilizes the ubiquity of personal electronic devices, such as smartphones and laptops, to create impromptu nodes that operate as mobile access point (MAP) relays. The maximum hop distance between relay nodes was found to be 290 meters. While the overarching goal of this system is similar to that of Ad-Hawk, the Ad-Hawk system relies on a smaller number of airborne vehicles to construct a bus network rather than a multitude of personal ground devices.

The research proposed in [10] is the most similar architecture to that of Ad-Hawk. Here, the primary objective was to provide live video feed on a UAS-mounted camera via a Wi-Fi mesh network with a high bit rate (~160Mbps) at short distances (<100m). This short-range, high-rate data transfer function is oriented towards military operational use. Ad-Hawk, on the other hand, is designed to aid in disaster response through long-range, low-rate data transfer.

IV. State of the Art

Several commercially available or near-available attempts to bring internet access to rural areas in emergency scenarios have emerged in recent years. AT&T's FirstNet is developing a tethered UAS deemed the Flying Cell on Wings (Flying COW), a mobile cellular tower with an advertised 10 square-mile cellular connectivity range, producing a 1.8-mile signal radius. It is stated to be weather resistant and capable of 24-hour flights when tethered to a generator. The Flying COW serves to bring signals further than if it were land-based, however, the signal would be 5G and not accessible via Wi-Fi as would be ideal for firefighter command [11]. The UAS can produce Wi-Fi, but over a range of just 500 feet according to FirstNet, and without in-field use, reliability has not been confirmed. Ground-based mobile cellular options such as AT&T's COW and COLT, or Verizon's THOR suffer from the same or worse range limitations and focus primarily on cellular output rather than Wi-Fi [12][13][14]. Each of these solutions is also limited in their mobility as they are either on-ground or tethered.

SpaceX's Starlink, a network of low-Earth orbit (LEO) satellites designed to provide global internet service, is another potential tool if applied to these rural areas. While Starlink has the potential to be a solution itself, it suffers from several limitations for the use case of rural wildfire operations. First, the receiver dish needs an unobstructed view of the sky to receive a signal from its low-orbit satellites, which is difficult to achieve with rough terrain, forest landscapes, and thick smoke from wildfires. Additionally, the smallest currently available dish is 0.29 meters (19 inches) by 0.25 meters (12 inches) and ~4.2 kg (~9.2 lb), making it highly unlikely it could be carried on-foot by first responders who are already stretched to their carrying capacities [15].

These currently available solutions are high-cost and low-range. What is necessary for this application is an adaptable solution capable of tapping into any available internet source in remote areas and extending the connection via Wi-Fi where needed within a wildfire management operation.

V. Project Overview

The goal of this paper is to examine one proposed method of achieving large aerial Wi-Fi networks through the interconnected use of established, commercially available hardware. The 2023 Ad-Hawk research team designed three testing arrangements, each designed to empirically explore a major component of the network's feasibility. At its most basic level, Ad-Hawk is designed to use internet bridging hardware to stretch internet connectivity between at least two points before ultimately converting it to a usable, internet-enabled Wi-Fi output. An initial testing setup dealt with the system's capabilities when bridging signal between two points on the ground; in doing this, data transmission rates at the system's most basic level were explored.

Building from this, the second testing setup followed the same format using three connected points rather than two. In doing so, the research team established and explored the functionality of a daisy-chained point-to-point network. Because the Ad-Hawk network is ultimately meant to be established through daisy-chaining, this testing setup was the first in which the research team attempted to empirically validate the system's intended use case.

Finally, the third setup tested the two-point system aboard UAS. Flight testing the system allowed the research team to demonstrate that internet connectivity can be bridged between UAS at various configurations. Additionally, flight testing confirmed that the frequencies emitted by the Ad-Hawk payloads do not cause electromagnetic interference with those emitted by the vehicles housing them. By exploring Ad-Hawk's functionality with two points on the ground and in the air as well as with three points on the ground, the research team aims to establish the feasibility of an aerial, multipoint ad-hoc Wi-Fi network.

VI. Framework Breakdown

The Ad-Hawk system was developed to rely on fielded off-the-shelf technologies; thus, each system component is commercially available and has well-established capabilities and specifications. While this team's research has sought to experimentally determine the efficacy of the general Ad-Hawk concept, the expected performance of an aerial bus network could be theoretically determined using hardware specifications. Being comprised of connected yet individual components, the Ad-Hawk system could be tailored by altering any individual component, and thus the framework is adaptable to a user's particular needs.

The testing arrangement presented was designed to have accessible replicability for emergency service organizations. Such replicability was guided based on resources available to California-based wildfire fighting agency CAL FIRE when testing took place.

A.) Connectivity

i.) Internet Source

Moving forward, the working assumption of this project is that a wildfire is occurring in a region in which there is faint or no pre-existing form of internet connectivity. Thus, to bring any form of connectivity to wildfire management, the fundamental source of the internet connection is of paramount logistical importance. An intensive scoping of all available resources fielded several viable internet connectivity sources dependent upon terrain and geographical location. Those options deemed most viable include mobile cellular network generator units, low-Earth orbit (LEO) satellites, and cellular boosters for pre-existing nearby cell towers.

a.) Mobile Cellular Network Generators

Two major U.S. cellular providers offer first responder services for emergency situations. AT&T FirstNet and the Verizon Response Team offer mobile cellular network generating options that create short-range cellular signals in rural areas lacking network coverage [11][12][13][14]. Various firefighting organizations already subscribe to first responder services, giving them access to these mobile cellular generating units when needed. Some examples of mobile cellular network-generating units include:

- **FirstNet:** Flying COW (Cellular on Wings), CRD COW (Compact Rapid Deployable Cellular on Wheels), COLT (Cell on Light Truck)
- **Verizon:** THOR (Tactical Humanitarian Operations Response), COW (Cellular on Wheels), COLT (Cell on Light Truck), SPOT (Satellite Picocell on Trailer)

This method of producing a mobile field of cellular coverage would solve the issue of having weak or no pre-existing cellular signal in the regions in which one would be necessary for wildfire management. The more effective of these existing technologies, FirstNet's Flying COW, for example, can produce a circle of cellular coverage up to 3.6 miles in diameter [11]. This range of capabilities is more than sufficient to support the successive components of this project necessary to produce the desired Wi-Fi coverage.

b.) Low-Earth Orbit Satellites

A constellation network of LEO satellites offers the potential to provide internet connectivity to any SIM-enabled device on Earth's surface. As this connection is only provided to devices with a corresponding SIM card, this method excludes many common electronic devices such as tablets and laptops. However, virtually any IoT device can connect to an internet-enabled Wi-Fi signal. This means the NEST could connect to a LEO satellite signal and the Ad-Hawks would convert and distribute the NEST connectivity in the form of an internet-enabled Wi-Fi signal allowing any IoT device within range to have a stable internet connection. SpaceX's Starlink is an existing constellation network consisting of thousands of these LEO satellites. The objective of the actively developing project is to provide internet connectivity across the globe and particularly for rural and developing areas with little to no internet infrastructure. Starlink claims to provide higher internet speed and bandwidth than traditional high-Earth orbit (HEO) satellite options as LEO satellites are in closer proximity to Earth's surface. Thus, signal latency and potential for physical interference are reduced. Currently, at least one satellite dish is required to receive Starlink connectivity, however, the volume and complexity of the required reception equipment are expected to decrease as the offering is developed further [15].

In the scope of the Ad-Hawk Network, Starlink is viewed less as a replacement solution and more as a potential tool for future integration. For Starlink to function as a comprehensive solution, it would require a significant number of mobile dishes and the ability to establish a reliable Wi-Fi -connection with LEO satellites through canopies, smoke, and other overhead obstacles. Instead, Starlink is another option for providing the necessary cellular internet signal to the NEST in which case only one Starlink satellite signal reception dish would be necessary.

c.) Cell-Booster Alternative

There must also exist an alternative, more reliable source of internet given services such as those outlined in the previous sections are not always subscribed to or readily available. For example, AT&T FirstNet's COW can take up to 14 hours to arrive and become operational according to discussions with FirstNet representatives, leaving firefighters without connectivity for variable and potentially extensive periods of time. In anticipation of this waiting period, the NEST can be outfitted with a long-range cellular booster and a multi-SIM router accessory to attempt communication with cell towers that are out of the detection range for the on-board router's stock antennas.

The multi-SIM accessory would communicate with the SIM-enabled router on the NEST to allow the strongest cellular source to be used regardless of provider. The accessory would switch between connections automatically based on signal stability and cell tower proximity. Various hardware options, for example, the Drive Reach OTR by weBoost, achieve this using existing technology [16]. This arrangement can be modular, allowing for quick installation and removal of this extra hardware from the NEST based on anticipated need. Once the mobile cellular source arrives, the hardware for this backup option can be easily removed to reduce weight and increase UAS flight efficiency.

ii.) Operating Frequencies

FCC and NTIA regulations determine which frequency ranges can be operated within and their limitations [17]. Any of the of the sources of internet identified in section VI.A.i would suffice for establishment of an internet-enabled Wi-Fi source at the NEST, though band 14 (700 MHz range) is proposed as the most reliable as it is exclusive to first responder networks for unthrottled access during emergency response situations [18]. Nonetheless, any LTE or 5G cellular signal is equally valid. Alternatively, SpaceX's Starlink would operate within the 12-14 GHz range [15].

Without the optional cell-booster, the only frequencies emitted would be on ISM bands, specifically in the 2.4000 - 2.4835 GHz and 5.725 – 5.875 GHz ranges as these are the frequencies Wi-Fi routers operate on [19]. During test demonstrations at NASA Langley Research Center, spectrum management personnel verified the comprehensive payloads proposed do not emit any frequencies outside of these ranges, nor is there potentially harmful electromagnetic radiation as a result of compounding emitting hardware. With this verification provided, the team further verified a lack of electromagnetic interference (EMI) with the 900 MHz and 2.4 GHz UAS command and control (C2) frequencies. The primary area of concern pertained to the 2.4 GHz remote control systems of the commercial off-the-shelf (COTS) vehicles selected for on-site testing: Freefly's Alta X and Alta 8. The primary C2 links used in UAS are 900 MHz and 2.4 GHz, however, should a similar system be employed outside the verifications of this research, it is advisable that testing be done with any UAS-payload combination to ensure a similar lack of EMI so as not to inhibit UAS control.

iii.) Data Packages Transferred or Streamed

For testing purposes, the '23 team conducted a set of download and upload runs of a generic 14.568MB PDF document at every bridge-bridge and router-user distance combination tested. To analyze the system's performance, the team measured the time it took to complete the downloads and uploads and used these times to calculate the network bandwidth at various distances and arrangements. To further evaluate the network connection, the team streamed a 1080p quality video with an approximate size of 250 MB via Youtube at each location, taking note if any significant buffering occurred [20]. Detailed testing procedures are included in Section VIII.

iv.) Upload/Download Speeds

As of 2022, the FCC broadband speed guide [21] defines 10 Mbps as adequate for file downloading speeds, 5 Mbps as adequate for telecommuting, and 1 Mbps as sufficient for general browsing and email. With file transfer and communication being the primary functions of an internet-enabled network in firefighting applications, a target download speed of 10 Mbps and a minimum speed of 5 Mbps were established as success criteria when analyzing test data. To determine target upload speeds, the FCC broadband requirements for consumer download/upload speeds were considered. As consumers must have access to actual download speeds of 25 Mbps but upload speeds of just 3 Mbps (an 88% decrease) this proportional relationship was applied to the success criteria of the Ad-Hawk system [22]. Thus, a target upload speed of 5 Mbps and a minimum speed of 1 Mbps was determined. It is worth noting that the aforementioned FCC broadband requirements for consumer access are exceptionally high with consideration for much greater degrees of data transfer. The Ad-Hawk system was designed to make currently impossible internet-demanding activities possible, even if this means at a slower pace than one can expect in-home from a closer, static modem-router station.

B.) Wireless Distribution System Bridge Antennas

The network signal is extended through a web of wireless distribution system bridge antennas (WDSBAs) that extend internet connectivity to extreme distances. Using a point-to-point method, a transmitting WDSBA on-board one UAS can bridge connectivity to a receiving WDSBA on-board another. Each Ad-Hawk UAS would then carry two of these WDSBAs and a long-range outdoor router. One WDSBA serves as a receiver for the source signal while the other serves as another transmitter to further extend the network. Thus, each Ad-Hawk UAS can receive connectivity from the NEST or another Ad-Hawk aircraft and then relay it on to further Ad-Hawk aircraft if required. Additionally, COTS products such as TRENDnet's 14 dBi point-to-point bridge kit have point-to-multipoint capabilities, enabling a single transmitting WDSBA to distribute the signal to multiple receiving WDSBAs at a time [23]. In this way, the Ad-Hawk Network is adjustable to the needs of users, as it can work with a single point-to-point connection, a chain of point-to-point connections, a single point-to-multipoint connection, or even a web of point-to-multipoint connections. In the case TRENDnet's solution is used, these connections could be stretched up to ~6 miles [23]. From here, the long-range outdoor router will simply receive the internet via a wired connection and emit a Wi-Fi signal to the ground below.

C.) SIM-Enabled Modem/Router

The NEST payload will include a SIM-enabled modem/router which connects to the internet via a SIM card. This SIM card gives the modem/router the ability to support 3G, 4G, or 5G networks and establish a connection with the cellular network provided by a mobile carrier. Once connected to the cellular network, the modem/router can transmit and receive data wirelessly, acting as a gateway for other devices in the network to access the internet. This hardware could emit a Wi-Fi signal at the NEST; however, it can also transmit this internet connection to the on-board transmitting WDSBA via a wired connection. Thus, all data transmitted and received across the Wi-Fi networks of Ad-Hawks will ultimately pass through the NEST's modem/router. This technology is similar to the concept of a cellphone Wi-Fi hotspot, but on a much larger scale—a commercially available example of this device is the Cradlepoint IBR900-1200M-B, which was used to gather the testing data provided in Section VIII [24].

