Ad-Hawk Aerial Connectivity Network

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Wildfires in the United States have been increasing significantly in both frequency and size in recent decades, requiring maximal efficiency on the part of wildfire management organizations. However, while the methodology and technology to combat wildfires has improved, the connectivity infrastructure in more 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 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 to any extent. They were simply selected analytically as examples of existing technologies and offerings to validate the proposed concepts of the Ad-Hawk Network.

I. Nomenclature

UAS = Unmanned Aerial System
Ad-Hawk = Play on Words for Ad-Hoc network
CoW = Cell on Wheels
Flying CoW = Cell on Wings
CRD = Compact Rapid Deployable
NEST = Network Enabled Source Technologies
MAMA = Making Another Mediocre Acronym
LOS = Line of sight
SIMO = Single-Input Multi-Output
WDS = Wireless Distribution System
SIM = Subscriber Identity Module
PDF = Portable Document Format
PoE = Power over Ethernet
AP = Access Point
API = Application Programming Interface
GIS = Geographic Information System
COP = Common Operating Picture
M/R = Modem/Router
FCC = Federal Communications Commission
NTIA = National Telecommunications and Information Administration
IoT = Internet of Things
LEO = Low-Earth Orbit
VTOL = Vertical Take Off and Landing
ISM = Industrial, Scientific, and Medical

II. Introduction

Fighting wildland fires requires a sizeable labor force of firefighters working in various crews spread out over vast distances. Additionally, ground vehicles support the effort by transporting supplies and personnel, aircraft provide logistical support and drop retardant and water where necessary, and industrial machinery such as bulldozers assist ground crews by clearing trees and other obstacles. With such a multifaceted and sizeable labor force, maintaining constant communication is vital to effective wildfire management. However, in more rural regions, cellular signals can be faint or nonexistent, drastically inhibiting communication lines. While radio can keep communication intact in these scenarios, only being able to transmit data vocally bottlenecks and generalizes the flow of information. Ground crews frequently use digital tablets capable only of connectivity via an internet-enabled Wi-Fi channel; without Wi-Fi, firefighting crews are often unable to upload/download time-sensitive information, operate apps, run wildfire simulation software, or efficiently communicate with operation leadership. Firefighters will be left without Wi-Fi connectivity in time-critical situations; stuck relaying 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. Broadcasting a stable internet-enabled Wi-Fi signal in remote areas would enable ground crews to transmit and receive large data files quickly in areas they may otherwise be unable to do so at all, which would significantly increase the efficiency of resource dispersal and fire suppression strategy.

This paper presents the conceptualization of a mobile ad-hoc Wi-Fi network that is capable of providing these first responders with the Wi-Fi internet connectivity they require to quickly upload/download vital data and communicate between the front lines and operation headquarters. With this connectivity, logistics teams can make informed decisions based on the analysis of real-time data received from crews on the front lines. The research team developed several distinct methods of delivering Wi-Fi connectivity; each method ultimately provides the same service, but the price and robustness of each system vary. The purpose of developing multiple methods to deliver the same service is to allow organizations the freedom to custom-tailor the system to appropriately reflect their unique circumstances and available resources.

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III. Similar Research

The authors of [1] confirmed the feasibility of delivering 2.4 GHz and 5GHz Wi-Fi internet derived from cellular towers via UAS with a reasonable number of UASs, identifying that the most significant limiting factor would be the inter-UAS distances. Their findings were based on simulations conducted to determine connectivity ranges based on standard Wi-Fi hardware specifications for a single UAS rather than a particular design proposition. Additionally, the authors of [2] and [3] explored the prospect of low-altitude, balloon-based Wi-Fi-enabled internet for disaster-afflicted areas. In [2] the authors confirmed the ability to employ the Emergency Broadband Access Network in Indonesia to effectively cover 72 square kilometers with Wi-Fi internet from an altitude of 440 meters. The authors of [3] provided experimental data from three trials indicating high data rates via Wi-Fi but over just around 3 square kilometers using their selected hardware.

The concept of a resilient network via UASs seeking out potential wireless connectivity stations and relaying data from those within internet-isolated areas was explored by the authors of [4]. They deemed this form of data transmission to be unstable due to the flight of the UASs. Based on the outstanding research around this concept, the focus worth pursuing appears to be maximizing the coverage distance and connectivity fundamentals of a more static, temporary network.

IV. State of the Art

Several commercially available or near-available attempts to bring internet access to rural areas in emergency responses have also emerged in recent years. AT&T's FirstNet is developing a tethered UAS deemed the Flying Cellular On Wings (Flying COW), a mobile cellular tower with an advertised 240 square-mile connectivity range, producing an 8.75-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 cellular signals further than if it were land-based, however, the signals would be cellular and not accessible via Wi-Fi as needed by firefighter command. The UAS can produce Wi-Fi, but over a range of just 500 feet according to discussions with FirstNet representative Art Pregler, 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 rather than Wi-Fi, rendering any Wi-Fi ranges in units of feet rather than the necessary miles.

Starlink, a network of low-Earth orbit 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, not all regions have official coverage yet. Despite substantial progressions in coverage monthly, it is still not capable of comprehensive coverage in its current state.

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

Discussions with officials from the Forest Service, firefighters from CAL FIRE, and local fire departments helped the team pinpoint mission-critical aspects of wildland firefighting that need improvement, particularly in the United States. Through these conversations, the following design criteria were established: first, the system must establish a long-distance network by spreading Wi-Fi connectivity at least 30 square miles. This criterion ensures that most medium-sized wildfires could have full Wi-Fi coverage, and even large fires would have large swaths of Wi-Fi coverage in the areas that need it most. Second, it must retain a minimum speed of 3 MBps with up to twenty user devices connected to the network. This criterion ensures the usability of the network for common needs such as downloading PDFs, using GIS apps, and sending data to COPs. Third, the system must be user-friendly to firefighter end-users. This criterion ensures the system can be set up quickly and efficiently by the users themselves saving time in active fire situations. The Ad-Hawk Network meets these design criteria and fulfills the purpose of spreading internet connectivity in wildland firefighting systems, especially in rural areas with no internet-enabled Wi-Fi service. This innovative system consists of three core components that work in tandem to spread Wi-Fi connectivity to areas that lack internet infrastructure.

The first component is a source of cellular connectivity which is most strongly recommended to be a mobile cell tower that generates a cellular signal. This cell tower will be located at the incident command for the fire and generate a sphere of cellular connectivity. One existing option for a mobile cell tower is the Compact Rapid Deployable (CRD) from AT&T FirstNet, but other cell services have similar products on the market as well. The CRD is a handcart-based mobile cell tower that generates an area of FirstNet Cellular and Wi-Fi coverage. Organizations like CAL FIRE have access to these CRDs with a FirstNet subscription, and access to the alternate mobile cell towers that exist with other cell companies. The CRD's cellular coverage is two miles, while the Wi-Fi coverage provided has a diameter of only 1,000 feet, and alternate options have similar coverage ranges. This small area of Wi-Fi coverage is not sufficient for firefighters' needs but is enough range to connect to the next component in the Ad-Hawk Network which will increase the area of connectivity.

The second component is an internet access point that converts the nearest available cellular signal to Wi-Fi and extends connectivity past the short range of the mobile cell tower. Called the Network Enabled Source Technologies ("NEST"), this component consists of a package of networking equipment hosted on a UAS. A SIM-enabled M/R takes the cellular signal from the CRD and converts it to Wi-Fi, which a product like the Cradlepoint R1900 Cellular Router with a Panorama MAKO Omnidirectional Antenna can accomplish. Next, a wireless bridge acts as a WDS AP to spread connectivity in a point-to-multipoint manner. An EnGenius ENH500v3 Wireless Bridge or similar product has this functionality and can bridge connectivity up to 5 miles away. The UAS package contains only Power over Ethernet (PoE) enabled equipment, is powered via a 4-port PoE power injection module and is affixed to the aircraft using a custom 3D-printed mount.

The third component, the ad-hoc UAS Network, is a web of long-range client-bridging access points that extend Wi-Fi connectivity to extreme distances. A fleet of UASs will each carry two wireless bridge WDS APs and a long-range outdoor router. The wireless bridge will serve as a WDS AP and pair with another of the same wireless bridges in point-to-point or point-to-multipoint mode to spread connectivity through client bridging. This technology or another similar alternative can take the Wi-Fi signal from the NEST and chain it 3-to-5 miles away at a time. This will form a mobile ad-hoc Wi-Fi network when the package on each UAS includes a long-range outdoors router with at least a 1.86-mile radius of connectivity to spread Wi-Fi to devices on the ground.

As implied, the three components of the overall system are not limited to the specific hardware choices described above; one of the strongest features of this system is how modular it is. Especially regarding the first component, cellular access can be provided by many sources besides a mobile cell tower. If the mobile cellular source is delayed or unavailable, the NEST could instead receive a cellular signal from the nearest functional cell tower with an alternate cellular boosting hardware package and still output Wi-Fi. Alternatively, low-Earth orbit (LEO) satellite network options like Starlink could be used as an initial satellite internet access point on the ground instead of cellular. Additionally, the hardware on the NEST is modular, with the custom 3D-printed mount featuring the ability to hold all the adjusted hardware needed to connect via cell tower or LEO options. This modularity of the overall system ensures the Ad-Hawk Network meets the client's exact needs and future-proofs the system.

Through the integration of these components, the novel Ad-Hawk Network spreads internet-enabled Wi-Fi connectivity as needed across an entire wildland fire operation. Firefighting devices on the ground that need connectivity would now have Wi-Fi connectivity with only 2 to 6 UAS in the vast majority of cases. With 7+ UAS even the largest fires could have complete coverage, and alternatively, UAS could be stationed precisely where needed in large and/or underequipped operations to keep communication lines stable.

