2022-12

USING COMMERCIAL 5G AND LEO TECHNOLOGIES TO ENHANCE NAVY-ARMY SENSOR-TO-SHOOTER NETWORKS

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https://hdl.handle.net/10945/71449

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THESIS

USING COMMERCIAL 5G AND LEO TECHNOLOGIES TO ENHANCE NAVY-ARMY SENSOR-TO-SHOOTER NETWORKS

by

Jonathan S. Dodge and James G. Carlton

December 2022

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2022	**3. REPORT TYPE AND DATES COVERED** Master’s thesis

4. TITLE AND SUBTITLE USING COMMERCIAL 5G AND LEO TECHNOLOGIES TO ENHANCE NAVY-ARMY SENSOR-TO-SHOOTER NETWORKS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Jonathan S. Dodge and James G. Carlton	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS 5G, LEO, Sensor-to-shooter, Starlink, OneWeb, AT&T, NOC, INFOSEC, data standards, IP services	**15. NUMBER OF PAGES** 81
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN NETWORK OPERATIONS AND TECHNOLOGY

and

MASTER OF BUSINESS ADMINISTRATION

from the

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The emerging commercial technologies of 5G and low Earth orbit (LEO) satellite communications have the capability to provide links that send large amounts of data with low latency. As the DOD continues to explore how to best leverage these technologies, it is important to develop potential use cases within the military. This thesis describes a sensor-to-shooter operational scenario and the network transport links currently in use to move data from a Navy sensor to an Army shooter. The current sensor-to-shooter network transport links are then compared to the emerging commercial alternatives of 5G and LEO satellite communications in the categories of throughput, latency and range. This analysis demonstrates the comparative advantages and disadvantages of both 5G and LEO technologies over current links.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFATDS	Advanced Field Artillery Tactical Data System
BLOS	Beyond-Line-Of-Sight
BU2	Block Upgrade 2
CVSD	Continuous Variable Slope Delta
DOD	Department of Defense
FMV	Full-Motion Video
FSCOORD	Fire Support Coordinator
GEO	Geostationary Orbit
GHz	Gigahertz
HF	High Frequency
HIMRS	High Mobility Artillery Rocket System
HPA	High Power Amplifier
JADC2	Joint All-Domain Command And Control
JFC	Joint Force Commander
JFE	Joint Fires Element
JFLCC	Joint Forces Land Component Commander
Km	Kilometers
LEO	Low Earth Orbit
LPC	Linear Protective Coding
Mbps	Megabits per second
MDC	Missile Defense Command
MHz	Megahertz
MUOS	Mobile User Objective System
SATCOM	Satellite Communications
SINCGARS	Single Channel Ground Airborne Radio System
SISO	System Interoperability Standards Organization
TDL	Tactical Data Link
UHF	Ultra-high Frequency
VMF	Variable Message Format

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ACKNOWLEDGMENTS

The authors of this study thank Dr. Raymond Buettner for his insight, guidance and patience throughout the research. Dr. Buettner’s experience with naval tactical communications as well as his network of connections were instrumental to this process. We would also like to thank Mr. Glenn Cook for his support and willingness to bridge the gap between two departments in order to make this study a possibility.

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I. INTRODUCTION

In recent years, the Department of Defense has made concerted efforts toward a joint all-domain command and control (JADC2) environment where services are more connected than ever. This increase in connectivity is necessary to enable the utilization of joint fires quickly in an ever-changing environment (Kruger et al., 2021). While the concept of JADC2 is certainly not new, the joint services are in a constant battle to ensure information is passed seamlessly across the battlefield in a manner that gets the right data to the right shooter quickly and securely. In this study, the throughput and latency of current sensor-to-shooter network infrastructure between the Navy and Army will be examined and compared to two emerging commercial network transport methods: 5G and low Earth orbit (LEO).

A. PROBLEM STATEMENT

When discussing shortening the sensor-shooter kill chain, Gen. Mike Murray had stated while conducting operations in Iraq "it was probably okay to take tens of minutes between identifying a target and actually putting rounds on that target," but when sizing our current capabilities against "our near-peer threats, both Russia and China… it's not going to be tens of minutes" (Freedberg, 2020). With the intent to provide an increased amount of sensor data to units at a faster rate, the need to look at the commercial sector and emerging technologies may be required in order to meet these higher standards. Current sensor-to-shooter transport methods that exist between the Navy and Army such as tactical data link (TDL) and Link-16 only provide a fraction of the throughput and speed of commercial 5G and LEO systems capabilities. Other links such as satellite uplinks have very limited bandwidth and are used extensively for other purposes on Naval vessels as well as land-based commands. Consequently, there are limited pathways for data to get to decision-makers in the kill chain resulting in the increased delay to translate that data into actionable targeting data. The primary focus of this study will be on the network bandwidth limitation of Naval vessels that prevent large amounts of sensor data from travelling beyond-line-of-sight (BLOS) to land-based elements. To combat this problem, the Navy and Army must pursue alternative transport options that allow for more sensor data, such as full-motion video (FMV), to get to decision-makers. This will increase the amount of actionable targeting data and decrease the time it takes to achieve effects on the battlefield.

B. PURPOSE STATEMENT

The purpose of this effort is to provide a comparative analysis ofthe effectiveness of commercial 5G and LEO technologies as potential network transport options in the sensor-to-shooter network between the Army and Navy. Utilizing commercial 5G and LEO infrastructure, the aim will be to demonstrate the potential of commercial network transport options to increase sensor data in the kill chain in order to achieve effects more quickly on the battlefield.

C. OPERATIONAL SCENARIO CHOSEN FOR THESIS

The elements of the sensor-to-shooter transport layer are numerous across the JADC2 environment, with sensor data using many of the available transport links in existence across the services. While the emerging technologies of 5G and LEO could certainly be compared to all available links within the JADC2 environment, this study will limit its scope to a particular operational scenario using discreet entities/assets from the Navy and Army. This will allow for a more focused comparison of how current transport link capabilities within the focused scenario compare to the alternative transport links of 5G and LEO.

This study will examine the links involved with a Navy airborne sensor passing raw targeting data through an Arleigh-Burke Class destroyer to an Army Missile Defense Command (MDC) or Command Post (CP). The MDC/CP then analyzes and confirms the targeting data before passing it to a High Mobility Artillery Rocket System (HIMRS) for action. See Figure 1 for a visual depiction of the operational scenario to be examined in this study.

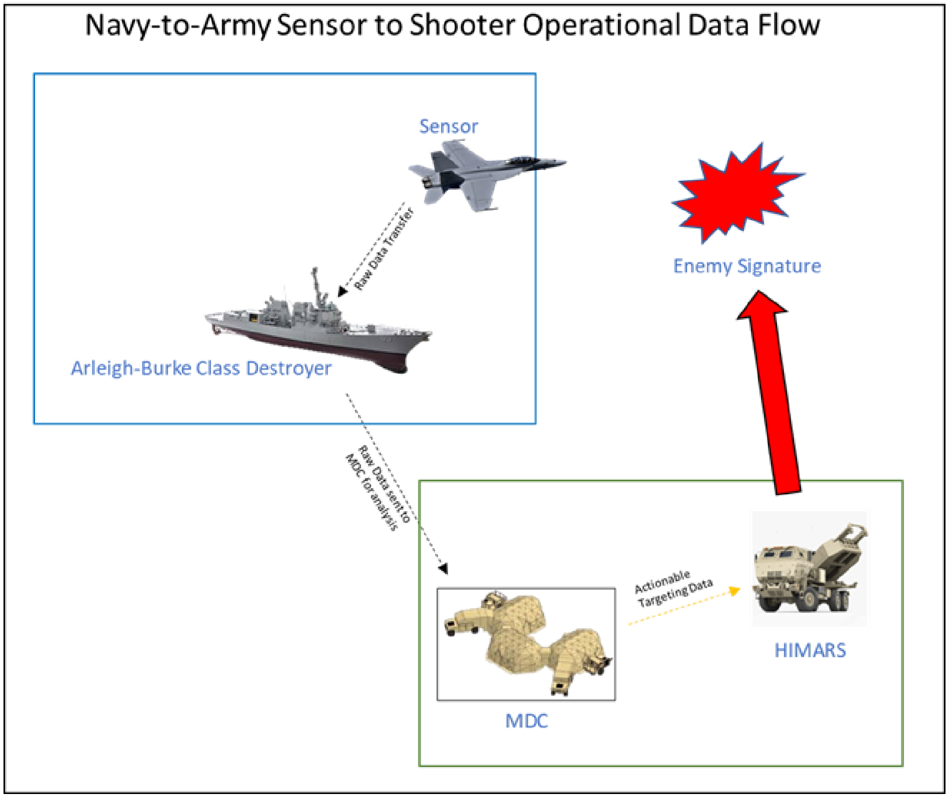


Figure 1. Navy-to-Army Sensor-to-Shooter Data Flow

D. RESEARCH QUESTIONS

This thesis examines the potential of commercial 5G/LEO to enhance sensor-t-shooter performance from a Navy sensor to an Army shooter. This examination focuses on the following questions:

1. What is the throughput, latency, and range of currently utilized transport methods?
2. What is the throughput, latency, and range of 5G and LEO?
3. What are the limitations of 5G and LEO?
4. How might the Army/Navy leverage commercial 5G and LEO capabilities to enhance the sensor-to-shooter network transport layer?
5. What sensor-to-shooter mission sets might be supportable by 5G/LEO?

E. ORGANIZATION OF THESIS

This thesis is organized into five additional chapters. Chapter II is a technical overview of the operational scenario chosen for this thesis including a review of current sensor-to-shooter network transport links. Chatper III explains the methodology and approach of this study. Chapter IV is an review of the capabilities of 5G and LEO technologies. Chapter V provides comparative analysis of the current sensor-to-shooter network transport links with the alternatives of 5G and LEO technologies. Chapter VI provides key insights, recommendations, and potential future work.

II. TECHNICAL OVERVIEW OF OPERATIONAL SCENARIO

A. OPERATIONAL SCENARIO OVERVIEW

1. Joint Fires Review and Definitions

Joint Publication 3-09 is the DOD's guiding document on Joint Fire Support and outlines the command structure, support relationships, and other factors involved in coordinating joint fires (Joint Chiefs of Staff [JCS], 2019). In order to understand the operational scenario used in this study it is first important to have a basic understanding of the doctrinal terms used in any joint fires scenario. Consequently, this section reviews basic definitions and processes from Joint Publication 3-09 that are pertinent to this study.

- Fires—Fires are "the use of a weapon systems or other actions to create specific lethal or nonlethal effects on a target." (JCS 2019, p. I-3).
- Joint Fires—Joint fires are "fires delivered during the employment of forces from two or more components in coordinated action to produce desired effects in support of a common objective." (JCS, 2019, p. I-3).
- Target Acquisition—Target Acquisition is "the detection, identification, and location of a target in sufficient detail to permit the effective employment of weapons" (JCS, 2019, p. IV-11).
- Target engagement—Target engagement is "when forces engage targets with fires." (JCS, 2019, p. I-4).
- Joint Force Commander (JFC)—The JFC is in charge of all joint forces and as pertinent for this study is responsible for all aspects of the planning and employment of fires. (JCS, 2019, p. I-1).
- Joint Fires Element (JFE)—The JFE is designated by the JFC and is responsible for "coordinating and synchronizing fires for all joint elements." (JCS, 2019, p. Viii).

- Joint Targeting—Joint targeting is the integration of joint fires into the battlefield through the use of "available capabilities to create a specific lethal or nonlethal effect on target." (JCS, 2019, p. I-4).
- Joint Forces Land Component Commander (JFLCC)—the JFLCC is the chief advisor to the JFC on "the best use of available land component fires capabilities." (JCS, 2019, p. II-11).
- Fire Support Coordinator (FSCOORD)—The FSCOORD is responsible for executing "the tasks of the fires function to create effects to achieve the commander's objective." (JCS, 2019, p. II-11).
- Advanced Field Artillery Tactical Data System (AFATDS)—AFATDS is a "multi-Service, integrated fire support system that processes fire missions, air support requests, and other related information to coordinate and maximize the use of all fire support assets." (JCS, 2019, p. II-22).

2. Operational Scenario

This section provides a brief overview of the operational scenario for this study in order to develop a discreet set of current transport links to compare with emerging 5G and LEO technologies. This section is organized into three phases that follow targeting data from point of target acquisition at the sensor to the point of target engagement. This overview is not exhaustive of every process involved in moving the targeting data from sensor to shooter but is instead intended to highlight only the processes that are pertinent to defining the network transport links involved.

This study examines a notional scenario where a Naval airborne sensor achieves target acquisition of an enemy signature and sends the raw data to the nearest command node. In this scenario, the nearest command node is an Arleigh Burke class Destroyer which processes the targeting data and relays it to the appropriate JFC or JFLCC at a land-based command post for analysis and confirmation. Once the targeting data is confirmed it is sent to the Army Field Artillery Data System in the form of actionable targeting data. See Figure 2 for a visual of each phase of the operational scenario.

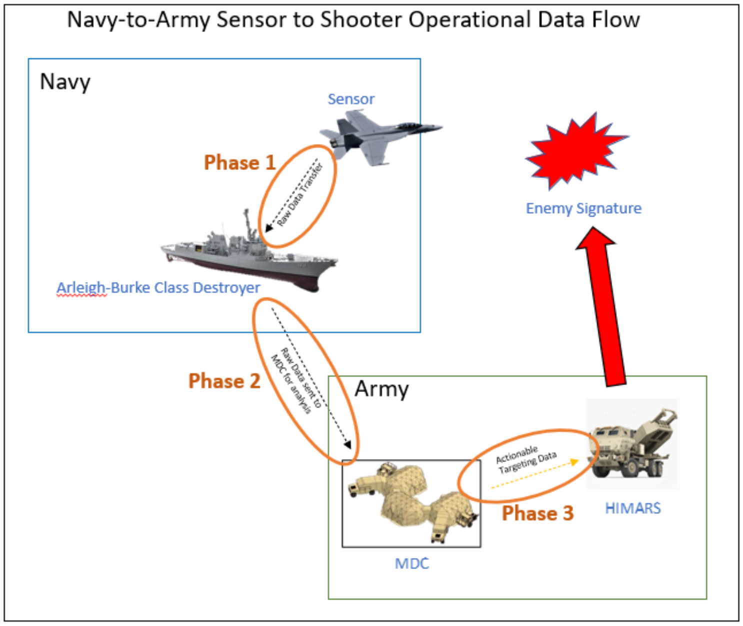


Figure 2. Navy-to-Army Sensor-to-Shooter Data Flow with Phases Highlighted

- Phase 1: Sensor to Arleigh Burke-class Destroyer—This study uses a Naval airborne sensor that acquires target acquisition of an enemy signature and sends the data to the nearest node for further dissemination. While the type of sensor data can vary depending on the type of ISR platform (Naval Information Warfare Center, 2021), this study will primarily utilize target imagery. In this scenario, a target image is sent to an Arleigh-Burke class destroyer.

