



WIRELESS TECHNOLOGY FOR THE FLIGHT LINE OF THE FUTURE: A MULTI-
CRITERIA DECISION MAKING AND UTILITY THEORY ANALYSIS

GRADUATE RESEARCH PAPER

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Abstract

To stay competitive and innovative, the Air Force needs to exploit all technological advancements. One of these advancements is sharing information between devices wirelessly on the Flight Line with the right quality of service for the situation. The flight line must be connected in order to rapidly share information which will require Wi-Fi, Cellular, 5G, or Satcom connectivity. The national rollout of 5G and the next generation of Low Earth Orbit (LEO) Satellite Communications (Satcom) constellations present not only an opportunity to catch up, but also to revolutionize the way the Air Force operates (Johnson K., 2019; Cohen, 2019).

This research used multi-criteria decision making and utility theory to choose the best wireless network based on coverage, throughput, hardware, reliability, and latency. The wireless networks considered were current state (Wi-Fi), upgraded Wi-Fi, 5G mmWave, Long Term Evolution, and Low Earth Orbit Satellite Communications. The data was obtained from a combination of field measurements, software simulations, literature, and a link budget calculation that uses modeled atmospheric radio propagation losses.

The satellite communication alternative was preferred for two of the three methods, while upgraded Wi-Fi infrastructure was the preferred alternative using utility theory. This research highlights a need for enhanced infrastructure on large flight lines. Two alternatives require electrical power, and both Wi-Fi and 5G will require power and backhaul (either fiber optic, microwave, or Satcom).

AFIT-ENS-MS-20-J-042

To my wife.

Acknowledgments

This research wouldn't be possible without the help of my advisor Lt Col Jason Anderson, and my sponsor Mr. Ward Walker, AMC/A6 CTO. I also thank Mr. Blair Nicodemus, AF/A4PA, for his technical review and advice.

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BEST WIRELESS TECHNOLOGY FOR THE FLIGHT LINE OF THE FUTURE: A MULTI-CRITERIA DECISION MAKING AND UTILITY THEORY ANALYSIS

I. Introduction

General Issue

Airmen cannot do their jobs without a network connection. The United States Air Force has failed to invest enough in information technology, and as such, faces challenges and opportunities as it tries to modernize (Fantini and Sotiriadis, 2020). The national rollout of 5G and the next generation of Low Earth Orbit (LEO) Satellite Communications (Satcom) constellations present not only an opportunity to catch up but to revolutionize the way the Air Force operates (Johnson K., 2019; Cohen, 2019).

Information Technology challenges and future technology opportunities are evident in the concept called Flight Line of the Future or FLoF. The FLoF aims to connect not only the Airmen, but also the aircraft, sensors, and maintenance equipment. Currently, maintenance Airmen are connected through Wi-Fi managed by a program management office called the Base Information Transfer Infrastructure program or BITI for short (Welsh, 2013). BITI is a major acquisition program and faces pressures to reduce program scope to reduce costs (SAF/AQ, 2017; DoD, 2016). Consequently, the wireless technology for the flight line is lacking, which leads to the problem statement.

Problem Statement

To stay competitive and innovate, the Air Force needs to exploit all technological advancements. One of these advancements is rapidly sharing information between devices wirelessly on the flight line with the right quality of service for the situation. The flight line must be connected in order to rapidly share information, which will require Wi-Fi, Cellular, 5G, or Satcom connectivity.

Research Question

Using multiple attribute utility theory and multiple criteria decision making, what is the best wireless technology for the Air Force Flight Line of the Future, with respect to coverage, throughput, latency, hardware, and reliability?

Investigative Questions

1. Which bands and how much Long Term Evolution (LTE) bandwidth are in use at the test location?
2. Which quality of service attributes are best-suited to assess wireless systems on the flight line?
3. Which wireless network is preferred using Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Utility Theory?

Methodology

This paper uses multi-criteria decision-making, and utility theory to pick the preferred wireless network using five different attributes: Coverage, throughput, reliability, hardware, and latency. The coverage and throughput attributes treat downloads and uploads equally (a weight of .5). Additionally, the hardware attribute is made of a power draw and antenna surface area sub-attribute, depicted in Figure 1.

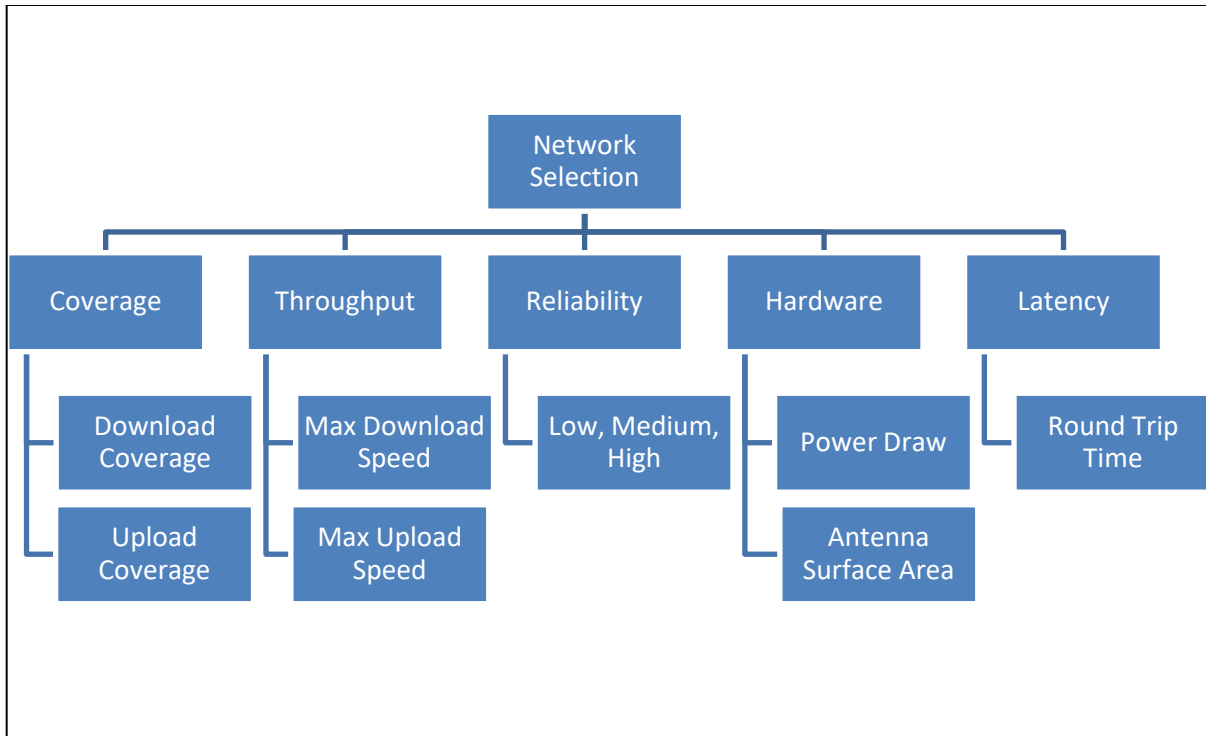


Figure 1 Attribute Hierarchy

There are five different wireless technology alternatives: Wi-Fi (current state), LTE, 5G mmWave, upgraded infrastructure, and Low Earth Orbit Satcom. The current state is the BITI wireless system, and LTE is the cellular system around Joint Base McGuire Lakehurst Dix (JBMDL), New Jersey. The 5G alternative represents a hypothetical employment of 5G mmWave on the JBMDL flight line. The Low Earth Orbit Satcom alternative is based on a full implementation of Starlink's first orbital shell, and a receiver with a clear line of sight on JBMDL's flight line. The upgraded infrastructure uses the same equipment that BITI uses, enables the 802.11AC protocol (phasing out of 802.11G and 802.11A), and moves the access points to the flight line parking spots.

The data for the alternatives was collected using field measurements, software simulation, estimates based on literature, a Satcom link budget, and an assessment of reliability. Because LTE and Wi-Fi are available, they were measured using field tests. The other alternatives are currently not available at JBMDL, and the author assessed those using

different methods. Table 1 summarizes which data collection method is used for a particular alternative, and the specifics are covered in the methodology chapter.

Table 1 Data Sources						F – Field Tests S – Simulation Software L – Literature LB – Link Budget R – Reliability
Wireless Tech	Coverage	Throughput	Hardware	Latency	Reliability	
BITI Wi-Fi	F	F	L	F	R	
LTE	F	F	L	F	R	
5G	S	S	L	L	R	
Upgrades	S	S	L	F	R	
Satcom	LB	LB	L	L	R	

Assumptions and Limitations

General Assumptions

There are several assumptions necessary in this study. The assumptions and limitations concern the field tests, software simulation, hardware, and using the link budget calculation.

Field Test Limitations

To make an inference about other Air Mobility Command (AMC) flight lines, two assumptions are necessary. One being that similarly sized ramps with comparable or the same aircraft will exhibit similar radio propagation environments. Furthermore, the LTE coverage may have better or worse coverage based on the distance between the ramp and the towers and the amount of surface clutter (trees, buildings, and other structures). A second assumption is that field measurements at JBMDL represent similar performance (coverage, throughput, and latency) compared to similar AMC bases.

The author used the commercial site speedtest.net to assess throughput for LTE and Wi-Fi. There are several limitations to using speedtest.net. For the Government Wi-Fi, the proxy server might be caching files used in the test, which could artificially inflate the results.

However, proxy caching could also improve the performance of a wireless system. As such no adjustment or consideration was made for proxy caching. A limitation with this approach (concerning LTE) is that carriers could be giving precedence to the site, a technique allegedly used on broadband tests (Ramachandran, Lillian, and FitzGerald, 2019). However, speedtest.net is broadly used to measure real-world system performance in the information technology industry.

Software Simulation Limitations

There are several limitations when using software to simulate a wireless system. Software modeling depends on capturing accurate inputs and being careful not to use the model in a scenario for which it was not designed. To combat these limitations, the author used inputs from an authoritative source; the Federal Communication Commission (FCC) to transmit power, for example. A limitation of the software package used is that it only models rectangular objects. Most features on the flight line are rectangular, save the airplanes, which have no flat surfaces except for the lifting and control surfaces. As such, the flight line was modeled without airplanes for the upgraded infrastructure and 5G mmWave alternative. Due to the placement of the access points in these scenarios, the communication mode is the line of sight, meaning that the modeling of tubular-bodied aircraft is not a primary concern.

Hardware Limitations

The ease-of-use, size, and other characteristics of the hardware of the Flight Line of the Future are important. For example, experience has shown that rugged lightweight devices are preferred (Nicodemus, 2020). To use Satcom on the flight line and in this study, we have to assume that the Satcom terminal has a Wi-Fi router, and it is situated close enough to a user to be useful. In other words, the Satcom alternative assumes that the end hardware is a laptop, tablet, or cell phone connected via Wi-Fi to the Satcom terminal.

Link Budget Limitations

The link budget calculation for Low Earth Orbit Satcom is detailed in the methodology section and involves adding or subtracting radio power gains or losses to determine the possible maximum throughput and coverage. Similar to the software simulation, the link budget depends on using accurate inputs. A current limitation of using this approach is that performance details about Starlink's user terminal remain a trade secret. The author used the same values employed by del Portillo et al. (2019), comparison of three Low Earth Orbit constellation proposals. In addition, if the values for the user terminal do change, it is not likely to improve the coverage and throughput significantly as the terminal accounts for only half of the link budget. Another limitation in the link budget is the use of estimated atmospheric losses. The losses are modeled after the International Telecommunications Union's (ITU) recommendation on modeling atmospheric losses for satellite systems, which are used extensively in the initial design phase of new wireless systems (ITU-R, 2017).

Implications

Choosing the right wireless network or networks for the FLoF is germane to the Department of Defense's (DoD) Joint All Domain Command Control (JADC2) concept. JADC2 is all about connecting the right system and sensor with the right person at the right time (Fantini and Sotiriadis, 2020). In some ways, finding the best wireless network(s) for the FLoF is much easier than the JADC2 problem-set, due to the small size of the flight line; however, the lessons learned from the FLoF will help make JADC2 a success.

Low Earth Orbit Satcom, specifically a project called "Global Lightning", has large implications for JADC2, and possible the FLoF. Global Lightning is run by the Air Force Research Laboratory and aims at using commercial Satcom aboard various aircraft (Cohen,

2019). The fact that there might be multiple Low Earth Orbit constellations available is an opportunity to reduce costs due to competition, and to have improved global coverage.

This work also fills a gap in research for field testing a large flight line. The other recent wireless testing studies were conducted at airfields with smaller aircraft parking areas, which may have a different radio environment. Additionally, this study incorporates the latest Starlink orbit and constellation changes.

II. Literature Review

Chapter Overview

This chapter explores some of the recent literature in wireless network selection, wireless standards and measurements, and wireless technology considerations.

Network Selection

Recent literature highlights the network selection problem. The problem involves choosing the best network based on the quality of service or other attributes. The issue has broad implications for the Air Force as selecting the best network is a concern of the Joint All Domain Command and Control concept.

Some of the specific methods used in network selection are Simple Additive Weighting, Technique for Order Preference by Similarity to Ideal Solution, Gray Relational Analysis, Weighted Product, Analytic Hierarchy Approach, Knapsack Optimization, Utility Theory, and Game Theory (Senouci, Hoceini, and Mellouk, 2016; Vangelis, Alonistioti, and Merakos, 2005; Watanabe, Menasché, De Souza E Silva, and Leão, 2008; Agrawal, Jeyakumar, and Pareek, 2016). The author chose to use Simple Additive Weighting, Technique for Order Preference by Similarity to Ideal Solution, and Utility Theory to pick the best network. These methods were chosen for their simplicity and the ability to implement them using a spreadsheet.

The author chose to use coverage, throughput, hardware, reliability, and latency as the attributes for this study. Some of the other attributes that can be used to make a network selection are packet delay, packet loss rate, block error rate, cost, user velocity (how fast a person is driving or walking), congestion, signal strength, signal to noise ratio, user

preferences, security and classification (Senouci, Hoceini, and Mellouk, 2016; McNair and Zhu, 2004; Vangelis, Alonistioti, and Merakos, 2005; Agrawal, Jeyakumar, and Pareek, 2016; Ahuja, Singh, and Khanna, 2018). There are also attributes that are useful when comparing wireless systems versus making a network selection. Some of the system related attributes are hardware costs, sustainment costs, supportability, and hardware supply chain security. The following sections describe why different attributes were chosen and how they are portrayed in the literature.

Coverage

There is not one formal definition of coverage, but it is generally the amount of signal strength required to provide quality of service for a specific user application (Aragón-Zavala, 2017). This is the approach was used in a HAF A4-sponsored wireless assessment of Homestead Air Reserve Base and a study at Davis Monthan Air Force Base that looked at LTE and Wi-Fi (Sierra Nevada Corporation, 2018; Strunk, 2018). However, the different wireless technologies used in this study have different radio-receiver sensitivities. For example, some consider greater than -65 dBm an excellent signal strength for LTE, and greater than -50 dBm for Wi-Fi (Sierra Nevada Corporation, 2018). To overcome this challenge, the author used a different approach and definition for coverage: the probability of exceeding a download or upload throughput speed at locations at which users will be active. For example, there was a .982 probability that the download speed for LTE would exceed 5 Mbps at the 26 parking spaces used in this study. This novel approach avoids some of the drawbacks of using signal strength in coverage determination.

Another drawback to using signal strength is that in many scenarios, an increased signal strength does not mean increased performance for users (Sonntag, Schulte, and Manner, 2013). Using the Wi-Fi data from the Homestead report, there was a .0067

correlation between signal strength and download speeds on the flight line (Sierra Nevada Corporation, 2018). In addition, the author found a .15 correlation between the Windows 10 signal level (a percent between 0 and 100) and write speed to the local area network storage. In these two instances, signal strength and signal level did not result in increased performance. However, there are known performance issues external to the Wi-Fi system that could be capping performance (Nicodemus, 2020).