VI. Framework Breakdown

A. Connection Source

Moving forward, the working assumption of this project is that a wildfire is occurring in a region in which there is either a 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 satellites, and cellular boosters for static nearby cell towers.

i. 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 that lack network coverage. 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 a 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 17.5 miles in diameter. This range of capabilities is more than sufficient to support the successive components of this project necessary to produce the desired Wi-Fi coverage.

ii. Low-Earth Orbit Satellites

A constellation network of LEO satellites offers the ability 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 UAS could connect to the LEO satellite signal and the Ad-Hawks would effectively 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 low-earth orbit satellites. The objective of the actively developing project is to provide cellular internet connectivity across the globe and particularly for rural and developing areas that have 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 opportunity 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 project progresses [5].

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 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 UAS whereby only one Starlink satellite signal reception dish would be necessary.

iii. Cell-Booster Backup

In the event of a wildfire, the firefighting command would contact their first responder network to request an existing mobile cellular solution. Such services are not always readily available. For example, AT&T FirstNet's COW can take up to 14 hours to arrive and become operational, leaving firefighters without connectivity for this entire period. Considering wildfire operations cease through the night, this 14-hour delay may lead to even longer response times for network-enabled resources. In anticipation of this waiting period, the Ad-Hawk Network 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 range for regular devices.

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 [6]. The next component for this package is an omni-directional antenna paired with a signal amplifier to establish communication with distant cell towers that are out of reach for traditional antennas found in regular communications devices. This arrangement can be modular in form, 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 efficiency.

B. Aeronautics & UAS

i. Flight Conditions

Often, large-scale fires can generate abnormally high winds and develop microclimates that create hostile and unpredictable atmospheric conditions. These microclimates have been known to create strong winds commonly sustaining around 30 mph and at times inducing up to 140 mph gusts [7][8]. The air has exceptionally low relative humidity and thick smoke often severely limits human visibility. Thus, reliable and resilient UAS designs need to be employed when used in such debris-ridden and highly volatile airspaces.

ii. Mission Parameters

The Ad-Hawk Network has two subsets requiring UAS solutions: the NEST and network-extending UASs ("Ad-Hawks"). The NEST will be mounted upon a stationary UAS located at the fire management's base of operation. Because the NEST acts as an internet connectivity booster for an existing signal, the primary objective of the NEST UAS is to prolong flight time. If relying upon the supplemental cellular boosting package, the NEST UAS will bear additional components and will require a heavier payload capability.

An additional consideration is the power consumption of the UAS. If the NEST UAS is forced to land to change batteries it could significantly decrease the area of connectivity while grounded, potentially causing the Ad-Hawks to lose internet-enabled connection for the Wi-Fi signal during these battery swaps. If the NEST UAS has a tethered power station on the ground it is plausible the UAS will be able to hover airborne indefinitely.

The Ad-Hawk UAS will carry equipment that will receive internet connectivity from the NEST in addition only to Wi-Fi-emitting hardware. Thus, the Ad-Hawk UAS will have a lighter payload than the NEST. However, this UAS will likely be deployed near the fire line, meaning the Ad-Hawk UAS must be able to operate in above-average ambient temperatures, gusting winds, and smoke-filled air. The Ad-Hawks will directly interact with the fire line ground crews, so crew safety is of paramount importance. This requires the UAS to be stable in relatively high sustained winds and gusts, and capable of operating in relatively hot, dry ambient temperatures with floating embers in smoke.

iii. Fixed-Wing UAS

The viability of using fixed-wing UAS was explored for its more efficient lift production and generally superior flight time when compared to rotary UAS. By design, fixed-wing aircraft are more stable than rotorcrafts, especially in high winds, and are capable of landing without power. These are useful advantages, but fixed-wing UAS do have several limitations. Fixed-wing aircraft need long runways or open flat areas to land. The forested environment in which firefighters operate makes it difficult logistically to operate these UAS. Fixed-wing UASs require more involvement from UAS pilots as well, meaning many pilots would be required to maintain a network. Additionally, payload capacity and volume are constrained on fixed-wing aircraft which is incompatible with the weight of devices required to make the Ad-Hawk Wi-Fi network functional.

iv. Endo-Atmospheric Balloon Satellite

The viability of a tethered helium balloon as a deployable aerial hardware station was explored. The greatest advantage of using a helium balloon is that once inflated and tethered to the appropriate position, it has no moving parts and relies solely on buoyancy to remain airborne. Thus, the balloon may require less maintenance and has fewer points of mechanical failure. Helium is also a fire retardant. However, the helium balloon would be vulnerable to puncture by hot embers being carried by the wind. In such a case, the equipment onboard would almost certainly suffer significant damage and be rendered nonfunctional thereafter. For this reason, the helium balloon would not be optimal for usage in a wildfire scenario—though the concept could prove viable for different use cases.

v. Rotary UAS

There are several significant advantages to using a rotary UAS over a tethered balloon or fixed-wing UAS. The greatest of these is the ease of mobility and maneuverability of a rotary UAS. The VTOL capabilities of rotary UAS combined with power via a tether station offering the ability for indefinite flight time make rotary UAS far superior to comparable fixed-wing counterparts. For these reasons, it is recommended that the NEST and Ad-Hawk aircraft be rotary UASs. Currently available off-the-shelf products that fit the criteria of the project were researched and the following rotary UAS were found to have adequate performance for either the NEST or Ad-Hawk role.

The Alta X is a quad-motor rotary UAS produced by Freefly Systems in Woodinville, Washington. The all-carbon fiber-reinforced nylon body lends to the UAS's 22.92 lb. lightweight design. The key features include its 35lbs payload capacity, long-range data link, vibration-dampening technology, and folding to half size for storage. The Alta X's flight time is between 50 minutes with no payload and 11 minutes with a 35lbs payload. The Alta X can operate in winds between 15 and 20 mph at an altitude of 13,000 ft [9]. Utilizing either a tether at the firefighter's base of operation or the loop deployment method for battery swapping would allow the Alta X to fill both the NEST and Ad-Hawk roles. The base model with batteries and equipment will cost approximately $20,000. The special Blue UAS model for sensitive Government agencies' applications will cost approximately $31,000. Freefly Systems offers numerous ways to customize the Alta X with different sensor suites, cameras, and body accessories.

A potential solution to extending Ad-Hawk flight time is to use a hybrid petroleum/electric rotary UAS. A gasoline engine would generate electricity to power the lift-producing electric motors. A unique advantage of hybrid UAS is that there is no need to recharge or replace batteries and it only takes a few moments to refill the gas tank. Skyfront's Perimeter 8 is a commercially available hybrid rotary UAS that has many of the characteristics desirable for an Ad-Hawk UAS [10]. The Perimeter 8 can fly for three hours with a 4 kg (8.8 lbs.) payload and for one hour under the maximum payload capacity of 7.5 kg (17 lbs.). The Perimeter 8 has a maximum operating temperature of 45°C (113°F) and has stable flight tests in wind speeds up to 35 km/h (25 mph). A base model Perimeter 8 costs $46,800 and has several upgrades available including the Perimeter 8+ upgrade package for an additional $10,000. The Perimeter 8+ upgrade would allow for two hours of flight with a 7.5 kg (17 lbs.) payload and would increase maximum payload capacity to 10 kg (22 lbs.) with a one-hour flight time. The Perimeter 8+ maximum operating temperature is 50°C (122°F) and a maximum altitude density of 4,000 m (13,000 ft).

vi. Deployment Options

There are three proposed methods of deployment for the Ad-Hawk UASs. The first method is stationing an Ad-Hawk in a single location and periodically taking off in short durations when Wi-Fi is needed and then recharging/swapping batteries as necessary; this method would require a pilot on the ground crew. The second option is similar to the first, except now the ground crew has a portable tether station to provide power to the UAS. This method would increase flight time but requires the ground crew to carry extra equipment to the fire line and limits the mobility of the Ad-Hawk to the radius of the power-tether. The third method entails deploying multiple UAS in a continuous loop along the fire line while strategically swapping batteries at offset intervals such that a stable internet-enabled Wi-Fi signal can be connected to all along the looped flight path. This method could potentially allow for a single pilot to operate the entire Ad-Hawk UAS network while reducing gaps in coverage.

C. Frequencies

FCC and NTIA regulations determine which frequencies can be operated within and their limitations [11]. Any LTE or 5G cellular signal would suffice for Wi-Fi conversion at the NEST, though band 14 (700 MHz range) is proposed as it is exclusive to first responder networks for unthrottled access during emergency response situations [12].

Another option for NEST connectivity is the 12-14 GHz range, which would be available if the system was integrated with Starlink once their network can provide reliable coverage in the areas where the Ad-Hawk Network would be needed most [13].

The ideal output frequency would be on ISM bands, specifically 2.4000 - 2.4835 GHz or 5.725 - 5.875 GHz, as this is the range Wi-Fi operates in [14].

D. WDS Client-Bridges

Finally, the network signal is extended through a web of long-range client-bridging WDS access points that extend Wi-Fi connectivity to extreme distances. Using a point-to-multipoint method, one transmitter WDS AP can bridge connectivity to multiple receptor WDS APs located on a fleet of UASs. Each Ad-Hawk UAS will carry two of these wireless bridge WDS APs and a long-range outdoor router. One of the WDS APs serves as a transmitter, the other as a receptor, enabling each Ad-Hawk UAS to receive connectivity from the NEST or another Ad-Hawk aircraft and then relay it on to further Ad-Hawk aircraft if required. In this way, the Ad-Hawk Network is adjustable to the needs of users, as it can work with a single point-to-multipoint connection, a chain of point-to-point connections, or even a web of point-to-multipoint connections. Devices like the EnGenius ENH500v3 wireless bridge could fulfill this WDS AP functionality and many feature a 5+ mile radius [15]. The long-range outdoor router will be wired into the receptor WDS AP in each Ad-Hawk UAS to receive the connectivity that was bridged over and then spread it to devices on the ground over as large a radius as possible.