D.) Cloud Manager

Due to the amount of hardware involved in the Ad-Hawk Network and the high likelihood of using multiple disparate hardware manufacturers to provide the necessary components, a cloud manager is another necessary component of Ad-Hawk. A cloud manager acts as a centralized platform for managing, monitoring, and configuring all the devices included on a single network. It would enable a single qualified user to control the entire network infrastructure from a single intergace, ensuring the security and cohesiveness of the network [24]. The selection of a cloud managing service or the creation of one from scratch would be the next step once hardware options are finalized. If a cloud manager option is not possible due to the hardware chosen, API integration methods can be used to configure all the network devices to function as a system for ease of use and reliability.

VII. Testing Equipment and Settings

The validity of this system was further demonstrated in the summer of 2023 at NASA Langley Research Center, following concept validation testing in the summer of 2022 in [6]. The team operated under several constraints to conduct on-center and in-flight testing. This included researching and procuring hardware via NASA's Commercial IT Request (CITR) process to verify it would not only satisfy the functional requirements of the system but also the security constraints to be used within a United States government-funded facility. This led to the procurement of the following hardware: the SIM-enabled modem/router (Teltonika RUTX11), WDS bridge antennas (TRENDnet TEW-840APBO), SIM-disabled router (Cradlepoint IBR900-1200M-B), Power over Ethernet (PoE) injector (Tycon Systems TP-DCDC-1224), and connective wiring and Ethernet cables.

First, the team needed to prove airworthiness of the system by working in conjunction with the LaRC UAS Operations Office (UASOO). The team developed and prepared an initial and final airworthiness presentation in front of the Airworthiness Review Board consisting of individuals from the UASOO from LaRC, Goddard Space Flight Center, and Wallops Flight Facility. A Hazards Working Group presentation and Operational Readiness Review were performed alongside the LaRC UASOO as well. After hardware was received, ground testing was conducted, and the payloads for both the NEST and Ad-Hawk UAS were constructed with guidance from the LaRC UASOO. During ground testing, a Spectrum Management official was present to record all frequency emissions, with the system being confirmed not to emit any extraneous signals. Before flight tests, a final airworthiness inspection was performed by the LaRC UASOO and cage tests were flown to ensure EMI would not inhibit UAS flight and piloting. Finally, flight tests were conducted to validate that an internet-enabled Wi-Fi system could be established along airborne vehicles to provide internet connectivity to on-ground end-users.

A.) Hardware Configuration

The testing configuration consisted of two UAS-optimized payloads integrated with commercial unmanned aircraft. The NEST UAS consisted of a RUTX11 cellular modem/router utilizing the FirstNet network and a TRENDnet WDS bridge antenna, while the Ad-Hawk UAS payload consisted of a paired WDS bridge antenna and an IBR900-1200M-B router. Figure 1 below provides a complete diagram of the system, which successfully bridged the internet connection from the NEST payload to the Ad-Hawk payload.

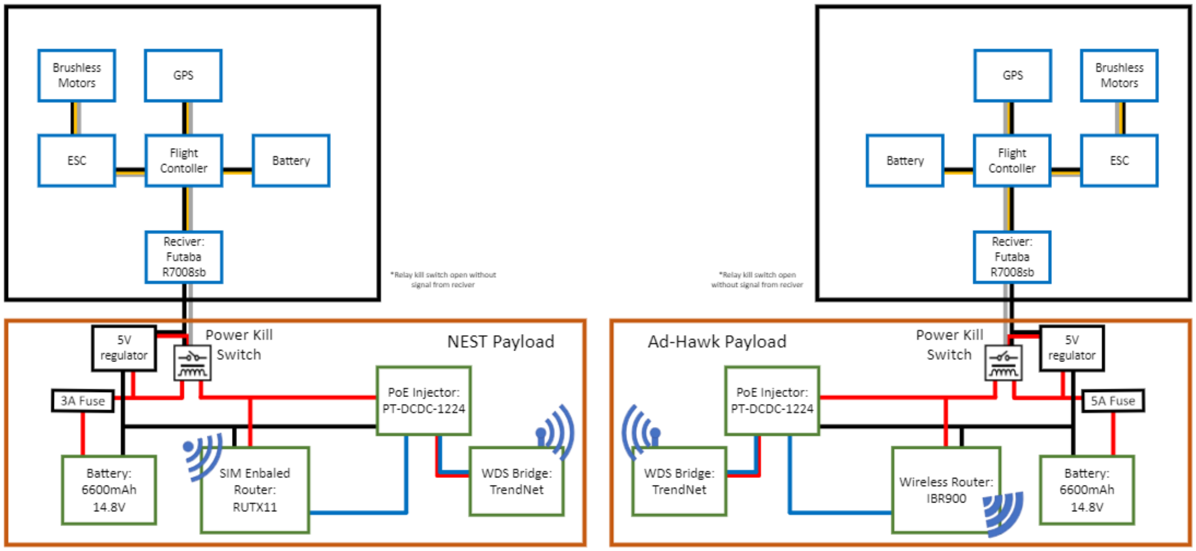

Figure 1. Comprehensive diagram of the Ad-Hawk system.

To integrate the proposed system with uncrewed aircraft, the team designed the payloads in Figure 2, which are mounted on 12x12 inch aluminum plates and can be easily mounted to UAS. These CAD models were used to plan the placement of system components to ensure a center of gravity (CG) near the geometric center of the payload baseplate.

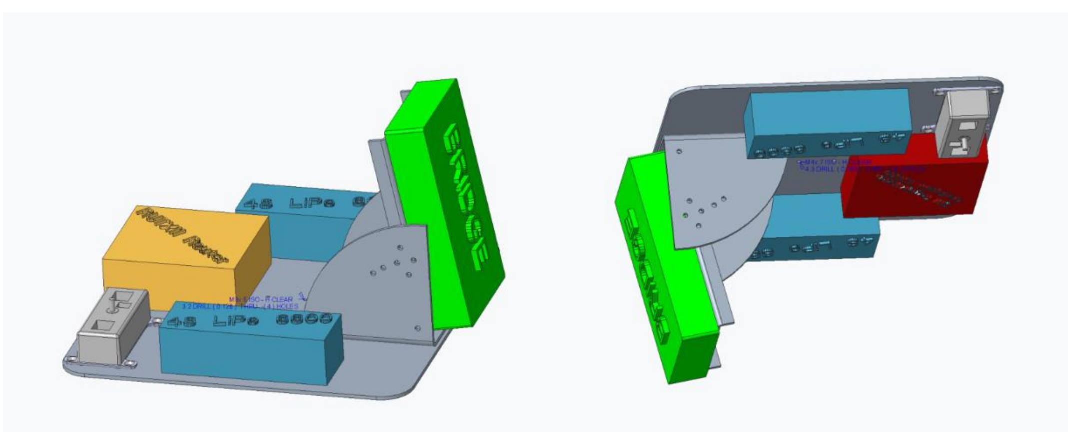

Figure 2. CAD models of the NEST (left) and Ad-Hawk (right) payloads.

Figure 3 below displays how the payloads were integrated with the aircraft via “toad-in-the-hole” quick-connect attachments. The NEST payload was mounted on top of the Alta 8 aircraft while the Ad-Hawk payload was mounted below the Alta X aircraft. This configuration was chosen to prevent either aircraft from obstructing the antennas as the NEST was always at a lower altitude than the Ad-Hawk when testing.

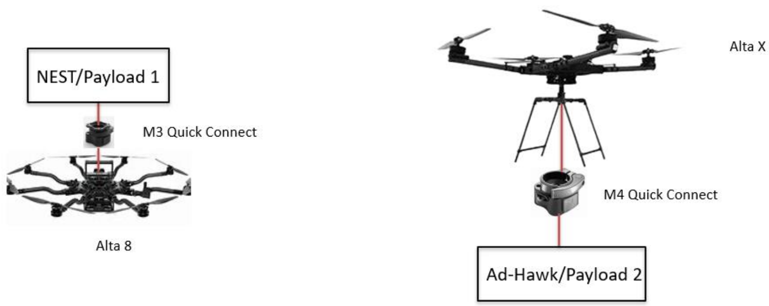

Figure 3. NEST (left) and Ad-Hawk (right) payload-to-UAS interfaces.

Figure 4. Final Ad-Hawk (left) and NEST (right) arrangements for flight testing.

Listed below is the specific hardware included in each testing payload.

NEST (Alta 8):

- SIM-Enabled router (Teltonika RUTX11)
- WDS bridge antenna (TRENDnet TEW-840APBO)
- PWM Relay (Payload Kill Switch)
- 24-volt output, passive, DC-powered PoE Injector (TP-DCDC-1224)
- Two 4S LiPo Batteries
- Connective Wire & Ethernet Cables

Figure 5. On-board NEST payload.

Ad-Hawk (Alta X):

- SIM-Disabled router (Cradlepoint IBR900-1200M-B)
- WDS bridge antenna (TRENDnet TEW-840APBO)
- PWM Relay (Payload Kill Switch)
- 24-volt output, passive, DC-powered PoE Injector (TP-DCDC-1224)
- Two 4S LiPo Batteries
- Connective Wire & Ethernet Cables

Figure 6. On-board Ad-Hawk payload.

B.) Equipment Settings

Before the Ad-Hawk team could complete testing, the selected hardware required initial configuration. This meant setting unique IP addresses for each of the four WDS bridge antennas. The testing would require two sets of bridges, each consisting of a WDS Access Point (AP) and a WDS Station. While some settings in TRENDnet's user interface were left the same for all the bridges (80 MHz Channel HT and 1 km bridge-bridge distance), others were altered to allow each set of bridges to successfully transmit. Depicted in Table 1 are the settings unique to each bridge which allowed for data transmission throughout the system. Separate channels were used for each of the bridge pairs to reduce the chance of interference during the daisy-chain tests.

IP Address	Operation Mode	Channel	Associated Device
192.168.10.50	WDS Access Point	161 (5.805 GHz)	192.168.10.51
192.168.10.51	WDS Station	-	192.168.10.50
192.168.10.52	WDS Access Point	48 (5.240 GHz)	192.168.10.53
192.168.10.53	WDS Station	-	192.168.10.52

Table 1. Individual WDS bridge antenna settings used during testing, creating two bridge pairs.

Several settings were changed on the IBR900 router to achieve the greatest throughput during testing. The IBR900 router was the device used to emit the Wi-Fi signal on-board the Ad-Hawk UAS. The cellular capabilities of the IBR900 were disabled, utilizing only its Wi-Fi network generating functionality. Additionally, the 2.4 GHz and the 5 GHz Wi-Fi signals were set to the most recent standards supported. Figure 7 shows the standards used for testing.

Figure 7. Wi-Fi standards tested for 2.4 GHz (left) and 5 GHz (right) signals.

Furthermore, the download and the upload speeds of the IBR900 Wi-Fi were set to their maximum values to ensure internet speeds were not limited by the device settings.

Prior to Ad-Hawk's use of the RUTX11, configuration changes had been made to the hardware by engineers at LaRC for other projects. These adjustments included disabling the Wi-Fi and Bluetooth capabilities, as well as cellular bands B5, B6, B18, B19, B26, B27, and WCDMA 850. These changes had no bearing on the RUTX11's ability to perform as necessary for Ad-Hawk system testing.

C.) Testing Limitations

i.) Airspace Regulations

Based on discussions with members of the organization CAL FIRE, it is understood that CAL FIRE has multiple Alta X vehicles, so the payloads and testing were designed to be compatible with the Alta X. With the specified hardware choices, the UAS would weigh less than 55 lbs. with either payload attached, qualifying the system for Pt. 107 with the FAA [25].

It should be noted that in an active fire scenario, wildfire fighting agencies may enforce additional regulations to work safely around UAS operations. This includes, but is not limited to, grounding manned aircraft if a UAS is airborne. For the system to work seamlessly and integrate with manned flight operations, agency regulations and procedures during active fire scenarios may require reevaluation to safely and simultaneously use both unmanned and manned aircraft in wildfire-related applications.

ii.) UAS Capabilities

According to Freefly specifications, the Alta X can fly for 50 minutes without a payload, and with either of the designed payloads, the Alta X can nominally fly for ~35 minutes using two 16Ah batteries in optimal, windless conditions [26]. However, with a powered tether attachment (as the NEST is recommended to be launched), a UAS could fly indefinitely. As these technologies improve, tethers and generators may eventually be mobile enough for a first responder to transport in the field.

VIII. Testing Procedures and Results

A.) Concept Validation (2022)

The initial proof of concept validated in [6], in which the 2022 Ad-Hawk research team was able to successfully download and upload a PDF file and stream a 1080p video with a modem/router and bridge antenna pair arrangement, provided the 2023 Ad-Hawk research team with a working design and testing procedures to expand upon. Key differences between testing in 2022 and 2023 were hardware specificity and testing comprehensiveness. Because 2023 testing took place at Langley Research Center, the research was confined to hardware approved via the Commercial IT Request (CITR) process, whereby all information-utilizing technology must have its manufacturing origins assessed for potential risk to US national security. This constraint would not necessarily apply outside of a government agency, and it is reasonable to assume that non-compliant hardware could further optimize the performance of this proposed system. Additionally, the 2023 research team designed more extensive testing procedures—including an in-flight demonstration of the system at varying distances and altitudes as well as more comprehensive ground testing to ensure airworthiness—to further validate the system and begin exploring the intricacies of its in-field employment.