- Phase 2: Arleigh Burke-class Destroyer to JFC or JFLCC—Once the raw targeting data is received by the Arleigh-Burke class destroyer it is sent to the JFC, JFLCC, or JFE for analysis. The command relationships and roles that determine which targeting data is actionable or not are defined by the JFC and can change based on theater requirements (JP 309, 2019, p. viii). For a given theater the JFC can reside in a variety of C2 nodes including ship or land-based. However, for the purpose of this study, a land-based

C2 node is utilized as the point where the targeting data is analyzed and turned into actionable targeting data. See Figure 2.

- Phase 3: JFE to AFATDS/HIMARS—The JFE or JFLCC determines that the targeting data received is actionable and sends it to the FSCOORD to coordinate fires. The FSCOORD then sends the actionable targeting data to the AFATDS system in the form of Variable Message Format (VMF) which is a free text-based format. This free text-based format allows the fires platform to receive only the necessary data to conduct the fire mission (Joslin et al., 2018). Once the actionable targeting data is received via AFATDS, the fires platform is able to conduct fires to neutralize the target.

B. CURRENT SHIP TO SHORE LINKS IN SCENARIO BY PHASE

This section will describe the various network transport links involved in the operational scenario by phase.

1. Phase 1: From Sensor to Arleigh Burke Class Destroyer

This section will summarize the technical capabilities of the primary network transport links from an aerial-based sensor to an Arleigh Burke-class Destroyer at sea. In this initial phase, an airborne sensor operating in conjunction with a destroyer at sea will acquire an enemy signature and begin to collect data on the target. Upon acquisition, the airborne pilot will coordinate with the deployed ship using Link 16 line of sight capabilities to pass both voice and J-Series (TADIL-J) messages. Through the active sharing of data between the aerial and surface unit, both parties gain an increased level of battlespace awareness within the local vicinity.

a. AN/USQ-140A (Line-of-Sight UHF Radio)

Developed by VIASAT for air and maritime use under the MIDS-LVT (Multifunctional Information Distribution Systems-Low Volume Terminals) configuration, the AN/USQ-140A shown in Figure 3 is one of the solutions provided for mobile UHF Link 16 line-of-sight communications. Awarded a contract in 2010 to the U.S. Navy, the AN/USQ-140A is currently utilized in both aircraft and naval vessels (SPAWAR, 2010). The baseline utilized for this study will be based on the Block Upgrade 2 (BU2) release of the radio which updated Link 16 to support Enhanced Throughput (ET) for improved data rates (VIASAT, 2019).

Figure 3. AN/USQ-140A Radio

(1) Throughput

Operating within the UHF frequency range between 960–1215 MHz as displayed in Figure 4, this signal is limited to line-of-sight communications (CJCSM 6520.01B, 2015, p. A-2). The data rates provided by this radio vary depending on the service utilized. For voice capabilities, the options are either a 2.4 kbps Linear Protective Coding (LPC) channel or the 16 kbps Continuous Variable Slope Delta (CVSD) modulation channel which provided higher, more efficient audio quality in comparison to LPC (Kohler, n.d., p. 4). Using TADIL-J formatted messages as its means of sensor data, the rates utilized for this format range from 26.8 to 1,102 kbps (VIASAT, 2019). With VIASAT's implementation of ET improving the data rate to 1,102 kbps, aircraft sensors hold the capability to provide more aircraft with a wider range of J Series messages such as surveillance (J3) and intelligence (J6).

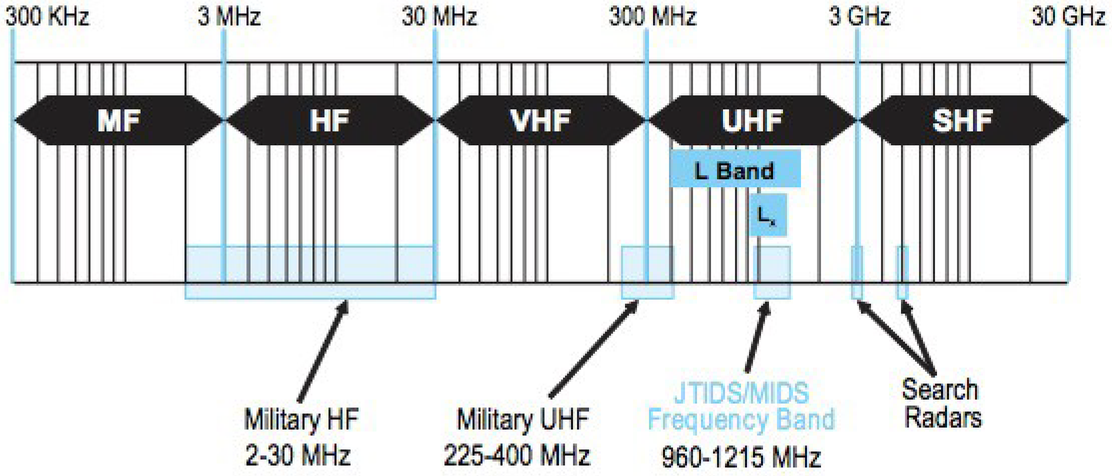


Figure 4. Link 16 Operating Spectrum. Source: Curtis (2015).

As Link 16 operates using Time Division Multiple Access (TDMA) to manage users on the network, it must be noted that although the radio can provide up to 1,102 kbps of data, timeslots limit the overall utilization of throughput. Each timeslot is designated an interval of 7.8125 ms and can only fit either 3, 6, or 12 data words (CJCSM 6520.01B, 2015, p. A-5). With the AN/USQ-140A providing ET capabilities, the maximum amount changes to 123 words at 75 bits per word (Stinson, 2003, p. 2-17) resulting in the vendor's estimate of up to 1,102 kbps.

(2) Latency

With this method of data transport using RF line-of-sight, factors such as weather and range must be considered regarding potential latency. Due to the size of the wavelength UHF utilizes, this RF frequency remains more resilient to inclement weather and cloud obstruction compared to higher data rate millimeter wavelength frequencies. Although the vendor does not provide data on latency at various ranges, System Interoperability Standards Organization (SISO) had standardized Ad-Hoc Link 16 networks to average under 3 ms (2005, p. 15). It is of note that this standard does not specify the conditions the data was collected under such as ranges, equipment utilized, or end-to-end latency. Compared to the latency data from a similar LOS data link, VHF Digital Link Mode 3

(VDL-3) which averages roughly 250 ms (White, 1999, p. 2), we suspect Link 16 to operate far above its reported standard during this scenario.

(3) Range

While operating in a maritime environment, UHF line-of-sight communications carry the potential to reach their maximum range due to the lack of obstruction between the sending and receiving terminals. With the support of a high-power amplifier (HPA), the AN/USQ-140A is able to transmit at up to 200 W, resulting in a maximum range of 300 mi (260.7 nmi) (Sabatini, 2008, p. 11-8). If operated in extended mode, the carrier wave can then reach up to 575 mi (500 nmi) or further depending on the number of relays used (CJCSM 6520.01B, 2015, p. A-2).

b. Phase 1 Links Summary

This section provided a summary of the primary link used to communicate between an airborne sensor and an Arleigh Burke Class Destroyer. A summary of this data can be found in Table 1 and Figure 9.

Table 1. Phase 1 Available Links Summary

Service	Throughput (max)	Latency	Range (max)
Link 16 LOS	1,102 kbps	<250 msec	575 mi

2. Phase 2: From Arleigh Burke Class Destroyer to JFC

This section will summarize the technical capabilities of the primary network transport links from an Arleigh Burke-class destroyer at sea. In this second phase, the Arleigh Burke Destroyer received the data from the airborne sensor and further distributed it to the JFC. Using UHF SATCOM capabilities to provide long-distance transport to shore facilities, the data travels to the satellite and ultimately to its intended recipient. This distribution of the sensor data to the JFC ensures commanders maintain battlespace awareness resulting in accurate decision-making.

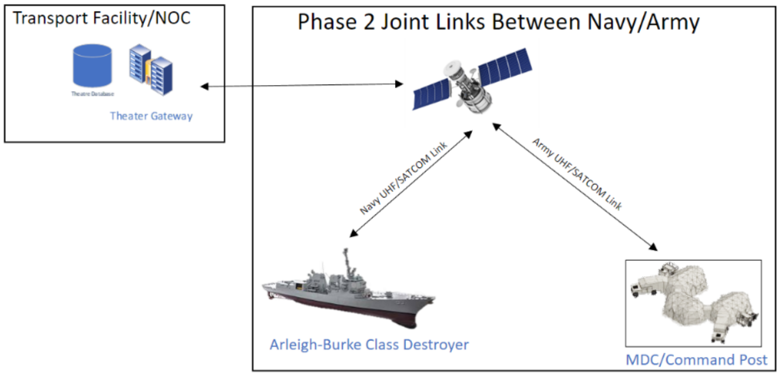


Figure 5. Link 16 Data Flow between Stations

a. *TD-1271B/U (UHF DAMA Multiplexer and Modulator/Demodulator)*

In order to access the DOD UHF SATCOM constellation, shipboard radio networks require a DAMA multiplexer paired with a supporting transceiver as shown in Figure 6. Following the military UHF standard of 225 MHz to 400 MHz frequency range, the AN/WSC-3 is able to connect to a UHF satellite through the provided azimuth, elevation, frequency pair, and offset (DOD, 2004, p. III-10). Upon tracking the satellite using the AN/WSC-3, the operator will configure the 25 kHz Link 16 channel using provided parameters on the TD-1271B/U. Once connected to the satellite the user will then receive a timeslot and share access to the channel with multiple users.

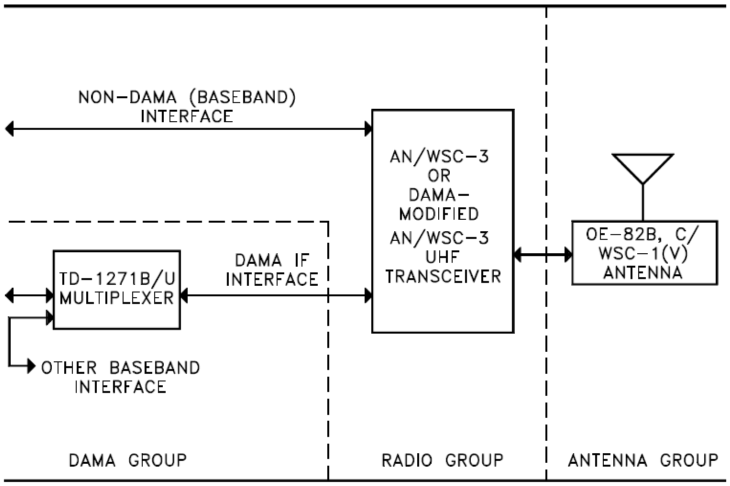


Figure 6. AN/WSC-3 with TD-1271B/U Block Diagram. Source: United States Navy (1992, p. 2-30).

The UHF satellites utilized within the path are the legacy UHF Follow-On (UFO) and the current Mobile User Objective System (MUOS) constellations. Both satellite systems follow a geosynchronous orbit at 22,236 mi above the equator and offer cross-link capabilities in order to transport data globally. Through the use of a geosynchronous orbit, maritime and land units are able to benefit from a large satellite footprint while also maintaining a stable connection to the same satellite without continuous swapping throughout the day.

(1) Throughput

Using the TD-1271B/U as the modem to connect to the UHF satellite, the device offers varying ranges of data rates depending on the channel requested. For a Link 16 25 kHz channel, the TD-1271B/U offers a data rate of up to 16,000 bps which is notably smaller than line-of-sight ET capabilities using an AN/USQ-140A. While the shipboard modem provides a relatively low data rate, the data rate can be further bottlenecked depending on the satellite accessed. When utilizing a UFO satellite, the narrowband channels it is able to provide are limited to 1.2 kbps while MUOS satellites hold the capability for up to 64 kbps channels (Matassa 2011, p. 18-27).

(2) Latency

Due to the long distances data is required to travel, the latency of a connection can exponentially grow depending on the number of hops required. With the minimum distance required to travel between the satellite from user to destination being above 44,000 mi, the average latency without additional hops averages roughly 275 ms (Tipper, p. 7). As this data path is expected to pass through the modem of the satellite transport facility and the supporting NOC, this ping can potentially delay the decision-making process.

(3) Range

As the primary mode of transportation relies on UHF SATCOM, the minimum range necessary to operate is set to the geosynchronous orbit altitude of 22,236 miles. Once received by the servicing satellite, the data sent is no longer limited by the individual satellite's footprint due to the cross-link capability the constellations hold which allows data transfer between satellites to support global transportation.

b. Phase 2 Links Summary

This section provided a summary of the three primary links used to communicate between maritime units and shore facilities. A summary of this data can be found in Table 2 and Figure 9.

