NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EVALUATING A BURSTY-SIGNAL MESH NETWORK TO SUPPORT C2 CONSTRUCTS OF EXPEDITIONARY ADVANCED BASE OPERATIONS

by

David M. Costanzo and Michael J. Tucker

June 2021

Thesis Advisor:	Alex Bordetsky
Second Readers:	Steven J. Iatrou
	Glenn R. Cook

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

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

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2021	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE EVALUATING A BURSTY-SIGNAL MESH NETWORK TO SUPPORT C2 CONSTRUCTS OF EXPEDITIONARY ADVANCED BASE OPERATIONS	**5. FUNDING NUMBERS**
6. AUTHOR(S) David M. Costanzo and Michael J. Tucker	
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)

The United States Marine Corps continues to develop Expeditionary Advanced Base Operations (EABO) as the future operating model in the Pacific. EABO will employ Marines using widely dispersed, low profile, highly potent, and tightly integrated Navy and Marine Corps teams. This operating model challenges the Marine Corps' ability to command and control due to inherent resource limitations, long communication ranges, and the enemy's ability to detect, intercept, and interfere in the electromagnetic spectrum. This study sought to evaluate bursty-signal mesh network (BSMN) technology as a potential solution to these problems. The technology's suitability was evaluated through a comparison of the character of command and control in EABO (established through qualitative case study analysis of recent EABO exercises) against the characteristics of BSMN technology (established through quantitative modeling analysis). Finally, the viability of acquiring and fielding the technology was evaluated through a quantitative financial analysis. Though the researchers recommend further study, they conclude that BSMN technology's long-range, stealth, and low-power capabilities are well suited for communication at-and-below the regimental level. Further, researchers conclude that the technology is viable to acquire and field, with a price point far below other long-range communication assets (i.e., satellite communication) currently in use.

14. SUBJECT TERMS busty mesh networks, command and control, low-power, resilient, chirp spread spectrum	**15. NUMBER OF PAGES** 139
	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

THIS PAGE INTENTIONALLY LEFT BLANK

EVALUATING A BURSTY-SIGNAL MESH NETWORK TO SUPPORT C2 CONSTRUCTS OF EXPEDITIONARY ADVANCED BASE OPERATIONS

David M. Costanzo
Major, United States Marine Corps
BBA, University of Notre Dame, 2009

Michael J. Tucker
Major, United States Marine Corps
BS, United States Naval Academy, 2009

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT

**MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY
(COMMAND, CONTROL, AND COMMUNICATIONS)**

MASTER OF BUSINESS ADMINISTRATION

from the

**NAVAL POSTGRADUATE SCHOOL
June 2021**

Approved by: Alex Bordetsky
Advisor

Steven J. Iatrou
Second Reader

Glenn R. Cook
Second Reader

Alex Bordetsky
Chair, Department of Information Sciences

Glenn R. Cook
Academic Associate, Graduate School of Defense Management

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The United States Marine Corps continues to develop Expeditionary Advanced Base Operations (EABO) as the future operating model in the Pacific. EABO will employ Marines using widely dispersed, low profile, highly potent, and tightly integrated Navy and Marine Corps teams. This operating model challenges the Marine Corps' ability to command and control due to inherent resource limitations, long communication ranges, and the enemy's ability to detect, intercept, and interfere in the electromagnetic spectrum. This study sought to evaluate bursty-signal mesh network (BSMN) technology as a potential solution to these problems. The technology's suitability was evaluated through a comparison of the character of command and control in EABO (established through qualitative case study analysis of recent EABO exercises) against the characteristics of BSMN technology (established through quantitative modeling analysis). Finally, the viability of acquiring and fielding the technology was evaluated through a quantitative financial analysis. Though the researchers recommend further study, they conclude that BSMN technology's long-range, stealth, and low-power capabilities are well suited for communication at-and-below the regimental level. Further, researchers conclude that the technology is viable to acquire and field, with a price point far below other long-range communication assets (i.e., satellite communication) currently in use.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1
- A. PROBLEM STATEMENT 1
- B. HYPOTHESIS 1
- C. LITERATURE REVIEW 2
  - 1. Literature Introduction 2
  - 2. National Security Guidance Literature 2
  - 3. Command-and-Control Literature 5
  - 4. Current DOD Electromagnetic Capabilities 7
  - 5. Literature Summary 15
- D. RESEARCH DESIGN AND METHODOLOGY 16
  - 1. Research Questions 16
  - 2. Research Design 16
  - 3. Research Methods 18
- E. STAKEHOLDER ANALYSIS 19
  - 1. Stakeholder Identification 19
  - 2. Stakeholder Needs 19
- F. DEFINITIONS 20

II. CASE STUDIES 25
- A. CASE STUDY ORIENTATION 25
  - 1. Case Study Purpose, Method, and End-State 25
  - 2. Case Study Design 25
  - 3. Selected Cases 26
  - 4. Conceptual Study 28
  - 5. Command Concept Theory 29
  - 6. Technical Study 32
- B. CASE STUDIES 35
  - 1. 1st Battalion, 6th Marine Regiment: Exercise Northern Apache 2020 35
  - 2. III Marine Expeditionary Force: Marine Expeditionary Force Exercise 2019 44
  - 3. I Marine Expeditionary Force & U.S. 3rd Fleet: Exercise Pacific Blitz 2019 49
  - 4. Case Study Final Conclusion and Recommendations 56

