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THESIS

5G AS A POTENTIAL REPLACEMENT FOR EXPEDITIONARY AVIATION COMMAND AND CONTROL TACTICAL FIBER OPTIC CABLE

by

Katherine L. Smith

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Thesis Advisor: Carl L. Oros
Second Reader: Joseph W. Lukefahr

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Tactical fiber optic cable connects aviation command and control systems to coordinate airspace operations. Tactical fiber impedes unit maneuverability during displacement to alternative battlefield positions in support of operational tempo. The purpose of this thesis is to assess the feasibility of replacing or augmenting tactical fiber with local 5G wireless communications networks for company size units to enhance operational logistics, mobility, and ultimately, lethality. This thesis examines technologies associated with 5G networks and ongoing experimentation compared to how tactical fiber is implemented now. It also explores how 5G networks would be employed in a dynamic operating environment in which effective data transmission must be balanced with allowing users to move quickly. Considerations regarding bandwidth, range, latency, and logistics are analyzed to assess the feasibility to implementing local 5G wireless communication networks. Sub-6 GHz frequencies provide the capabilities required to replace tactical fiber but will require further development of tactical equipment to effectively implement. Millimeter wave technologies have not sufficiently matured in technical readiness to be ready for fielding. Further research, development and field testing is required to develop secure frameworks for 5G networks, but these capabilities provide a promising alternative to tactical fiber optic cable.

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5G AS A POTENTIAL REPLACEMENT FOR EXPEDITIONARY AVIATION COMMAND AND CONTROL TACTICAL FIBER OPTIC CABLE

Katherine L. Smith
Captain, United States Marine Corps
BS, United States Naval Academy, 2014

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Approved by: Carl L. Oros
Advisor

Joseph W. Lukefahr
Second Reader

Alex Bordetsky
Chair, Department of Information Sciences

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Tactical fiber optic cable connects aviation command and control systems to coordinate airspace operations. Tactical fiber impedes unit maneuverability during displacement to alternative battlefield positions in support of operational tempo. The purpose of this thesis is to assess the feasibility of replacing or augmenting tactical fiber with local 5G wireless communications networks for company size units to enhance operational logistics, mobility, and ultimately, lethality. This thesis examines technologies associated with 5G networks and ongoing experimentation compared to how tactical fiber is implemented now. It also explores how 5G networks would be employed in a dynamic operating environment in which effective data transmission must be balanced with allowing users to move quickly. Considerations regarding bandwidth, range, latency, and logistics are analyzed to assess the feasibility to implementing local 5G wireless communication networks. Sub-6 GHz frequencies provide the capabilities required to replace tactical fiber but will require further development of tactical equipment to effectively implement. Millimeter wave technologies have not sufficiently matured in technical readiness to be ready for fielding. Further research, development and field testing is required to develop secure frameworks for 5G networks, but these capabilities provide a promising alternative to tactical fiber optic cable.

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LIST OF ACRONYMS AND ABBREVIATIONS

1G	first generation of mobile communication
2G	second generation of mobile communication
3G	third generation of mobile communication
3GPP	Third-Generation Partnership Project
4G	fourth generation of mobile communication
5G	fifth generation of mobile communication
5GC	core network
ACE	Aviation Command Element
AI	artificial intelligence
AMF	Core Access and Mobility Management Function
C2	Command and Control
CAC2S	AN/TSQ-263 Common Aviation Command and Control System
CIA	confidentiality, integrity, and availability
COTS	commercial off the shelf
CTN	AN/MSQ-143(V)1 Composite Tracking Network
CEC	Cooperative Engagement Capability
C/N	carrier-to-noise ratio
DDR&E	Director of Defense Research and Engineering
DOD	Department of Defense
DoS	denial of service
EABO	Expeditionary Advanced Base Operations
E_b	modulated energy per information bit
EIRP	Equivalent Isotropically Radiated Power
eMBB	enhanced mobile broadband
EMI	electromagnetic interference
EMS	electromagnetic spectrum
FARP	Forward Arming and Re-fueling Point

FSPL	free space path loss
FCS	Future Combat System
FDM	frequency division multiplexing
FDD	frequency division duplex
GOTS	government off-the-shelf
HMMWV	high mobility multipurpose wheeled vehicle
IP	internet protocol
ISR	intelligence, surveillance, and reconnaissance
G/ATOR	A/N TPS 80 Ground/Air Task Oriented Radar
G-BOSS	ground-based operational surveillance system
gNB	next generation node base station
JTRS	Joint Tactical Radio System
LOS	line of sight
LTE	long-term evolution
MACCS	Marine Aviation Command and Control System
MACG	Marine Air Control Group
MAGTF	Marine Air Ground Task Force
MIMO	multiple-input, multiple-output
ML	machine learning
mMIMO	massive multiple-input, multiple-output
mMTC	massive machine-type communication
mmWave	millimeter wave
MOS	military specialty occupation
MRQ 13	A/N MRQ 13 communications system
N_0	noise spectral density
NGRAN	next generation radio access network
NR	new radio
NWDAF	network data analytics functions
OEF	Operation Enduring Freedom

OIF	Operations Iraqi Freedom
OFDM	orthogonal frequency-division multiplexing
OFDMA	orthogonal frequency-division multiple access
OSI	open systems interconnection
P2P	point-to-point
PLEO	proliferated low earth orbit
QAM	quadrature amplitude modulation
RAN	radio access network
RF	radio frequency
SISO	single-input, single-output
S/N	signal-to-noise ratio
SPEED	Systems Planning, Engineering, and Evaluation Device
TRL	technology readiness level
TDD	time division duplex
THOR	Tactical Humanitarian Operations Response
TFOCA	tactical fiber optic cable assembly
VHF	very high frequency
UAV	unmanned aerial vehicle
UE	user equipment
UHF	ultra high frequency
UPF	user plan function
URLLC	ultra reliable and low latency communications
WCDMA	wideband code division multiple access
WiMAX	worldwide interoperability for microwave access
WPPL-D	wireless point-to-point link version D

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I. INTRODUCTION

A Marine Corps air defense company relies on tactical fiber optic cable to link dispersed air command and control (C2) system elements. Employing tactical fiber is time and manpower intensive and inhibits maneuverability. Exploring emerging networking solutions, like fifth generation of mobile communication (5G), may improve the speed of setup and teardown of C2 networks. In turn, this would improve the air defense company's maneuverability, survivability, and operational lethality. This thesis investigates advancements of 5G new radio (NR) in the context of aviation C2 to qualitatively assess the viability of replacing or augmenting tactical fiber optic cable. The following notional Marine Corps vignette provides the context for how a typical air defense company employs.

When an air defense company arrives to employ their sensors and provide C2 functions within the airspace, tents with computer consoles are set up. Switches and server stacks are emplaced to ensure data transmission from multiple sensors to the computers to be shared via radio frequencies like very high frequency (VHF) and Link 16 to aircraft. Other Marines begin the setup of the radar system to track aircraft operating overhead. Additional Marines ensure the radios are configured and operating for effective ground-to-air communication, utilizing multiple omni and directional antennas providing optimal coverage of tactically assessed communication links. The Composite Tracking Network (CTN) will allow for Marine forces to connect to the Cooperative Engagement Capability (CEC) and enhance the data shared between sensors and agencies in the battle space. For each of these systems, power sources like mobile loaded generators are employed to keep them operational, and air conditioning units on to ensure the system is operating at a sustainable temperature. Grounding rods are placed in the dirt around these systems to give a path for electricity to discharge. Crucially, each of these systems are networked together via tactical fiber optic cable.

Multiple reels of tactical fiber optic cable are laid in sequence to extend the distance between sensors. This allows for the sensors associated with an air defense company to utilize a larger area, providing additional survivability through increased dispersion. Connecting stationary systems via tactical fiber optic cable has been the standard and continues to serve as an effective method of ensuring data transmission between multiple systems. This laying of tactical fiber optic cable is a relatively slow process requiring multiple Marines to lay out the fiber over hundreds of meters between sensors, regardless of the type of terrain. In areas where there is likely to be any sort of vehicular traffic, ditches must be dug to lay the fiber optic cable in to prevent breakage which will result in inoperability and take time to repair. Once emplaced, an air defense company can operate effectively but may be required to move as the fight continues. In order to move, not only do all of the individual systems need to be broken down and packed for transport, but that same fiber needs to be re-rolled onto reels.

Tactical fiber optic cable is one aspect that decreases maneuverability within an air defense company. Investing in a technology that allows for faster maneuverability between locations will be an essential endeavor in coming acquisitions. This thesis investigates the advancements of 5G NR as it relates to employment in an air defense company and if it could augment or entirely replace the need for tactical fiber optic cable. 5G has been integrated into commercial cellular service globally in recent years and experimentation within the Department of Defense (DOD) continues to advance 5G technology for future employment in the military space.

A. INTRODUCTION

Technological advances in the realm of military operations continue to push the limits of what forces are capable of and how they conduct their missions. As the United States focuses on specific threats and areas for future warfare, advances in technology will occur independent of geographic region. In an age where different forms of information are everywhere, the ability to effectively obtain and transmit data to the right people in the right places has only increased in speed and complexity. Systems and methods of communication have increased in speed from radios and telephones to the internet and satellites, providing global coverage. In recent battles, like in the Russian invasion of Ukraine, the current commercial cellular technologies have been effectively employed to relay important communications. Conversely, the use of such communications has also resulted in the ability of the enemy to detect and find individuals or units via such signals.

The Marine Corps will need to define how it will compete in this information environment, securely transmitting pertinent information to tactical units on the ground while ensuring that it is passed quickly enough to still be relevant. Although there are many levels associated with ensuring communication chains are implemented effectively, the physical hardware is a key component that can speed up some of the processes. This thesis focuses on the Marine Air Command and Control System (MACCS). Marine Corps C2 structures, connectivity, and the effective transfer of data between capabilities are vital to integrating systems across the battlespace: the MACCS must synchronize ground systems while simultaneously linking them to various air capabilities, both Marine aviation and joint assets. In the Marine Air Control Group (MACG), multiple squadrons provide different types of data to both aircraft and other ground units in support of a mission set. This thesis assesses how to improve the speed of data transmission at the company level with physical hardware changes.

As the political landscape of the world continues to change, the Marine Corps has moved its focus toward Expeditionary Advanced Base Operations (EABO). In an EABO, the speed of setup and teardown within a MACCS' communication and data-sharing infrastructure becomes critical, allowing for faster maneuvering. However, such rapid deployment and redeployment is a challenge for communication and data-sharing platforms of the past, with the advent of long-distance weapon threats and enhanced targeting capabilities. The integration of multiple systems and sensors throughout the battlespace provides an improved picture both to aviation assets and allows critical judgments to be made on the ground. Each of these systems requires technical and tactical proficiency in and of themselves by the Marines working on them, but the ability to connect them is a factor common to each. Tactical fiber-optic cable provides a reliable data-sharing connection between multiple ground-based C2 systems, however, the laying of fiber takes time where expeditious execution across the entire setup is critical.

B. EXPEDITIONARY ADVANCED BASE OPERATIONS

The 38th commandant of the Marine Corps published his planning guidance in July 2019, outlining where the force needs to head in the future to be more effective and sustainable in an increasingly versatile world (Berger, 2019). Improved weapons systems and technological advances, both of allies and adversaries, have dominated the discussion of the future of warfare and the ability to combat these advancements. In addition to such advancements, how the Marine Corps seeks to employ its forces has gained a new name, EABO. The Marine Corps remains expeditionary in nature, but the EABO construct further outlines how naval forces will support the forward deployment of Marines ashore, increasing mobility and reducing the signatures while moving throughout a littoral zone including on mainland or island chains (Headquarters Marine Corps, 2021b). With the ability to conduct EABO operations, the Marine Corps must also possess the infrastructure to support rapid movement from ship to shore and over the distances that future operations are expected to occur. Figure 1 provides a depiction of the expected flow of forces that may occur in an EABO scenario.

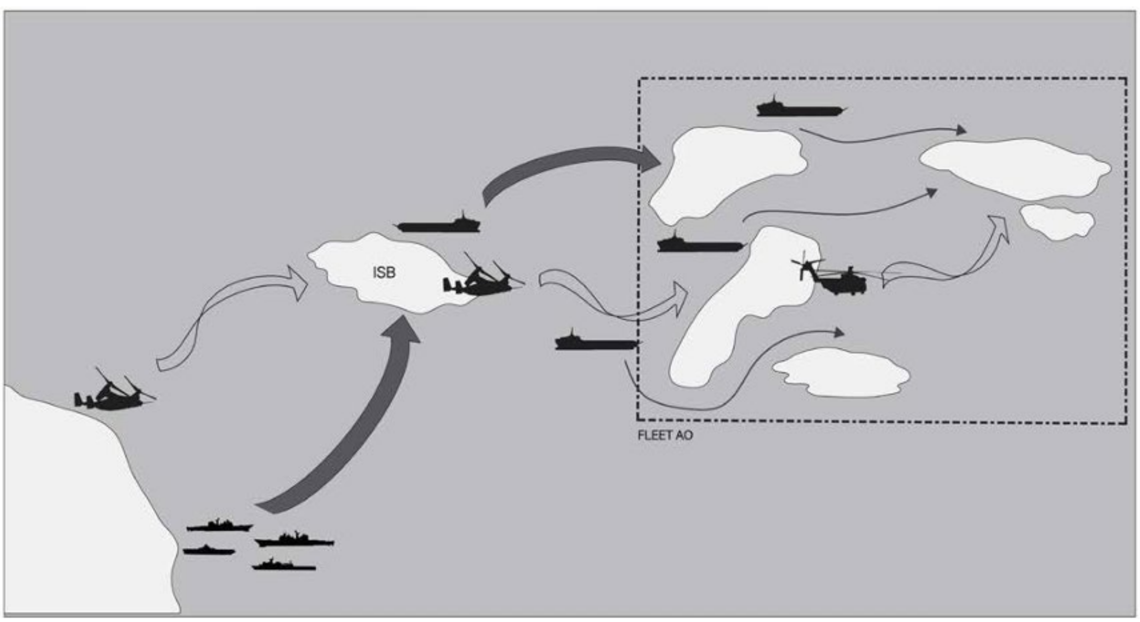

Figure 1. EABO Maneuver of Forces. Source: Berger (2019).