An additional problem with using signal strength is that the author found the flight line environment to be a reflective radio environment for Wi-Fi. This means that the signal strength is artificially higher, and multi-path interference could be adding noise to the connection. A slightly better indicator of user performance is Signal to Noise Ratio or SNR, which is the signal strength minus the noise in decibels. The wireless survey at Homestead Air Reserve Base captured the SNR while the study at Davis Monthan did not (Sierra Nevada Corporation, 2018; Strunk, 2018). A limitation of applying the Davis Monthan and Homestead survey findings to AMC is that those bases have fighters. AMC bases often have a flight line packed with larger jets like the C-5 and C-17, and the larger jets may reflect more radio energy possible, causing more interference.

Problems with Heat Maps

AMC A4 makes heat maps quarterly to give leaders a picture of the Wi-Fi coverage on the flight line. The author found several instances of the government using heat maps to display signal strength. In a 2016 report for Air Force Space Command, Lt Col Mark Bortiatynski found several issues with how the BITI Program uses Air Magnet software to create a signal strength heat map. The heat maps do not depict actual coverage measured by walk tests or take into consideration physical objects that might impede signals (airplanes, bunkers, KC-10 engine stands, or hangars for example) (Bortiatynski, 2016). Moreover, the

heat maps don't depict network throughput, only theoretical signal strength (Bortiatynski, 2016). Finally, the report asserts that heat maps don't stand alone and that stress tests and throughput tests would increase confidence in the wireless system.

The AMC A4 surveys use GPS and a laptop to capture signal strength and position to provide a color-coded map of signal strength. As mentioned previously, there may not be a correlation between signal strength and user performance, so these maps could mislead users and leaders to thinking wireless system performance is adequate. Another issue with the surveys is that the signal propagation assessment appears to be set at the software default of 250 feet for convenience (netAlly, 2020). This means that the software interpolates the signal strength to be the same 250 feet out from a sample point, which could be under an aircraft or obstruction. It is imprudent to use data interpolation without an empirical sample to validate results. Figure 2 graphically shows the issue of using too large of a value.



Figure 2 Graphical Depiction of Different Interpolation Distances

Throughput

The author chose to use maximum download and upload speeds because of the link to user satisfaction (Ramasubramanian, Geetha, and Yadav, 2013). In keeping with the other wireless surveys, the author chose to use maximum download and upload speeds to assess throughput (Sierra Nevada Corporation, 2018; Strunk, 2018). Using maximum throughput as an attribute for network selection is common (Senouci, Hoceini, and Mellouk, 2016; Song

and Jamalipour, 2005; Trestian, Ormond, and Muntean, 2012; Aryafar, Keshavarz-Haddad, Wang, and Chiang, 2013). Researchers use average throughput often as well and is more applicable for use for when a specific throughput is required consistently, like in device-to-device communication scenarios.

Hardware

The author chose to assess the antenna size and radio power draw to evaluate the user hardware. The amount of power used on a radio used to be an important consideration when selecting whether to use cellular data; however, as cellular radios became more energy-efficient, it is not as important. Researchers have used power draw in network section problems (Trestian, Ormond, and Muntean, 2014). However, it appears that the antenna surface area has never been used. The author chose to use surface area and power to highlight the implementation challenges of 5G mmWave and Satcom.

Reliability

There are differing definitions of reliability based on different fields of study. In general, reliability is the probability of a product or service performing without failure for a set period (Stavroulakis, 2003). Neither government study measured reliability, but the author thought it was important to assess the reliability of the different wireless systems (Sierra Nevada Corporation, 2018; Strunk, 2018). Reliability is used in literature as an attribute to select the best network (Senouci, Hoceini, and Mellouk, 2016; Joo and Jeong, 2017; Adams, 2018; Khiat, Bahnasse, El Khaili, and Bakkoury, 2017).

Latency

There are several definitions of latency, but a general definition is the time it takes for a system to return an output after sending an input (Lu and Grabs, 2011). The author chose to assess latency as the round trip time of pings sent to the default gateway. Latency is common

in network selection problems, and the Homestead Wireless Survey used it (Sierra Nevada Corporation, 2018; Senouci, Hoceini, and Mellouk, 2016; Bare, 2012).

Standards and Measuring Performance

Performance Standards

The technical requirements document for BITI sets a threshold for the performance of the system, that is to say, a “the minimum performance acceptable to the Government” (Data Networks Transport Branch (HNIB), 2015, p. 4). The threshold for outdoor flight line wireless is to achieve at least a 3Mbps Transmission Control Protocol (TCP) throughput with a dropped packet percentage below five percent, and a Received Signal Strength Indicator (RSSI) of higher than -80dBm, and a Signal to Noise Ratio of 7dBm or higher (Data Networks Transport Branch (HNIB), 2015). The document doesn’t give details on how the TCP throughput measurement. A liberal interpretation is Local Area Network (LAN) transfers, while a strict interpretation would be Wide Area Network (WAN) transfers; however, WAN transfers involve boundary equipment that is beyond the scope of the BITI Wireless program. The author was unable to find any documentation on how BITI measured TCP performance so that the bases could accept the performance of the wireless system on the flight line. Further, the author could not find an approved tool to validate current installations. Moreover, the requirements in the document may be outdated as several government documents have levied higher thresholds for future systems, especially those supporting the FLoF.

For example, the Air Force Wireless Connectivity Scenario, states that the “BITI Technical Requirements Document (TRD) specifies Wireless Local Area Network performance requirements for the flight line, maintenance shops, hangars, etc. that are far below industry best practices” (CIO/A6, 2020, p. 3). Further, the annex proposes a

requirement of -65dBm, 25Mbps download speed, 3Mbps upload speed, and a 20ms response time from the Local Area Network gateway (CIO/A6, 2020). The scenario is specific in its description of response times being measured by ICMP pings to the gateway; however, the buffer size and the number of packets is not specified as it is in the SNC report (1000 bytes, and 20 respectively) (CIO/A6, 2020; Sierra Nevada Corporation, 2018). Although just a suggestion, the SNC Report recommended a 5 Mbps, -65dBm, and a 20ms ping response time as the thresholds to support the FLoF (Sierra Nevada Corporation, 2018).

Three-Tiered Metric Approach

Baltrunas, Elmokashfi, and Kvalbein (2014) proposed a three-tiered metric approach in their paper on measuring the reliability of mobile networks. The three-tiered approach aims at improving the user experience by measuring performance at the application, network, and link Open Systems Interconnection model layers (Baltrunas, Elmokashfi, and Kvalbein, 2014). This tactic measures the user's application performance, network performance, and radio performance. This is in contrast to heat maps that only measure signal strength, which is an incomplete picture of radio performance. Moreover, the users do not care about signal strength as long as their application is performing. As such, applying a three-tiered approach to the FLoF the author proposes that HTTP throughput, packet loss, and block error rate be used to assess wireless performance.

There are challenges in measuring performance and the tools available to a researcher (Goel, Wittie, Claffy, and Le, 2016). Goel, Wittie, Claffy, and Le (2016) did a comparative analysis of network measurement testbeds, services, and tools, and assessed their measurement capabilities, device-specific criteria, and usage limits. For measuring wireless coverage without using proprietary carrier data, researchers are limited to platforms, mobile

applications, purpose-built wireless-tools (like spectrum analyzers), software-defined radios (SDRs), and modeling or simulation software. Table 2 summarizes some of the relevant studies and the tools used to assess performance.

Table 2 Use of Wireless Tools in Literature

	Apps	Purpose Tools	SDRs	Mod and Sims
(Ruslan, Akhpashev, and Drozdova, 2018)	X			
(Sonntag, Sebastian, Jukka Manner, and Lennart Schulte, 2013)	X			
(Strunk, 2018)	X	X		
(Sierra Nevada Corporation, 2018)		X		
(Wakim and Weitzen, 2017)	X	X		
(Marina, Radu, and Balampekios, 2015)	X			
(Imoize, Ibhaze, Nwosu, and Ajose)		X		
(Salib and Funkhouser, 2017)			X	
(Kumar, Hamed, Katabi, and Li, 2015)			X	
(ITU-R, 2017)				X
(del Portillo, Cameron, and Crawley, 2019)				X
(Fagiani, Vogel, and Cerqueira, 2018)				X

Wireless Technology Considerations

Wi-Fi, LTE, 5G, and SATCOM are distinctly different technologies with characteristics that make one more suited for a specific scenario than another. Two of these defining characteristics are the radio spectrum used, and the radio environment (urban, rural, flight line).

Radio Spectrum Considerations

“Spectrum is the oil of the wireless industry” (Fogg, 2019). There are three chief aspects of wireless spectrum to consider when selecting a wireless technology: frequency, available bandwidth, and licensing.

Radio Frequency Band

As frequency increases, there are penalties due to increased losses. This can be seen with a graph of the free space loss (FSL) for the first 300 meters (Figure 3).

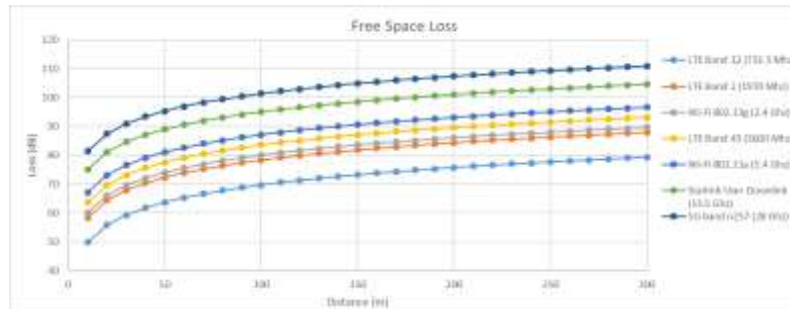


Figure 3 Free Space Loss for Different Wireless Technologies

There is an immediate 30 dB penalty for using a 5G mmWave band n257 over LTE band 12. In addition, the lower frequencies have better building and structure penetration in addition to longer range in rural situations (Fogg, 2019). Moreover, for frequencies over 10 GHz, rain can cause significant signal loss and outages depending on the rain rate and cloud height (Dey and Sahoo, 2014). Gaseous attenuation is also a concern at higher frequencies, most specifically a notch around 60 GHz due to oxygen, as noted from the author-generated plot from ITU-Rpy below (delPortillo, 2020).

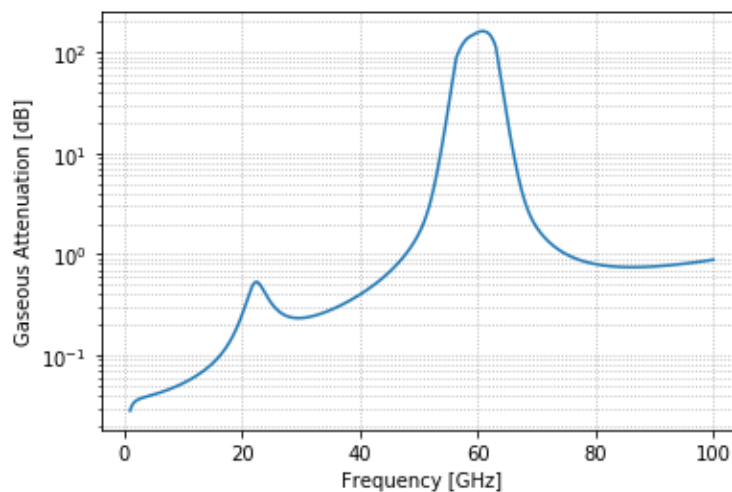


Figure 4 ITU-Rpy Generated Plot of Gaseous Attenuation versus Frequency

Despite the drawbacks of using higher frequencies, there is generally more bandwidth

available at higher frequencies.

Bandwidth

Bandwidth is the difference between the highest and lowest useable frequency. The greater the bandwidth the greater the theoretical throughput (Shannon's Law). The appeal of using higher frequencies, like 5G mmWave is the large contiguous bandwidths. For example, the n257 band (mmWave) has 47 times more bandwidth than the LTE band 43, as depicted graphically in Figure 5.

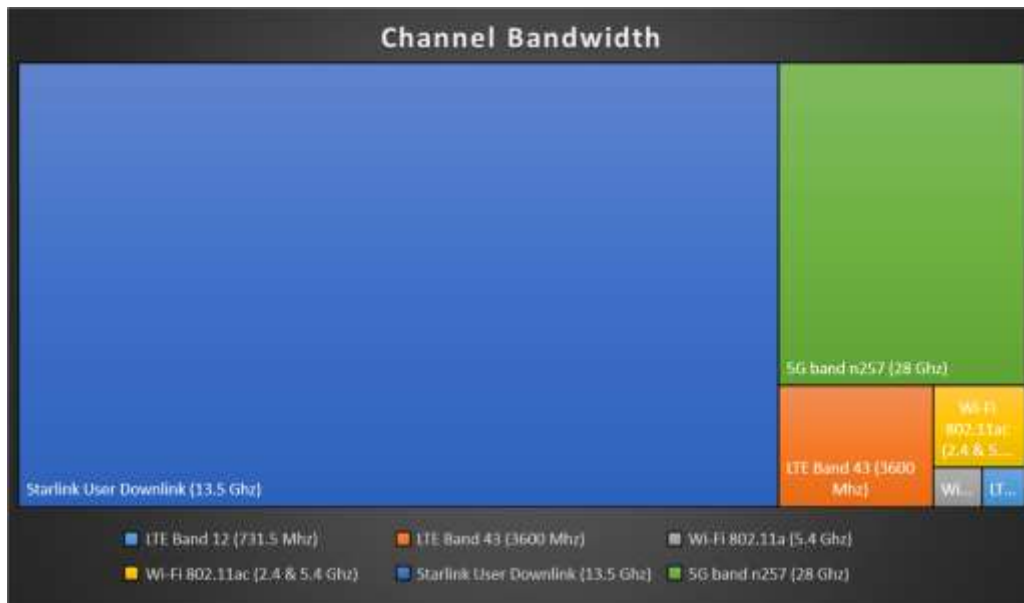


Figure 5 Channel Bandwidths

Licensing

The Federal Communications Commission licenses spectrum to “encourage the highest and best use of spectrum” (FCC, 2020, p. 1). The FCC licenses both cellular and Satcom spectrum, while Wi-Fi is unlicensed and uses an Industrial, Scientific, and Medical band (ISM). Being unlicensed allows great flexibility and ubiquity for Wi-Fi; however, it comes with some drawbacks. First, anyone and anything from a microwave oven to a baby monitor can use the ISM bands, which can cause interference (Title 47 CFR, 2020).

Additionally, the transmitter is limited to 1-Watt of power, which is a constraint given the large area of AMC flight lines (Title 47 CFR, 2020; CIO/A6, 2020).

Radio Environment

The engineers who created Wi-Fi and the LTE standards used different radio environments and use cases for their assumptions. For example, LTE has a use case to support a user on a train moving 350 km/h (217 mph) (Sesia, Toufik, and Baker, 2011). Each technology can have a use case for different radio environments and the generally accepted path loss model to use in each scenario. For example, the ITU-R has four-channel models for IMT-Advanced (LTE): Indoor, Microcellular (urban with antennas below building tops), Macrocellular (urban with antennas above building tops), and high speed (trains or cars) (ITU-R, 1997). Not surprisingly, the models for Wi-Fi, 802.11AC, focus on indoor situations, with the following environments: residential, residential office, typical office, large office, and a large space (Perahia and Stacey, 2018; Erceg, et al., 2004). For 5G New Radio, 3GPP and ITU-R have defined the scenarios as an indoor hotspot, dense urban, rural, urban macro (focused on a high number of devices), and urban macro focused on low latency communication (ITU-R, 2017). Arguably, none of the models are a good fit for a large cement flight line with parked KC-10s and C-17s, found on a typical AMC flight line. The data from a walk test and calculations on page 46 back up this assertion.