III. TECHNICAL TESTING 65
- A. TECHNICAL STUDY INTRODUCTION 65

        1. Technical Study Purpose 65
        2. Technical Study Method 65
        3. Technical Study End-state 66
    B. TECHNICAL STUDY DESIGN 66
        1. Overview 66
        2. Chirp Spread Spectrum Characteristics 66
        3. LoRa Modulation Characteristics 67
    C. TECHNICAL STUDY OBSERVATIONS AND FINDINGS 76
    D. SUITABILITY ANALYSIS OF BSMN FOR C2 IN EABO 78

IV. FINANCIAL ANALYSIS 81
    A. FINANCIAL STUDY INTRODUCTION 81
        1. Financial Study Purpose 81
        2. Financial Study Method 81
        3. Financial Study End-state 81
        4. Financial Study Design 81
    B. COST COMPONENTS AND ESTIMATION 83
        1. Cost of Payload Development 84
        2. Cost of Ground Station Development 84
        3. Cost of Personnel, Operations, and Maintenance 85
        4. Costs of Constellation Launch 86
    C. TOTAL COMPONENT COSTS 86
    D. FINANCIAL STUDY OBSERVATIONS, FINDINGS AND VIABILITY OF BSMN FOR C2 IN EABO 92
    E. FINANCIAL ANALYSIS SUMMARY 94

V. CONCLUSION 95
    A. SUMMARY OF FINDINGS 95
        1. Hypothesis Test 95
        2. Answers to Research Questions 95
    B. ADDITIONAL RESEARCH RECOMMENDATIONS 99

LIST OF REFERENCES 103

INITIAL DISTRIBUTION LIST 111

LIST OF FIGURES

Figure 1. Research Design Illustration 18

Figure 2. Notional EABO Task Organization with Recommendations 57

Figure 3. Illustration of Strategic, Operational, & Tactical Warfare Destratification in EABO 60

Figure 4. Illustration of LoRa Layer One Communication Channel. Source: Ray (2018). 70

Figure 5. Antenna Efficiency, Gain, & Frequency Relationship. Source: Hong et al. (2014). 71

Figure 6. CSS Modulation with a 0.5-Watt Power Output 76

Figure 7. LoRa Modulation with a 0.158-Watt Power Output 76

Figure 8. Average S/N Ratio for CSS and LoRa Modulations by Transmission Range 77

Figure 9. Average Number of Satellites in LEO Constellations 83

Figure 10. Average Payload Development Costs 84

Figure 11. Ground Station Development and 10-Year Service Cost. Source: Marco Polo (2020). 85

Figure 12. Personnel, Operations, and Maintenance Cost. Source: Marco Polo (2020). 85

Figure 13. Average Launch Cost 86

Figure 14. Average Payload Development Costs 87

Figure 15. Portion of the $\text{Cost}_{\text{Payload}}$ Simulated Data Set 88

Figure 16. $\text{Cost}_{\text{Total}}$ with Standard Deviation Included 91

Figure 17. Portion of Forecasted $\text{Cost}_{\text{Payload}}$ Data Set 91

Figure 18. Graph of Forecasted $\text{Cost}_{\text{Payload}}$ Data Set 92

Figure 19. Acquisition Program Baseline (APB) 2010. Source: GBS (2018). 93

Figure 20. Annual Funding, Air Force WGS Program. Source: GBS (2018). 93

LIST OF TABLES

Table 1. Frequency Bands Characteristics Employed by DOD. Adapted from Stine and Portigal (2004). 9

Table 2. Exercise Northern Apache Technical Characteristics....................42

Table 3. MEFEX-19 Technical Characteristics....................48

Table 4. Exercise Pacific Blitz Technical Characteristics....................54

Table 5. Combined Technical Study Observations....................63

Table 6. LoRa Spreading Factors at 125 kHz . Source: Semtech (2013). 69

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

1/6	1st Battalion, 6th Marine Regiment
3/12	3d Battalion, 12th Marine Regiment
A2AD	anti-access area denial
AAR	after action report
APB	acquisition program baseline
AO	area of operations
AOR	area of responsibility
ATO	air tasking order
BSMN	bursty-signal mesh network
C2	command and control
CAS	close air support
CBS	cypher block system
CENETIX	Center for Network Innovation and Experimentation, Naval Postgraduate School
CLD	combat logistics detachment
COC	company operations center
COMMSTRAT	communication strategy & operations
CSS	chirp spread-spectrum
CubeSat	cube satellite
DIM	daily intention message
DL	distributed lethality
DMO	distributed maritime operations
DOD	Department of Defense
EAB	expeditionary advanced base
EABO	expeditionary advanced base operations
EHF	extremely high frequency
ELF	extremely low frequency
EM	electromagnetic
ESG	expeditionary strike group
EW	electronic warfare