Table 2. Phase 2 Available Links Summary

Service	Throughput (max)	Latency	Range (max)
TD-1271B/U	16 kbps	N/A	N/A
UFO	1.2 kbps	>275 msec	Unlimited
MUOS	64 kbps	>275 msec	Unlimited

3. Phase 3: From JFC/JFLCC to AFATDS/HIMARS

This section will summarize the technical capabilities of the primary network transport links for AFATDS. Once a decision is made that the targeting data received from the Navy sensor is actionable, it is sent to the AFATDS system for routing to the appropriate fires platform. When the actionable targeting data is sent to the fires platform in the form of a VMF message, there are two primary links used; VHF/UHF via the Single Channel Ground and Airborne Radio System (SINCGARS) and High-Frequency Radios (HF) (JP 309, 2019, p. II-22). While the Army is exploring alternative network transport links such as the Joint Battle Command Platform (JBCP), the Army is still working to integrate JBCP into AFATDS networks (Joslin, Harshberger & Greely, 2018). Consequently, this section will focus primarily on SINCGARS and HF.

a. SINCGARS

SINCGARS is a waveform used within the DOD for secure line-of-sight communications (USA ASC, 2021). Although the primary platform used by the Army today is the RT-1523 made by L3Harris (Aerotech News, 2022), the SINCGARS waveform runs on multiple radio platforms. Consequently, the throughput, latency, and range vary (ATP 602, 2020). In order to provide a baseline for comparison to alternative transport links, this study uses the technical capabilities of a typical ground configuration of SINCGARS radios as outlined in Army Techniques Publication (ATP) 6–02. ATP 602 is the Army's defining source for the capabilities and employment of tactical radio networks (ATP 602, 2020, p. vii). Figure 7 provides a visual example of a SINCGARS radio.

Figure 7. Example of a SINCGARS Radio

(1) Throughput

While the SINCGARS waveform is primarily used for joint voice communications, it is also capable of transmitting data (ATP 602, 2020, p. 3-2). While recent SINCGARS enhancements have increased the data rate of SINCGARS to 9,600 bps, the typical data mode used by fire direction systems allows for a maximum, of 4,800 bps (ATP 602, 2020, p. 3-2). While 4,800 bps is by no means a high throughput by today's standards, it is sufficient to pass basic targeting data in VMF/free text format (Gholi, 2022).

(2) Latency

While ATP 6-02 does not specify the exact latency of SINCGARS, it does address the variables involved in determining timing and latency. These variables include channel size, frequency range, data protocol, and the number of hops within a SINCGARS network (ATP 6-09, 2020, p. 3-11). However, the ATP does specify a max time delay of four seconds that is allowed within a SINCGARS network before a transmission is accepted by a SINCGARS node (ATP 6-09, 2020, p. 3-3). While this four-second rule has more to do with timing vs. latency, it does imply a maximum latency of four seconds, given both nodes are synchronized to the same timing data.

While ATP 602 may not specify the latency of SINCGARS, other studies have conducted Quality of Service (QoS) testing with SINCGARS radios. One such study was conducted in 2021 by the Institute of Infocommunications and Software Engineering in Odesa Ukraine. This study used L3Harris SINCGARS radios in ideal conditions to measure QoS by using various file transfer protocols. While the study found a latency range from 126 msec to 1189 msec, this is more a representation of SINCGARS latency in ideal conditions demonstrating that at best, SINCGARS sees latencies of around 120 msec. (Strelkovskaya et al., 2021).

Given the large number of variables involved in determining the latency of a single link within a SINCGARS network, the latency range used in this study is a maximum or worst-case latency of 4 seconds and a minimum or best-case scenario of 120 msec.

(3) Range

Much like latency, there are multiple variables that affect the range of the SINCGARS waveform. SINCGARS radios come in multiple configurations depending on use. While a dismounted configuration of a SINCGARS radio transmitting on low power can transmit only 200 meters, a mounted or command post configuration can transmit up to 40 kilometers with a power amplifier (ATP 6-02, 2020, p. 3-2). While this range can be extended even further with retransmission sites or relays, the max range for a single SINCGARS link in optimum conditions is still 40 kilometers before significant signal degradation occurs (ATP 6-02, 2020, p. 3-2).

b. High-Frequency Radios

High-frequency (HF) radios are typically used in the Army for long-range voice communications due to the ability of HF to talk over-the-horizon in certain configurations. However, certain configurations of the HF radio are also able to send data (ATP 6-02, 2020, p. 3-13). The most common HF radio configuration that processes data is the AN/PRC-150 (see Figure 5). HF radios were added as an alternative transport option between AFATDS systems in 2005 based on user feedback (Kenyon, 2005). However, due to the limited number of available HF radios, SINCGARS has been the preferred transport method for the past few decades (Global Security, 2022). This section will summarize the throughput, latency, and range capabilities of the AN/PRC-150 as described in ATP 6-02. Figure 8 provides a visual example of an HF radio.

Figure 8. AN/PRC-150

(1) Throughput

While the AN/PRC-150 has a modem with the capacity to provide up to 9,600 bps, the throughput depends mostly on how large the channel size is (ATP 6-02, 2020, p. 3-15). Other factors that impact the data throughput of HF are interference, time of day, and antenna configuration (ATP 6-02, 2020, p. 3-15).

(2) Latency

The latency of HF radios can be difficult to quantify due to the fact that the latency of an RF network is largely dependent on frequency, channel size, and the amount of data being sent. While ATP 602 does not specify latency expectations for HF radios, the equipment manufacturer of the AN/PRC-150 specifies a transmission time required for sending various amounts of data. This transmission time can range anywhere from less than one second to a maximum of 15 seconds (15,000 msec) before the transmission will drop (L3Harris, 2007).

(3) Range

Similar to SINCGARS radios, the range of HF radios is largely dependent on configuration and environmental factors. For example, a dismounted configuration of an HF radio with a small whip antenna may have a range of a few kilometers. However, an HF radio with the proper antenna configuration can transmit voice and data over-the-horizon (ATP 602, 2020, p. 3-17). This makes HF radios unique in the fact that HF is one of the few terrestrial waveforms that allow for transmission beyond line of sight.

c. *Phase 3 Links Summary*

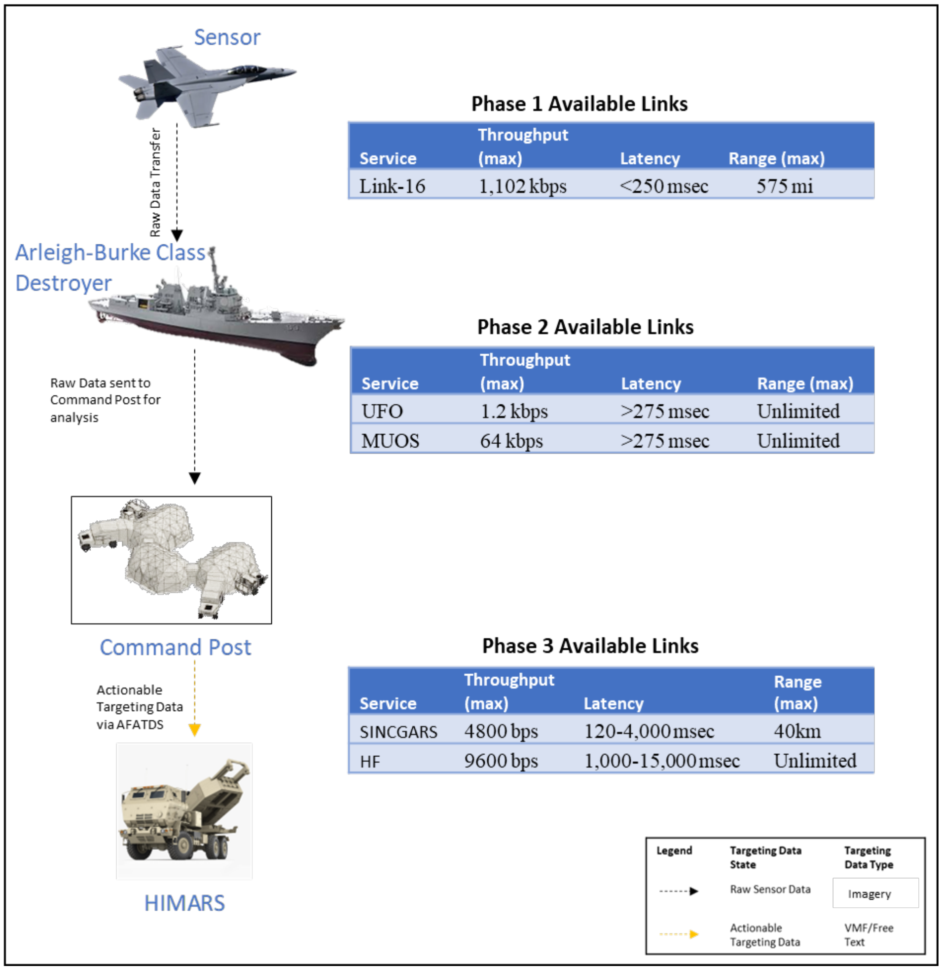
This section provided a summary of the two primary links used to communicate between AFATDS systems. A summary of this data can be found in Table 3.

Table 3. Phase 3 Available Links Summary

Service	Throughput (max)	Latency	Range (max)
SINCGARS	4.8 kbps	120-4000 msec	40km
HF	9.6 kbps	1000-15000 msec	Unlimited

C. CHAPTER SUMMARY

This chapter reviewed the network transport links in an operational scenario connecting a Navy Sensor to an Army shooter. The operational scenario was broken down into three distinct phases, each with its own set of possible paths for sensor data to flow. Each link within the scenario was summarized by throughput, latency, and range. This data allows for a comparison of these links later in this study with the alternative commercial transport links of 5G and LEO. A summary of the technical review conducted of the operational scenario in this chapter can be found in Figure 9.



Phase 1 Available Links

Service	Throughput (max)	Latency	Range (max)
Link-16	1,102 kbps	<250 msec	575 mi

Phase 2 Available Links

Service	Throughput (max)	Latency	Range (max)
UFO	1.2 kbps	>275 msec	Unlimited
MUOS	64 kbps	>275 msec	Unlimited

Phase 3 Available Links

Service	Throughput (max)	Latency	Range (max)
SINCGARS	4800 bps	120-4,000 msec	40km
HF	9600 bps	1,000-15,000 msec	Unlimited

Figure 9. Sensor-to-Shooter Scenario Summary—Network Transport Links by Phase

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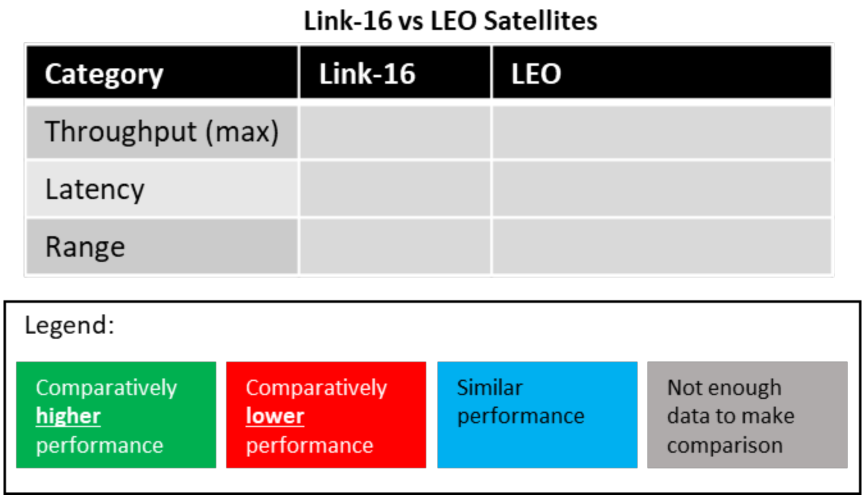
III. METHODOLOGY

A. APPROACH

The research conducted within this thesis uses a qualitative approach to answer the listed research questions. As the alternative services in review are currently available in the public sector, the supporting data reviewed consisted of commercial presentations (e.g., white papers, seminars), public DOD vendor information, (websites, manuals), and the study of practical applications. Upon aggregating the data from these sources, the study then defines the capabilities and limitations of the current and alternative data links which are then compared with the available data on the commercial alternatives of 5G and LEO. This study uses the following categories for comparison: (1) Throughput, (2) Latency, and (3) Range. The comparisons will be conducted by the three operational phases described in Chapter II. Each link will be compared with both 5G and LEO and summarized in the following four categories: (1) comparatively higher performance, (2) comparatively lower performance, (3) similar performance, and (4) not enough data to make comparisons. An example of a comparison table used in this study is shown in Table 4.

Table 4. Comparison table example



Link-16 vs LEO Satellites

Category	Link-16	LEO
Throughput (max)		
Latency		
Range		

Legend:

Comparatively **higher** performance

Comparatively **lower** performance

Similar performance

Not enough data to make comparison

The approach taken to the first two research questions regarding the "Throughput, Latency, and Range of (2) currently utilized transport methods and (3) 5G and LEO," the aggregation of practical and academic data collected from both commercial and DOD sources would support metrics for their respective services. While each service had varying infrastructure and transportation methods for data, the measurement capabilities of the desired metrics remain the same.

When exploring the third question, "What are the limitations of 5G and LEO?" the study reviewed the practical applications of the two services. Upon collection of the commercial data, a comparison of the acquired metrics would be applied to their use in an operational environment at sea. These limitations would focus on effects that would prevent or hinder mission capabilities including high latency, weather interference, and range limitations.

Regarding the fourth and fifth research questions regarding how and where the Navy/Army might leverage 5G and LEO technologies, a focus on the capabilities and limitations of each service is necessary to match it to currently available methods and their respective missions. For the purposes of this study, bottlenecks in the current sensor-to-shooter network are identified by utilizing the data gathered in answering the first research question. By identifying where throughput, latency, or range limitations exist in current sensor-to-shooter networks, potential use cases for the augmentation of commercial alternatives are identified.

B. CHAPTER SUMMARY

This chapter introduced and defined the methodology used within the analysis chapter of this thesis. Three primary data metrics were identified and defined in order to compare the capabilities of each service: (1) Throughput, (2) Latency, and (3) Range.

Throughput, Latency, and Range were targeted as metrics as the services researched are data links. A comparative analysis based on available data is used to provide a numerical comparison between services. Capabilities and limitations are identified in order to identify use cases for the alternative data services.