In Force Design 2030, General Berger (2019) outlines how and why the Marine Corps needs to initiate changes that will support the EABO. Figure 1 illustrates what an island-hopping campaign may entail, which includes the maneuvering of units and tactical systems. The equipment and doctrine utilized must advance with the technological pursuits that support this employment. Individual Marines must have the training and understanding of how to effectively operate in an EABO environment while using the appropriate equipment to execute the mission. Some technologies that were outlined as future areas where the Marine Corps must improve in the near term to be successful included upgrading air defense systems, improved capabilities of unmanned systems, better, faster long-range precision fires, and the ability to countering to an enemy in a maritime environment effectively (Berger, 2019).

C. MARINE AVIATION COMMAND AND CONTROL WITHIN AN EXPEDITIONARY ADVANCED BASE OPERATION

Although the commandant's planning guidance and force design indicates where the entire Marine Air Ground Task Force (MAGTF) is headed, the scope of this thesis is within the confines of the MACCS. The MACCS consists of ground agencies and systems that work together in support of the air picture, controlling and coordinating the use of air space by both air and ground units. This thesis is focused specifically on the ability to wirelessly transmit data over short distances utilizing 5G wireless technology to different sensors or command and control systems to better build an air picture for local users. Although the ability to push information back to higher headquarters and provide timely updates is important, the using 5G within the MACCS at the company level system allows data sharing at the forward edge. Additional updates and data sharing to higher headquarters or adjacent units, although important, are outside the scope of this thesis and likely beyond the near-term capabilities associated with 5G. It is also noteworthy that a commander can scale the size and capabilities of the MACCS to fit specific mission requirements, bringing different systems and units to the fight based on the situation.

In an EABO, the MACCS is employed by the Aviation Command Element (ACE) commander to support aviation operations, some of which include airspace control and

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management, air surveillance to include intercept of enemy aircraft and missiles, and coordination with other C2 agencies in support of troops on the ground (Headquarters Marine Corps, 2021a). Due to the mass amount of information associated with this endeavor, the ability to process, transmit, and effectively use this data will become more critical as technology advances the speed at which the battle evolves. Current and future systems, like active radars, passive sensors, communications suites, and consoles used to execute C2 must reliably connect, function, and be appropriately manned, potentially even on the move, to relay data through the battlespace. In addition to executing the mission, tactical units are also responsible for quick maneuvers, deployment and re-deployment, basic corrective and preventive maintenance, and effective troubleshooting of systems when forward deployed. When employing an EABO construct, increased deployment speed improves survivability, and augmenting such systems with technologies that enhance swift tactical operations and responsive C2 is a key factor to consider.

D. PROBLEM STATEMENT

The establishment of connectivity to synchronize multiple systems has historically been a slow and relatively cumbersome process involving the laying of tactical fiber-optic cables to transfer data between systems within the operational employment of various MACCS unit tactical architectures. Looking forward at potential conflicts, the speed of emplacement and displacement will be critical for improved maneuver. Between the slowness of setting up the fiber optic cables and the potential logistical footprint for using them, this legacy method hamstrings the maneuverability of various systems. Compounding this issue, the dispersion of multiple C2 systems creates more security and protection from enemy targeting, enabling more survivability of these systems, but creates even longer distances over which systems need to connect efficiently. The Marine Corps has effectively employed tactical fiber optic cables to connect MACCS systems in various, though stationary, environments. In addition to the setup of individual systems in support of C2 applications, laying tactical fiber optic cables is labor-intensive and prone to breakage.

This thesis reviews the considerations that need to be addressed to find a faster solution to connecting systems, such as bandwidth, speed and latency, security, power requirements, transportability, and reliability. Although tactical fiber optic cable provides some of the features necessary for mission accomplishment, it is critical to analyze transferring data via a 5G local network, that could transfer data effectively while also allowing the user to move quickly across the battlespace.

E. PURPOSE STATEMENT

The purpose of this thesis is to explore the feasibility of transmitting data via a local 5G wireless network rather than using tactical fiber optic cables. This thesis examines considerations for the implementation of 5G local networks under a variety of conditions. There are a multitude of operating environments where Marines may find themselves in future conflicts. Assessments about bandwidth, range, latency, speed, logistics, cost, and security can be made for 5G local networks and provide insights about their use in a variety of operational environments. This thesis also explores if there are instances in which tactical fiber optic cable is a better choice for connectivity than 5G or if other solutions need to be explored.

In addition to 5G supporting connectivity requirements within the MACCS, it could extend to data transfer requirements from MACCS units to other ground C2 agencies to enhance situational awareness throughout the battlespace. In the future, it may also be able to extend to air-to-ground or air-to-air applications. This research increases the understanding of how and under what conditions 5G could be an effective alternative to current data-sharing capabilities. If 5G is successful within the MACCS, there are further areas it could be implemented.

F. RESEARCH QUESTIONS

Are 5G wireless technologies a suitable replacement for tactical fiber optic cable in an air defense company application? Under what conditions does 5G provide a comparable application to tactical fiber optic cable?

What is the effective range of tactical 5G wireless communications? How does the range change under different parameters of employment?

Are 5G wireless communications suitable for typical aviation command and control tactical operations and the EABO environment?

II. CURRENT SYSTEMS

This chapter outlines the current capabilities of the MACCS within the Marine Corps and how 5G experimentation has taken place to date across the DOD. In order to understand the tools that 5G brings to the table and how they may provide additional functions in the future systems in the Marine Corps, it is essential to define some of the current features and capabilities where tactical fiber cable is already employed and in what ways it has successfully connected Marine Corps platforms. Specifically, this chapter outlines the MACCS platforms and sensors that the Marine Corps currently employs, the specifics of the tactical fiber optic cable that connects those systems, and the evolution of 5G across the Marine Corps. The associated current parameters are essential to assess how a capability like 5G may play a role in the future of data transfer in aviation command and control networks.

A. MARINE AVIATION COMMAND AND CONTROL PLATFORMS

Within an air defense company, Marines rely on these platforms and sensors to coordinate the use of the airspace, providing control and deconfliction. It is important to note some of the individual roles of the sensors and other platforms being discussed within this thesis to effectively understand how and why 5G would be applied in this architecture. These sensors also inform situational awareness data for both aircraft and ground units that may need to operate within the airspace for firing weapons like artillery or missiles from ground systems. An air defense company can be employed to function as an Early Warning and Control Detachment or as a Tactical Air Operations Center which are scalable units that provide air defense to suit the specific missions based on assigned mission. Some of the most common systems regularly employed include the AN/TSQ-263 Common Aviation Command and Control System (CAC2S), the A/N TPS 80 Ground/Air Task Oriented Radar (G/ATOR), the A/N MRQ 13 communications system, and the AN/MSQ-143(V)1 Composite Tracking Network (CTN). Currently, the previously mentioned systems are connected via tactical fiber optic cable. The underlying question is where 5G could replace or supplement this tactical fiber-optic cable architecture. Figure 2 represents one of the ways in which this system can be connected with the black lines representing tactical fiber optic cables between systems facilitating data transmission.

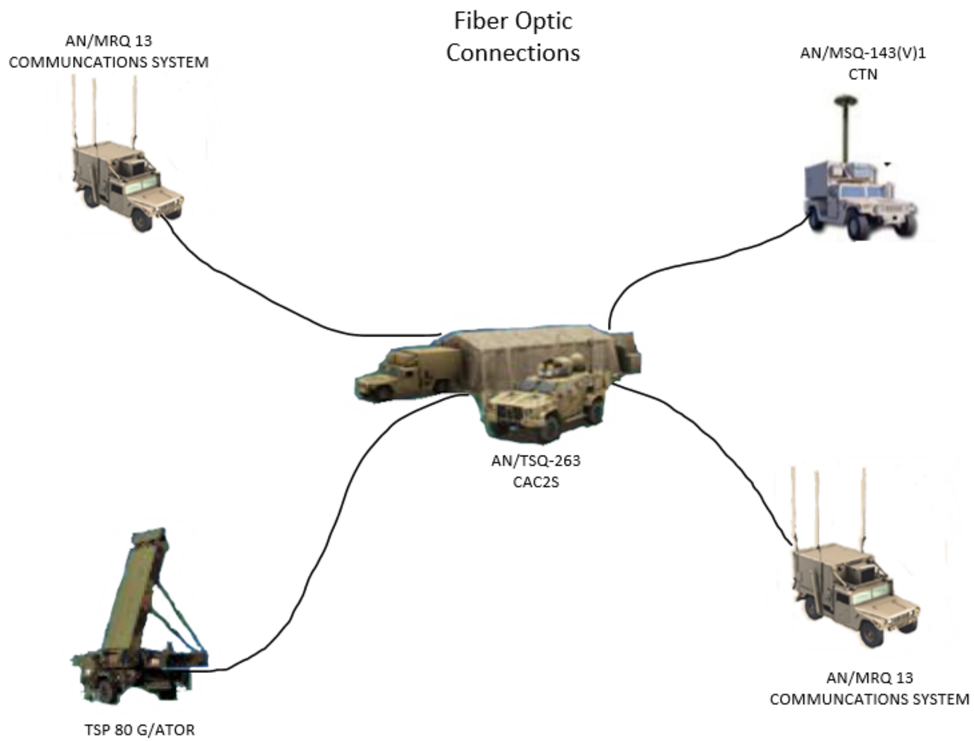

Figure 2. MACCS Tactical Fiber Optic Cable Layout. Adapted from Gerlach & Falk (2021).

These platforms integrate to provide situational awareness about the battlespace. The CAC2S transmits an air picture and provides command and control functions from controllers on the ground, primarily to aircraft within line-of-site via Link 16. The G/ATOR collects radar hits that can provide a picture via the CAC2S or other connected systems. The radar provides track data that is low latency enough that it can be used for weapons targeting solutions for airborne assets to employ missiles against. The MRQs provide VHF and ultra-high frequency (UHF) communications to aircraft operating in the airspace or other users within line-of-sight to the vehicle's antennas. The CTN allows the MACCS to connect to other joint sensors via the CEC network with real-time tracks. The

CTN is also connected to the CAC2S where joint tracks and the tracks from the G/ATOR are combined to provide a more robust picture of the airspace by operators at the consoles.

Although this basic setup is one example of how these systems can currently be employed, in the future, more systems, both already in the Marine Corps arsenal or future acquisitions, could augment this setup. More connections will require the laying of more tactical fiber optic cable which will take more time to emplace and displace. In addition to the increased connections externally to connect these systems, each current and new system relies heavily on their own internal network architectures to move the data in the correct forms to the end users. Within the CAC2S, there are multiple switches and routers that transfer the data from the various sources and into tracks for users on their respective consoles. Tactical fiber optical cables are laid between each of the systems and sensors to effectively transfer this data over the physical distance between each independent platform.

B. FIBER-OPTIC CABLES

Infrastructure throughout the world relies on the data transmission capabilities of fiber optic cable which in turn has been applied for the use of tactical systems with additional parameters to allow for employment in more rugged and austere environments. Fiber optic cables have been used for decades in global communication to move information quickly and effectively at great distances. Fiber optical cables within a global network can transmit billions of bits per second while reducing the effects of noise between transmitter and receiver. Over the long term, fiber is more durable and reliable to environmental conditions like corrosion associated with copper-based wiring; however, the glass inside fiber optic cable is the greatest concern for damage when placing it between endpoints (Hecht, 2004, p. 229).

Historically, tactical fiber optic cable has been proven effective over decades of employment and connecting command and control systems. It provides a reliable, connection with sufficient data rates to allow the flow of information between multiple systems and into the hands of the appropriate end user for decision-making. Moreover, tactical fiber optic cable is exceptional at providing longer-term, stationary data transmission capabilities. In previous conflicts, like during operations in Iraq and Afghanistan, the use of tactical fiber optic cable was used reliably to control aircraft through missions and transmit data throughout command and control agencies.

Due to the evolution of the Marine Corps trending towards the ability to operate in an EABO scenario, tactical fiber optic cables impede maneuverability. Any solution that may provide the increased speed required of employment and re-deployment must also be comparable or provide improved functions over that which tactical fiber optic cable already exhibits. The assessment for 5G as a replacement or augmentation for tactical fiber optic cables is based on the MACCS's connections. The data rate, latency, distance covered, durability, and speed of emplacement and displacement are some of the parameters that guide the assessment of 5G's ability to replace a tactical fiber optic cable structure. Other important parameters that are beyond the scope of this thesis include security, power requirements, and network architecture configurations.

The current parameters of tactical fiber optic cables provide a baseline for minimum requirements that 5G must meet in order to be considered a viable replacement. The tactical fiber optic cable used by the Marine Corps is made by Fiber Systems International Inc and comes on reels that can be connected to stretch just over a mile. Each reel is listed at approximately 1640 feet and connected via a four channel Tactical Fiber Optic Cable Assembly (TFOCA) II plugs. Each of these reels weighs 38 pounds and requires Marines to pull the reel along the terrain to lay the fiber from point to point to connect the systems. As Marines set up the fiber, the terrain determines if they can use a vehicle to help lay each reel or if the reel must be carried over areas where vehicle traffic cannot traverse. Figure 3 provides an example of what typical tactical fiber optic cable that Marines lay looks like. The tactical fiber optic cable is required to transmit 100 Mbps to effectively transmit data. The current tactical fiber optic cable used to connect MACCS systems is multi-modal.