B.) Ground Testing (2023)

i.) Single-Bridge Pair Test

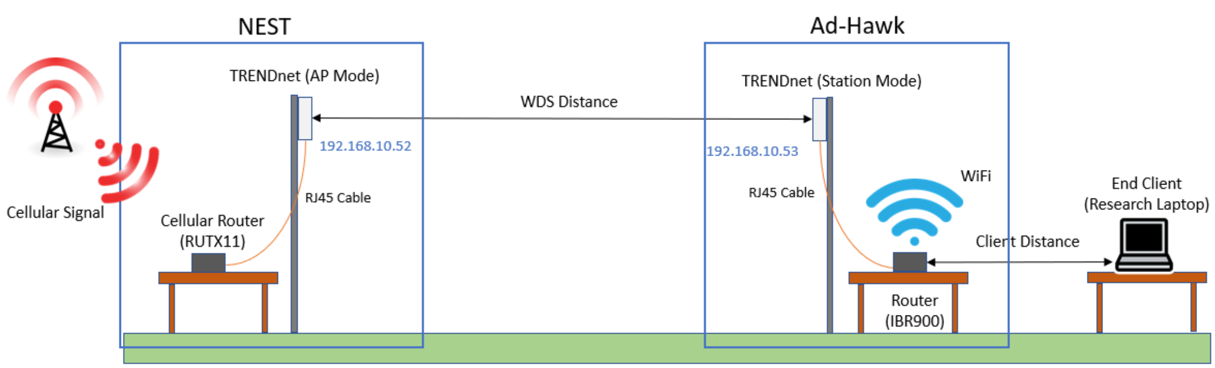

Figure 8. Testing setup with one WDS bridge pair; "WDS Distance" and "Client Distance" vary by test set.

a.) Configuration

The single-bridge pair ground tests' purpose was threefold: first, to verify the system's functionality, providing a justification for plans to flight test. Second, to test throughput speeds for a single-bridge pair in a controlled environment. The goal was to estimate speeds the team could expect to see during the in-air tests. Lastly, for the Spectrum Management Office to measure any erroneous RF emissions. Figure 8 above outlines the system configuration for these tests.

b.) Procedures

An RUTX11 SIM-enabled router was placed on a table and directly connected via RJ45 cable to a WDS bridge configured in "Access Point" mode. The internet was then bridged to the second WDS bridge configured in Station mode, which was directly wired via RJ45 cable to the IBR900 router set on a table. Testing was done with various WDS bridge distances as well as various client distances (from router).

The WDS bridges were tested at four distances: 50 ft, 250 ft, 1000 ft, and 2640 ft (1/2 mile). At each of these, four client distances were tested: 75 ft, 150 ft, 250 ft, 500 ft. Testing included downloading and uploading a 14.568 MB PDF file and recording the time taken to do so, as explained earlier. Several upload and download tests were taken on both the 2.4 GHz Wi-Fi signal and 5 GHz Wi-Fi signal. Initially, three download and three upload tests were run at each trial configuration, however, the team decided to increase to five runs each for more conclusive data. Speeds were calculated in Mbps using following equation:

$$Speed\ in\ Mbps = \frac{File\ size\ (MB) \times 8}{Time\ to\ upload/download\ (sec)} \quad [1]$$

Lastly, a video approximately 250 MB in size was streamed at 1080p quality via Youtube and recorded as either a pass or failure [20]. The pass/fail criterion for this was simply whether the video would stream; any buffering was noted as well.

c.) Results

Bridge Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	75	6.80	6.51	0.55
	150	16.77	16.12	2.45
	250	10.76	11.38	3.95
	500	5.49	5.33	0.978
250	75	8.16	8.62	2.92
	150	9.52	8.10	4.10
	250	13.29	12.50	2.25
	500	10.47	9.73	1.52
1000	75	20.53	22.57	14.27
	150	13.92	22.27	15.23
	250	38.57	36.30	6.40
	500	14.36	13.90	1.94
2640	75	59.74	55.85	6.92
	150	15.74	16.60	6.17
	250	23.67	26.02	10.52
	500	18.47	17.11	7.81

Table 2. 2.4 GHz download speeds at varying WDS bridge and client distances, measured during the single bridge pair testing phase.

Bridge Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	75	2.33	3.06	1.52
	150	4.11	6.07	3.85
	250	9.66	8.97	1.37
	500	7.73	7.53	1.04
250	75	8.50	9.95	2.79
	150	10.16	9.86	0.62
	250	9.82	9.94	0.44
	500	8.84	8.33	1.21
1000	75	21.42	21.18	0.42
	150	15.04	14.83	1.25
	250	19.46	19.63	1.32
	500	2.47	4.56	4.09
2640	75	20.52	17.75	6.47
	150	11.83	8.35	5.91
	250	12.40	8.33	5.87
	500	2.59	2.24	1.92

Table 3. 2.4 GHz upload speeds at varying WDS bridge and client distances, measured during the single bridge pair testing phase.

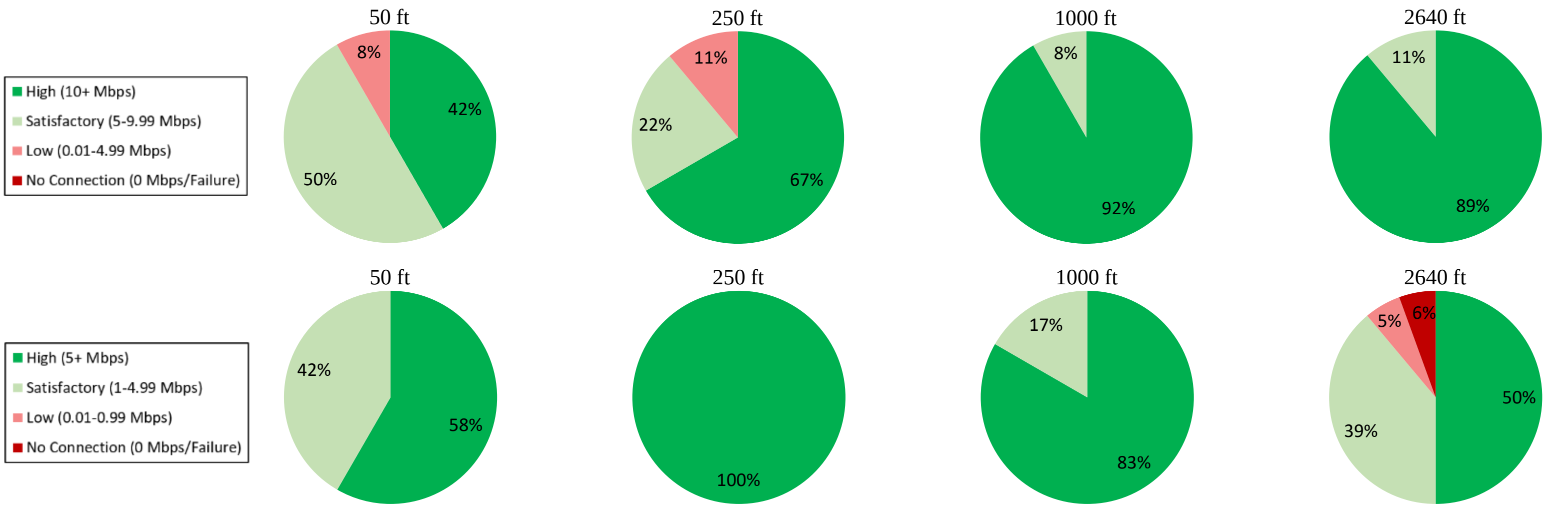

Figure 9. Characterization of the recorded download (top) and upload (bottom) speeds by WDS bridge distance, according to the established download and upload speed success criteria (refer to legend).

To explore the impact of both bridge distance and client distance on throughput, correlation analyses were performed. Analysis of the recorded 2.4 GHz download speeds found a moderate positive correlation between bridge distance and download speed (r = 0.50) whereby the download speeds increased with increasing bridge distance. Alternatively, the relationship between the client distance and download speeds was defined by a moderate negative correlation (r = -0.24) whereby, as the distance between the client and router decreased, the download speeds increased. This is more consistent with the inverse square law, a fundamental principle in wireless communication, which dictates that signal strength diminishes as the distance between the transmitter (in this case, the router) and the receiver (the client device) increases. In contrast, the correlation between bridge distance and upload speed was slightly negative (r = -0.011) while that between client distance and upload speed was more significantly negative (r = -0.43). Thus, there appears to be a consistent and moderate negative correlation between the client distance and throughput, as would be expected. Conflicting relationships between bridge distance for each of the download and upload speeds indicate the need for further analysis.

Multiple linear regression analyses were conducted to more accurately model the relationships between bridge/client distances and throughput. These models, which reliably explained 33% of the variability in download speeds (R-squared = 0.33; p = 4.0×10^{-5}) and 18% of the variability in upload speeds (R-squared = 0.18; p = 0.0057), respectively, found the client distance far more influential on throughput than bridge distance. Regarding bridge distance, a notable increase in download speed resulted from bridge distance (β = 0.0064±0.0014 Mbps/ft, p = 3.8×10^{-5}) while no significant influence on upload speed was found. Meanwhile, the client distance demonstrated a significant negative relationship with both download and upload throughput (β = -0.023±0.010 Mbps/ft, p = 0.022; β = -0.016±0.0048 Mbps/ft, p = 0.0014).

The download and upload speed characterizations shown in Figure 9 are according to their respective success criteria derived from Section VI.A.iv. For download data, "high" speed is at least 10 Mbps (dark green). A "satisfactory" speed is between 5 – 9.99 Mbps (light green), a "low" speed is between 0.01 – 4.99 Mbps (light red), and "no connection" is indicated by a download failure (dark red). For upload data, "high" speed is at least 5 Mbps (dark green). A "satisfactory" speed is between 1 – 4.99 Mbps (light green), an unsatisfactory speed is between 0.01 – 0.99 Mbps (light red), and "no connection" is indicated by an upload failure (dark red). Characterization of the data according to these criteria was limited to recordings differing only in bridge distance as the negative correlation between signal strength and client distance is well documented. To demonstrate the ability for a robust connection to be made at an assortment of client distances, however, a consistent number of recordings were made ranging from 75 – 500 feet from the emitting router.

In assessing the download speed distributions in Figure 9, a lack of failures across all bridge distances is encouraging, indicating a robust overall network. The proportion of high-speed outcomes increased substantially as the bridge distances extended from 50 ft to 1000 ft, with a slight decrease observed at 2640 ft. Still, the 50 ft and 250 ft trials were largely successful as only 8% and 11%, respectively, fell below the satisfactory download speed range. The longer distance testing proved particularly successful with 92% and 89% high-speed download rate success rates at the 1000 ft and 2640 ft trials, respectively.

The 50 ft, 250 ft, and 1000 ft trials proved highly successful with high-speed upload rate percentages of 58%, 100%, and 83%—respectively. Furthermore, for these three trial set distances, no recorded speeds fell below the satisfactory upload speed range. The long-distance 2640 ft recordings were less consistent, including the only failed upload or download attempts, though with 89% of the speeds being satisfactory, the arrangement still demonstrated a usable internet connection. In assessing these results with those in Tables 2 and 3, an increase in standard deviation with increasing bridge distance points to a drop-off in reliability as the total client distance is stretched.

These analyses provide several key takeaways from the 2.4 GHz download and upload recordings. First, bridge and client distance demonstrated a smaller-than-anticipated influence on overall throughput, with the linear regression models explaining less than half of the variance in the data. Additionally, the exact nature of this influence is not entirely clear, though there are a number of potential factors which would explain the mixed results. Client distance consistently demonstrated a negative relationship with download and upload speeds, as would be expected according to the inverse square law. However, bridge distance demonstrated no relationship with upload speed and a notable positive one with download speed. While this is not consistent with the inverse square law, it is plausible that as bridge distances approach 1 km (~3281 ft) – the manually set transmission power setting of the TRENDnet bridging antennas – there may be a spike in connection reliability. This would additionally explain the improvement in speeds from bridge distances of 50 ft to 1000 ft, though the variance at 2640 ft indicates this trend may not continue all the way to 3281 ft. Nonetheless, while the current study lays a foundational understanding of bridge technology's capabilities, further research is likely necessary to fully understand all the factors at play. To gauge the full scope of this system's potential, subsequent research should aim to incorporate a wider range of controlled variables and more extensive distance testing. Nonetheless, these distance increments demonstrate that, at the very least, a sufficient signal can be established up to a half-mile away from the internet establishing station. The bridge distance relationships support the potential for even greater distances without significant decrease in network reliability.

Bridge Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	75	6.00	5.97	0.58
	150	9.54	9.76	2.08
	250	5.46	5.48	1.50
	500	10.20	9.79	3.20
250	75	13.89	14.93	2.74
	150	14.48	14.98	3.73
	250	10.72	11.75	3.22
	500	10.54	10.38	1.20
1000	75	52.54	52.48	3.87
	150	18.16	25.66	13.50
	250	19.58	25.21	12.51
	500	28.38	28.74	3.97
2640	75	12.65	12.26	4.73
	150	15.86	22.50	11.98
	250	14.91	17.94	13.86
	500	16.37	25.30	13.53

Table 4. 5 GHz download speeds at varying WDS bridge and client distances, measured during the single bridge pair testing phase.

Bridge Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	75	7.01	6.87	0.99
	150	7.68	8.03	2.44
	250	8.29	8.88	2.22
	500	6.74	6.38	3.80
250	75	12.78	12.70	2.17
	150	7.72	7.91	0.78
	250	6.81	6.07	3.10
	500	15.14	15.20	1.44
1000	75	21.31	21.59	0.56
	150	13.26	14.56	2.45
	250	20.52	20.95	1.59
	500	14.72	14.20	3.04
2640	75	4.26	8.09	7.47
	150	6.87	6.21	4.23
	250	4.51	6.71	5.70
	500	11.77	9.17	5.17

Table 5. 5 GHz upload speeds at varying WDS bridge and client distances, measured during the single bridge pair testing phase.