IV. 5G AND LEO OVERVIEW

As the DOD seeks to adapt and advance the speed and capacity of its networks, there are two emerging technologies that have the potential to revolutionize the way the DOD connects disparate elements within the JADC2 construct. Both LEO-based satellite communications and terrestrial commercial 5G antennas provide enormous improvement in performance vs. their legacy counterparts. In October 2022 the DOD's Space Development Agency (SDA) awarded a $200 million contract to build LEO prototypes for the DOD (Sheetz, 2022). In addition to development efforts, the DOD has made recent investments and partnerships with Starlkink for use of their existing LEO technology (Erwin, 2022a). In addition to its investments in LEO, the DOD has also been exploring commercial 5G. In early 2022 the DOD unveiled its plan to have a $3 million competition to speed up the "development and adoption of open interfaces, interoperable components, and multi-vendor solutions toward the development of an open 5G ecosystem" (Maucione, 2022). While the adoption of LEO and 5G is still in progress and the DOD has not solidified which areas of the DOD network will be connected by LEO and 5G, both have the potential to greatly improve the performance of critical mission sets such as sensor-to-shooter networks.

This chapter will provide an overview of both LEO and 5G technologies with a focus on throughput, latency, and range. While the exact performance of 5G and LEO within these categories may vary as the technologies mature and commercial adoption increases, this study will use data already available today to summarize the expected performance of both LEO and 5G.

A. LEO

LEO-based connectivity is quickly becoming the fastest and most reliable option for connecting people and organizations in remote areas to the internet. While the concept of LEO communications certainly is not new, it is only recently that companies began investing heavily in the technology required to make large-scale LEO connectivity functional. (Daehnick, Klinghoffer, Maritz & Wiseman, 2020). This is due both to technological improvements made in the past few decades, as well as increased demand for higher speed internet globally. (Daehnick et al., 2020). As a result, there has never been a better time than now for the DOD to begin exploring commercial LEO for military applications.

While other companies such as Amazon Kuiper, and OneWeb are working to provide LEO-based systems both to the government and commercially, Starlink is currently the leader in the industry based on the proliferation of constellations available today (Dienes, 2022). Consequently, the primary focus of this section will be on available data from tests conducted with Starlink systems.

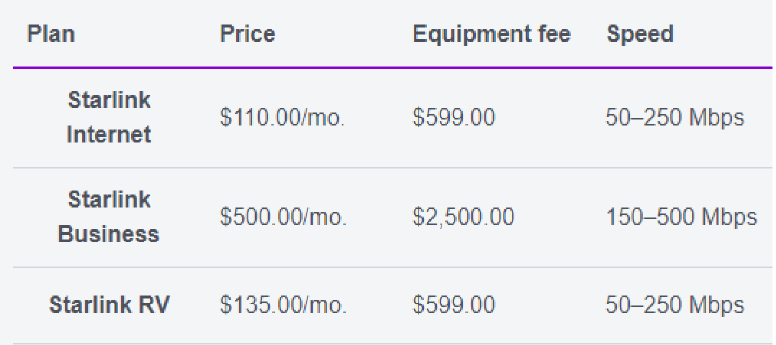
1. Starlink

The rise of Starlink as a commercial LEO provider stems from the company's origins in Elon Musk's spaceflight organization SpaceX (CNET, 2021). Since the company's first launch in 2018, Starlink had over 2,000 functioning LEO satellites by mid-2022 (Clark, 2022). Consequently, Starlink is the largest commercial LEO provider as well as the only one currently available for use. As of October 2022, Starlink provides service to five continents including North America, South America, Europe, Africa, and parts of the Indo-Pacific (Starlink.com, 2022).

Due to its high proliferation, Starlink has quickly become of interest to the DOD. Of note, Starlink has quickly risen to fame in the military community due to its high degree of success in Ukraine's struggle against Russia. As of October 2022, Starlink had around 20,000 terminals in Ukraine providing vital communications to the Ukrainian military at a time when communications infrastructure is badly damaged. (Hitchens, 2022). Due to the success Ukraine is seeing with Starlink, LEO technology has never been more relevant to the DOD.

a. Starlink Throughput

The throughput, or capacity, of LEO communications is one of the primary factors that make companies like Starlink so appealing. While companies that offer traditional GEO constellations only provide an average throughput of around 20 Mbps, Starlink has been able to offer throughput between 100–200 Mbps for standard residential packages and upwards of 500 Mbps for business packages. (Haynes, 2022). Figure 10 provides a comparison of Starlink’s tiered subscription packages.



Plan	Price	Equipment fee	Speed
Starlink Internet	$110.00/mo.	$599.00	50–250 Mbps
Starlink Business	$500.00/mo.	$2,500.00	150–500 Mbps
Starlink RV	$135.00/mo.	$599.00	50–250 Mbps

Figure 10. Starlink Internet Plan Comparison. Source: Haynes (2022).

While the advertised throughput of Starlink systems is typically based on optimal conditions, the actual throughput of Starlink can vary depending on factors such as time of day, geographic location, and weather (Crist, 2022). For example, a recent test conducted at the Naval Postgraduate School using the standard Starlink internet package found variations in throughput ranging anywhere from 0.89 to 311 Mbps, with an average throughput of around 151 Mbps. (Dienes, 2022). Another recent study conducted by popular internet speed testing site Ookla.com found that in North America Starlink users were seeing a median throughput of around 90 Mbps (Fomon, 2022). This lower rate is likely attributable to the fact that Starlink is still rolling out coverage across North America which could cause a wide disparity in performance.

b. Starlink Latency

While the throughput of LEO providers like Starlink may be the most appealing, the lower latency of LEO satellites is another factor driving the tech industry to invest in LEO infrastructure. The lower latency of LEO systems is due to the drastic differences in distance between a traditional GEO orbit compared to a LEO orbit. For example, a satellite operating in the GEO range would typically be around 35,000 km from the Earth while a satellite operating in the LEO zone could be as low as 160–2,000 km from the Earth (CSIS, 2022). See Figure 11 for a depiction of the different orbits.

Figure 11. LEO, MEO, and GEO Orbit Comparison. Source: CSIS (2022).

The distance to GEO satellite constellations as compared to the distance to LEO constellations is a primary factor in the differences in network latency between the two (Dienes, 2022). For example, an antenna connected to traditional GEO satellites such as Hughes Net could see network latencies of up to 550ms (Dienes, 2022). In comparison, Starlink's network of LEO-based satellites gives users a latency of as low as 20ms due to the short distance traveled from an antenna on the ground to a satellite in orbit (Starlink, 2022). The same test conducted at the Naval Postgraduate School that found an average throughput of 151 Mbps, found Starlink antennas that saw latency of as low as 19.81ms with an average of 39.81ms (Dienes, 2022). Assuming the average of 39.81ms remains steady in the future, the latency of Starlink-connected systems is almost 14 times faster than systems connected to GEO-based satellites. Essentially this means that a user could send and receive around 14 pings on a network via LEO at the same time it would take a user to send and receive a single ping via a GEO-connected system.

c. *Starlink Range*

Given the fact that all satellite-based systems enable beyond line of sight communications, the range of any satellite communication system is of significant importance to a prospective military user when compared with terrestrial-based communication systems. While Starlink certainly is unique in the fact that its connectivity offers virtually unlimited range, the relative closeness of LEO-based systems is a factor that significantly increases the network performance as discussed in the previous section. Consequently, Starlink's ability to give users the freedom to move around virtually anywhere and still see high network performance is a significant advantage over any terrestrial-based communication system limited to line of sight.

2. Emerging LEO Providers

While Starlink may be the current leader in LEO communications, they are certainly not the only company seeking to capitalize off the advantages LEO-based service can provide customers. While this study does not provide an exhaustive list of every potential LEO service provider, it is important to provide a brief overview of Starlink's notable competitors. This will allow for a more holistic baseline for expected performance values of LEO-based communications.

a. Amazon Kuiper

Amazon's Project Kuiper is a notable contender for providing broad coverage LEO services that could potentially compete with Starlink in the near future. Although Amazon has not officially disclosed when Kuiper will be able to provide services, it plans to launch over 3,000 LEO satellites within the next decade (Palmer, 2022). Of note to the DOD, Project Kuiper is one of the contenders to work with the U.S. military in the future to provide LEO service for tactical use (Erwin, 2022b). While there is currently limited data regarding the throughput, latency, and range of Kuiper systems relevant to this study, the company plans to provide similar capabilities as Starlink with throughput speeds up to 400 Mbps (Rivera, 2022). While this may not be as fast as Starlink's premium packages that get upwards of 500 Mbps, it is still significantly better than the performance of GEO-based satellite networks.

b. OneWeb

United Kingdom-based OneWeb is another contender for the future of LEO communication systems. The company began launches of LEO-based satellites in 2019 and has 464 Satellites in orbit as of October 2022 (OneWeb, 2022). OneWeb is somewhat unique in the fact that it is pursuing a hybrid strategy of both LEO and GEO-based satellites. The company currently advertises that users will be able to seamlessly switch between LEO and GEO satellites without changing antennas (OneWeb, 2022). While there is still limited data available regarding the throughput and Latency of OneWeb, the company expects to provide antennas capable of data throughputs of over 200 Mbps (OneWeb, 2022). However, given the fact that OneWeb is pursuing a hybrid strategy of both LEO and GEO, the throughput and latency seen by a user of OneWeb will likely vary based on which type of constellation they are connected to at a given time.

3. LEO Summary

LEO is a fast-evolving technology that is emerging as one of the best options for users that are not connected to the fiber infrastructure of the world. Given both the proliferation, as well as the relatively small distance between a satellite and user compared to GEO-based systems, LEO is fast becoming the preferred option over traditional satellite communications. Consequently, the U.S. military will likely continue to work with emerging LEO providers as it seeks to find ways to integrate the technology into military operations.

In order to provide a comparison of LEO service as a potential alternative to current sensor-to-shooter network links, a summary of currently available LEO performance is summarized in Table 5.

Table 5. LEO throughput, Latency, and Range Summary

Service	Throughput (max)	Latency	Range (max)
LEO	500 Mbps	As low as 20ms	BLOS

B. FIFTH GENERATION CELLULAR NETWORKS (5G)

1. 5G Overview

Since the initial release of 1G in the 1980s, mobile telecommunications has grown from an audio-centric focus to supporting rich media such as broadband data and video. These advancements, or "generations," have improved the network since its initial release where it had shifted from simple data such as email in 2G to supporting internet services and multimedia with the release of 3G in 2000 (Fizza et al., 2015, p. 95). As the consumption of mobile data grew over the years, telecommunications providers adapted to user demands with the release of 4G in 2011 to provide a focus on data-intensive rich media.

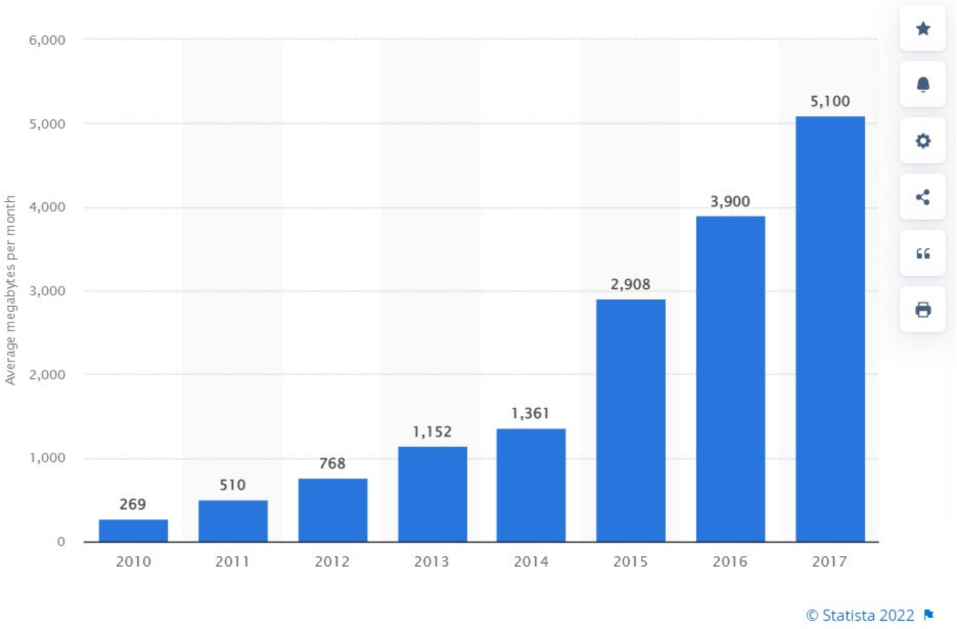


Figure 12. Average Mobile Data Usage per Smartphone in the U.S. from 2010 to 2017/ Source: Statista (2018).

Serving as the next milestone in the wireless evolution of mobile data, 5G continues the trend of improving user experience through higher throughput and lower latency. Initially launched on April 3, 2019 in both Chicago and Minneapolis by Verizon (Verizon, 2019), its network coverage was fairly small due to its frequency range. Although it covered a small location at the time, the throughput it was able to provide was a significant step forward compared to its 4G counterpart.

As the coverage of 5G within the U.S. has now grown more prevalent, its spread is due to the use of employing varying spectrum frequencies. The 2019 release performed by Verizon utilized what is defined as Millimeter Wave (mmWave) and resides in the upper EHF spectrum. Ranging from 17 to over 100 GHz, this broadcast approach allows for an area of concentrated use with the benefit of high transfer rates.

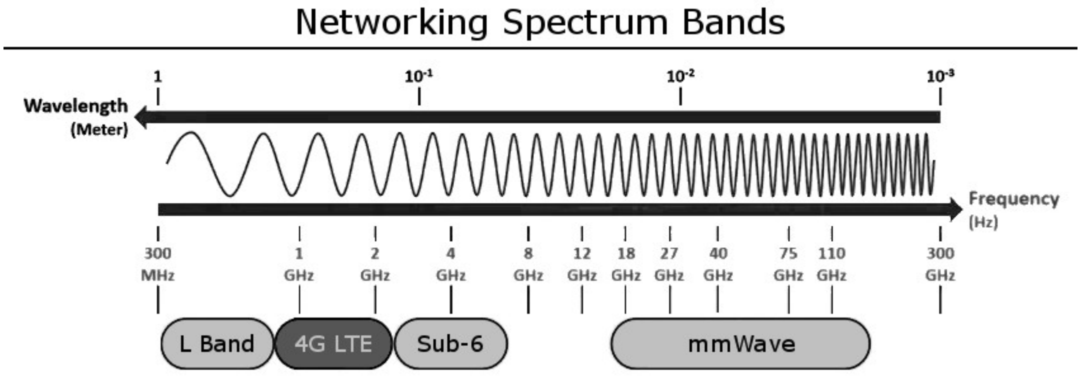


Figure 13. Networking Spectrum Bands. Source: Triggs (2022).