Due to the amount of hardware involved in the Ad-Hawk Network, and the high likelihood of using multiple disparate hardware manufacturers across the system, there will additionally be a cloud manager located at incident command or on the NEST. This cloud manager integrates all hardware into one virtually managed network controller, ensures the security of the network, and can work with devices from multiple manufacturers through API integration.

E. SIM-Enabled Modems/Routers & Antenna

The NEST UAS payload will include a SIM-enabled modem/router which connects to the internet via cellular signal using a SIM card—the SIM card could be tuned to band 14 for emergency services. This SIM-enabled modem then converts the cell signal received into a Wi-Fi signal output. The router device then directs internet traffic routing the IP addresses to the correct destinations. 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 R1900 [16].

F. Cloud Managers

A cloud manager offers the ability to monitor and maintain the private network the Ad-Hawk Network would create. The implementation of this service would ensure the security and cohesiveness of the network by providing an all-encompassing interface through which each access point and client could be managed in real-time. 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.

G. Power Requirements

The power systems will vary based on the specific hardware that is used and, in the case of the NEST, the configuration as well. If the NEST is in the mobile cell tower configuration, it is estimated to consume 41 watt-hours of power under maximum load with the investigated hardware. If it is in the static cell tower configuration, the max consumption nearly doubles to 94 watt-hours from the addition of the cell booster and extra equipment necessary for the modem router combo. The Ad-Hawks are estimated to consume approximately 40 watt-hours of electrical power between the router and the two WDS bridges it requires.

The suggested wiring of the NEST in both of its configurations are very similar. In the mobile cell tower configuration, the modem router device can be powered straight from some power source (discussed later), or more likely with a voltage regulator in between. The WDS bridges are powered through POE only, so there must also be a PoE injector between them and the power source. The injectors may also require a regulated voltage. The only difference in the static cell tower configuration is the need to power the cell booster. The power source again will send regulated power to this device.

The router on an Ad-Hawk will be powered directly. A PoE injector will also be necessary to power both of its WDS bridges. Ideally, this would be a single injector with dual PoE ports. A router that provides PoE capabilities may also be commercially available though there are fewer options available in that regard.

One of the greatest limiting factors of rotary UAS is the battery draining quickly, resulting in UAS having a short flight time. The flight time decreases further as the payload weight increases. For example, the Freefly AltaX UAS has a maximum flight time of approximately 59 minutes but flying with full payload (~35lbs), the AltaX can only fly for approximately 20 minutes. A solution to increase the flight time is to tether the UAS with a power cable. In theory, a tethered UAS could fly indefinitely as long as the ground station is transmitting power. There are several UAS power tether manufacturers. Elistair is one such company that produces UAS power tethers that fit the required parameters of this product [17]. Elistair makes the Safe-T 2.2 UAS power tether for maximized flight time extension, while still being able to mount the Safe-T 2.2 in the bed of a standard one ton truck. Elistair also produces an even lighter and more mobile power tether called the Ligh-T 4 tethering station. The Ligh-T 4 is lighter, more compact, and has an ergonomic handle for increased mobility—all of which are desirable characteristics for a tether station that could be paired with an Ad-Hawk UAS [17]. The flight time of an Ad-Hawk UAS with one of these Ligh-T 4 tether stations would likely vary greatly depending on the total weight of the payload. Experimentation using the exact equipment and configuration of an Ad-Hawk with the Ligh-T 4 would be necessary to determine the actual improvement of UAS flight time. In theory, the tether station could also provide power for the network connectivity hardware. Additionally, the tether station has the safety benefit of preventing the UAS from flying beyond the tether's radius in the event of gusting winds or receiver malfunction.

Alternatively, instead of a tether, a separate battery to power the network hardware could be used. This has the advantage of the network not having to power off while changing the UAS's battery and saving its power exclusively for itself. But there is the disadvantage of adding additional weight to the UAS, decreasing flight time. Weight is a significant concern for the additional battery. With the hardware investigated, it would be necessary to find a battery of at least 24 volts because of the POE injectors. This battery would also need to have dense enough energy storage to allow multiple UAS battery changes before the signal equipment battery has to be changed. If the equipment battery has to be changed as often as the UAS battery, then having separate power sources offers an effectively negligible advantage over powering the entire system with the UAS battery. The balance between power capacity and weight of the extra battery is an area needing more thorough investigation before the design is finalized.

VII. Theory & Testing

A. Testing Procedures

Due to insufficient funding and time, comprehensive testing was not completed. Although not fully through, two preliminary proof of concept tests were conducted. The following rudimentary testing procedure was followed to prove the concept. The primary focus of testing was to verify functionality of the individual devices and demonstrate integration as an ad-hoc network. Further testing would be needed to verify complete system functionality.

1. Connect external battery and insert SIM card into Modem/Router (MR) device.
2. After M/R device has booted, connect to it with a laptop and ensure internet connectivity.
3. Download a generic PDF via internet while tracking download time with a stopwatch and note PDF size.
4. Upload the same PDF to a cloud source and use the stopwatch to record the upload time.
5. Find a generic video on the Internet, set the resolution manually, attempt to stream it, note any buffering, and record success or failure.
6. Run a generic internet speed test 5 times and record the average download speed.
7. Connect one WDS bridge to the MR (i.e., the NEST) and plug into the same battery as the MR. Also connect a different WDS bridge to a separate router (i.e., Ad-Hawk 1) and connect those to their own battery.
8. With the WDS bridges pointing at each other at close range (1 foot apart or less), connect to Ad-Hawk 1 and run through steps 3-6 again.

9. Connect another WDS bridge to Ad-Hawk 1, attaching it to the same battery, and set up another router (i.e., Ad-Hawk 2) with its own WDS bridge pointing at the previous bridge 1 ft away and again, connect their own battery.
10. Repeat steps 3-6 connected to Ad-Hawk 2.
11. Set up the NEST above the ground on the 2nd or 3rd floor of a building to simulate an elevated UAS.
12. Repeat steps 3-6 again to ensure connectivity.
13. Set up Ad-Hawk 1 at ground level over 100ft from the NEST and repeat steps 3-6 connected to Ad-Hawk 1.
14. Set up Ad-Hawk 2 at ground level over 100 ft away from Ad-Hawk 1 and repeat steps 3-6 connected to Ad-Hawk 2.

B. Validation

The first test had the NEST situated about 30ft above the ground. The NEST had a direct line of sight to both Ad-Hawks, the first of which was placed 143ft away from the NEST, and the second was placed 219ft away from Ad-Hawk 1. A 1.64mb PDF and a 40-second-long 480p video were tested. The PDF had successful downloads and uploads while the video was able to run without buffering in every iteration. The download speeds from the speed tests were consistent at each point as well, all of which can be seen in Table 1.

Test 1	***NEST***	***Ad-Hawk 1***	***Ad-Hawk 2***
Distance (from previous)	0ft	143ft	219ft
1.64mb PDF Download	Success - 14 sec	Success - 15 sec	Success - 16 sec
1.64mb PDF Upload	Success - Instant	Success - Instant	Success - Instant
40 second 480p Video	Success	Success	Success
Avg Download Speed	0.6mbps	0.56mbps	0.59mbps

Table 1 – First Proof of Concept Test Results

The second test saw increased distances of the Ad-Hawks and stationed the NEST at ground level. The same tests were conducted, starting at the NEST, which gave similar results as in test 1. Moving on to Ad-Hawk 1, the download and upload of the PDF was again successful, but with a noticeable increase in the time it took to download. The video ran smoothly without any buffering, but the speed test was a problem. Unfortunately, no data was recorded for Ad-Hawk 2 due to a connection drop, despite repeated attempts no reconnect was possible, which is reflected in Table 2.

Test 2	***NEST***	***Ad-Hawk 1***	***Ad-Hawk 2***
Distance (from previous)	0ft	575ft	-
1.64mb PDF Download	Success - 14 sec	Success - 19 sec	-
1.64mb PDF Upload	Success - Instant	Success - Instant	-
40-second 480p Video	Success	Success	-
Avg Download Speed	0.6mbps	Fail	-

Table 2 – Second Proof of Concept Test Results

The connection drop was likely due to the use of poor hardware and its limited range. Using more specialized equipment should improve this. Interestingly, there were negligible performance differences between the NEST and each Ad-Hawk before hitting the edge of their usable range, where there is expected to be a significant drop-off from jump to jump. One possible reason for this is the relatively short ranges at play compared to the grander scope of the project, combined with the possible bandwidth limits of the SIM card used. These two tests successfully proved the technology can receive a cell signal, convert it into an internet-enabled Wi-Fi signal, and then wirelessly transmit that Wi-Fi signal to another device. This, in turn, confirms the plausibility of the Ad-Hawk Network.

C. Use Cases

This section highlights the effectiveness of the Ad-Hawk Network by retroactively applying it to past wildfire situations. The assessed cases are of significant California wildfires including the Camp Fire of 2018 [18], the North Complex Fire of 2020 [19], the Electra Fire of 2022 [20], and the Oak Fire of 2022 [21]. In each of these use cases, Cal Fire was the primary respondent and thus, the Ad-Hawk Network was retroactively considered within the means Cal Fire had available at the respective time periods as well as anticipated future resource development. The primary resources available to Cal Fire critical to the design of this project were their quantity of Ad-Hawk-sufficient UASs, as well as the number of UAS pilots. Cal Fire currently employs three UAS pilots, with three more currently in training. Additionally, Cal Fire has four sufficient UASs in the form of Freefly Systems' Alta X.

The Camp and Electra Fires were evaluated using fire progression maps due to their notable size. These occurred in higher altitudes during the late summer and early autumn and are notable for a distinct lack of internet connectivity [18] [20]. The North Complex and Oak Fires were smaller and thus evaluated using the total area burned. These occurred during the middle of summer in areas with a relatively greater degree of internet connectivity on average [19] [21].