III. Methodology

Introduction

The methodology chapter has two divisions: data collection and MDM analysis details. The data collection division contains field measurements, software simulation, estimates based on literature, Satcom link budget, and reliability. Table 3 summarizes the source for data for the different wireless technologies.

Table 3 Summary of Data Sources

Alternative	Coverage	Throughput	Hardware	Latency	Reliability
BITI Wi-Fi	Field Measurements	Field Measurements	Device Whitepapers	Field Measurements	Subjective Assessment
LTE	Field Measurements	Field Measurements	Device Whitepapers	Field Measurements	Subjective Assessment
5G mmWave	Simulation Software	Simulation Software	Device Whitepapers	Literature	Subjective Assessment
Infrastructure Upgrades	Simulation Software	Simulation Software	Device Whitepapers	Field Measurements	Subjective Assessment
Satcom	Link Budget Calculation	Link Budget Calculation	Device Whitepapers	Test Report	Subjective Assessment

Data Collection

Field Measurements

The researcher gathered data through field tests on the flight line at JBMDL. The following paragraphs describe the data collection and preparation.

The researcher gathered data over two separate days (in October 2019 and January 2020) with the airfield in operation. Measurements were taken at 26 different aircraft parking spaces on the parking apron at JBMDL. The field measurements were taken within a maintenance van to simulate a technician trying to access an external website while performing maintenance (for example accessing the GO81 maintenance program). Any

failure of a device to connect to a wireless network was counted as a zero reading for maximum throughput and coverage but omitted when calculating the average round trip time. The measured spots varied from 68 meters to 274 meters away from the Wi-Fi access points, and an average of 142 meters away. The majority of cell towers are not on JBMDL, and range from 1.8 to 4 kilometers away from the Romeo 1 parking spot.

To measure the throughput attribute, the researcher used Speedtest.net on a mobile phone (LG K70) and a government ToughBook laptop.

For the round trip time, the researcher wrote a PowerShell script and used an Android Shell Emulator to send 10 echo requests (pings) to the default gateway. Echo requests that failed were recorded with an error code. Failures are an indicator of errors within the wireless system and should be investigated if practical. For comparison of the wireless systems the failed echo requests are not used in the average calculation due to different time-out values of the different wireless systems. One of the field measurements exhibited a high failure rate, and it is explained in the analysis section.

LTE Band Measurements and Drive Test

To answer the investigative question one, the author used an Anritsu Spectrum Analyzer. The author used a website called Cell Mapper, an Android App called LTE Discovery, a software-defined radio (RTL-SDR) and the iPhone field test mode to discover which LTE channels were likely being used around JBMDL (Cell Mapper, 2019; Powertec Telecommunications, 2014; LTE Discovery, 2019). The channels are identified by their E-UTRA Absolute Radio Frequency Channel Number or EARFCN. Armed with the EARFCNs the author loaded them into the spectrum analyzer in channel scan mode, with a 5 Mhz channel width. It should be noted that the EARFCN identifies the uplink and downlink channel unless the band uses time-division multiplexing. At JBMDL there was no evidence

of a carrier using time-division multiplexing, and only the downlink channel was measured. At each parking spot visited during the field tests, the author recorded the channel signal strengths into internal memory. At the end of the day, the author retrieved the files from the spectrum analyzer using a USB memory stick.

In addition to a channel scan, the author also accomplished a drive test for a channel centered around 738 Mhz. This recorded the signal strength and GPS coordinates once per second for a drive around the perimeter of the flight line.

Simulation

The author used Altair's Proman software to establish reasonable predictions for how a 5G mmWave system and an upgraded Wi-Fi infrastructure would perform on the flight line (Kopacz and Herberling, 2018). Proman allows a user to input the parameters of a physical environment, visualize how radio signals would propagate in the environment, and then estimate the performance of a wireless system (Altair, 2020).

To set up the simulation, the researcher orthorectified a base map of the airfield and set a proper scaling factor. Next, the default material catalog was loaded to provide the material properties used for radio propagation. A limitation of the software is that only rectangular objects can be modeled; airplanes on the ramp are omitted from the model. The flight line buildings were created using data from AMC Maps, and modeled as having a uniform surface of 1 mm thick metal, which is consistent with the sheet metal of the flight line hangars (AMC/A4, 2019).

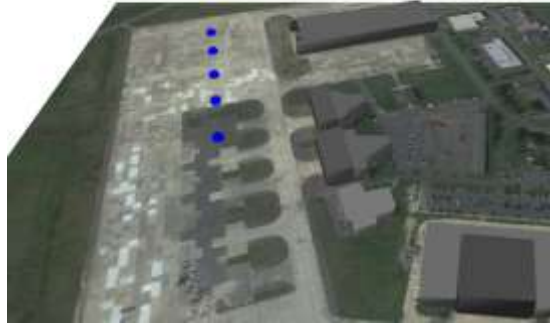


Figure 6 3D Model View

Table 4 below organizes the inputs shared for both simulations.

Table 5 and Table 6 depict the unique scenario inputs for the upgraded infrastructure and 5G mmWave scenario, respectively.

Table 4 Software Simulation Inputs

Description	Value	Reference
Building Material	1 mm thick metal	
Building Height	10 – 29 m	(AMC/A4, 2019)
Receiver Height	1.5m	(ITU-R, 1997)

Table 5 Upgraded Infrastructure Scenario Inputs

Description	Value	Reference
Technology	802.11AC	
Access Point Transmit Power	29 dBm (2400 - 2483.5 MHz) 23.8 dBm (5150 - 5725 MHz)	(FCC, 2017)
Antenna Gain	2dBm	(FCC, 2017)
Antenna Height	2m	(ITU-R, 1997)
Laptop Transmit Power	20 dBm (2400 - 2483.5 MHz) 21 dBm (5150 - 5725 MHz)	(Intel Corp, 2019)
Laptop Antenna Gain	2dBm	(Intel Corp, 2019)
Receive Sensitivity	-54 to -79 dBm (BPSK to 256 QAM, 40 Mhz Channel)	(Verma and Fakharzadeh, 2013)

Table 6 5G Scenario Simulation Inputs

Description	Value	Reference (if applicable)
Access Point Frequency	28Ghz	Channel n257
Access Point Transmit Power	40.59 dB	(Ericsson, 2018)
Access Point Antenna Gain	15.3 dB	(Ericsson, 2018)
Device Transmit Power	23 dB	(IWPC, 2019)
Device Antenna Gain	9 dB	(IWPC, 2019)
MIMO	2 Streams	
MIMO Beamforming Gain	3 dB	
Bandwidth	200 Mhz	
Carrier Separation	60 Khz	
Body Loss	4 dB	
Receiver Noise Figure	4 dB	
Multiplexing	TDD (8 blocks DL, 1 UL)	

Simulation Versus Collected Data

To assess the usefulness of the software simulation, the author built a third scenario that models the current BITI Wi-Fi system. To compare this with empirical data, the researcher used a GPS position logging app, and the Airmagnet system to capture the received power versus position. Figure 7 and Figure 8 compare the predicted powers versus the measured power levels for 802.11A and 802.11G respectively. The R^2 for the 802.11A was .87 and .47 for 802.11G. Both sets of collected data have increasing power levels with distance, from 100 to 150 meters. The power level at these distances is above the free space loss (FSL), which seems to suggest that there is an unaccounted for gain. This could be due to a Multi Input Multi-Output (MIMO) gain, interaction, or a signal reflection off the hangar or cement creating a gain, or it could be false reading in the Airmagnet system.

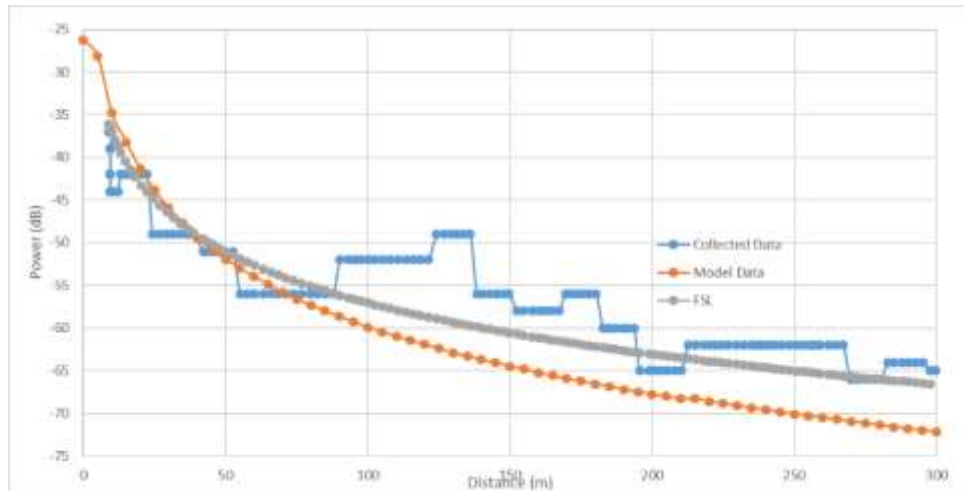


Figure 7 802.11A Model Comparison

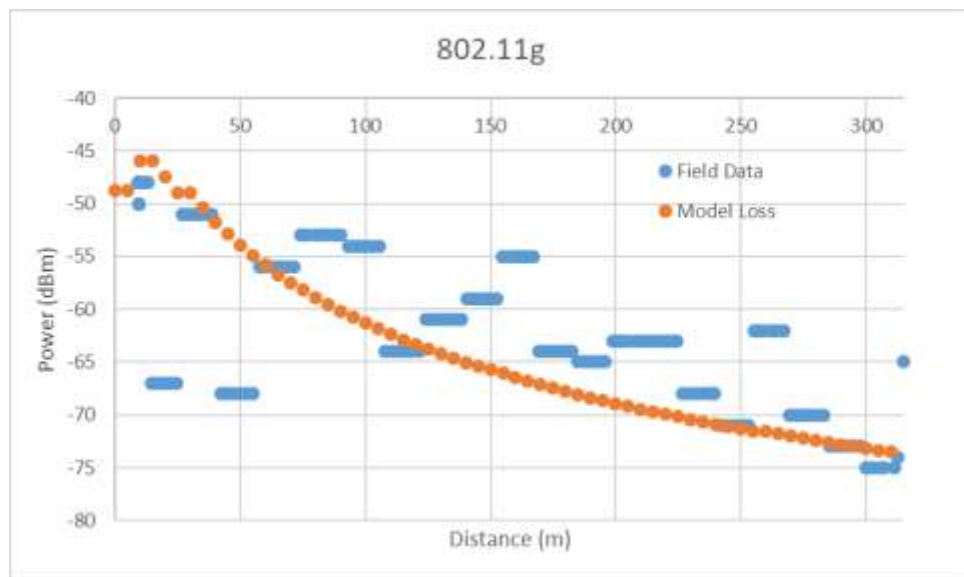


Figure 8 802.11G Model Comparison

Value Estimations

As noted earlier in Table 3 (items shaded green), 7 areas are estimated based on the literature, tech data, whitepapers, and program reports. Table 7 below enumerates the estimated power draw for each end device. Where possible, comparable estimation (comps) provide a range of potential values.

Table 7 Hardware Power Estimations

End Device	Power Draw	Reference	Comps	Notes
BITI Wi-Fi (Intel AC 8260)	1.25 Watts (40 Mhz channel, constant traffic)	(Zeng and Mohapatra, 2014)		
LG K70 (LTE)	1.5 Watts (2x2 MIMO, LTE Cat 4)	(Mads, 2015; Fallis and Spachos, 2018; Malik, 2013)	1.4 Watts (LTE Cat 3) 2.5 Watts (Samsung S4 mini) 2.2 Watts (Samsung S2)	Fallis and Spachos measured total power consumed under different scenarios, which does not isolate radio power consumption, with a net effect of over-estimating power.
5G	3.79 Watts (4x4 MIMO, 200 Mhz channel, mmWave)	(Mads, 2015)		Smaller 5G frames and increased data rates should reduce transfer times, which should offset higher energy usage. For example, it will take less time to download webpages if the connection is faster (Lähetkangas, et al., 2004). Mads estimates that 5G power consumption should be on par with LTE by 2025 due to Moore's Law (Mads, 2015).
Upgraded Infrastructure (uses same Intel AC 8260)	1.25 Watts (40 Mhz channel, constant traffic)	(Zeng and Mohapatra, 2014)		
SATCOM	150W		150W Intellian FB250 (Intellian, 2019) 300W Kymeta Ku Terminal (Kymeta , 2019) 50 W TT-3710A EXPLORER (phased array) (Thrane and Thrane, 2019)	Both OneWeb and Starlink have not released details of their terminals, but both plan on using phased array antennas.

Table 8 below summarizes the frontal surface area (using the largest surface) for each of the five end devices.

Table 8 Antenna Surface Area Estimations

End Device	Antenna Surface area	Reference	Comps	Notes
Intel AC 8260 (BITI Wi-Fi)	154.8mm ²			
LG K30 (LTE)	96.7mm ²	(Kathroytia, 2020)	135.5mm ² iPhone 8 (Suovanen, 2020)	
5G	399mm ²	(Smith, 2018; OLED Association, 2019; Amadeo, 2018)	5G moto Mod (532mm ²)	19x7mm (3 antenna modules) QTM052 mmWave antenna module.
Upgraded Infrastructure	154.8mm ²			This assumes no change in equipment.
SATCOM	145,161mm ² (15 x 15 inches)		12 to 30 inches OneWeb (Barnett, 2019) 32 x 32 inches Kymeta (Kymeta, 2019). 8.6 x 8.6 inches Thrane Explorer (Thrane and Thrane, 2019)	

Table 9 below combines the field data (BITI Wi-Fi, LTE, and Upgraded Infrastructure), with the values obtained from Project Lightning (Starlink), and the estimates from literature for 5G.

Table 9 Latency Summary

	Round Trip Time	Reference	Comps	Notes
BITI Wi-Fi	16.8ms		57ms Homestead ARB (Sierra Nevada Corporation, 2018)	From field measurements
LTE	126.2ms		60ms average between Verizon, T-mobile, and AT&T (Flitchard, 2019).	From field measurements
5G	11.7ms	(Loghin, et al., 2019)		Average value based on Loghin's field measurements.
Upgraded Infrastructure	6.5ms			Value is the average of the responses within 50m of the access point measured with current infrastructure.
SATCOM	50ms	(Beal, 2020)	75ms (Bhattacharjee and Singla, 2019)	Bhattacharjee and Singla compared the latency of a 1600 satellite constellation with actual current values for 8 of the largest cities in the world (Bhattacharjee and Singla, 2019; WonderNetwork, 2019)

Satellite Link Budget Calculation

As highlighted earlier in Table 3 in red, a satellite link budget is used to estimate the throughput and coverage attributes for the satellite communication alternative. Figure 9 depicts the process model to complete the throughput calculation from the link budget.