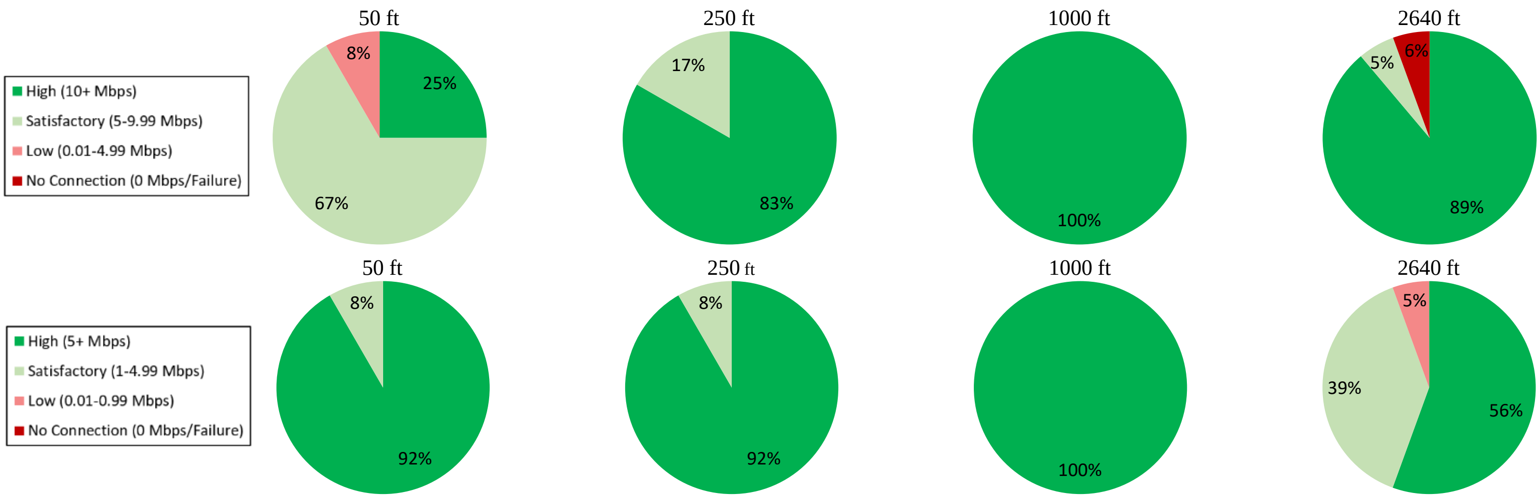

Figure 10. Characterization of the recorded 5 GHz download (top) and upload (bottom) speeds by WDS bridge distance, according to the established download and upload speed success criteria (refer to legend).

Applying these same statistical analyses to data acquired via the 5 GHz signal, little influence of either distance was found on throughput. A correlation analysis found a moderate, positive correlation between bridge distance and download speed ($r = 0.29$), whereas client distance had just a slight, negative correlation ($r = -0.027$). A multiple linear regression analysis of these distances on download speed produced a model of questionable significance ($p = 0.10$), which only explained 8.5% of the variance (R-squared = 0.085). In this case, both bridge and client distance were found to have a nearly identical (yet opposite) impact on download speed ($\beta = 0.0035 \pm 0.0016$ Mbps/ft, $p = 0.035$; $\beta = -0.0034 \pm 0.011$ Mbps/ft, $p = 0.76$). However, only the relationship with bridge distance was found to be statistically significant. The linear regression model of these distances' relationship with 5 GHz upload speed was predictably insignificant ($p = 0.51$), as is consistent with the minimal correlation coefficient. Thus, it would seem there is little evidence that either bridge or client distance meaningfully influences 5 GHz throughput in this single bridge-pair application.

In assessing the download speed distributions in Figure 10, there was once again a distinct lack of failures (including only 6% of attempts failing at a 2640 ft bridge distance). The proportion of high-speed outcomes once again increased substantially as the bridge distances extended from 50 ft to 1000 ft, with a slight decrease observed at 2640 ft. Across all distances, only 8% of 50 ft measurements and 6% of 2640 ft measurements fell below the satisfactory download threshold of 5 Mbps. The standard deviations observed in Table 4 once again increased, however, with increasing bridge distance, indicating a drop-off in reliability as the total bridge distance is stretched.

Similar trends are observed in the 5 GHz upload speed distributions in Figure 10 as well. All recorded upload speeds in the 50 ft, 250 ft, and 1000 ft ranges were at least satisfactory, with 92% or greater demonstrating exceptionally high throughput. Once again, measurements tend to consolidate at faster speeds as bridge distance approaches 1000 ft (100% high-speed), with a slight reduction at 2640 ft. Still, 95% of all measured speeds at 2640 ft are sufficient according to the established success criteria. Further, the standard deviations observed in Table 5 remain consistent with all aforementioned data and demonstrate an increase with increasing bridge distance, particularly at the 2640 ft range. Again, it appears that, while throughput remains in an acceptable range the majority of the time—including the furthest distances tested—the overall robustness of the signal diminishes.

These results are consistent with those of the 2.4 GHz throughput analyses in that the distance variables that were controlled for displayed a generally weak influence on throughput. It is possible the tested distances did not exceed the optimal transmissive power of the hardware used, indicating a need for further research to be conducted pushing these distances further. If this is the case, this would support the validity of this system to stretch a single internet source to great distances, as a half-mile can be sufficient for the designed purpose of the Ad-Hawk system. Nonetheless, research is necessary to further support these conclusions.

Stream 1080p Video Y=Yes, N=No	2.4 GHz				5 GHz			
Client Distance↓ / Bridge Distance ->	50 ft	250 ft	1000 ft	2640 ft	50 ft	250 ft	1000 ft	2640 ft
75 ft	Y	Y	Y	Y	Y	Y	Y	Y
150 ft	Y	Y	Y	Y	Y	Y	Y	Y
250 ft	Y	Y	Y	Y	Y	Y	Y	Y
500 ft	Y	Y	Y	Y	Y	Y	Y	Y

No Buffering	Buffer 0-5 seconds	Buffer 5.1-10 seconds
Buffer 10.1-30 seconds	Buffer >30 seconds	Fail

Table 6. Outcomes of 1080p video testing at varying bridge and client distances for the single bridge pair testing phase.

Table 6 displays the results of the video stream attempts at each testing configuration. A "Y" indicates the video was streamed successfully, whereas an "N" indicates a failure to stream the video. Refer to the legend in Table 6 for notes on buffer times. Refer to Section VII.B.i.c. for further details regarding video selection and success criteria. In all cases, regardless of bridge or client distance, the video was streamed with no buffering, reinforcing the extent to which the download capabilities of the network could be stretched. In comparison to the throughput basic web browsing, pdf downloads, and even video conferencing would require by emergency service providers, HD video streaming is notably demanding. Nonetheless, the evidence suggests this would be plausible at the distances tested in this study.

ii.) Bridge Daisy-Chain Test

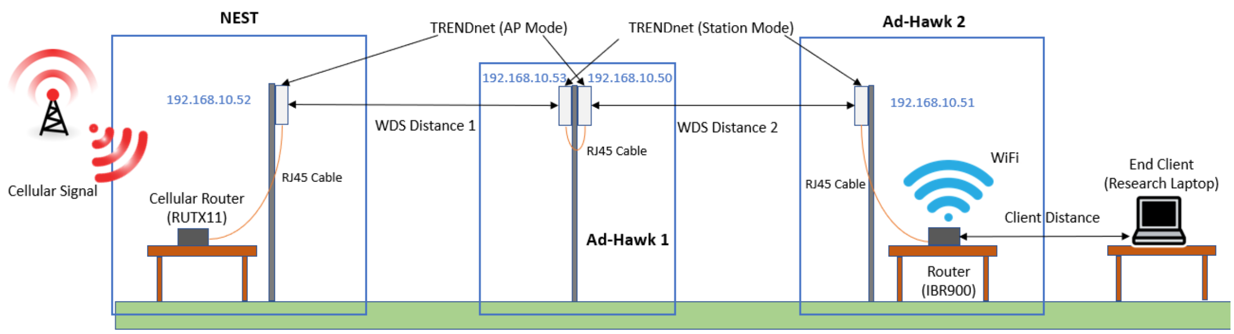

Figure 11. Testing setup with two WDS bridge pairs; "WDS Distance 1", "WDS Distance 2", and "Client Distance" vary by test set.

a.) Configuration

The purpose of the daisy-chaining tests was to simulate how the Ad-Hawk system would behave in a situation with multiple UAS. To test the system's daisy-chaining capabilities, an additional pair of WDS bridges was added to the system.

Shown in the diagram above, the daisy-chain setup consists of the NEST with two ensuing Ad-Hawks, simulated by the two sets of bridge pairs. In the daisy-chain network, the NEST is the same as in the single-pair test in both structure and function. The setup diverges once connection is bridged to the first WDS Station in Ad-Hawk 1; instead of the first WDS Station bridge connecting to the Wi-Fi router, it is directly connected to the second WDS Access Point (WDSAP) bridge via RJ45 cable. The second WDSAP bridge's connectivity to its respective WDS Station bridge, thereby adding a second simulated Ad-Hawk and creating a daisy-chained network. In the daisy-chain test setup, the second WDS Station bridge functions identically to the WDS Station bridge in the single-pair setup, ultimately connecting to the Wi-Fi router which then emits usable internet-enabled Wi-Fi.

Ideally, a daisy-chained Ad-Hawk system could include more than two bridge pairs. In a general daisy-chain design, the NEST would always possess a WDS Access Point which connects to the desired SIM-enabled router, and the terminal Ad-Hawk would always possess a WDS Station which connects to the emitting Wi-Fi router. In the final proposed system, the NEST and all Ad-Hawks in the network would have the ability to emit usable Wi-Fi to the ground via a router, and non-terminal Ad-Hawks would be able to bridge connection throughout the system by daisy-chaining.

b.) Procedure

Testing began with setting up the system as shown above, beginning with 50 ft between the NEST and Ad-Hawk 1, and 200 ft between Ad-Hawk 1 and Ad-Hawk 2. Then, the end-user conducted tests at 75 ft, 150 ft, and 250 ft from the router. Testing included downloading and uploading a 14.568 MB PDF file and recording the time taken to do so, as well as streaming an approximately 250 MB video via Youtube, just as in the single-bridge pair testing outlined in Section VIII.B.i.b. [20].

The end user moved to the three aforementioned distances from the router and conducted the tests at the following testing configurations:

Distance Between NEST & Ad-Hawk 1 (ft)	Distance Between Ad-Hawk 1 & Ad-Hawk 2 (ft)
50	200
50	1000
250	200
250	1000
2640 (1/2 mile)	1000
2640 (1/2 mile)	2640 (1/2 mile)

Table 7. Varying WDS bridge pair distances and combinations for the bridge daisy-chain testing phase.

c.) Results

Bridge Pair #1 Distance (ft)	Bridge Pair #2 Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	200	6.80	7.56	1.86
	1000	10.51	10.73	4.68
250	200	4.09	3.74	2.42
	1000	4.11	5.83	4.48
2640	1000	9.42	9.20	5.50
	2640	20.89	24.12	12.52

Table 8. 2.4 GHz download speeds at varying Bridge Distance #1 and Bridge Distance #2 lengths, measured during the bridge daisy-chain testing phase.

Bridge Pair #1 Distance (ft)	Bridge Pair #2 Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	200	4.90	4.59	1.95
	1000	6.58	7.11	3.05
250	200	2.23	3.63	3.77
	1000	6.01	7.11	4.92
2640	1000	0	2.97	5.26
	2640	0.89	3.56	5.43

Table 9. 2.4 GHz upload speeds at varying Bridge Distance #1 and Bridge Distance #2 lengths, measured during the bridge daisy-chain testing phase.

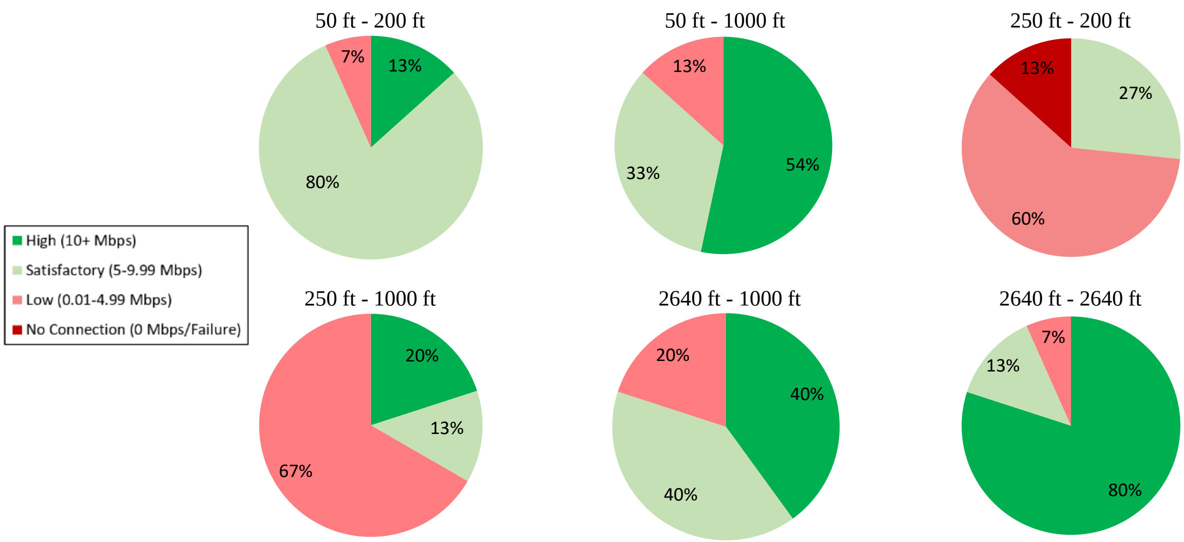

Figure 12. 2.4 GHz download speed categorizations with varying Bridge Distance #1 and Bridge Distance #2 lengths (Bridge #1 ft – Bridge #2 ft), according to established success criteria.

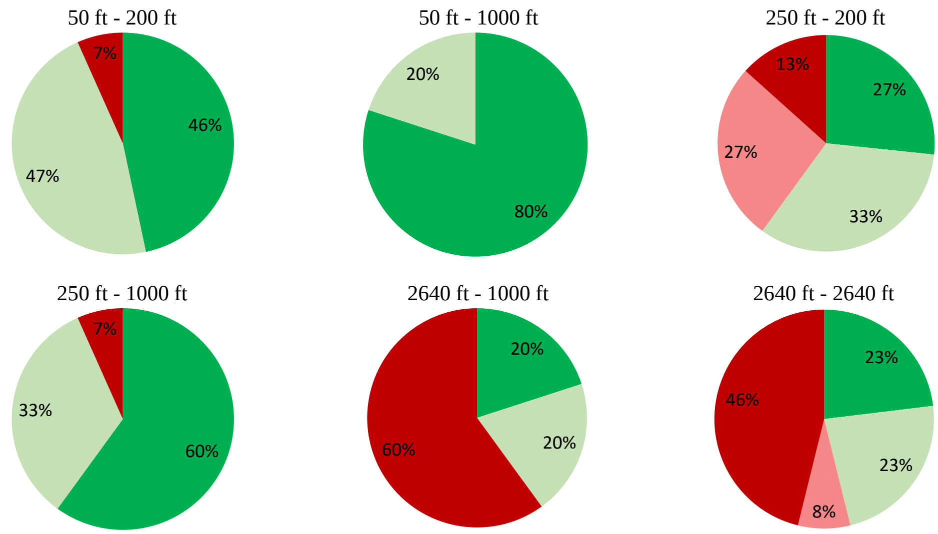

Figure 13. 2.4 GHz upload speed categorizations with varying Bridge Distance #1 and Bridge Distance #2 lengths (Bridge #1 ft – Bridge #2 ft), according to established success criteria.