Lastly, the multi-day assessments only consider where the Ad-Hawk Network could be launched and do not take into consideration the potential positive effects of this project in aiding the mitigation of the fires in real-time. They are simply visualizing the realistic extent of coverage if this system were implemented into Cal Fire's approach.

i. Camp Fire of 2018

The Camp Fire burned over 150,000 acres from November 8th to November 25th, 2018, with total fatalities reaching 85. It remains the deadliest wildfire in California history [18] [22]. It was selected for this assessment not only due to its high-profile news coverage, but its unique characteristics. It began at higher altitudes and burned toward the Sacramento Valley floor. In its initial stages, strong southwestern-oriented winds incited the fire to spread 300 yards each second. From here it burned westward, decimating the small town of Paradise. It initially burned through coniferous timber forests, but as it moved further west it made its way into chaparral and grasslands.

a. Current Resources

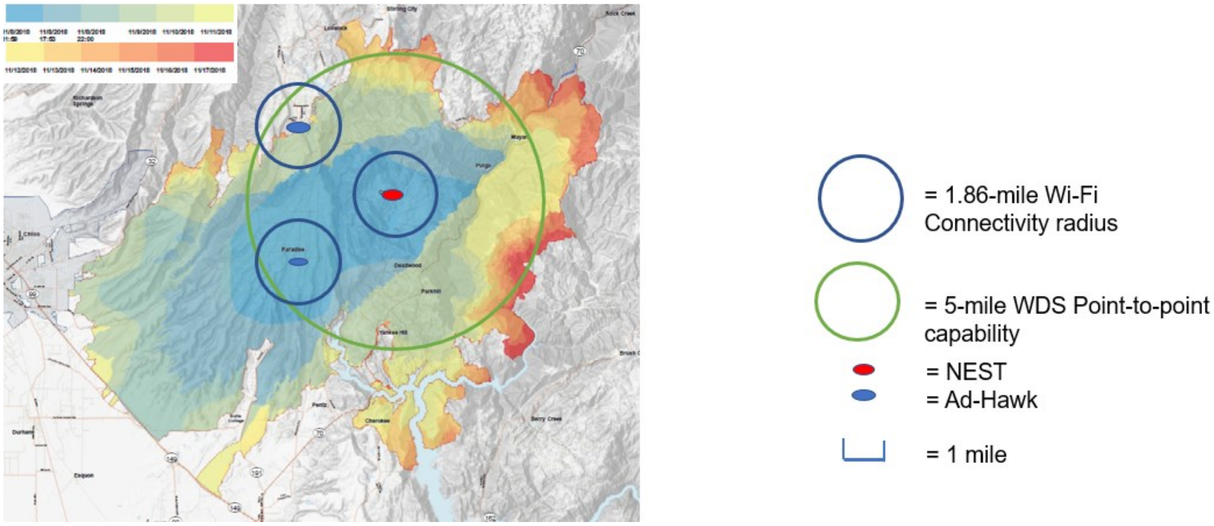

Figure 1 – Camp Fire Map, Day 1 (Current Resource Availability); Figure adapted from [23]

Given the current availability of three UAS pilots and three out of four Alta X UASs owned by Cal Fire, this is a hypothetical deployment scenario on the first day of the fire, highlighted in the darker blue color. The NEST would be located at Concow, a small town in the Sierra Nevada mountains. Two Ad-Hawks could then be established anywhere within the five-mile WDS capability of the NEST. One could be located approximately four miles to the southwest in Paradise and the other in Magalia, another high-priority town to protect during this fire.

Almost the entirety of what was burned on the first day is within the area of the NEST's WDS capability, meaning that Cal Fire could have deployed the two Ad-Hawk UASs anywhere on the fire line over the first day. Additionally, this test shows that the 3.72-mile Wi-Fi diameter of each Ad-Hawk could have been established at the NEST, in Paradise, and in Magalia.

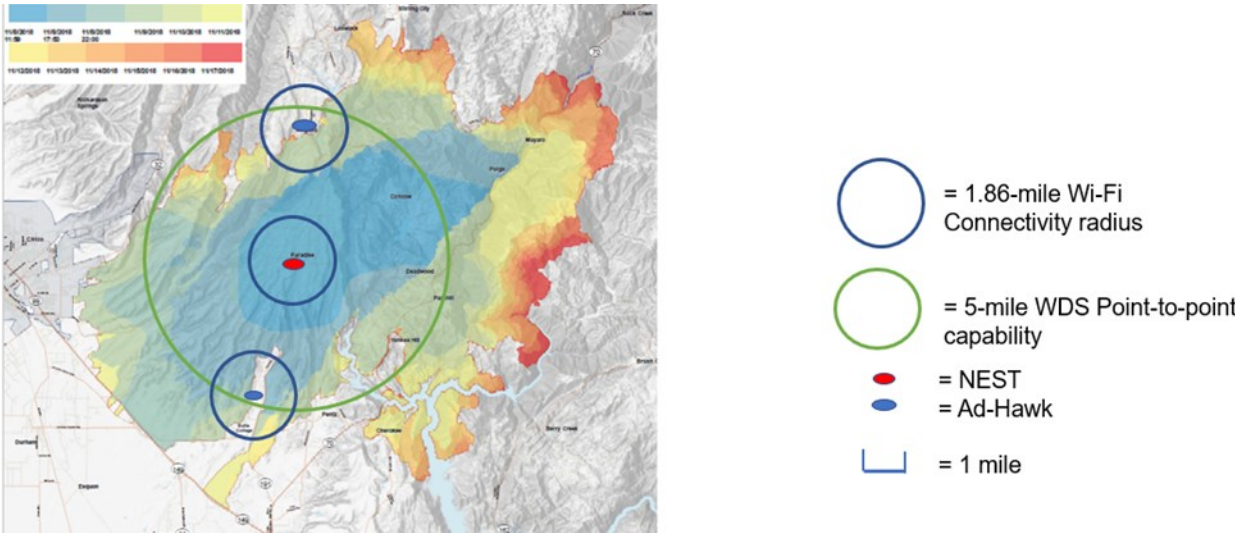

Figure 1.2: Camp Fire, Day 2, Current Resources; Figure adapted from [23]

On Day 2, the NEST could have been moved to Paradise, enabling WDS potential over the area that burned on day two (lighter blue color in Figure 1.2). The Ad-Hawks could then be positioned over high-priority assets Butte Community College and Magalia. This would bring Wi-Fi service to those strategic positions, as well as over Paradise.

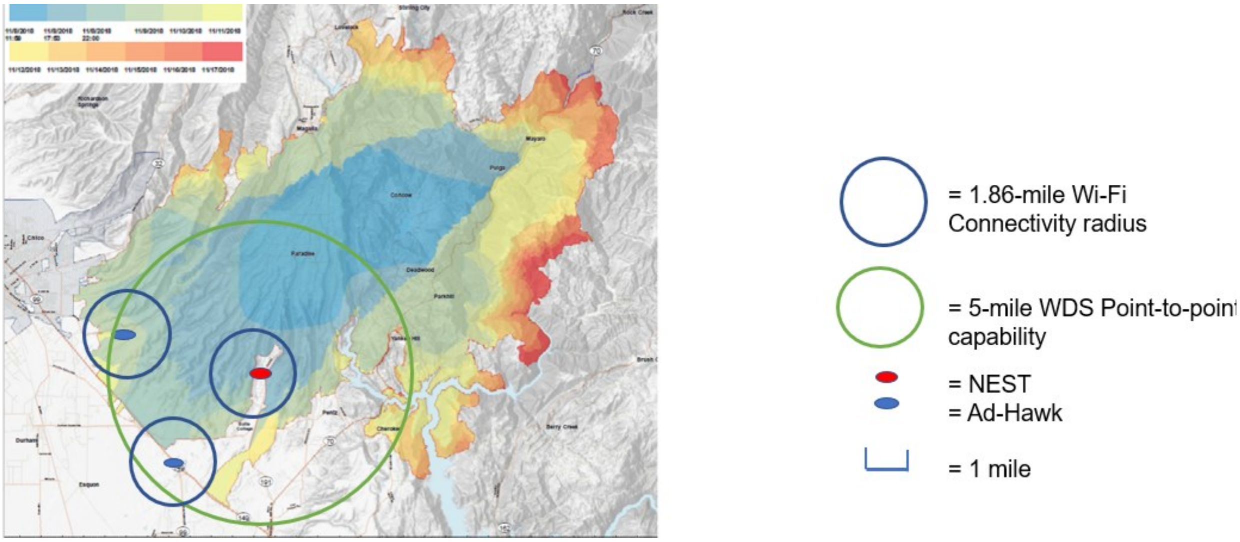

Figure 1.3: Camp Fire, Day 3, Current Resources; Figure adapted from [23]

On Day 3, as the fire continued its move southwest towards Chico and state highway 99, Butte College would offer an optimal location for the NEST, enabling WDS connectivity over the entirety of the fire line. Ad-Hawks would then be enabled to cover valuable assets such as the State Highways 99 and 149 Interchange, as well as Chico.

b. Future Resources

With three more Cal Fire UAS pilots in training, the number of available pilots will soon increase to six. And with the development of SIMO UAS piloting and autonomous UAS swarming, the future is bright for UASs. This next section highlights the potential deployment options of the Ad-Hawk Network given these potential future resources applied to the Camp fire.