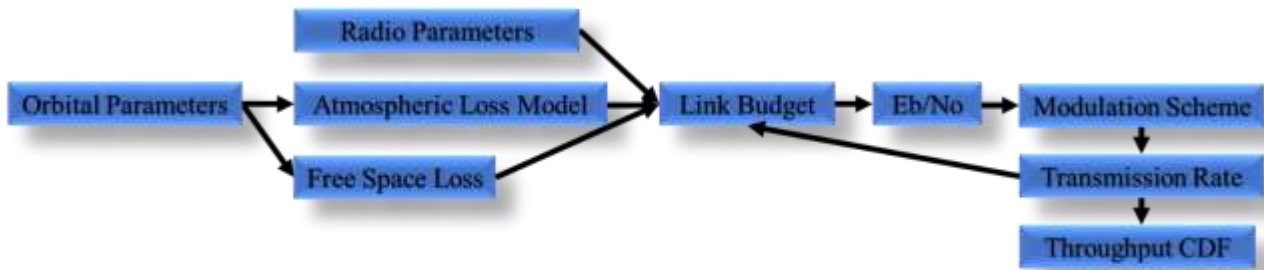


Figure 9 Process Model for the Link Budget

$$\frac{E_b}{N_0} = G_t + P_t + \frac{G_r}{T_s} - L_s - L_a + 228.5 - 10 \log_{10} R$$

Equation 1 Satcom Link Budget

Where

$\frac{E_b}{N_0}$ = Energy/bit / noise energy density

G_t = Transmitter gain (dB)

P_t = Transmitting power (dBW)

$\frac{G_r}{T_s}$ = Receiver gain / degree Kelvin (dB/K)

L_s = Free space loss (defined below) (dB)

L_a = Atmospheric loss (dB)

R = Data rate (bits/second)

Radio Parameters

The radio parameters are taken from del Portillo, Cameron, and Crawley's paper on a technical comparison of Starlink, OneWeb, and Telesat's proposed constellations as of 2018 (del Portillo, Cameron, and Crawley, 2019). Since 2018, Starlink's orbit parameters have changed to a 550Km height and 72 orbital planes; however, there is no indication of changes to the radio parameters.

Estimated Satellite Elevation

In general, as the elevation angle increases, the atmospheric losses decrease, as the radio transmission slices through a smaller cross-section of atmosphere, as noted in Figure 10 below.

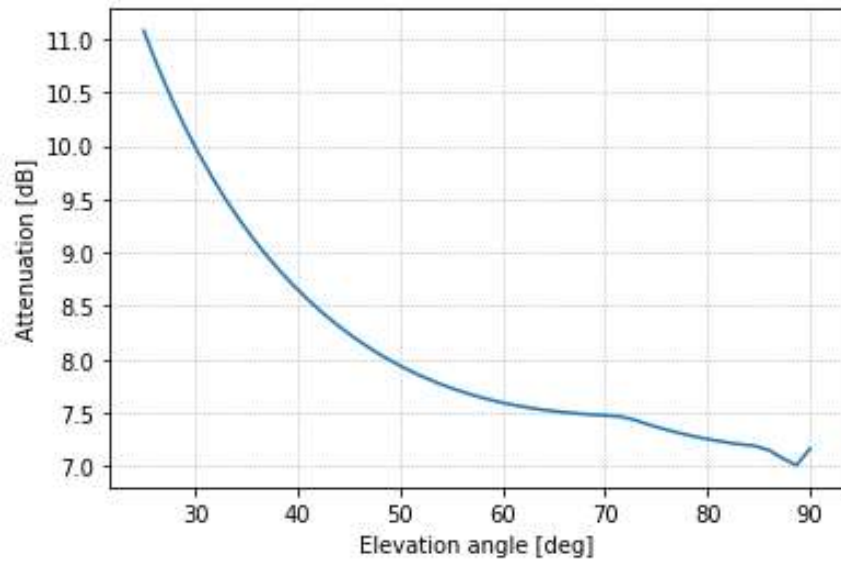


Figure 10 Total Atmospheric Attenuation for 12.325 GHz and 550Km Orbit

To estimate the average elevation of a Low Earth Orbit satellite constellation, the researcher used Savi, a Satellite Constellation Visualization Software on a Linux virtual machine (Wood and Worfolk, 2017). The constellation models the first orbital shell of the Starlink Constellation with 72 orbital planes and 22 satellites per orbital plane (1584 total satellites) as depicted in Figure 11.

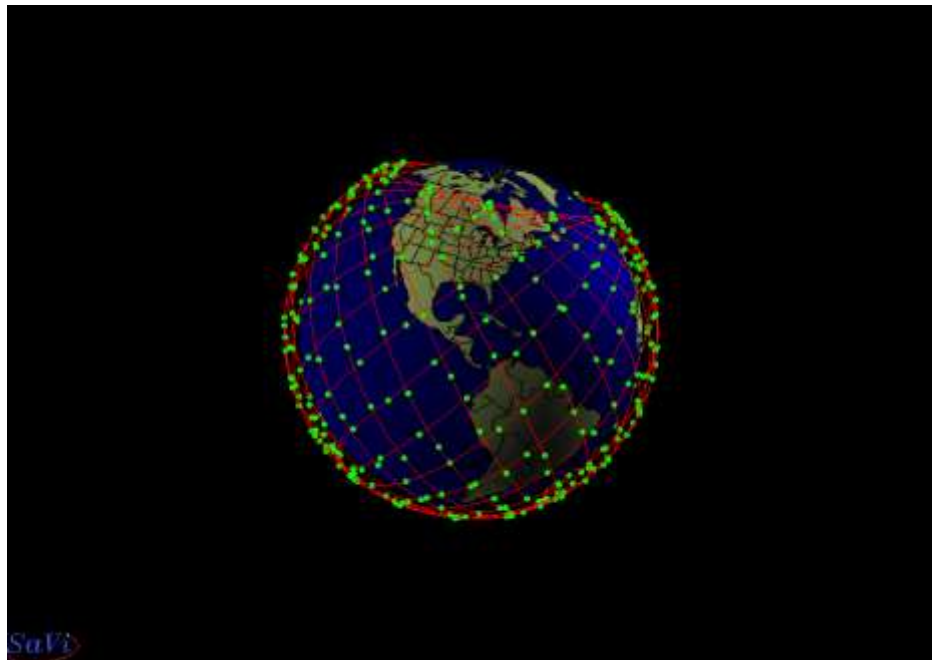


Figure 11 Savi Simulation of the First Orbital Shell of Starlink

Savi has a fish-eye view, which shows how many satellites are in view at one time. The author ran the Savi simulation for 5 hours in 1-minute steps and transposed the number of satellites in view from JBMDL (Figure 12).

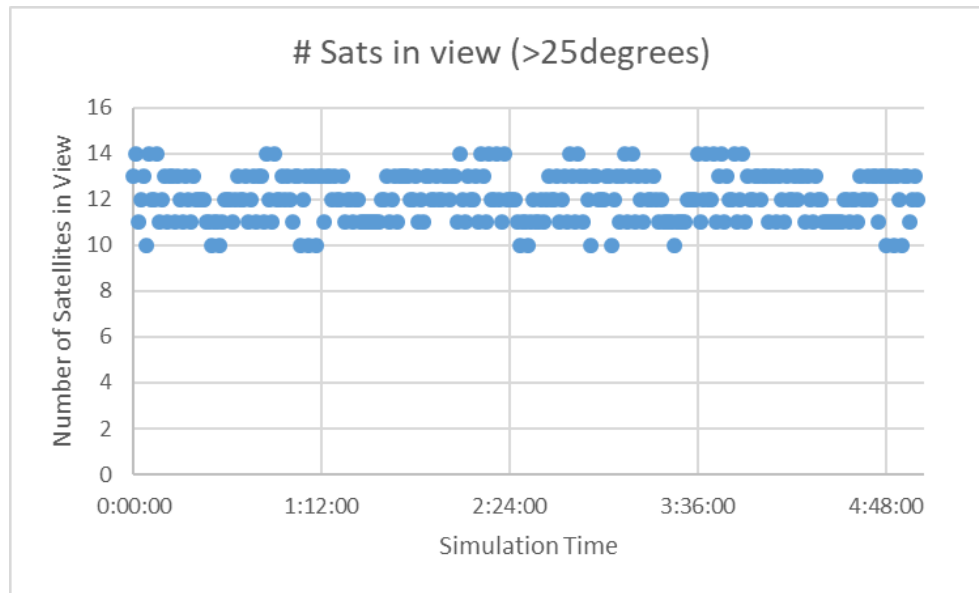


Figure 12 Number of Satellites in View

The average number of satellites in view was found to be 12.05, with a standard deviation of 1.00. Plotting the elevation of the two highest satellites in view at any time, the average elevations were found to be 66.9 and 57.3 degrees respectively. As such, the author chose to use an elevation of 55 to 85 degrees when modeling the free space and atmospheric losses.

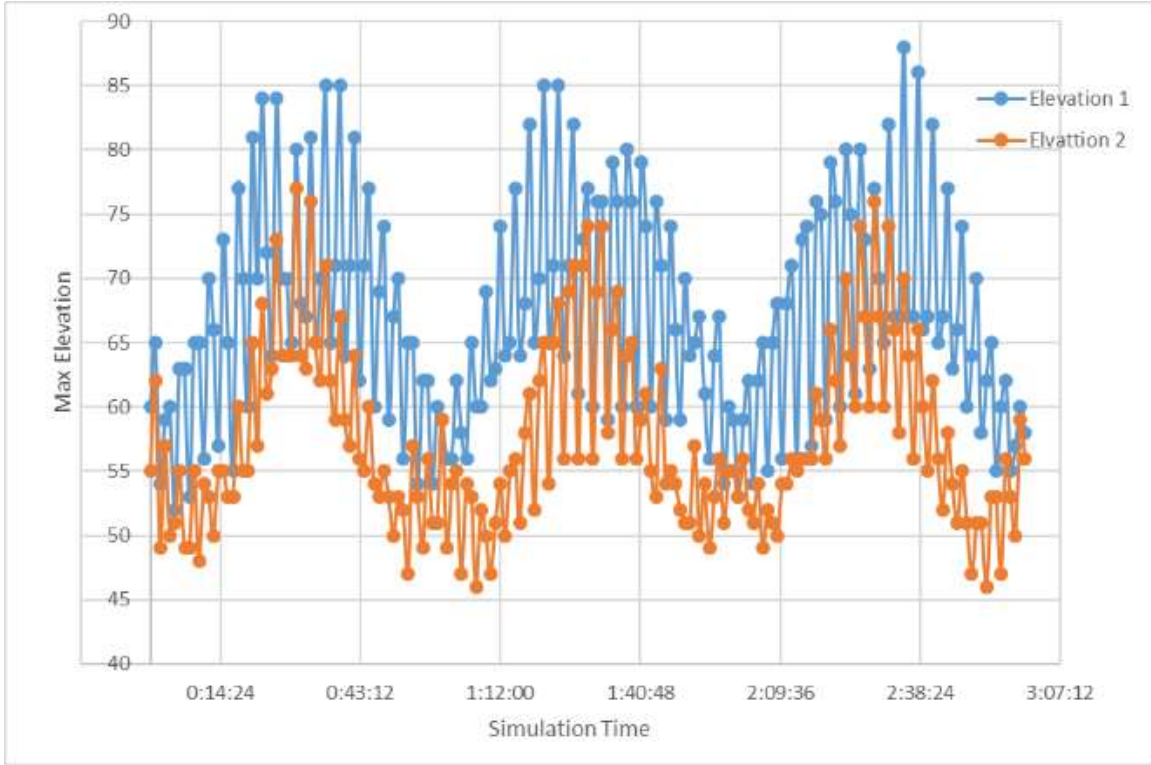


Figure 13 Best Two Satellite Elevations over Time

Atmospheric Loss

The atmospheric loss, L_a , was estimated using ITU-Rpy, a series of python scripts that implement International Telecommunications Union (ITU) models for atmospheric losses for different locations on the planet, different slant angles, and different orbital parameters (delPortillo, 2020). For example, Figure 14 shows the output of ITU-Rpy for JBMDL, a satellite orbit of 550 Km, a frequency of 11.325 GHz (Starlink download), and a satellite elevation of 55 degrees.

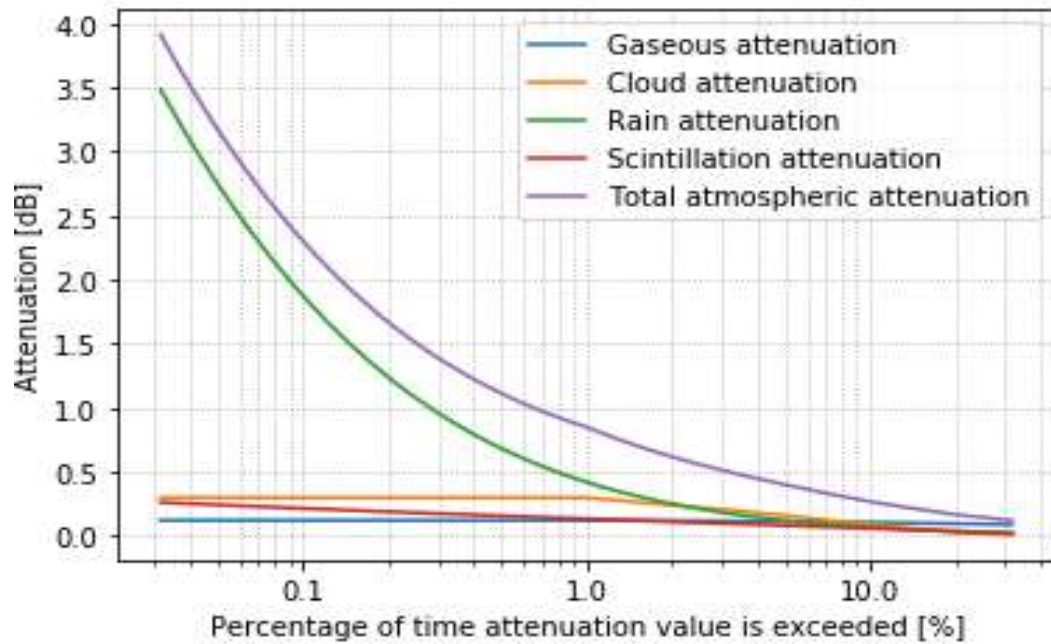


Figure 14 Example Atmospheric Losses

As depicted above, the largest contributor to atmospheric losses is due to rainfall. To check the consistency of ITU-Rpy's outputs, the author compiled 20 years of rainfall data from JBMDL (NOAA, 2020). The hourly rainfall totals were converted to mm/hr from in/hr and then sorted from largest to smallest to create a Cumulative Distribution Function (CDF). The CDF was entered into a Matlab computer program that uses synthetic rain cells, and a genetic algorithm to interpolate 1-min rain rates from 60 min rain rates, depicted in Figure 15 (ITU-R, 2017).

