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A Study of 5G Cellular Connectivity to Unmanned Aerial Vehicles

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A Study of 5G Cellular Connectivity to Unmanned Aerial Vehicles

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

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by
Jackson Peter Murrin
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Accepted by:
Dr. Fatemeh Afghah, Committee Chair
Dr. Kuang-Ching Wang
Dr. Linke Guo

Abstract

The market of unmanned aerial vehicles (UAVs) has seen significant growth in the past ten years on both the commercial and military sides. The applications for UAVs are endless and options by manufacturers allow users to modify their drones for their specific goals. This industry has opened up the excitement of piloting vehicles in the air, photography, videography, exploration of nature from a different point of view and many other hobbies assisted by the emergence of UAVs. The growth of this industry coincides with the roll out of new 5G cellular network technology. This upgrade in cellular network infrastructure allows users higher bandwidth, lower latency, more devices per cell and higher reliability. This has created the question, is 5G suited to support UAV activity? Potentially allowing for two-way transmission of images, videos and data between ground users and the unmanned aerial vehicle. There are many challenges that are presented in flying under these communication conditions which need to be explored such as signal reliability, especially in rural areas, the effects of rapidly changing altitudes or velocity of the drone and the effects of antennas that are tuned for terrestrial users.

The first of its kind work provided in this thesis, will show results for different UAV experiments on a commercial 5G cellular network in the Clemson, South Carolina area. This is a comprehensive study of both low-band and mid-band 5G cellular coverage relating to UAVs as well as a baseline to existing LTE coverage when available. Featuring first of its kind permission to conduct research on a fully commercial cellular network. This research area is largely new, limited information is currently public on the research into commercial 5G cellular networks supporting UAVs. Other researchers are also starting to collect different key performance indicators (KPIs) for flight signals. Most of their works differ in setup, often using private base stations to give connection, but many of these works will be discussed further in the thesis. LTE and 5G enabled flight allows for a wide variety of applications to use UAVs such as natural disaster assessment, animal poach-

ing surveillance, wild fire detection and prevention, assessing the scene of an accident before police arrive and other more hobby or recreational uses. The end goal is to assure that 5G connection is strong enough to transmit the UAVs real time data, which necessary to help first responders on the ground. When many of the potential uses of a cellular connected UAV are potentially life saving, every second counts and signal needs to be fast, reliable and low latency. Therefore, reliable and high bandwidth communication is necessary for unmanned aerial vehicles to take the next step in real life use cases and to begin to explore the option of beyond visual line of sight (BVLoS) flight and 5G might be the network tools which can get it there.

Dedication

I would like to dedicate this thesis to my parents, Melissa and Warren Murrin for supporting me through every part of my life. The have always encouraged me to pursue my dreams and always give one-hundred percent in everything that I do. I would not have been able to achieve this academic goal without their unwavering support in my quest for higher education.

Acknowledgments

I would like to first and foremost thank the Clemson University Holcombe Department of Electrical and Computer Engineering for the opportunity to study and conduct research with this great department. Acknowledgments should be given to the facilities and students in the Intelligent Systems and Wireless Networking (IS-WiN) laboratory, which provided the proper and necessary tools to complete research. Next, I would like to thank my faculty and research advisor Dr. Fatemeh Afghah, who has guided me through every step of the process in my thesis work. Her knowledge and expertise in the subject matter allowed for me to get quickly involved in the research described in this thesis. Many thanks are also deserved by Research Specialist, Dr. Mohammed Gharib, for his assistance and close guidance within the various parts of research. Research and data collection could not be completed without the assistance of undergraduate students Bryce Hopkins and Andre Koka. Finally, I would like to give my thanks to Dr. Kuang-Ching Wang and Dr. Linke Guo for sitting on my thesis committee.

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Chapter 1

Introduction

Cellular network connection has become a required need in people's day to day lives. It has found a part in all aspects of life: navigation, communication, health, nutrition and leisure. With the advent of 5G technology allowing for speeds 10 to 100 times that seen of LTE and 10 times the devices supported per cell [2], researchers have been able to begin to expand the internet of things (IoT). IoT are devices which have a network that are capable of acquiring and sharing information, often using internet protocol [3]. Within IoT there are many categories of device types including one called flying IoT. One example of these newly connected flying devices are unmanned aerial vehicles (UAVs) or more commonly referred to as drones. UAVs have endless use cases as they are easily operable, start at a low price point and can be adapted for many tasks [4]. For this reason UAVs as an industry are getting lots of research money, which is being given to explore the capabilities of this new flying technology. Drones are now a large part of internet of things as they are able to send real time images and other data points from the air, back to the operators on the ground. 5G cellular networks could allow for the expansion of use of UAVs with more reliable service, faster throughput and low latency [5].

One of the major issues plaguing the western part of the United States are wildfires. These natural disasters take lives, ruin property and scorch the earth. It is estimated that about 400 million hectares are burned every year in wildfires all over the world, but the men on the ground can be aided using UAV technology [6]. Drones are increasingly being researched as a solution to getting valuable real time information to the fire fighters on the ground. These drones can be used to give ground users real time images, thermal imaging through the smoke for hot spots, AI can be used to model next steps of the fire path and other key data points which aren't able to be collected as efficiently or quickly on the ground or in a helicopter [7]. Though this thesis does not deal directly with wildfire work, the research completed helps tie into other lab members work on UAVs being used to help fight wildfires.

1.1 Overview of Issue

Drones have been tested and are used on communication technologies other than cellular networks, such as WiFi, LoRA and WiMAX but these protocols all provide sub-optimal challenges for the communication protocol. WiFi does not offer the range needed for large flight areas [8]. Most normal WiFi networks have a range of about 100 meter with some extended products on the market offering enhanced range of 300 meters to 1 kilometer. But these are often subject to a high amount of RF interference, therefore a very unreliable option, especially when exploring the option of expanding beyond visual line of sight flight. The next option, WiMAX offers poor latency results [9] as well as high interference rates from other devices in the same frequency range. With the widespread adoption of LTE as the cellular network on the future in the early 2010s, no updates to WiMAX have been made since 2013. The final option, LoRA has its positive uses for drone use such as long range coverage but it quickly loses utility with its typical throughput in the single digit kbps [10], no where close to the Mbps speeds needed for real time information transfer of UAVs.

This leaves a deep dive into the possibility of relying on cellular networks to reliably connect to UAVs [11]. To begin with a well studied technology, LTE. It offered researchers a glimpse at the possibility of long range connection combined was decent throughput rates. Unfortunately it seems that LTE does not fulfil latency or reliability standards [12] for real time data transfer. Throughput rates are not typically high enough for live video feed as well as latency levels not sending feedback quick enough. Therefore, LTE is a great option in some flying scenarios but it is not capable for situations where real time data is needed. 5G appears to check all of the boxes with low latency, high throughput rates and large network range. But, challenges arise with the lack of comprehensive studies conducted on this topic, along with many challenges of the brand new mmWave frequencies. This thesis will be an analysis of research on UAVs viability using 5G networks for reliable communication. This is done through various flight tests with KPI collection, which will be thoroughly explained and presented throughout the paper.

The research conducted for this thesis is very unique and some of the first of its kind, with no group ever having permission to collect and then publish results of a commercial wireless network from an aerial point of view. This allows for a whole new perspective on the feasibility of UAV use on 5G networks, being able to collect directly from the source, a commercial cellular network. The other published works that are seen on this topic do the following, use simulated models or set up private cellular networks. The latter of these options is a great way to collect numbers but this poses a problem since the network is set up for the specific test scenario and there are only test scenario created user traffic seen on the network. The results published from private network testing should be assumed as stronger than what is to be expected on a commercial cellular network. Results seen later in the paper will be positive for signal strength and data throughput giving the conclusion that existing commercial 5G network infrastructures are in-fact strong enough to support drones.

Chapter 2

Background

In this background chapter, an understanding of many of the technologies explored and their significance should be seen. It will begin with an overview of many of the keys to upgrades seen in 5G cellular communication over its predecessor networks. The discussion of cellular communications will tie into the next part of UAV communication protocols. Finally, key performance indicators focused on in data collection will be defined with some of their thresholds given.

2.1 5G Cellular Communication

When 5G cellular networks began rollout in late 2018, there was a lot of excitement and many questions within the general public. After four generations of cellular networks, often having differing standards across the globe, cellular network providers finally decided there would need to be standard rollout procedures for this new fifth generation of network. It was decided that 3rd Generation Partnership Project, more commonly referred to as 3GPP would set industry standards for 5G deployment internationally [13]. There were many wild conspiracy theories at the beginning of deployment that made it to the public such as 5G signal waves would cause brain cancer or having a 5G connected phone would cause a sharp decrease in fertility. These claims were based in no scientific evidence but having mainstream news outlets pick up these stories made it an uphill battle from the start for cellular companies to win over consumers. Consumers soon started upgrading their personal devices to include 5G service and many were not impressed with the "upgraded" coverage. This is because of the way in which 5G was originally released to the general public.

From the deployment viewpoint, 5G is separated into two distinct types, non standalone (NSA) and stand alone (SA) [14]. Non standalone is a network which leverages existing physical and virtual network infrastructure along with some some new components along with upgraded programming to improve metrics. This is in contrast to stand alone which incorporates a whole brand new system of infrastructure to create the network.When 5G was first released to the public, only the non standalone was available and this did not show the public much of the potential which 5G offers. This is because NSA mode uses existing LTE infrastructure. It works by pairing a 5G Radio Access Network (RAN) and a LTE Evolved Packet Core (EPC), leveraging the existing LTE infrastructure and giving the carrier more reliable Enhanced Mobile Broadband (eMBB). The non standalone network can see speeds up to 1 Gbps which is still very impressive, but nothing compared to metaphorically taking the training wheels off for standalone 5G. 5G NSA is great steps in reducing latency, increasing bandwidth, increasing reliability of strong coverage, reducing buffering and increasing devices on a cell [15].

To create a standalone network, 5G SA pairs the 5G radios with a 5G core network. This is the creates an ultra fast network with speeds up to 20 Gbps [16]. The stand alone network creates ultra-low latency and a much higher capacity for bandwidth and devices on the cells. The latency of the standalone network is lower among the whole spectrum of bandwidth tested. A key pillar of 5G technology is the inclusion of ultra-reliable low latency communications, URLCC. This is technology which engineers point to when saying that 5G latency will make communication standards jump forward when compared to LTE. The increased statistics can also be seen in uplink which shows a faster rate of throughput across bandwidth as a whole. As well as in downlink, with throughput speeds beating NSA across the tested bandwidth. These metrics are just some of the many key performance indicators showing the superiority of SA over NSA within commercial cellular networks.

5G networks have three distinct different types of bands, low band, mid band and mmWave. These different network types have been rolled out in phases with low band coming to market first and mmWave being the latest and most advanced technology for 5G. Low band 5G consists of frequencies of less than 1 GHz, this technology often uses NSA mode which was covered earlier in the background. Therefore, KPIs on low band are often only marginally better to those seen in LTE [17] The next frequency range fall under 1 to 6 GHz and this is for mid band 5G [18]. This is the focus area of the research in this thesis with the majority of important data collection falling under this threshold. Mid band 5G infrastructure is majority stand alone so this gives a great first impression on how the new 5G networks truly perform. The final band of 5G is mmWave, which is seen in the frequencies greater than 24 GHz [19] This type of signal provides the highest bandwidth with the largest throughput seen on commercial networks. Due to the high frequency signal, directional antennas are needed on both the UE and base station side [20]. The potentials of mmWave are huge offering downlink speeds of up to 2.1 Gbps, but there are many challenges to this technology which need to be overcome before it can be counted on as a reliable connection source. Connection problems for mmWave arise from the need for directional antennas. Just about anything and everything from daily life can effect the signal of mmWave. Physical objects such as buildings, trees, vehicles and humans can weaken signal strength from reaching the [21]. Weather also plays a negative part in signal strength with rain and moisture in the air causing increased attenuation and wind causing vibration of the antennas [22] Therefore, it seems with the present day infrastructure, mid band 5G is the best option to begin using UAVs on a cellular network. Mid band is known for offering much fast throughput and better bandwidth over low band and LTE, while also offering a more reliable solution to mmWave.

One of the reasons that 5G is seen as such an improvement over LTE is due to the massive MIMO improvement. MIMO stands for, multiple-input multiple-output, which is a method of multiplying the capacity of a radio link using many transmission and receiving antennas to improve multipath propagation [23]. LTE used an older technology called frequency division duplex, FDD [24]. 5G has introduced a new protocol for MIMO with larger arrays of smaller antennas. This has shown to allow more users per antenna and boost bandwidth. This is called time division duplex, TDD. MIMO antennas break high data signals into many lower data rate signals and then recombine them at the receiver. It bounces and reflects signal, which makes staying within line of sight less of a necessity for good bandwidth. Overall, this results in significantly increased network coverage, optimized data transfer, increased user throughput and increased network capacity for 5G users.

Another technique 5G uses to increase speed is with beamforming. This controls the directionality of transmissions or receptions of signals on antennas and it improves the signal to noise ratio (SNR) [25]. Beamforming focuses more on directional transmission and identifying the most efficient data delivery path. Working with multiple antennas to change the direction of a wave and weighing the magnitude and phase of the signal to create a targeting efficient signal and then using special multiplexing to output a strong and efficient signal back to the user. It works in tandem with MIMO to improve throughput and connection of 5G networks.

2.2 Unmanned Aerial Vehicle Communication Protocols

Typically civilian drones communicate on the frequencies of 2.4 GHz and 5.8 GHz [26]. One of the frequencies is used for the controller on the ground to communicate with the UAV and the other frequency is used to transmit desired data such as measurements, photos or live video from in air. Therefore, drones are using a radio frequency, RF, protocol to communicate data. This is what is relied upon in line of sight flight which is what is required by the FAA currently for drone operators. This series of data protocols is also called command and control. This refers to communications between the UAV and the ground station which is responsible for the control and management of the UAV [27]. With the research and hopefully trustworthy findings of 5G, beyond line of sight flight might be a reality. Reliable connection with 5G will allow for drones to be operated remotely with no concern for loss of vehicle.

To get into RF communication, drones use either high frequency, HF or ultra high frequency, UHF to communicate [28]. RF datalinks are analog or digital and as said before, but digital is the most commonly used especially for larger files such as video. Most high end drones on the market currently have controllers with a range of 2.5 to 4.5 miles, allowing for exceptional connectivity abilities for beyond line of sight flight if the network connectivity can allow for it. In present day, most drones use local WiFi networks to create communication, which often ends up being a phone hot spot running off commercial cellular networks. WiFi though does not offer sufficient range for long flights, such as beyond line of sight flights. It also does not offer decent latency results for the real time data and inputs which are needed. LTE does not offer reliable connection coverage as well as having throughput speeds far too low for most UAV data transfer, while also having a bad latency issue. With 5G allowing for more devices per cell, drone swarms could also be a possibility on the network, using 5G to communicate with each other and the ground user [29].

2.3 Key Performance Indicators

To get an understanding and baseline of results, a few key performance indicators (KPIs) were selected to focus on. As can be implied from the name, KPIs are important data points which can be observed to draw conclusions from research being done. The first KPI investigated in this thesis upload and download throughput. Upload and download throughput is the speed at which a device can either upload or download data to or from a network and this is measured in megabits per second (Mbps). This is arguably the most important piece of data from the flight tests as this will effect if the drone is able to send and receive real time data from in air. Qualcomm, an industry leader in making wireless communication electronics, says the chips they are currently selling for 5G phones are able to download at speeds of 10 Gbps and upload at 1.6 Gbps while on a fully optimized mmWave network [30], but a typical 5G user will see download speeds around 250 Mbps and uploads at 25 Mbps. A UAV transmitting 1080p quality video will need an upload speed of at least 7 to 11 Mbps, so this is well within expected operating windows for 5G technology.

The next KPI is reference signal received power (RSRP). This a measured power of the signal spread across the band's spectrum and it is given in decibel milliwatts (dBm). The ranges differ for the three different band types of 5G but very minimally [31] so numbers seen in 2.1 apply for both low and mid band 5G. But, the closer to zero the better the power, whereas the further negative the worse power in the signal. A rule of thumb for our testing was wanting to see the results below triple digits. RSRP collection for 5G differs pretty significantly from how it was set up for LTE testing. For LTE, a single reference signal is received by the phone and this is across the whole frequency spectrum and it is called, cell specific reference signal (CRS) [32], which is considered a one size fits all for reference signal. As a paper [33] notes, these signals are one of the key factors in interference within LTE networks as other cells are constantly sending these signals out and interfering with devices. This is in contrast with 5G which uses synchronizing signal (SS) [34]and channel state information (CSI) [35] for their reference signals. These signals offer much more flexibility in terms of deployment and collection modes. They also do not constantly run in the background, they only are collecting when they are called for. Leading to far more energy efficiency and less interference. Reference signals in 5G are also not one size fits all, they differ based upon the different cell frequencies [36]. Therefore, it is not suitable to compare the RSRP values between LTE and the two 5G bands.

Following RSRP examination, is looking at the reference signal received quality (RSRQ). This is the ratio of carrier power to the interference power and this is measured in decibels (dB). As with RSRP, the closer to zero the better the signal. The range is a lot smaller on these values only ranging from around -10 dB for excellent results to around -16 dB for poor signal power. Many

Range	RSRP(dBm)	RSRQ (dB)	RSSNR
Excellent	>-90	>-9	>13
Good	-90 to -105	-9 to -12	13 to 9
Fair	-106 to -120	-13 to -16	9 to 6
Poor	<-120	<-16	<6

Table 2.1: Range of 5G KPIs

industry experts say that for 5G the RSRP is a much better indicator of signal, but it is still good to collect this KPI. As with RSRP, LTE handles this measurement much differently than the 5G counterpart. LTE, also uses channel specific reference signals for RSRQ. LTE metrics often times prefer to look at RSRQ versus RSRP [37], but it once again takes its one size fits all approach. 5G is the same protocol as in RSRP, with the two types of reference signals, SS and CSI. They once again run in the background and are only seen when called upon. Different reference signals are seen from the different cell frequencies [38]. As with RSRP, it is not suitable to compare these metrics side by side with LTE to 5G.

The final major data type collected was reference signal signal to noise ratio (RSSNR), this is a measurement of the power in reference signals relative to the noise in the signal. It is measured in dB and values are positive. The higher the number, the better of a result with ranges from around 6 dB at the poor end to around 13 dB at the excellent end. These values hold very similar in comparing results seen in LTE versus 5G, but there is a difference in the way in which the system records the data.

Chapter 3

Research Design and Methods

The research conducted for this thesis revolves around proving that new 5G network technology is developed enough to support full aerial use. This goal starts with being able fly connected to a 5G network and have constant real time data communication. This goal will then evolve into showing the potential for beyond line of sight flight and drone swarm capabilities. Proving 5G network capabilities is achieved by collecting key performance indicators (KPIs) pertaining to commercial 5G cellular signal from the perspective of a unmanned aerial vehicle (UAV). This was done through various data collection flight trials and data analyzing which will be described through out this section. This work was not completed alone, as there were two other students working side by side with me to complete these data collections. My part of the project involved the majority of dealing with all things to do with the cell phones including, software setup, validation of proper test environment, log file management, file transfer and upkeep of devices. I also contributed to mapping, data set validation and test procedure design.

This research design and methods section will cover the purpose of the study, highlighting the importance of this research to the reader. Next, a deep dive into the hardware and software used in testing will give a proper explanation on how and what were needed to collect KPIs. This will include figures to show what was seen on the software UI as well as how we assembled our test equipment. This will transition into a description of and many figures highlighting the areas in which testing was performed. Finally, the various test procedures are described in detail to allow for the ease of recreation of all experiments.

3.1 Purpose of the Study

This study focuses on the implementation of 5G cellular networks for UAV communication. Proving the ability to use this cellular signal will help make UAVs more accessible for people to fly. Currently there is a problem with having a reliable enough signal to fly and with current communication protocols data throughput is not high enough to send real time photos and videos. Part of this problem stems from cell towers being optimized for ground users. So it is beneficial research to collect information at different altitudes and velocities in air. This information will be useful to commercial cellular companies to begin to optimize consumer networks for aerial purposes. The ability to send real time videos and photos will allow for UAVs to be used for positive things such as helping to fight wildfires [39]. They can be used on the front lines in the danger areas to send real time images and thermal data to firefighters on the ground to determine where is best to move resources without putting people in harms way to check conditions. This can help reduce area burned in fires and give a brand new outlook on how to fight these fires.

3.2 Hardware

Hardware is arguably the most important and most expensive part of the experiments. The hardware allows your data to be categorized as ”real-world” numbers and not just computer generated simulations. The hardware consisted of a drone to fly into the air, cellular devices to collect the KPIs and a mounting device to hold the payload safely on the drone. These components will be described in detail in the following section.