FARP	forward arming and refueling point
FDC	fire direction center
FEX	field exercise
FM	frequency modulation
FSK	frequency shift keying
FRAGO	fragmentary order
FSO	free space optics
GSP	ground sensor platoon
HF	high frequency
HIMARS	High Mobility Artillery Rocket System (M124)
IPB	information preparation of the battlespace
ISR	intelligence, surveillance, and reconnaissance
LAN	local area network
LEO	low-earth-orbit
LCT	littoral combat team
LLB	littoral logistics battalion
LNO	liaison officer
LOCE	littoral operations in a contested environment
LoRa	long range
LoRaWAN	long range wide area network
LOS	line-of-sight
LPD	low probability of detection
LPI	low probability of interception
MAGTF	Marine air ground task force
MANET	mobile ad-hoc network
MARDIV	Marine division
MAW	Marine air wing
MCCLL	Marine Corps Center for Lessons Learned
MCDP	Marine Corps doctrinal publication
MCRP	Marine Corps reference publication
MCWP	Marine Corps warfighting publication
MEF	Marine expeditionary force

MEFEX	MEF exercise
MIG	MEF information group
MLG	Marine logistics group
MLR	Marine littoral regiment
MSTP	MAGTF Staff Training Program
MUOS	Mobile User Objective System
NDS	national defense strategy
NMS	national military strategy
NSS	national security strategy
NTA	northern training area (Okinawa Japan)
ODA	Operational Detachment Alpha
OPORD	operation order
PB-19	Exercise Pacific Blitz 2019
PIR	priority information request
Recon	reconnaissance
RF	radio frequency
RFI	request for information
ROC	reconnaissance operations center
RTW	road-to-war brief
SATCOM	satellite communications
SF	spread factor
SFG	special forces group
SINCGARS	Single Channel Ground and Airborne Radio System
SIGINT	signals intelligence
S/N	signal to noise (ratio)
SVTC	secure video teleconference
SHF	super high frequency
SOF	Special Operations Forces
TAC	tactical
TE	tasking element
T/E	table of equipment
TEAMS	tactical elevated antenna mast system

TSB	transportation support battalion
UAS	unmanned aerial system
UHF	ultra-high frequency
USINDOPACOM	US Indo-Pacific Command
USMC	United States Marine Corps
USN	United States Navy
VHF	very high frequency
VMM	Marine medium tiltrotor squadron
WEZ	weapon engagement zone

EXECUTIVE SUMMARY

Since World War II, the United States' capability to project military power from the sea with physically massive and exquisitely capable aircraft carriers and amphibious ships has gone largely uncontested (Commander, Naval Surface Forces [COMNAVSURFOR], 2017; Jackson et al., 2020). In recent years, however, the development and proliferation of long-range precision anti-ship missiles, which endanger naval vessels long before they are in range of their objective, has challenged the way United States naval forces operate (Office of the Secretary of Defense [SecDef], 2017, p. 57). In response to the threat of long-range anti-ship missiles, the Department of the Navy has developed a new strategy of Distributed Maritime Operations (DMO), in which widely dispersed naval forces with greater individual lethality achieve sea control, instead of the relatively dense and vulnerable formations of previous naval operating models (COMNAVSURFOR, 2017). *Expeditionary Advanced Base Operations (EABO)* (Headquarters Marine Corps [HQMC], 2021) is the Marine Corps' operating concept which actualizes the principles of DMO by deploying forces in a highly integrated, widely dispersed, and physically and electromagnetically stealthy manner (COMNAVSURFOR, 2017; Office of the Chief of Naval Operations [CNO], 2018; HQMC, 2021).

One of several warfighting functions that require refinement to fully support DMO is command and control (C2): in the *38th Commandant's Planning Guidance*, Marine Corps Commandant, General Berger, explicitly cites the need for flexible and resilient C2 systems that support high tempo and decentralized decision making (Commandant of the Marine Corps [CMC], 2019, p. 9). The researchers' preliminary understanding of emerging bursty-signal mesh network (BSMN) technology was informed by the research of exhibited in Bordetsky, Benson, and Hughes' *Signal Magazine* article, "Hiding Comms in Plain Sight" (2016): this article lends to the hypothesis that BSMN technology could offer the flexibility and resilience desired for DMO C2. *Bursty-signal* is simply defined as the method of transmitting a large amount of data in a relatively short burst of radiation (Cambridge, n.d.), which lends itself to an inherently lower probability of the detection, interception, or interference by adversaries (Walkenhorst, 2020). A *mesh network* is a communication network scheme in which nodes are able to serve as dynamic routers to pass transmissions to other nodes, creating dynamic and flexible networks without any infrastructure beyond the users themselves (Law, 2009). Between these attributes, the researchers hypothesize that BSMN technology is a suitable technological solution to provide flexible and resilient communications for C2 in EABO. Researchers further hypothesize that, given the current commercial use of BSMNs, it is also a financially viable solution for C2 in EABO.