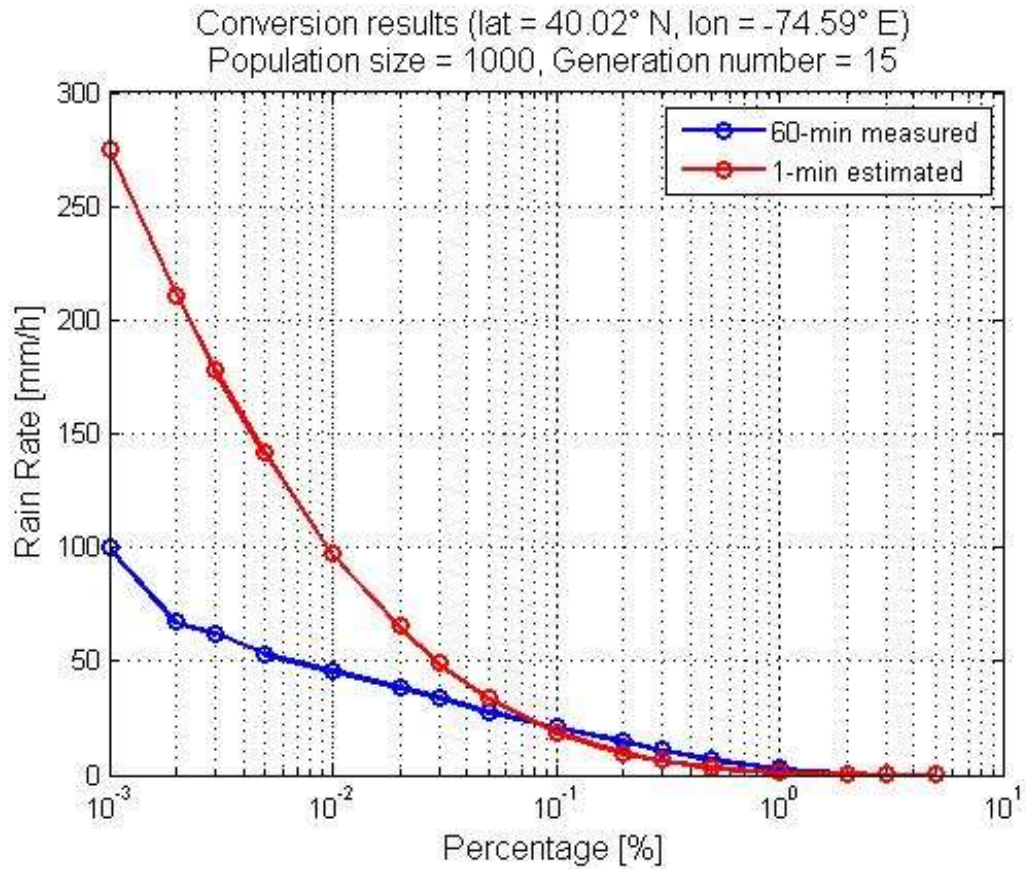


Figure 15 Interpolated One-Minute Rain Rates for JBMDL

Using the ITU-R 837-7 module in ITU-R, JBMDL's latitude and longitude, and .01% probability as inputs, Python outputs 44.02mm/hr as the estimated rain rate. For comparison purposes, the data from ITU-R is graphed below. Although the data is on the same order of magnitude, the actual weather data shows higher rain rates. One possible explanation for this is New Jersey being hit by hurricane Irene in 2011, and hurricane Sandy in 2012 (NOAA Coast, 2020). Ultimately, the author chose to use the ITU-Rpy readings as they provide a good fit from about .05 to .1 percent of the time. For example, using the ITU-Rpy numbers, we could expect the rain rate to exceed a rate of 40 mm per hour .01 percent of a year or 52 minutes a year.

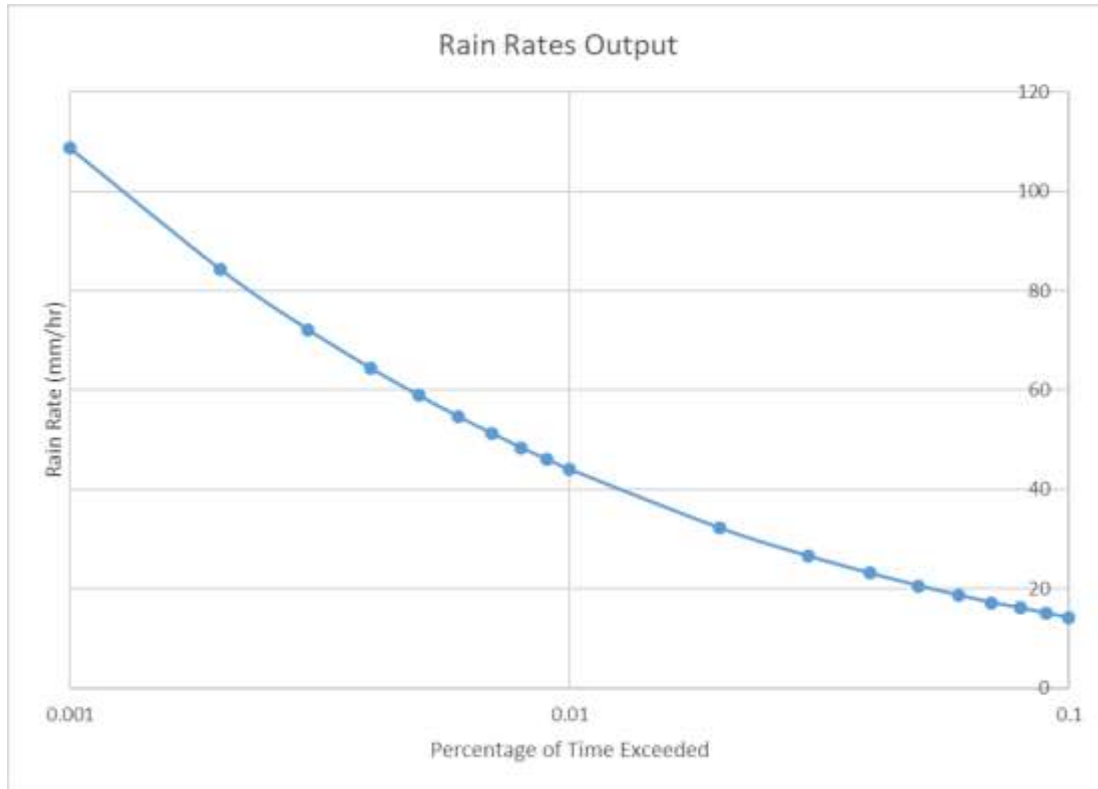


Figure 16 Rain Rates Estimated Using ITU-Rpy

Free Space Loss

Free space loss varies by frequency and distance as noted in Equation 2.

$$L_s = 10 * \log \left[\frac{4\pi df}{c} \right]^2$$

Equation 2 Free Space Loss

Where

d = Distance (m)

f = Frequency in (Hz)

c = Speed of light (m/s)

The distance is approximated as the orbital height (550km) divided by the Sine of the elevation. Figure 17 shows the loss doesn't vary significantly at 55 to 90 degrees, but can be significant at lower angles.

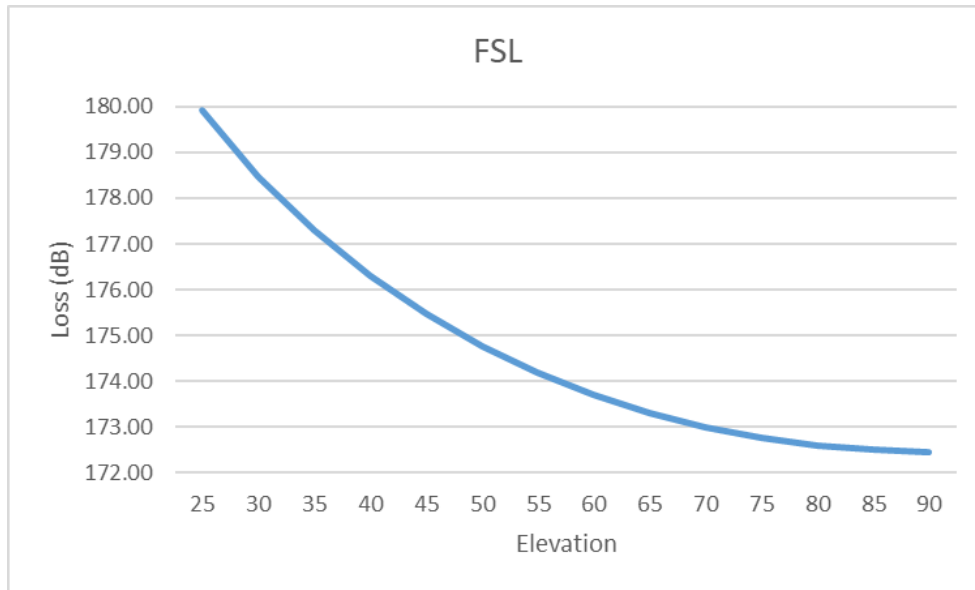


Figure 17 Free space Loss vs. Elevation for 18.2Ghz

Modulation and Coding

The link budget, Equation 6, page 47, yields the E_b/N_o , which determines the modulation scheme that maximizes spectral efficiency. As E_b/N_o approaches zero, the noise is greater than the signal, which can result in a communications outage. Likewise, as E_b/N_o increases, better modulation schemes are available, and the spectral efficiency improves.

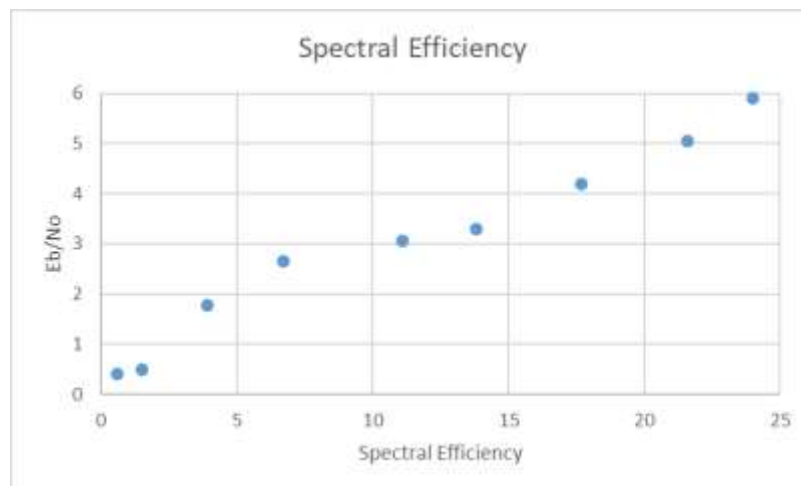


Figure 18 Spectral Efficiency versus E_b/N_o

Table 10 shows the modulation schemes chosen for the link budget calculation.

Anything below an E_b/N_o of .6 was treated as a communication outage.

Table 10 Modulation Scheme Details

Modulation Schemes	Required E_b/N_0	Spectral Efficiency
BPSK	0.6	0.4
QPSK 1/4	1.5	0.49
QPSK 8/9	3.9	1.77
8PSK 8/9	6.7	2.65
16QAM 3/4	11.1	3.05
32 APSK 2/3	13.8	3.3
64APSK32/45	17.7	4.2
256APSK 29/45	21.6	5.06
256APSL 3/4	24.02	5.9

Throughput Calculation

The researcher computed a cumulative distribution function (CDF) for L_a , atmospheric losses, for all the frequencies (gateway uplink/downlink, receiver uplink/downlink) and expected elevations. The CDF was fed back into the link budget (Equation 1) to determine the modulation scheme. The maximum throughput is the spectral efficiency times the available bandwidth, and useable bandwidth is 75% of the maximum throughput. For example, .03 percent of the time, the user uplink will have an atmospheric loss of 6.5 dB, causing the E_b/N_0 to drop below the threshold of .6, resulting in an outage (row 1, Table 11).

Table 11 Example for User Uplink, 55 Degrees Elevation

% of time	Atmospheric Loss	E_b/N_0	Modulation	Max Throughput (spectral efficiency * Bandwidth)	Typical Throughput (.75 max)
.03	6.50 (dB)	-.85 (dB)	Outage	0	0
5.15	.64 (dB)	5.01 (dB)	QPSK 8/9	221.25 MBps	165.9 Mbps
10.36	0.41 (dB)	5.24 (dB)	QPSK 8/9	221.25 MBps	165.9 Mbps

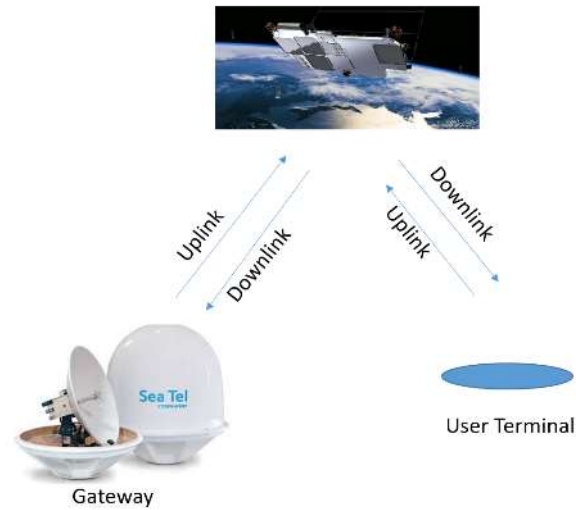


Figure 19 Starlink Radio System Diagram

A user download involves a user downlink and a gateway uplink (Figure 19). As such, outages are treated as independent events and added together to represent a worst-case scenario for the CDF. The edge cases near 1 percent of the time need to be checked to see if the aggregate user downloads exceed the capacity available for the gateway uplink. The frequency allocation, bandwidth and channels are aggregated to Table 12 (del Portillo, Cameron, and Crawley, 2019; FCC, 2016).

Table 12 Starlink Frequencies

Segment	Frequency (GHz)	Bandwidth (MHz)	# of Channels
Gateway Uplink	28.5	4000	8
Gateway Downlink	18.2	2250	9
User Uplink	14.2	500	4
User Downlink	11.5	2000	8

Finally, a 1 percent aiming error was assessed for 0 – 499 Mbps and a 2 percent error above 500Mbps on user downloads. On the upload side, 1 a percent correction for 0 – 99 Mbps and 2 percent above 100 Mbps were added. This is to account for the cases when the gateway, satellite, or user terminal are out of alignment momentarily.

Reliability

The author intended to use a quantitative measure of reliability for LTE and BITI Wi-Fi. This was to be accomplished via a Powershell script that would run every 15 minutes. However, after two weeks of running the script for Wi-Fi, the longest stretch of data was only two hours' worth of data. The laptop was in a non-line of sight (NLOS) situation approximately 100 meters away from the access point, and the signal varied between 50 and 75 percent. A root cause for the interruptions was not found, but transiting aircraft or maintenance vehicles may have been a contributing factor.

In light of the difficulties, the researcher used subjective categorical scores of low, medium, and high, with scores of .25, .75, and 1, respectively.

Multicriteria Decision Making Process

This section describes the procedures for using Simple Additive Weighting, TOPSIS, and Utility Theory to compare the wireless networks. Several of the methods use weighting, and for simplicity, the researcher used the ranked ordered centroid method to assign weights. The researcher asked five subject matter experts (SMEs) from the field to rank the attributes they believe are most and least important (from 5 to 1 respectively). The weights for five items using rank order centroid are .457, .257, .157, .09, and .04.

The network score was computed using the SAW method, and normalization of the inputs (Jansen, 2011; Wira Trise Putra and Agustian Punggara, 2018). The researcher used the weights obtained from the SMEs and the rank-ordered centroid method.

Additionally, the researcher computed the results using the TOPSIS method using the SME weighted factors (Senouci, Hoceini, and Mellouk, 2016). To investigate different weights, the investigator computed all the permutations (5! or 120) of the centroid weights to

see how sensitive the results were to change.

For Utility Theory the different attributes were looked at individually to see which utility function would be most appropriate. Table 13 along with Equation 3, Equation 4, and Equation 5 prescribe the utility functions used.

Table 13 Summary of Utility Functions for the Attributes

Attribute	Function Type	Equation	a	b	ρ
Downloads	Increasing Exponential	Equation 3	0	600	200
Uploads	Increasing Exponential	Equation 3	0	300	75
Upload Coverage	Continuous Linear	Equation 4	-	-	-
Download Coverage	Continuous Linear	Equation 4	-	-	-
Reliability	Categorical	High = 1, Medium = .75, Low = .25			
Power Draw	Decreasing Exponential	Equation 5	0	150	37
Antenna Dimensions	Decreasing Exponential	Equation 5	0	0.618	0.1
Round Trip Time	Decreasing Exponential	Equation 5	0	150	37

$$F(x) = \frac{e^{[-(x-a)/\rho]} - 1}{e^{[-(b-a)/\rho]} - 1}$$

Equation 3 Exponentially Increasing Utility

Where

a = minimum value

b = maximum value

ρ = ~b/4

$$F(x) = x$$

Equation 4 Linearly Increasing Utility

$$F(x) = \frac{e^{[-(b-x)/\rho]} - 1}{e^{[-(b-a)/\rho]} - 1}$$

Equation 5 Exponentially Decreasing Utility

Where

a = minimum value

b = maximum value

ρ = b/4

V. Analysis and Results

Chapter Overview

This chapter is organized into a section for each attribute, a discussion on the attribute weights, a section on data consistency, a section on the results of the three different MDM methods, a section on LTE bands, and the flight line radio environment.