3.2.1 Unmanned Aerial Vehicle

This research involved the use of many key hardware components that allowed for the proper data collection to occur. The most important component was the unmanned aerial vehicle. The drone used for all of the testing was DJI Corporation’s Matrice M30T commercial grade drone, which can be seen in figure 3.1. This is a state of the art, new model UAV which was designed for harsh conditions as well as quality functionality. Some of the features included a 48 megapixel camera with 200x zoom, a 12 megapixel wide-angle camera, 8k photo and 4k video, laser rangefinder good for 1200 meters away and infrared camera abilities. This UAV is truly top of the line for image

Figure 3.1: Matrice M30T Drone

purposes. Other key features include ability to hover on it's own, return itself to home, planning flight paths for automated flight, anti crash technology and water and dust resistant. It also is able to carry payload, which was a necessary task as this research would need to have cell phones collecting KPIs from in the air. It was found that adding the payload decreased battery life but not significantly enough to effect the test procedure to be explained later in the section. The metrics can be seen 3.1 but the important ones include the top speed which is over 50 mph and the battery life being 40 minutes, this can give a further idea of the specifications of this craft. For this thesis, 2 sets of batteries were available allowing for more than enough flight time for all of the test procedures.

The other important part of the UAV set up is the DJI RC Plus controller 3.2. The handheld controller for the M30T boasts a large 7 inch color screen, which allows for users to see flight data such as altitude, velocity and direction clearly. It also allows users to see crystal clear real time images from all of the camera options on the drone, including 200x zoom and thermal imaging. An example screen can be seen in figure 3.3. The controller is also rated as IP54 water and dust proof, as well as -20 degrees Celsius to 50 degrees Celsius, showing the ability to fly with this under any harsh conditions. Battery life on this is about 6 hours, so this allows for many flights without the worry of recharging. Other features on the controller include setting autonomous flight plans,

Category	Value
Max Flight Time	41 minutes
Wind Resistance	12 m/s
Service Ceiling	7000 meters
Maximum Speed	23 m/s
Dimensions	365x215x195 mm (LxWxH)
Diagonal Wheelbase	668 mm
Weight	3770 grams
Max Takeoff Weight	4069 grams
Operation Frequency	2.4-2.4835 GHz; 5.725-5.85 GHz
Hovering Accuracy	Vertical: 0.1 meters; Horizontal: 0.3 meters
Max Angular Velocity	Pitch: 150deg/s; Yaw: 100deg/s
Max Tilt Angle	35 degrees
Max Ascent/Descent Speed	6 m/s; 5 m/s
Max Tilt Descent Speed	7 m/s

Table 3.1: DJI Matrice M30T Specifications

route mapping and setting flight tasks. Overall, it is like having a computer program for the drone communicating real time while in air.

3.2.2 Cellular Devices

To accomplish the task of collecting the ever important KPIs for 5G while in the air, cell phones were used. The phones and sim cards were provided by T-Mobile corporation and only allowed for use on their cellular network. The first phone which was given to the research project was a Samsung S21+ 3.4. This was used in the first few data collections using TEMS Pocket, as will be explained in further sections. This phone was sent back to the commercial cellular carrier's headquarters as it began to develop bugs with the new testing software which was run for the majority of testing. For most of data collection, three different phones were used. Two of which were Samsung S22+ and the last being a Samsung S22 Ultra 3.5. This allowed for simultaneous data collection of LTE, low band and mid band 5G. All of these cell phones were running a normal commercially available android operating system, of the latest release. These phones were straight forward and allowed for easy file transfer of log files with the internal storage being accessible. Battery life was not an issue with these phones being able to run the full test procedure on a normal charge.

Figure 3.2: DJI RC Plus Controller

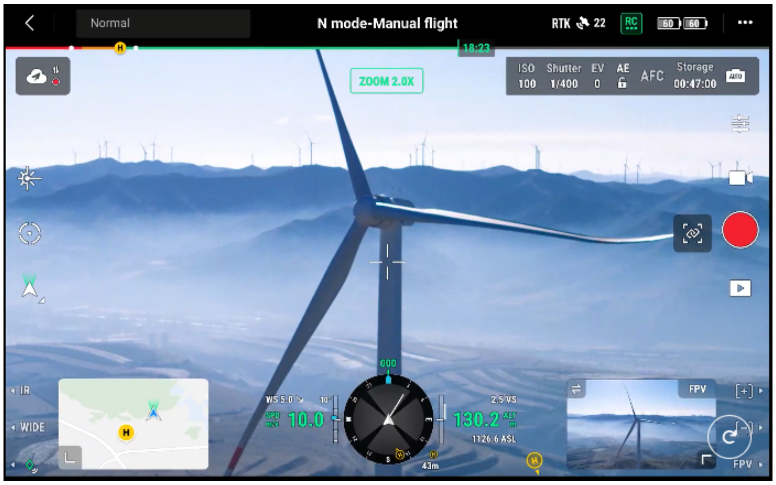


Figure 3.3: DJI RC Plus Screen View

Figure 3.4: Samsung S21+

Figure 3.5: Testing phones: two Samsung S22+ and one Samsung S22 Ultra

3.2.3 Mounting Devices

With this research being so unique and cutting edge, there is nothing on the market to mount multiple cellphones onto the M30T drone as payload. Therefore, a creative solution was needed to be created to complete testing. The first idea brainstormed consisted of mounting a box on top of the UAV using the existing screw holes on the top of the drone which are there for mounting. After a visit to the hardware store, a plastic first aid box was found to fit the dimensions well. Holes were drilled into the bottom of the first aid box with screws, washers and nuts put in for mounting. The inside of the box was lined with bubble wrap to protect phones from any shocks which it may experience while flying, seen in figure The box has enough room inside to fit three phones stacked on top of each other, which allowed for the data collection needed. Phones were also wrapped in a styrofoam sheet for added protection against rubbing against the other phones, this can be seen in 3.6. This setup seemed to provided ample protection in the few short tests completed but once longer test procedures began, it was evident that there was a major problem. When looking at the data for longer test flights, there were large periods of time from seconds to minutes long with missing data, where phones were reporting no signal. It became evident that the phones were overheating and turning off their own signal. 5G in present day inherently causes phones thermal difficulties due to the high throughput of data. The testing set up was not allowing any airflow to the phones as this was a solid plastic box and the added protect around the phones was trapping this warm temperature inside and it created a cycle of overheating. With the size restriction of the box holding three phones, only one gel ice pack was able to be fit inside the box. This was not enough and the overheating problems continued. It was evident than this set up would not work for the procedure as needed.

Knowing that airflow was going to be necessary for keeping the phones in their operational window, it was back to brain storming. Seeing how few options were available on the market, it was decided to create a specialized mount for our specific procedure. The mount measurements were taken for the drone holes and also the phone dimensions. A mount was designed in a CAD software and then printed using a 3D printer. The design consisted of a a base plate which mounted to the done, which had cut outs that the 3 phones could slide into vertically on their side. A top piece was then placed on top of the three phones which held the phones place and this was secured in place using screws and nuts. The design can be seen in figure 3.7, and phones put into the mount here

Figure 3.6: First Aid Kit used for Mounting

3.8. Having the phones out in the clear air proved to provide the needed wind and airflow to keep phones within their operational temperature. The full set up while on the drone can be seen in the figure 3.9.

3.3 Software

This section will discuss the software used within the data collection for this thesis. Two android based data collection software were utilized, starting with Infovista TEMS Pocket and then ending with T-Mobile's RFInisghts for most of the data collection. Along with TEMS Pocket, TEMS Discovery was used for the data processing portion. The original software, TEMS Pocket, was utilized because it is considered the industry standard for KPI collection and allows for highly personalized test procedures. We then transitioned to RFInsights because the company rolled out this software platform in-house and wanted our research to utilize it. This section will begin with discussing the TEMS platform and then the RFInisghts.

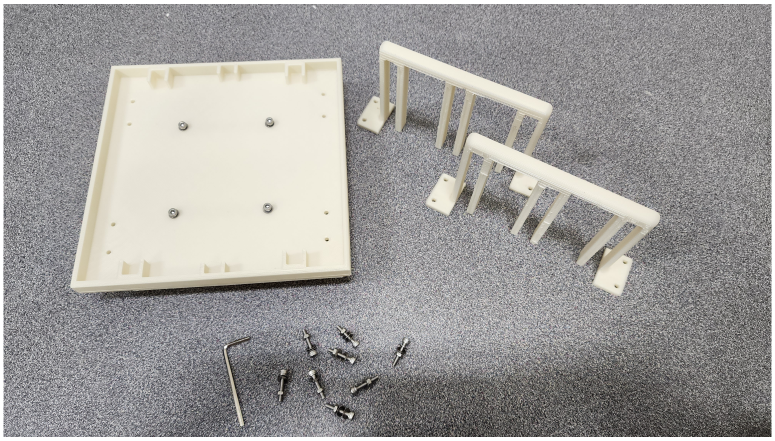


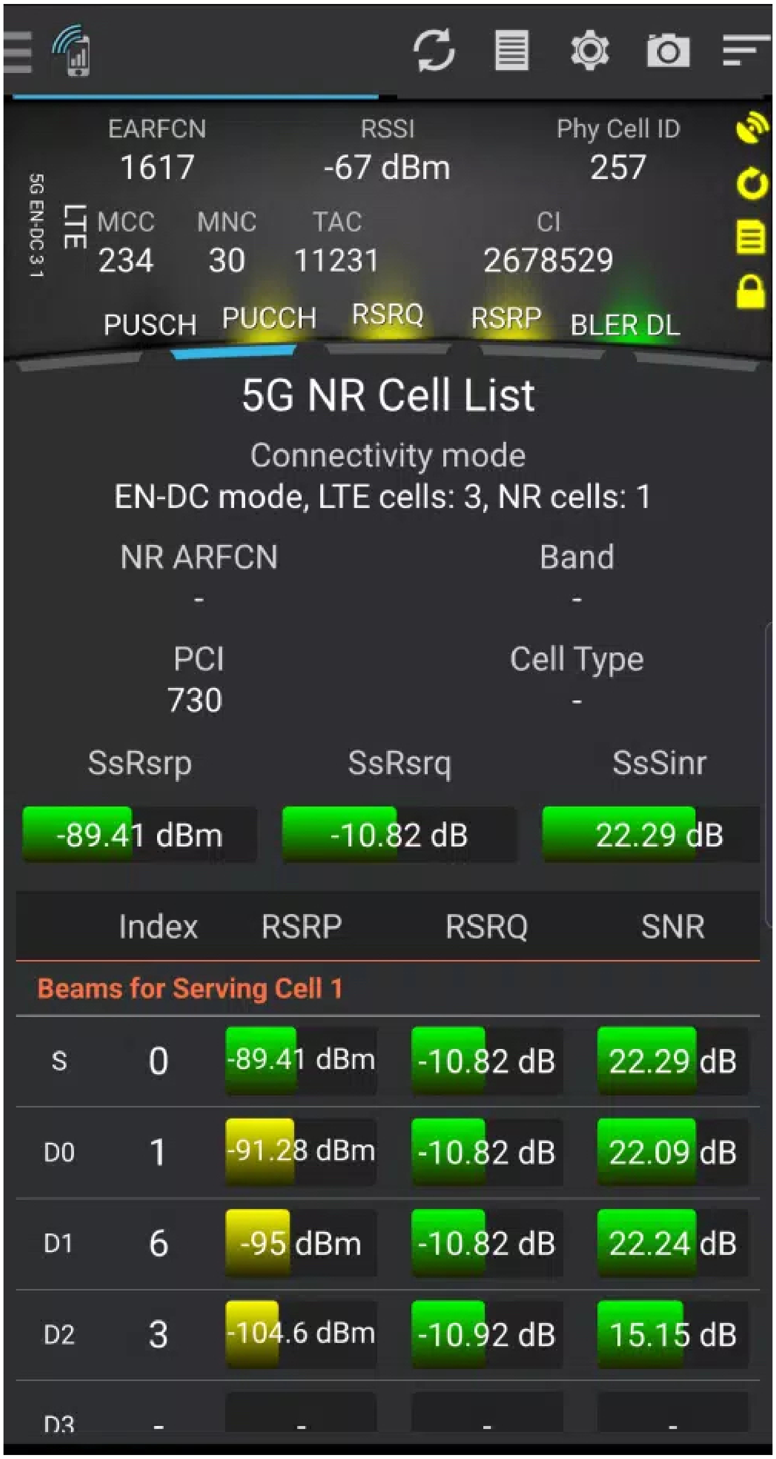
Figure 3.7: Pieces to the 3D Printed Mount

Figure 3.8: Three phones fitting in the 3D printed mount

Figure 3.9: UAV With 3D Printed Mount [1]

3.3.1 Infovista's TEMS Pocket

Two different software platforms were used over the duration of testing. For the first few data collections, Infovista's TEMS Pocket android application was used. This software was loaded onto the S21+ phone. It allowed for a personalized testing procedure with highly specialized user options. To begin TEMS Pocket allows for the user to design a script to run stating exactly when data collection is to start and end corresponding to different testing parameters such as, HTTP put/get, making a voice call, sending an email, sending a text message and running a background application for example. Within TEMS, it collects data at an interval in the hundredths of a second, allowing for lots of data points. This is very important as discussed later. The application itself has lots of information on the real time menu screens as seen 3.10. This is great for being able to identify all towers which the cell phone might be seeing in that area. Unfortunately, this software was only used in the first few test sessions as will be discussed in depth in the results section.



EARFCN	RSSI	Phy Cell ID
1617	-67 dBm	257

MCC	MNC	TAC	CI
234	30	11231	2678529

5G NR Cell List

Connectivity mode
EN-DC mode, LTE cells: 3, NR cells: 1

NR ARFCN	Band
-	-

PCI	Cell Type
730	-

SsRsrp	SsRsrq	SsSinr
-89.41 dBm	-10.82 dB	22.29 dB

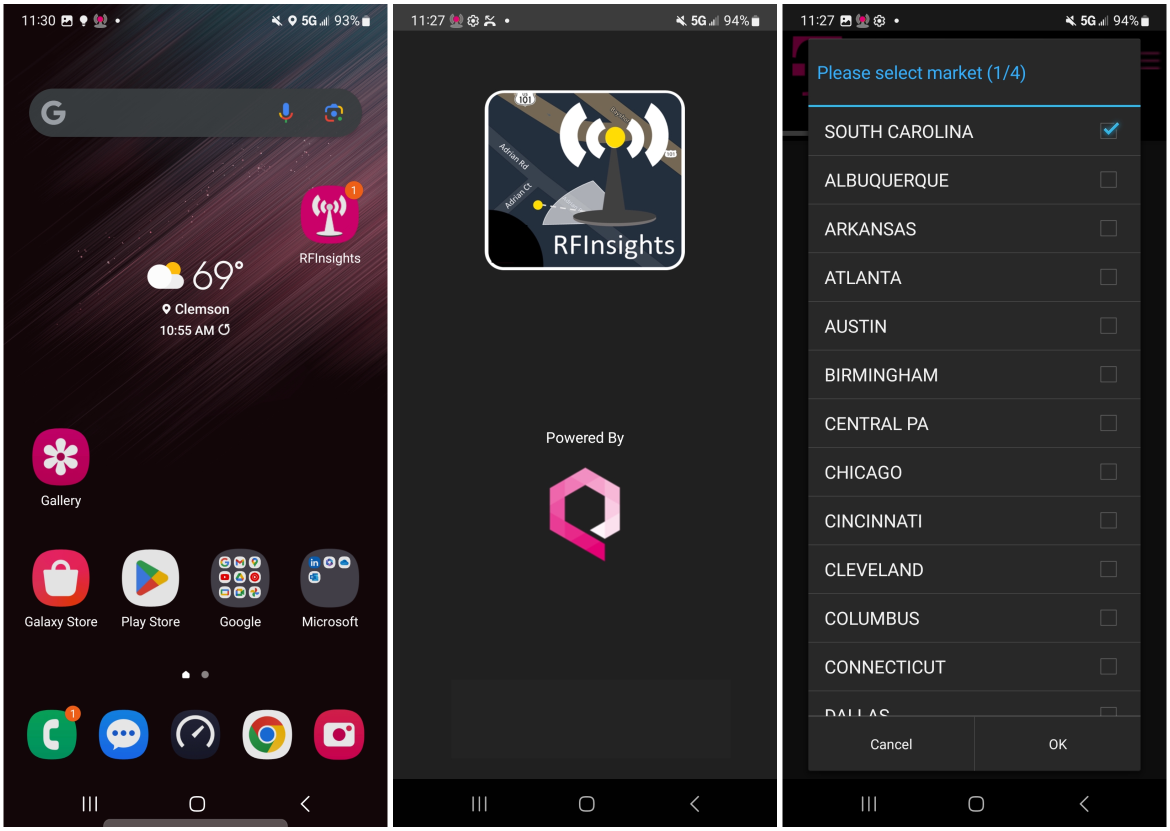
	Index	RSRP	RSRQ	SNR
Beams for Serving Cell 1				
S	0	-89.41 dBm	-10.82 dB	22.29 dB
D0	1	-91.28 dBm	-10.82 dB	22.09 dB
D1	6	-95 dBm	-10.82 dB	22.24 dB
D2	3	-104.6 dBm	-10.92 dB	15.15 dB
D3	-	-	-	-

Figure 3.10: Home Screen of TEMS Pocket

3.3.2 T-Mobile's RFInsights

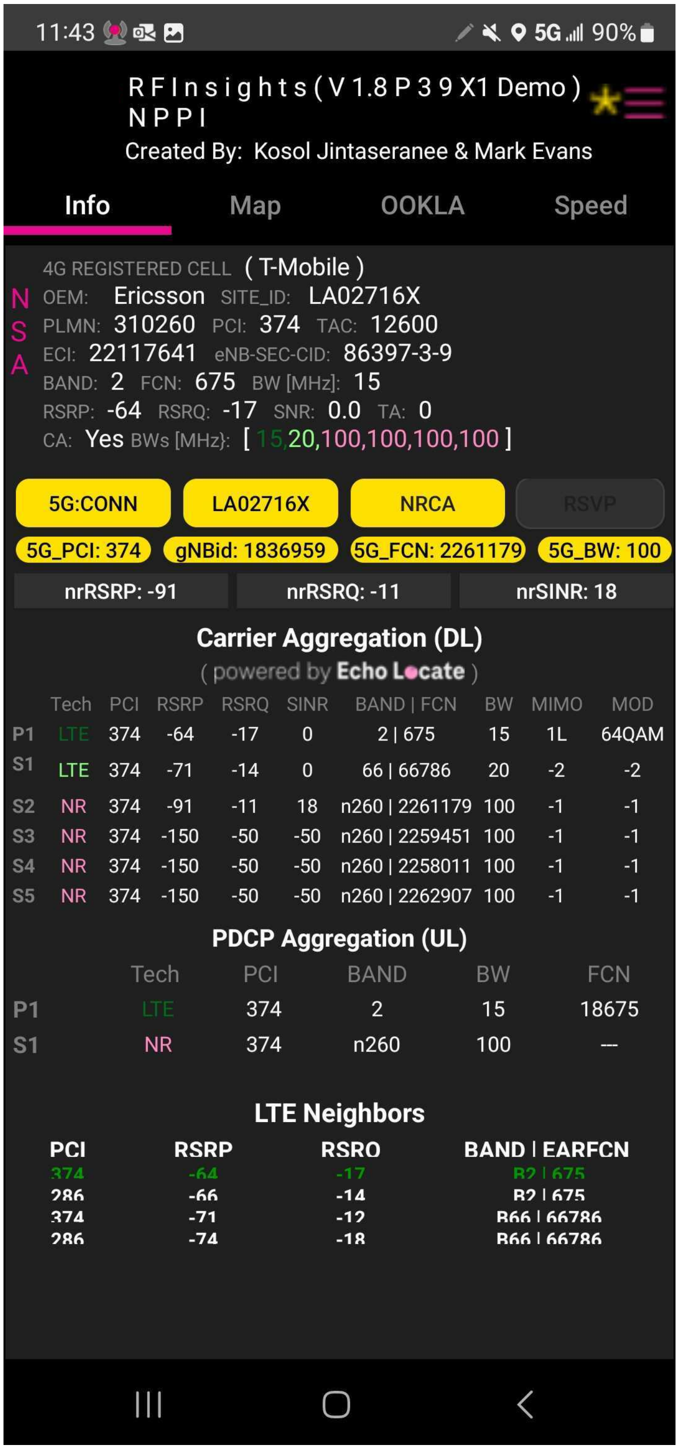
The second software used for data collection as stated before is RFInsights. This android application was developed in house for the commercial network company. For all of the reported data of this thesis, the results come from the use of this application. The software was downloaded and run on both S22+ and the S22 Ultra phones. The start up sequence to the application can be seen below. The user starts by finding the unlisted application on the home screen 3.11a, then a loading screen will pop up 3.11b, the location of coverage will be selected which for this thesis was South Carolina 3.11c and finally the home screen will populate the application. Their home screen has a list of area towers and their ID information which helps to locate which tower the phone is connected to and the bands offered at all area towers 3.12. This application held many very useful capacities, the first is found in the Map tab. The map found here was of the cell phone's surrounding area with all of the 5G cell towers in their exact location, they also have the corresponding low, mid or high band listed on the tower so it is easy to identify the best towers for the testing parameters. This is very useful in identifying towers and planning test flights. The trends tab follows, this is a new capability to the application and it lists the time on each band type in a pie chart, along with carrier aggregation and speed for a 5 minute window in a graph 3.13a. This is useful for understanding which band the phone has recently connected to. The next tab is the speed tab, from this the user has the capability to start and stop upload and download testing and see the corresponding metrics for it 3.13b. This is a testing server that the company is soon discontinuing in favor of the more favorable, Ookla speed test.