Figure 3. Tactical Fiber Optic Cable Reels. Source: Amphenol FSI (n.d.).

In Figure 3, the reels of tactical fiber optic cable are shown which provides a reference to how they must be carried by Marines to lay fiber or mobile load to distribute it. Even when Marines use a vehicle to lay tactical fiber optic cable, the vehicle has to move at a walking pace to ensure no tangles or obstructions occur that could damage the fiber. Due to the potential environment where these fiber optic cables may be employed, additional requirements about how it can be transported or where it can operate are necessary to consider. For example, the reels are considered stackable, have been drop tested at forty-two inches, and can withstand temperatures as low as -60°C (CablesPlus, n.d.). The associated connectors to extend the distances of the fiber optic cables have similar requirements to function in these types of environments, including a crush resistance of up to 450 pounds (Amphenol FSI, n.d.). Figure 4 provides additional parameters, such as the losses associated with the connectors. Losses associated with the fiber and connectors are important factors that dictate the effects on the signals being sent between systems.

DESCRIPTION	MEASUREMENT/DETAIL
Insertion Loss (Multimode)	0.30dB – Typical, 0.75dB – maximum
Insertion Loss (Single Mode)	0.40dB – Typical, 0.75dB – maximum
Back Reflection (Single Mode-UPC Polish)	-50dB – Typical, -40dB – maximum
Operating Temperature	-46° C to + 71° C
Storage Temperature	-55° C to + 85° C

Figure 4. Tactical Fiber Optic Cable Assembly Connectors Parameters. Source: Amphenol FSI (n.d.).

The parameters outlined by Fiber Systems International, Inc. were designed for legacy Army and Marine Corps system employment and are adequate for their function. The current tactical fiber optic cable used by the Marine Corps came from the previous command and control system which was fielded in the early 1990s (Pike, 1999). By comparison, phase 1 of the CAC2S was completed with delivery to all units by 2013 utilizing the same type of fiber optic cable procured for the TAOMs (PEO Land Systems, 2013). This tactical fiber optic cable remains in use nearly forty years after its initial employment in this capacity. In an EABO scenario, units will be required to move much more often amplifying the fragility concerns associated with laying fiber and slowing movement. In future use cases, the MACCS could be required to emplace and displace multiple times each day, and in its current state, do so while ensuring proper laying and re-rolling of tactical fiber optic cable on its reels.

C. DEPARTMENT OF DEFENSE 5G EXPERIMENTATION

The DOD is moving forward with potential applications for 5G across all branches and locations. Although technological advances in cellular networks have given rise over the last several years, further consideration about the security, power requirements, antennas, and network architectures associated with adding 5G to Marine systems will need to be evaluated. If 5G is a suitable replacement or augmentation for tactical fiber optic cable in the future of MACCS platforms, further development of 5G across the DOD is required to provide adequate capabilities.

Both the DOD and the Marine Corps have sought to fund more projects using 5G to assess what its capabilities are within warfare and to determine if and how it could be used in the future of the military. 5G technology experimentation is being conducted across the DOD to assess potential capabilities for military data transmission in an all-domain environment. The DOD has an online portal that provides links to different bases that are experimenting with using 5G, including each of the branches across the United States (Chief Technology Office, n.d.). As 5G commercial technology develops, further experimentation will provide greater detail about how, when, and where it could be used in the military environment. 5G experimentation within the Marine Corps provides some insight as to what the priorities are for this technology as a force.

Since the beginning of 2022, the Marine Corps has been investigating further use of 5G networks at Camp Pendleton, CA. One example of this integration of 5G is through Lockheed Martin which was awarded a $19.3 million agreement to develop a prototype that would utilize the high bandwidth capabilities associated with 5G while reducing latency compared to other radio communications (Gill, 2022). Lockheed Martin is one of many companies that are trying to integrate 5G networks with DOD platforms to connect current military systems via 5G wireless technology (Lockheed Martin, 2022)

In addition to the contracts being sought by companies to support the implementation of 5G, the Marine Corps has published additional guidance about network modernization which includes efforts to focus on the future of 5G as a communications capability. Currently, some installations are going through the process of upgrading from traditional copper wires to fiber optic cables. The Marine Corps is also exploring future experimentation with wireless and 5G capabilities aboard installations to improve connectivity (MCICOM, 2022). The Marine Corps is focused on the development of local 5G networks. The end state is that Marines will utilize this technology whether at home, at their respective installations, or forward deployed as 5G could be implemented into tactical communication systems. Ideally, by continuously using 5G networks, Marines will be able to operate in various environments more easily while not having to switch between communications systems.

The EABO concept is one such area that requires further research to implement 5G into an effective communications architecture that the Marine Corps is exploring. The DOD has included Viasat Inc. in its $600 million initiative to explore 5G technology in military operations (Viasat, Inc., 2022). Viasat Inc. is one such company that is exploring how 5G can support command and control networks in an EABO. Especially in an expeditionary capacity, needs like “Long Range Precision Fires, Forward Arming and Re-Fueling Points (FARP), and persistent Intelligence, Surveillance, and Reconnaissance (ISR) capability” are areas of interest when implementing a 5G network (Viasat, Inc., 2022). Over the next several years, Viasat Inc. will continue to explore how 5G can be applied to tactical applications in support of users at the tactical edge who require communication capabilities in a multi-domain battlespace.

This thesis focuses on 5G wireless communications capabilities between aviation command and control units on the ground. Previous thesis work has also investigated the ability to apply 5G technology between aviation command and control elements on the ground with aircraft. White (2021) explored the possibility of utilizing mmWaves that could be steered with antenna beams between the aircraft and ground station to quickly and effectively transmit data while limiting the ability of an adversary to detect or interfere with that communication channel. Within the aviation command and control space, ground users are continually looking for methods to speed up the flow of information to pilots in the cockpit.

III. WHAT IS 5G?

This chapter outlines the technical aspects associated with current and potential future technology associated with 5G wireless communications. Different institutions have been developing 5G internationally for a multitude of purposes, but many of the same technologies overlap. Due to the associated frequency band considerations, all development is limited by similar parameters which will continue to drive how 5G is implemented. This chapter includes critical background information about hot 5G functions like network architectures, spectrum considerations, antenna technologies, and modulation schemes. By outlining parameters surrounding 5G wireless communications, this chapter provides a point of comparison as an alternative to tactical fiber optic cable.

A. THE EVOLUTION TO 5G

Beginning with first generation of cellular network technology (1G) in the 1970s, there has been a continued evolution in the expansion of capabilities utilizing radio waves to transmit information with wireless technology. With the development of second generation of mobile communication (2G), messaging was added to the capability provided by mobile devices. As third generation of mobile communication (3G) and fourth generation of mobile communication (4G) developed, the ability to transmit information beyond voice, as wireless internet connections proliferated the airspace. Advancements through 4G long-term evolution (LTE), brought the capability to be able to transmit approximately 300 Mbps (Medin & Louie, 2019). Most recently, 5G has increased the frequency bands and speeds that are being used. Figure 5 provides a depiction of the frequencies where 4G currently operates and the bands associated with 5G. In the news, 5G is primarily about commercial systems that users and companies can apply to better connect. Mobile networks are leading the charge in many cases with 5G connectivity, seeking to expand the 5G frequencies to millions of users in the United States and other countries.

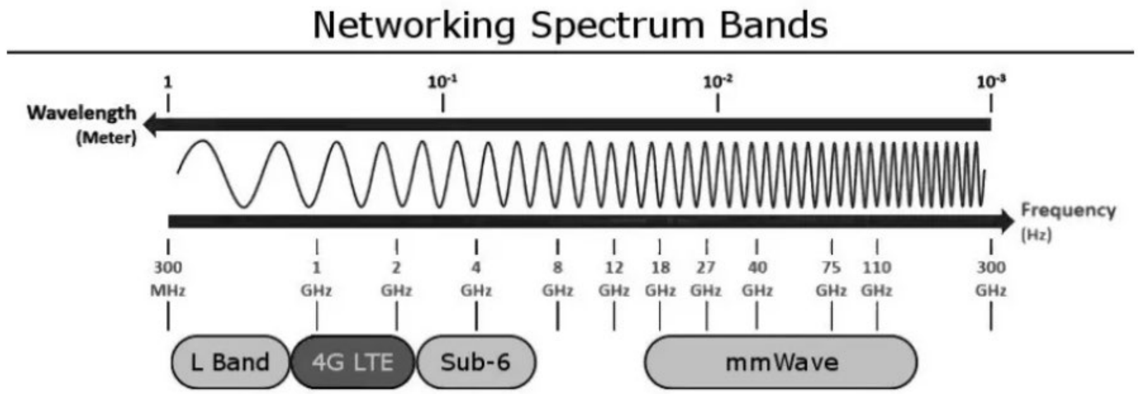

Figure 5. Frequency Spectrum of 5G. Source: Triggs (2022).

5G consists of two frequency ranges shown in Figure 5. Frequency range 1, sub-6, transmits from 450 MHz to 6 GHz and supports bandwidth channels between 5 and 100 MHz in size. Comparatively, frequency range 2, millimeter waves (mmWaves), utilizes higher frequencies from 24.25-52.60 GHz with bandwidth channels ranging from 50 to 400 MHz (Johnson, 2019). Frequency range 2 frequencies are known as mmWaves because the wavelength of the frequency is on the scale of millimeters in length where longer wavelengths are characteristic of lower frequencies. The characteristics of these frequencies provide varying levels of data transmission properties and subsequent challenges in using them effectively.

Figure 6 provides additional parameters associated with 5G Release 15 which came out in 2019. As of May 2023, Release 18 has come out with even more advancements for further study, and Release 19 projects are expected in December of 2023 (*3GPP Release 18 Overview*, 2023). Historically, different Releases have been issued annually with varying upgrades in technology.

	5G New Radio (Release 15)
Ideal Data Rate	> 10 Gbps
Ideal Latency	> 1ms
Frequency Support	Up to 40 GHz
Channel Bandwidth	Up to 500 MHz
Max carriers	16 (LTE + NR)
Max Bandwidth	1000 MHz
MIMO antennas	64 to 256
Spectrum Sharing	mmWave & NR Dual Connectivity NR-based LAA+ NR MulteFire LTE-U

Figure 6. 5G Release 15 Parameters. Source: Triggs (2022).

As seen in Figure 6, each release for 5G, provides upgrades in capabilities from previous years. Although Release 15 is from 2019, it provides a reference for what 5G will continue to develop in the future. 5G provides improvements over previous generations of mobile wireless networks. Idealized data rates and latency demonstrate what the theoretical capability of 5G is, but performance relies on additional factors when integrating with devices to process the data.

B. THIRD-GENERATION PARTNERSHIP PROJECT STANDARD

The Third-Generation Partnership Project (3GPP) standard was developed for industry to establish a baseline with technology beginning with the evolution to 3G. Notably, 3GPP is an open standard that has the collective input from multiple countries including the United States and China. The ability for users to seamlessly transition between multiple service providers while using wireless technology can be contributed to the establishment of such standards across the different specifications for this technology. Originally, separate standards were being created in different regions globally for 3G including the United States, Europe, and Japan, but ultimately it became vital to get establish a unifying construct for this area of wireless communications. As many similarities were being worked on within these separate entities, by combining efforts, the technologies being developed could be shared ideas. Wideband code division multiple access (WCDMA) is one such technology that was being developed separately within both the European and the Japanese regions (Dahlman et al., 2021, p. 5). Ultimately, in 1998, the 3GPP was created to ensure the successful development of WCDMA across multiple regions by various countries exploring this technology. WCDMA enables multiple users on a 3G network to access high-capacity service by splitting up a channel or allocating different times for different users (Rouse, 2012). As technologies further developed, like 4G and now 5G, 3GPP has remained the global authority for overseeing the development of such technologies and determining specifications and standards across the community.

The technical work for 5G began in early 2016 as the extent of capabilities of 4G LTE technology had reached its maximum. The 3GPP initiative was to develop 5G NR, making it commercially available for use only a couple of years later. The creation and implementation of 4G LTE has provided a basis that can be further built upon as future frequency ranges are explored (Dahlman et al., 2021). In addition to the technology improvements associated with the radio access, the core network for 5G also needed to be upgraded to be compatible not only with 5G capabilities but also with 4G LTE as many mobile users had not made the switch to 5G yet and it had not proliferated the space. Currently, 4G and 5G mobile cellular networks allow users to access both generations of communication from their compatible devices depending on what service is available in their respective locations.

C. CLASSES OF USE CASES

There are three main uses within 5G, Ultra Reliable and Low Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB), and Massive Machine-Type Communication (mMTC) (Johnson, 2019; Sultan, 2022). Each of these classes of use provides different capabilities to the end user and can be tailored based on the needs of different platforms. Figure 7 demonstrates how each of these cases of use are connected, but each are separate functions that service provides can implement based on the needs of their users.

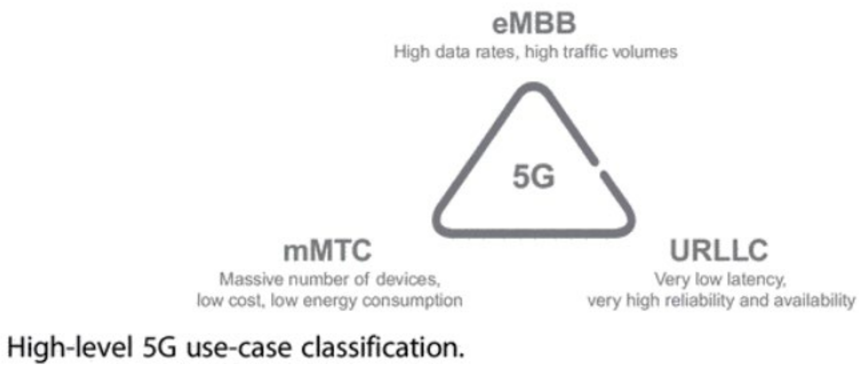

Figure 7. Classes of Use for 5G. Source: Dahlman et al. (2021).