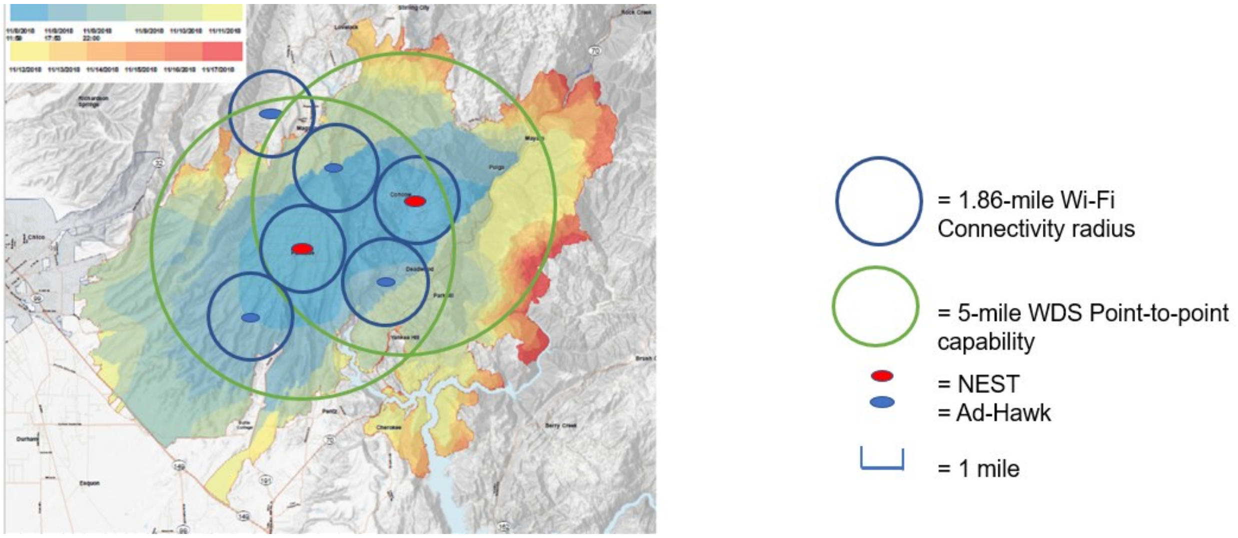

Figure 2.1: Camp Fire, Day 1, Future Resources; Figure adapted from [23]

On Day 1, higher pilot availability would enable deployment of two NESTs, each at Concow and Paradise, with a series of Ad-Hawks hovering over Paradise and following State Highway 70 to Magalia. This would enable Wi-Fi coverage for approximately 15 square-miles of active wildfire, aiding firefighters in search and rescue, evacuation direction and traffic control, updating fire maps in real-time, and communicating with off-site command centers.

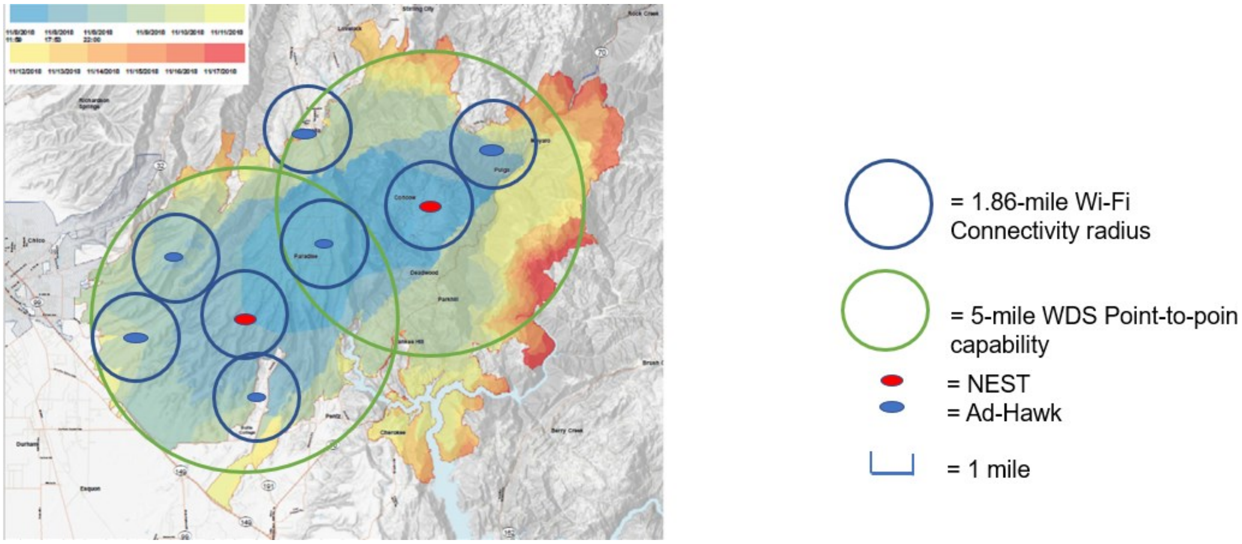

Figure 2.2: Camp Fire, Day 2, Future Resources; Figure adapted from [23]

On Day 2, two NESTs could deploy in Concow and Paradise once again, but with the Ad-Hawks moved down the mountain closer to State Highway 99 as the fire roared towards Chico, Butte Community College, and Magalia.

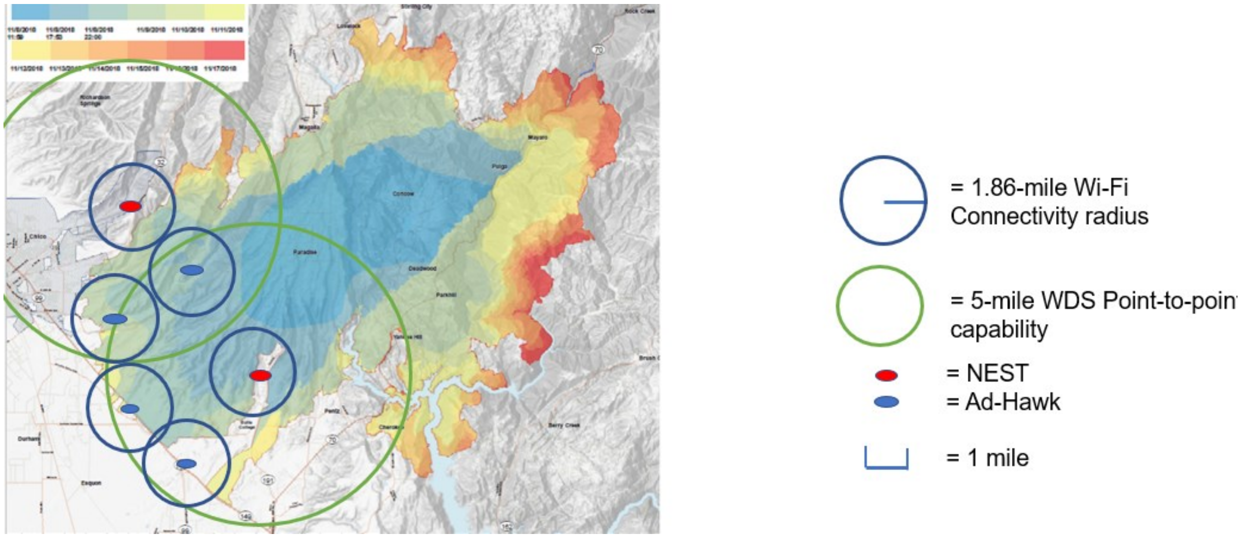

Figure 2.3: Camp Fire, Day 3, Future Resources; Figure adapted from [23]

On Day 3, Two NESTs would ideally be deployed in lower elevations as shown in Figure 2.3, with the Ad-Hawks positioned to increase connectivity in the foothills to prioritize forces closer to State Highway 99 and Chico.

This use case considered the application of the Ad-Hawk Network given the two evaluations of both current and future resources for the infamous Camp Fire. These findings indicate that the potential benefits of implementing the Ad-Hawk Network even with Cal Fire's current resources offer drastically improved connectivity not only as resource availability increases but in their current state as well. This system would significantly bolster connectivity in areas where firefighters need it most – regions with minimal or no cell service. These are the areas that are more prone to wildfires, highlighting the demand for connectivity, specifically Wi-Fi internet over the fire line. Given Cal Fire's current resources, internet-enabled Wi-Fi could not be established over the entirety of the burned area, but it could be in strategic places depending on need. For example, Cal Fire could prioritize Wi-Fi availability for the on-site incident command center, enabling the command center to be positioned in areas previously impossible due to lack of internet and pushing the extent of communication deeper than is currently possible. With anticipated future resources, the entire active burning area can be laden with Wi-Fi, enhancing real-time communications and making current and future technologies accessible. The benefits of this potential infrastructure are clear. Both present and future resources would vastly improve wildfire management's current communications abilities.

ii. Electra Fire

The Electra fire started on July 4, 2022 and burned for three weeks. This was a relatively small fire in comparison to other use case scenarios, having burned around 4,500 acres [20].

a. Current Resources

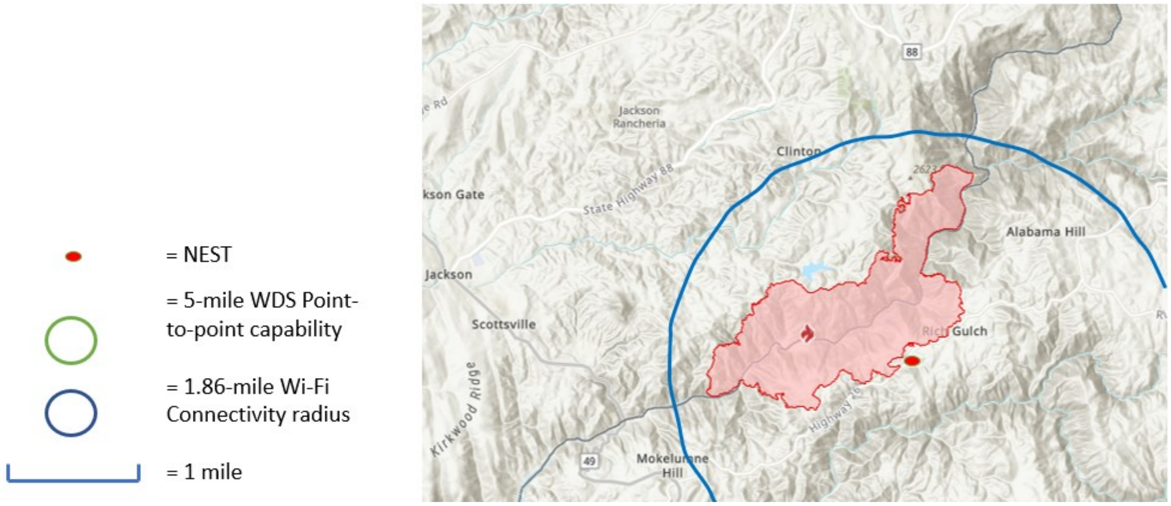

Figure 3.1: Electra Fire, Days 1-21, Current Resources; Figure adapted from [20]

For a smaller fire like this, only the NEST would need to be deployed. The NEST could be launched in the air above State Highway 26 around a quarter mile southwest of the small town of Rich Gulch. This would be the optimal location for the mobile cellular solution. The Wi-Fi signal emitted by the NEST would be sufficient to provide coverage across the entirety of the burned and surrounding area. As can be seen in Figure 3.1, the five-mile WDS capability radius far exceeds the area covered.