The Ookla speed test server is the final major capability in the RFInsights application. This runs the upload and download throughput testing. Ookla's servers are considered some of the best on the market for testing speeds of different signals. The test is very easy to begin, starting by clicking on the Auto button 3.14a. Then, the interval of testing in seconds and number of tests are to be set 3.14b, finally results will begin to show up on the screen showing Ping and Jitter in milliseconds, along with the real time upload speeds 3.15a or download speed 3.15b. Ookla speed testing uses a transmission connection protocol (TCP) to collect throughput data. TCP is a highly reliable end to end, connection oriented protocol that guarantees delivery of the data [40]. More information about this will be provided in the related work section. This is arguably the most useful feature of the application for KPI collection as it combines starting the log file along with throughput collection.



(a) Find on Home Screen (b) App Opening (c) Select Cellular Market

Figure 3.11: How to open RFInisghts



11:43 5G 90%

RFInsights(V1.8P39X1 Demo)
NPPI
Created By: Kosol Jintaseranee & Mark Evans

4G REGISTERED CELL (T-Mobile)
NSA
OEM: Ericsson SITE_ID: LA02716X
PLMN: 310260 PCI: 374 TAC: 12600
ECI: 22117641 eNB-SEC-CID: 86397-3-9
BAND: 2 FCN: 675 BW [MHz]: 15
RSRP: -64 RSRQ: -17 SNR: 0.0 TA: 0
CA: Yes BWs [MHz}: [15,20,100,100,100,100]

5G_PCI: 374 gNBid: 1836959 5G_FCN: 2261179 5G_BW: 100
nrRSRP: -91 nrRSRQ: -11 nrSINR: 18

Carrier Aggregation (DL)
(powered by Echo Locate)

	Tech	PCI	RSRP	RSRQ	SINR	BAND | FCN	BW	MIMO	MOD
P1	LTE	374	-64	-17	0	2 | 675	15	1L	64QAM
S1	LTE	374	-71	-14	0	66 | 66786	20	-2	-2
S2	NR	374	-91	-11	18	n260 | 2261179	100	-1	-1
S3	NR	374	-150	-50	-50	n260 | 2259451	100	-1	-1
S4	NR	374	-150	-50	-50	n260 | 2258011	100	-1	-1
S5	NR	374	-150	-50	-50	n260 | 2262907	100	-1	-1

PDCP Aggregation (UL)

	Tech	PCI	BAND	BW	FCN
P1	LTE	374	2	15	18675
S1	NR	374	n260	100	---

LTE Neighbors

PCI	RSRP	RSRQ	BAND | EARFCN
374	-64	-17	B2 | 675
286	-66	-14	B2 | 675
374	-71	-12	B66 | 66786
286	-74	-18	B66 | 66786

Figure 3.12: Home Screen of RFInsights

4G REGISTERED CELL (T-Mobile)

OEM: **** SITE_ID: ****

PLMN: 310260 PCI: 439 TAC: 31523

ECI: 32288261 eNB-SEC-CID: 126126-5-5

BAND: 66 FCN: 66711 BW [MHz]: 15

RSRP: -110 RSRQ: -8 SNR: 12.0 TA: 0

CA [MHz]:

CA [BAND]:

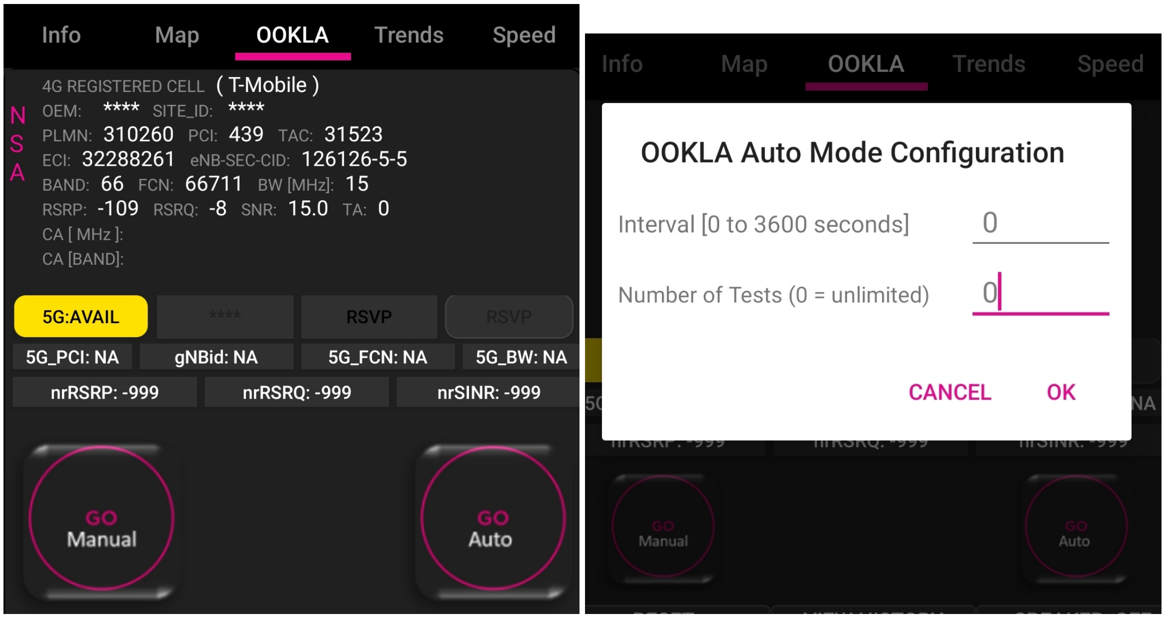
5G_PCI: NA gNBid: NA 5G_FCN: NA 5G_BW: NA

nrRSRP: -999 nrRSRQ: -999 nrSINR: -999

(a) Trends Tab of RFInsights

(b) Speed Tab of RFInsights

Figure 3.13: Various RFInsight Capabilities



4G REGISTERED CELL (T-Mobile)
OEM: **** SITE_ID: ****
PLMN: 310260 PCI: 439 TAC: 31523
ECI: 32288261 eNB-SEC-CID: 126126-5-5
BAND: 66 FCN: 66711 BW [MHz]: 15
RSRP: -109 RSRQ: -8 SNR: 15.0 TA: 0
CA [MHz]:
CA [BAND]:
5G_PCI: NA gNBid: NA 5G_FCN: NA 5G_BW: NA
nrRSRP: -999 nrRSRQ: -999 nrSINR: -999

OOKLA Auto Mode Configuration
Interval [0 to 3600 seconds] 0
Number of Tests (0 = unlimited) 0

(a) Ookla Tab in RFInsights

(b) Settings for Ookla Speed Test

Figure 3.14: Ookla Information

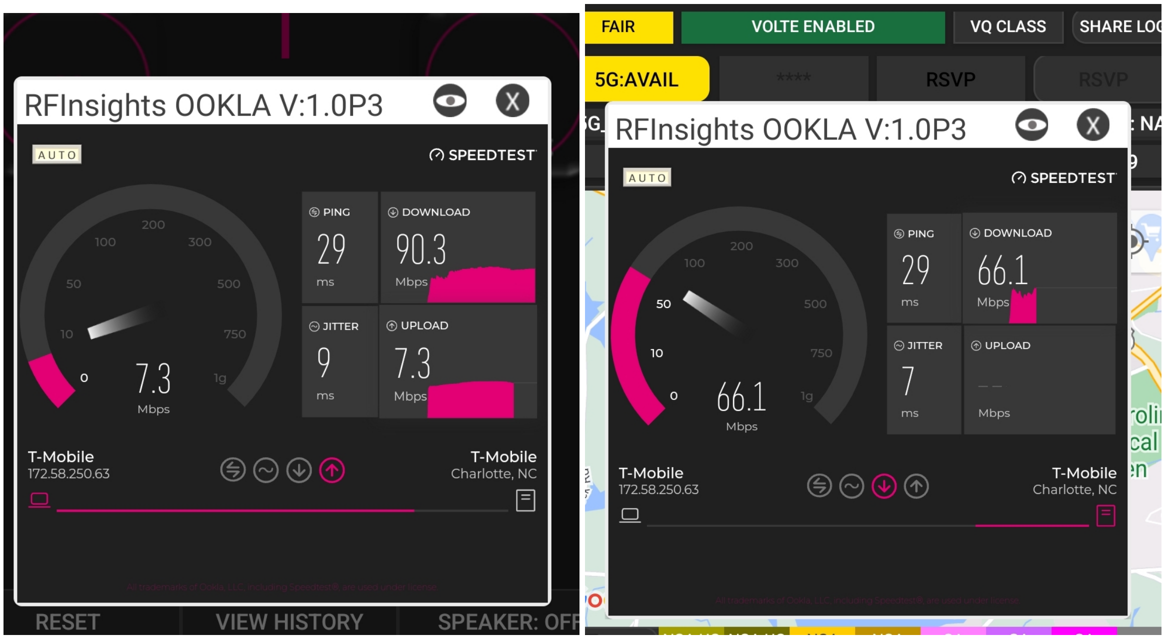
The data collection period on this application is every second. The files are saved directly to the phone's physical storage which makes it very easy to quickly view and begin to interpret data. As with the other software, it will be discussed in depth in the results section.

3.4 Locations

For the flight testing, we identified a few potential locations in the Clemson area to collect data that were then evaluated for their feasibility in strong results. This was a combination of looking at signal strength, bands available, flight conditions and access ability. Many challenges were faced when picking a location for testing such as signal strength, access for flight, lack of different desired bands and often being limited by weather and access abilities. Below, will discuss a few of the major locations which were used to test.

3.4.1 Anderson, South Carolina Site

A few miles from main campus, Clemson University has a building which is the National Brick Research Center. This building has a corresponding field and forest area which we were given



(a) Ookla Upload Stats

(b) Ookla Download Stats

Figure 3.15: Ookla Speed Test Running

permission to fly at. This area as seen In the image of the map 3.16, allows for over 1,500 feet of flight distance each direction without crossing over a road. It is also easily accessible and never busy. This location was not the final location because the signal was found to be very poor. The mid band 5G connectivity was found to be very poor and this would not be acceptable for the level of testing needed.

3.4.2 Clemson Band Practice Field

An on campus location was identified as having the possibility to fly the UAV at for data collection, this was the Clemson University Band Practice field. This site was used by the marching band a few hours a week for rehearsals in the afternoon for football game performances. They are the only group allowed to use this field so it was very easy to work around their schedule for flight time. After a few walking and short flight tests it became evident this site would not be a viable option for data collection. The field offered very poor to no quality mid band 5G signal. It also as seen in the map 3.17, only had about a football field length to fly which left us about 400 feet and this was not long enough for sustained speed testing.

Figure 3.16: Map of Anderson, South Carolina Test Site [1]

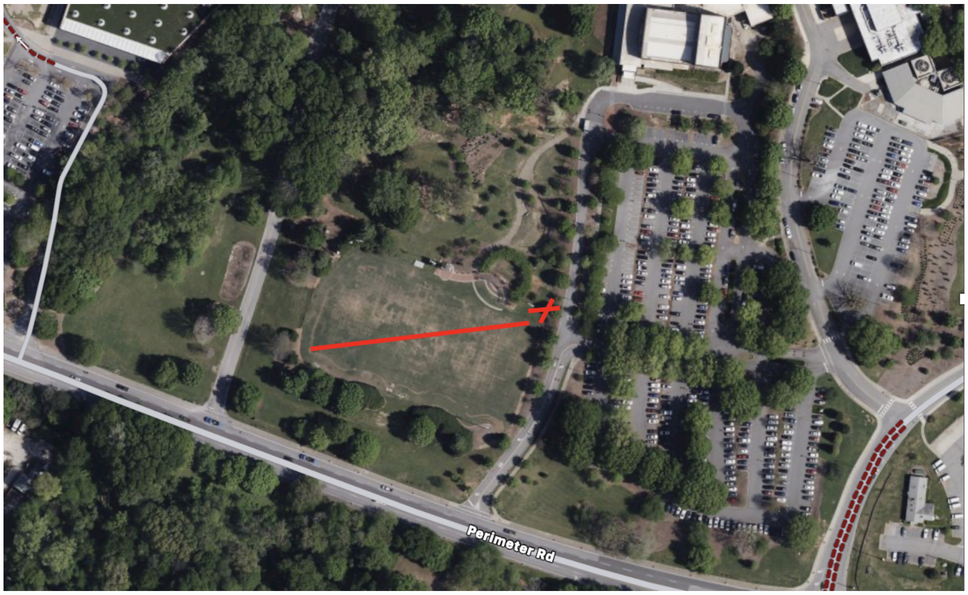


Figure 3.17: Map of Clemson Band Field Test Site

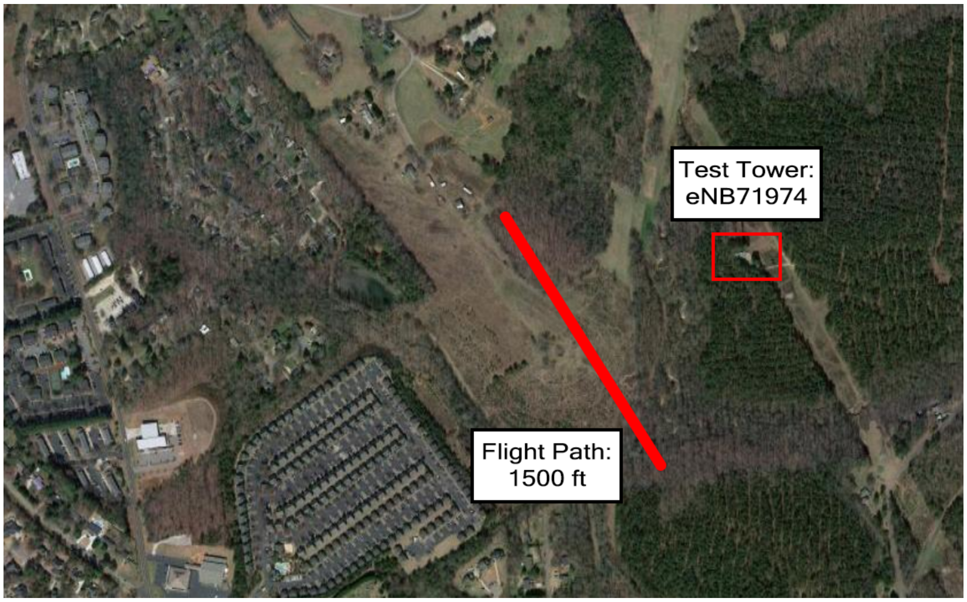


Figure 3.18: Map of Central, South Carolina Test Site

3.4.3 Central, South Carolina Site

As discussed prior, the RFInsights application gives tower locations in their exact positions on the map. This made finding a new location much easier, as the bands available and location were all able to be seen before going to the physical location. A new spot was found in the town next to Clemson University, Central, South Carolina. Upon arrival to the site, it was discovered to be a deforested area that was a large active construction site. After getting approval from the site foreman, we were able to complete data collection at this site. As seen in the map, it offered ample room to fly long flight paths without any interference or worry for power lines, roads or heavily forested area 3.18. As seen, the flight path was decided upon as 1,500 feet to help preserve battery as speeds were able to be reached with plenty of distance left. It can also be observed in the image 3.19 that the cellular tower was within direct line of site. This made the location an optimal location for strong signal quality for LTE, low and mid band 5G.

Figure 3.19: Cellular Tower at Central Site

3.5 Test Procedures

3.5.1 TEMS Pocket Testing

The first tests completed were using the TEMS pocket software. These data collection sessions were completed at the Anderson, South Carolina testing location. As previously discussed, the software was loaded onto a Samsung S21+ cell phone. The test script for this test was to start recording, make a voice call to a phone which would have it run the entire duration of the flight, upload a large file to a server and finally end recording data upon landing. With the script taken care of, the VPN has to be started to upload this file to a Clemson server. The first aid box gets secured onto the top of the UAV and the test is started. The flight plans called for three different elevations to be tested, 200 feet, 300 feet and 400 feet. At each of these elevations, three different speeds are tested, 10 mph, 20 mph and 30 mph. This will give results for low and fast speeds along with low and high altitudes. After the test flight was complete, the log files were sent off to Infovista to be processed. The results of this test flight can be seen discussed in the results section.

3.5.2 RFInsights Velocity and Altitude Testing

Even with the introduction of a new testing software, RFInsights, the testing procedure stayed very close to the original plan with TEMS. The goal was to fly at the three different elevations, 200 feet, 300 feet and 400 feet. With each of these elevations, three different speeds to be tested, 10 mph, 20 mph and 30 mph. We felt as though this was a good baseline for multiple scenarios which might be experienced as a drone. Each phone had the auto mode ookla speed test server started to collect the throughput data. Both parameter options were set to 0 for unlimited testing at the shortest time interval between tests. For the RFInsights testing, the Central site was used as it is found to be the most reliable area. Differing with the new software was now there were 3 phones set up to test at the same time. Also, the phones being set to a specific band to be sure the only data collected is what is being looked for. The phones were set to LTE, low band 5G and mid band 5G respectively. For the first few unsuccessful tests the first aid box was used as the mount, but overheating issues as discussed previously caused that to be changed. So, the new 3D printed mount was attached to the UAV and the phones were placed into the mount for data collection. This resulted in a successful collection with the new mount and these velocity and altitude parameters.

Data was then uploaded from a text file into a csv data type to look at in spreadsheet format to be sure of good results passing the eyeball test. Text files can also then be uploaded to the company's online dashboard which takes data from the file and displays it in multiple KPI plots and maps. Figures for the KPIs are then created to help focus in on the important trends in the data. These results can be seen later on in the thesis.

3.5.3 Coverage Mapping

For the next testing data set, the outer cellular limits of the Central, South Carolina site tower were found for the mid-band 5G. This was completed by completing a drive test of the surrounding area. The 5G mid band phone had the RFInsights application opened with a log file running. Then the map tab was pulled onto the screen to view which tower the phone was connected to. When approaching the tower, a close eye was kept at the point of handover. In the car was a physical printed out map with all of the surrounding streets on it. Area roads were driven for over an hour circling 360 degrees the tower to find the handover points for the tower. The final map can be been in the results section.

3.5.4 Column Testing

The final data collection completed was a series of vertical column tests. These were flights which used the previously collected coverage mapping, to see how well signal was gained or lost when increasing altitude from a ground boundary. Three phones were once again used in this test, with LTE, low band 5G and mid band 5G being tested. A spot along the defined coverage boarder good for testing was found and then 4 locations forming a straight line to the tower were picked. Each phone had the auto mode ookla speed test server started to collect the throughput data. Both parameter options were set to 0 for unlimited testing at the shortest time interval between tests. These flights were very quick as the drone was flown from the ground to 400 feet at a constant velocity and then back down again. They took about 3 minutes in total, so very quick. The data was then processed in the same was as the other RFInsights tests.

Chapter 4

Related Work

In the related work section, other research works will be discussed. Some of these papers include data collection for LTE flight scenarios, 5G ground user KPI collection and 5G flight testing. These papers consist of both real world flight testing as well as simulations. Other topics will be discussed such as AERPAW experiments, transmission control protocol and channel modeling experiments.

4.1 LTE Flight Testing

The research completed by the University of Northern Arizona in this paper is the basis for the continuation of the current research on 5G connectivity to UAVs at Clemson University [41]. A few of the contributors to this paper are now working on the project at Clemson. Though this paper is a few years old and highlights LTE coverage to drones, it serves as the baseline for all of the work presented within this thesis paper. It discusses the many concerns about connecting drones to cellular networks including, considerable interference when at altitudes above ground objects, coverage areas in high altitudes and the effect that UAV users might have on ground level users. Trial conditions are clearly outlined as being at flight elevations of 40, 80 and 120 meters. Two different speeds are used 30 and 60 kilometers per hour. Call quality, up-link and down-link are the main measured targets. A commercially available drone is used for the testing, the DJI Matrice 200. A Samsung S20 cell phone was attached to the drone for the measurement running the TEMS pocket application for data collection. The Verizon network is used at the 1700 MHz band. The testing site is a rural forested area near Flagstaff, Arizona. This group does a great job at describing the test scenarios so that reproduction of the testing is very easily completed.

The results gathered by the group show in their analysis that low altitude flights gather the worst results. The higher elevation flights were shown to have better results for voice calls and throughput of data. It was found that the middle flight altitude of 80m had the strongest results for transfer of data. It also was found that the middle altitude had the highest number of handovers recorded. Contrasting with the higher elevation flight which had the least number of handovers. In relation to speed, it was found that the changing in speed had a very negligible effect on their results for data throughput. Though, slower flights have a marginally better performance. The major difference noted when dealing with velocity is in the handover count. The higher the speed, the less number of handovers were observed.

The various metrics which were closely monitored and recorded are RSRP, RSRQ, RSSI, SINR, downlink throughput and uplink throughput. Different numerical benchmarks are provided in the paper to rate the strengths as excellent, good, fair to poor, or no signal. Many graphics and charts are provided of the results which makes the data collected very easy to read and interpret.