URLLC provides different priorities that can be used to categorize the data being sent. Ultimately, mission critical services will be defined as the greatest priority for utilizing a network to ensure data transmission occurs, even in periods of network congestion. Not all data transmitted is required to be low latency, but the ability of the system to define what and when specific information is critical, like for emergency services, allows for continued operation as needed by the highest priority users (Johnson, 2019). With URLLC, there is a 99.999% chance of 32 bytes of data being transmitted within a 1 ms duration (Johnson, 2019; Sultan, 2022). The 3GPP also outlines the coupling loss requirements for the uplink and downlink of 5G transmissions. Extremely high levels of reliability data rates are expected up to 100 Mbps, allowing for latency between devices to be as low as 50 ms (Sultan, 2022).

Johnson (2019) also outlines differences between the uplink and downlink capabilities of the different uses. Although the eMBB could operate as fast as the URLLC, it does not have the same requirements to do so. Additionally, many of these parameters are based on ideal operating conditions for the system with limited interference occurring from the environment or other sources in the electromagnetic spectrum (Johnson, 2019). eMBB is an improvement over previous capabilities, but it is merely an incremental improvement in mobile services where larger amounts of data can be shared. Greater data rates directly result in users having more features available because the improvement in data rates is passed on to the end users while also increasing the number of users who have access to the bandwidth (Dahlman et al., 2021, p. 3). In eMBB, there is a 95% reliability to data being transmitted (Johnson, 2019). In an outdoor environment, the expected downlink could be as great as 50 Mbps and 25 Mbps for uplink (Sultan, 2022).

Additionally, mMTC within 5G greatly increases the number of users who can operate on the network at the same time. Within mobile networks, individual users will have relatively low data rates individually so many more users can be connected at once. These data rates will mean costs for both the device and power output requirements will also be lower (Dahlman et al. 2021). In mMTC, the expectation is that connected machines will be able to exchange data with limited or no human intervention thereby allowing all users to achieve connectivity and successfully transmit as needed without established priorities based on mission factors or service providers (Dahlman et al., 2021).

D. NETWORK ARCHITECTURE AND TOPOLOGY

5G NR is composed of the Next Generation Radio Access Network (NGRAN) which has several options that have been standardized by the 3GPP. According to Johnson (2019), there are two types of architectures for 5G, reference-based and service based. A reference-based architecture utilizes point-to-point connections to link network elements. Each interface uses a specific procedure to signal between two interfaces. Conversely, a service-based architecture utilizes network functions rather than network elements. In this type of architecture, a common bus is used for interconnecting the network functions (Johnson, 2019). The 5G system separates the user plane and control plane functions in the 5G system. Internet protocol (IP) address allocation is a session management function while packet formation is a user plane function. Figure 8 demonstrates how data is sent in a 5G wireless communications network.

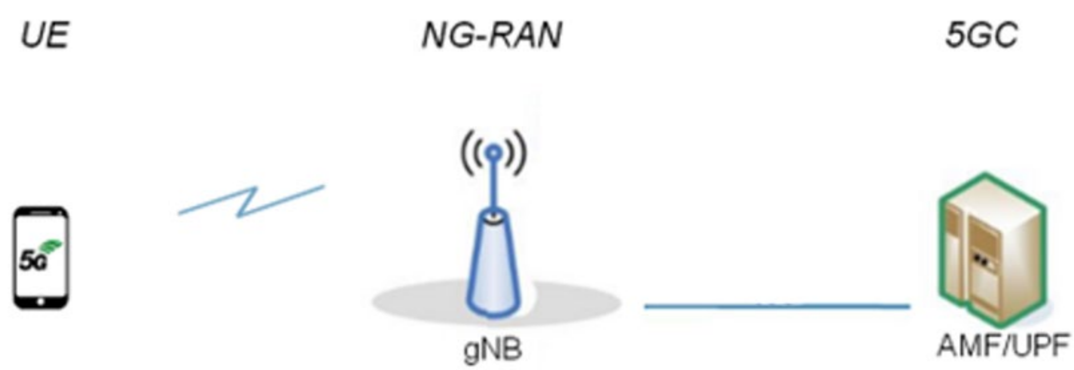

Figure 8. 5G NR Wireless Communication Architecture. Source: Sultan (2022).

A 5G system is comprised of the User Equipment (UE), a Radio Access Network (RAN), and the Core Network (5GC). The UE is the device that connects to the 5G network like a cell phone or radio. The equipment for a RAN is the Next Generation Node Base Station (gNB) that receives signals from one or more UEs. The 5GC is made of the Core Access and Mobility Management Function (AMF) or the User Plan Function (UPF). The AMF is responsible for routing access to messages and authentication and functions to secure messages from the UE through the transmissions process. The UPF is responsible for moving the message traffic to the correct users at the packet level and forwarding or routing those packets appropriately ("5G Reference Network Architecture," 2017).

E. RADIO FREQUENCY PLANNING

When seeking to implement a network, the capabilities and limitations associated with the specific radio frequencies being used are required to plan for locations and resources necessary to create a functioning network that provides the anticipated throughput. Link budgets provide a means to analytically estimate RF network coverage and capacity requirements of a given system. Link budget predictions rely on mathematical propagation models and may not accurately account for all environmental phenomena. The main link budget outputs are the cell radius that the 5G base station is capable of covering, the number of 5G base stations that will be required to effectively cover a specified area, and what the capacity and throughput will be at the cell edges (Lamali, 2019). From there, other planning considerations, like access to specific terrain or logistical footprint requirements, like power supply, can be determined to provide an assessment of suitability. It is important to note that although 4G locations may be a reasonable option, they are not necessarily going to be effective or optimal for 5G base stations to set up due to the difference in frequency characteristics (Lamali, 2019).

Link budgets consider many factors including the differences in frequency used, the alteration of power levels, thermal noise of the signals, the gain of the antennas being used, the signal amplitude, and the range the signal is being transmitted over, to name a few (Lamali, 2019). Alterations of any or all components can dictate the difference between the success of signal transmission from source to destination or that the signal will not be heard over the noise associated with the systems and space. Link budgets are a vital planning consideration for determining the cell radius, cell edge performance, and if multiple base stations will be required to achieve adequate coverage, but there are limitations ("5G mmWave 28 GHz Band Link Budget - N257," 2020). Environmental factors or interference, beyond just the signal itself, can factor into the ability and clarity in which a signal is transmitted and received.

1. Range Considerations

Link budgets associated with these frequencies are a planning consideration for how many base stations a 5G network will require at that range. When planners are considering setting up base stations, how many will be required is a planning factor as to how wide UE can be. Also, when considering the movement of UEs or base stations, redundancy must be built into the structure of the architecture to ensure connectivity can be established as users maneuver. As shown in Figure 9, lower frequencies can cover larger ranges, but at the expense of less data capacity and slower speeds. Alternatively, when looking at the high band, including frequencies that make up the mmWave frequency range, each base station will have to be closer together to cover the same area at lower frequencies (Simmons, 2022). Although 4G cellular towers can provide a guide for some base stations in a cellular network, mmWaves cannot travel in a similar manner as lower frequencies, requiring more base stations for equivalent coverage areas.

Spectrum	Low-Band	Mid-Band	High-Band
Frequencies	600 MHz 700 MHz 850 MHz	2.5 GHz C-band and CBRS 3.45 GHz	24 GHz 27.5 to 31 GHz 37, 39, 47 GHz
Cell Tower Range	Up to 25 miles *(40 kilometers)*	1 to 12 miles *(1.6 to 19 kilometers)*	50 to 2,000 feet *(15 to 600 meters)*
Coverage	Wide	Moderate	Limited
Capacity	Low	Medium	High
Locations	Rural / Suburban / Urban	Suburban / Urban	Urban / Dense Urban

Figure 9. Spectrum Characteristics by Frequency. Source: Simmons (2022).

Figure 9 provides a comparison of the type of terrain associated with each frequency band. 5G frequencies are shown in the mid-band and high-band columns as below 6 GHz and above 24 GHz, respectively. These frequencies perform better when they are transmitted in closer, urban areas where the signals have less attenuation over the distance they are transmitted. Higher frequencies, like 5G, are better able to bounce off of structures in an urban environment than they are at penetrating foliage or traveling greater distances.

2. Environment

In addition to the range considerations within the electromagnetic spectrum (EMS), the operating environment can produce significant changes in how a signal moves through the air. Humidity, temperature, and particulates in the air are examples of factors that affect transmission capabilities. Radio frequencies travel through the air and factors in that space can affect their trajectory and therefore their ability to transmit data to the intended receiver. Below 6 GHz, signals can travel more easily through the air with lower attenuation losses and less of an impact from the environment like foliage, rain, or dust. As the frequencies increase, such as with mmWaves, the impacts of the environment can be significant as the signal bounces off objects and particles in the air. The result at higher frequencies can be a lower transmissibility of the signal and greater signal path loss over the same distance as when a lower frequency is used.

F. SPECTRUM

As with any RF signal that is emitted into the environment, there is a concern that frequencies could overlap different users or systems and cause interference. Spectrum management is vital to keep different systems functioning. In the context of warfare and combat units, understanding the possible effects of enemy RF emissions is important. The enemy will likely also operate in similar frequencies for their own systems or intentionally use those frequencies to create excess noise and create jamming effects on friendly systems. The spectrum will also have to be considered for what civilian usages may be and where because 5G is also used in the commercial industry as a cellular network. In the United States, or even allied nations, the use of military 5G can be readily deconflicted with civilian 5G signals to ensure both can be used successfully and safely. In other areas where military forces are unable to deconflict 5G frequencies from other users, there is an inherent risk of electromagnetic interference (EMI) that could be unintentional, intentional, or both. Figure 10 depicts the frequency allocations that have been claimed by different countries in the 5G spectrum. In addition to 5G cellular networks, other applications like flight altimeter radars and satellites can operate in the same frequency ranges (Robin et al., 2020).

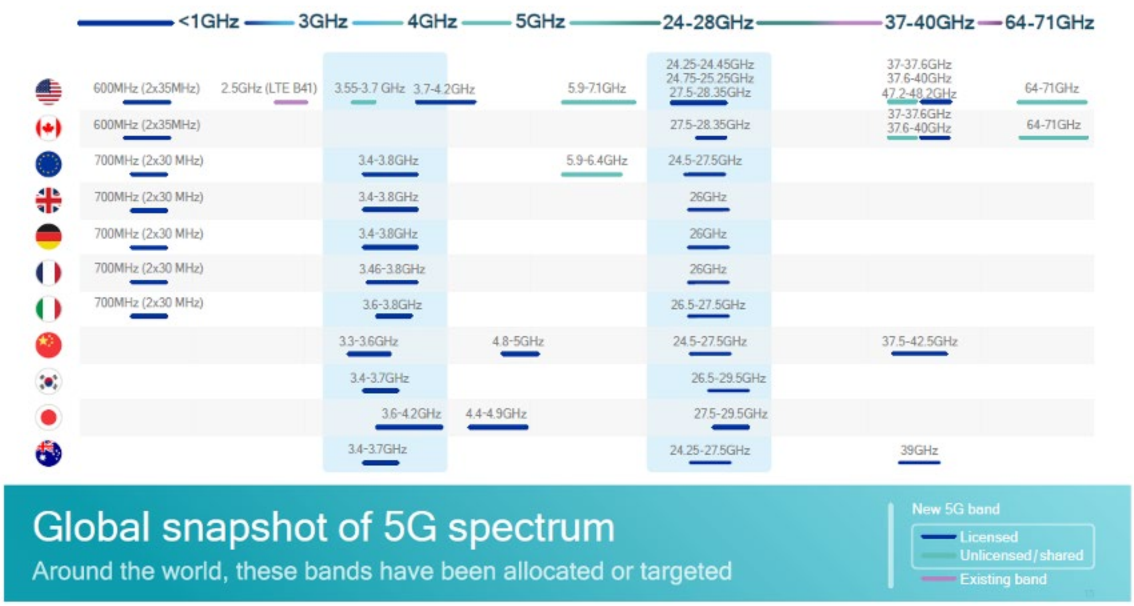

Figure 10. Frequency Allocation by Country. Source: Medin & Louie (2019).

In Figure 10, as of 2019, there were limited spectrum allocations globally established by countries in the 5–6 GHz frequency range. In the future, with more providers servicing more users and further improvements of 5G in the commercial sector, there will be more overlap between nations or regions. This in turn will increase create greater deconfliction requirements for any user operating within the part of the spectrum, including military users operating in those areas. As such, a military user operating in the United States may have deconflicted their 5G network locally but moving the same equipment to another region for training or conflict could induce spectrum management problems and potential EMI.

A notable concern that has surfaced with the spread of 5G across the United States civilian sector is the impact on radar altimeters in aircraft. Radar altimeters use frequencies from 4.2-4.4 GHz to determine the altitude of an aircraft Above Ground Level. With the rise of the mid-band spectrum by cellular mobile networks, the frequencies used by radar altimeters are being encroached upon. The signal strength coming from the radar altimeter and returning to the aircraft can be affected by the high-powered 5G cellular networks (Robin et al., 2020).