Coverage Results

Coverage was assessed using field measurements (Wi-Fi, LTE), simulation software (5G, upgraded infrastructure), and a link budget calculation (Satcom). Table 14 summarizes the results for the coverage attribute.

Table 14 Coverage Attribute Summary

	Download Probability					Upload Probability				
(Mbps)	>5	>10	>50	>100	>500	>5	>10	>50	>100	>500
Current State	0.118	0.059	0.000	0.000	0.000	0.157	0.000	0.000	0.000	0.000
LTE	0.982	0.874	0.056	0.000	0.000	0.982	0.963	0.000	0.000	0.000
5G mmWave	0.993	0.993	0.909	0.320	0.062	0.984	0.984	0.867	0.479	0.000
Infrastructure Upgrade	0.993	0.993	0.771	0.251	0.027	0.966	0.771	0.062	0.027	0.000
Satcom	0.998	0.998	0.998	0.998	0.998	0.996	0.996	0.986	0.986	0.000

Weighting the different speeds equally results in the following rank from best coverage to worst coverage: Satcom, 5G mmWave, Upgraded Infrastructure, LTE, and Current State.

Throughput

The throughput attribute had that same data sources as coverage; however, it captures the maximum throughput for download and upload (Table 15). If considering the download and upload having equal weights, the ranking from best to worst are Satcom, upgraded infrastructure, 5G mmWave, LTE, and Current State.

Table 15 Throughput Attribute Summary

	Max Upload (Mbps)	Max Download (Mbps)	The ratio of Upload/Download
Current State	14.3	14.8	.96
LTE	27.6	70.0	.39
5G mmWave	106.3	606.4	.17
Infrastructure Upgrade	299.6	299.6	1
Satcom	165.9	662.5	.25

The ratio between upload and download yields some interesting considerations. For example, for the current state Wi-Fi the ratio is .96 and 1.0 for upgraded infrastructure, which is harmonious with the detail that Wi-Fi uses the same bandwidth to upload and download. The implementation of 5G in this paper also uses the same bandwidth for uploads and downloads; however, the Time Division Duplexing is set at a ratio of 8 to 1 for download to upload.

Hardware

The hardware data was obtained from literature and whitepapers. Table 16 contains the summary of the attribute. When weighting power and surface area equally, the technologies ranked from best to worst: Current state and upgraded infrastructure (tie), LTE,

5G mmWave, and Satcom. The Satcom alternative is an outlier when it comes to hardware, due to the large antenna and power required.

Table 16 Hardware Attribute Summary

	Power Draw (W)	Surface Area mm ²
Current State	1.25	154.84
LTE	1.50	96.77
5G mmWave	3.79	398.71
Infrastructure Upgrade	1.25	154.84
Satcom	150.00	145161.00

Latency

During the field measurements, Wi-Fi exhibited a relatively high ping failure rate of 5.2% (27/513) while at each parking spot. However, a walk test from the access point to the far edge of the flight line (~310 meters) yielded only a .8% failure rate (2/228). The walk test was a line of sight situation, whereas, at each parking spot, there were many obstructions in the form of C-17s, KC-10s, and Aerospace Ground Equipment. Although measurement at each parking spot represents a real-world result, the 5G mmWave, upgraded infrastructure, and Satcom alternatives were modeled using a clear line of sight; as such, the author chose to use the walk test data versus the latency measurement at each parking spot. As the parking spots ranged from 74 to 274 meters away from the access point, the author used an average response time between for that range based on the walk test.

Table 17 Wi-Fi Walk Test Round Trip Times

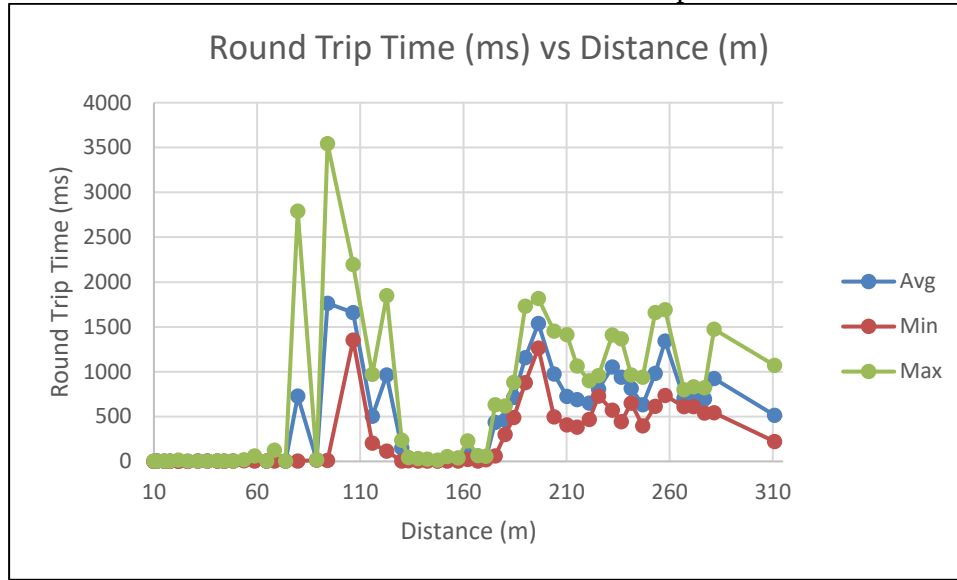


Table 18 contains the values used for the latency attribute.

Table 18 Latency Result Summary

	Round Trip Time (ms)
Current State	609
LTE	126.2
5G mmWave	11.7
Infrastructure Upgrade	6.5
Satcom	50

The latency attribute has a reverse scale, in that a lower response time is better.

Analyzing this attribute only, the ranking from best to worst is upgraded infrastructure, 5G mmWave, Satcom, LTE, and current state.

Reliability

As mentioned in the methodology chapter, the reliability attribute was subjective based on observations and literature. The categorical scores for high, medium, and low reliability are 1, .75, and .25, respectively. Table 19 contains the scores for the reliability

attribute.

Table 19 Reliability Attribute Summary

	Reliability Score
Current State	0.25
LTE	1
5G mmWave	0.75
Infrastructure Upgrade	0.75
Satcom	0.75

Attribute Weights

Attribute weights are used for utility theory, SAW, and TOPSIS. When five subject matter experts were asked to rank the attributes from most important to least important, three out of five experts came up with: coverage, throughput, reliability, hardware, and latency. Table 20 contains the SME rankings and weights assigned using the rank-ordered centroid method.

Table 20 Expert Assessed Attribute Weights

Attribute	Preference	Weight
Coverage	1	.457
Throughput	2	.257
Reliability	3	.157
Hardware	4	.09
Latency	5	.04

LTE Band Measurements and Drive Test

There were 10 unique EARFCNs (LTE channels) identified and measured. Using the categories used in the SNC wireless survey, seven channels were excellent, two were good, and one was marginal using the average Received Signal Strength Indicator (Sierra Nevada Corporation, 2018). Table 21 summarizes the data obtained using the channel scan on the spectrum analyzer.

Table 21 Summary of LTE Signal Strength Measurements

Channel (EARFCN)	Center Frequency (Mhz)	Average RSSI (dBm)	Max Values (dBm)	Min Values (dBm)	Categorical Assessment
739	1944	-64.31	-58.42	-70.57	Excellent
8290	1955	-62.42	-54.93	-70.89	Excellent
1000	1970	-55.47	-46.80	-61.93	Excellent
1150	1985	-64.51	-56.04	-73.82	Excellent
2125	2128	-56.18	-44.48	-63.64	Excellent
2300	2145	-61.78	-55.70	-68.70	Excellent
5035	731.5	-74.31	-64.96	-79.92	Good
5110	739	-69.59	-59.45	-79.61	Excellent
5230	751	-67.18	-60.37	-73.90	Good
2585	887.5	-70.24	-61.00	-77.99	Marginal

The drive test collected 1207 data points, and the results are in Table 22. 56% of the data points had an excellent RSSI, 42.1% rated good, and 1.4% were marginal. Figure 20 plots the data points using the SNC developed scale. The areas of marginal signal strength tend to be in the shadow of the aircraft hangars, where the cell tower is not in the line of sight. This result gives credibility to the idea that this LTE band would provide basic connectivity 98.1% of the time where the vehicle drove on the flight line. However, this gives only a partial picture of the coverage, as modern LTE devices can use carrier aggregation, which can combine up to five different LTE bands, to provide 1Gbps speeds with 100Mhz of aggregated bandwidth (Blanco, 2014; Montojo and Damnjanovic, 2011).

Table 22 LTE Drive Test Summary

	RSSI (dBm)
Average	-63.60
Max	-44.00
Min	-78.30
Count	1207
Standard Deviation	6.28



Figure 20 Drive Test Results

Wi-Fi Radio Environment

The author used a single slope path loss model and the High Throughput Task Group Two-Slope model to see which better characterizes an empty flight line (Erceg, et al., 2004; Heereman, et al., 2009). Equation 6 is the single slope model while Equation 7 is the two slope model. Table 23 contains the parameters found by the least-squares method for the single slope model and the walk test data. On the other hand, Table 24 contains the parameters for an outdoor open space environment, the closest environment to a flight (Erceg, et al., 2004).

$$Path Loss (dB) = PL_0 + 10n \log(d) + X\sigma$$

Equation 6 Single Slope Path Loss

Where

PL_0 is the reference path loss

n is the path loss slope

d is the distance from the reference point

$X\sigma$ is a normally distributed variable with a mean of zero and a standard deviation σ_x

Table 23 Single Slope Model Parameters

Case	n	σ_x	R^2
802.11A	1	1	.876
802.11G	.65	1	.55

$$Path Loss (dB) = L_{fs}(d)$$

$$d \leq d_{BP}$$

$$Path Loss (dB) = L_{fs}(d_{BP}) + 35 \log_{10}(d)$$

$$d > d_{BP}$$

$$\text{Equation 7 Two Slope Path Loss}$$

Where

L_{fs} is the free space loss

d_{BP} is the distance to the break point

d is the distance from the reference point

Table 24 Two Slope Model Parameters

Case	d_{BP} (m)	Slope before d_{BP}	Slope after d_{BP}	Shadow fading σ_x before d_{BP}	Shadow fading σ_x after d_{BP}	R^2
802.11A	35	2	3.5	3	6	.85
802.11G	35	2	3.5	3	6	.5

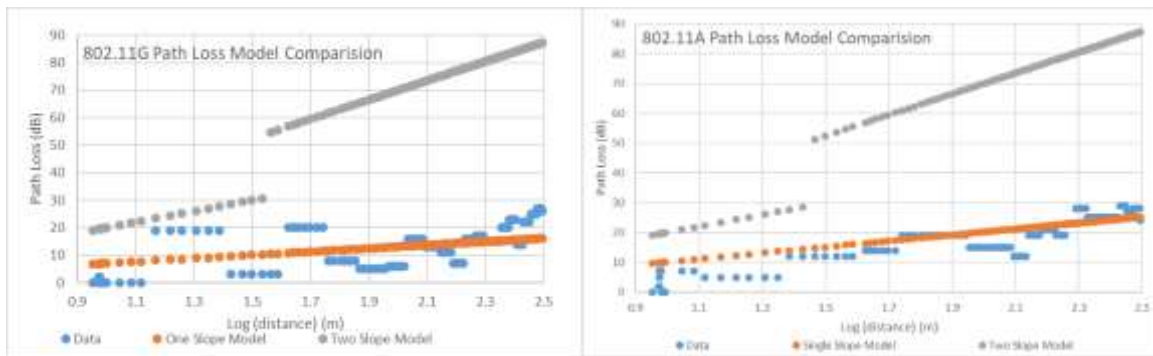


Figure 21 Comparison of Path Loss Models

The slope in the single path loss model for both frequencies is lower than expected. A slope of two is equal to the slope of free space loss, and the slope was .65 and 1 respectively for 802.11G and 802.11A. Heereman (2009) found a pathloss slopes of 1.2 to 1.7 for large

conference rooms, while Phaiboon (2007) found a concrete building had a slope of 1. Slopes of less than two are characteristic of radio environments that reflect radio energy rather than attenuate it. The unique path loss slope means that flight line maintainers likely experience a higher than normal signal strength; however, the interference noise may be significant due to signal reflections. This is an important planning consideration for the Flight Line of the Future, a factor of safety should be added to the link budget, and tests should confirm a proposed network could achieve the desired performance.

Consistency of Data

The field measurements were generally consistent with other surveys and reports. For example, the Homestead report noted a maximum download speed of 5.27 Mbps, while the maximum measured at JBMDL was 14.83 Mbps (Sierra Nevada Corporation, 2018). However, the average download speeds were 2.93 Mbps for Homestead and 2.06 Mbps for JBMDL (Sierra Nevada Corporation, 2018). The differences could be due to the ramp size (JBMDL has a larger flight line), and the size of aircraft (Homestead has fighters).

The Homestead flight line averaged a round trip time of 57ms, where the same test at JBMDL averaged a 16.8ms; however, the number of lost pings was similar at 2.8% and 5.2% (Sierra Nevada Corporation, 2018).

The Davis Monthan Wireless Survey noted an average maximum LTE download speed of 6.6 Mbps, where the average from JBMDL was 27.1 Mbps (Strunk, 2018). The literature indicates that the average download speed depends on the device used, the distance to the cell tower, the signal to noise ratio, and the number of LTE bands in use (and many other factors) (Sesia, Toufik, and Baker, 2011). Since these are not known for the Davis Monthan survey, a comparison cannot be made, other than the speeds were in the same order

of magnitude.

The results for Starlink testing from an airplane in flight are in the same order of magnitude as the link budget calculation; however, the receiver specifications and angles are different; therefore, no inference can be made about the consistency of the link budget estimation (Beal, 2020).

SAW Results

Table 25 summarizes the normalized and combined inputs for the attributes before the weights being added. Green colors are closer to one, and red colors are closer to zero for comparison purposes.

Table 25 SAW Normalized Inputs

	Coverage	Throughput	Reliability	Hardware	Device Latency
Current State	0.033	0.035	0.250	0.813	0.011
LTE	0.387	0.099	1.000	0.917	0.052
5G mmWave	0.662	0.635	0.750	0.286	0.556
Infrastructure Upgrade	0.488	0.726	0.750	0.813	1.000
Satcom	0.900	0.777	0.750	0.005	0.130

Multiplying the weights and adding the attributes together produces a ranking depicted in Table 26. Using SAW, SME assessed weights, and rank-ordered centroid weighting, Satcom is the preferred alternative followed by upgraded infrastructure, 5G mmWave, LTE, and current state. However, when alternative options for ranking are used, Satcom only finishes 1st 10% of the time, compared with 86% of the permutations for the upgraded infrastructure alternative, as depicted in Figure 22.