Overall this group finds that already deployed LTE systems are capable of handling UAV connection for throughput of data successfully. They mention that since they only tested in a rural area, more testing would need to be completed to roll this out in a more populated area. Though this paper is a few years old and uses LTE, it is a great example of different tests to run and what metrics might be important for the 5G UAV testing.

The next related work done by the Ericsson company of Finland, focuses their research on studying LTE connectivity for low altitude flying drones beyond visual line of site [42]. Tests were conducted using a quadcopter DJI Phantom 4 Pro drone. Connection data was collected using TEMS Pocket 16.3 on an unspecified smart phone. The test scenarios were then completed at ground level, 50 meters and 150 meters. For ground level results, a car driving test was used for the data collection driving between 20 km/h and 40 km/h due to traffic flow. For the drone a constant speed of 18 km/h was held. Their results provided are only in the 800 MHz band.

The first metric provided to the reader is their reference signal received power (RSRP) results. Results at both 50m and 150m were higher dB readings than for the ground level test. The conclusion drawn by the authors is that the drone collection equipment was served by the low gain parts of the main lobes or the sidelobes of the downward facing base station antennas.

The next collected metric was reference signal received quality (RSRQ). At heights of 50m and 150m the RSRQ is lower than what is observed at ground level. The authors deduce this is due to stronger downlink interference from non serving cells to the cell phone collecting the data. At this higher altitude, many more base stations are seen and picked up by the cell phones. This theory can be backed up by the metric collection of signal to interference plus noise ratio (SINR). This showed a much higher dB reading than at ground level, proving the theory of much strong downlink interference from non serving base stations while in the air.

The authors deduce from their data that in general as height of the drone increases the signal quality will decrease. But, higher throughputs will be observed as there is less interference as is seen on ground levels. Though most of the data presented was downlink, the authors collected some uplink results. These were very promising as there was a minimal difference seen in ground level uplink results to the flying uplink speeds. Much closer than the downlink results collected. Throughput levels at flying heights were observed to be higher than ground levels. The strong uplink results are believed to be the result of close to free space propagation conditions while in the sky.

As TEMS pocket reports data for many different base stations which are able to be seen by the cell phone, the authors elaborate on the same metrics discussed above for the non primary base stations in the data collection. The RSRP and RSRQ results show that as the drone gains altitude, the spread between results decreases between the various area base stations. The strongest signal at a random point in time is not always the serving cell, but handover thresholds have to be met for the base stations to switch. A negative RSRP gap between the primary and secondary base stations was seen 11% of the time on the ground testing. When at 50m it grows to 21% and at 150m it balloons to 33%. This is just due to the hand off threshold not being met but these other antennas delivering a stronger signal in that point in time. This could lead to an interesting problem with handover at altitudes.

This paper gives a great baseline for various testing procedures and results which would be good to compare with. Since the work only focuses on LTE coverage, it will be interesting to see how closely 5G characteristics resemble these results.

4.2 5G Ground Testing

The work that follows is partly what the previous team from Northern Arizona University called for, that is urban and city testing of signal strength for civilian cell towers [43]. It is done in cooperation with members from University of Chicago along with Florida International University to complete testing in Chicago and Miami. Dr. Monisha Ghosh is one of the leading researchers in this field and contributed to this paper. The research focuses on all three types of 5G bands, low-band (¡ 1 GHz), mid-band (1 - 6 GHz), and high or mmWave (¿24 GHz). mmWave has the potential to deliver up to 2Gbps in downlink throughput.

Data collection was completed over several months all time of day in 2020 and 2021 throughout the cities of Miami and Chicago. Google Pixel 3 and 5 phones were used for the 5G metric collection. The Android applications SigCap, FCC Speed Test and Network Signal Guru were the apps used for this data. In Chicago it was seen that at that time Verizon had done the best job in deploying mmWave technology in public places that showed high throughput speeds. Seeing maximum throughput of 1.92 Gbps observed. One of the major problems seen by the research group is that the phone they were using could not properly process this high of a band. Most of the experiments they were getting better throughput at on high band LTE than 5G because if the old technology they had in the phone, this was at 421 Mbps. One major finding is that the human body appears to act as a signal blocker for mmWave technology. With an observed 20% signal degradation from human body blockage.

The takeaways from the group is that 5G technology is a rapidly evolving field and with antennas continuously being put up and improved, the signals will get better as time goes on. User devices will also continue to have better internal antennas which are able to better connect to the networks to fully utilize their power. Primary channels appear to be determined based on RSRP and RSRQ which is not necessarily the highest throughput. Finally mmWave technology is still very unknown with much interference from bodies, foliage, line of sight problems. Therefore, much more research needs to be completed on how to make this much quicker network a usable and reliable option.

4.3 5G Flight Testing

A group of professors and researchers at Tampere University in Finland explored connectivity of 5G networks with aerial mobility [44]. Two major test types are performed by the group. The first being how a commercial grade 5G network performs metrics wise with a cellphone collecting data on the drone flying at differing speeds and altitudes. This shows that aerial measurements are a prompt way to estimate antenna patterns for operators to see their 5G antenna equipment capabilities. The second test case being agile measurements for all mobile networks in Finland, to estimate 5G network availability to estimate network availability to a particular area and altitude. This test case allows for operators to see their current 5G network capabilities which is imperative to the sustainability of growing UAV usage for various services.

The authors quickly detail one of their proposed largest issues with 5G integration into UAVs will be with the lack of handover mechanisms in place to prevent the so called ping pong effect of handovers constantly occurring. They define this problem as mobility management, the need to better improve in air handovers. The authors also discuss the possibility of private 5G networks on a micro or local scale which companies might study for better UAV coverage. University or other test networks are also a possibility for testing without the interference of public use.

For the Tampere University conducted research, all of the testing was conducted on their campus. It was conducted using the University's commercial grade 5G network, operating at the frequency band n78, 3.5 GHz. The network supports both non-stand alone and standalone connectivity. The system also utilizes radio access network sharing which is connected to the 5G Test Network Finland. The drone used for testing is the Inspire 2 from DJI, with an unspecified 5G capable phone as the payload collecting data. The software on the phone to collect data was MediaTek and QualiPoc.

For the first test scenario described above, antenna pattern studies were conducted by the group. This was done at a fixed drone height of 33m above ground. This was the same altitude as the nearest 5G antenna. The UAV was flown in a arcing shape back and forth across a field, without stopping when it goes back and forth. It was completed at speeds of 4 km/h, 18 km/h and 30 km/h. The research group plots their antenna strength findings on a few graphs, showing correlations between different speeds and dB readings for various angles from the antenna. The results show that the most consistent signals occur when flying at the lowest speed. But, this is not often reality due to not being able to cover the needed flight path on the full battery charge. So, the data collected at higher speeds show the signal is still plenty reliable enough at these higher speeds.

For test scenario 2, three different flight paths were taken under a constant speed of 18 km/h to assess three different commercial networks in the area. The 3 flight paths were at ground level, 20m above the ground and 40m. For the ground level testing, a bicycle was used since you can get up to high speeds and not worry about traffic which might be encountered in a car. Uplink and downlink data was collected in this testing. The numerical results gathered are not very important to the research of this thesis, but the test procedure and KPIs collected are used as a reference and influence to the testing done for the Clemson research.

The next related work was conducted by two professors in Mexico about the incorporation of 5G technology into UAVs [45]. They use many hypothetical examples and some simulation work to explain the mutual benefits that 5G and UAVs can have on each other. The text begins by describing the three types of service categories for 5G. The first being Enhanced Mobile Broadband (eMBB) which is used to achieve both extreme high peak data rate and extreme wide-area coverage. The next is, Massive Machine Type Communications (mMTC) which supports a massive number of devices, mainly, oriented to IoT. The final being, Ultra-Reliable Low-Latency Communications (URLLC) to simultaneously support low-latency and very high reliability transmissions. The latter is the most important for UAV flight as this ensures the safe operation of drones in air. These service categories will help ensure that UAVs can be used both as performance and coverage enhancers as flying base stations. Along with as being used as new user equipment using the 5G network to complete tasks defined by the user. Since on the fly base stations are not in the scope of this thesis report, this part of the paper will not be discussed further.

An important piece of using UAVs on civilian mobile networks is considering the interference which might occur in both directions. This topic is studied in the paper and different mitigation techniques are tested in simulations, interference cancellation (IC), intercell interference coordination (ICIC), and beam switching at the UEs. In the end it was found that beam switching was the best way to decrease any interference. Machine learning has also been identified as a way for networks to identify UAVs using the antennas and applying mitigation strategies to not effect the UAV or terrestrial users of the network.

Based on the research conducted by the paper, UAVs flying at 100m have a best system performance when external antennas on the base stations point downwards. But, UAVs need to also be able to adapt to areas with poor 5G coverage and have robust algorithms and make the correct handoffs to not effect the flights mission while in air in some poor connected areas. Network slicing is a technique which can be implemented by cellular networks on 5G to make sure that UAVs carrying out critical missions can have a dedicated logical network which service capabilities can be completed on. This will isolate services and resources between the in air and terrestrial users.

This paper touches on many key points for the implementation of 5G networks and UAVs together, but it lacks any hands on experimenting. It also only discusses a few simulations which were completed with very little set up on these test cases mentioned. So, though it discusses many positive points about implementation, more concrete works needs to be done by this group.

The third study found, was completed by a group of scholars and industry professionals in Germany highlights their findings in performance metrics for UAVs connected to 5G networks [46]. The beginning of the paper highlights the relatively new and expanding field that this research is in. With UAVs finally becoming more economically and technologically available to people and 5G coverage strong enough to have decent throughput it has made this an emerging field. But some of the challenges are the current line of sight regulations which do not allow for drone operation when the pilot can not see the drone. This highly limits the flight planning available to complete the desired missions. The authors feel though with the proven reliability of the wireless network connections it will allow regulators to allow some instances of beyond line of sight flying for missions.

As with the research paper mentioned before from Mexico, the German researchers mention the three different application scenarios of 5G networks, eMBB, URLLC and mMTC. Some of the challenges of these application scenarios are given such as obstructed signal propagation in mm-wave links for eMBB and not enough sensors for covering large areas in mMTC.

The testing was conducted using a 5G network, a drone, and a ground station taking measurements. The mobile network was set up using Ericsson corporations 5G testbed. Which consisted of an Evolved Packet Core (EPC) and a Radio Network (RAN) with six base stations that cover a 30 km long area in Germany. The base station operates in the LTE band 28 at 700MHz with 10MHz channel bandwidth. The drone used is the Trinity F90+ made by Quantum Systems. The main objective of these tests is to measure the end to end performance of the connected drone. Three main testing scenarios were completed, first a short distance flight at 100m in a circular flight path of a radius of 500m. The next scenario is two network slices were video data and C2 streams are being sliced. The final scenario is the throughput in a long distance flight of 7km in a straight line course with data load for video and C2 data. Throughput, latency and link signal quality indicators were collected.

For the first test, the circular flight, the mean downlink was 30.2 Mbps with a mean RSRP of -85.4 dBm. Overall the throughput was consistent and it did not dip to critical levels at any of the elevations or points in the circular flight path. A general trend observed though was the throughput decreased as elevation increased on the drone. In the second test, network slicing was measured. Some outages were observed in the data and the throughput dropped the most when ground devices were also attempting to use the same cell tower signals. When all the devices were attempting to use the same network link, it caused these reduced throughputs which is something to know for future UAV use with 5G connection. For the final test, the long distance flight has a reported, average to good signal quality through the duration of the flight. Uplink throughput is averaged at about 2 Mbps for the duration of the flight. It is reported that the RSRP tends to decrease with increased altitude. Handovers did occur, but data shows a negligible impact on performance of the flight.

The research done by this group, draws them to the conclusion that mobile networks in their current 5G state are able to sustain short and long distance automated flight. They feel that throughput for data is strong enough to support this advance in UAV flight. They would like further research on antenna tilt for supporting for aerial vehicles as currently all towers are made to support terrestrial devices only.

4.4 5G/LTE Experimental Work Using AERPAW Testbed

One of the major research groups currently within the 5G cellular connected drone industry is a group called the Aerial Experimental and Research Platform for Advanced Wireless (AERPAW) [47]. This is a research testbed based out of NC State University in Raleigh, North Carolina. The goal of the research is to become the leading testbed system for 5G data collection in relation to unmanned aerial systems (UAS) [48]. They are getting funding from the National Science Foundation to develop a state of the art data collection operation and determine the feasibility of UAVs on 5G networks. In one of their works [49], they discuss the ways in which they have set up emulating programs for offline testing to validate information before performing a real life test. Emulations were created for both unmanned ground and aerial vehicles, along with wireless channels including packet level, IQ level and radio frequency. These emulations were all able to then be run on virtual machines to help run repeated simulations without the time consuming nature of physical testing.

In another publication [50], they describe all of the physical vehicles they are using for testing along with some of the node hardware used. There are three nodes which AERPAW are using: portable radio nodes, which are the most used by them on testing vehicles, fixed radio nodes, installed on radio towers, light poles or other non moving areas and cloud nodes, which have no radios. For their vehicles they require them to be fully programmable to allow for experiments to be conducted in their exact terms. They decided to build their own UAVs from scratch to get the exact specifications which they desire. They have build a Large AERPAW Multicopter (LAM6), which has 6 propellers each with a thrust of 12 kg. This allows the UAV to reach the FAA's max all weight of 25 kg. The batteries allow for about 40 minutes of hovering capabilities. The max speed which is electronically limited is 30m/s. All in, it cost about $5,000 to produce. They have also produced the Small AERPAW Multicopter (SAM4). This is a much smaller UAV and houses only 4 propellers. The drone can also hover for about 40 minutes and its payload is about 3kg. This paper was using the actual user equipment and do not get into any results on a private or commercial network.

In the final work to be covered about AERPAW's impressive work, they cover tests which are very similar to the work done in this thesis [51]. They test flight and then analyze the probability of occupancy in common sub 6GHz cellular network bands while in air of LTE and 5G. They also brought in different components to their test such as the effects of rural versus urban testing areas. One of their UAVs was used to reach the testing altitude of 140m in the urban setting and 180m in the rural setting. A software defined radio (SDR) was used to collect the data from the drone and then a python script was used to capture and analyze the data. They found that the chances of occupancy on a band generally increases with higher altitudes. They also concluded that line of sight seems to be much more important with the higher frequency bands of 5G. As mentioned before, this test incorporated data collection using user equipment, SDRs and only private cellular networks.

Overall, AERPAW's test facility and modeling capabilities make it a very large asset for the long term experimentation of 5G networks in relation to UAVs. They have been able to combine simulation and physical infrastructure to create this facility. It includes emulations as discussed previously, both urban and rural testing sights close to the NC State campus, programmable SDRs, commercial radio equipment, many programmable UAVs, 3 different types of portable nodes and a large number of local cellular towers carrying 5G bands [52]. Therefore, it will be very interesting to keep up with publications that they put out on future work pushing the exploration of UAV connectivity.

4.5 Transmission Control Protocol

As briefly covered in the section about the ookla speed testing server, it uses a transmission control protocol (TCP) to transport the data between the server and phone. This is the most popular transmission protocol currently used for the internet. TCP uses host to host connectivity in a connection oriented manner. The authors of a paper discussing the challenges and issues of TCP over wireless environments, describe it as being able to control and minimize packet loss therefore providing reliable packet transmission [53]. They also point out that the most common reason for loss of packets within TCP is network congestion. But, they also point out the resiliency of the protocol and how it is able to adapt to packet loss. This can be added to a paper written by University professors from Hong Kong, where they state TCP is so widely uses due to its multi-path routing, route fluttering and re-transmission of packets [54]. Finally, a paper reviewing TCP over mmWave was a great insight into research being done very similar to what was happening in the thesis data collection. They tested how TCP performs on the new mmWave networks, which differed from many of the older papers written before 5G was available [55]. They believe that TCP needs to be optimized and improved to make it better used with mmWave, but that it is still the strongest transmission protocol option still.

Therefore, it can be concluded that the use of TCP for the ookla speed testing server is one of the best ways to collect uplink and downlink data. Using a protocol that shows a low amount of packet loss and is not effected by many issues which may arise in an unpredictable wireless network.

4.6 Channel Modeling

When 5G technology was in its infancy state, researchers needed a way to begin to model and simulate the networks which were being created. They turned to a technique called channel modeling. The various parameters which were created allowed for researchers and industry to have an idea of how 5G networks might perform before rolling them out. A group of professors at Shandong University in China put out a work that goes into detail the parameters which they believe are important for channel modeling and then review other current 5G channel modeling techniques [56]. Some of their key points of channel modeling include, a wide frequency range which allows for compatibility with lower bands even when at a higher band. Broad bandwidths, to support the large channels seen in 5G. A wide range of scenarios, for example rural versus urban or high speed vehicle versus walking. Double-directional three-dimensional modeling, showing full 3D maps for antenna modeling and propagation modeling. Smooth time evolution, to involve different parameters to drift and cluster fade in and out over time. Spacial consistency, having two closely located transmitters or receivers that have similar characteristics. Frequency dependency and frequency consistency, channel parameters at adjacent frequencies should have strong correlations and they should vary smoothly. Massive MIMO, as discussed before 5G networks boast a large MIMO as an improvement. Direct D2D/V2V, both the transmitter and receiver are equipped with lower antennas to interact with a large number of scatters. Finally, high mobility, supporting high speed connection of devices on something such as a bullet train moving at a high rate of speed. These are the ten parameters which these professors identified as the most important ones to focus on in 5G channel modeling.

To discuss a few of the various channel models which they reviewed, starting with MiWEBA Channel Model [57]. This was one of the first studies performed relating to mmWave networks, with the research frequency at 57 to 66 GHz. It helped to illustrate that mmWave propagation, line of sight and low order reflection components contribute the most to the receiving power of the signal [58]. This is obviously still a very pressing issue with mmWave as it is highly dependant on line of sight. The next channel model is the QuaDRiGa which is a geometry based stochastic model which supports a frequency range between 0.45 and 100 GHz [59]. This channel model supports 3D antenna modeling, massive MIMO antennas, multi-user, multi-hop and multi-cell networks. Following was the METIS channel model, which provided a map-based stochastic model. It supported frequency ranges up to 70 to 100 GHz [60]. This testing technique allowed for a flexible and scalable channel modeling framework that could handle urban scenarios especially well. It allows for dense area simulation and data is obtained from the 3D map model. A channel model created by a special interest group made up of industry professional along with academics was the 5GCMSIG [61]. This channel model was set up at a wide frequency range of 0.5 to 100 GHz, with a large bandwidth of 100 MHz for under 6 GHz and 2 GHz for above 6 GHz. It covered many new scenarios with large crowds such as sporting events, shopping areas and busy streets. The modeling includes path loss, shadow modeling, line of sight probability and other models. Therefore this was one of the most advanced at the time. Finally, the 3GPP channel model was discussed [62]. As mentioned previously, 3GPP sets the industry standards for constructing 5G networks. Therefore seeing how they construct a channel model is very interesting to the industry. They opted for a wide frequency range of 0.5 to 100 GHz. They considered spatial consistency, blockage effects and atmospheric attenuation as possible hindrance of mmWave. This model was seen to have a limited capability though and the paper did not see it as one of the best models.

Overall there are countless channel models that researchers and industry professionals have created to model different 5G characteristics without having to collect data in the real world. Though simulation is great to create baseline hypothesis, there is nothing compared to testing real situations. This is why this thesis work is so important, as it is the first group approved for full data collection on a commercial cellular 5G network.

4.7 Summary of Related Work

As read about in the different related works covered above, there have been many different procedures and test scenarios set up to measure 5G and LTE coverage both on the ground and in air on a UAV. One of the most interesting papers is the group from Tampere University in Finland. They are flight testing on the 5G mid band at frequency 3.5 GHz, which has not had many published works. As with the work in this thesis, they experimented with both velocity and altitude. The results showed that slower speeds led to better connection but these were menial advantages as mid band still offers sufficient coverage at higher speeds. This research differed in the sense they had a private commercial grade network for data collection. Therefore, there was no ground user interference which might effect results for the better. Authors also were able to dive into the handover concerns with 5G which is called the ping pong effect. Unfortunately with the software used for data collection, handover was not able to be explored in our research.

The study held in Germany also focused on 5G connectivity with drones. This paper used low band frequencies but still has positive findings. They concluded that even low band shows strong enough results to support command and control protocols for potential autonomous flight and throughput rates are high enough for secure data transfer. The paper with research from Mexico, touches on many different positive features of 5G and how they might positively impact UAV flight. They conclude that UAVs at 100m altitude have the best performance when using a commercial converge network with antennas optimized for ground users. They also believe that UAVs need to better account for poor coverage areas by use of different techniques. They touch on many key points of 5G but they have no real world testing. All of the study is simulation and hypothetical writing, so the follow up to their hypothesis would be interesting.