1. Sub-6 GHz

Part of the 5G NR frequency range consists of frequencies that are below 6 GHz, also referred to as sub-6. The wavelengths associated with sub-6 GHz frequencies result in less disruption from attenuation than higher frequencies. Because sub-6 GHz frequencies can travel further distances, relative to higher frequencies like mmWaves, the associated base stations can be further away from each other while still capable of effectively transferring data in a 5G network (Medin & Louie, 2019). 4G LTE operates in only a slightly lower frequency range with licensed spectra at 3.5 GHz and, more recently, in unlicensed spectra up to 5 GHz (Dahlman et al., 2021). Since 5G operates in an overlapping part of the spectrum, meaning that the successful implementation that has been used for 4G LTE over the past several years, successful methods of employment can be carried forward with minor adjustments, and in mobile cellular networks, the same infrastructure can be added onto in some cases (Medin & Louie, 2019).

The sub-6 GHz frequency range is considered the mid-band which provides some of the improved data rates with larger channel bandwidths compared to 4G LTE, but without the limitations in coverage of higher frequencies (Dahlman et al., 2021). Much of this part of the spectrum has already been divided up by different regions of the world for use. This overlap with existing infrastructure for 4G, has crowded the spectrum, proving more difficult to add additional improvements associated with 5G NR (Medin & Louie, 2019).

2. Millimeter Waves

5G is comprised of a large range of frequencies, from 450 MHz-52.60 GHz. Some of the characteristics associated with higher frequencies, especially those in the mmWave compared to sub-6 GHz frequencies, are based on the size of their wavelength. For the purposes of 5G networks, mmWaves include approximately 24 to 100 GHz. Use in 5G is more limited with a defined endpoint at 52.60 GHz for the high-band (Dahlman et al., 2021). Because of the location in the higher frequency range, mmWaves can be used at different channel bandwidths, including 50, 100, 200, and 400 MHz (Johnson, 2019). In general, the higher frequencies have poor ranges, require line of sight (LOS) compared to sub-6 GHz, and have higher power requirements to transmit data (Triggs, 2022). Figure 11 below shows an example of the difference in signal transmission based on propagation limitations of different frequencies over the same area.

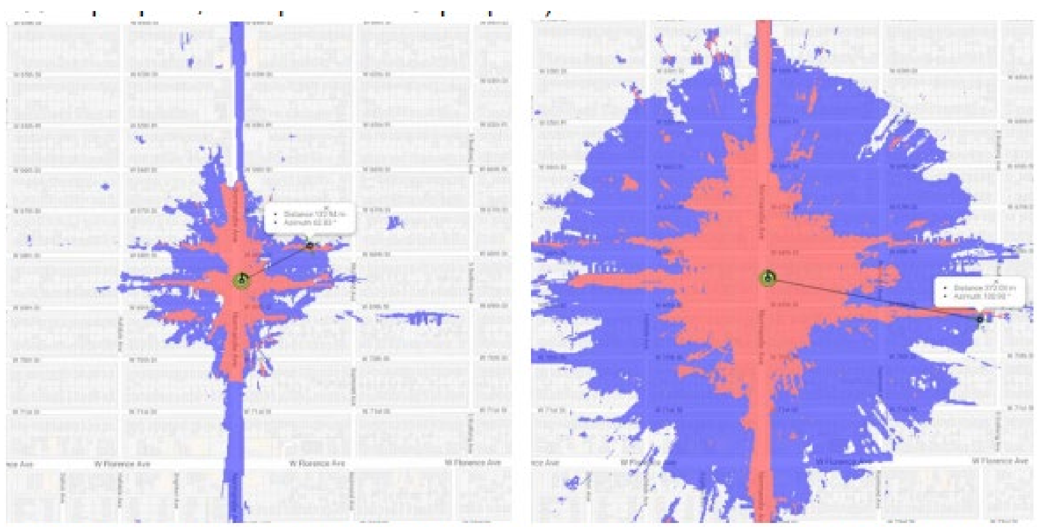

Figure 1: "Splat" chart with mmWave propagation   Figure 2: "Splat" chart with sub-6 propagation

Figure 11. Coverage Areas by Frequency. Source: Medin & Louie (2019).

In addition to challenges with using higher frequencies, the push to effectively utilize mmWaves is the significant increase in data transmission rates and the reduction in latency. Figure 11 depicts the range concerns about the use of mmWaves and the impact of terrain on signal transmission. The number of cell sites required, the performance at the cell edge based on the required data rate at the cell edge, and the achievable coverage, all impact the planning of mmWave base stations and 5G networks ("5G mmWave 28 GHz Band Link Budget - N257," 2020). Other methods of implementing mmWaves into networks may help prevent path loss if signal energy can be directed to a receiver rather than allowing it to spread everywhere.

G. DUPLEX SCHEMES

Duplex schemes are used in the uplink and downlink of data to allow end users to transmit and receive data at the same time. The use of Time Division Duplex (TDD) in unpaired bands and Frequency Division Duplex (FDD) in paired bands have been incorporated in the use of 5G which produces different effects based on the frequency range being utilized (Dahlman et al., 2021; Johnson, 2019). In FDD, signal transmission occurs simultaneously on the uplink and downlink because they are traveling on different frequencies. Conversely, TDD maintains the use of the same frequency to transmit both the uplink and downlink, but the signal is sent at different times (Huo et al., 2017). Figure 12 provides a comparison of TDD and FDD features.

Feature	5G FDD	5G TDD
Application	FDD version is used where both uplink and downlink data rates are symmetrical.	TDD version is used where both uplink and downlink data rates are asymmetrical.
Frame structure	FDD frame structure type is used.	TDD frame structure type is used.
Interference with neighboring Base Stations	Less	More
Deployment type	Not suitable for very dense environments.	It is used in very dense deployments with low-power nodes.
Frequency bands	It is preferable for lower frequency bands.	It is preferable for higher frequency bands usually above 10 GHz.
Channel response	Downlink and uplink channel responses would not match perfectly due to different frequency bands used in both these directions.	It matches and hence TDD delivers better performance in MIMO/Beamforming algorithms compare to FDD.

Figure 12. Comparison of FDD and TDD Usages. Source: Huo et al. (2017).

FDD and TDD schemes are used in different cases. FDD is commonly used at lower frequencies where uplink and downlink are conducted on different frequencies which provides greater separation for interference to occur. In contrast, TDD is being investigated further to better utilize at higher frequencies, where the separation in uplink and downlink is created with time, but occurs on the same frequency (Dahlman et al., 2021).

H. MULTIPLE-INPUT, MULTIPLE-OUTPUT

Single-Input, Single-Output (SISO) was the conventional way to transmit signals with limited data rates due to the single frequency channel being used at one time (Biglieri, 2007). In the last decade, Multiple-Input, Multiple-Output (MIMO), has taken off by enhancing the performance of transmitters and receivers in wireless technology. Multi-path fading is an issue of wireless communications due to the angles, reflection, refraction, time delays, and frequencies utilized by the electromagnetic spectrum within the environment. Multiple antennas at the transmitter and receiver provide the ability to exploit the spatial dimension in addition to the time and frequencies. By increasing the number of antennas, the resource constraint in both power and bandwidth remains unchanged compared to SISO, but with great increases in data rate comparatively (Biglieri, 2007).

Within wireless networks, a cellular network has a centralized communication hub where multiple users connect via the base station where all the signals are transmitted and received. With a cellular base station responsible for transmitting and receiving the signals of hundreds of users at one time, MIMO was the leap in technology allowing for this to take place.

I. MASSIVE MULTIPLE-INPUT, MULTIPLE-OUTPUT

Like with MIMO, the ability to increase the number of antennas on a single array can greatly increase the capacity for the number of users on the same array. Unlike MIMO, which only has a couple of antennas, massive MIMO increases the number of antennas on a single array. 5G base stations have upped the number of ports compared to its predecessor, 4G, with 100 ports. By adding massive MIMO (mMIMO), the number of users that can transmit through the same base station is greatly increased with potentially dozens of antennas on the same single array. Although it has been primarily tested in the lab to date, mMIMO could effectively increase the capacity of users substantially. Because of the number of signals going to a single base station with mMIMO, however, it likely increases the amount of interference that can occur making it more difficult to transmit signals and send data. Because of this complication produced by mMIMO, beamforming can be coupled with this upgrade to better steer the signal (Nordum & Clark, 2017).

mMIMO is still considered a developing technology that has yet to make it to the main stage in 5G mobile communications. It is likely to increase the amount of data sharing available not only in 5G networks but also in future generations of networks using even higher frequencies. mMIMO was first designed for use in the lower frequency ranges associated with 5G, below 6 GHz, but it has been further imagined for mmWave use (Bjornson et al., 2019).

J. BEAMFORMING

As a base station is receiving multiple signals from various users, beamforming is a developing technique that focuses the signal to the array to deconflict one user from the signal being transmitted by another user that is close by. When used in conjunction with mMIMO, the spectrum would be used better by directing a signal to the appropriate path to reach the antenna. As data packets are transmitted, they can be directed to deconflict routes and the time they reach the antenna (Litva & Lo, 1996; Nordum & Clark, 2017). Because of the amount of interference that can potentially occur from multiple users on the same base station, signal-processing algorithms are required to determine how to best transmit each signal.

mmWaves create a slightly different effect in which beamforming can provide a solution. Unlike at lower frequencies, such as the mid-band of 5G, higher frequencies have a much more difficult time transmitting over longer distances, especially with obstacle or environmental factor interference. Beamforming in this case can similarly direct the path that the frequency is transmitted, but can do so in a more direct manner, like a directional antenna. Beamforming in this capacity can improve the likelihood that the signal reaches its intended target, reduce the potential for interference from other signals being transmitted, and reduce the power required to transmit the signal compared to an omnidirectional antenna (Litva & Lo, 1996; Nordum & Clark, 2017).

K. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

In recent years, the concepts of Artificial Intelligence (AI) and Machine Learning (ML) have dominated discussions for use in military fields, processing data, and informing decision-makers about appropriate courses of action. In previous releases in 5G, Network Data Analytics Functions (NWDAF) provided the ability to analyze network slicing, improved data collection and exposure capabilities, and enabled the UE data application (Montojo, 2022). The ultimate goal in many of these analyses is to improve the way the network is functioning for example in conserving energy requirements when able, load balancing, and optimizing the system overall (Montojo, 2022). The ability to effectively employ AI and ML to gain effective solutions is not a capability that has reached a point where it can be successfully employed to support missions.

L. ORTHOGONAL FREQUENCY-DIVISION MULTIPLE ACCESS

5G NR utilizes digital modulation to transmit data efficiently and with a high throughput. In frequency division multiplexing (FDM), by splitting up a frequency range into smaller channels, multiple users can transmit on each of these frequencies simultaneously without impeding adjacent channels from also transmitting their respective signals. By adding an orthogonality component, signals can overlap but not interfere with each other, produce greater data rates, and support larger numbers of users while maintaining the same bandwidth requirements (*Difference between FDM and OFDM | FDM vs. OFDM*, n.d.). Orthogonal frequency-division multiplexing (OFDM) is the common modulation used for 5G NR. OFDM occurs when frequency subcarrier functions are mathematically orthogonal to each other (Witte, 2020). Figures 13 and 14 show the same signals represented in the time and frequency domains, respectively.

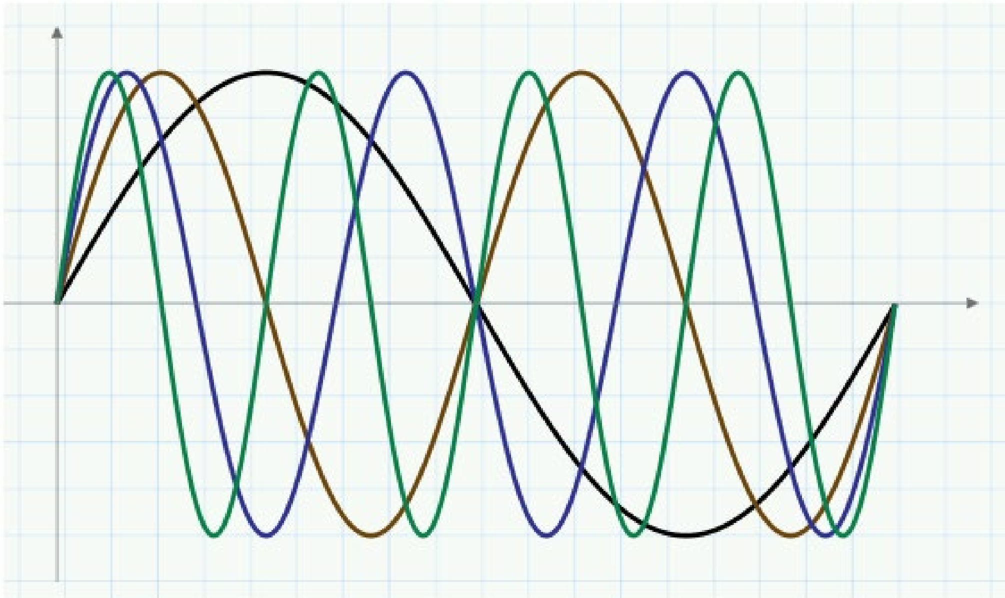

Figure 13. Time Domain. Source: Witte (2020).