To determine the suitability of BSMN technology for DMO, the researchers first conducted case studies of Marine Corps exercises modeled after EABO. These case studies sought to characterize both the quantitative and qualitative aspects of C2 in EABO exercises to determine what manner of communication BSMN would have to support to be a suitable technological solution. The researchers studied three separate cases, spanning over two years, and involving several Marine Corps units across I and III Marine Expeditionary Forces (MEFs), as well as U.S. 3d Fleet, and Army Special Operating Forces (SOF), and ranging from the battalion to the MEF-level (3d Marine Division [3dMARDIV], 2019; 9th Communications Battalion [9th Comm], 2019; 1st Battalion, 6th Marine Regiment [1/6], 2020).

While the case material was sufficient for a preliminary BSMN suitability analysis, the researchers strongly recommend further study with more comprehensive and precise source material, particularly relating to the technical aspects of C2 in EABO. In summary, the key conceptual and technical lessons derived from these case studies are as follows:

Organizational observations and recommendations

- Additional guidance for the integration of the naval force (i.e., Navy, Marine, and Coast Guard) is needed. Given the stated desire for tight naval integration down to the EAB level (CMC, 2019; HQMC, 2021), BSMN will have to be designed with the interoperability of a variety of naval platforms in mind to be a suitable technological C2 solution.

- Authorities for activities, like intelligence and fires, are best vested at the lowest level feasible (e.g., at the Littoral Combat Team [LCT] level for the launch of HIMARS in a sea-denial role) (HQMC, 2021).

- Communications systems take on two distinct characteristics depending on the echelon of command in question: units at and below the Marine Littoral Regiment (MLR) level require communications systems that prioritize a lower probability of detection and interception, higher scalability, lower power consumption, and channels plentiful enough to support the required doctrinal networks (1/6, 2020; HQMC, 2021). At and above the division level, communications systems should prioritize throughput (i.e., data rate capacity) and bandwidth (3dMARDIV, 2019; 9th Comm, 2019) to support data-rich communications, like video-teleconferencing.

Institutional observations and recommendations

- Across the Marine Corps, tactical-level commanders must be chosen, trained, and empowered to take tactical actions that will have strategic impacts (HQMC, 1997, 2021; CMC, 2019).

- The naval force must renew its emphasis on mission command to allow EABO forces to act with initiative and expedience, particularly in the absence of continuous or data-rich communications (HQMC, 2018; 3dMARDIV, 2019; 9th Comm, 2019; HQMC, 2021).

- Considering the importance of mission command to EABO operations (HQMC, 2018, 2021), the researchers and this study's advisor recognize that operational EABO communications are likely to occur in hourly, daily, or even weekly bursts, coined as the *bursty rhythm of C2*. The researchers assert that the operational tempo of EABO units will correlate to the regularity of C2 bursts: thus, increasing the rhythm of bursty C2 will increase unit tempo. The researchers stress that the quality of information in these bursts must also be high and should adhere to the principles of mission command.

  - Given the high degree of integration of different naval forces in EABO, emphasis on providing liaisons vertically and horizontally in the force structure have shown to be highly beneficial and should be given emphasis as a means of improving unit-intrinsic communication (3dMARDIV, 2019).

- The following technical observations concern measurable aspects of communications in the cases studied. Members of Marine Corps fleet forces assert that EABO communications belong in two distinct categories separated by, what they coined as, the “digital divide” (3dMARDIV, 2019, p. 2): the *digital divide* lies between the regimental and division level: communications above the divide (above the MLR) require high bandwidth and throughput to support data-rich communication applications; communications below the MLR level, in contrast, prioritize power savings, flexibility and scalability, and stealth. The researchers recommend further study with more detailed source material to verify these technical observations (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020).
  - The maximum transmission ranges below the digital divide were measured between 30 and 90 miles (50 to 150 km), while transmissions above the digital divide were measured at 90 miles (150 km) (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020).
  - Units below the digital divide operated under constraints of 60 MHz of bandwidth and data rates of 9.6 kbps. Units above the digital divide used systems with data rates upwards of 3 Mbps to 1 Gbps (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020).
  - Units above the digital divide were relatively unconstrained by power requirements due to access to infrastructural power capabilities (grid and industrial generator power). Units below the digital divide were

  constrained to 50 W for vehicle mounted communication systems, and around 20 W for man-portable communication systems (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020; L3Harris Technologies 2019).

  - Units operating below the digital divide are constrained in antenna size due to their expeditionary nature: typical antennas for vehicle mounted and man-portable communication systems are under 35 ft (11 meters) long. Units above the digital divide commonly use antenna that are 113 ft (35 meters) tall (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020; Headquarters Army, 1991; Contact Corporation, n.d.).
  - While the number of nodes (i.e., the points in a communication network from/through/to which data flows) was difficult to estimate, units below the digital divide ranged from 40 to 120 nodes, and those above the digital divide were estimated to be as many as 1,500 (3dMARDIV, 2019; 9th Comm, 2019; 1/6, 2020).

With the conceptual and technical characteristics of BSMN thus identified, the researchers then conducted a technical study of BSMN technology through conceptual technical modeling (i.e., the conceptual simulation of a system bound by technical parameters) (Tatomir et al., 2018). These models sought to compare the operational characteristics of two different BSMN modulation schemes (Chirp-signal Spread Spectrum (CSS) and Long Range (LoRa).) against EABO requirements. The modeling of BSMN in this study yielded the following essential characteristics (listed by CSS and LoRa, respectively): a maximum range of 150 km and 125 km; a power requirement of 0.5 W and 0.158 W; and a directional antenna diameter of 0.5 m (~20”).