In an optional deployment plan, two other Ad-Hawks could be launched to expand Wi-Fi coverage in the areas surrounding the wildfire. One of these Ad-Hawks could be hovering around a mile up State Highway 88 from Jackson, within the 5-mile radius of the NEST's WDS-Bridge capability, given a clear line-of-sight. The third and final Ad-Hawk could be deployed two miles up State Highway 88 from the previous Ad-Hawk, around two to three miles to the northeast of Jackson, and about a half of a mile to the northwest of the town of Clinton.

Given this hypothetical scenario of fire size, geography, and accessibility, the entire fire would be within the Wi-Fi coverage area of the NEST and Ad-Hawks. This successfully fits the design criteria: battalion chiefs could download fire maps in real-time, as well as run simulations and update the common operating picture on-site. This use case assessment was the most promising situation out of the four fires considered. Thus, fires that match similarly to this situation in size and available resources would be optimal for implementing the Ad-Hawk Network.

b. Future Resources

Given the sufficiency of current resources to implement the Ad-Hawk Network optimally in this scenario, future resources would only expand coverage in areas around the fire, not over the fire. However, SIMO piloting and autonomous swarming would still benefit the deployment of the system given the current infrastructure but expanded coverage would not be necessary to meet the design criteria.

iii. North Complex Fire

The North Complex Fire burned in the Fall of 2020 [24]. It is unique in that it was one of the ten largest wildland fires in California history but was actually a combination of two smaller fires. Lightning strikes sparked each initial fire in mid-August but, on September 8th, a strong southwestern wind re-ignited the smoldering fires, crossing containment lines and burned over 300,000 acres [22] [24]. This use case was selected to emphasize the need for enhanced connectivity at the beginning stages of fires to prevent such avoidable catastrophes. This use case is evaluated as a progression due to the size of this wildland fire.

a. Current Resources

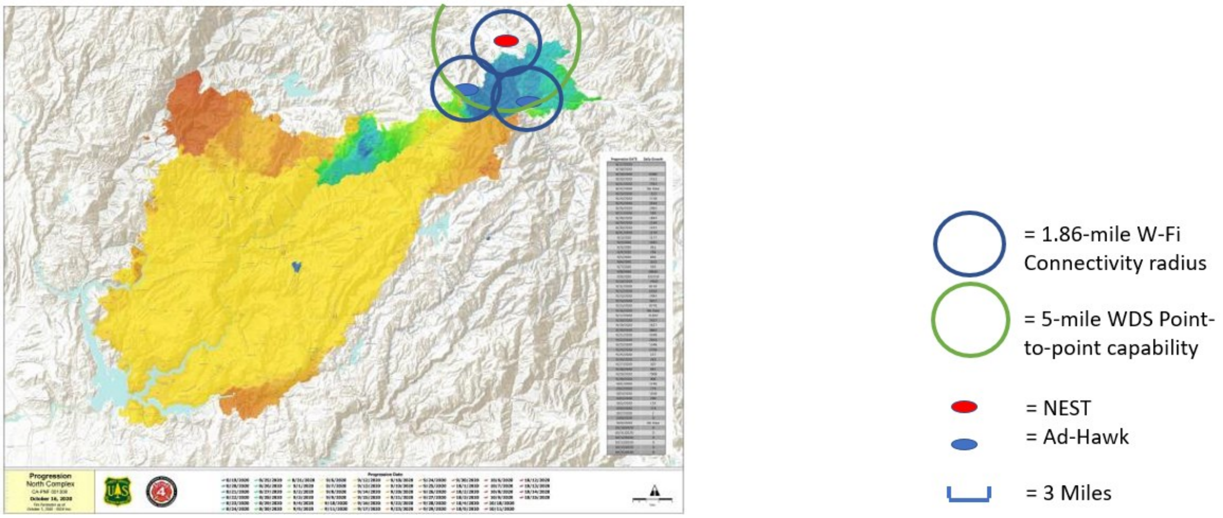

Figure 4.1: North Complex Fire, Weeks 1-2, Current Resources; Figure adapted from [19]

In the first two weeks of this fire, as shown in the areas of dark blue and green in Figure 4.1, two small fires burned in the Sierras of Northern California. Per Cal Fire's current resources, the NEST could be deployed in the small town of Quincy with the first Ad-Hawk deployed three to four miles southwest. The second Ad-Hawk could be deployed southeast of the first, putting both within the five-mile WDS-bridge capability of the NEST. In this arrangement, almost the entirety of the on-ground fire management forces for the initially small fire would have Wi-Fi coverage.

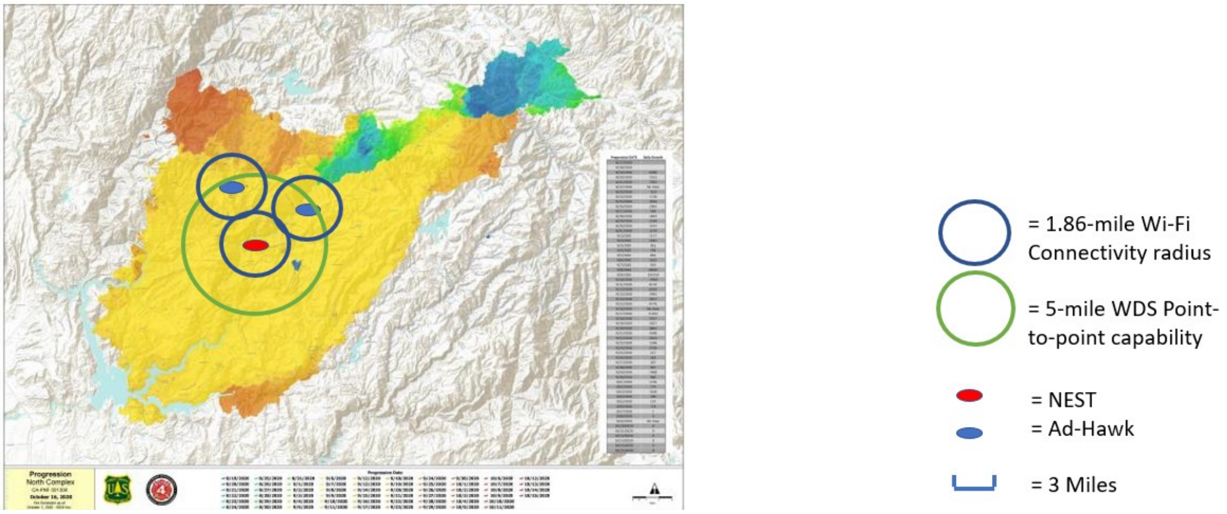

Figure 4.2: North Complex Fire, Week 3, Current Resources; Figure adapted from [19]

Throughout the third week, the fire grew substantially, highlighted in the yellow and light orange coloring in Figure 4.2. Given Cal Fire's current resources, the NEST would be deployable near State Highway 162. Due to the fire size, however, three UASs would not be enough to bring Wi-Fi to the entirety of the fire line. To solve this issue, it is recommended that pockets of Wi-Fi be prioritized for larger fires like those at North Complex and Camp. The baseline this package would offer is Wi-Fi to the areas that most demand the service, such as an on-site command center.

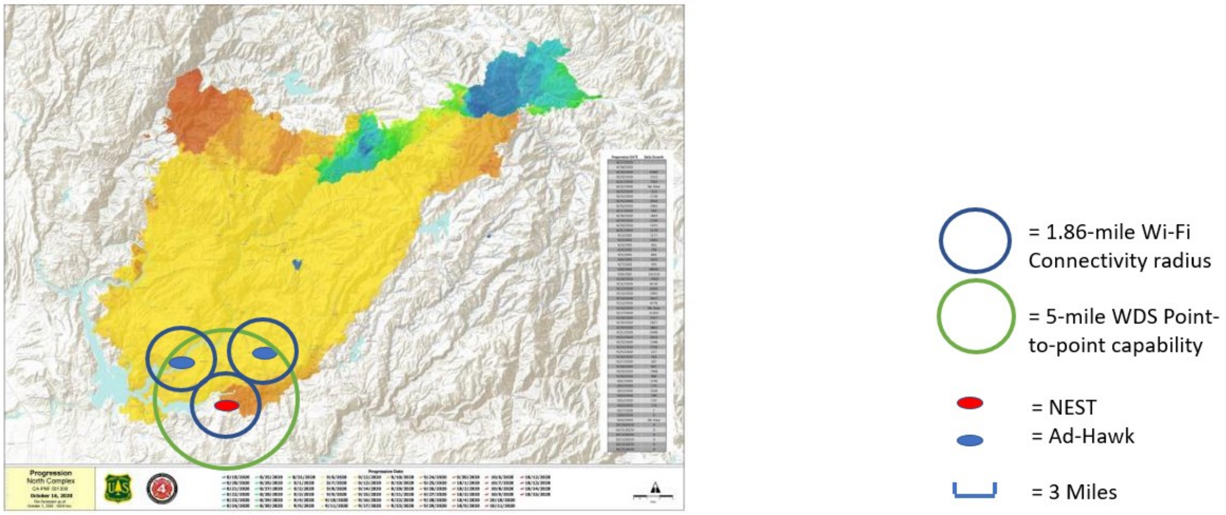

Figure 4.3: North Complex Fire, Weeks 4-8, Current Resources; Figure adapted from [19]