As was done for the on-ground single bridge pair testing data, correlation and multiple linear regression analyses were performed to understand the relationships between the various distance variables and throughput. Regarding 2.4 GHz download throughput, a strong, positive correlation was found with both bridge distance 1 (BD-1) (r = 0.60) and bridge distance 2 (BD-2) (r = 0.70) while a slight, negative correlation was found with client distance (CD) (r = -0.15). Interestingly, when considering 2.4 GHz upload throughput, the exact opposite relationships were observed. Both bridge pair distances were found to have slight, negative correlations (r = -0.22 and r = -0.033, respectively) with upload throughput while a slight, positive correlation was observed with client distance (r = 0.030).

In conducting a multiple linear regression analysis, the nature of these relationships was more deeply explored. These models, which reliably explain 52% of the variability in download speeds (R-squared = 0.52, p = 5.8×10^{-12}) and 11% of the variability in upload speeds (R-squared = 0.11, p = 0.032), respectively, were a mixed bag in clarifying these relationships. Regarding BD-1, no significant relationship was found with download throughput (p = 0.75), whereas a slight, negative relationship was found on upload throughput (β = -0.0023±0.00075, p = 0.0034). Regarding BD-2, slight, positive influence was observed on both download (β = 0.0072±0.0015 Mbps/ft, p = 9.8×10^{-6}) and upload (β = 0.0021±0.00094 Mbps/ft, p = 0.027) throughput, respectively. The relationship between BD-2 and upload speed – revealed by the linear regression model – conflicting with the initial correlation analysis here is likely due to the significant reduction in upload speed as a result of the increase in BD-1 to 2640 ft. For each BD-1 value, increasing BD-2 consistently demonstrates an improvement in both download and upload performance. Finally, regarding CD, a moderate, negative impact on download throughput was observed (β = -0.019±0.011 Mbps/ft, p = 0.079) whereas no significant influence on upload throughput was found (p = 0.64).

The results pertaining to increasing CD are relatively consistent with those observed in the single bridge pair testing results in which a moderate drop in throughput is expected. Only upload throughput in the daisy-chain testing phase was unaffected by CD, however, this may simply be a result of insufficient data or external factors, considering the linear regression model for this observation only explains a small portion of the variation in the data, similar as well to the single bridge pair testing results. Meanwhile, an increase in BD-1 was observed to negatively influence upload speed, as is consistent with the inverse square law. An increase in BD-2 demonstrated a small improvement in both download and upload throughput, consistent with results observed in the single bridge pair testing results.

The inconsistency in the relationship with increasing bridge distances may once again be attributable to the tested distances not exceeding the optimal transmissive power of the hardware used, indicating again, that further research should be conducted that pushes these distances further. Still, it is promising the distances tested are within the capabilities of the hardware.

The download and upload speed characterizations shown in Figures 12 and 13, respectively, are according to their respective success criteria derived from Section VI.A.iv. For download data, "high" speed is at least 10 Mbps (dark green). A "satisfactory" download speed is between 5 – 9.99 Mbps (light green), a "low" download speed is between 0.1 – 4.99 Mbps (light red), and "no connection" is indicated by a download failure (dark red). For upload data, "high" speed is at least 5 Mbps (dark green). Characterization of the data according to these criteria was limited to recordings differing only in bridge distance as the negative correlation between signal strength and client distance is well documented. To demonstrate the ability for a robust connection to be made at an assortment of client distances, however, a consistent number of recordings were made ranging from 75 – 500 ft from the emitting router.

Analysis of the download speed distributions in Figure 12 further contextualizes the statistically observed relationships. The trend of increasing BD-2 at each BD-1 revealed by the linear regression model can be observed with an increase in sufficient or better throughput at the higher of the BD-2 values for each BD-1 value. This observation serves as further evidence of the bridges communicating more optimally as the distance approaches the manually set transmission distance of 1 km (3281 ft). It may also indicate the daisy-chain signal emitted between BD-1 and BD-2 is not optimized at increasingly close-range, and instead there exists an extended range for which the system could be optimized. If true, this phenomenon could prove advantageous to the Ad-Hawk network as stable long-range connectivity is ultimately the purpose of the system. Through further evaluation of Figure 12, a sizeable increase in insufficient download speeds is observed when BD-1 is equal to 250 ft, the median tested distance. The largest proportion of insufficient download speed tests at BD-1 values of 50 ft and 2640 ft were 13% and 20%, respectively. Meanwhile this percentage was at least 60% across both 250 ft stages. There is no apparent reason for this discrepancy. Perhaps further research would reveal the additional factors at play. Nonetheless, achieving 93% sufficient or better speeds at the furthest extent tested across all experimental phases (BD-1 and BD-2 values of 2640 ft) spell great potential for stretching an internet-enabled Wi-Fi network to even greater distances. This is, of course, assuming external factors influencing throughput at shorter distances can be controlled for.

In observation of upload speed distributions in Figure 13, the aforementioned trend of measurably improved download throughput with respect to increased BD-2 also holds true for upload throughput. This discovery further suggests that there may be an optimized distance for the bridging antennas. The standard deviation of each distance pairing continues to increase with increasing bridge distance, further affirming the loss in robustness as the network is stretched. Unlike previous trends, however, the number of failed or insufficient upload measurements consistently increases with increasing BD-1, particularly at 2640 ft. This is not entirely unexpected, though, it provides evidence that there will be a reduction in upload speed in comparison to download speed, independent of the user device's transmissive ability. The trends observed in the upload distribution are consistent with the relationships defined by the linear regression model, however, as this model only explains 11% of the overall variance, further research is necessary to confirm the influence of and identify potential confounding factors.

Bridge Pair #1 Distance (ft)	Bridge Pair #2 Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	200	3.04	3.30	2.29
	1000	3.04	3.66	1.97
250	200	2.14	1.98	1.44
	1000	3.18	3.78	2.34
2640	1000	-	-	-
	2640	11.83	13.58	11.00

Table 10. 5 GHz download speeds at varying Bridge Distance #1 and Bridge Distance #2 lengths, measured during the bridge daisy-chain testing phase.

Bridge Pair #1 Distance (ft)	Bridge Pair #2 Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
50	200	0	0.28	0.52
	1000	0	0.54	1.05
250	200	0	0.27	0.51
	1000	2.58	2.99	2.56
2640	1000	-	-	-
	2640	0	0.16	0.33

Table 11. 5 GHz upload speeds at varying Bridge Distance #1 and Bridge Distance #2 lengths, measured during the bridge daisy-chain testing phase.

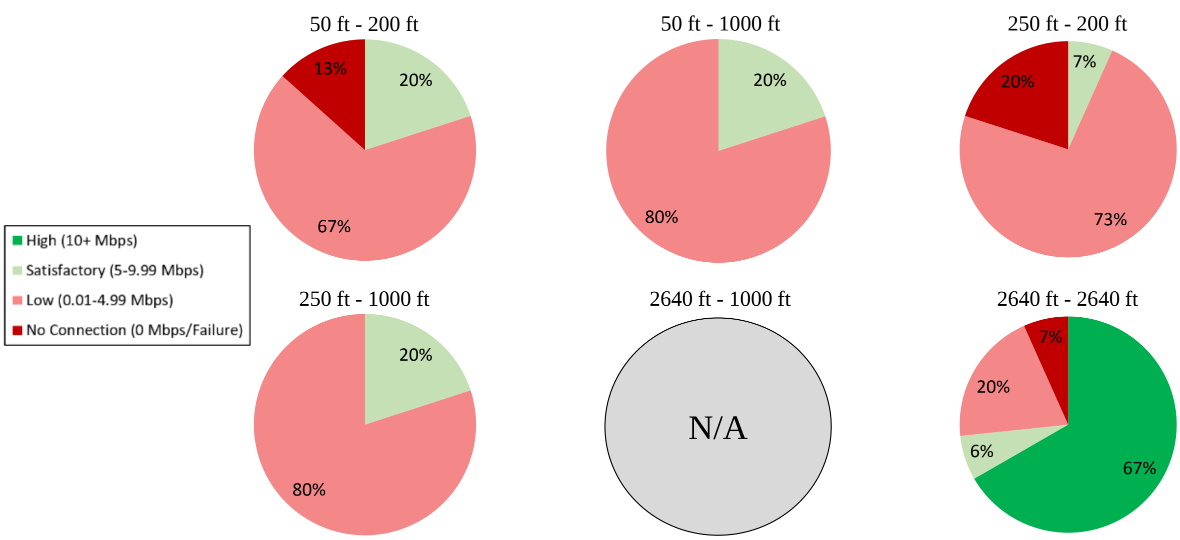

Figure 14. Characterization of the recorded 5 GHz download speeds by varying Bridge Distance #1 and Bridge Distance #2 lengths (Bridge #1 ft – Bridge #2 ft), according to established success criteria.

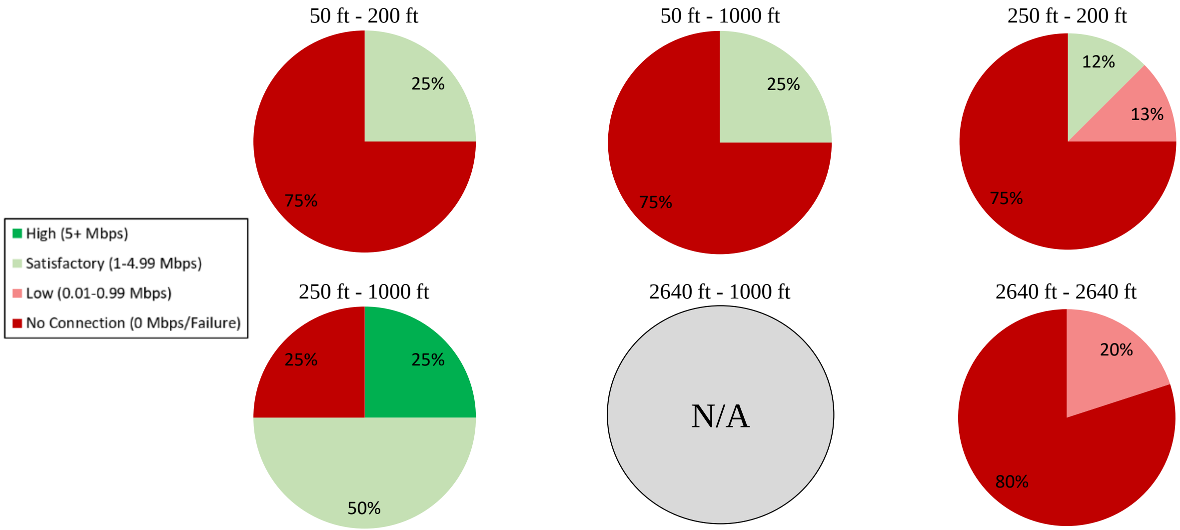

Figure 15. Characterization of the recorded 5 GHz upload speeds by varying Bridge Distance #1 and Bridge Distance #2 lengths (Bridge #1 ft – Bridge #2 ft), according to established success criteria.

Applying these same statistical analyses to data acquired via the 5 GHz signal, a linear regression model explaining 41% (R-squared = 0.41, $p = 4.4\times 10^{-8}$) of variance in download data was produced, indicating once again that a significant portion of the variance remains unaccounted for. Download throughput exhibited a marginally significant positive relationship with BD-1 (β = 0.0028±0.0015 Mbps/ft, p = 0.063), marked by a notable positive correlation (r = 0.63), indicating a tendency for download speeds to increase alongside bridge distance. Meanwhile, neither BD-2 (β = 0.0016±0.0017 Mbps/ft, p = 0.32) nor CD (β = 0.0071±0.0084 Mbps/ft, p = 0.40) were statistically significant factors. In analyzing upload throughput, a linear regression model explaining only 20% (R-squared = 0.20, p = 0.0256) of variance was produced. A significant negative relationship with BD-1 (β = -0.0018±0.00062 Mbps/ft, p = 0.0059) was observed, marked by a negative correlation (r = -0.22). BD-2 demonstrated a positive influence (β = 0.0017 ± 0.00071 Mbps/ft, p = 0.022) despite a slightly negative correlation (r = -0.062). This conflict between download/upload speeds and bridge distances indicates the relationship is not strongly linear, implying other factors are responsible for much of the variance. CD was not observed to have a significant influence on upload speed (β = -0.0043±0.0035 Mbps/ft, p = 0.23), marked only by a small, negative correlation (r = -0.16).

Analysis of the 5 GHz download speed distributions in Figure 14 reveals that daisy-chaining trials using 5 GHz frequency appear far less effective than those using 2.4 GHz (Figure 12)—with only one 5 GHz trial (2640 ft – 2640 ft) having a sufficient download speed percentage greater than 20%. The research team was unable to perform the 2640 ft – 1000 ft 5GHz trial due to time constraints, however the exceptional speeds (73% of measurements were satisfactory or better) recorded during the 2640 ft – 2640 ft test should be noted and investigated in future research.

Evaluation of the 5 GHz upload speed distributions in Figure 15, reveals that the percentage of satisfactory upload speeds was 25% or less (with no high-speed connections) in all trials with the lone exception of the 250 ft – 1000 ft trial having a high-speed percentage of 25% and a satisfactory upload speed test success percentage of 50%. Interestingly, increase in successful test connections with increased BD-2 (noted in the 2.4 GHz daisy-chain trial analysis) was also largely seen in the 5 GHz trials, further supporting the need for future research to investigate distance payload and UAS formation optimization.