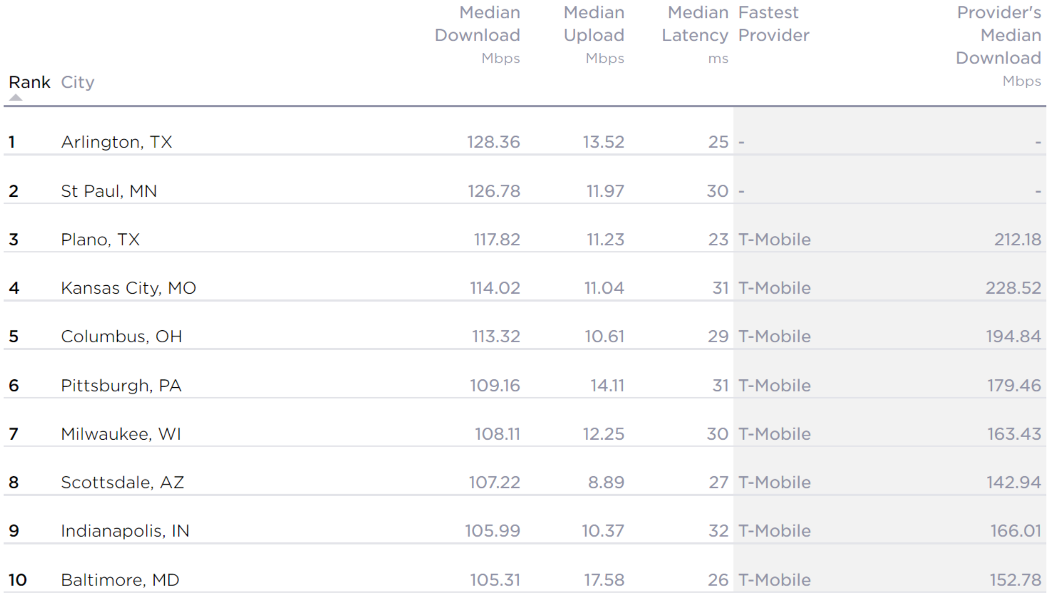
In order to provide a wider area of coverage while still improving on 4G data rates, vendors use the Sub-6 spectrum which consists of frequencies below 6 GHz. To cover the large distances within the cities, vendors will utilize mid-band frequencies between 1.7 and 2.5 GHz that provide a balance between speed and range (Celona, 2020). An alternative method dropping as low as 600 MHz comes with the widest area of coverage known as low-band. While this method provides a much lower throughput, this allows the service to be acquired at a much greater distance with less interference caused by environmental barriers such as buildings or terrain.

2. 5G Service Providers

Within the U.S. there are currently three major 5G service providers: AT&T, T-Mobile, and Verizon. Although each vendor utilizes a combination of Sub-6 and mmWave frequencies consumer needs, the names for mmWave vary as there is no commercial standard. When discussing commercial 5G mmWave, T-Mobile's equivalent is titled "Ultra Capacity 5G," AT&T's is "5G Plus," and Verizon's is "Ultra Wideband" (ON5G, 2021). In contrast, the use of low-band and medium-band is combined when defining the standard 5G service of all three.

In terms of U.S. 5G infrastructure, T-Mobile holds a significant amount of square mileage covered with 1.6mil largely in part due to its merger with Sprint in 2020 (ON5G, 2021). Because of this merge in assets, T-Mobile has taken a significant lead in mmWave customers with 125mil in comparison to its nearest competitor Verizon with only 3mil.

According to quarterly speed tests, as shown in Figure 14, T-Mobile currently provides the fastest speeds in 77 out of 100 of the most populated cities in the U.S. with Verizon trailing behind with five (SpeedTest, 2022).



Rank	City	Median Download Mbps	Median Upload Mbps	Median Latency ms	Fastest Provider	Provider's Median Download Mbps
1	Arlington, TX	128.36	13.52	25	-	-
2	St Paul, MN	126.78	11.97	30	-	-
3	Plano, TX	117.82	11.23	23	T-Mobile	212.18
4	Kansas City, MO	114.02	11.04	31	T-Mobile	228.52
5	Columbus, OH	113.32	10.61	29	T-Mobile	194.84
6	Pittsburgh, PA	109.16	14.11	31	T-Mobile	179.46
7	Milwaukee, WI	108.11	12.25	30	T-Mobile	163.43
8	Scottsdale, AZ	107.22	8.89	27	T-Mobile	142.94
9	Indianapolis, IN	105.99	10.37	32	T-Mobile	166.01
10	Baltimore, MD	105.31	17.58	26	T-Mobile	152.78

Figure 14. 5G City Speeds for Q3 2022. Source: SpeedTest (2022).

Although T-Mobile currently holds the lion's share of 5G capabilities in the U.S., AT&T is currently supporting the DOD in two 5G experiments at separate facilities. Its first experiment revolves around the development of a 5G Smart Warehouse to further improve logistic support to naval units. AT&T was able to successfully deploy and test a network capable of providing over 4 Gbps with less than 10 ms of latency to support the use of autonomous robotics and cameras within the warehouse (AT&T, 2022). The second project consists of developing a 5G architecture that can transition between fixed and mobile configurations to support Command and Control (C2) needs in an agile combat environment (DOD, 2020).

3. Throughput

Depending on the transmission frequency used, either Sub-6 or mmWave, the throughput can vary greatly. Within cities, the majority of users will tend to be covered by using a Sub-6 frequency with mmWave specifically reserved for concentrated areas such as stadiums and airports (Oliver, 2021). In the Speedtest 2022 Q3 Market Analysis report, it is of note that median performance varies greatly between T-Mobile and its competing vendors. Using only a Sub-6 5G connection on mobile, T-Mobile was able to provide a median download speed of 193.06 Mbps (SpeedTest, 2022). According to telecom consulting firm STL Partners, Sub-6 throughput is expected to mature in 2025 and bring an estimated download speed of over 400 Mbps (AT&T, 2020, p.10).

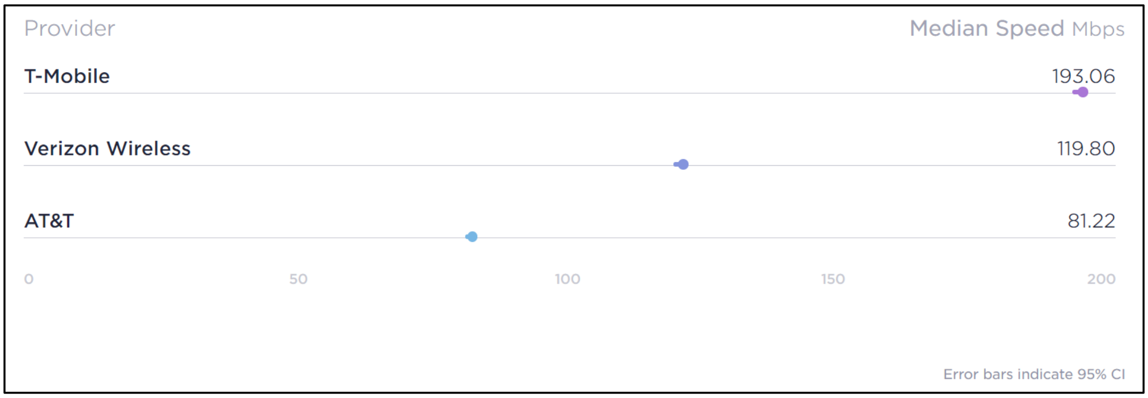


Figure 15. 5G Performance in Q3 2022. Source: SpeedTest (2022).

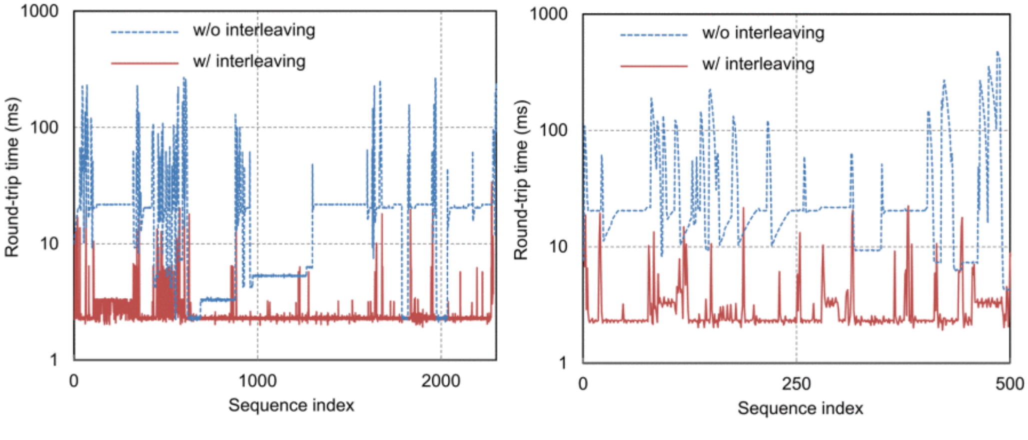
During the 2021 Superbowl in Tampa, Florida, all three vendors deployed mmWave infrastructure to support an influx of 25,000 fans. Among the three, AT&T held the highest mmWave speeds along with an average nearly triple its nearest competitor. With a maximum of 1.71 Gbps and an average of 1.26 Gbps (Fletcher, 2021), mmWave proved to be a significant method of providing high throughput to users. The tests for each vendor were standardized using a Samsung Note 20 and were conducted within the stadium before, during, and after the game (Fletcher, 2021).

4. Latency

With an industry goal of utilizing 5G to support autonomation, lower latencies play a critical role in allowing this capability to flourish. Although AT&T had proven that a latency lower than 10ms is capable for the smart warehouse in Naval Base Coronado, San

Diego, CA, the vendor's expectation is that 5G will eventually provide under 5ms (AT&T, 2020, p. 2).

As of current, mmWave technology comes the closest in consistently achieving low-latency requirements. In a field experiment conducted in Yokosuka, Japan in 2016, researchers evaluated the latency of a receiver using LOS transmission both while stationary and mobile. Utilizing a 73.5 GHz frequency to achieve a targeted 1 Gbps and interleaving to support latency reduction, the experiment was able to successfully achieve an average of 3 ms (Yoshioka et al., 2016).ms (Yoshioka et al., 2016).



(a) 5 km/h

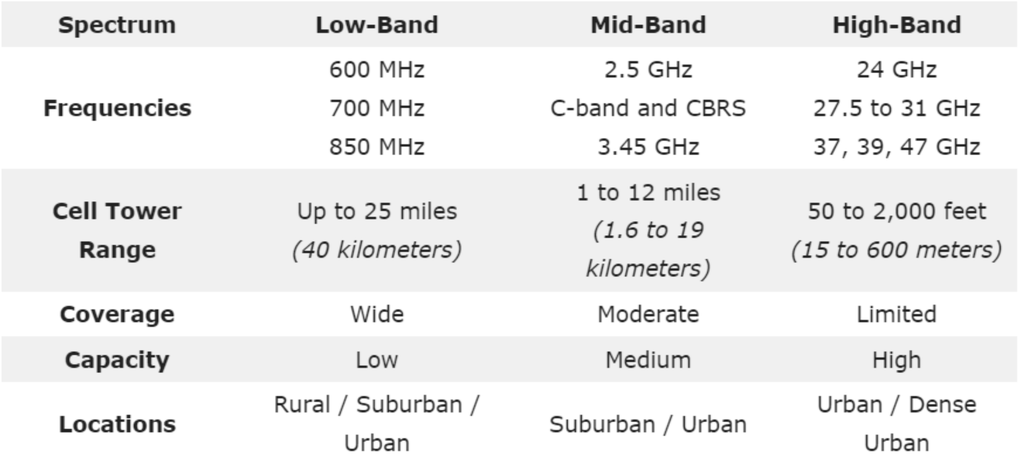
(b) 20 km/h

Figure 16. Latency Performance by Ping. Source: Yoshioka et al. (2016).

In comparison to mmWave, Sub-6 frequencies are currently unable to meet similar latencies. According to the median, as shown in Figure 16, the average latency for consumers averages roughly 25–30ms. This higher rate is largely due to the nature of Sub-6 frequencies reaching longer distances in comparison to mmWave. Although it remains at a similar latency to 4G services, according to Mats Norin, 5G Program Manager for Industries at Ericsson Research, it is expected to eventually "reach well below 10ms, and in best cases around 1ms delays" (2022).

5. Range

As frequencies within 5G vary to support its user base, the capability of using a wide spectrum allows for high flexibility when deploying networks. As shown in Figure 17, the lower a frequency reaches, the further its broadcast can effectively reach. With low-band offering roughly 50 Mbps (Celona, 2020), this frequency range trades throughput and latency for higher coverage. In comparison, although mmWave offers a high throughput and lower latencies, this frequency range struggles with reaching long distances as it is also impeded by structures and terrain.



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 17. 5G Cell Tower Coverage Radius. Source: Simmons (2022).

6. Summary

5G serves as the next advancement in mobile telecommunications with a wide frequency range to support various consumer needs. While all frequency ranges provide a boost in throughput compared to its 4G predecessor, the use of mid-band and mmWave technology provides high throughput and low latency to match increasing data consumption rates. The DOD is currently experimenting with the uses of 5G in support of improved C2 and the automation of logistics warehouses.

In order to provide a comparison of 5G service as a potential alternative to current sensor-to-shooter network links, a summary of currently available 5G performance is summarized in Table 6.

Table 6. 5G Throughput, Latency, and Range Summary

Service	Throughput (max)	Latency	Range (max)
Sub-6 GHz	40-400 Mbps	10-30ms	25 mi
mmWave	1-2 Gbps	1-10ms	.38 mi

C. CHAPTER SUMMARY

This chapter reviewed the data currently available on commercial 5G and LEO satellite transmissions. Both LEO and 5G are emerging technologies that have to potential to provide vastly superior network performance across the globe. This chapter helps to establish a baseline for the expected performance of these commercial network transport methods in order to compare them to the current sensor-to-shooter transport links outlined in Chapter II.