Northern Arizona University's work is a big inspiration for the experiments and data collection performed in this thesis. Their paper highlights UAV connectivity with LTE, but the basic similarities are shared. Altitude and velocity testing is needed to properly evaluate different scenarios the UAVs might experience while connected to the 5G network. Their findings are positive as they believe the rural LTE network was capable of supporting throughput from UAVs. The findings are in line with those in the Ericsson company's research out of Finland. Who also studied LTE from a UAV's perspective. The RSRQ and RSRP metrics both show that as the altitude increase the results get worse. It also highlights problems that may arise from handover procedures and the need to study this further at altitude.

Finally, University of Chicago and Florida International University's collaboration helps introduce metric collection on the ground for the three 5G band types. This paper discusses the challenges and many things to look for when collecting 5G information. Important KPIs, most of which will be shown in the results section, are also listed by name giving the reader a good idea of the most important. Overall, there are many works by other authors to help and inspire the research in this thesis, but these select papers are some of the ones used for inspiration and guidance. Important topics covering AERPAW's testbed in North Carolina for UAV 5G testing, transmission control protocol and channel modeling are also covered.

Chapter 5

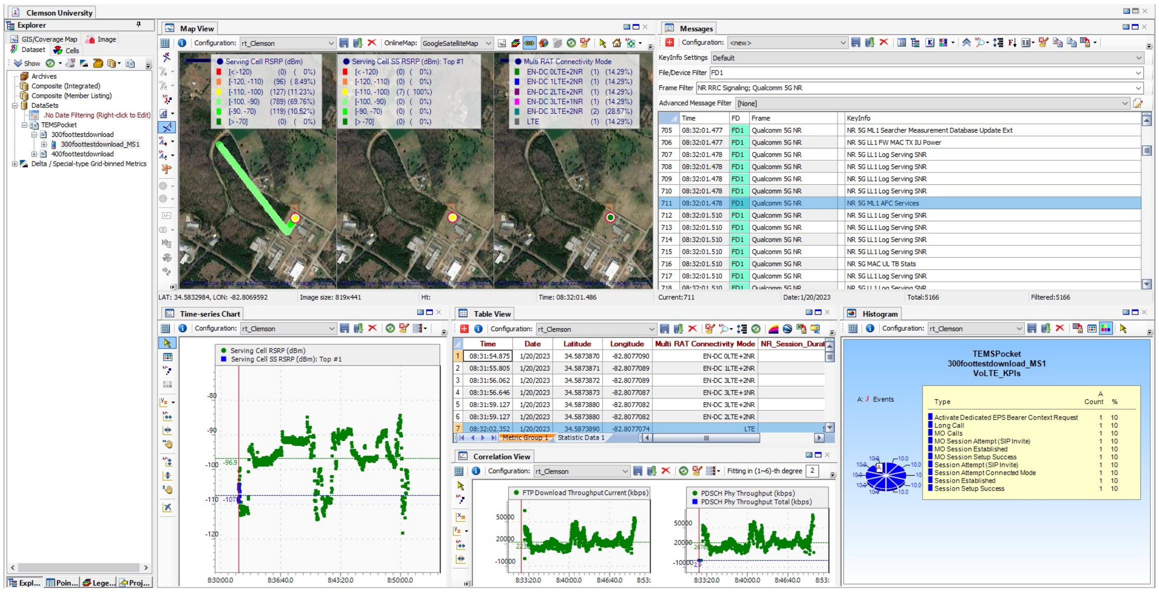
Results

The results section will share the numerical results of the various experiments, as well as commentary on how well or how poorly they went. IT will begin with the TEMS pocket data collection trials. Then, RFInsight trails will be focused on with all of the various unsuccessful and successful trials, as well as the boundary testing for mapping and column testing. To conclude a comprehensive review on the two different software used will be given for reference.

5.1 TEMS Pocket Collection

As explained in the previous section, for the first part of the data collection for the thesis, Infovista's TEMS Pocket application was used on the S21 phone. The data was logged into their .trp file type in the phones internal storage. We completed a few test cases with the drone at the Anderson site, as previously explained, flying at 400, 300, 200 feet at velocities of 10, 20 and 30 mph for each altitude. A drive test was also conducted with the phone logging data from Clemson's campus all the way to the Anderson site. Without the license to the TEMS Discovery application, the collected files had to be sent to a contact at Infovista for processing. Unfortunately, this is where the problems began with using this application for data collection.

In the research partnership with commercial cellular network company, they provided the cell phones, sim cards and software licenses for the data collection. They are the ones who originally paid the large fees for us to be able to use TEMS Pocket. The original deal also allowed for us to send in our recorded log files and be returned a file with all of the important KPIs. Unfortunately,



Serving Cell RSRP (dBm)

🟥 [< -120)	(0)	(0%)
[-120, -110)	(96)	(8.49%)
🟨 [-110, -100)	(127)	(11.23%)
🟩 [-100, -90)	(789)	(69.76%)
🟩 [-90, -70)	(119)	(10.52%)
🟩 [> -70]	(0)	(0%)

Serving Cell SS RSRP (dBm): Top #1

🟥 [< -120)	(0)	(0%)
[-120, -110)	(0)	(0%)
🟨 [-110, -100)	(7)	(100%)
🟩 [-100, -90)	(0)	(0%)
🟩 [-90, -70)	(0)	(0%)
🟩 [> -70]	(0)	(0%)

Multi RAT Connectivity Mode

EN-DC 0LTE+2NR	(1)	(14.29%)
EN-DC 1LTE+2NR	(1)	(14.29%)
EN-DC 2LTE+2NR	(1)	(14.29%)
EN-DC 3LTE+1NR	(1)	(14.29%)
EN-DC 3LTE+2NR	(2)	(28.57%)
LTE	(1)	(14.29%)

LAT: 34.5832984, LON: -82.8069592 Image size: 819x441 Ht: Time: 08:32:01.486

Messages

Configuration: <new>

KeyInfo Settings: Default

File/Device Filter: FD1

Frame Filter: NR RRC Signaling; Qualcomm 5G NR

Advanced Message Filter: [None]

	Time	FD	Frame	KeyInfo
705	08:32:01.477	FD1	Qualcomm 5G NR	NR 5G ML1 Searcher Measurement Database Update Ext
706	08:32:01.477	FD1	Qualcomm 5G NR	NR 5G LL1 FW MAC TX IU Power
707	08:32:01.478	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
708	08:32:01.478	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
709	08:32:01.478	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
710	08:32:01.478	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
711	08:32:01.478	FD1	Qualcomm 5G NR	NR 5G ML1 AFC Services
712	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
713	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
714	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
715	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
716	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G MAC UL TB Stats
717	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
718	08:32:01.510	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR

Current:711 Date:1/20/2023 Total:5166 Filtered:5166

Table View

Configuration: rt_Clemson

	Time	Date	Latitude	Longitude	Multi RAT Connectivity Mode	NR_Session_Dural
1	08:31:54.875	1/20/2023	34.5873870	-82.8077090	EN-DC 0LTE+2NR	
2	08:31:55.805	1/20/2023	34.5873871	-82.8077089	EN-DC 1LTE+2NR	
3	08:31:56.062	1/20/2023	34.5873872	-82.8077089	EN-DC 3LTE+2NR	
4	08:31:56.646	1/20/2023	34.5873873	-82.8077087	EN-DC 3LTE+1NR	
5	08:31:59.127	1/20/2023	34.5873880	-82.8077082	EN-DC 3LTE+2NR	
6	08:31:59.127	1/20/2023	34.5873880	-82.8077082	EN-DC 2LTE+2NR	
7	08:32:02.352	1/20/2023	34.5873890	-82.8077074	LTE	

Metric Group 1 Statistic Data 1

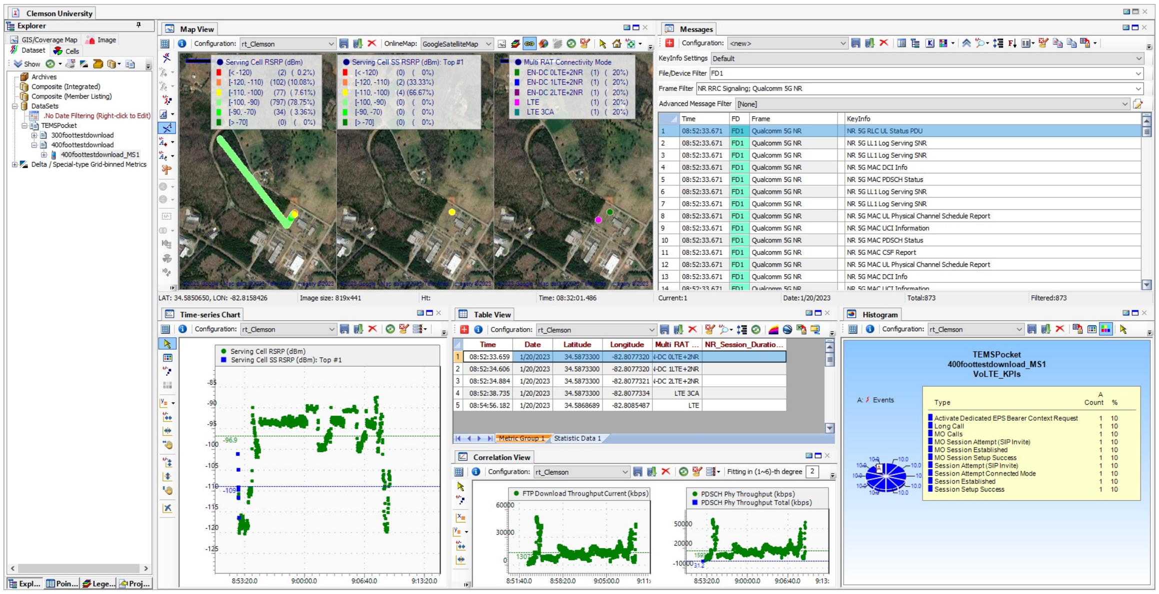
TEMSPocket
300foottestdownload_MS1
VoLTE_KPIs

Type	A Count	%
Activate Dedicated EPS Bearer Context Request	1	10
Long Call	1	10
MO Calls	1	10
MO Session Attempt (SIP Invite)	1	10
MO Session Established	1	10
MO Session Setup Success	1	10
Session Attempt (SIP Invite)	1	10
Session Attempt Connected Mode	1	10
Session Established	1	10
Session Setup Success	1	10

Figure 5.1: TEMS Discovery Dashboard for 300 Foot Elevation Flight Test

this is not how things worked out. The company was ready to roll out their own mobile application for KPI collection and was not paying the licensing fees to Infovista. Therefore, we were not getting a full file of KPIs and only screenshots showing a dashboard with the processed files and snippets of data in it. As you can see in the figure 5.1 and 5.2 the map on the upper left hand corner shows the flight path at the Anderson site. Another piece of mildly interesting data seen in the screen capture is in the middle lower portion and that is the FTP Download Throughput. With it only being a screen shot and how tiny the figure is relatively, it is almost impossible to draw any conclusions besides just the shape of the plot. It is also seen that at both elevations the RSRP stays above -90dB for over 90% of the time. This shows beginning positive signs that 5G cell towers optimized for ground users can have a strong received power at high elevations. In the drive test figure 5.3, it was interesting to look at the map and see the different percentages of time on the different bands, but overall this screen capture was not necessary to any of the research for this project.

The system which TEMS pocket used for file transfer, as discussed in the test procedure was HTTPS. This required the user to either already have a server or to create one of their own. We decided to use the Clemson School of Computing's server which was able to use the HTTPS protocol. But, as a downside this required the phone to be logged into a VPN with the university to access the server. It is believed that this VPN most likely was throttling data throughput for



Messages

Configuration: <new>

KeyInfo Settings: Default

File/Device Filter: FD1

Frame Filter: NR RRC Signaling; Qualcomm 5G NR

Advanced Message Filter: [None]

	Time	FD	Frame	KeyInfo
1	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G RLC UL Status PDU
2	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
3	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
4	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC DCI Info
5	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC PDSCH Status
6	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
7	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G LL1 Log Serving SNR
8	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC UL Physical Channel Schedule Report
9	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC UCI Information
10	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC PDSCH Status
11	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC CSF Report
12	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC UL Physical Channel Schedule Report
13	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC DCI Info
14	08:52:33.671	FD1	Qualcomm 5G NR	NR 5G MAC UCI Information

Current:1 Date:1/20/2023 Total:873 Filtered:873

Table View

Configuration: rt_Clemson

	Time	Date	Latitude	Longitude	Multi RAT ...	NR_Session_Duratio...
1	08:52:33.659	1/20/2023	34.5873300	-82.8077320	N-DC 0LTE+2NR	
2	08:52:34.606	1/20/2023	34.5873300	-82.8077320	N-DC 1LTE+2NR	
3	08:52:34.884	1/20/2023	34.5873300	-82.8077321	N-DC 2LTE+2NR	
4	08:52:38.735	1/20/2023	34.5873300	-82.8077334	LTE 3CA	
5	08:54:56.182	1/20/2023	34.5868689	-82.8085487	LTE	

Histogram

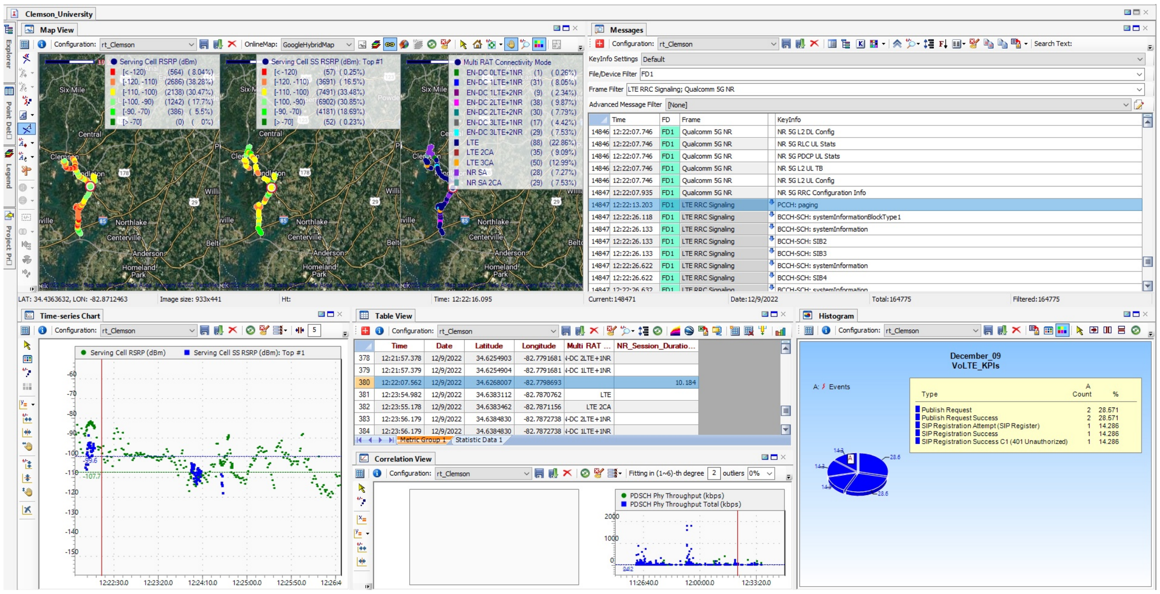
Configuration: rt_Clemson

TEMSPocket
400foottestdownload_MS1
VoLTE_KPIs

A: Events

Type	A Count	%
Activate Dedicated EPS Bearer Context Request	1	10
Long Call	1	10
MO Calls	1	10
MO Session Attempt (SIP Invite)	1	10
MO Session Established	1	10
MO Session Setup Success	1	10
Session Attempt (SIP Invite)	1	10
Session Attempt Connected Mode	1	10
Session Established	1	10
Session Setup Success	1	10

Figure 5.2: TEMS Discovery Dashboard for 400 Foot Elevation Flight Test



Messages

Configuration: rt_Clemson

KeyInfo Settings: Default

File/Device Filter: FD1

Frame Filter: LTE RRC Signaling; Qualcomm 5G NR

Advanced Message Filter: [None]

	Time	FD	Frame	KeyInfo
14846	12:22:07.746	FD1	Qualcomm 5G NR	NR 5G L2 DL Config
14846	12:22:07.746	FD1	Qualcomm 5G NR	NR 5G RLC UL Stats
14846	12:22:07.746	FD1	Qualcomm 5G NR	NR 5G PDCP UL Stats
14846	12:22:07.746	FD1	Qualcomm 5G NR	NR 5G L2 UL TB
14846	12:22:07.746	FD1	Qualcomm 5G NR	NR 5G L2 UL Config
14847	12:22:07.935	FD1	Qualcomm 5G NR	NR 5G RRC Configuration Info
14847	12:22:13.203	FD1	LTE RRC Signaling	PCCH: paging
14847	12:22:26.118	FD1	LTE RRC Signaling	BCCH-SCH: systemInformationBlockType1
14847	12:22:26.133	FD1	LTE RRC Signaling	BCCH-SCH: systemInformation
14847	12:22:26.133	FD1	LTE RRC Signaling	BCCH-SCH: SIB2
14847	12:22:26.133	FD1	LTE RRC Signaling	BCCH-SCH: SIB3
14847	12:22:26.622	FD1	LTE RRC Signaling	BCCH-SCH: systemInformation
14847	12:22:26.622	FD1	LTE RRC Signaling	BCCH-SCH: SIB4
14847	12:22:26.632	FD1	LTE RRC Signaling	BCCH-SCH: systemInformation

Current: 148471 Date: 12/9/2022 Total: 164775 Filtered: 164775

Table View

Configuration: rt_Clemson

	Time	Date	Latitude	Longitude	Multi RAT ...	NR_Session_Duratio...
378	12:21:57.378	12/9/2022	34.6254903	-82.7791681	N-DC 2LTE+1NR	
379	12:21:57.379	12/9/2022	34.6254904	-82.7791681	N-DC 1LTE+1NR	
380	12:22:07.562	12/9/2022	34.6268007	-82.7798693		10.184
381	12:23:54.982	12/9/2022	34.6383112	-82.7870762	LTE	
382	12:23:55.178	12/9/2022	34.6383462	-82.7871156	LTE 2CA	
383	12:23:56.179	12/9/2022	34.6384830	-82.7872738	N-DC 2LTE+1NR	
384	12:23:56.179	12/9/2022	34.6384830	-82.7872738	N-DC 1LTE+1NR	

Histogram

Configuration: rt_Clemson

December_09
VoLTE_KPIs

A: Events

Type	A Count	%
Publish Request	2	28.571
Publish Request Success	2	28.571
SIP Registration Attempt (SIP Register)	1	14.286
SIP Registration Success	1	14.286
SIP Registration Success C1 (401 Unauthorized)	1	14.286

Figure 5.3: TEMS Discovery Dashboard for Drive Test

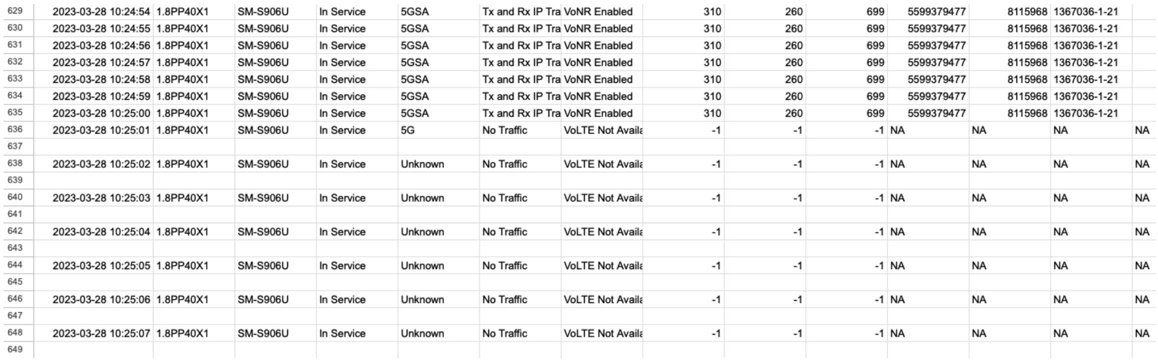
both the upload and download. So, though we did not see the full data sets, from the snippets seen, this was an issue that was anticipated we would've had to face. Another problem encountered was the application would not allow for simultaneous upload and download in the same testing script. This was an unresolved error that we were not able to workout with Infovista before the end of the working relationship. Two identical test scripts were written, just swapping the get/put, but for the testing seen in this thesis, the download test is given for the example figures in this thesis.

5.2 T-Mobile RFInsights Collection

5.2.1 First Trials of Testing

The switch to RFInsights brought about a few challenges in learning the new software and creating experiments to conduct. This took longer than anticipated as there were many bugs to be fixed and emails back and forth with the team from the commercial cellular company concerning how to properly download and fix the application on the devices. After getting a test procedure created, as explained previously in the paper, it was time to fly the UAV. On the first few test flights all at the Central site, it became evident that something was wrong in the data. For the test procedure one of the phones was set to only pick up LTE and the other phone was set to 5G. After reviewing the spreadsheets seemed that the cellular signal was cutting out mid flight for the 5G connected phone. As can be seen in the figure 5.4, at seemingly random parts of the data, the network would be lost and then sometimes seconds, sometimes minutes later it would just turn back on. These trends can also be observed in figures 5.5 showing the network that the 5G phone was connected to for the flight was disconnected from any network for over 50% of the flight. The download throughput can also be seen in figure 5.6 showing how it seemingly cut out for extended periods of test flight.