During the final weeks of the North Complex Fire, the fire burned south toward the small town of Oroville, as well as to the northwest toward Tobin. The NEST could be positioned near State Highway 70, and both Ad-Hawks to the North and Northwest around three miles away. Both Ad-Hawks are within the five-mile radius of WDS capability and, without overlap, approximately 33 square miles of Wi-Fi coverage could be generated.

b. <u>Future Resources</u>

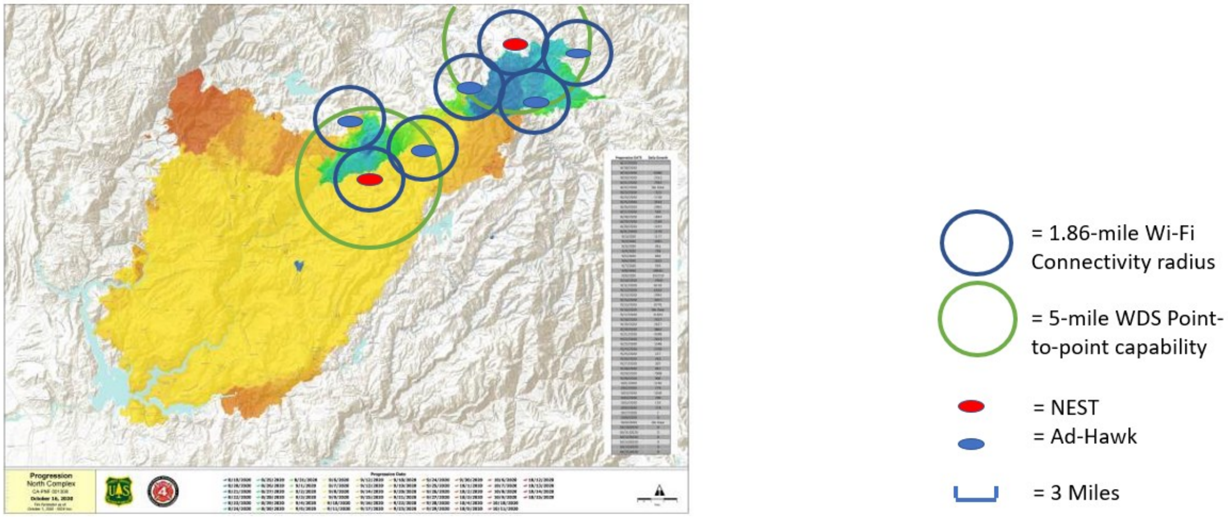

Figure 5.1: North Complex Fire, Weeks 1-2, Future Resources; Figure adapted from [19]

With greater UAS and pilot availability, two NESTs could be deployed over both smaller fires with multiple Ad-Hawks deployed over the fire area, establishing coverage for the entirety of each fire line and beyond.

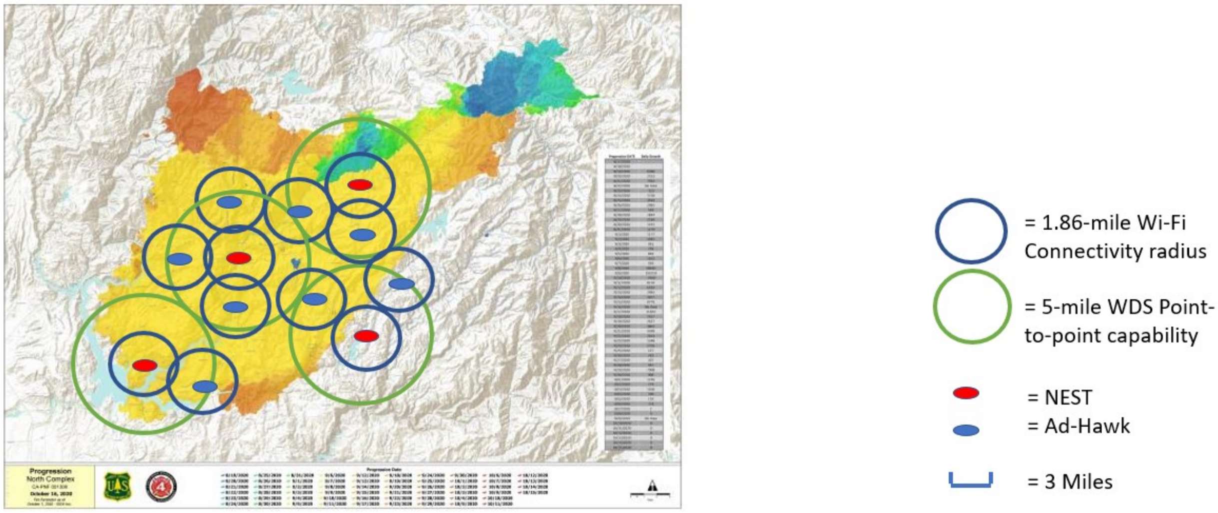

Figure 5.2: North Complex Fire, Week 3, Future Resources; Figure adapted from [19]

With Week 3 seeing the most fire growth, a significant number of NESTs and Ad-Hawks would be required to establish Wi-Fi over the entire burn area. A potential arrangement is shown in Figure 5.2, where four NESTs are deployed alongside eight Ad-Hawks. While the anticipated increase in resources does not translate to full coverage, this would certainly be sufficient for the areas in which fire management would realistically expect to demand Wi-Fi access.

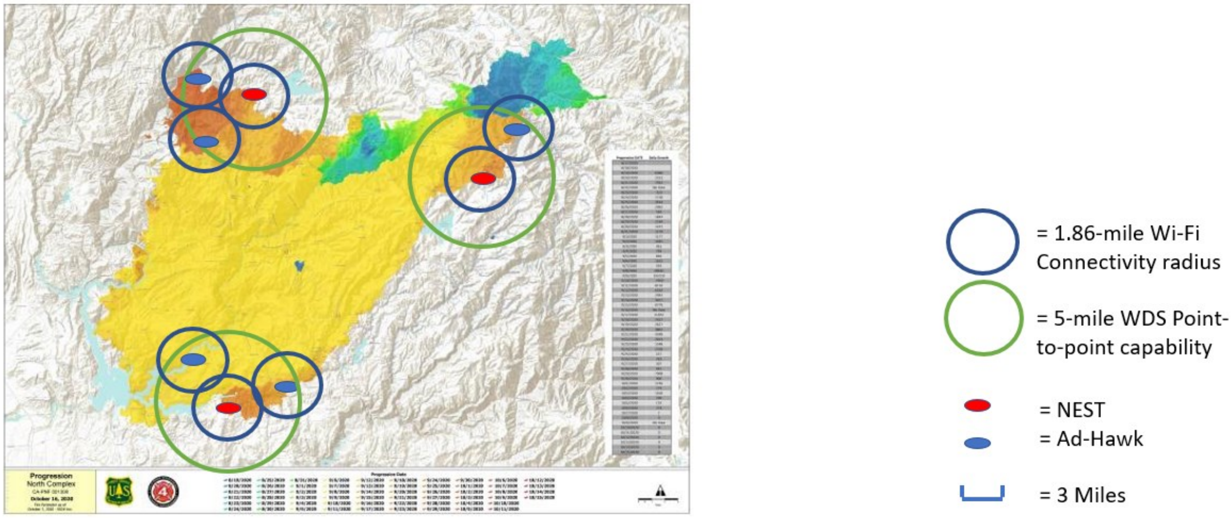

Figure 5.3: North Complex Fire, Weeks 4-8, Future Resources; Figure adapted from [19]

The final stretch of the North Complex Fire occurred over another four weeks, shown in the dark orange colors in Figure 5.3. In this potential deployment option, three NESTs and five total Ad-Hawks would be more than sufficient for the remaining demand.

iv. Oak Fire

In the summer of 2022, the Oak Fire burned nearly 50,000 acres over two weeks. This occurred in the Sierra Nevada mountains in central California, near Yosemite National Park [21]. This was a moderate-sized fire that burned across various forest biomes, from oak-forested foothills to higher-altitude pine forests. With low levels of internet connectivity present, it would be an optimal use case for the Ad-Hawk Network.

a. Current Resources

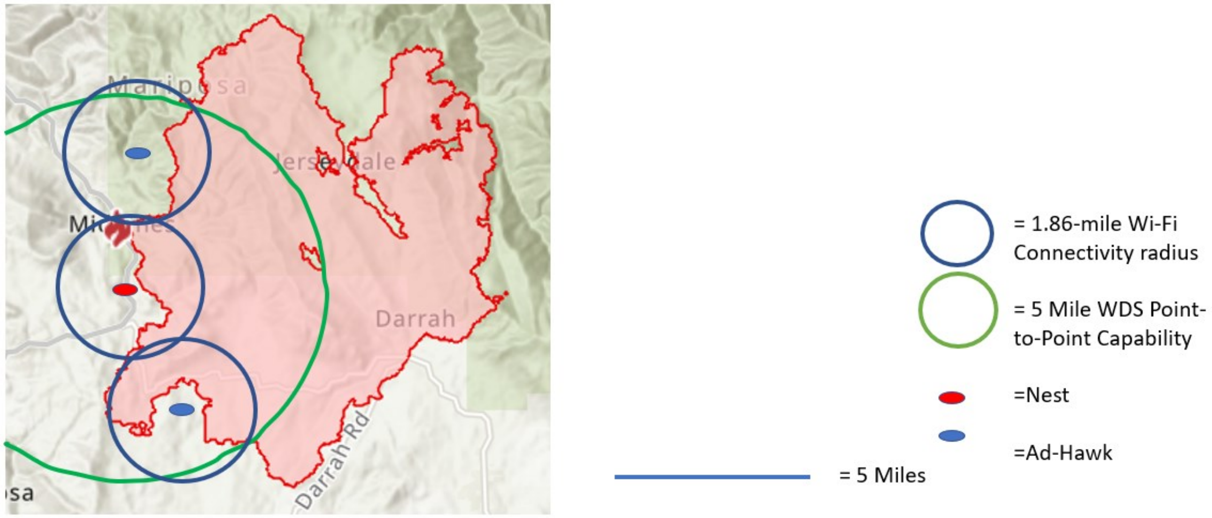

Figure 6.1: Oak Fire, Days 1-16, Current Resources; Figure adapted from [21]