Table 26 Simple Additive Weighting Results

Alternative	Score	Rank
Satcom	0.734	1
Infrastructure Upgrade	0.640	2
5G mmWave	0.632	3
LTE	0.444	4
Current State	0.137	5

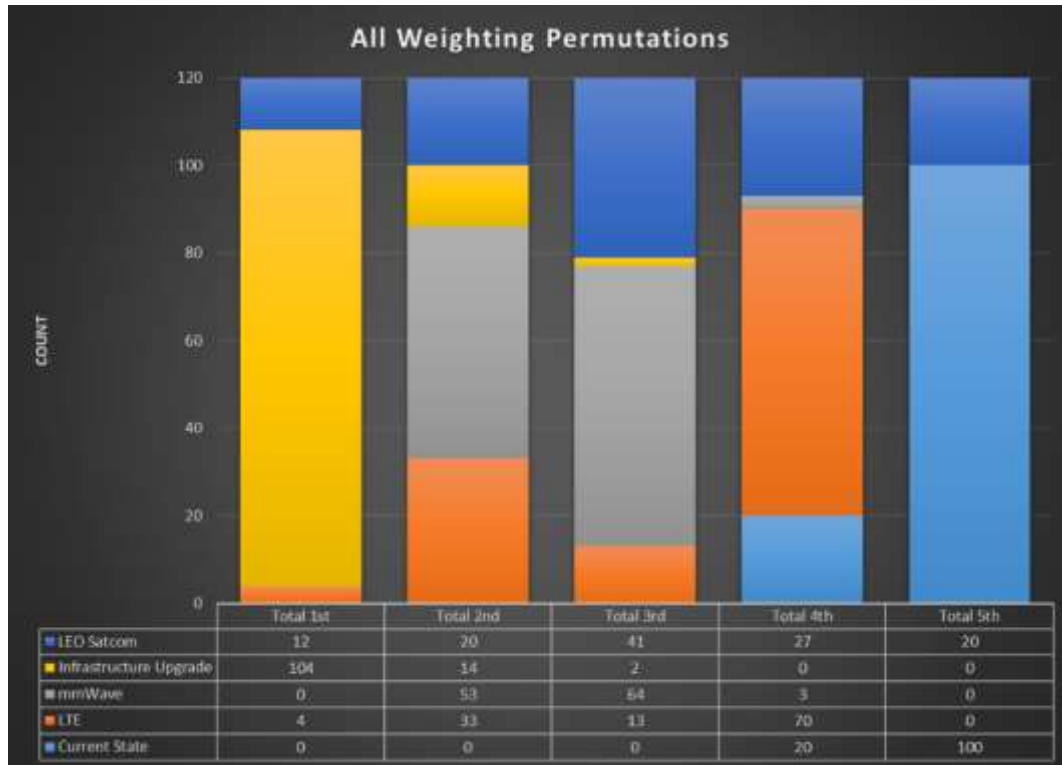


Figure 22 All Simple Additive Weighting Weight Permutations

Table 27 and Figure 23 shows how much an attribute weight needs to change to switch a ranking. It appears that the throughput attribute is most sensitive, while reliability is the least sensitive to rank reversals.

Table 27 Sensitivity Figures for Simple Additive Weighting

Attribute	Current Weight	Weight to Change Ranking
Coverage	.457	.337
Throughput	.257	.002
Reliability	.157	.687
Hardware	.09	.19
Latency	.04	.16

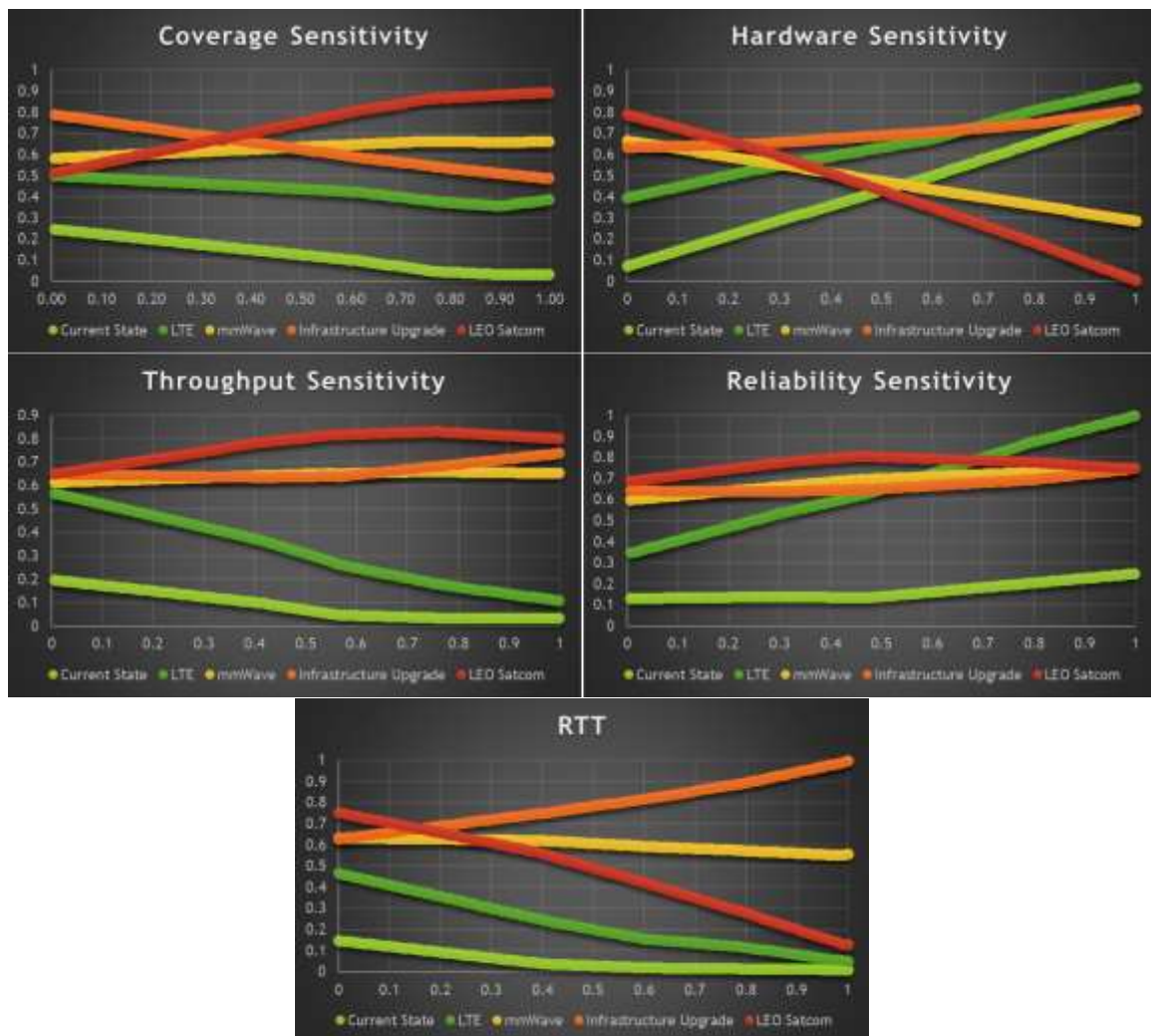


Figure 23 Sensitivity Plots for Simple Additive Weighting

TOPSIS Results

TOPSIS uses the same weights as simple additive weighting; however, it seeks to calculate a performance score that is closest to the ideal solution and farthest away from the

worst case. Table 28 shows the intermediate step of a weighted normalized matrix and the best and worst cases for each attribute.

Table 28 Weighted Normalized TOPSIS Matrix

	Coverage	Throughput	Reliability	Hardware	Device Latency
Current State	0.008	0.007	0.024	0.090	0.001
LTE	0.091	0.019	0.095	0.090	0.032
5G mmWave	0.186	0.120	0.071	0.089	0.039
Infrastructure Upgrade	0.125	0.148	0.071	0.090	0.040
Satcom	0.287	0.149	0.071	0.000	0.037
Best Case	0.287	0.149	0.095	0.090	0.040
Worst Case	0.008	0.007	0.024	0.000	0.001

When the SME scores are used in a TOPSIS methodology, Satcom is the preferred solution with 5G mmWave, upgraded infrastructure, LTE and current state following in rank order.

Table 29 TOPSIS Score Summary

	Euclidian Distance from Best Case	Euclidian Distance from Worst Case	Score	Rank
Satcom	0.093	0.318	0.775	1
5G mmWave	0.107	0.237	0.689	2
Infrastructure Upgrade	0.163	0.213	0.566	3
LTE	0.235	0.145	0.383	4
Current State	0.323	0.090	0.217	5

Similar to the simple additive weighting results, if all the different swing weight

combinations are enumerated, the Satcom alternative doesn't rank first a majority of the time. Using all the possible TOPSIS swing weighting combinations, 5G mmWave comes in first 45% of the time, followed by upgraded infrastructure (32%), Satcom (18%), and LTE (5%), as depicted in Figure 24.



Figure 24 Summary of all TOPSIS Weight Permutations

Figure 25 shows how the TOPSIS rankings change with different weights. Similar to the simple additive weighting sensitivity, the hardware attribute appears very sensitive to change, where throughput shows little sensitivity to rank reversal.

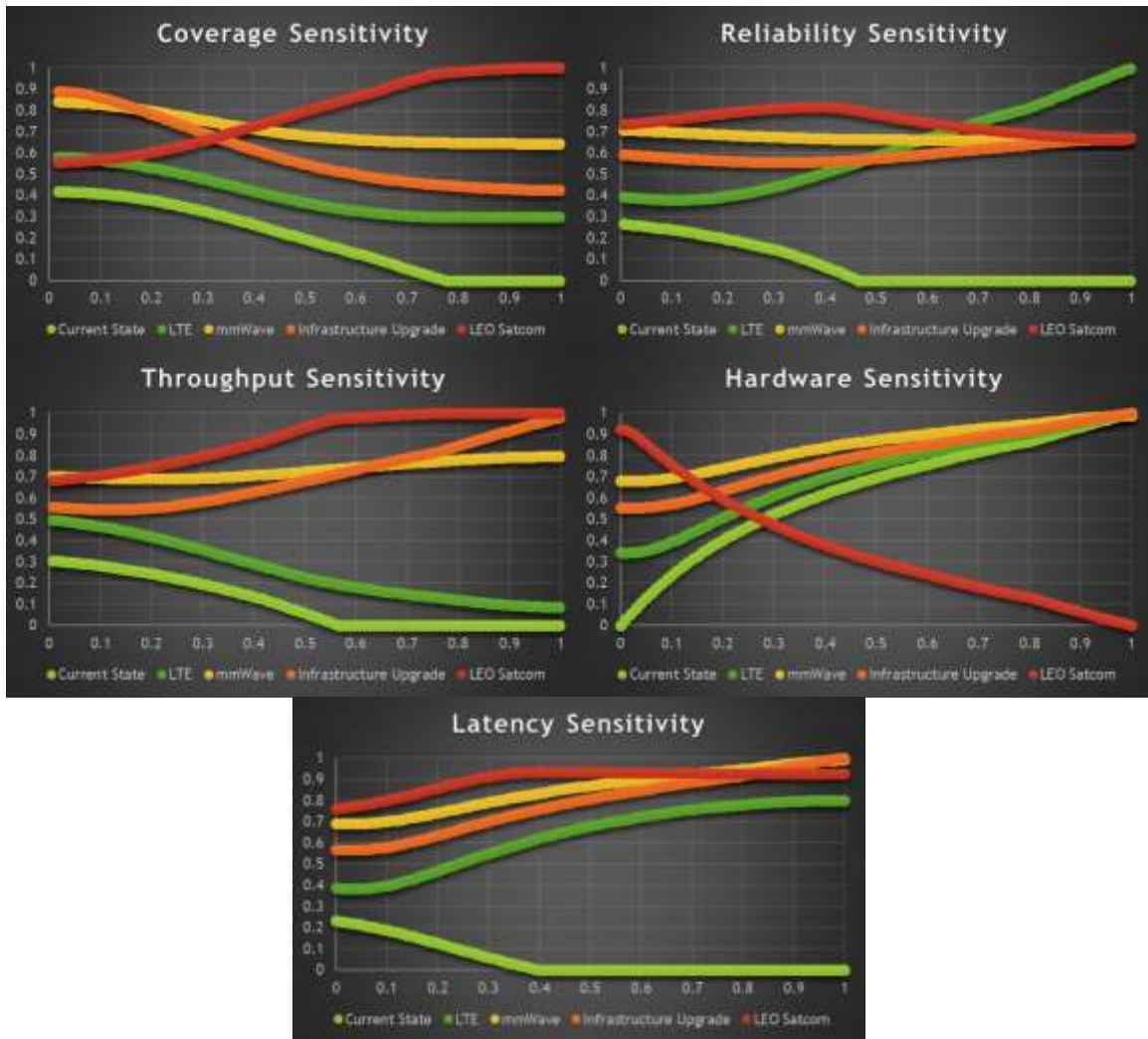


Figure 25 TOPSIS Sensitivity Charts

Utility Theory Results

For utility theory, the preferred alternative is upgraded infrastructure followed by Satcom, 5G mmWave, LTE, and current state, as summarized in Table 30 and Figure 26. The radar comparison of Figure 26 highlights the shortcomings of the current state—latency, coverage, throughput, and reliability.

Table 30 Utility Theory Results

Alternative	Value	Rank
Infrastructure Upgrade	.825	1
Satcom	.804	2
5G mmWave	.663	3
LTE	.521	4
Current State	.174	5

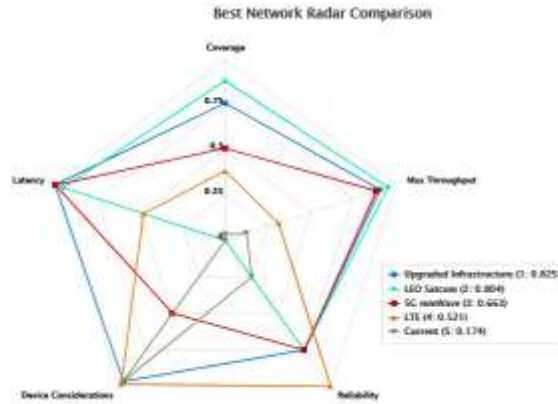


Figure 26 Radar Alternative Comparison

Changing the weights of some of the attributes does result in a change in the preferred alternative. For example, if the weight of reliability increases beyond 60%, then LTE becomes the preferred alternative, Figure 27. Hardware is particularly sensitive to rank order reversal, Figure 28. The coverage attribute is not sensitive to changes in weighting (Figure 29).