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V. COMPARATIVE ANALYSIS

This chapter provides a comparitive analysis of the data outlined in chapters II and IV. First, a of performance in the categories of throughput, latency, and range is provided between current sensor-to-shooter network transport links and commercial alternatives of 5G and LEO satellites. Second, in order to determine which legacy links are candidates for potential replacement or augmentation with 5G and LEO, bottlenecks in the current sensor-to-shooter network are identified. Third, potential limitations and risks of replacing current sensor-to-shooter links with commercial alternatives are identified.

A. THROUGHPUT, LATENCY AND RANGE COMPARISON BETWEEN CURRENT SENSOR-TO-SHOOTER LINKS AND 5G AND LEO SATELLITE

Before identifying links in the current sensor-to-shooter network that are candidates for potential replacement or augmentation with 5G and LEO, it is first important to understand the differences in performance between the legacy links and their commercial alternatives. This section provides a summary comparison in the categories of throughput, latency, and range. This section will separately compare the performance of 5G and LEO satellites against each of the legacy links by the operational phases outlined in Chapter II.

1. Phase 1: Sensor to Arleigh-Burke Class Destroyer

The operational scenario in Chapter II of this study defined Link-16 as the primary link used to send target imagery from the airborne sensor to a nearby Arleigh-Burke Class Destroyer. This section will look at how Link-16 compares to 5G and LEO satellite communications.

a. Link 16 and 5G

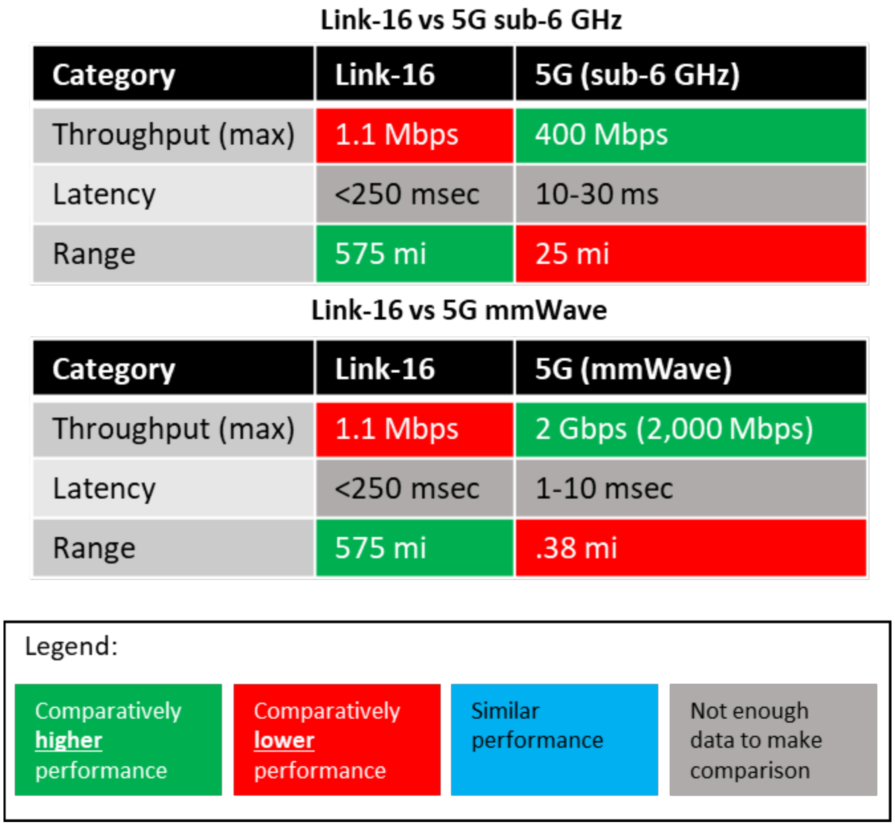
While both Link 16 and 5G are categorized as line-of-sight transmissions, there are some differences in performance when both types of transmissions are compared. Overall, both 5G sub-6 GHz and 5G mmWave outperform Link-16 in overall throughput but underperform in the maximum range for a single link. As both Link-16 and 5G transmissions have similar latency that can vary based on the environment, there is not a clear winner when it comes to latency. A summary of the comparison between Link-16 and 5G is in Table 7.

When it comes to throughput, 5G sub-6 GHz and mmWave have significant advantages, offering as much as close to 2,000 times the overall throughput over Link-16. This advantage is primarily due to the extremely wide frequency ranges in use with 5G as compared to Link-16. As a result either common form of 5G communications far outpaces Link-16 when it comes to the amount of data that can be sent on a single link.

While 5G decidedly outperforms Link-16 in throughput, it is much more difficult to compare when it comes to overall latency. While there is limited unclassified data on the latency of Link-16, the expected latency is a maximum of 250 msec but potentially better depending on the environment. In comparison, 5G sub-6 GHz latency can vary between 10–30 msec and 5G mmWave has a slightly lower latency of 1–10 msec. Given the potential for varied performance based on the environment, and limited open source data concerning Link-16, further testing is needed to make a true comparison of Link-16 and 5G latency. However, given the extremely low latencies of both 5G sub-6 GHz and mmWave, it is likely that 5G outperforms L-16 in transmission latency.

A clear difference lies in the maximum ranges of 5G and Link-16. Due to the higher frequency and bandwidth of 5G, its range is limited to a max of 25 miles when operating at sub-6 GHz and a max of less than half a mile when operating at mmWave. In contrast, Link-16 has a maximum range of up to 575 miles making it the superior option from the perspective of range.

Table 7. Link-16 and 5G Comparison



Link-16 vs 5G sub-6 GHz

Category	Link-16	5G (sub-6 GHz)
Throughput (max)	1.1 Mbps	400 Mbps
Latency	<250 msec	10-30 ms
Range	575 mi	25 mi

Link-16 vs 5G mmWave

Category	Link-16	5G (mmWave)
Throughput (max)	1.1 Mbps	2 Gbps (2,000 Mbps)
Latency	<250 msec	1-10 msec
Range	575 mi	.38 mi

Legend:

- 🟩 Comparatively **higher** performance
- 🟥 Comparatively **lower** performance
- 🟦 Similar performance
- ⬜ Not enough data to make comparison

b. Link-16 and LEO Satellite Communications

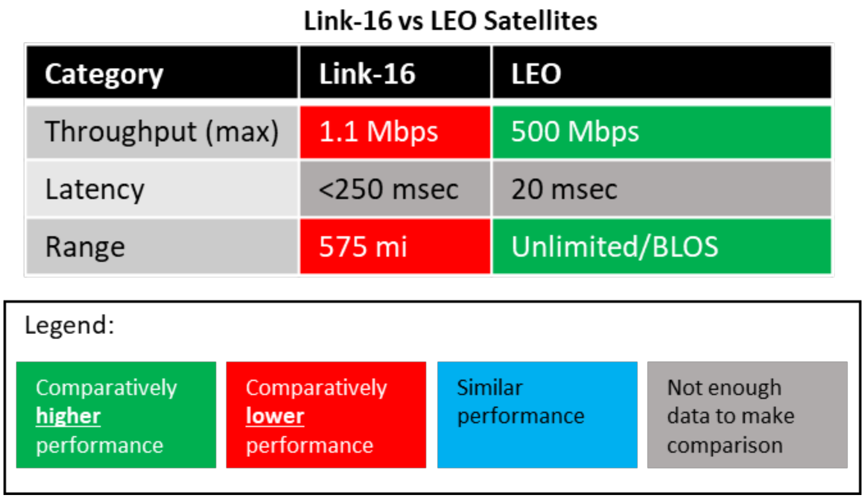
Link-16 and LEO Satellite Communications are distinct from each other as Link-16 is a terrestrial transmission, while LEO satellites use celestial transmissions. Consequently, there are some key differences when it comes to performance in the categories of throughput, latency, and range. A summary of these differences is in Table 8.

Link-16 transmissions have a maximum throughput of 1.1 Mbps compared to 500 Mbps in LEO transmissions. Consequently, LEO-based satellite links have a significant advantage over Link-16. The low distance to orbit and wide bandwidth of LEO transmissions allow for a significant amount of data to be sent via a single link.

Similar to the comparison of Link-16 and 5G, the data on Link-16 is too limited to make a true comparison between the latencies of the two types of transmissions. While LEO transmissions have latencies as low as 20 msec, Link-16 has a latency range of <250 msec. Consequently, LEO transmissions are likely to have a better overall latency when compared to Link-16, but further testing is required to confirm.

Due to the fact that LEO transmissions are beyond-line-of-sight by design, while Link-16 is a terrestrial or line-of-sight transmission, LEO transmissions have a distinct advantage when it comes to range. While Link-16 is limited to a maximum range of 575 miles, LEO transmissions essentially have no range limit provided they have a clear view of the sky.

Table 8. Link-16 and LEO Comparison



Link-16 vs LEO Satellites

Category	Link-16	LEO
Throughput (max)	1.1 Mbps	500 Mbps
Latency	<250 msec	20 msec
Range	575 mi	Unlimited/BLOS

Legend:

- 🟩 Comparatively **higher** performance
- 🟥 Comparatively **lower** performance
- 🟦 Similar performance
- ⬜ Not enough data to make comparison

2. Phase II: Arleigh-Burke Class Destroyer to Command Post

During Phase II of the operational scenario used by this study, a joint transmission between the Navy and the Army is required in order to transmit the raw sensor data received in phase I to a land-based command post. As previously found in Chapter II there are two primary links available in current sensor-to-shooter networks to transmit this data. This section will summarize how the current links of UHF Follow-on (UFO) SATCOM, and MUOS SATCOM, compared to the commercial alternatives of 5G and LEO.

a. UFO and MUOS comparison with 5G

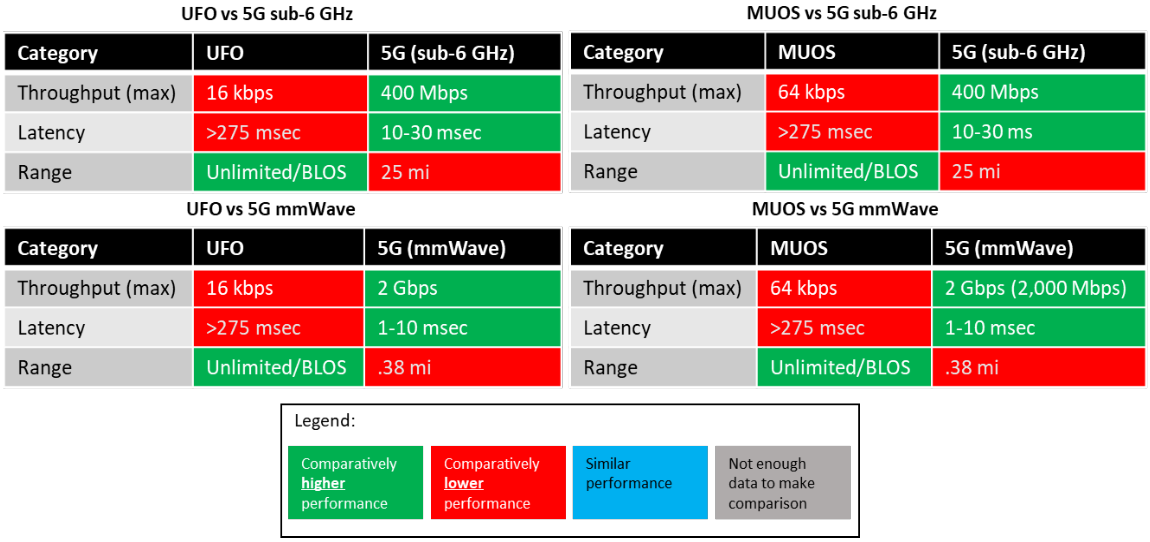
Both UFO and MUOS SATCOM have a similar outcome when compared with 5G. UFO and MUOS SATCOM have a superior transmission range compared to 5G due to the fact that both UFO and MUOS are celestial transmissions, whereas commercial 5G is largely used in terrestrial transmissions limited by line of sight. However, 5G significantly outperforms UFO and MUOS when it comes to both latency and overall throughput in a transmission. A summary of this comparison is in Table 9.

Given the extremely low data rate of both UFO and MUOS narrowband channels, the much wider channels in commercial 5G far outperform UFO and MUOS when it comes to overall throughput. While UFO and MUOS are limited to 16 kbps and 64 kbps in a single channel, respectively, 5G sub-6 GHz can support upwards of 400 Mbps and 5G mmWave can support up to 2 Gbps.

When it comes to latency, 5G again outperforms both UFO and MUOS. Given the fact that UFO and MUOS are both celestial transmissions that rely on geosynchronous antennas at an altitude of 22,236 miles, the latency is higher than 275 msec. In contrast, both 5G sub-6 GHz and mmWave support latencies lower than 30 msec making them significantly faster.

Range is the one metric where UFO and MUOS outperform both 5G sub-6 GHz and mmWave. 5G again suffers from the fact that its wide channel size and high-frequency range limit its range. While UFO and MUOS transmit beyond line-of-sight to GEO satellites, 5G is limited to 25 miles for sub-6 GHz and less than half a mile for mmWave. Consequently, UFO and MUOS SATCOM have a virtually unlimited range compared to a very limited range for 5G.