After a few flights of this occurring and meetings with representatives from the company and other universities conducting 5G testing, we came up with the hypothesis that the phones were overheating and shutting off their own connection in attempt to cool off. The LTE connected phone was seemingly having none such issues, only the 5G phone was having this thermal challenge. This showed us that 5G uses much more power to bring the higher throughput speeds, but the thermal capabilities of cellular devices have potentially not caught up to the needs of the phone. Our testing setup of housing the phones inside a plastic first aid box with copious amounts of bubble wrap allowed for no cooling and this caused the overheating problems to arise. Often times when taking



629	2023-03-28 10:24:54	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
630	2023-03-28 10:24:55	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
631	2023-03-28 10:24:56	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
632	2023-03-28 10:24:57	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
633	2023-03-28 10:24:58	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
634	2023-03-28 10:24:59	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
635	2023-03-28 10:25:00	1.8PP40X1	SM-S906U	In Service	5GSA	Tx and Rx IP Tra	VoNR Enabled	310	260	699	5599379477	8115968	1367036-1-21	
636	2023-03-28 10:25:01	1.8PP40X1	SM-S906U	In Service	5G	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
637														
638	2023-03-28 10:25:02	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
639														
640	2023-03-28 10:25:03	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
641														
642	2023-03-28 10:25:04	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
643														
644	2023-03-28 10:25:05	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
645														
646	2023-03-28 10:25:06	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
647														
648	2023-03-28 10:25:07	1.8PP40X1	SM-S906U	In Service	Unknown	No Traffic	VoLTE Not Availa	-1	-1	-1	NA	NA	NA	NA
649														

Figure 5.4: Spreadsheet showing loss of cellular connection

the phone out of the first aid box after completing a flight, they would be very warm to the touch, validating our hypothesis. With the data having many different losses of signal and irregularities, none of the tests performed with the overheating produced usable data.

5.2.2 Successful Flight Test

Overcoming the overheating problem was a large step in the success of the data collection. This came when the 3D printed mount was introduced to the testing procedure and allowed for the sufficient airflow to cool the phones as discussed prior. On the morning of May 3, 2023, at the Central, South Carolina testing site, a successful flight test took place. With the three phones attached to the top of the drone, a full test procedure was able to be completed. The first S22+ phone was set to LTE, the other S22+ set to mid band 5G and the S22 Ultra set to low band 5G. For flight conditions they were clear skies, a temperature of 62 degrees Fahrenheit, with wind speeds of 13 mph on the ground and up to 30 mph gusts in air, a 39% humidity and a UV index of 5. Almost perfect conditions for flight. Once in air, it took about 30 minutes to run through the full testing procedure. Altitudes of 400, 300 and 200 feet were flown respectively. Each altitude had three test cases at the velocities of 10, 20 and 30 miles per hour. After testing was complete, the data was reviewed and put into plots to further analyze.

5.2.2.1 Downlink Throughput

As previously mentioned, the first KPI analyzed was the downlink throughput. This describes the rate at which data was able to be downloaded from the ookla speed test server to the cell

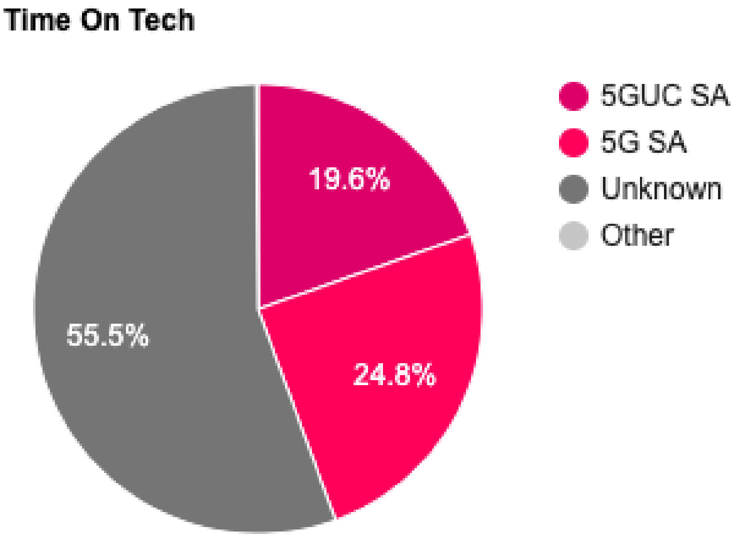


Figure 5.5: Pie chart showing cellular network usage

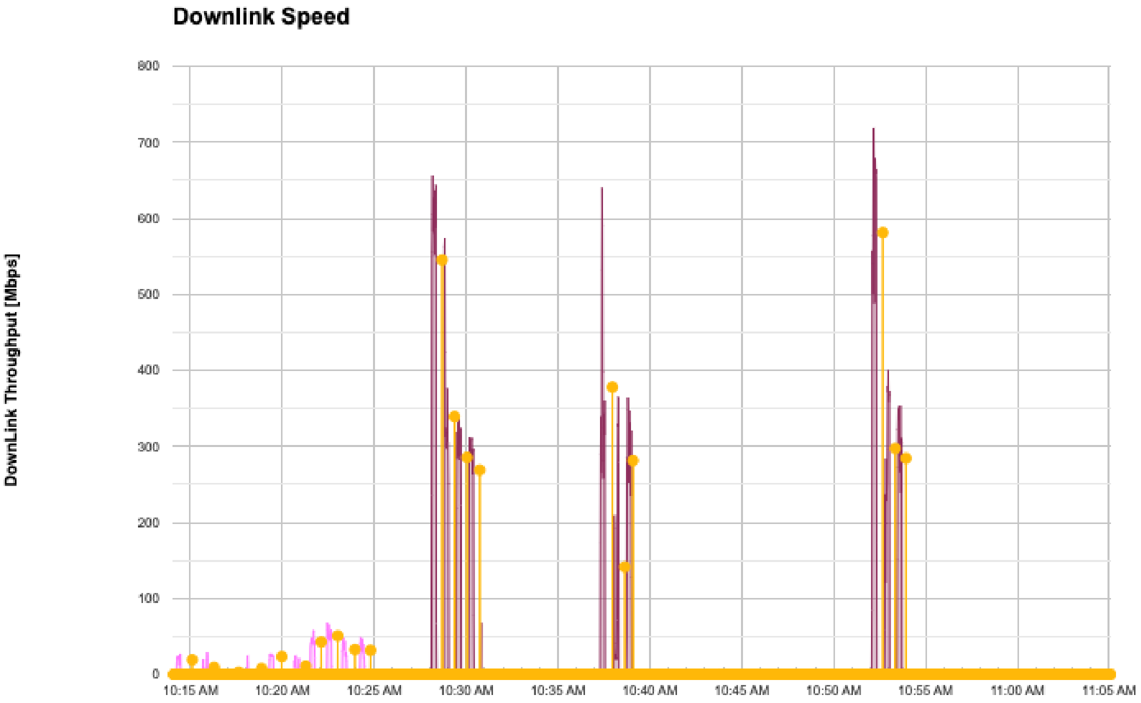
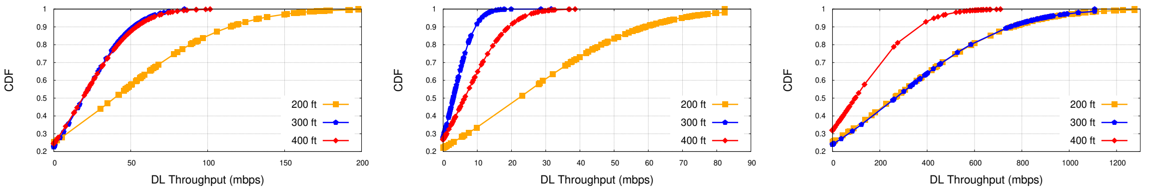


Figure 5.6: Downlink chart showing loss of cellular connection

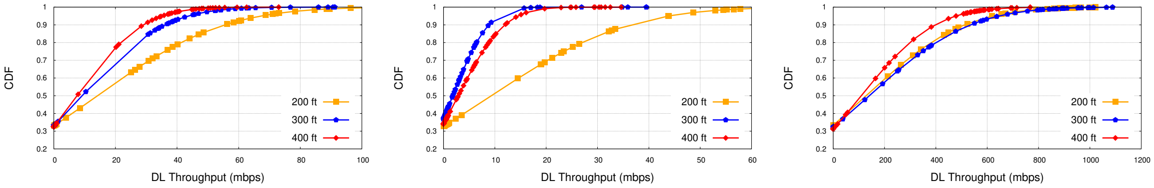


(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.7: CDF of downlink throughput for different elevations and network bands (speed=10 mph)

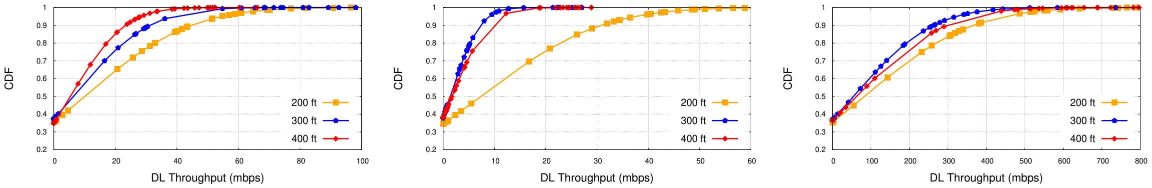
phone. This test was carried out on three cell phones on LTE, low band 5G and mid band 5G. As stated in the test procedure, the data is seen for three different altitudes, as well as three different velocities at each altitude. The first figures 5.7, 5.8 and 5.9 compare the 3 different elevations on each plot with it then being broken up by band and velocity. It can be seen that for mid-band 5G speeds at both 200 and 300 feet were often very similar with the 50% mark falling around 300 Mbps for 10 mph. This is very promising for ensuring strong mid band connection at low speeds for mid level attitudes. When flying at the faster velocity, speeds drop to around 50Mbps for the 50% mark but all three altitudes become very close. When looking at the next three groups of figures, 5.10, 5.11 and 5.12 the three velocities are compared while changing the elevation on each set and one plot for each band type. Here it is easy to see that for low band 5G, the 300 foot elevation has all three of the velocities around the same downlink throughput. Mid band continues to be shown with very strong results with the lowest velocity and altitude reaching close to 1 Gbps at times. The final set of figures 5.13, 5.14 and 5.15 change velocity for each set and elevation changes on each plot from the set. These are the least helpful of the sets of plots because of how far advanced the speeds of the mid band are, it causes the LTE and low band to be put far to the left on the plot.

The data shows very promising speeds for mid band 5G when compared to LTE downlink throughput. Results often show it being hundreds of Mbps faster when at most all of the altitudes and speeds. This can ensure a UAV will be able to download large files while at low or high altitudes and at various flying velocities. The surprising result falls in the comparison between LTE and low band 5G where throughput speeds are very similar. This could be explained by NSA being used for low band, as discussed previously, uses the existing LTE infrastructure and this could be causing these similar results. In some cases the LTE is even seen to out perform the low band. Such as in 5.13b , the LTE often is around the 30 Mbps, whereas the low band is topping out at 20 Mbps.



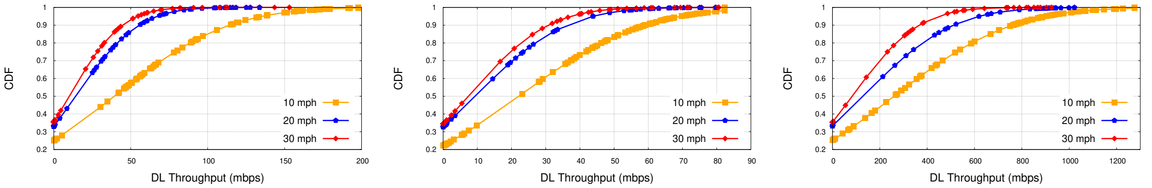
(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.8: CDF of downlink throughput for different elevations and network bands (speed=20 mph)



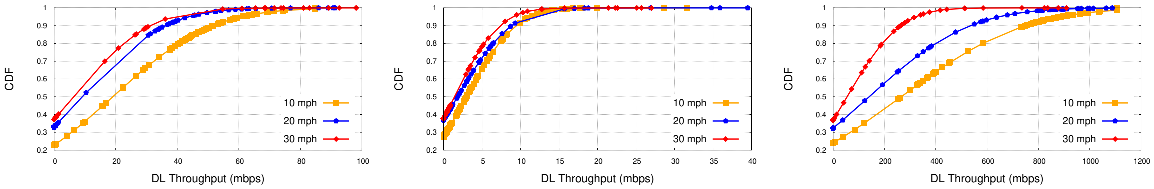
(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.9: CDF of downlink throughput for different elevations and network bands (speed=30 mph)



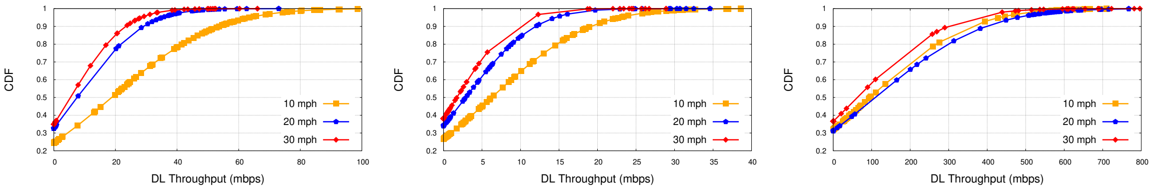
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.10: CDF of downlink throughput for different velocities and network bands (elevation=200 feet)



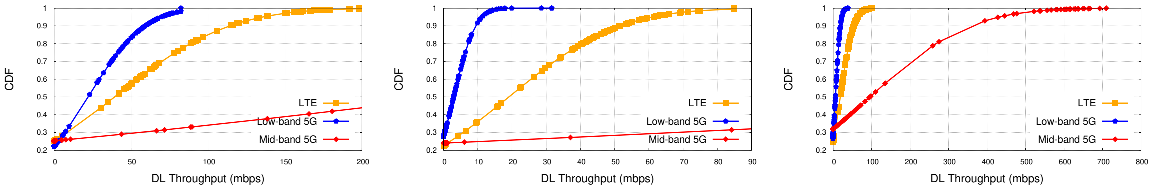
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.11: CDF of downlink throughput for different velocities and network bands (elevation=300 feet)



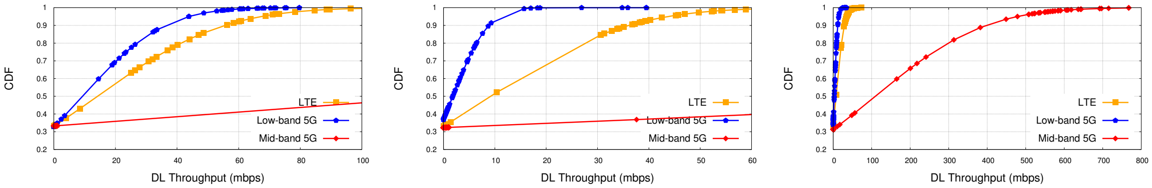
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.12: CDF of downlink throughput for different velocities and network bands (elevation=400 feet) [1]



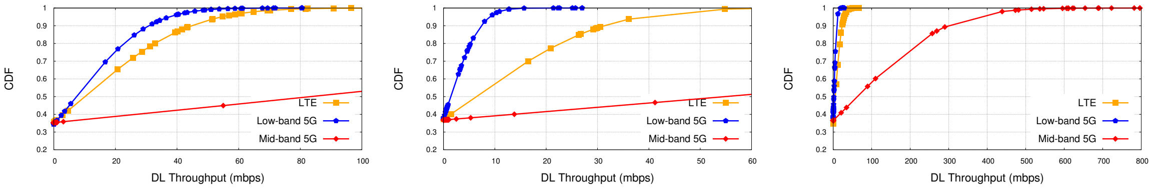
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.13: CDF of downlink throughput for different bands at constant velocity (speed=10 mph)



(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.14: CDF of downlink throughput for different bands at constant velocity (speed=20 mph)



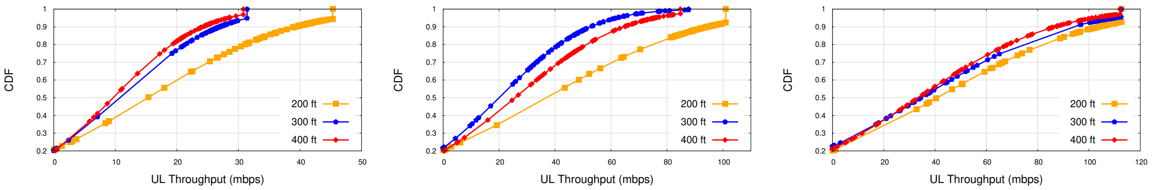
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.15: CDF of downlink throughput for different bands at constant velocity (speed=30 mph)

5.2.2.2 Uplink Throughput

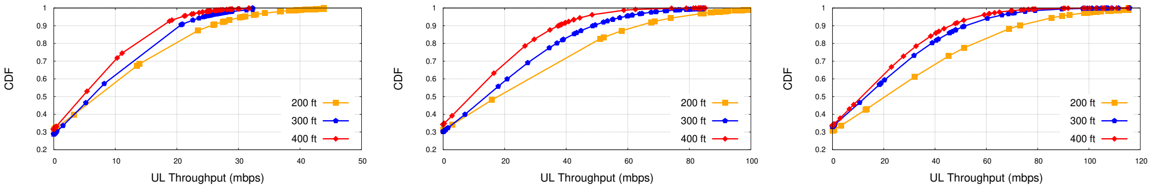
The next KPI seen in the figures is the uplink throughput. These plots are very similar to the previously discussed downlink section. This was measured by testing the maximum upload speed to the ookla servers. Similar to downlink, the three cellphones were all set to differing band types with the three altitudes tested using three velocities for each test. The first figures 5.16, 5.17 and 5.18 hold velocity constant for each group of figures and display the three altitudes for each band on the individual plots. At 10 mph all three of the altitudes show almost identical throughput values with the midpoint falling around 40 Mbps. It appears as though speed effects this as the jump to 20 and 30 mph see the midpoint of the uplinks fall below 20 Mbps. At 20 mph, the low band and mid band 5G have very similar uplink throughput. When going 30 mph, uplink for both low and mid band are still above 10 Mbps for all altitudes. The next set of figures 5.19, 5.20 and 5.21 show the three velocities on the same plot while changing the elevation in each set, with the three bands having their own plot. This makes it easy to see the effect that high speed has on all of the elevations and band types. The slow 10 mph flights are consistently outperforming the faster flying data. For mid band 5G, the 20 and 30 mph are seen to be very similar with 50% uploads still showing to be around 10 Mbps. Finally, the last set of plots 5.22, 5.23 and 5.24 have the three bands on a singular plot, changing elevation in each plot and holding velocity constant in each set. These figures make the upgrade of 5G stand out when compared to the LTE results. Both low band and mid band 5G are seen here to very clearly outperform the curves of LTE on every plot.

Overall these plots are some of the most important data which was gathered for the thesis. A huge reason for using cellular networks in relation to UAVs is for the usefulness of real time data communication. These figures have the raw data showing that low band and especially mid band have the capability to be relied upon to have sufficient uplink throughput of 5 Mbps required to send a live 1080p video stream. But with the seemingly reliable speeds seen in the mid band, especially at low speeds of almost 40 Mbps at the 50% point, there should be plenty of uplink throughput left over for other data being sent besides a single video feed. LTE on the other hand, though it shows that occasionally it has enough throughput, it certainly does not occur enough to be relied upon.