With these figures modeled, the researchers conclude that these BSMN methods are suitable for supporting C2 below the digital divide in EABO operations; further, adding power could also render BSMN suitable for C2 above the digital divide, though researchers recommend caution, as adding power decreases the LPI/LPD qualities of BSMN, as well as sacrificing the logistical advantages of low power consumption.

Finally, given these findings on the potential suitability of BSMN for EABO, the question of the viability (i.e., the realistic potential for developing, acquiring, and employing the technology) was answered through a financial analysis in which a forecasting model was developed to estimate to total program life cycle cost of acquiring, developing, deploying, and maintaining the software and hardware required to establish a space-based terminals to include in a BSMN topology. After analysis, this study demonstrated the total cost of a BSMN space-based constellation at LEO would be less than 1% of the entire WGS program budget and less than the average yearly funding allocation for the WGS program. As such the researchers are that it is financial viability to fund such a program.

In conclusion, researchers fail to reject the hypothesis: BSMN is a suitable and viable technological solution for supporting C2 in Distributed Lethality operations in support of EABO below the digital divide (150 km). However, further testing and research should be conducted to conduct field testing and support the theoretical conclusions of this study. Lastly, based on total cost estimation and financial forecasting analysis, it is reasonably feasible for the DOD to develop, deploy, and maintain the software and hardware required to establish a space-based terminals to include in a BSMN topology as it is less than one percent of the acquisition program baseline for the established Wideband Global Satellite system.

References

1st Battalion, 6th Marine Regiment. (2020, July 7). *1st Battalion, 6th Marines expeditionary advanced based operations exercise after action report (AAR)*. Department of the Navy. Forward Deployed Battalion-East, 3d Marine Division. https://eis.usmc.mil/sites/mccll/LLDocuments/1-6_EABO_FEX20_AAR.pdf#search=northern%20apache

3d Marine Division. (2019). *After action report for III Marine Expeditionary Force Exercise (MEFEX), 29 April 2019 through 10 May 2019*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/3d%20MARDIV%20MEFEX-19%20AAR%20190603-FILEID-43626.pdf#search=MEFEX%2D19

9th Communications Battalion. (2019). *Pacific Blitz 19: I MEF flat enterprise domain*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/9th%20Comm%20Pacific%20Blitz%20%20Final%20Report-I%20MEF%20Flat%20Domain%20190802-FILEID-43723.pdf#search=Pacific%20Blitz%2019

Bordetsky, A., Benson, S., & Hughes, W. (2016, June 1). Hiding comms in plain sight. *Signal*. https://www.afcea.org/content/?q=Article-hiding-comms-plain-sight

Cambridge University Press. (n.d.). Bursty. In *Cambridge dictionary*. https://dictionary.cambridge.org/dictionary/english/bursty

Commandant of the Marine Corps. (2019). *38th Commandant's planning guidance*. Headquarters, Marine Corps. Department of the Navy. https://www.hqmc.marines.mil/Portals/142/Docs/ 38th Commandant's Planning Guidance_2019.pdf?ver=2019-07-16-200152-700

Commander, Naval Surface Forces. (2017). *Surface force strategy: return to sea control.* Department of the Navy. https://media.defense.gov/2020/May/18/2002302052/-1/-1/1/SURFACEFORCESTRATEGY-RETURNTOSEACONTROL.PDF

Contact Corporation. (n.d.). *USMC TEAMS; tactical elevated antenna mast system* [Fact sheet/brochure]. https://contactcorp.net/images/teams%20brochure.pdf

Headquarters, Army. (1991). *Technical manual for antenna group OE-254* (TM 11-5985-357-13) [Technical manual]. Department of the Army. http://www.radiomanual.info/schemi/Surplus_Accessories/OE-254_antenna_serv_user_TM11-5985-357-13_1991.pdf

Headquarters, Marine Corps. (1997, August 1). *Campaigning* (MCDP 1-2). Department of the Navy. https://www.marines.mil/Portals/1/Publications/MCDP%201-2%20Campaigning.pdf

Headquarters, Marine Corps. (2018). *Command and control* (MCDP-6). Department of the Navy. https://www.marines.mil/Portals/1/Publications/MCDP%206.pdf?ver=2019-07-18-093633-990

Headquarters, Marine Corps. (2021, February). *Tentative manual for expeditionary advanced base operations*. Department of the Navy. https://intelshare.intelink.gov/sites/mcwl/TMEABOAssessment/Current%20Manual/TM%20EABO%20-%20First%20Edition%20Rev%2020210211.pdf

Jackson, K., Scobell, A., Webber, S., & Ma, L. (2020). *Command and control in U.S. naval competition with China*. RAND. https://www.rand.org/pubs/research_reports/RRA127-1.html

L3Harris Technologies. (2019). *L3Harris Falcon III AN/PRC-117G(V)1(C)* [Fact sheet]. Melbourne, FL. https://www.l3harris.com/sites/default/files/2020-07/cs_tc_datasheet_an-prc-117g-multiband-networking-manpack-radio.pdf

Law, K. (2009). Chapter 10: Transport protocols for wireless mesh networks (pp. 255–276). In S. Misra, S. C. Misra, I. Woungang (Eds.), *Guide to wireless mesh networks* (1st ed.). Springer.