These results further indicate the transmission distance does not, itself, determine the quality of throughput a client can expect to receive given a sufficient transmitting power of the selected equipment. Rather, both upload and download speeds appear to be heavily dependent upon at least one other external factor, given the evident inconsistencies and insufficient explanatory power of the models. It is plausible that as bridge distances approach 1 km – the manually set transmission power setting of the TRENDnet antennas – there may be a spike in connection reliability, warranting an extended range of testing to authenticate this hypothesis. While the current study lays a foundational understanding of the bridge technologies' capabilities, further research is likely necessary to fully understand all the factors at play. To gauge the full scope of this system's potential, subsequent research should aim to incorporate a wider range of controlled variables.

Stream 1080p Video Y=Yes, N=No		2.4 GHz			5 GHz		
Distance Between Bridge Pair #1	Distance Between Bridge Pair #2	Distance Between Client & Router			Distance Between Client & Router		
		75	150	250	75	150	250
50 ft	200 ft	Y	Y	Y	Y	Y	Y
	1000 ft	Y	Y	Y	Y	Y	Y
250 ft	200 ft	Y	Y	Y	Y	Y	
	1000 ft	Y	Y	Y	Y	Y	Y
2640 ft	1000 ft						
	2640 ft	Y	Y	N	Y	Y	Y

No Buffering	Buffer 0-5 seconds	Buffer 5.1-10 seconds
Buffer 10.1-30 seconds	Buffer >30 seconds	Fail

Table 12: Outcomes of 1080p video testing at bridge pair #1, bridge pair #2, and client-router distances for the double bridge pair testing phase.

Table 12 displays the results of the video stream attempts at each testing configuration. A "Y" indicates the video was streamed successfully, whereas an "N" indicates a failure to stream the video. Refer to the legend in Table 12 for notes on buffer times. Refer to Section VII.B.i.c. for further details regarding video selection and success criteria.

Overall, as is consistent with all previous analyses, 2.4 GHz outperformed 5 GHz in most cases. Notably, the 2.4 GHz signal performed better at the further BD-2 for each BD-1, though quality appeared to diminish at the furthest bridging distances (2640 ft – 2640 ft). Meanwhile, 5 GHz performance appears to have diminished with increasing BD-1 with little discernable relationship with BD-2. Nonetheless, across all attempts, only one instance was recorded in which the video failed to load altogether. Otherwise, 1080p video was reliably played with buffers lasting no longer than 30 seconds.

C.) Flight Testing (2023)

i.) Cage Testing

Figure 16: Cage-testing of NEST payload on board an Alta 8

Figure 17: Cage testing of Ad-Hawk payload on board an Alta X

A series of tests were conducted within a large mesh cage to ensure that the research payloads were safe to fly, both structurally and with regards to electromagnetic interference (EMI). Given the Ad-Hawk system emits 2.4 GHz Wi-Fi, and as the RC command and control link operates in the 2.4 GHz band, there was reasonable concern that EMI would inhibit flight operations. First, standard airworthiness tests were conducted, which included ensuring both the 900 MHz and 2.4 GHz command-and-control links were working properly with the research payloads powered on. Functionality of the payload "kill switch" was confirmed by the pilot in command (PIC) by toggling the preset switch on the transmitter. Additionally, the payload was inspected to ensure that it was structurally secure. A low-power range check was conducted, during which the PIC moved 30ft from the vehicle with the RC transmitter and cycled through all the flight modes with the research payload powered on, thus ensuring the 2.4 GHz link was functioning properly.

Upon confirming the "kill switch" repeater functionality and the lack of interference with the command-and-control links, the payload was turned off and the vehicle climbed to a height of 5-10 feet. After several minutes of hovering to ensure a satisfactory flight envelope, the payload power was activated. Once all crewmembers were satisfied that the powered payload did not interfere with flight safety, the UAS landed. This process was repeated for both aircraft. While the Ad-Hawk UAS (Alta X) completed its flight test, the NEST payload was powered on while on the ground to ensure both UAS functioned properly with a fully powered Ad-Hawk system. With all system components powered on, the research team was able to establish a wireless connection and verify the functionality of the core Ad-Hawk system, proving that the system could be safely and successfully integrated with unmanned aircraft. This allowed the research team to continue with plans to conduct flight tests.

ii.) Flight Testing

a.) Configuration

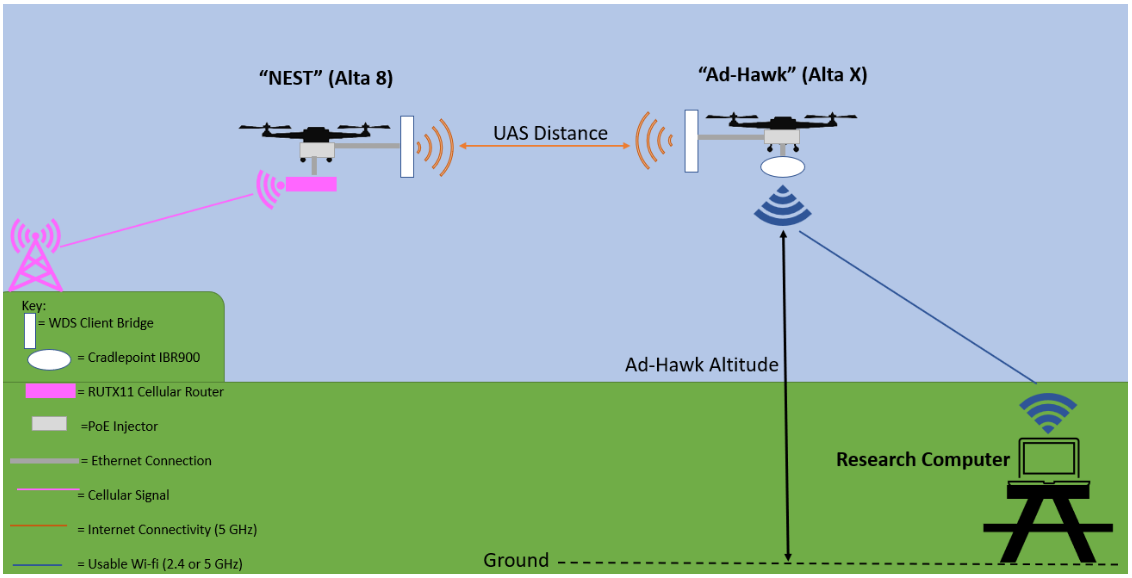

Figure 18. Visualization of flight-testing operations including a single WDS bridge pair and variable UAS distances and Ad-Hawk altitudes.

Figure 19. Active data collection during in-flight test.

Figure 18 provides a visual of the in-air testing procedure. The cellular-enabled NEST would bridge connectivity to the Ad-Hawk, which would then transmit usable internet-enabled Wi-Fi to the ground. Researchers then conducted tests to determine download and upload speeds while maintaining a minimum of 100 ft horizontal distance from the Ad-Hawk UAS, as seen in Figure 19.

b.) Procedure

The same initial airworthiness tests conducted during cage testing (low-power range check, payload security checks, vehicle inspections) were completed before the in-flight testing.

Full-scale flight tests were conducted at the City Environment Range Testing for Autonomous Integrated Navigation (CERTAIN) range at NASA's Langley Research Center, where five flight tests were conducted over the course of two days. To test the system, both the Ad-Hawk (Alta X) and NEST (Alta 8) UAS climbed, maneuvered, and hovered at predetermined locations at known horizontal distances from each other. For all tests, the NEST hovered at an altitude of 50 ft AGL while the Ad-Hawk then climbed to different altitudes. Figure 20 shows the predetermined hover locations for both the NEST and Ad-Hawk UAS at the three distances tested. During each flight test, researchers recorded download and upload times of a 14.568 MB PDF file and the streamability of an approximately 250 MB video via Youtube [20] as outlined in Section VI.A.iv. Client distances of just 50 ft and 200 ft were tested at in accordance with UAS heights.

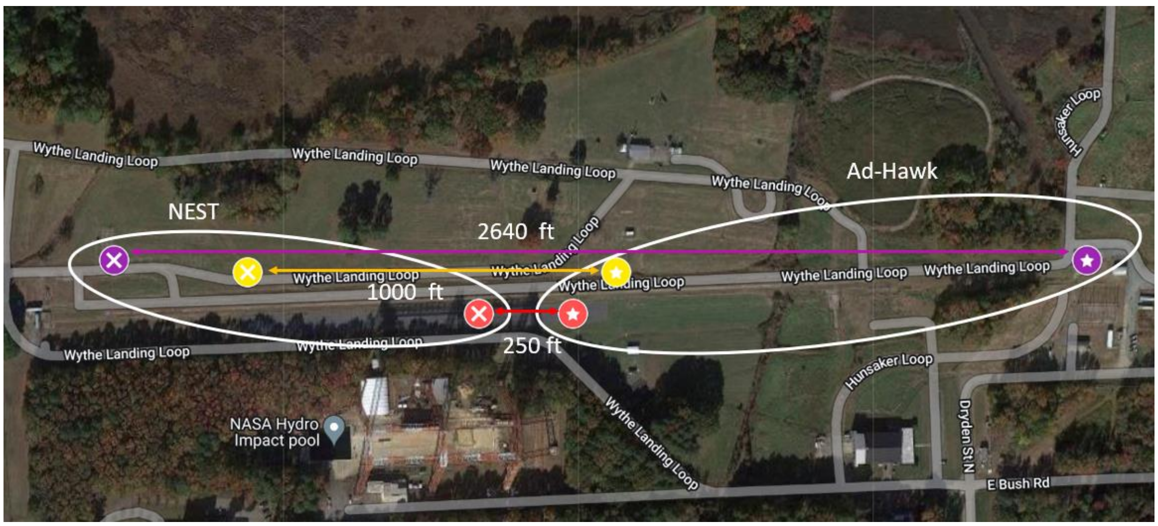

Figure 20. Outline of flight test profile. Flights 1-4 (red) would consist of both UAS launching 250 ft from one another, flights 5-8 (yellow) would launch 1000 ft from one another, and flights 9-12 (purple) would launch 2640 ft from one another. At each launch site, the NEST would consistently elevate 50 ft while the Ad-Hawk elevated to 50 ft, 100 ft, 150 ft, and finally 200 ft.

A major component of the payload design, flight control, and testing setup was the need to have the WDS bridges—which are high-gain antennas—pointing at each other while the payload was powered on. To account for this, the research team determined the optimal angle to set the bridges at during each flight based on the predetermined positions the UAS would hover at. These angles were determined using Equation 2, where X and Y are the horizontal (ground) and vertical (altitude) distances between the UAS, respectively.

$$\alpha = \tan^{-1}\left(\frac{Y}{X}\right) \quad [2]$$

Once these angles had been determined, the team designed an adjustable bridge mount that would allow the bridges to be angled appropriately for elevation difference between participant UAS (see Figure 21). Due to the 30° beamwidth of the TRENDnet bridges, any pointing less than 5° ($\alpha<5°$) was ignored and approximated to zero, meaning no elevation adjustment was made. For example, two UAS 2640 ft apart horizontally with a 150 ft altitude difference can be approximated to be on the same horizontal plane. Prior to each flight, the team was able to adjust the bridges as necessary for pointing the altitude axis. To account for pointing in the azimuth axis, the predetermined UAS hover locations were set at the same latitude, meaning that heading the NEST due east and the Ad-Hawk due west would allow for the alignment of the directional antennas.

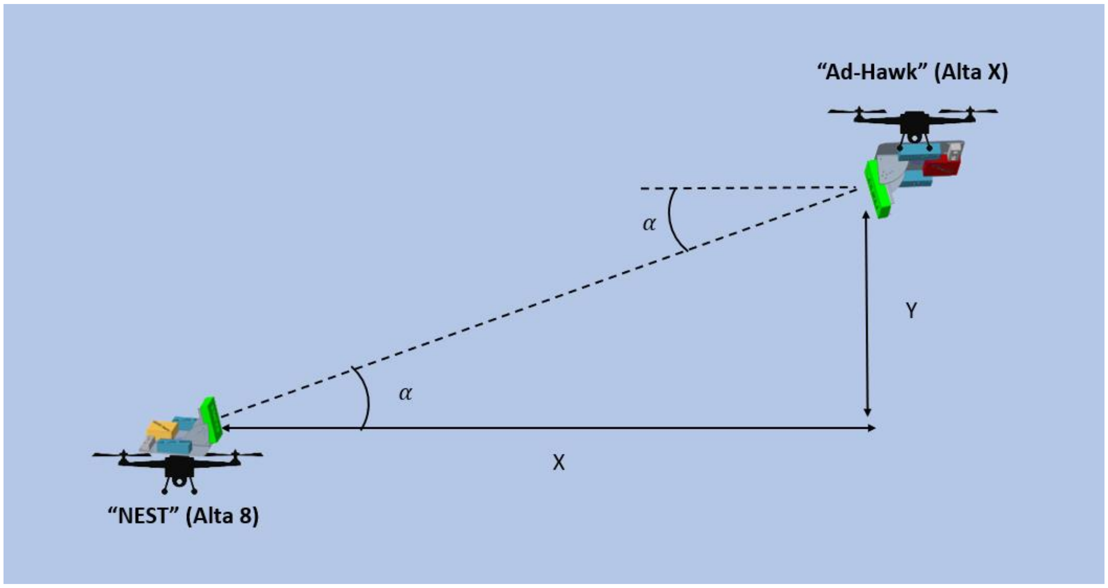

Figure 21. Utilization of geometry to determine the necessary WDS client bridge angles to maintain a constant link.

c.) Results

The first day of flight testing produced two data points as shown in Table 13, below. Once the UAS were in the testing configuration with 250 ft horizontal separation and both at 50 ft AGL, the research team was able to connect to the IBR900 Wi-Fi router mounted on the Ad-Hawk payload. However, due to an unstable connection and degrading weather conditions, testing at 250 ft was terminated. Because all use-cases of the Ad-Hawk system involve much greater distances between UAS, the researchers deemed it unnecessary to use their remaining time to complete the 250 ft tests.