Table 9. UFO and MUOS Comparison with 5G



UFO vs 5G sub-6 GHz

Category	UFO	5G (sub-6 GHz)
Throughput (max)	16 kbps	400 Mbps
Latency	>275 msec	10-30 msec
Range	Unlimited/BLOS	25 mi

MUOS vs 5G sub-6 GHz

Category	MUOS	5G (sub-6 GHz)
Throughput (max)	64 kbps	400 Mbps
Latency	>275 msec	10-30 ms
Range	Unlimited/BLOS	25 mi

UFO vs 5G mmWave

Category	UFO	5G (mmWave)
Throughput (max)	16 kbps	2 Gbps
Latency	>275 msec	1-10 msec
Range	Unlimited/BLOS	.38 mi

MUOS vs 5G mmWave

Category	MUOS	5G (mmWave)
Throughput (max)	64 kbps	2 Gbps (2,000 Mbps)
Latency	>275 msec	1-10 msec
Range	Unlimited/BLOS	.38 mi

Legend:

- 🟩 Comparatively **higher** performance
- 🟥 Comparatively **lower** performance
- 🟦 Similar performance
- ⬜ Not enough data to make comparison

b. UFO and MUOS comparison with LEO

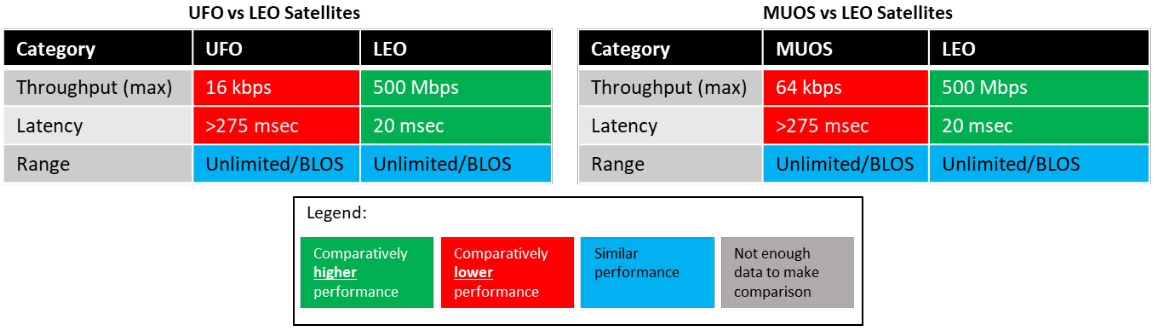
While LEO satellites as well as UFO and MUOS SATCOM are both celestial transmissions. Consequently, their range from a transmission perspective is overall similar in the fact that all three transmit beyond-line-of-sight. However, due to their relative closeness to terrestrial-based antennas, LEO-based satellite constellations far outperform their GEO-based counterparts in both throughput and latency. A summary of this comparison is in Table 10.

Where UFO and MUOS are limited to 16 kbps and 64 kbps, respectively, LEO-based satellite transmissions offer up to 500 Mpbs. This large disparity is again due to the fact that the LEO network provides a high proliferation of orbiting satellites that are much closer to ground antennas. Consequently, LEO-based networks have the ability to offer much higher throughput or data rate compared to GEO satellites. As a result, LEO satellite transmissions far outperform both UFO and MUOS when it comes to throughput.

For similar reasons that LEO offers much better throughput than UFO or MUOS, LEO also has significantly better latency. While UFO and MUOS have a latency greater than 275 msec, LEO transmissions offer latencies as low as 20 msec.

While LEO satellites offer far better throughput and latency than UFO and MUOS, the relative transmission range is the same from an employment perspective as both are celestial or beyond line-of-sight transmission. Consequently, there is essentially no range limit on UFO, MUOS, or LEO-based satellites.

Table 10. UFO and MUOS comparison with LEO



UFO vs LEO Satellites

Category	UFO	LEO
Throughput (max)	16 kbps	500 Mbps
Latency	>275 msec	20 msec
Range	Unlimited/BLOS	Unlimited/BLOS

MUOS vs LEO Satellites

Category	MUOS	LEO
Throughput (max)	64 kbps	500 Mbps
Latency	>275 msec	20 msec
Range	Unlimited/BLOS	Unlimited/BLOS

Legend:

- 🟩 Comparatively **higher** performance
- 🟥 Comparatively **lower** performance
- 🟦 Similar performance
- ▨ Not enough data to make comparison

3. Phase III: Command Post to HIMARS

During the third and final phase of the operational scenario used by this study, the sensor data has been determined to be actionable and is sent to the gun line in the form of a VMF message. This VMF message is sent primarily by either SINCGARS or HF. This section will provide a comparative analysis of the current sensor-to-shooter network transport methods of SINCGARS and HF, with the commercial alternatives of 5G and LEO satellite communications.

a. SINCGARS and HF comparison with 5G

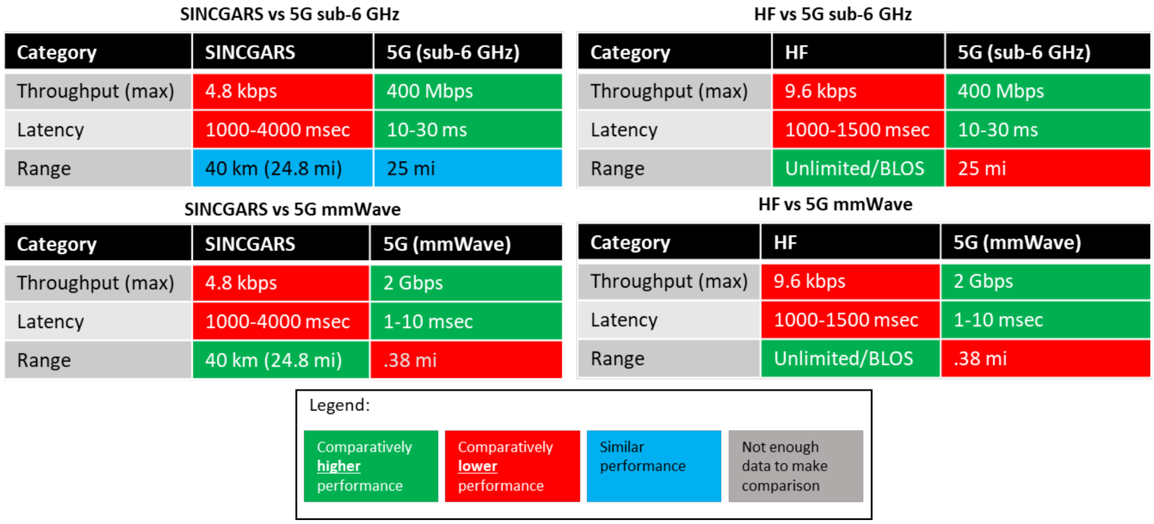
Both SINCGARS and HF radio systems are alike in the fact that they are primarily used for voice communications. Although they are both used for limited data transfers as is the case in phase III of this study’s operational scenario, the data rates and latencies of both radios are poor compared to 5G and LEO satellite communications. However, 5G does not outperform SINCGARS and HF when it comes to transmission range. Table 11 contains a summary of this comparison.

The throughput of SINCGARS and HF radios is 4.8 and 9.6 kbps, respectively. This low network throughput limits network traffic sent via SINCGARS or HF to small text-based files only. In contrast, 5G sub-6 GHz has a throughput of 400 Mbps and mmWave a throughput of 2 Gbps. This is an increase of at least 4,000% in overall network throughput when comparing either alternative of 5G to SINCGARS and HF. As a result, both 5G 6GHz and mmWave have comparatively higher performance than SINCGARS or HF when it comes to network throughput.

Latency is not much different than throughput when it comes to comparing SINCGARS and HF to 5G. SINCGARS has a minimum, or best, latency of around 120 ms with a maximum, or worst case, the latency of around 4,000 msec. HF transmissions have a latency of around 1,000 msec in optimal conditions, with latency as much as 1,500 msec in subprime conditions. In contrast, 5G has latencies as low as one msec for mmWave, as low as 10 msec for sub-6 GHz, and higher-end latencies of 10 and 30 msec, respectively. As a result, 5G communications have significantly improved network latencies compared to SINCGARS or HF.

Overall transmission range is the one category where 5G does not always outperform SINCGARS and HF transmissions. SINCGARS has a maximum range of around 40 km, or 24.8 mi, while HF has a virtually unlimited transmission range depending on the configuration. In contrast, 5G sub-6 GHz has a range of around 25 mi, and mmWave has a very limited range of less than half a mile. Consequently, SINCGARS has a very similar transmission range as 5G sub-6 GHz, and a much better transmission range than 5G mmWave. Additionally, HF radios outperform both 5G sub-6 GHz and mmWave due to the ability of HF to transmit BLOS.

Table 11. SINCGARS and HF Comparison with 5G



SINCGARS vs 5G sub-6 GHz

Category	SINCGARS	5G (sub-6 GHz)
Throughput (max)	4.8 kbps	400 Mbps
Latency	1000-4000 msec	10-30 ms
Range	40 km (24.8 mi)	25 mi

HF vs 5G sub-6 GHz

Category	HF	5G (sub-6 GHz)
Throughput (max)	9.6 kbps	400 Mbps
Latency	1000-1500 msec	10-30 ms
Range	Unlimited/BLOS	25 mi

SINCGARS vs 5G mmWave

Category	SINCGARS	5G (mmWave)
Throughput (max)	4.8 kbps	2 Gbps
Latency	1000-4000 msec	1-10 msec
Range	40 km (24.8 mi)	.38 mi

HF vs 5G mmWave

Category	HF	5G (mmWave)
Throughput (max)	9.6 kbps	2 Gbps
Latency	1000-1500 msec	1-10 msec
Range	Unlimited/BLOS	.38 mi

Legend:

🟩 Comparatively **higher** performance
🟥 Comparatively **lower** performance
🟦 Similar performance
⬜ Not enough data to make comparison

b. SINCGARS and HF comparison with LEO

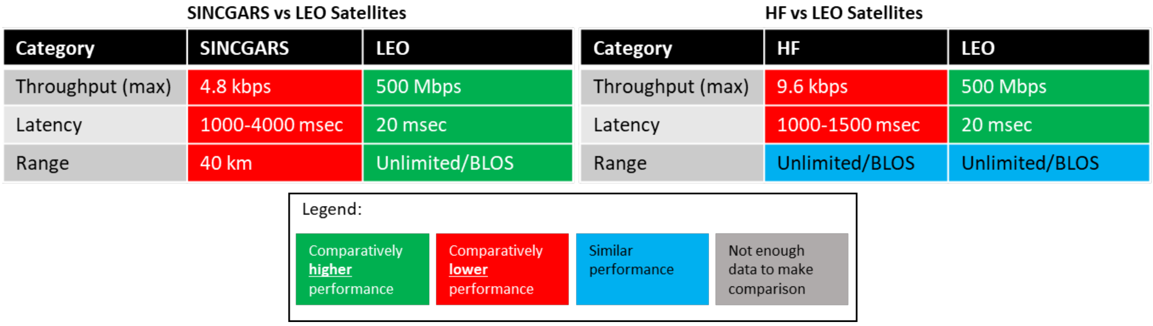
When comparing SINCGARS and HF to LEO satellites it is again important to understand that SINCGARS and HF are primarily used for secure voice communications and not for large amounts of data. Consequently, LEO satellite networks outperform both SINCGARS and HF in the categories of network throughput and latency. Additionally, LEO satellite networks outperform SINCGARS in the category of transmission range and are similar to HF transmission ranges as both transmit BLOS. Table 12 contains a summary of this comparison.

The network throughput of SINCGARS and HF is 4.8 and 9.6 kbps, respectively. In contrast, LEO-based satellite networks have the ability to provide up to 500 Mbps for a single link. Consequently, LEO communications have the potential to process significantly higher volumes of data in a single link vs either SINCGARS or HF.

Similar to network throughput, LEO-based communications have far better performance in the category of network latency. While SINCGARS and HF both have best-case latencies of 1,000 ms, LEO transmissions have latencies as low as 20 msec.

When comparing overall transmission ranges, LEO networks have virtually unlimited range due to the fact they are celestial transmissions. In contrast, SINCGARS is limited to a maximum transmission range of 40 km. While HF radios can transmit BLOS similar to LEO transmissions, HF radios do not automatically transmit BLOS and must be configured with a directional antenna. However, for employment purposes, HF radio transmission ranges have the potential to be unlimited. Consequently, LEO far outperforms SINCGARS but has a similar transmission range when compared to HF.

Table 12. SINCGARS and HF Comparison with LEO



SINCGARS vs LEO Satellites

Category	SINCGARS	LEO
Throughput (max)	4.8 kbps	500 Mbps
Latency	1000-4000 msec	20 msec
Range	40 km	Unlimited/BLOS

HF vs LEO Satellites

Category	HF	LEO
Throughput (max)	9.6 kbps	500 Mbps
Latency	1000-1500 msec	20 msec
Range	Unlimited/BLOS	Unlimited/BLOS

Legend:
🟩 Comparatively **higher** performance
🟥 Comparatively **lower** performance
🟦 Similar performance
⬜ Not enough data to make comparison

B. POTENTIAL USE CASES FOR 5G AND LEO SATELLITE NETWORKS

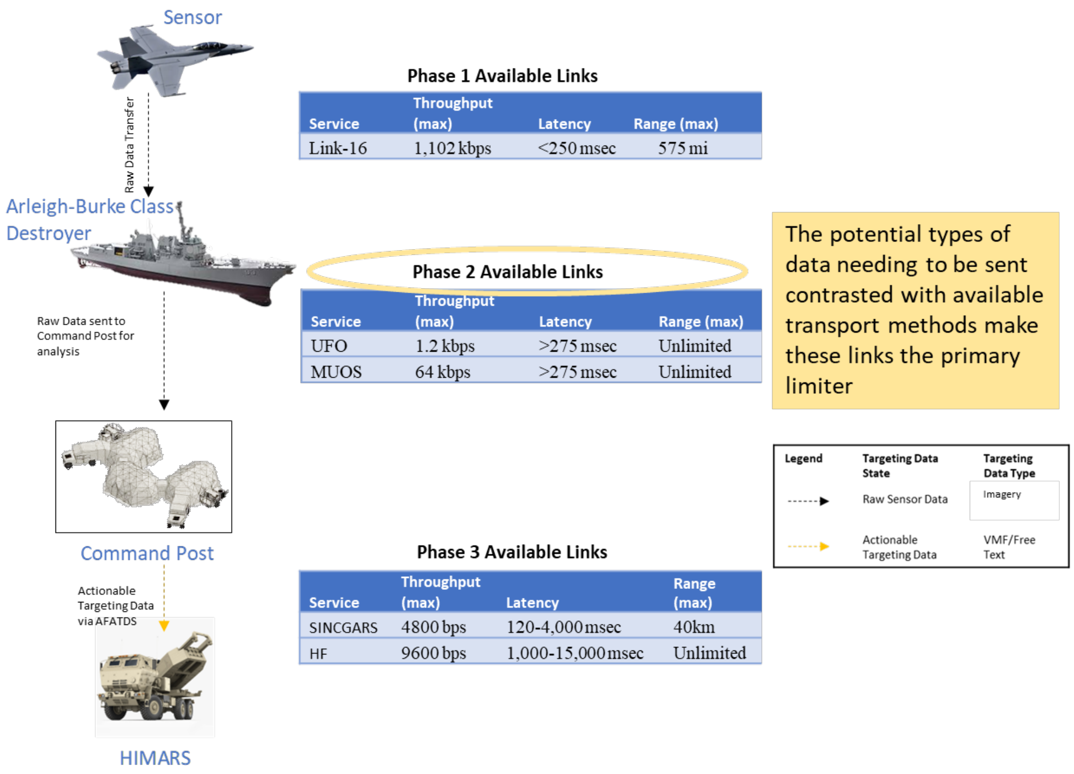
In order to determine where the commercial network transport alternatives of 5G and LEO best fit within the sensor-to-shooter network described by this study, it is first important to determine where bottlenecks exist within the network. While the performance of 5G and LEO technologies may be comparatively higher than currently available links within a sensor-to-shooter network, a replacement of all links would not necessarily be necessary, efficient, or practical. This section will examine where commercial 5G and LEO technologies best fit within the sensor-to-shooter network by determining where bottlenecks exist in the network based on the type of data being sent in each phase.