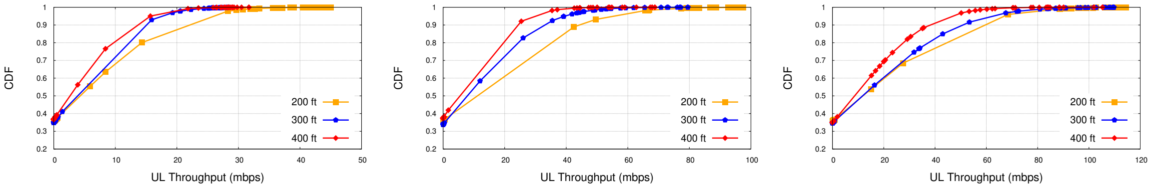
(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.16: CDF of uplink throughput for different elevations and network bands (speed=10 mph)



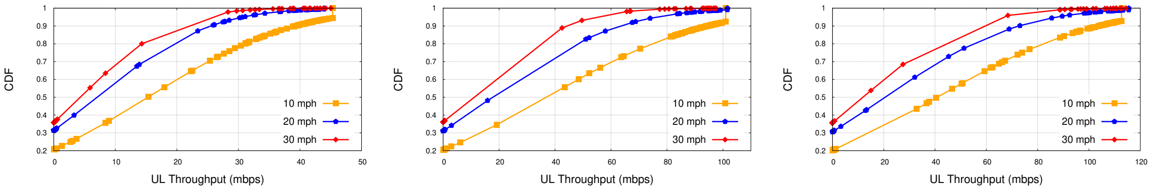
(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.17: CDF of uplink throughput for different elevations and network bands (speed=20 mph) [1]



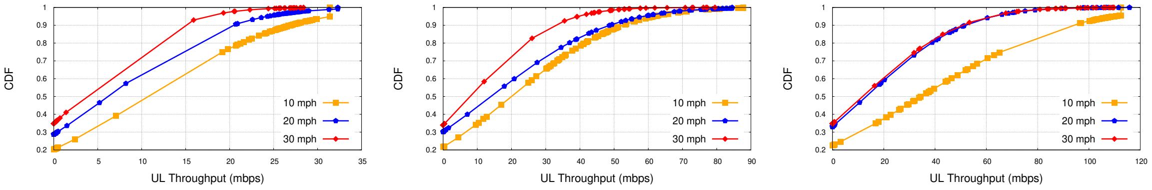
(a) LTE (b) Low-band 5G (c) Mid-band 5G

Figure 5.18: CDF of uplink throughput for different elevations and network bands (speed=30 mph)



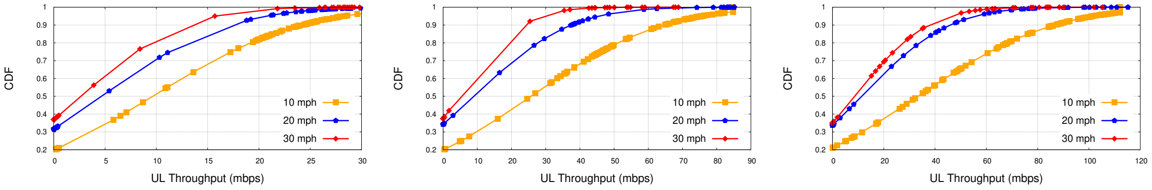
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.19: CDF of uplink throughput for different velocities and network bands (elevation=200 feet)



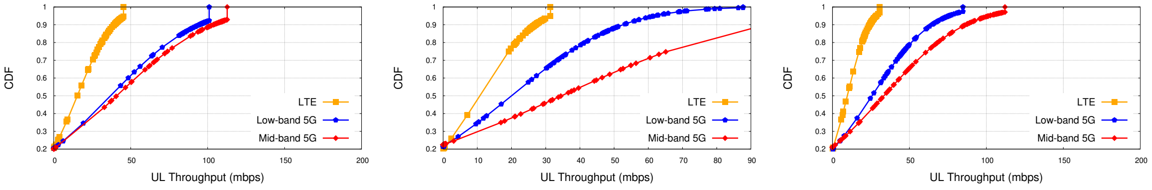
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.20: CDF of uplink throughput for different velocities and network bands (elevation=300 feet)



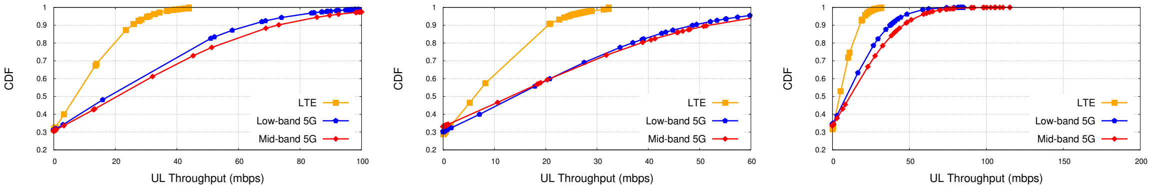
(a) LTE (b) Low-Band 5G (c) Mid-Band 5G

Figure 5.21: CDF of uplink throughput for different velocities and network bands (elevation=400 feet)



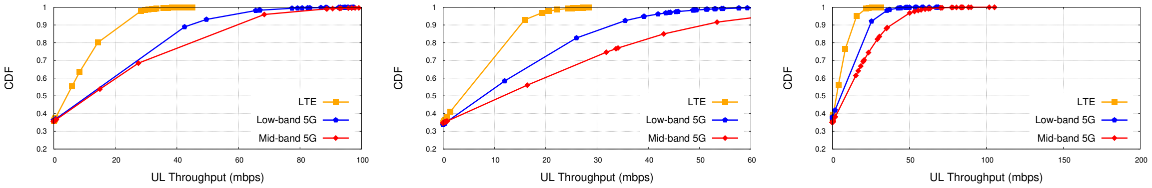
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.22: CDF of uplink throughput for different bands at constant velocity (speed=10 mph)



(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.23: CDF of uplink throughput for different bands at constant velocity (speed=20 mph)



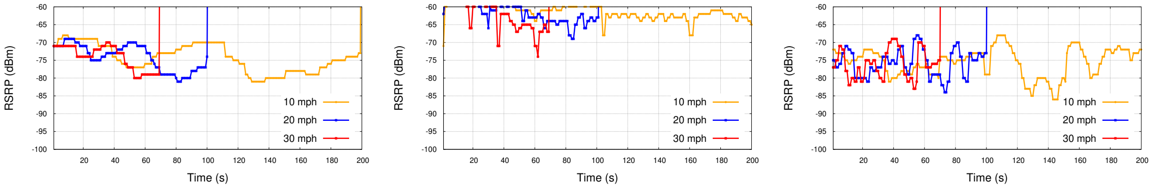
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.24: CDF of uplink throughput for different bands at constant velocity (speed=30 mph)

5.2.2.3 RSRP

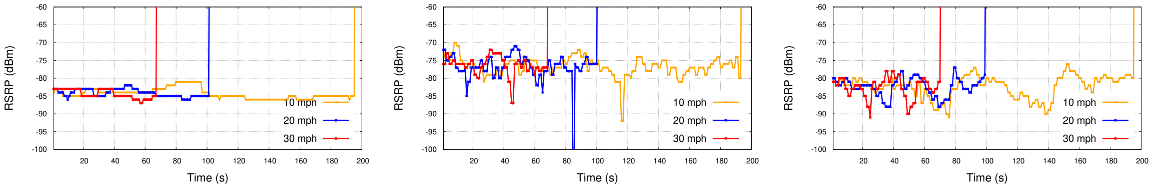
After discussing both of the throughput KPIs, reference signal received power (RSRP) follows. This measurement is the indication of power within the cellular network. The table for how this KPI is judged can be found in the previous background section. As with all of the test flights, the three cell phones are each set to a different band and the three altitudes are flown each flying the three different velocities. The first group of figures 5.25, 5.26 and 5.27 show the three velocities on each plot, while holding elevation constant across the row, with each band having its own plot. The plots show fantastic readings for all three bands when flying at 10 mph, LTE and low band almost never go outside of the excellent signal strength, above -90 dBm, category for all three altitudes a this speed. Mid band 5G briefly dips into the good category, -90 dBm to -105 dBm a few times in the 400 foot elevation but this is quickly changed back to excellent. When increasing the speed, LTE and low band 5G continue to stay well within the excellent category for again all of the elevations as seen in the plots. Mid band again has some slips into the good category, but these are not for extended periods of time and still are very close to being back in the excellent classification. The next group of plots hold elevation constant for each grouping, while displaying the three velocities on each plot for each band. These figures back up the claims seen in the previous grouping of plots, that the bands are staying within the excellent range for almost the entirety of the test flights at all velocities and altitudes. The final group of figures hold the velocity constant for each grouping while putting the three altitudes on each figure and comparing the three bands in each grouping. It is interesting to see the tiny spikes downwards at random intervals that quickly get corrected.

The third grouping of plots were the best suited to display this information as the first group was combining different time scales on one plot making it more difficult to display the information. This is because naturally, the faster velocity flights took shorter to complete as the flight path was a set distance. Nevertheless, these RSRP results are a very positive sign for categorizing low band and mid band 5G as reliable for UAV use. The received power of the cell tower signal was almost exclusively in the excellent category for the duration of the test flights at all of the altitudes and velocities.



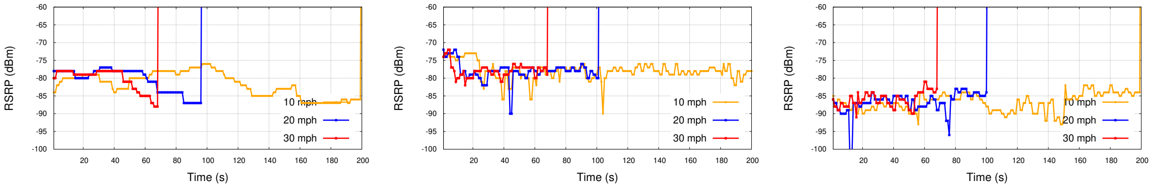
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.25: RSRP comparison for different velocities and network bands (Elevation=200 feet)



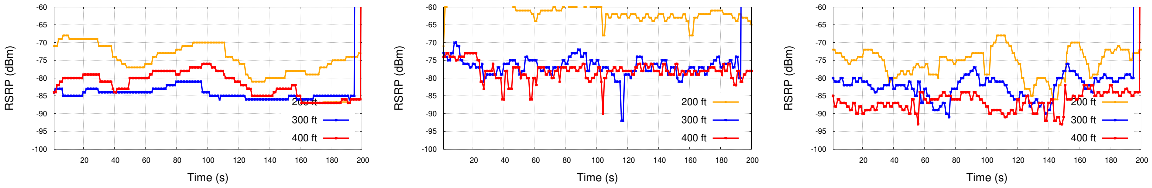
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.26: RSRP comparison for different velocities and network bands (Elevation=300 feet)



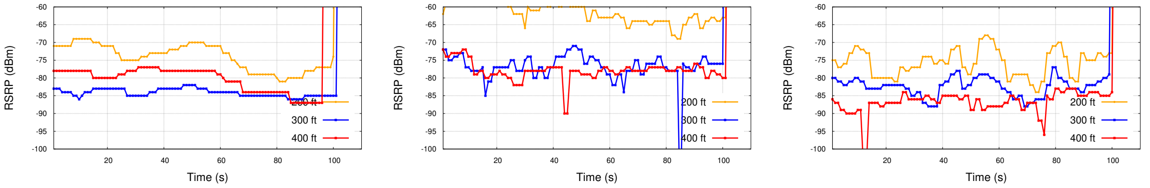
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.27: RSRP comparison for different velocities and network bands (Elevation=400 feet)



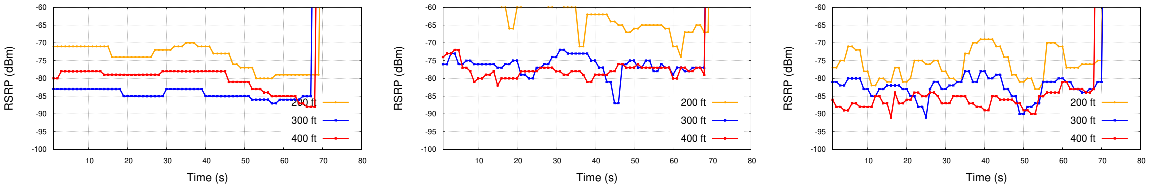
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.28: RSRP comparison for different elevations and network bands (speed=10 mph) [1]



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.29: RSRP comparison for different elevations and network bands (speed=20 mph)



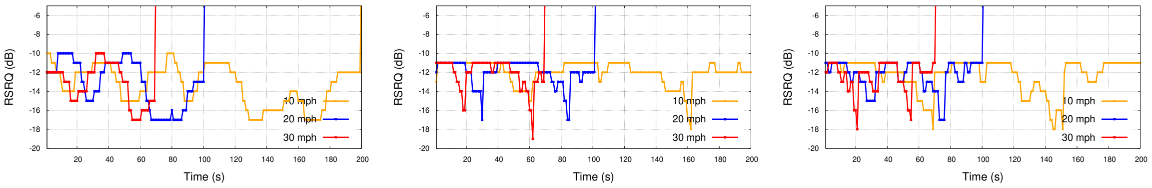
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.30: RSRP comparison for different elevations and network bands (speed=30 mph)

5.2.2.4 RSRQ

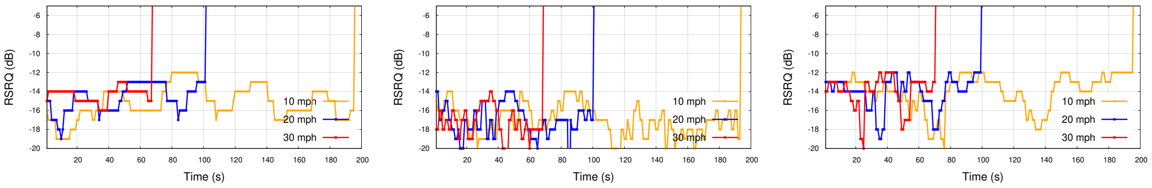
For the following KPI, reference signal received quality (RSRQ) was studied. This data point is more important for LTE than 5G, but it still can be studied for 5G signal quality. The same testing set up was utilized as described in the test procedure, with three cell phones all set to different bands. Flight tests were conducted at three different altitudes, each at the three chosen speeds. For the first group of figures 5.31, 5.32 and 5.33, the three velocities are compared on each plot as the altitude changes in each row and each band type can be seen on the individual plots. The results for LTE place it within the excellent, less than -10 dB, or good , -10 dB to -15 dB , categories for most all of the elevations and velocities with only the occasional dip below good. This can not be said the same for low band and mid band 5G as they are all over the plot. When at 10 mph the RSRQ readings have less of a change staying within the good category for most of the flight for all elevations. When increasing the velocity, the range of values increases with the results dipping into the poor results. This is at its worst for mid band 5G at 30 mph, at an elevation of 400 feet when the signal dips to poor for a few seconds. The last grouping of plots 5.34, 5.35 and 5.36 help to illustrate these trends since they have all of the altitudes on one plot for each velocity and splitting up the bands into separate plots. As previously stated, LTE holds strong results for most of the tests. With low band 5G at 200 feet also getting strong results for all speeds. Higher elevations though drop these results into the poor category. For 5G mid band, there are large swings in results but it seems as though low altitudes also are the best for this band.

RSRQ readings are not as important to 5G as they are to LTE, with RSRP being a much better KPI to use for 5G results. Therefore, some of the more poor data collected should not raise a huge red flag. Especially seeing how mid band has decent results when flying at low speeds and low elevation. In some instances the mid band was out performing the low band and this is a topic which might be explored further in future research by others.



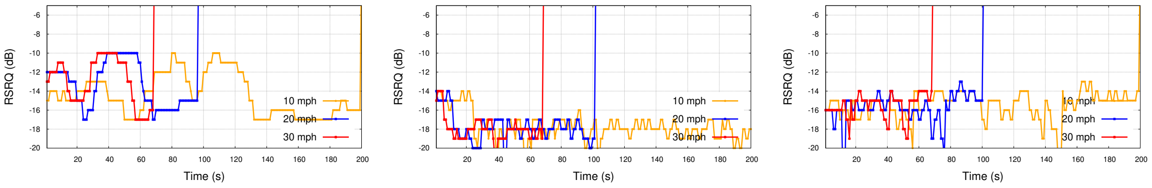
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.31: RSRQ comparison for different velocities and network bands (Elevation=200 feet)



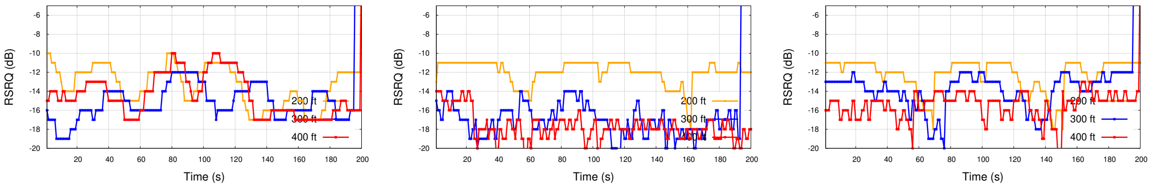
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.32: RSRQ comparison for different velocities and network bands (Elevation=300 feet)



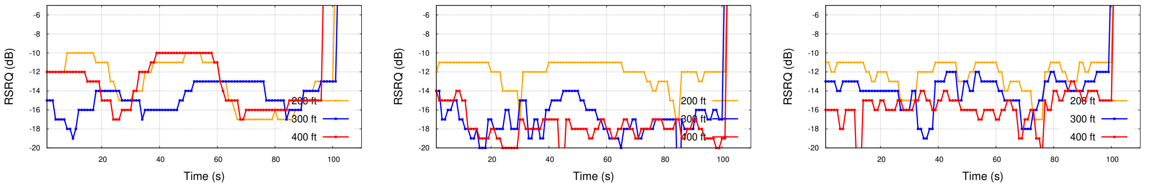
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.33: RSRQ comparison for different velocities and network bands (Elevation=400 feet)



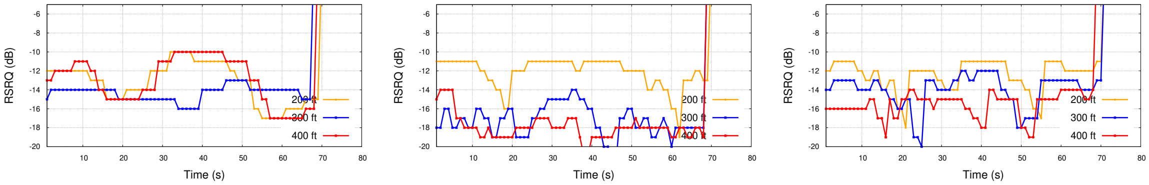
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.34: RSRQ comparison for different elevations and network bands (speed=10 mph) [1]



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.35: RSRQ comparison for different elevations and network bands (speed=20 mph)



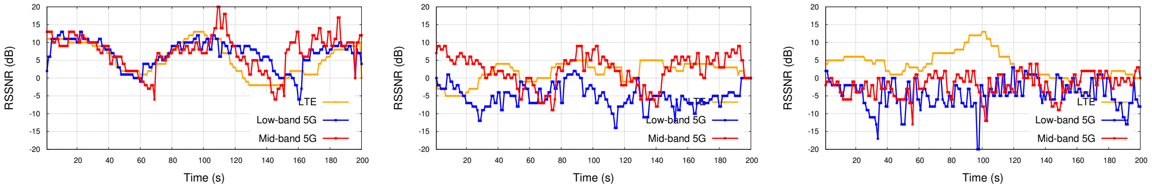
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.36: RSRQ comparison for different elevations and network bands (speed=30 mph)

5.2.2.5 RSSNR

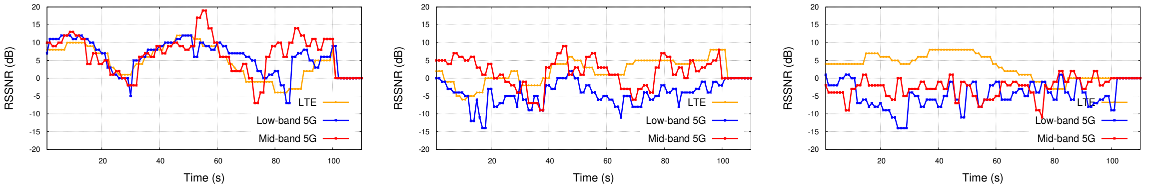
The final KPI recorded was reference signal signal to noise ratio (RSSNR). These plots show the power in reference signals relative to the noise in the signal. This is a great indication on if the signal has a lot of noise and interference or if it is clear. Test procedure was the same as all of the other KPI collections with the three cell phones all being set to differing band types. The experiments were conducted at three different altitudes, with each altitude having data collection for the three various velocities. The first group of figures 5.37, 5.38 and 5.39 hold velocity constant for each grouping, while displaying the three bands on each plot while changing the elevation from plot to plot. At 10 mph and 200 feet of altitude, the values are pretty consistent, with only a few downward spikes in the signals which all three seem to do at similar points. This leads to the impression that the noise is not just seen by one particular band, but all three which is a positive when looking at 5G. As altitude and speed increases though, LTE seems to have much better results with their plot staying above the two 5G bands for most of the duration the test. The final grouping of plots 5.43, 5.44 and 5.45 are a great way to compare the effect altitude might have on the signals. LTE shows itself to consistently stay within the good range with only the occasional downward trends. Low band and mid band 5G are all over the plot with very large swings in values. The trends show that signal is better at lower altitudes and that speeds does not seem to have a major effect on the results.

Overall the results of the RSSNR plots are mostly positive. This is because the greater trends show that when LTE encounters noise, the 5G does as well. Noise should be expected when flying at higher altitudes with the antennas not optimized for aerial use. Also with commercial ground users noise should also be expected. Therefore, in a perfect world RSSNR will be excellent, this will not be achieved constantly on a commercial network.