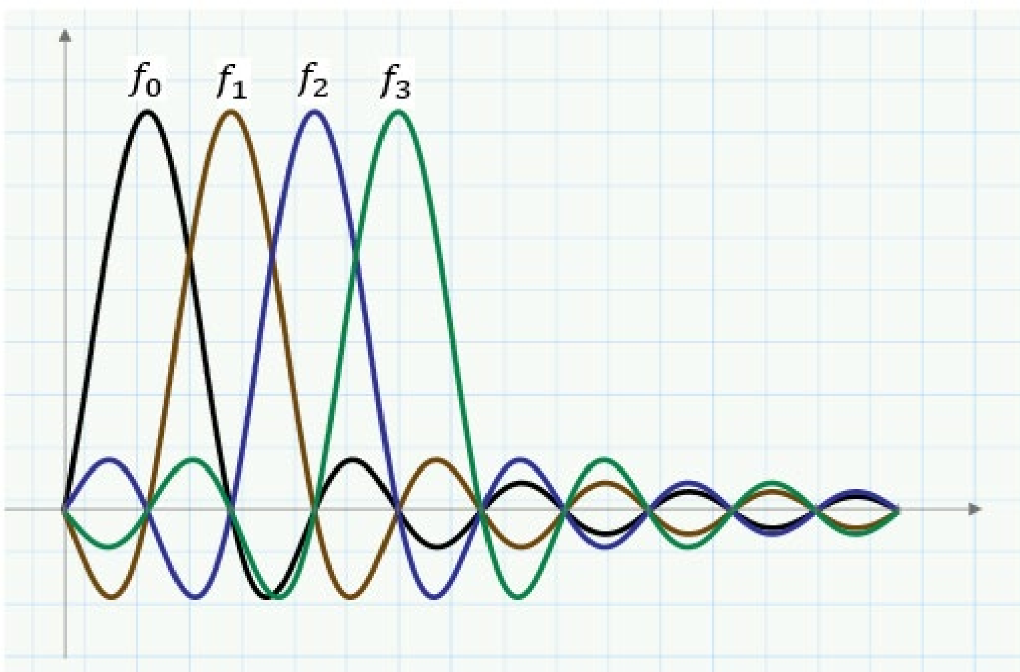

Figure 14. Frequency Domain. Source: Witte (2020).

In Figure 13, f_0 depicts the time that it takes for one period to occur for that frequency. For the other frequencies, f_1, f_2, and f_3, they are each able to complete 2, 3, and 4 periods, respectively. By comparison, in Figure 14, the frequency domain is represented and for each of the peaks in the respective frequencies, the other subcarriers cross zero at the same time which reduces the interference impact from adjacent subcarriers (Witte, 2020). With OFDM, a single user is sending data across all frequencies to minimize the time required to send a message. Orthogonal Frequency Division Multiple Access (OFDMA) is the modulation scheme required for multiple users to transmit data on different frequencies at the same time which supports a greater number of users compared to OFDM. Although similar in how it works, individual users can be assigned a unique subchannel which may be comprised of multiple subcarriers (*OFDM vs. OFDMA | Difference between OFDM and OFDMA*, n.d.).

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IV. LINK BUDGET SIMULATION

This chapter provides data based on the performance of link budgets at frequencies associated with 5G capabilities at similar ranges to that of tactical fiber optic cable. It is noteworthy that not all parameters associated with the 5G frequencies can be reasonably assessed and that this is a rough generalization of these frequency capabilities. Broadband wireless link simulations were performed using the Systems Planning, Engineering, and Evaluation Device (SPEED) software. SPEED was developed by Northrop Grumman for the Marine Corps in 1988 and has been continuously used since (Lamar, 2013). The current version of SPEED does not possess a 5G network planning capability. Government off-the-shelf (GOTS) Worldwide Interoperability for Microwave Access (WiMAX) based radios (Redline Communication AN-80i and Harris RF-7800) were selected to emulate similar 5G sub-6 GHz wireless point-to-point (P2P) transmissions with associated data rates equivalent to or greater than tactical fiber.

As previously discussed, there are a significant number of factors that contribute to the transmission ability, but link budgets provide a baseline for where a system could be used and some of the likely considerations associated with terrain, environment, or frequencies used. The link budget simulation described in this chapter suggests that, as a baseline, sub-6 GHz frequencies can readily support adequate data rates at longer ranges when compared to a standard MACCS deployment with tactical fiber optic cable. Based on the SPEED software analysis, sub-6 GHz frequencies should be further explored as a replacement for tactical fiber optic cable within the MACCS.

A. SYSTEMS PLANNING, ENGINEERING AND EVALUATION DEVICE (SPEED) SOFTWARE

The SPEED application is a planning tool for assessing communications, radio, and jamming in the EMS between two locations (Lamar, 2013). It considers information like terrain, antenna heights, power requirements, frequencies, and radios being used to assess connectivity. In this application, assessments of sub-6 GHz frequencies were used to assess their range and compatibility within the MACCS. The radios and antennas to choose from within the application are limited and not specifically designed for 5G systems, however, a general result can provide data to analyze how these frequencies could be applied in similar scenarios. The version of SPEED used for this assessment was 12.0.0.1 and parameters were simulated in the vicinity of Monterey, CA.

B. SPECIFICATIONS

The SPEED application provides different features to change the radios, antennas, terrain, environment, and other planning factors that affect RF communications. Each of these specifications dictates how capable a frequency may be to operate in a specific environment. As discussed in Chapter III of this thesis, link budgets provide a planning tool for determining where a specific frequency may work for communications.

The radio used in this SPEED link budget simulation was the Redline AN-80i which is a commonly used radio capable of operating in the sub-6 GHz frequency range. Redline Communications was acquired by Aviat Networks in July 2022 (Redline Communications Group Inc., 2022). The Redline AN-80i WiMAX broadband radio P2P links were simulated using the SPEED link analysis software. A tactical radio, the Harris' Falcon III RF-7800W, is a close variant to the AN-80i which was incorporated into the Marine Corps' Wireless Point to Point Link Version D (WPPL-D). WPPL-D mast and tactical data radios were integrated into the Ground-based Operational Surveillance System (G-BOSS) and used extensively during Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF). The Falcon III is a LOS tactical radio that operates in the same frequency range of 4.4-5.875 GHz with the ability to transmit up to 430 Mbps. For the purposes of this simulation, receiver sensitivity associated with the Falcon III RF-7800W is -98 to -67 dBm (L3Harris, 2022). For the purposes of the link analysis, -67 dBm was used as the minimum required receiver sensitivity to achieve the maximum data rate. In setting modulation, 64 Quadrature Amplitude Modulation (QAM) was used, which is the highest data rate possible for Falcon III.

SPEED provides several antenna options for the AN-80i/Harris RF-7800 radios. For this link budget simulation, directional antennas were used. Directional antennas point the RF signal to the end user thereby increasing the passive antenna gain and narrowing the RF field of propagation. This reduces the power required and limits where the enemy could interfere with the signal. The link analysis was conducted with both the MT0485028/N/A WPPL-D which is a 1-foot flat panel and the SP 3–5.2 WPPL-D which is a 3-foot parabolic reflector on the AN-80i radio. The other parameters remained the same between link budget simulations when the antenna was changed. The Falcon III RF-7800W also has comparable antennas with a 1-foot flat panel and a 3-foot parabolic reflector.

C. LINK BUDGETS

The SPEED analysis conducted provides range and link capabilities associated with different frequencies. In this simulation, two AN-80i radios were linked at frequencies in the sub-6 GHz range. One radio was located on Point Lobos at 36 31 21.11N, 121 57 08.47W and the other was at Carmel Point, located at 36 32 37.29N, 121 56 03.99W. Both locations are on the coast with a separation of 1.76 miles as the crow flies, as seen on the map. The P2P link was primarily over water and void of any obstacles. Figure 15 provides the geographic laydown of the simulated radio link placed along the Carmel Bay coastline.

Figure 15. AN-80i Carmel C2 P2P Link Laydown

Figure 15 provides a map of the radio laydown, indicated as aqua-colored circles with a radio at the center. The terrain resolution for the map was 231.92 m (760.89 ft). Both radio locations were selected to minimize both natural and man-made obstacle interference with most of the signal transmission distance occurring over the ocean, depicted by the green line. Data transmission over the ocean is not necessarily the environment that MACCS radios will operate over, but this link budget analysis provides a realistic case for an EABO environment where island hopping could occur.

1. Link Budget Simulation Parameters

The same radio and parameters were utilized for both locations. Table 1 provides the parameters associated with the radios.

Table 1. Radio Parameters for SPEED Simulation

Radio	AN-80I
Band	40 MHz
Channel Spacing	2.5 MHz
Frequency	5.275 GHz
Power	132 mW
Line of Sight?	Yes
Modulation	64 QAM
Data Rate	108 Mbps
Data link?	Yes
Bit Error Rate	1e-6

Table 1 outlines each of the settings chosen within SPEED. The bandwidth associated with 5G is generally wider in comparison to the AN-80i at 50, 100, 200, or 400 MHz, but due to the limitations of this specific radio, 40 MHz was used. The channel spacing is the distance between the bands selected to operate in. The sub-6 GHz frequency selected was 5.275 GHz which was a default setting and met the needs of 5G for this link budget simulation. The power range was dictated by the SPEED application and the default setting was used. Because of the nature of frequencies in this range, LOS was determined to be a requirement. There were several modulation possibilities, and 64 QAM was selected for these radios. 64-QAM is a modulation technique where data is encoded into 64 different combinations of amplitude and phase states which allows for higher data transmission rates while efficiently using available bandwidth (Robertson, 2022). Although the maximum required data rate for tactical fiber optic cable is 100 Mbps, 108 Mbps was selected in this link budget simulation since the software provided that as a max capability of the radio being used. The bit error rate is the number of bits lost per transmission compared to the total number sent and the default was used for this simulation.

The antennas used for this link budget simulation were selected because they were compatible with the sub-6 GHz frequency range for the radio selected. Table 2 depicts the two antennas utilized. In the first simulation, both radios utilized the 1-foot flat panel antenna and then for the subsequent simulation, the 3-foot parabolic reflector was used.

Table 2. Antenna Parameter Comparison

	Antenna 1	Antenna 2
Antenna Name	MT0485028/N/A (WPPL-D)	SP 3–5.2 (WPPL-D)
Description	1-foot flat panel:	3-foot parabolic reflector
Polarization	vertical	vertical
Antenna Height	10 ft	10 ft
Cable Line Loss	1 dB	1 dB
Default Mainbeam Gain	22 dB	31.4 dB
Horizontal Beamwidth	9 degrees	4.2 degrees

The polarization, height, and cable line loss remained the same for both the 1-foot and 3-foot antennas for this simulation. The antenna height was set for 10 feet in order to clear any obstructions for both LOS and within the Fresnel zone. This zone is the theoretical envelope surrounding the LOS path that can reduce the signal transmissibility if penetrated, even if the LOS path is clear (Ulaby & Ravaioli, 2015). The default gain was 9.4 dB higher for the parabolic reflector than the flat panel. The default gain was unable to be changed by the operator but does represent a realistic difference between the types and sizes of antennas available. The beamwidth was also 4.8 degrees smaller in the parabolic reflector.

The environmental conditions remained the same for both antenna simulations. Different operating environments, like the humidity, the terrain being operated on, foliage or obstacles, and any particulates in the air, like smoke or sand, can affect the RF signals transmission through the air. Table 3 provides the specific environmental conditions that could be adjusted based on the operating location.

Table 3. Environmental Parameters for SPEED Link Budget Simulation

Environment:	Rural Area
Humidity:	Average
Ground Type:	SaltWater
Refractivity:	320
Net Type	Point to point

A rural area was used for this link budget simulation in average humidity. The transmission was sent over the ocean and the refractivity remained at the default setting. The radios were set up to operate only from one to the other in this simulation.

2. Link Budget Simulations Results

Once the settings in Tables 1, 2, and 3 were input, the simulation was run to assess the feasibility of the link between the two radios. The bi-directional analysis revealed that the link and LOS statuses were both successful. Figure 16 provides a profile view of the terrain and the link between the two radios.

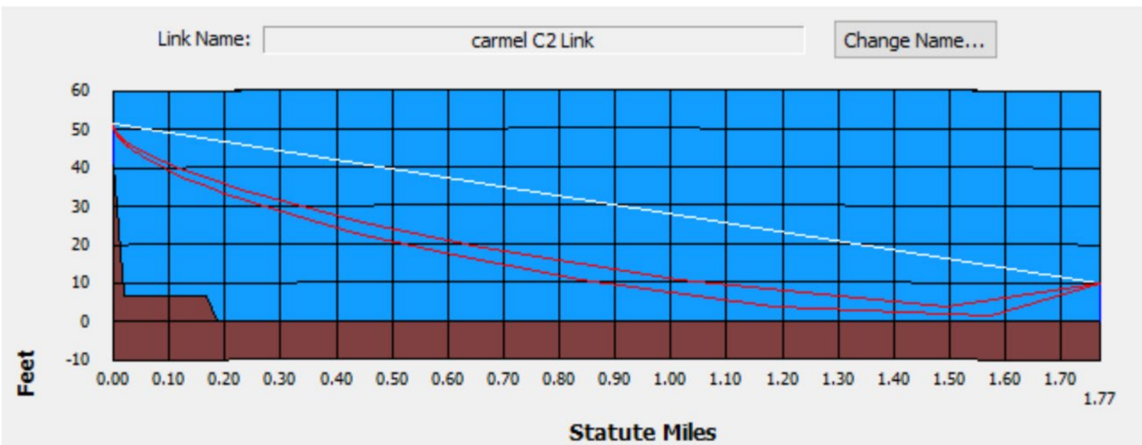

Figure 16. SPEED Link Analysis

In Figure 16, Point Lobos is on the left on an elevated terrain feature with a 10-foot antenna height. The white line represents the LOS link to the Carmel Point radio which is at sea level and indicates that the signal can be transmitted effectively. The red lines are associated with the Fresnel zones. Neither the LOS line nor the Fresnel zone lines are obstructed in this simulation based on the link analysis because the Point Lobos antenna is on an elevated piece of terrain. The height of one or both antennas could have been increased to ensure the Fresnel zone was clear of obstructions.

In Table 4, the analysis of the links provides the differences between the two simulations.