The second day of flight testing had more favorable weather conditions and yielded more successful flights. A total of four flights were conducted with the following configurations:

UAS 1000 ft apart, Ad-Hawk 50 ft AGL

UAS 1000 ft apart, Ad-Hawk 200 ft AGL

UAS 2640 ft (1/2 mile) apart, Ad-Hawk 50 ft AGL

UAS 2640 ft (1/2 mile) apart, Ad-Hawk 200 ft AGL

Download/Upload times were recorded, and speeds calculated using Equation 1. The resulting speeds are tabulated in Tables 13 and 14, below. Success criteria were identical to that applied to ground testing data.

Bridge Pair Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
250	50	37.27	37.27	1.52
	200	-	-	-
1000	50	65.47	74.04	23.09
	200	70.63	69.01	12.25
2640	50	84.45	79.72	12.25
	200	2.28	8.16	10.18

Table 13. Download speeds using the 2.4 GHz signal at variable Ad-Hawk altitudes (red) and UAS distances (green).

Bridge Pair Distance (ft)	Client Distance (ft)	Median (Mbps)	Mean (Mbps)	STD (Mbps)
250	50	-	-	-
	200	-	-	-
1000	50	7.50	7.60	4.38
	200	1.53	4.42	7.30
2640	50	2.28	8.16	10.18
	200	0	0	0

Table 14. Upload speeds using the 2.4 GHz signal at variable Ad-Hawk altitudes (red) and UAS distances (green).

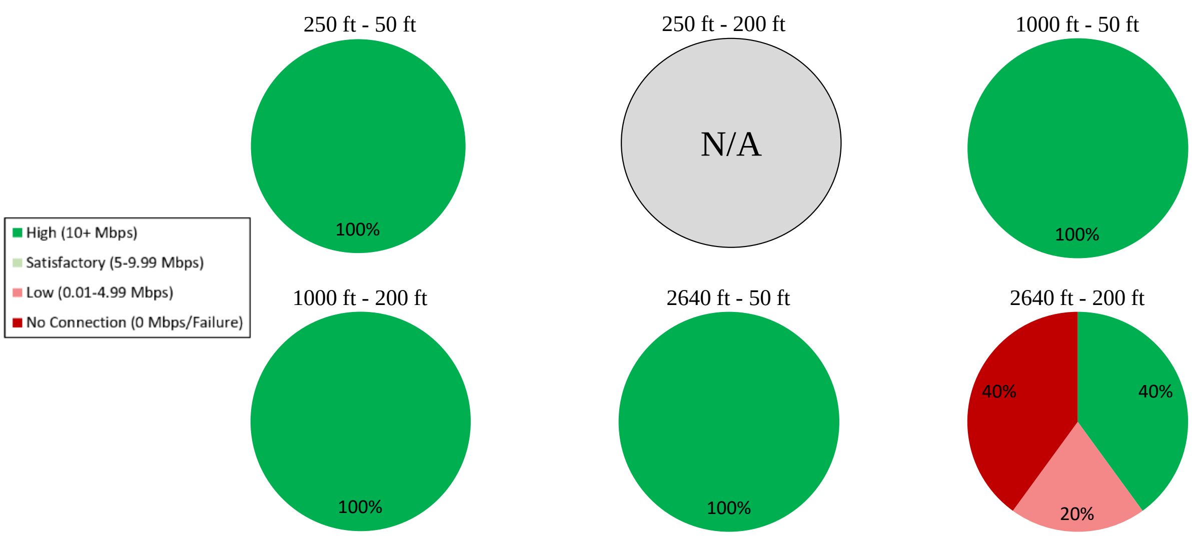

Figure 22. 2.4 GHz download speed categorizations by varying bridge and client distances (bridge ft – client ft), according to established success criteria.

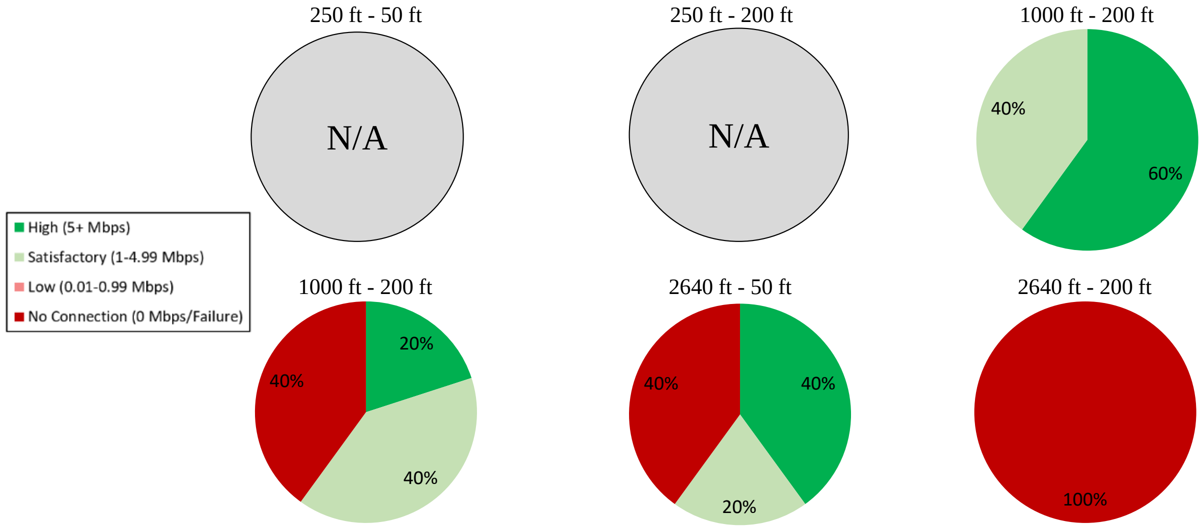

Figure 23. 2.4 GHz upload speed categorizations by varying bridge and client distances (bridge ft – client ft), according to established success criteria.

To explore the impact of both bridge and client distance on throughput, correlation analyses were performed. Analysis of the recorded 2.4 GHz download speeds found a partial, negative correlation between bridge distance and download speed (r = -0.25). Similarly, a moderate, negative correlation between client distance and download speed was observed (r = -0.60). In assessing the recorded 2.4 GHz upload speeds, similar, though less pronounced relationships were observed. Bridge distance demonstrated a slight, negative influence on upload speed (r = -0.064) while client distance had a more moderate, negative influence (r = -0.37). Thus, all these indicators are consistent with the inverse square law, as would be expected.

Multiple linear regression analyses were conducted to more accurately model the relationships between bridge/client distances and throughput. These models reliably explained 37% of the variability in download speeds (R-squared = 0.37, p = 0.019) but could not reliably define the relationships between bridge distance and client distance on upload speeds (R-squared = 0.15, p = 0.3). While no significant relationships were identified in the upload data with respect to client distance (p = 0.13), a significant, negative relationship was observed between client distance and download (β = -0.25±0.086 Mbps/ft, p = 0.010). No evidence of a relationship between bridge distance and download (p = 0.59) nor upload (p = 0.65) speed was observed. It is, however, worth mentioning that, while not significant according to the thresholds of this study, the relationship between client distance and upload speed (β = -0.035±0.022 Mbps/ft, p = 0.13) was close enough given the relatively small dataset that further research should be conducted to validate this conclusion. From these analyses, it would appear only client distance had a noticeable influence on either download or upload throughput.

The download and upload speed characterizations shown in Figures 22 and 23 are according to their respective success criteria derived from Section VI.A.iv. For download data, “high” speed is at least 10 Mbps (dark green). A “satisfactory” speed is between 5 – 9.99 Mbps (light green), a “low” speed is between 0.01 – 4.99 Mbps (light red), and “no connection” is indicated by a download failure (dark red). For upload data, “high” speed is at least 5 Mbps (dark green). A “satisfactory” speed is between 1 – 4.99 Mbps (light green), an unsatisfactory speed is between 0.01 – 0.99 Mbps (light red), and “no connection” is indicated by an upload failure (dark red). Characterization of the data according to these criteria was limited to recordings differing only in bridge distance as the negative correlation between signal strength and client distance is well documented. To demonstrate the ability for a robust connection to be made at an assortment of client distances, however, a consistent number of recordings were made ranging from 75 – 500 feet from the emitting router.

In assessing the download speed distributions in Figure 22, four of the five trials conducted had high-speed download rates in 100% of tests (250 ft – 50 ft, 1000 ft – 50 ft, 1000 ft – 200 ft, and 2640 ft – 50 ft). The 2460 ft – 200 ft trial was the only download trial to demonstrate speeds below the satisfactory classification, and yet, 40% of the recordings were still high-speed. The 2.4 GHz upload trials were not nearly as successful with 40% or more failed upload attempts in three of the four trials conducted (250 ft – 1000 ft, 2640 ft – 50 ft, and 2640 ft – 200 ft). Not a single upload attempt was successful during the 2640 ft – 2640 ft trial. Additional evaluation of Figure 23 shows the percentage of high-speed upload rates decreases with respect to both increasing BD-1 and BD-2. Neither of these relationships were found to be significant via the linear regression model, however, indicating further research with a larger dataset may be necessary to more reliably assert these conclusions. The previously noted ground test trend of increasing successful data transfer with respect to increasing BD-2 does not appear to be present in the flight test trial data—though the researchers still advocate for further investigation into system distance/formation optimization.

These results provide optimism, particularly in reference to download capabilities, for the long-distance stretching of an internet-enabled Wi-Fi network. Download throughput was notably high-speed in all instances aside from the furthest extent of testing, at a bridge distance of 2640 ft and client distance of 200 ft. The overall percent increase in high-speed download rate may potentially be explained by the lack of physical obstruction between transmitting hardware due to being on-board UAS. Nonetheless, this appeared to have a negative influence on upload capabilities, something the team speculates may be a result of poor transmitting power of the client device. However, no significant relationships were identified in relation to this data, so further research is a necessity to make definitive conclusions.

Stream 1080p Video Y=Yes, N=No	2.4 GHz	
UAS Distance↓ / Ad-Hawk Altitude ->	50 ft	200 ft
1000 ft	Y	Y
2640 ft	Y	Y

No Buffering	Buffer 0-5 seconds	Buffer 5.1-10 seconds
Buffer 10.1-30 seconds	Buffer >30 seconds	Fail

Table 15. Outcomes of 1080p video testing at varying UAS distances (red) and Ad-Hawk altitudes (green).

Table 15 displays the results of the video stream attempts at each testing configuration. A "Y" indicates the video was streamed successfully, whereas an "N" indicates a failure to stream the video. Refer to the legend in Table 12 for notes on buffer times. Refer to Section VI.A.iv. for further details regarding video selection and success criteria. In all cases, even at the furthest tested extents of the bridge or client distances, the video was streamed with no buffering, reinforcing the extent to which the download capabilities of the network could be stretched. In comparison to the throughput basic web browsing, pdf downloads, and even video conferencing would require by emergency service providers, HD video streaming is notably demanding. Nonetheless, the evidence suggests this would be plausible at the distances tested in this study. Because the required angle α (See Figure 21) at this configuration was < 5° (~3.3°), no elevation adjustment was made to the mount. It is possible this imperfect pointing caused the failures experienced during the 2640 ft – 200 ft tests, though this could not be confirmed.

IX. Limitations

A.) Technological Limits

Any UAS utilized in the system would be subject to the operational limits (e.g., payload weight limit, sustained wind/gusting limits, etc.) specified by the manufacturer. The hardware selected to carry out bridging and daisy-chaining will ultimately determine the payload size and, subsequently, the UAS flight time and flight envelope. Furthermore, the implemented connectivity hardware will determine the telecommunication range capabilities of the entire system. The daisy-chaining ability of the network is a function of the bridging antennas implemented; similarly, the ground end-user's ability to connect to the Ad-Hawk's internet-enabled Wi-Fi is a function of the router and antenna performance.

B.) Regulatory Limits

The Ad-Hawk system the team constructed and tested was subject to general FAA regulatory limits (e.g., 14 CFR Part 107); however, the system had to operate within additional constraints for testing to take place on-site at NASA's Langley Research Center (LaRC). All hardware used at LaRC must be compliant with both the Trade Agreements Act (TAA) and the National Defense Authorization Act (NDAA). Hardware also must be approved through LaRC's Commercial IT Request (CITR) process. Such requirements limited the hardware options available to the team when designing the payloads. It is reasonable to assume there exists hardware that could further optimize performance of the system beyond what was demonstrated in Section VIII.

There are also regulations regarding airspace and air traffic that limit the performance of the Ad-Hawk system. Current FAA rules dictate that there must be a one-to-one ratio of active pilots to airborne UAS, therefore daisy-chaining any number of Ad-Hawks requires an equivalent quantity of available certified pilots. There are also limiting regulations internally imposed within potential stakeholder entities, such as CAL FIRE, which currently requires that all crewed CAL FIRE aircraft be immediately grounded if a UAS is airborne within the designated disaster airspace above the wildfire. While regulations such as these would severely limit the practicality and effectiveness of the Ad-Hawk system, it should be taken into consideration that technological advances may soon render these regulations obsolete, thus future implementation and research may not be hindered in the same manner described in this paper.

C.) Project Limits

The 2023 Ad-Hawk research was limited to a ten-week timeframe, making it difficult to perform comprehensive testing of the system. Given more time to explore the project, the researchers would have chosen to carry out extensive and comprehensive ground and in-air testing. For example, the flight tests did not include multiple pairs of bridges and thus airborne daisy-chaining was never tested. Airborne WDS bridge daisy-chaining, which is the Ad-Hawk system's intended use-case, would require the team to have had access to at least three UAS (one NEST UAS and two Ad-Hawk UAS) in addition to the necessary increase in payload equipment, ground crew, and testing space. Any attempt at gathering these additional resources and acquiring the necessary approval is an extremely ambitious endeavor under such a constricted timeline and the risk of failure in procuring the necessary hardware to perform airborne daisy-chaining was deemed too high by the researchers. The research team determined that acquiring equipment and approval for the usage of two UAS was all that could reasonably be accomplished given these circumstances.

Additionally, the team had limited funding for development of the Ad-Hawk project. All hardware purchased was commercial off-the-shelf and had to be procured through the NASA Commercial IT Request website. The process of selecting and ordering hardware that was both TAA/NDAA compliant and met all desired specifications only exacerbated time limitations for payload construction and flight approval processing.