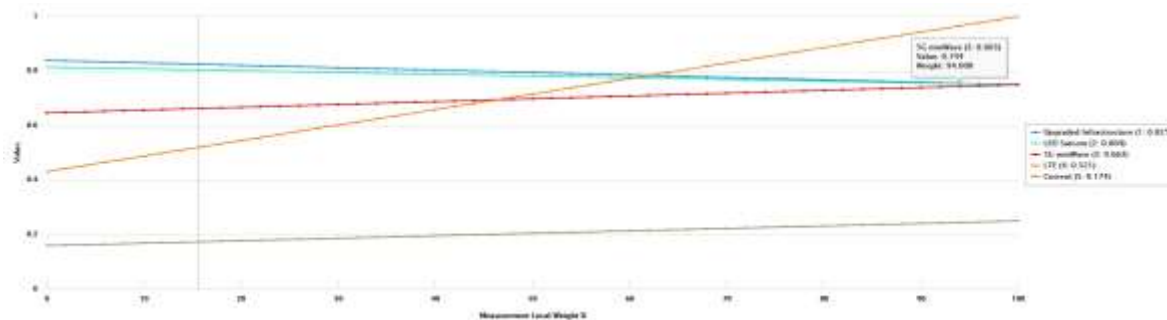


Figure 27 Sensitivity Analysis for Reliability

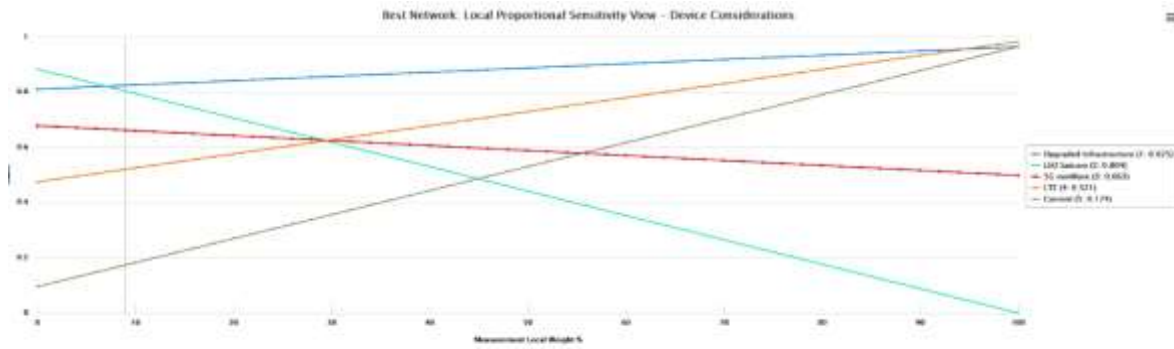


Figure 28 Sensitivity Analysis for Hardware

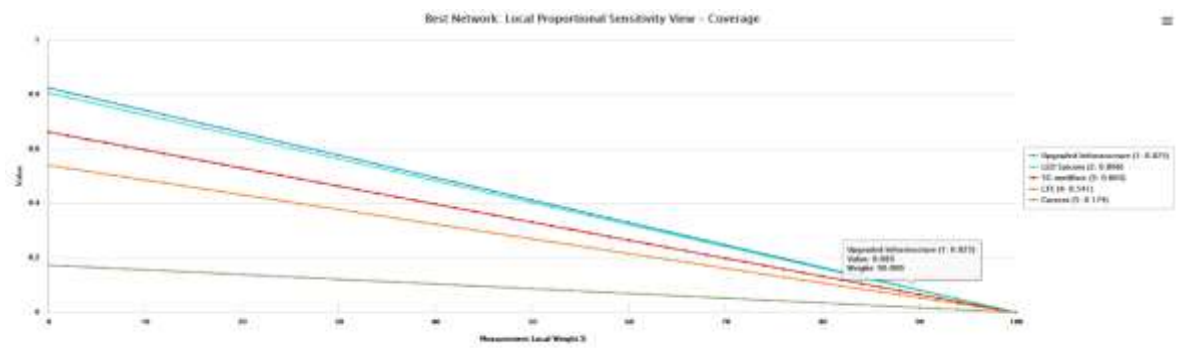


Figure 29 Sensitivity Analysis for Coverage

V. Conclusion and Recommendations

Research Conclusions

The Satcom alternative is the preferred alternative using SAW and TOPSIS, and the second most preferred using utility theory, while 5G mmWave and upgraded infrastructure both had a second-place ranking. Upgraded Infrastructure was the preferred alternative using utility theory. If taking the average of the three methods, the Satcom alternative averages first, upgraded infrastructure is second and 5G mmWave third, as noted in

Table 31.

Table 31 Result Summary

Alternative	SAW Rank	TOPSIS Rank	Utility Rank	Average
Current State	5	5	5	5
LTE	4	4	4	4
5G mmWave	3	2	3	2.67
Infrastructure Upgrade	2	3	1	2
Satcom	1	1	2	1.33

Given the sensitivity issues with the hardware attribute, Table 32 explores the possibility of deleting that attribute. Satcom still is the preferred alternative, but 5G mmWave edges out upgraded infrastructure for the second most preferred alternative averaging the results from the three methods.

Table 32 Results if the Hardware Attribute is Deleted

Alternative	SAW Rank	TOPSIS Rank	Utility Rank	Average
Satcom	1	1	1	1
5G mmWave	2	2	3	2.33
Infrastructure Upgrade	3	3	2	2.66
LTE	4	4	4	4
Current State	5	5	5	5

Recommendations for Action

Pursue Cellular Kits Now

Given the coverage, performance, and reliability issues demonstrated in this study, the AF should pursue cellular kits for the extra performance and reliability. Cellular kits consist of a hardened case, a battery, and a router that are capable of delivering up to 600 Mbps download speeds through tri-band Wi-Fi (Cradlepoint, 2020). The devices can be mounted inside vehicles without vehicle modification, which could provide connectivity to the worksite for some on the flight line. Additionally, the cellular kits, like the Cradlepoint COR IBR1700 support carrier aggregation of multiple bands, and specifically LTE Bands 2, 4, and 13 in use at JBMDL (Cradlepoint, 2020; Montojo and Damnjanovic, 2011). A calculation will need to be made if enhanced connectivity is worth the cost of cellular kits. The Air Force has blanket purchase agreements (BPAs) and contracts with all the major cellular providers to provide the best price to the government. If cellular kits are going to be used as a stopgap fix for wireless, then the terms of the BPAs should be investigated to see if they support this strategy.

Metrics Makeover

As noted earlier, AMC creates quarterly heat maps of Wi-Fi on the flight line. This only captures the signal strength and can mislead leaders into thinking coverage and performance are adequate. Additionally, the heat maps don't measure what flight line personnel value most, which is often a reliable and fast connection to a website. Accordingly, the author proposes that AMC add HTTP-throughput, packet loss, signal to noise ratio, and block error rate as performance metrics to account for the poor correlation between signal strength and throughput speeds. Many tools, such as those captured in Goel, Wittie, and Claffy's (2016) comparative analysis paper can measure these performance metrics.

Infrastructure Investment

The Air Force Enterprise Wireless Connectivity Scenario suggests an inter-access point space maximum of 150 feet, or around -64dBm received signal strength (CIO/A6, 2020). Using the field data: at 0 to 150 feet, there were no lost packets, the average round trip time was 2.8ms, and the lowest received signal strength was -51dBm in the walk test; however, currently the closest access point to parking spot is 233 feet, and an average distance of 466 feet away from parking spots. The 150-foot recommendation is excellent for ACC bases or areas with a structure to mount an access point; however, AMC does not have this luxury. This is a challenge noted for further research (page 62). Ignoring this challenge, an access point at every parking spot is a reasonable starting point for an initial design. The current access point density is one access point per 420,000 square feet of ramp space (15/6.3M sq ft).

There is a significant need to invest in the wireless infrastructure. The current access point locations will not support 5G mmWave or future Wi-Fi upgrades due to the distance. For example, the simulation of 802.11AC in Figure 30, where the estimated throughput is only 13.23 Mbps at the edge of the KC-10, and the coverage doesn't extend to the 2nd row of

4 rows of parking spaces.

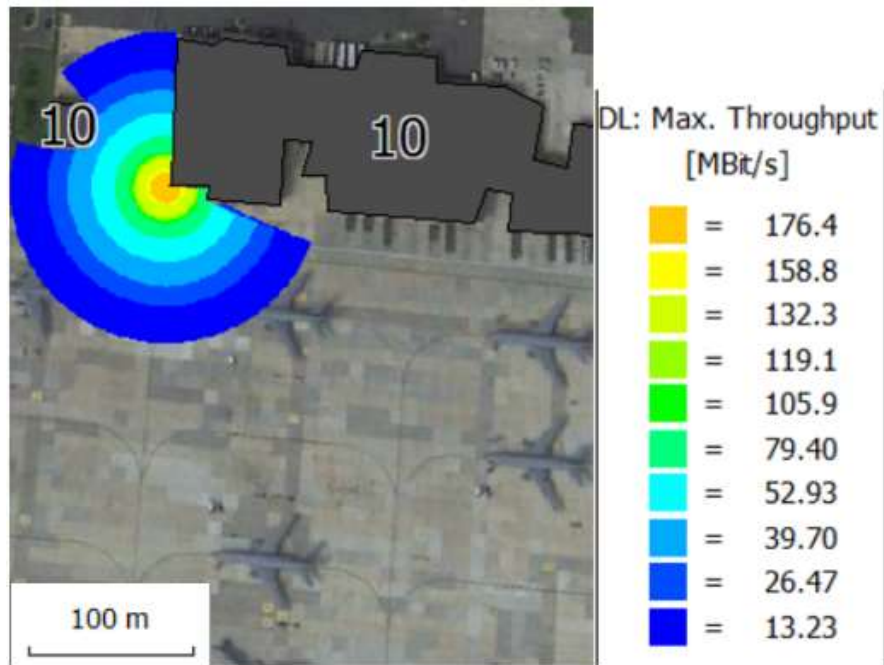


Figure 30 802.11AC Simulation for Current Access Point Locations

Some, in the commercial airline industry, have embraced a blanketing approach for Wi-Fi. For example, the author observed a national air carrier using one access point per parking spot, and the same access point. This approach yields better connectivity density, as shown in the model from Denver International Airport (Figure 31). However, currently, there is not any structure or power to mount access points to on most AMC flight lines.

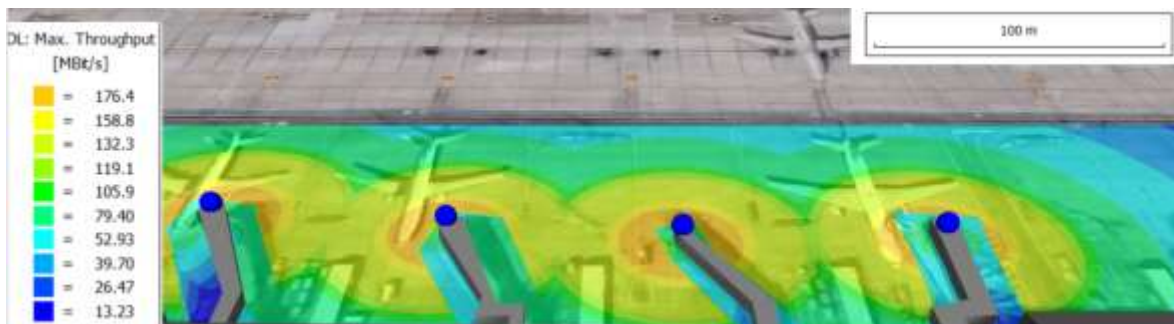


Figure 31 Wi-Fi Simulation of Denver International Airport

Wi-Fi is not the only technology that would require infrastructure upgrades. Both the 5G mmWave and Satcom alternative would need power, and 5G might need fiber optic

connections as well. However, running power to every parking spot does have significant additional benefits. If both fiber and power are run to every parking spot, then the planes can be continuously powered and connected. This would solve the challenge of reliably connecting while doing maintenance inside of an aircraft. Moreover, if power is run to the parking spots, and Satcom antennas are installed on the aircraft, then, the aircraft themselves can become the access points. Power, fiber, and structures (something to store tools, and equipment in) on tarmacs are common in the commercial industry.



Figure 32 Cellular Antenna on a Floodlight above a Shelter at Frankfurt (Koser, 2020)

Speed Leases for 5G Access

The Air Force Civil Engineering Center is working on no-cost leases to Air Force bases to deploy 5G service using small cells (Beckman, 2019). The strategy is to group bases to make the business opportunity more appealing to the carriers. The Air Force should allocate resources on expediting these leases. Additionally, for the non-military application, like a flight ramp for FedEx or UPS, the companies should explore small cell leasing opportunities for their operations.

Satcom is a Gamechanger

Starlink is poised to change the wireless industry, specifically in providing backhaul.

Backhaul is traditionally accomplished via fiber optics lines that are expensive to install. If the Starlink constellation can be fully deployed, it can be used to create satellite-connected microcells that service hard to reach areas similar to JBMDL’s flight line. Additionally, it presents an opportunity for the Air Force to have connectivity in all their wide-body jets, for a large proportion of the globe.

Although this paper used JBMDL’s weather data, other locations should see similar coverage results. Figure 33 shows the total atmospheric attenuation estimated for various implementation locations.

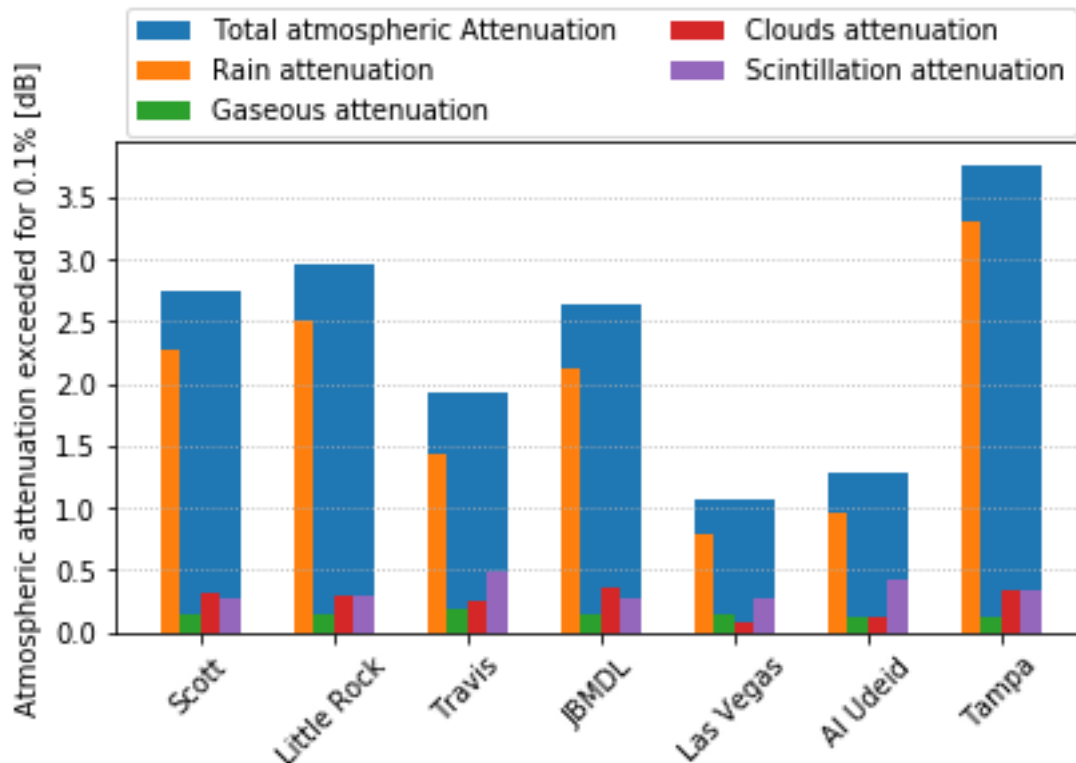


Figure 33 Atmospheric Attenuation for Various Locations

Recommendation for Future Research

After the first implementation of 5G on Air Force bases, a field study on quality of service attributes is a natural extension of this research. This would allow a comparison of

real-world values with the simulated numbers in this study. Additionally, when Starlink's constellation reaches its initial operating capability, a researcher could gain insight into some of the quality of service attributes. The average elevation will be much lower than when the constellation is complete, but it would give a researcher insight into the latency and peak throughput of the system. The wireless industry will be very interested in using Starlink as a backhaul connection for cellular service, and this has implications for remote locations without fiber connections or microwave links.

A challenge not addressed in this project is the placement of access points on the flight line. The main ramp is analogous to a flat parking lot with no structures on which to mount antennas. There have been some creative flat implantations, like 5G antennas built into manhole covers, that may help ease this challenge (Johnson D., 2018). Additionally, antenna placement will need to be coordinated with airfield managers to ensure no interference is with airfield systems, like navigation aids. Moreover, unique antenna arrangements are still dependent on power; however, some areas might be able to operate off solar power.

Conclusion

While the current state of connectivity manages to meet minimum mission requirements, the Flight Line of the Future is likely to be more of a vision than a reality unless we upgrade the infrastructure. Fortunately, the technologies that will turn the vision into reality are approaching maturity. The time is now to take action and invest in infrastructure and programs that will connect our Airmen and platforms together.

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