Table 4. SPEED Simulation Analysis by Antenna Types

	Antenna 1	Antenna 2
Free Space Loss	115.98 dB	115.98 dB
EIRP	42.21 dBm	51.61 dBm
Predicted S/N	22.81 dB	41.61 dB
Calc C/N	44.29 dB	63.09 dB
E_b/N_0	39.52 dB	58.32 dB
Excess Margin	14.81 dB	33.61 dB
Rx Signal Level	-50.77 dBm	-31.97 dBm

Table 4 provides the analysis of the link. The free space path loss (FSPL) is the amount of attenuation that occurs between the two antennas based on the distance the RF must travel, represented in decibels. In both antennas, the distance was kept constant, resulting in the same FSPL. The Equivalent Isotropically Radiated Power (EIRP) is the "amount of power emitted from an isotropic antenna to obtain the same power density in the direction of the antenna pattern peak with gain" (Stutzman & Thiele, 2013). Predicted signal-to-noise (S/N) is the expected signal strength compared to the noise associated with the transmission. If the noise level is too high or the signal too low, the receiver will be unable to interpret the signal effectively and the transmission will be unreadable. The calculated carrier-to-noise ratio (C/N) is a measure of the received carrier signal compared to the noise in the transmission. The modulated energy per information bit (E_b) and the noise spectral density (N_0) are often compared as a unitless ratio, E_b/N_0, which is used as a digital reference for S/N measured at the bit level (Haykin, 2007). This is useful for comparing the bit error rate when assessing digital modulation. The parabolic dish provides a more directed beam which improves the performance over the smaller, flat panel antenna in EIRP, S/N, C/N, and E_b/N_0. The excess margin is the difference between what the receiver can receive and how much more attenuation the receiver could tolerate and still receive the signal. With the improved capability of the 3-foot, there is a greater margin for the larger antenna. The received signal level reflects the power of the RF signal at the receiving antenna, As discussed in Section B of this chapter, the receiver sensitivity threshold used to ensure the maximum data rate was achieved was -67 dB which is associated with the higher frequency ranges for the Falcon III 7800W radio.

Both radios are within the receiver sensitivity limit, but the 3-foot antenna provides a greater fade margin.

For the link analysis, the frequency used for 5G was in the sub-6 GHz range using 5.275 GHz. This frequency is in the same range as 4G signals and other radar frequencies already being used. The SPEED analysis did not take into consideration other sources of RF that are likely radiating in the same area and any interference that may be associated. Based on the SPEED analysis conducted, sub-6 GHz frequencies are capable of effectively transmitting at least the same amount of data over at least the same distances as can currently be achieved by tactical fiber optic cables. In this simulation, both the data transmission rate and distance were greater than that associated with current MACCS capabilities using fiber. The 3-foot antenna provided greater signal strength, but the pointing accuracy is also more specific due to the smaller, more direct beamwidth associated. Users must be more precise in the antennas' directions and angles to be able to transmit between different locations.

Using the same parameters as done with the sub-6 GHz SPEED link budget simulation, the FSPL was used to compare the 30 GHz link feasibility. Table 5 compares the FSPL at sub-6 GHz to a 5G mmWave at 30 GHz at various distances to assess potential attenuation impacts.

Table 5. Free Space Path Loss Comparison of Sub-6 GHz and mmWave Frequencies

Distance (miles)	5.275 GHz	30 GHz
0.5	105 dB	120 dB
1	111 dB	126 dB
1.5	115 dB	130 dB
2	117 dB	132 dB
2.5	119 dB	134 dB
5	125 dB	140 dB

In the sub-6 GHz simulation, the antennas were 1.76 miles apart. The FSPL equation can be used to estimate the attenuation based on the frequency in Hz, f, and the distance in miles, D. The equation used in Table 5 is:

$$FSPL = 36.6 + 20\log_{10} f + 20\log_{10} D$$ (Coleman & Westcott, 2021, p. 123)

At 1.5 miles, the mmWave frequency has an increase of FSPL of 15 dB. With this increase, on the 1-foot flat panel antenna, the excess margin would be exceeded and unable to transmit in the link budget simulation. The 3-foot antenna may be able to transmit at the given range, but the signal would be near its limit. It is also important to note that due to the frequency and equipment limitations of SPEED, the comparison of the mmWave frequency is a rough estimate of its capabilities under similar circumstances to the sub-6 GHz frequency. The SPEED program is unable to adjust for specific radio and antenna parameters that occur at 30 GHz. Given the data rate capacity and bandwidth available in the 5G mmWave spectrum, it is anticipated that achieving 100 Mbps should not be a problem as long as the radio's separation is within the tolerance of the receiver sensitivity based on FSPL.

V. SYNTHESIS

This chapter outlines the assessment of 5G capabilities in the application of the MACCS based on how tactical fiber optic cable is currently implemented, current and potential future 5G technology, and a comparison between the two. This chapter assesses the feasibility of implementing 5G, logistical considerations, security requirements for future investigation, and Marine Corps considerations. It also distinguishes the suitability differences between 5G in the sub-6 GHz and mmWave frequency ranges.

A. FEASIBILITY CONSIDERATIONS FOR 5G

When considering the implementation of 5G wireless communications for the application in aviation C2 in an EABO scenario, the capabilities, limitations, and technologies vary by frequency. The employment of sub-6 GHz and mmWave frequencies have demonstrated different levels of readiness for implementation in a tactical environment based on their use thus far in the commercial industry.

1. Sub-6 GHz

Based on the simulated scenario presented in Chapter IV of this thesis and the 5G wireless communication technology available now, sub-6 GHz should be pursued for implementation. Sub-6 GHz can and does operate effectively now at the commercial industry level with 5G capable UEs being continually used and updated. In terms of range, latency, and data rates, sub-6 GHz frequencies provide improved metrics to tactical fiber optic cable in these areas.

2. mmWaves

mmWave technology is still an evolving technology and has yet to firmly mature. The Marine Corps should cautiously pursue further mmWave experimentation. mMIMO and beamforming antenna capabilities are technologies primarily associated with the future use of mmWaves that are still in the research stage of development. The gap between current mmWave technology and being employed in a military environment is too large at this time for investment in these types of technologies. Testing should remain within the commercial industry until more advancements have occurred. It is recommended that the Marine Corps wait until the commercial industry can effectively demonstrate and operationally employ mmWaves reliably in field environments before investing in it. mmWaves do not possess the ability to cover the same ranges compared to sub-6 GHz without significant changes to current antenna technologies. Additionally, relay stations as used in commercial 5G, between base stations, increase the logistical footprint.

3. Range

In comparison to tactical fiber optic cable, sub-6 GHz frequencies can reach equivalent and further distances in which the MACCS is employed. Four reels of tactical fiber optic cable, the standard maximum used to connect platforms, reaches 1.24 miles. In the link budget simulation conducted, the platforms were 1.76 miles apart and the link budget assessed that the connection would be made effectively at this range. Maintaining this dispersion is vital for both survivability and spectrum management. Directional or sector antennas within LOS will be key for focusing the signal between users on the ground. In flat, desert terrain this may be a simple consideration, but in other operating areas, it is likely to make setup locations terrain driven or require the capability to elevate the antennas to gain LOS over terrain features. The power associated with the antennas will also impact the distance that sub-6 GHz frequencies can cover. At sub-6 GHz frequencies, 5G wireless communications can cover the maximum distance required of tactical fiber optic cable, making it a feasible solution in terms of range. Additionally, utilizing 5G provides the added capability to transmit data over water, unlike tactical fiber optic cable, thus extending the networking range potential in an EABO island chain scenario.

mmWaves, given the same parameters, have a reduced range. In urban terrain, signals can bounce off of infrastructure, which may or may not improve range. In a rural environment, the path loss is significant, and different atmospheric conditions will greatly affect the attenuation associated with mmWave frequencies.

4. Data Rate

5G also exceeds the data rate requirements associated with the MACCS as required by current tactical fiber optic cable. The data rate capabilities exceed those of tactical fiber optic cable already in service. Sub-6 GHz readily provides this capability with speeds above 100 Mbps and idealized to over 10 Gbps (Triggs, 2022). Tactical radios today, like the Falcon III RF-7800W, can transmit up to 430 Mbps utilizing sub-6 GHz frequencies (L3Harris, 2022).

mmWave frequencies have an even greater idealized capability to transmit data, above 10 Gbps. In both instances, 5G exceeds the requirements for the capabilities of MACCS platforms in wireless communication. 5G frequencies also provide a greater ability to network multiple users and base stations should the Marine Corps procure additional systems that need to connect.

5. Latency

URLLC provides data transmission rates within 1 ms for the highest priority users (Johnson, 2019) This latency can be used for MACCS platforms to allow for weapons targeting solutions. In the other use cases, like eMBB, latency can be slightly lower at 50 ms duration, which is still acceptable for use in this application (Sultan, 2022). 5G URLLC can further prioritize communications based on the system or data being processed. With the limited number of users in the MACCS scenario, minimal prioritization will be required. In future applications, the URLLC capability is useful to ensure that the most valuable data is transmitted when required as users are added.

Although the actual latency rates in moving data have been more highly studied at sub-6 GHz, similar, if not reduced latency can be expected in the mmWave frequencies. The size of the channel bandwidth associated with each frequency will provide greater capacity and help to limit interference.

An area of concern about latency in both frequency ranges of 5G is that for every added system, more network architecture must be constructed. The transition of data from one form to another can slow down this process. With tactical fiber optic, the media converters are configured to take the data from one system and create an output for the other system for the warfighter to use. The transmission latency is not an issue, but the ability to change data between operating systems is a consideration. An additional concern is the associated network security considerations that may slow down data transfer. In most 5G cases in the commercial industry, there is less consideration for the malicious intercept of data compared to that within a contested environment. Between MACCS platforms, classified data would need improved security. Encryption and authentication between MACCS 5G systems can potentially impact data transmission speeds but actual device testing would be required to examine these effects.

6. Spectrum

As seen in the link analysis in Chapter IV, the FSPL means that the fade margin was reduced due to the path loss and limited transmit power of the devices. Enemy jamming is a concern in that the noise may be too high to overcome and transmit RF between platforms. With more users on 5G frequencies, there may be unintentional interference, though directional or mMIMO antennas will mitigate this potential. In the United States, the frequencies operated on are controlled and licensed to reduce interference among users. The military operates on frequencies that are either designated or requested in advance. Fighting in other locations or a contested space produces greater frequency deconfliction requirements, potentially including making dynamic adjustments considering enemy maneuvers within the spectrum.

Although detection and signals management are considerations whenever radio frequencies are considered, for the purposes of this thesis and considering all the other frequencies already being used within a MACCS unit, it was of lesser concern. Between the CTN, GATO/R, MRQ-13s, and Link 16 radiating, there are already significant signal considerations across the spectrum for a MACCS unit. Even with only one of these systems operating, a MACCS unit considers when it will be detected, not if. Additionally, by using directional or sector antennas, the effects of jamming, interference, and detection can be minimized compared to other platforms which emit with omnidirectional antennas.

7. Commercial Off-the-Shelf

Part of the feasibility assessment in the use of 5G sub-6 GHz frequencies is the progress that has already been made in establishing this technology. The ability to procure an effective 5G base station for tactical use needs to be developed. One solution is to utilize commercial off-the-shelf (COTS) products like in Figure 17.

Figure 17. Verizon's Tactical Humanitarian Operations Response Vehicle. Source: Durie (2021).

Should the Marine Corps seek to employ a 5G sub-6GHz base station to create a network for tactical platforms, it must be maneuverable like Verizon's Tactical Humanitarian Operations Response (THOR) Vehicle in Figure 17 (Durie, 2021). THOR was created for use by emergency personnel to provide a local, private network that can be used by first responders when local infrastructure is not working or does not exist. For example, following natural disaster events, THOR can be utilized to provide 5G network coverage while local towers do not have power or have sustained damage. This vehicle provides an on-the-go capability for emergency personnel to establish reliable 5G services and maintain connectivity locally.

B. LOGISTICS

1. Setup Speed

Although the ability to set up and tear down a 5G sub-6 GHz network is currently unknown, this is the most pressing requirement for maneuverability on the battlefield. The current emplacement and displacement of tactical fiber optic cable is the central concern in this thesis. Critical to the use of a 5G wireless communications network is the operational employment speed. The ability to set up and tear down a 5G system must be faster than the time it takes to lay fiber over terrain. Mobile loading a 5G base station on a tactical vehicle, (i.e., a High Mobility Multipurpose Wheeled Vehicle (HMMWV)), is one potential solution, as depicted in Figure 18.

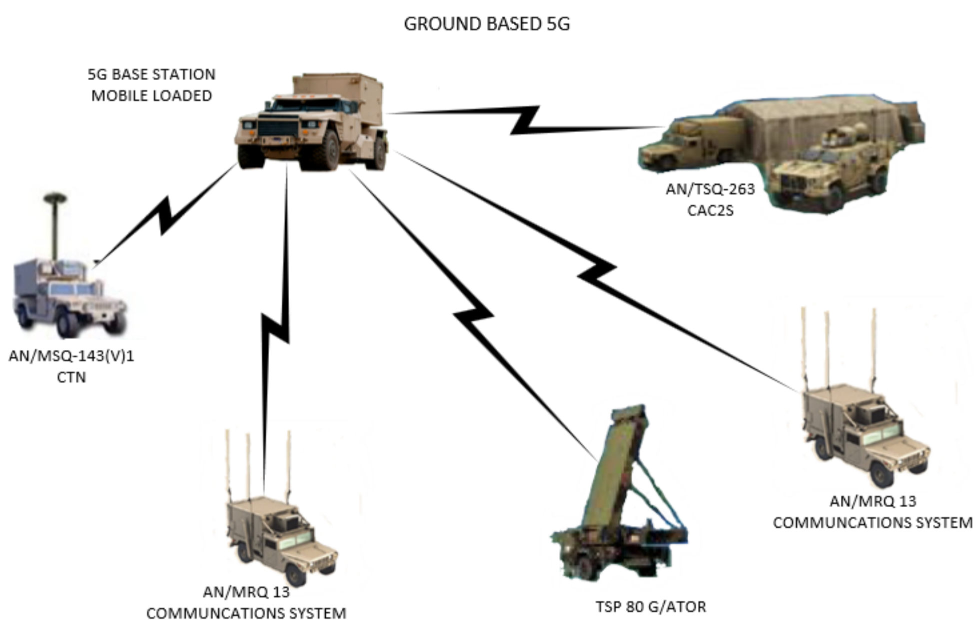

Figure 18. Mobile Loaded 5G Base Station with 5G Connected MACCS Setup. Adapted from Gerlach & Falk (2021).