1. Limitations in Phase 1 Links

During phase one, the raw sensor data of a target is transmitted from the sensor to an Arleigh-Burke class destroyer in the form of target imagery via a Link-16 transmission. With a maximum throughput of just over 1,000 kbps, Link-16 provides enough of a data pipe to send basic sensor data such as imagery. However, the main limitation of Link-16 lies in the fact that while processing, voice, navigation, and imagery, it is limited in its ability to send full-motion video. (Defense Industry Daily, 2019). Consequently, while Link-16 provides a sufficient pipeline for its intended purposes it is limited in its ability to process higher amounts of data.

2. Limitations of Phase 2 Links

During this phase, the Arleigh-Burke class destroyer retransmits the sensor data received in phase one to an Army command center. The two primary links defined in this study offer an extremely limited data pipe of 1.2 kbps for UFO transmissions and 64 kbps for MUOS transmissions. Additionally, the links in phase two have relatively high latencies of greater than 275 msec. These combined limitations in the phase two links have the potential to limit the type and quantity of data sent to joint partners making the links in this phase a primary limiter on sensor-to-shooter data flow. See Figure 18.



Phase 1 Available Links

Service	Throughput (max)	Latency	Range (max)
Link-16	1,102 kbps	<250 msec	575 mi

Phase 2 Available Links

Service	Throughput (max)	Latency	Range (max)
UFO	1.2 kbps	>275 msec	Unlimited
MUOS	64 kbps	>275 msec	Unlimited

The potential types of data needing to be sent contrasted with available transport methods make these links the primary limiter

Phase 3 Available Links

Service	Throughput (max)	Latency	Range (max)
SINCGARS	4800 bps	120-4,000msec	40km
HF	9600 bps	1,000-15,000msec	Unlimited

Figure 18. Highlight of Primary Bottleneck in Sensor-to-Shooter Network

3. Limitations of Phase 3 Links

Phase three of the operational scenario used by this study is unique from the other two phases in the fact that phase three is sending actionable targeting data in the form of a VMF-free text message. This is due to the fact that analysis of sensor data has already occurred and the only data necessary for a gun line to take action is the basic targeting data in the form of text. As a result, while the links available in this phase have a much higher latency, they provide sufficient throughput to carry the type of data sent.

4. Best Candidate Links for Augmentation with 5G and LEO

Given the bandwidth and latency limitations of the links in phase two, this study finds that the best place for potential augmentation with commercial 5G and LEO technologies lies in phase two. The links of UFO and MUOS in phase two are not only small data pipes but also share duty for other key functions aboard a ship. Augmenting the joint connection between the Navy and Army in phase two with the emerging technologies of 5G and LEO not only provides faster links but allows for the potential of other types of sensor data such as full motion video to be sent as well. Consequently, the best use case for the implementation of 5G and LEO lies in the bottleneck that currently exists between the Navy and Army.

5. Other Candidate Links for Augmentation with 5G and LEO

While UFO and MUOS are certainly the best target candidates for augmentation with 5G and LEO, there are potential benefits of studying the implementation of these technologies in other parts of a sensor-to-shooter network. For example, an airborne sensor could benefit from added throughput and range to enable it to send high-resolution full-motion video. Additionally, a terrestrial 5G network could have the potential to speed up the time it takes to send actionable targeting data to the gun line. While both these use cases deserve attention, they have less potential to make good use of 5G and LEO than the link between the Navy and Army.

C. LIMITATIONS AND RISKS OF 5G AND LEO SATELLITE TECHNOLOGY IN SENSOR-TO-SHOOTER NETWORKS

With 5G and LEO data services emerging into the consumer market as recently as 2017, the gradual adoption of these new technologies has allowed for observation of their vulnerabilities and limitations while in practice. As both technologies are improvements on previous commercially available services, each runs the risk of remaining vulnerable to previous issues while introducing new concerns through varying hardware. This section provides a summary of the limitations and vulnerabilities addressed in their commercial use.

1. Cyber

In the handling of information, both sensitive and general use, cyber security continues to be a prevalent concern when ensuring user data. In order to secure both data in transit and at rest from malicious actors, an organization's infrastructure must meet three main security principles within the CIA Triad: Confidentiality, Integrity, and Availability. The focus of confidentiality is to ensure that data is only able to be accessed by the parties involved while attackers are unable to view the information. Integrity is the assurance that data remains in its intended state without compromise through manipulation by unauthorized parties. Lastly, availability is the assurance that data remains accessible to its intended parties. In the event of a cyber-attack, an attacker will attempt to exploit a vulnerability found within one or more of these security principles.

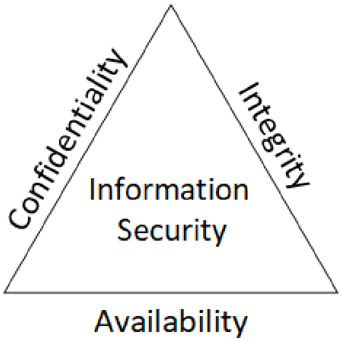


Figure 19. CIA Triad

Throughout the Russo-Ukrainian War that was relaunched at the beginning of 2022, SpaceX has been a prevalent entity in providing the Ukrainian government with a stable means of communication by delivering roughly 25,000 Starlink units (Marquardt, 2022). As the Ukrainian military has been using Starlink as a primary means of communication, Starlink has remained a valuable target to Russian forces. Although there are currently no reports of a successful hack by Russian forces, SpaceX had confirmed multiple instances of jamming. Elon Musk confirmed on March 5, 2022 that "Some Starlink terminals near conflict areas were being jammed for several hours at a time" (Berger, 2022). Several weeks after the availability attack Musk reported that SpaceX issued a software update that managed to resist further hacking and jamming attempts (Insinna, 2022).

During the timeframe the cyber attack occurred on Starlink services, the loss of reliable availability served as a major risk to Ukrainian forces. When serving as a pathway for tactical data in a hostile environment, ensuring continued data flow to units and providing assured C2 to commanders is critical. While these attacks showed the service was capable of being jammed, its resilience against attacks since the software update had shown the service is capable of fortifying its cyber posture.

SpaceX, like many other major IT corporations, offers a bug bounty to incentivize researchers to find security flaws in their product and reward based on the severity of the issue. During the 2022 BlackHat USA event, one researcher was able to exploit a vulnerability in their Starlink terminal which demonstrated a critical security flaw within their equipment. Belgian security researcher Lennert Wouters was able to perform a successful voltage fault injection attack which allowed him root access to the terminal (Gasic, 2022). Through root access on the terminal, the researcher had access to horizontal movement through the Starlink network with the potential for further exploitation.

While the process of performing a voltage fault injection attack requires a high level of tampering with the terminal, the access to the root level console holds the potential to attack all three pillars of the triad if exploited further. As the researcher held the capability to explore the network at the highest privilege level, the capability of either observing, manipulating, or denial of data remained possible. In order to remedy this issue, the company would ultimately require a hardware revision of the terminal to harden it against future attacks.

Although 5G has improved upon existing 4G infrastructure and services for user performance, it had not properly addressed an existing vulnerability from its predecessor. Carried over from 4G and LTE services is the risk of exploiting pre-authentication messages used by devices during a connection's authentication process (Marojevic, 2018, p. 7). Through legitimate functions such as null encryption and null authentication, the 5G service opens the risk to attacks ranging from denial of service (DoS) to man-in-the-middle (MitM) attacks which can attack various triad principles depending on intent. As there is currently no security framework that addresses these security issues, researchers Marojevic and Jover recommended no longer supporting vulnerable pre-authentication messages in order to harden the service (2018).

2. 5G Range

In order to reach higher levels of throughput, 5G relies on increasingly higher frequency ranges necessary to meet the requirements. As previously observed in Figure 17, although mmWave provides high throughput its effective range was less than half a mile. In contrast, the use of the lower end of the Sub-6 GHz range allowed cell towers to up to roughly 25 miles at the expense of throughput.

To effectively utilize the 5G service within the scenario, units within the local environment would be forced to maintain close proximity to others in the network even at the lowest frequency available to Sub-6 GHz. Due to this range limitation, the use of 5G would remain impractical in most operations involving aircraft. 5G's ranges however, would prove appropriate for command post operations.

3. Spectrum Limitations

Depending on the frequency range of the service utilized, inclement weather can play a major role in network degradation. With mmWave residing in the EHF range and averaging around 24 GHz, this service remains the most susceptible to attenuation from rain and snow. Although SHF services such as Starlink and Sub-6 GHz 5G reside in a lower frequency range, each can still have its services either degraded or denied depending on the severity of the storm. While these services can attempt to raise power to mitigate signal loss on the broadcast, this brute force method is limited to the amount of power available to the transmitter.

As the DOD continues to auction frequency ranges to companies for 5G (FCC, 2021), the military's frequency pool will continuously shrink in order to support mid-band commercial availability for Sub-6 GHz. With the gradual loss of frequencies controlled by the DOD, the military risks an inflexible mid-band pool when attempting to utilize 5G within an operational environment. Limited frequency ranges for 5G services may ultimately deny potential capabilities such as frequency hopping which allow for resilient anti-jamming communications in hostile environments.

D. CHAPTER SUMMARY

This chapter provided a comparative analysis of current sensor-to-shooter network links and the commercial alternatives of 5G and LEO technologies. This chapter used the data resulting from the comparative analysis to identify potential bottlenecks in current network links. These bottlenecks provide a basis to determine where the commercial alternatives of 5G and LEO are best positioned to improve sensor-to-shooter networks between the Navy and Army. Additionally, this chapter provided an overview of the limitations and risks of implementing commercial 5G and LEO technology within a sensor-to-shooter network.

VI. CONCLUSIONS

As the DOD continues to seek ways to leverage the commercial industry to enhance its modernization efforts, the emerging technologies of 5G and LEO-based satellites show great potential to augment current sensor-to-shooter networks. While these commercial technologies may not be best suited for every network connection within the JADC2 construct, they are worth exploring as alternative pathways to speed up the time it takes for targeting data to get from sensor to shooter. This chapter highlights key insights and recommendations that come from this study's review of a current example of a sensor-to-shooter network compared with alternative network transport methods of commercial 5G and LEO satellite technology.

A. KEY INSIGHTS

This section describes two key insights derived from this study's analysis on comparing the commercial alternatives of 5G and LEO satellite technology with current sensor-to-shooter network transport links

1. Commercial 5G and LEO Have a Comparatively Higher Performance Than Current Sensor-to-Shooter Network Links in Most Instances

While further testing is required to make a quantitative comparison of current sensor-to-shooter network links compared with commercial 5G and LEO technologies, this study's review finds that 5G technologies offer a much higher network throughput and latency over legacy sensor-to-shooter network links, but may have a comparatively inferior transmission range that could limit its applicability. This study further finds that LEO satellite-based technology has higher throughput and increased latency than all legacy sensor-to-shooter network links and a transmission range that is as good or better than current links. Consequently, LEO-based satellite technology shows the greatest potential for further research as an alternative network link in a sensor-to-shooter network.

2. Current Sensor-To-Shooter Network Links That Exist between the Army and Navy Are the Primary Bottleneck for Sensor-To-Shooter Data

When answering the question of which use cases are best suited for the commercial technologies of 5G and LEO-based satellites, this study finds that the network links that exist between the Navy and Army in phase two of the operational scenario described by this study are the best candidates. The limited throughput of BLOS transmission links that exist onboard an Arleigh-Burke class destroyer limits the type of data that can be sent, as well as the speed at which that data can traverse a network. This creates a potential bottleneck for sensor data between the Navy and Army and makes this particular portion of a sensor-to-shooter network the best candidate for the alternative network transport links of 5G and LEO satellites.

B. RECOMMENDATIONS

This study used a qualitative review of currently available data to make a comparative analysis of current sensor-to-shooter network links and commercial 5G and LEO. However, given the limited data that exists on using commercial 5G and LEO in sensor-to-shooter networks, further research is required to determine the feasibility of using these commercial transport alternatives. This section highlights some recommendations for future work and testing on this subject

1. Conduct Network Testing to Baseline a Quantitative Comparison between Legacy Network Transport Links and Commercial 5G/LEO

While this study used available data to conduct a comparative analysis, a modeling/ simulation or live network test is recommended in order to provide a more thorough comparison between current sensor-to-shooter network links and commercial alternatives. This test would require representative or actual assets from the Navy/Army in a lab or real-world environment to gather network data on the currently available transport links compared with the commercial alternatives.

2. Conduct a Cyber and Threat Analysis to Determine Security Vulnerabilities of Implementing Commercial Transport Methods as Alternatives

In addition to a simulated or live network test, a cyber and threat analysis is required to determine the security concerns that may exist when implementing commercial alternatives within a sensor-to-shooter network. While the performance of 5G and LEO technologies may be far greater than the current links, the potential security vulnerabilities of utilizing commercial infrastructure need to be thoroughly examined before implementation inside a sensor-to-shooter network.

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