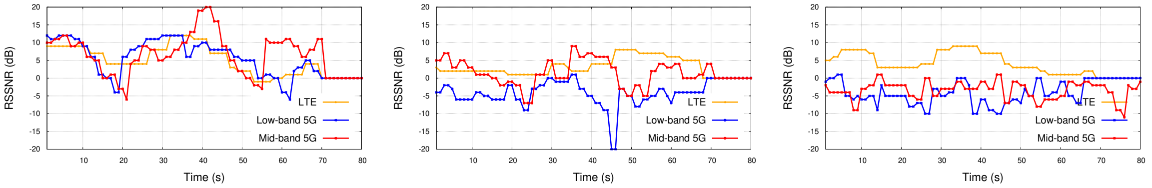
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.37: RSSNR comparison for different elevations and network bands (speed=10 mph)



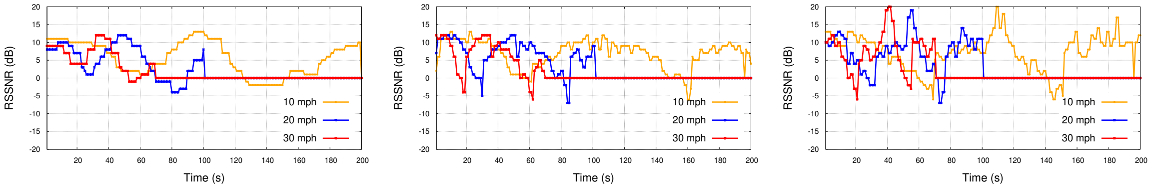
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.38: RSSNR comparison for different elevations and network bands (speed=20 mph)



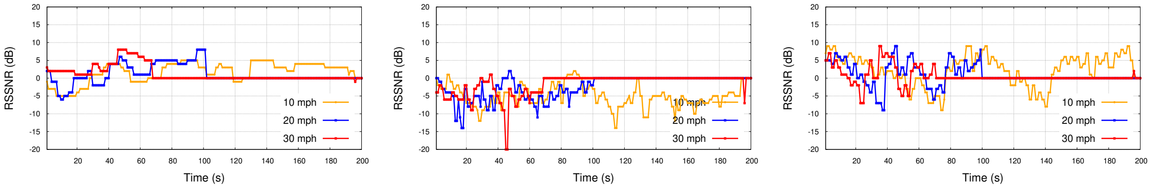
(a) Elevation 200 feet (b) Elevation 300 feet (c) Elevation 400 feet

Figure 5.39: RSSNR comparison for different elevations and network bands (speed=30 mph)



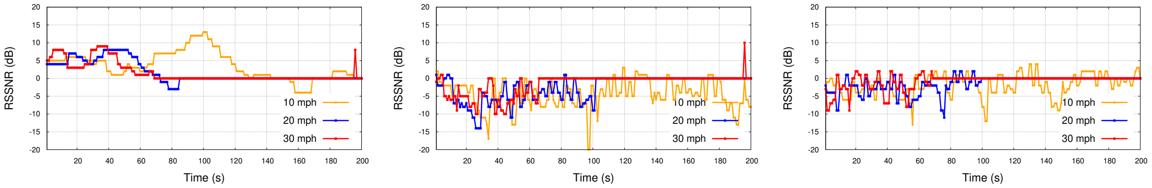
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.40: RSSNR comparison for different velocities and network bands (Elevation=200 feet)



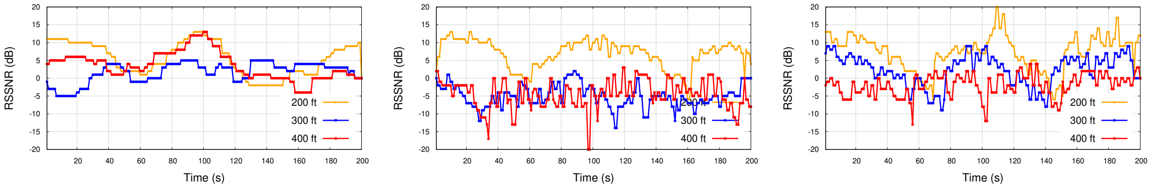
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.41: RSSNR comparison for different velocities and network bands (Elevation=300 feet)



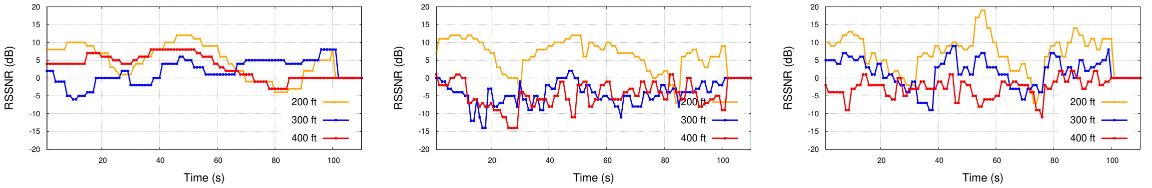
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.42: RSSNR comparison for different velocities and network bands (Elevation=400 feet)



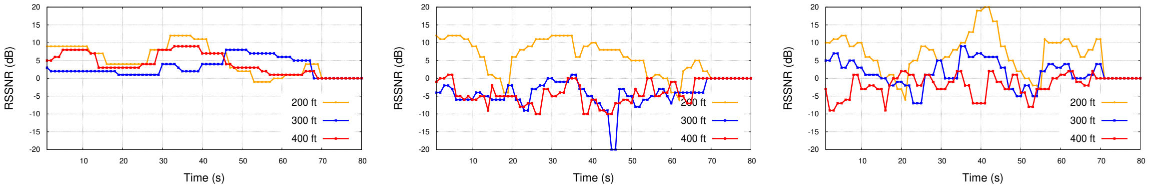
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.43: RSSNR comparison for different elevations and network bands (speed=10 mph) [1]



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.44: RSSNR comparison for different elevations and network bands (speed=20 mph)



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.45: RSSNR comparison for different elevations and network bands (speed=30 mph)

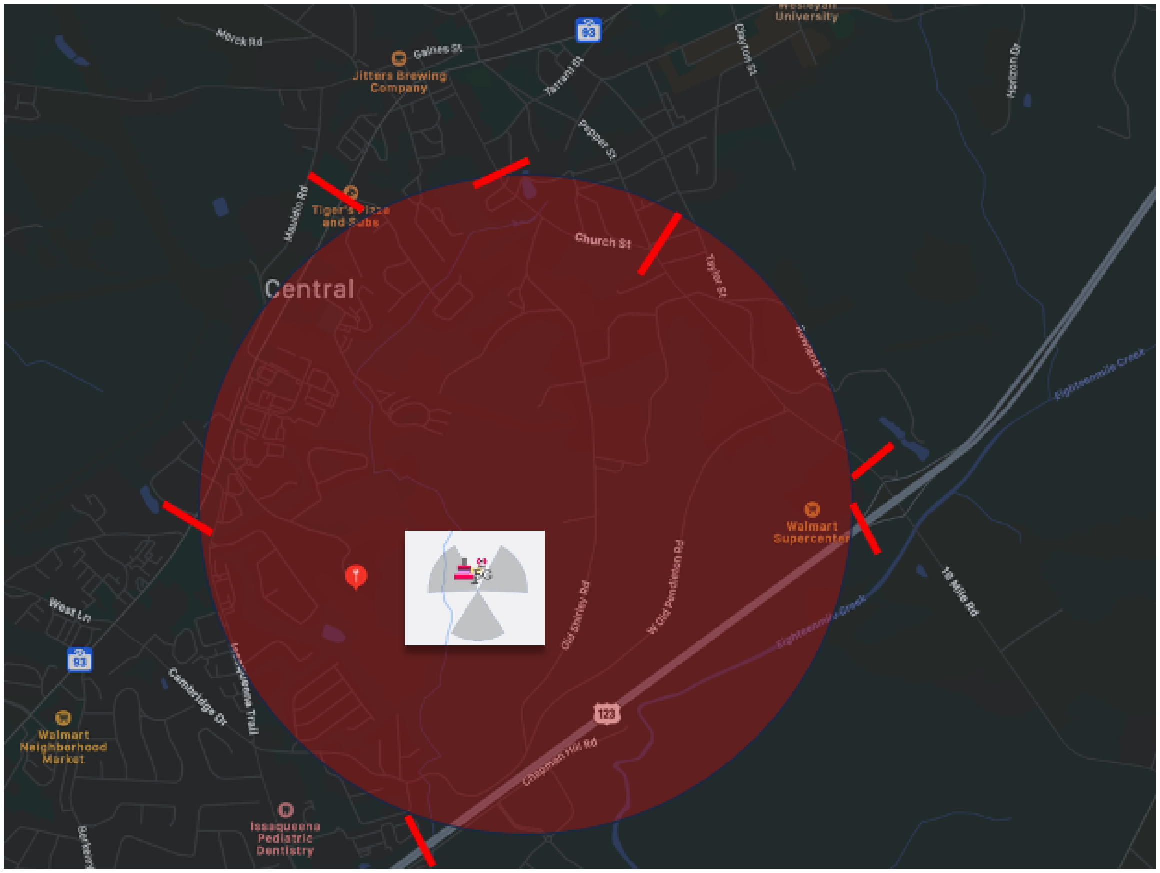
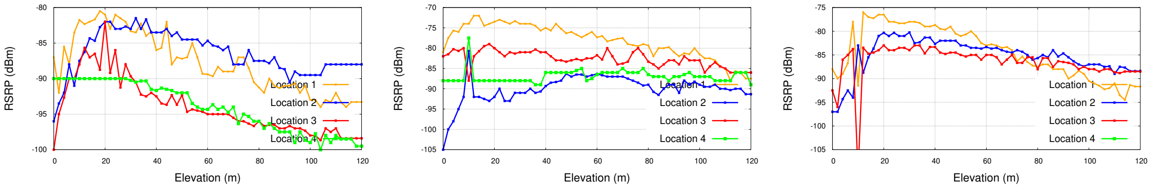


Figure 5.46: Coverage Map for Central, South Carolina Tower

5.2.3 Coverage Mapping and Column Testing

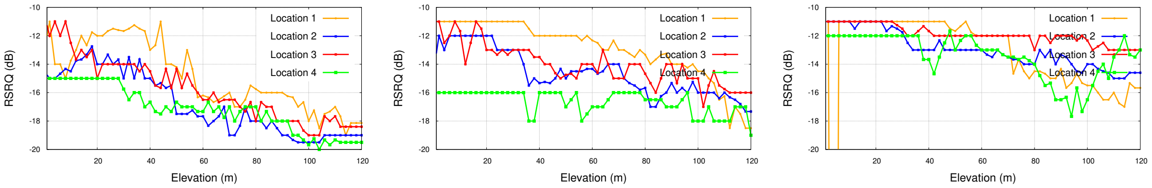
As discussed in the research design section, this test was completed to have an understanding of the outer boundaries of the cell tower which was being used for data collection, the Central, South Carolina tower. This data collection took about two hours worth of driving around the area to find the network boundaries. The final map can be seen in figure and as can be observed, it is not a perfect shape with the tower in the center. The tower is located towards the southern part of the coverage area. This is due to other cells being in the area. With more cell towers to the southeast, which is towards the University, the phone was found to begin to jump to stronger signals. This event was the opposite to the north of the tower, because in the rural town of Central, South Carolina there are far fewer network options so the cell tower stretched its signal further to the north.

The coverage mapping was completed so we could perform our last test, the column flights. As seen in the test procedure, we picked 4 sites along the outskirts of the coverage zone. The drone



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.47: RSRP plots for column flights



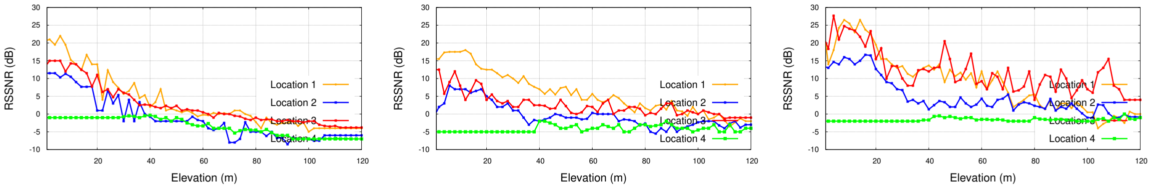
(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.48: RSRQ plots for column flights

was flown up and down in attempt to see if signal is improved when flying at an altitude from a ground optimized network. The results seen in 5.47, 5.48 and 5.49 are pretty inconclusive and not too many results can be drawn from them. This is due to lack of testing sites and a few of them being either too far inside or outside the true coverage region. This problem is tough to avoid when flying in areas with many roads and property lines, it becomes increasingly difficult to find places to fly. This test would need to be recreated in different circumstances with more of an open and accessible land area.

5.3 Comparison of Software Platforms

Both software platforms have their own unique sets of pros and cons. Starting with TEMS Pocket, from reading the user manual and other papers using the software, it is evident that it



(a) LTE (b) Low-band 5G (c) Mid-Band 5G

Figure 5.49: RSSNR plots for column flights

provides a wealth of useful KPIs. There is no such thing as too much data when the data is provided within spreadsheets along with a very user defined dashboard. It also collects data in time intervals in the hundredths of seconds. This is very helpful in collecting handover data as it has been found that these can occur in as short as 10ms on 5G networks. TEMS Pocket will give all of this handover data within the reported data. TEMS user interface also gives a detailed list of the LTE and 5G cells that it can see from where the phone is, this list gives cellID, channel, band and RSSI along with other metrics. This could be a helpful piece of information for the group testing depending on test procedures. TEMS is can also be highly personalized in most aspects of the app, from what KPIs are collected, to the test script for data collection, only collecting different bands or cellIDs. Overall the TEMS Pocket application is able to be highly personalized to fit test procedures.

To begin with some of the drawback of TEMS Pocket, the major one which this thesis had direct impact from was the need for the TEMS Discovery license to be able to interpret any of the data from the log files. This was a major inconvenience having to go through another party to get the files. The high price of these licenses makes it difficult to get them easily under a university research budget. Another drawback is having no map of the cell towers, either in the application or in the data. This often times makes it tough to find where the cellular base stations are located as this information is often not posted directly on the internet. Tower locaters rely on user inputted data that is often not very accurate to the actual position of the towers. This is also made harder with 5G being so new, positions online are lacking. The group struggled to correctly locate and identify which towers were connecting to the phone when using TEMS pocket. Script writing was a challenge on this application as stated prior, with the upload and download not being able to run simultaneously in one script. The application not having a dedicated server for file transfer, made the throughput testing harder to set up than it should have been.

For the RFInsights application, a big positive is the map tab on the application. Being able to see in real time the tower the phone is connected to on a map, along with tower identification metrics such as ID number and bandwidth. On the map the different bands were seen in a graphic on the tower location, making it easy to identify testing locations that had low, mid, or mmWave 5G coverage. The next major advantage to RFInsights was the log files creating a simple .txt file to the phones internal storage. This makes accessing and reading log files quick and easy. Having ookla speed testing as a function of the application, makes throughput testing simple. This saves the hassle of setting up a dedicated server for file transfer and the readings are accurate and automatic, unlike the procedure which had to be done in TEMS pocket.

One of the major drawbacks of the RFInsights application is the data collection time, with the application collecting data every second. This time interval is not able to be changed and is a big drawback for the application as cellular network information is changing constantly and this is far too long of an interval. As stated before, handovers on 5G are found to occur in as small a time as 10ms, so this app could miss all of the fast occurring handovers. RFInsights also does not collect any unique handover information when they do occur in the one second time, which is something that the group wanted to be able to investigate further for trends. This application is highly set in the way in which it was constructed and not customizable like TEMS is. It overall does not seem to focus on user experiments, rather just the metrics which the commercial cellular network corporation wishes to see. With the app still in its first few month, there are many bugs being actively fixed and even the log files often have blank columns missing information because the metrics have not been fully developed into the application yet.

5.4 Discussion of Results

The results shown from the data are very positive for the implementation of 5G cellular networks into UAV use. The most promising results can be seen in the uplink throughput. The data shows that both low band and mid band 5G can be reliably counted upon to have speeds sufficient enough for transmitting live video. The data showing that the lower altitude gives the most throughput is also an encouraging sign, as it shows that if cellular providers optimize their antennas through tilt angle and software solutions for aerial users, throughput will grow even larger. These strong uplink results are also seen in the downlink as well. Though the UAV will not have to download excessively large files, knowing that mid band is occasionally pushing 1 Gbps while at an altitude is a big accomplishment for cellular providers. The most important of the other KPIs for 5G, RSRP, was almost always in the excellent category for low and mid band 5G. So as stated before, with cellular networks continuing to consider the effects on opening up for aerial users, this infrastructure is prepared.

For other experiments, the column testing was a great concept to explore, but the tools and location in place might not have been the best for it. RFInsights not giving handover information is a large part of this reason, as we were testing at the edges of a tower, so it is important to know where in the sky a handover might be occurring. Also finding good locations right on the edge of the network was hard as it fell within residential areas and busy streets. This would be a great experiment to be set up in a more controlled location with TEMS Pocket collecting data.

Troubleshooting the overheating problem was a big break through for the project. Seeing multiple data collection flights go to waste with large portions of the data missing was very discouraging. Working through the problem and then custom designing a mount to fix this problem offered a very unique element to this project. The thermodynamic challenges which 5G seems to present are going to have to be extensively studied in the application of the UAV being connected. It is clear that 5G does have the capability to offer two way communication, with low latency and reliable signal strength, but that will all go to waste if the internal antenna overheats and the UAV is constantly losing the connection or even worse melts its own components. Therefore, UAV makers and pilots need to be very careful with integrating 5G connectivity into their plan and make sure the proper steps are taken.

Chapter 6

Conclusion

6.1 Conclusions

The unmanned aerial vehicle industry is rapidly expanding with new operators trying their hand at flying every day. The tasks which drones can achieve are also growing every day, with new features and add-ons being added to beginner drone kits and new high tech options pushing the boundaries in professional models. Improvements in camera technology, battery capacities and downsizing of computer components are making it more of a reality to use drones for everyday tasks which they can be set-up to complete. With reliable communication protocols, the industry will see an even larger boom in their usefulness.

After completing data collection on a commercial network for three bands, LTE, low band 5G and mid band 5G it is seen that mid band 5G allows for strong enough characteristics to support UAV flight with data transfer. This was especially proven with the very strong uplink throughput seen from mid band 5G in the results section, with plenty of throughput to transmit 1080p video as well as space for other data. With the reliable connection offered by mid band, the throughput will allow ground users to monitor the information being received from in air. As discussed, the low band results are also very strong and could also sustain UAV two way communication. The results for the RSRP KPI staying in the excellent category in both low and mid band 5G at all of the different velocities and altitudes shows that the signal power is strong enough as well. This will only improve as cellular providers focus on this aerial market and begin to tilt antennas upwards and optimize the software. Therefore, the KPIs shown in the results section have proven the increased quality of 5G networks and their abilities to improve connectivity for aerial users over the previous LTE infrastructure. This can help lead to the use of drones for an increased integration into the daily lives of people. This will be very useful in cases like fighting wild fires and being first on the scene for emergency responders to gather useful information when every second matters. The guarantee of reliable communication and cellular signal could cause the FAA to begin to allow beyond line of site flying. This can move the industry ahead even further with users not having to always stay within visual contact of the device being flown.

It is clear that commercial cellular providers are interested in joining the aerial unmanned vehicle market, as shown by a privately owned cellular provider's commitment to funding this research project. They see the potential in this largely untapped market. Their next steps will involve tuning antennas upwards to focus on the aerial users versus the current networks which are tuned towards terrestrial users as we tested upon. It could also involve allocating certain bands of their coverage to only drone users to avoid buffering and low bandwidth caused by ground users. There are lots of steps which the networks can take to help improve the infrastructure for the drones.

There have been many set backs and struggles with the test procedure for this thesis. Hardware problems caused by thermodynamic setbacks, causing us to design and print a brand new mounting piece on our own. Software changes also offered a unique set of challenges mid-testing, having to essentially start over in the collection process. Showing the often difficult nature of dealing with many different entities in research. All of these challenges were overcome with unique solutions and allowed for the completion of the project.

6.2 Recommendations for Further Research

There is lots of room for continued experiments and learning within this research area. As discussed, this thesis only collected low band 5G and mid band 5G data as this was the only options in the area. These trials should be expanded to include mmWave 5G signal as this is the most high tech and quickest signal commercial available today. With the small commercial rollout only occurring within the past few years, it is difficult to find a testing ground for these trials. mmWave also has many limiting factors such as weather, environment type, and obstructions. As previously discussed in the background section, this is anticipated to be the most difficult type of 5G to use as antennas often have to be pointed directly at the receiving device and unobstructed by anything including buildings and nature. Weather also has been seen to have a negative impact on mmWave, as rain causes increased attenuation and wind makes the antennas shake. Therefore, this research area should be focused on in future work.

With the switch to the RFInsights application, the group lost the ability to collect handover data. With their 1 second data collection time, many of the small handovers were completely missed. This is believed to be a major factor in the viability of integration in using 5G for drone communication, so this is a focus area to be looked into in further testing. Using a new data collection software, which has a shorter time between collection points, will be necessary to complete this task.

Thermal effects should also be explored, as it was seen that the cell phones used for testing often could not handle the high temperatures. These were caused by the constant high throughput on mid band 5G. Research published within the past year has shed a light on this potentially major issue, especially with mid band and mmWave [63]. Their findings included massive temperature increases felt on the exterior of the cellular device when throughput was sustained for long periods of time. Thermal characteristics of both the drone and the controller when under high throughput situations could potentially be a limiting effect on the abilities of the UAV. For use cases such as fighting wildfires, real time images and video feed need to be sent back to the ground, which will incur the need for a high throughput. The ensured reliability of the drone needs to be proven before it is put into a potentially high risk situation and the connection unexpectedly cuts off after the device overheats. These three focus areas discussed are the next steps which I believe should be taken in the research.

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