Figure 18 depicts a layout of a MACCS unit where each of the required systems would connect via 5G sub-6 GHz to the base station. The base station could be collocated with the CAC2S, another platform, or be dispersed. The size of the setup could also dictate if there should be other base stations either for redundancy or to extend the range between platforms. In addition to a vehicle-mounted base station, another potential solution is an Unmanned Aerial Vehicle (UAV) mounted base station. This would increase the antenna height and provide greater LOS capabilities depending on the terrain. In either case, the setup and tear down should provide easier maneuverability than the legacy system of tactical fiber optic cable.

2. Power Requirements

Tactical fiber optic cable requires limited power considerations to transmit between MACCS platforms, while the introduction of one or more base stations to a MACCS setup creates power and fuel considerations. Batteries or generator-powered base stations are a logistical planning factor. Any base station procured through the acquisition process would ideally utilize similar power sources to provide commonality and availability to users.

3. Transportability

Tactical fiber optic cable creates issues within transportability where reels, backup reels, and repair tools require extra space on or in tactical vehicles. A 5G base station, or multiple base stations, would need to fit within the air and sea lift footprints of the MACCS. Each of the individual platforms requires sea-to-shore transport. By adding another system, the need for greater load-carrying capacity increases.

4. Durability

Tactical fiber optic cable has proven to be effective at connecting MACCS platforms, but a continued issue is fragility when laid across the terrain. RF signals do not encounter the same risks as fiber laying on the ground might endure. COTS products are designed to commercial standards that are not sufficiently robust to endure harsh, tactical environments while maintaining high mission reliability. Military Standards provide the requisite guidance for industry on how to appropriately ruggedize military equipment to operate in austere environments and 5G system compliance with these manufacturing standards is essential.

C. SECURITY IMPLICATIONS

One of the biggest concerns with the use of sub-6 GHz 5G is the confidentiality, integrity, and availability (CIA) triad. Encryption will be a key consideration in order to ensure that an adversary is unable to decipher or manipulate the collected signal. Employing directional antennas, or perhaps beamforming antennas in the future at sub-6 GHz frequencies, can provide more secure transmission by limiting the RF propagation area in which the frequency can be received.

As it stands now, the DOD controls a significant portion of the 5G frequencies below 6 GHz (Sayler, 2023). China is likely to be the first country to successfully establish a 5G wide-area network. Beyond the distribution of 5G products from Chinese-based companies, China's National Intelligence Law from 2017 further forces Chinese-based industries to provide greater amounts of data on their users, regardless of where those users are located (Sayler, 2023). There are significant security concerns for cellular networks based on Chinese protocols and systems. In the overall strategy of EABO, the key characteristic is avoiding detection long enough to employ effects on the enemy before the enemy's capabilities can be brought to bear on friendly forces.

1. Reliability

URLLC provides improved latency but also ensures that data sent will be received by the end user. There is a 99.999% chance that 32 bytes of data will be received with URLLC and a 95% chance of reliability to data being transmitted with eMBB (Johnson, 2019). These high probabilities of transmission are critical to ensuring data transmission for weapons quality solutions on enemy targets. Timely, reliable data availability will be critical in the implementation of sub-6 GHz communications. The warfighter must be able to trust that the data received is timely and accurate to make decisions.

2. Open Standard Considerations

Another security consideration is that 5G wireless communication is based on a known, published open standard. 3GPP includes multiple countries, including China, and integrates global knowledge and development. Although this can be useful for the commercial industry, an open standard allows for potential adversaries to gain insight into how operational equipment is configured and employed. In turn, this provides the enemy with easier insights to construct potential offensive cyber attack strategies. While COTS solutions can provide novel C2 network solutions, they also present potential security implications.

D. ADDITIONAL PROCUREMENT CONSIDERATIONS

The following sections outline other considerations about how the Marine Corps would acquire 5G systems and outlines how individual units would acquire and utilize 5G base stations.

1. Training

The ability to effectively employ a new platform, like a 5G wireless communications base station, is not without significant training impacts on a unit. From a technical perspective, the ability to quickly ensure the directionality of multiple antennas is done correctly is crucial to set up speed. The ability to practice utilizing the system before employment in a contested environment is vital to successful operation. The 5G spectrum and potential interference make this matter more difficult. Because of the allocation considerations associated with 5G in different countries, as depicted in Figure 10, Marines will have to understand how the spectrum will impact where and how they can operate. Currently, Marines submit frequency requests for training exercises to deconflict the RF spectrum they plan to use but in a contested environment, it is unlikely that users will know which frequencies to deconflict in advance with more users, both civilian and military. Additionally, the ability to provide and switch to backup frequencies is a key component for redundancy to ensure that communications can be maintained.

In addition to the parameters associated with operating a 5G base station, the performance of first and second-echelon maintenance requires formal education & training (United States Marine Corps, 1998). Marine technicians would be required to learn an entirely new C2 system to troubleshoot and maintain operability. Training MACCS Marines on the tactical employment of 5G base stations should also be considered as this novel technology exceeds traditional radio position or antenna alignment instruction. There is the potential that Marines could be crossed trained to complete this task or it could result in the formation of a new Military Specialty Occupation (MOS).

2. Cost and Acquisitions

As with every DOD procurement initiative, money is a consideration and 5G experimentation will continue to cost the DOD significant sums of money. The 2022 defense budget was approved for an additional $600 million for 5G experimentation (DeMerse, 2022). Turning sub-6 GHz technologies into Marine Corps functional networks will require improvements in design for more risky, mobile, and geographically challenging Air-Ground-Sea operating environments than commercial systems are employed in now. mmWave technology and associated mMIMO antennas could prove costly based on the current technology readiness level (TRL) and the DOD acquisitions and contracting processes to procure developing technologies which would require C2 networks to be designed with limited input of current operational systems. Field testing and experimentation initiatives should continue to determine the feasibility of future contracts as new systems are designed.

a. Historical Precedent

The DOD has a troubled track record for procuring advanced operational and tactical networking C2 solutions. Recent examples include the Army's Future Combat System (FCS), and Joint Tactical Radio System (JTRS). The FCS was envisioned in 1995 to change the way the Army fights by integrating assets and connecting networks, costing over $200 billion (Pernin et al., 2012). After over a decade, the technologies imagined had not come to fruition and the program was canceled. Similarly, the 15 years JTRS program of record spent over $6 billion without producing a single radio as the program sought to add software-defined radios for use across military systems (Gallagher, 2012). The JTRS program was canceled in October 2011.

Experimenting and iterating continuous improvement by evaluating technology in several diverse funded implementations may avert costly mistakes, like the FCS or JTRS.

At present, the Future G & 5G Office within the Under Secretary of Director of Defense Research and Engineering (DDR&E) is funding and assessing several 5G research initiatives across ten military installations (Chief Technology Office, n.d.). This should help mitigate procurement risks associated with low TRL rated C2 networking technologies. In addition to 5G initiatives, the Marine Corps might also explore proliferated low earth orbit satellites (PLEO) as a means to connect EABO C2 platforms.

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VI. CONCLUSION

This thesis outlined the potential of 5G wireless communications as a replacement for tactical fiber in aviation C2 units in order to enhance EABO maneuverability. This chapter summarizes the analysis of the research questions from Chapter I of this thesis and provides recommendations for future research that were beyond the scope of this thesis.

A. SUMMARY

There were several research questions proposed in Chapter I of this thesis to consider when applying 5G wireless technologies to the EABO aviation C2 domain.

5G wireless technologies are a suitable replacement for tactical fiber optic cable in an air defense company application, but not across all 5G frequencies. Sub-6 GHz frequencies have been developed in the commercial industry to a point where the technology is sustainable for use in a tactical environment. Conversely, mmWave is not a mature technology, and the Marine Corps should wait for the commercial industry to further research and develop this technology before seeking to procure it. Link budget analysis suggests that 5G is capable of providing improved data rates and latency over tactical fiber optic cable over comparable ranges. Critically, 5G provides an overwater EABO C2 link capability, compared to tactical fiber which is terrestrially bound. There are security and spectrum concerns, but with appropriate encryption and planning considerations, these obstacles can be mitigated.

The effective range of tactical sub-6 GHz 5G wireless communications depends on several factors including, but not limited to transmit power, receive sensitivity, RF LOS transmission frequency, antenna selection, and gain. on the antennas and frequencies. mmWave frequencies however have a shorter range and higher attenuation. Future mMIMO and beamforming antenna technology may extend these ranges in the future, but current commercial cell tower limits for mmWaves are approximately 1.2 miles (Simmons, 2022). Environmental factors or other signals in the battlespace can further affect the range of RF signals, but these considerations are specific to each location where they may be used.

5G wireless communications in the sub-6 GHz range are suitable for typical aviation C2 tactical operations in the EABO environment with range capabilities at or exceeding those that tactical fiber optic cable currently covers. The data rate is greater than that of tactical fiber, the low latency enables users to employ sub-6 GHz 5G for weapons targeting solutions, and the range allows for C2 systems to maintain dispersion to improve survivability. Tactical 5G systems procured will need to meet air defense C2 setup and teardown parameters that allow the MACCS to quickly relocate across the battlespace, employing their sensors in new locations.

B. CONCLUSIONS

Sub-6 GHz 5G technologies provide the potential for the replacement of tactical fiber optic cable. Tactical fiber has proven to be reliable for stationary purposes, but in an EABO scenario, where expeditious emplacement and displacement of MACCS C2 networks are critical, 5G seems an attractive alternative. At the very least, 5G could provide for communications link redundancy. It is thus conceivable that modest increases in logistical efficiency could potentially translate into enhanced MACCS EABO maneuverability, survivability, and lethality. The DOD should continue to explore and operationally evaluate and field test sub-6 GHz 5G technology to better assess its potential fielding to aviation C2 units.

The theorized data rates and latency capabilities of mmWave exceed that of sub-6 GHz frequencies and this technology holds promise to potentially reduce P2P RF emission signatures through the use of narrower beams. However, mmWave technology, including mMIMO and beamforming antenna arrays, have not reached a level of maturity to effectively replace tactical fiber optic cable. It is recommended that the Marine Corps continue to evaluate, and field test this technology in order to iterate mmWave toward a tactically viable capability.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

As 5G experimentation continues across the DOD, more field testing should be conducted to assess the emerging tactical and mobile 5G capabilities. Also, 5G GOTS equipment can provide competition and produce a cost-benefit analysis for what these systems will bring to the fight with 5G. In conjunction with new systems being procured, updates to SPEED software in a future release could potentially increase the 5G planning capability as new systems are tested and fielded. Some areas of future research should address how 5G can be implemented to fulfill the aviation C2 requirements of the Marine Corps while simultaneously fitting into the architecture of the system. Such areas include latency, security, and time synchronization between MACCS platforms (K. P. Dougherty, personal communication, April 21, 2023).

Although 5G can transmit data fast enough to meet or exceed current tactical fiber optic cable requirements, the addition of parameters in the architecture or in adding encryption to protect the data being transmitted could change the latency. Further investigation will be required to determine the latency concerns associated with the connections between the current systems and a 5G architecture. The physical layer will need to be adjusted to incorporate 5G radios into the individual platforms that utilize the data transmitted, but this will come with additional challenges of converting the media appropriately so it may be used by the person at the console. In addition to the physical layer, protection of the data via encryption can slow the transfer of data while ensuring the connections made are legitimate and satisfy the security requirements.

Future research should also address the security concerns associated with the RF transmission of sensitive information. Tactical fiber currently connects C2 systems, providing direct P2P links. Beyond the destruction of physical tactical fiber optic cable, the enemy's ability to disrupt or change the transmitting data is minimal, resulting in higher levels of integrity and RF emission control. It is also more difficult for the enemy to intercept the data being transmitted via fiber since they would require direct access to the tactical fiber cable. Conversely, with the implementation of 5G, the enemy could potentially disrupt the sharing of data between systems (i.e., open systems interconnection (OSI) layer-2 denial of service (DoS); layer-1 RF jamming). In terms of the CIA triad, each of these components needs to be addressed. Confidentiality can be disrupted by the potential intercept in sending data via radio frequencies. Validation that the data received is accurate will be vital for the integrity and ensure users feel confident in their system. Concerning availability, although the destruction of any system remains a concern, RF noise, jamming, and the threat of RF homing weapons present additional security risks. Additionally, considerations for shared 5G RF spectrum usage increase the potential interference with other friendly systems too. With multiple sources radiating simultaneously, the impact of 5G radio frequencies may have significant effects on the architecture of the entire frequency spectrum that need to be further explored.

Lastly, an additional area for future research is the time synchronization efforts that will be required with implementing more physical devices into the already complex system. Within a MACCS setup, one platform defines the time synchronization for the rest of the network. Tactical fiber provides an infrastructure that allows an individual MACCS platform to control the time across the network. Adding a 5G base station to this architecture would impact both the timing considerations and the interfacing between systems. Substantial coordination between sensors is required to ensure that time synchronization occurs, and the addition of more devices requires added oversight to ensure continued interoperability.

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