X. Future Considerations

A.) Hardware Recommendations

As described in Section IX. payload configurations used for the presented research purposes had project-specific limitations. The team's testing hardware choices may not be the optimal selections for the Ad-Hawk system's intended use-case. While the intended Ad-Hawk application—a wildfire scenario—involves a less controlled environment than testing, it also lacks the hardware purchasing restrictions which the team operated under. Considering these factors, it is recommended that a final configuration Ad-Hawk system use higher-grade and more ruggedized hardware than those described in this research project.

It has additionally been recommended in discussions with industry experts that equipping end-users with plug-in antennas would maximize the distance at which they could connect to and utilize the Ad-Hawks' Wi-Fi signals. Given upload speed is also heavily dependent on the capabilities of the end-user's device, this addition would drastically improve these speeds at any distance from the nearest Ad-Hawk.

B.) Mechanical Development

To demonstrate the viability of an airborne network, the only orientation-dependent hardware, the WDSBAs, were manually arranged so as to ensure a direct connection at each instance of data collection. To be a viable solution in the field, there must be developed means through which these bridges will automatically face one another as their UAS positions and orientations change during flight. Therefore, the team recommends that the antenna-tracking system be developed so the bridges can be optimally aligned at all times. Such development could include the use of a gimbal system, which can maneuver such that the bridges would not require manual adjustment or the use of approximated angles.

C.) Software Development

To more accurately orient the bridges in gimbal system proposed in Section X.B., software development should integrate GPS data provided by the piloting software of the UAS used in the Ad-Hawk system. This is the simplest way to ensure accurate information regarding the position and orientation of each WDSBA.

Lastly, it is recommended that a cloud-management/API integration system is included with the Ad-Hawk system. This would enable end-user IT to ensure security measures are present within the system. For example, this would enable an admin to create two different Wi-Fi networks activated on the Ad-Hawk platform – one unthrottled network for personnel taking more data-heavy actions, and one throttled network for personnel in need of more basic processes such as file download/upload and telecommunication. This would ensure that if a low-priority user is using the internet, it does not increase latency and decrease bandwidth for high-priority users. Such security measures would also ensure data privacy.

XI. Conclusion

The research conducted by the 2023 NASA Academy Ad-Hawk Team provided significant evidence for the technical feasibility of an aerial connectivity network originally as proposed by the 2022 NASA Academy. Bridge-bridge distance demonstrated inconsistent and minimal influence on throughput, warranting further research at even greater distances. Client distance demonstrated a more consistent, negative influence on throughput, justifying the exploration of a client antenna to boost the client device's transmission power. Daisy-chain testing indicated higher variability in throughput, though download success rate at the furthest distance iteration (2640 ft – 2640 ft) incites optimism for further optimization of system hardware and future UAS-based testing. Thus, the experimental data collected supports the potential to convert an external cellular signal to Wi-Fi and daisy-chain it between access points to establish an aerial internet-enabled Wi-Fi network to be reliably accessed by an end-user on the ground. Still, there are still aspects which warrant further, more extensive investigation, including optimal performance distances, alternative and potentially more optimal hardware arrangements, and the absolute limitations of the network.

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Appendix

Within this section can be found the individual download and upload speed recordings summarized in Section VIII., sorted according to the success criteria established in Section VI.A.iv. This is simply for the purposes of verification and supplemental detail of testing procedures.

2.4 GHz download speeds (Mbps)				
Client Distance↓ / Bridge Distance ->	50 ft	250 ft	1000 ft	2640 ft
75 ft	6.80	11.75	37.75	59.95
	5.87	5.96	9.44	47.86
	6.85	8.16	20.53	59.74
150 ft	13.41	11.30	39.84	13.59
	16.77	3.49	13.05	17.98
	18.17	9.52	13.92	26.14
				9.56
				15.74
250 ft	7.77	9.97	38.57	36.19
	15.60	13.29	29.08	18.41
	10.76	14.25	41.25	23.67
				37.66
				14.19
500 ft	5.49	7.98	11.78	6.82
	6.21	10.73	15.58	27.62
	4.28	10.47	14.36	12.83
				19.80
				18.47

5 GHz download speeds (Mbps)				
Client Distance↓ / Bridge Distance ->	50 ft	250 ft	1000 ft	2640 ft
75 ft	6.53	18.04	52.54	16.78
	5.37	12.85	56.33	7.34
	6.00	13.89	48.58	12.65
150 ft	7.80	14.48	41.25	34.60
	11.93	18.93	17.58	36.32
	9.54	11.53	18.16	15.86
				11.06
				14.66
250 ft	3.99	10.72	39.55	27.20
	5.46	15.36	16.51	35.69
	6.99	9.17	19.58	11.89
				14.91
				Fail
500 ft	12.76	9.11	24.97	40.30
	10.20	11.49	28.38	39.90
	6.39	10.54	32.88	14.15
				15.80
				16.37

Table A-1. Download speeds for 2.4 GHz (left) and 5 GHz (right) at variable distances between WDSBAs (green) and variable distances between the end-user and emitting router (red). Instances of a complete failure to download within 3 minutes are indicated via "Fail" and a dark red coloration, whereas the data rate of each completed download is marked in relation to the minimum 5 Mbps benchmark: < 5 Mbps (light red), 5 – 10 Mbps (light green), 10+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.

2.4 GHz upload speeds (Mbps)				
Client Distance↓ / Bridge Distance ->	50 ft	250 ft	1000 ft	2640 ft
75 ft	2.05	8.19	20.70	10.35
	4.80	8.50	21.42	20.52
	2.33	13.17	21.42	22.37
150 ft	3.59	10.28	13.49	2.08
	4.11	10.16	15.96	12.91
	10.51	9.16	15.04	1.72
				11.83
				13.20
250 ft	7.39	10.43	21.04	1.23
	9.86	9.58	18.41	12.64
	9.66	9.82	19.46	2.62
				12.40
				12.78
500 ft	7.73	9.21	2.47	Fail
	8.45	8.84	9.26	3.12
	6.40	6.95	1.94	4.78
				0.71
				2.59

5 GHz upload speeds (Mbps)				
Client Distance↓ / Bridge Distance ->	50 ft	250 ft	1000 ft	2640 ft
75 ft	7.01	10.48	21.31	4.26
	5.81	12.78	21.23	16.70
	7.78	14.83	22.24	3.32
150 ft	7.68	7.72	13.26	6.87
	10.62	7.25	13.04	3.00
	5.79	8.78	17.39	7.74
				1.34
				12.11
250 ft	11.33	8.74	19.62	4.51
	8.29	2.68	20.52	12.40
	7.01	6.81	22.72	1.48
				13.24
				1.94
500 ft	6.74	13.79	10.93	7.54
	2.42	15.14	14.72	12.31
	9.99	16.67	16.94	11.77
				0.82
				13.40

Table A-2. Upload speeds for 2.4 GHz (left) and 5 GHz (right) at variable distances between the WDSBAs (green) and variable distances between the end-user and emitting router (red). Instances of a complete failure to upload within 3 minutes are indicated via "Fail" and a dark red coloration, whereas the data rate of each completed upload is marked in relation to the minimum 1 Mbps benchmark: < 1 Mbps (light red), 1 – 5 Mbps (light green), 5+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.

2.4 GHz Download Speeds

Distance Between Bridge Pair #1	Distance Between Bridge Pair #2	Distance Between Client & Router: 75 ft	150 ft	250 ft
50 ft	200 ft	8.41	6.35	6.57
		10.7	6.66	6.24
		5.82	6.80	9.59
		7.10	5.79	10.5
		8.66	4.71	9.48
	1000 ft	15.6	9.21	4.35
		4.02	11.2	8.11
		17.2	12.6	10.5
		18.3	6.77	7.62
		17.3	11.3	6.71
250 ft	200 ft	4.56	Fail	4.09
		3.23	1.14	5.69
		4.97	2.23	1.96
		6.88	4.86	Fail
		6.83	7.29	2.35
	1000 ft	10.8	4.78	2.08
		15.0	2.55	3.63
		15.8	2.30	3.17
		4.99	2.01	4.11
		6.40	3.94	5.80
2640 ft	1000 ft	9.42		
		2.37		
		14.6		
		14.5		
		5.11		
	2640 ft	39.1	34.4	27.3
		3.34	7.66	20.9
		17.9	24.5	20.8
		18.0	45.7	8.37
		36.9	36.7	20.0

2.4 GHz Upload Speeds

Distance Between Bridge Pair #1	Distance Between Bridge Pair #2	Distance Between Client & Router: 75 ft	150 ft	250 ft
50 ft	200 ft	3.52	Fail	1.30
		3.41	4.79	5.80
		4.63	5.70	3.96
		5.50	6.95	5.89
		4.90	5.24	7.23
	1000 ft	1.79	6.31	13.2
		5.28	6.34	9.40
		4.98	8.61	9.62
		5.72	7.70	8.95
		6.58	1.92	10.2
250 ft	200 ft	4.74	2.23	0.78
		3.94	0.84	6.51
		Fail	0.97	Fail
		1.15	6.89	13.24
		0.95	8.28	3.89
	1000 ft	12.9	1.23	5.30
		14.7	2.98	6.01
		12.6	4.90	7.94
		10.7	Fail	9.36
		13.6	2.08	2.45
2640 ft	1000 ft	12.1		
		2.70		
		Fail		
		Fail		
		Fail		
	2640 ft	3.97	2.09	1.76
		8.66	13.6	Fail
		Fail	0.89	Fail
		Fail	Fail	
		15.3	Fail	

Table A-3. Download (left) and upload (right) speeds for 2.4 GHz at variable distances between WDSBA pair #1 (green), WDSBA pair #2 (tan), and the end-user and emitting router (red). Instances of a complete failure to download/upload within 3 minutes are indicated via “Fail” and a dark red coloration, whereas the data rate of each completed download is marked in relation to the download or upload success criteria. For download: < 5 Mbps (light red), 5 – 10 Mbps (light green), 10+ Mbps (dark green). For upload: < 1 Mbps (light red), 1 – 5 Mbps (light green), 5+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.

5.0 GHz Download Speeds

Distance Between Bridge Pair #1	Distance Between Bridge Pair #2	Distance Between Client & Router: 75 ft	150 ft	250 ft
50 ft	200 ft	5.03	2.18	2.99
		3.04	1.39	Fail
		3.13	3.96	3.86
		2.28	Fail	4.45
		2.09	6.61	8.56
	1000 ft	3.87	8.37	6.26
		5.34	3.04	2.11
		4.05	2.74	4.70
		1.54	1.33	4.89
		1.87	2.14	2.65
250 ft	200 ft	2.48	Fail	2.45
		0.95	1.88	2.48
		1.99	2.48	Fail
		Fail	5.65	3.21
		2.14	2.42	1.58
	1000 ft	3.88	4.32	3.23
		7.69	1.38	1.70
		7.97	1.85	8.31
		2.97	3.18	2.89
		1.95	3.45	1.85
2640 ft	1000 ft			
	2640 ft	14.9	17.7	23.0
		4.40	11.1	8.33
		10.2	43.3	12.7
		3.40	11.8	3.44
		12.5	Fail	26.9

5.0 GHz Upload Speeds

Distance Between Bridge Pair #1	Distance Between Bridge Pair #2	Distance Between Client & Router: 75 ft	150 ft	250 ft
50 ft	200 ft	Fail	1.16	1.10
		Fail	Fail	Fail
			Fail	Fail
	1000 ft	Fail	Fail	Fail
		Fail	Fail	2.73
				1.61
				Fail
250 ft	200 ft	Fail	Fail	0.90
		Fail	Fail	1.26
				Fail
				Fail
	1000 ft	Fail	5.53	Fail
		1.87	2.19	Fail
		1.55	3.16	
		6.45	4.78	
		7.42	2.97	
2640 ft	1000 ft			
	2640 ft	0.82	Fail	Fail
		Fail	Fail	Fail
		0.74	Fail	
		Fail		
		Fail		

Table A-4. Download (left) and upload (right) speeds for 5 GHz at variable distances between WDSBA pair #1 (green), WDSBA pair #2 (tan), and the end-user and emitting router (red). Instances of a complete failure to download/upload within 3 minutes are indicated via "Fail" and a dark red coloration, whereas the data rate of each completed download is marked in relation to the download or upload success criteria. For download: < 5 Mbps (light red), 5 – 10 Mbps (light green), 10+ Mbps (dark green). For upload: < 1 Mbps (light red), 1 – 5 Mbps (light green), 5+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.

2.4 GHz Download Speeds (Mbps)			
Ad-Hawk Altitude/UAS Distance	250 ft	1000 ft	2640 ft
50 ft	38.3	65.5	58.9
	36.2	54.2	86.3
		98.8	89.6
		53	79.3
		98.8	84.5
200 ft		56	Fail
		80.4	2.28
		70.6	19.6
			19
			Fail

Table A-5. Download speeds using the 2.4 GHz signal at variable Ad-Hawk altitudes (red) and UAS distances (green). Instances of a complete failure to download within 3 minutes are indicated via "Fail" and a dark red coloration, whereas the data rate of each completed download is marked in relation to the minimum 5 Mbps benchmark: < 5 Mbps (light red), 5 – 10 Mbps (light green), 10+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.

2.4 GHz Upload Speeds (Mbps)			
Ad-Hawk Altitude/UAS Distance	250 ft	1000 ft	2640 ft
50 ft		4.8	Fail
		12.4	2.28
		7.5	19.6
		1.96	19
		11.3	Fail
200 ft		Fail	Fail
		1.53	Fail
		Fail	Fail
		3.31	
		17.2	

Table A-6. Upload speeds using the 2.4 GHz signal at variable Ad-Hawk altitudes (red) and UAS distances (green). Instances of a complete failure to upload within 3 minutes are indicated via "Fail" and a dark red coloration, whereas the data rate of each completed upload is marked in relation to the minimum 1 Mbps benchmark: < 1 Mbps (light red), 1 – 5 Mbps (light green), 5+ Mbps (dark green). More details on success criteria can be found in Section VI.A.iv.