Office of the Chief of Naval Operations. (2018, December). *A design for maintaining maritime superiority* (ver 2). Department of the Navy. https://media.defense.gov/2020/Jul/23/2002463490/-1/-1/1/A%20DESIGN%20FOR%20MAINTAINING%20MARITIME%20SUPERIORITY_2.0.PDF

Office of the Secretary of Defense. (2017). *Annual report to Congress: Military and security developments involving the People's Republic of China 2017*. Department of Defense. https://media.defense.gov/2020/Sep/01/2002488689/-1/-1/1/2020-DOD-CHINA-MILITARY-POWER-REPORT-FINAL.PDF

Tatomir, A., McDermott, C., Bensabat, J., Class, H., Edlmann, K., Taherdangkoo, R., & Sauter, M. (2018). Conceptual model development using a generic Features, Events, and Processes (FEP) database for assessing the potential impact of hydraulic fracturing on groundwater aquifers. *Advances in Geosciences*. https://adgeo.copernicus.org/articles/45/185/2018/

Walkenhorst, B. (2020, September 24). The impact of LPI/LPD waveforms and anti-jam capabilities on military communications. *The Modern Battlespace*. https://modernbattlespace.com/2020/09/24/impact-lpi-lpd-waveforms-anti-jam-capabilities-military-communications/#.YHJ1sqySmUn

ACKNOWLEDGMENTS

Maj Dave Costanzo would like to thank Dr. Alex Bordetsky for his patience, and guidance throughout this research. His leadership and mentorship made this project truly enjoyable, and his efforts are greatly appreciated. Maj Costanzo would also like the thank Mr. Glenn Cook and Mr. Steve Iatrou for their support and guidance throughout this thesis and especially in the classroom. Maj Costanzo would like to thank his thesis partner, Major Tucker, for his patience and efforts throughout this project as he was a driving force for our group and our thesis. Lastly, Maj Costanzo would like to thank his wife, Attea, and their children, Kim, Michael, and Gianna, for making the last two years enjoyable while understanding that Daddy always had work to do. Thank you for your love, support, and understanding through this process. We could not have done it without you.

Maj Mike Tucker would like to thank Dr. Alex Bordetsky for his guidance throughout this research, and his passion for the subject matter: particularly given Dr. Bordetsky's myriad of responsibilities, his time and expertise were indispensable and greatly appreciated. Maj Tucker would also like the thank Mr. Steve Iatrou and Mr. Glenn Cook, not only for their guidance and flexibility throughout this research, but also for their instruction outside of this research, which added significantly to Maj Tucker's understanding of command and control. Maj Tucker thanks Maj Dave Costanzo for his hard work on this thesis during the strange times of its writing, and for originating the idea of teaming up to complete this work. Finally, Maj Tucker is grateful to his family, Sharon, Eli, and Abby, for putting up with him while he hid away for so long; he looks forward to making it up to them in the near future.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. PROBLEM STATEMENT

Navy and Marine Corps leadership have identified Littoral Operations in a Contested Environment (LOCE) through Expeditionary Advanced Base Operations (EABO) as the future naval operating model (Commander, Naval Surface Forces [COMNAVSURFOR], 2017; Headquarters, Marine Corps [HQMC], 2021). However, the practices and systems by which a commander understands the enemy and environment and makes known their intent for action (i.e., command and control [C2]) (HQMC, 2018), remains in development for EABO (Commandant of the Marine Corps [CMC], 2019). Furthermore, the C2 systems and practices used in recent operations in the Middle East may not be suitable to support EABO due to the different environment, enemy, and means of operating. Specifically, in the researcher's experience, the C2 systems used in recent operations in the Middle East often required hardened infrastructure to operate (e.g., large, semi-permanent antenna and massive power generating facilities): many of these requirements are unlikely to be available in prolonged deployments to austere environments without creating significant logistical and electromagnetic footprints, both of which are vulnerable to detection and attack by enemy forces (CMC, 2019).

These shortfalls present a risk-to-force and risk-to-mission when conducting Distributed Maritime Operations (DMO) and EABO in contested environments. These risks to EABO can be reduced by increasing the resiliency and decreasing detectability of the force's C2 networks. The researchers sought to evaluate the suitability of bursty-signal mesh networks (BSMN) in achieving resilient and stealthy C2 networks, as well as the financial viability of developing, procuring, and fielding BSMN technology.