With Cal Fire's current resources, nearly half the fire line is laden with usable Wi-Fi from a single NEST and two Ad-Hawks. In this first evaluation, one NEST is deployed near the town of Midpines, with two Ad-Hawks deployed approximately 3 miles to the north and south, within the scope of the WDS bridges. This would provide fire management the ability to use their applications and communication devices on-site, even in this rough terrain and connectivity-sparse region. Wi-Fi can still be prioritized just as in the larger fires, however, the area of coverage is more comprehensive due to a lesser stretched fire line

b. Future Resources

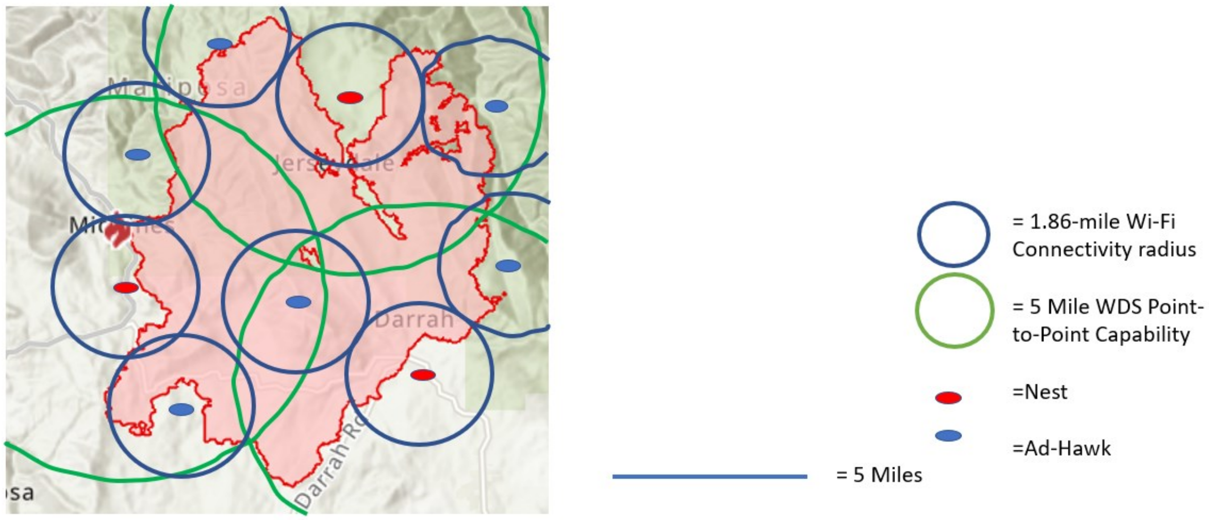

Figure 7.1: Oak Fire, Days 1-16, Future Resources; Figure adapted from [21]

With greater resource accessibility, the entire burn area can have Wi-Fi coverage. In this scenario, three NESTs are deployed and almost the entire fire has Wi-Fi connectivity, shown by the blue circles. Six Ad-Hawks are deployed in this scenario as well. Another factor to consider when deploying the NESTs is where the mobile cellular units can be deployed. The NEST must be near a road where the mobile cellular unit can be dropped off. Stakeholders like Cal Fire would need to set up the network with this fact in mind to be confident regarding which areas will have reliable connectivity.

These use case tests display how the Ad-Hawk Network could be deployed for these four fires in the past given present as well as future resources. Four fires were evaluated: the Camp fire of 2018, the Electra Fire of 2022, the North Complex Fire of 2020, and the Oak fire of 2022. The variables present in each wildfire were numerous, but these four fires covered a variety of cell coverage areas, types of forest (coniferous, chaparral, etc.), altitudes, and degrees of accessibility. The use case tests indicate, given the current resources of most firefighting organizations, small to medium size fires would be the ideal application for the Ad-Hawk Network. However, for large fires, instead of the priority being to bring Wi-Fi internet to the entire fire line, critical Wi-Fi spheres should be prioritized.

VIII. **Limitations**

Though this project has gained interest at NASA Langley Research Center and with potential stakeholders, the authors had a tight ten-week timeframe to both conceive and develop the project. The authors were only capable of conducting simple proof-of-concept tests using personal hardware as outlined in the *Theory and Testing* section of this report. While the concept was successfully proven on the ground, mounting the system on a UAS as intended is not currently permitted due to FCC and NTIA regulations. Aside from getting approval to mount the hardware on a UAS, the project would also require special approval to operate on the frequencies intended, such as ISM, Private, or Emergency Service bands. Advisors on the project believe this use case would qualify for approvals, and temporary authorizations could be granted to allow for testing with the proposed hardware on a UAS. If approved, the data collected with tests at NASA using the proposed hardware could demonstrate why permanent authorization should be granted for the project in the future. The novel aspects of this project would provide a solution to address the lack of internet-enabled Wi-Fi in rural emergencies so modern wireless IoT devices can be reliably used to aid emergency responders.

Physical limitations are dependent on interference between proposed hardware and UAS operational signals. Based on the research conducted, there should not be any interference between the Ad-Hawk Network systems and the UAS flying them. Langley Research Center Spectrum Management would determine if interference may occur and would advise potential solutions in the case interference is detected.

Another limitation is the antenna for the Ad-Hawk router providing usable Wi-Fi at the distances necessary. Due to the range requirements and terrain, a custom antenna would likely need to be created, though an off-the-shelf solution within the required specifications may still be available with an NDAA-compliant supplier.

Final power supply arrangements are also a point of limitation. The Ad-Hawk Network systems require relatively low power, but the varying types of power inputs within the systems would require adapters, adding mass to the systems which should be as lightweight as possible. With more time to research power, a proper off-the-shelf solution could be identified or innovated upon. The physical limitations are not impossible to resolve, but it is unlikely that the research necessary to solve these problems will be conducted without more time or funding.

IX. Future Work

In a future continuation of this project, there are improvements and optimizations that can be made to the hardware. Time prioritization was given to researching network hardware. Over the span of this project, the list of viable UASs was limited. Viable options must be capable of operating in wildfire conditions, have the payload capacity necessary for the network equipment, have a reasonable amount of flight time, and be NDAA compliant such that the team could conduct experiments using NASA facilities and resources. Another aspect of research is the consideration for the total Wi-Fi coverage. This would involve analyzing how different obstructions (e.g., trees, mountains, ambient smoke, etc.) will affect the Wi-Fi signal strength. Transmission power also needs to be investigated to optimize the ratio between Wi-Fi coverage radius and UAS flight time. Further research into an off-the-shelf option for a project-compatible antenna is warranted. Additionally, the development of a custom antenna within FCC restrictions could also be done to ensure the correct coverage pattern for first responders depending on a strong, stable Wi-Fi connection on the ground. Once all the hardware devices are finalized, it will be possible to determine the exact power requirements and necessary cable connections for the project.

There are a couple of software items that will make the system much easier to use. Firefighter organizations do not have many certified UAS pilots, and this system may require several pilots for even medium-sized fires. Current FAA regulations limit one pilot to operating only one UAS at a time. Therefore, software that legally enables a single pilot to control multiple UASs would allow Ad-Hawk to be used more frequently and effectively in much larger fires. For network devices, some form of cloud manager that works with a variety of hardware needs to be found or developed. This software will create a centralized location to monitor the analytics. It will also help reduce network downtime due to technical issues by giving operators a way to troubleshoot without dropping the rest of the network and making testing changes easier for the end user.

In addition to hardware and software, the proper approvals need to be acquired. The process to get hardware approved must be initiated, and for anything not approved, alternative devices must be found and submitted for approval themselves. This hardware must also be reviewed by Spectrum Management to ensure its frequencies will not interfere with UAS operations. Next, the hardware will need to be procured. Then, to be able to legally test this hardware on a UAS, temporary approval from the NTIA and FCC will need to be acquired through Spectrum Management. Finally, assuming the tests are successful, the team could submit a proposal to the NTIA and FCC to permanently authorize a UAS to emit a usable Wi-Fi signal from the air.

X. Conclusion

In discussions regarding future improvements to the wildfire management process, lack of connectivity in rural areas is frequently referenced as one of the most pertinent issues with a distinct lack of comprehensive solutions. This paper proposes a system that, through the utilization and integration of various existing hardware solutions, can not only bring a stable blanket of internet coverage to such areas but can provide internet-enabled Wi-Fi coverage to maximize wildfire management's use of any internet-dependent devices. The generalized structure of this system as presented allows for complete freedom of customization to fit whatever extent of coverage is necessary for the employing organization. Proof-of-concept testing supports the feasibility of establishing an ad-hoc Wi-Fi signal and extending it over a significant distance using existing off-the-shelf hardware. Retroactive application of the Ad-Hawk Network to past wildfires displays the real-world relevance and benefit such a network could provide. Further testing of the network hardware aboard UASs, finalization of compatible and effective hardware, and application for necessary approvals are all further focuses necessary to enable the real-world adoption of this system in the future.

Acknowledgments

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