B. HYPOTHESIS

In the article *Hiding Comms in Plain Sight* (2016), Bordetsky, Benson, and Hughes offer mesh network communication technology as a suitable communication solution for providing the reliability, agility, and scalability demanded by future maritime operations. Bordetsky et al. further expand on the potential use of littoral combat ships as critical nodes within this hypothetical network, and the capacity of such a communication network to support unmanned systems. Furthermore, the authors describe bursty transmission methods of transmitting signals within the mesh network that decrease the probability of detection and interception by adversaries (Bordetsky et al., 2016). The combined effect of self-healing and evolving networks that transmit signals discretely is to create a communication apparatus that is difficult to detect, disrupt, or interpret: this is the essence of BSMN, and is worth investigating for use in EABO.

With this initial understanding of both the communication problem in EABO, and the advertised benefits of BSMN, the researchers hypothesized that BSMN is a suitable technological solution to provide both the resilience and stealth required for C2 in EABO. Furthermore, and given the current commercial use of BSMN technology, the researchers hypothesize that BSMN is financially viable to develop and field BSMNs.

C. LITERATURE REVIEW

1. Literature Introduction

The researchers regarded the stated problem as being composed of three primary elements. First, the research question concerns a specific expression, or form, of military operations (i.e., EABO) which must be thoroughly understood. This area of research and the literature that informs it is listed below as National Security Guidance. Second, the research question concerns the essential nature of C2, the literature concerning which is listed as Command-and-Control literature. Finally, within the context of these two subjects, the research question addresses a specific technology to support C2 in the specific military operation, the literature concerning which is listed as Bursty-Signal Mesh Network literature.

2. National Security Guidance Literature

The United States' uncontested military dominance over the last three decades is disappearing at an alarming rate. The unfettered, worldwide access for U.S. forces, its allies, and commercial industry is vulnerable to emerging global threats. Global powers are increasingly applying their own instruments of power (diplomatic, information, military, and economic) to increase their regional and international influence. "It has been decades since we last competed for sea control, sea lines of communication, access to world markets, and diplomatic partnerships" (Chief of Naval Operations [CNO], 2018). In response, the United States has published clear guidance and direction to combat these threats and ensure the United States will maintain global superiority.

a. National Security Strategy 2017

The 2017 National Security Strategy (NSS) identified, acknowledged, and addressed the threats to, "United States in pursuit of shared interests, values, and aspirations" (White House, 2017, p. 1), and has stated that the "United States will respond to the growing political, economic, and military competitions we face around the world" (White House, 2017, p. 2). It acknowledges that the United States' significant competitive advantages are shrinking as rival states modernize and build up their governments, economic institutions, and conventional militaries. Technological advances and access to global markets have empowered state actors to influence both regional and international arenas. Competitors are specifically challenging the western culture and economic structures to gain leverage for their own gain and prosperity. "Rival actors use propaganda and other means to try to discredit democracy. They advance anti-Western views and spread false information to create divisions among ourselves, our allies, and our partners" (White House, 2017, p. 3).

The NSS also addressed how critical collection, analysis, and access to data will be to leveraging power and influence at an international level. "The contest over information accelerates these political, economic, and military competitions" (White House, 2017).

b. National Defense Strategy 2018

The 2018 National Defense Strategy (NDS) echoes the key themes of the NSS, however, it directly applies the threats and responses from a military perspective and aligns its strategies to nest with those from the NSS. Specifically, it highlights the military's hostile operating environment. "Today, every domain is contested—air, land, sea, space, and cyberspace" (Secretary of Defense [SecDef], 2018, p. 3). Former Secretary of Defense Jim Mattis stated, "In a security environment where the homeland is no longer a sanctuary and every operating domain is contested, competitors and adversaries will continue to operate across geographic regions and span multiple domains to offset or erode Joint Force advantages" (Joint Chiefs of Staff [JCS], 2018, p. 2).

c. *Design for Maintaining Maritime Superiority, Version 2.0, 2018*

The Department of the Navy further aggregated all the strategic concepts and goals from the NSS, NDS, and National Military Strategy (NMS) to develop tangible capabilities to enable a secure and versatile tactical network to support Joint and Naval operations in contested environments. The Chief of Naval Operations stated in 2018 that it will "aggressively compete, harnessing three forces that continue to shape our modern security environment:

i. The increasing use of the maritime domain—the oceans, seas, waterways, and seafloor.

ii. The rise of global information systems, especially the role of data in decision making.

iii. The increasing rate of technological creation and adoption. We will adapt to this reality and respond with urgency." (CNO, 2018, p. 3)

In pursuit of these three broad objectives, the Chief of Naval Operations directed the naval force to concentrate on developing and employing forces according to the Distributed Maritime Operations (DMO) model, which enhances resiliency in contested environments (CNO, 2018). "This architecture will provide accurate, timely, and analyzed information to units, warfighting groups, and fleets" (CNO, 2018, p. 10). The operational architecture will include scalability to support Joint and coalition forces. "It will include a development environment to rapidly generate enhancements and support its continued evolution" (CNO, 2018, p. 10).

d. *DOD Report to Congress: Military and Security Developments Involving the PRC*

The annual DOD reports to congress (the latest published as of 2020) regarding the *Military and Security Development Involving the People's Republic of China* is a comprehensive description of China's strategic posture, capabilities, and intentions. The report describes the situation in the Pacific which prompts the Distributed Lethality (DL) strategy and summarizes tactical/technical data useful for defining C2 requirements for BSMN (e.g., data concerning China's missile threat ranges and capabilities).

e. United States Marine Corps' Commandant's Planning Guidance 2019

In the *38th Commandant of the Marine Corps' Commandant's Planning Guidance 2019*, C2 is described as a critical function which is challenged by peer threats in future Pacific conflicts. The passage of information through C2 and information operations remains imperative, but with a caveat that signature management and reduction is also a priority for C2 systems (CMC, 2019). This document and its outlined priorities for research are a primary motivation for the conduct of this study.

f. Marine Corps Force Design 2030

Realigning force design and the composition of the Marine Corps relative to the potential peer-level conflict in the Pacific is identified in the 38th Commandant's Planning Guidance (2019) as a top priority. The Marine Corps Force Design 2030 outlines concepts in support of Distributed Lethality (DL) and/or DMO, including the Marine Littoral Regiment (MLR) force design (CMC, 2020).

3. Command-and-Control Literature

Literature addressing the concepts and techniques for command and control can be broken down into three essential categories in the context of this research. The first category, hereafter called C2 theory, contains literature that broadly describes the process of communicating with application beyond a strictly military context. The second category is military C2 literature, which is written by military entities, and specifically applies to a military context. The third and final category is EABO C2 literature, which is not only of a military nature, but also applies specifically to the context of the EABO.

a. Command and Control Theory

In 1949, Weaver published *Recent Contributions to Mathematical Theory of Communication,* with contributions from Shannon. In this work, Weaver described a theory that broke down communication into three distinct levels, applicable to all kinds of communicative interactions, whether it be verbal exchanges, technical/digital communication, or even artistic and musical expressions (Weaver, 1949). Briefly, these three levels are the technical, semantic, and effectiveness aspects of a communication system. This research will address *Level A* (the technical aspect of communication) of Weaver's theory. The case studies in this thesis used to derive the elements of effective communication in contested littoral environments will use Weaver's theory and terminology to draw distinctions in observed C2 aspects of the cases studied.

b. Military C2 Literature

Military C2 literature draws from both civilian studies of C2 and from doctrinal publications directing the planning and execution of C2 in military operations. With regard to civilian studies of C2 in a military context, the RAND Institute's 1999 study, *Command Concepts: A Theory Derived from the Practice of Command and Control* (Builder et al., 1999) provides a theory of command and control which suggests ten distinct metrics for measuring the success of command and control in military operations. This study bases these metrics on the case studies of several major military operations. This study could benefit from not only an analysis of contemporary case studies (particularly with relevance to EABO), but also to informing the authors as to how to structure their own case studies.

The primary foundational documents concerning C2 in terms of common naval/military understanding is the doctrinal publications for the Marine Corps, *Marine Corps Doctrinal Publication (MCDP) 6: Command and Control* (HQMC, 2018). This publication provides the language and conceptual framework with which to define the command-and-control constructs being compared.

c. EABO Command and Control Literature

The most recent and substantial literature concerning EABO, the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021) emerged during the course of this study. The stated primary purpose of the *Tentative Manual for Expeditionary Advanced Base Operations* is to provide context and direction for the future experimentation and development of EABO concepts. This document includes information concerning, among other topics, force structures, mission, and fundamental definitions and considerations for EABO that proved useful for this study.

d. *EABO Case Study Literature*

The conceptual and technical characterization of C2 in EABO was derived from unclassified After-Action Reports (AARs) from the AAR repository at the Marine Corps Center for Lessons Learned (MCCLL) website. The three exercises examined in these case studies were: 1st Battalion, 6th Marine Regiment's Exercise Northern Apache (1st Battalion, 6th Marines [1/6], 2020), the account of which comes from a single, but relatively comprehensive, AAR; III Marine Expeditionary Force's Marine Expeditionary Force Exercise, 2019 (MEFEX-19), which was informed by AARs from two participating units (3d Marine Division [3dMARDIV], 2019; and I Marine Expeditionary Force's Exercise Pacific Blitz, which draws from two subordinate unit AARs (3dMARDIV, 2019; Marine Air Squadron 6 [MASS-6], 2019).

The use of AARs as the sole source of case study documentation in this study is suboptimal for the purpose of understanding C2 completely. Originally, the researchers sought to build case studies from comprehensive documentation of exercises resembling EABO: documents would have included complete operation orders to build an understanding of the commander's vision of the enemy and environment, their intent to act, and particular aspects of timeframe, tasks to accomplish, contingencies, and other insights examined in *Command Concepts* (Builder et al., 1999). Researchers also sought to conduct focused interviews with leaders experienced in the exercises in question. Due to a lack of interest, however, these interviews were not accomplished.

4. Current DOD Electromagnetic Capabilities

The proliferation of communication infrastructure and technologies over the last three decades have created an environment in which strategic leaders and military commanders have reasonable expectations to maintain a robust, consistent, and reliable communication network capability. Commanders have become accustomed to on-demand access to both wired and wireless communication technologies to transmit and receive messages throughout the chain of command using much of the electromagnetic spectrum

(Hoehn et al., 2021). DOD wireless communications use specific radio frequencies and are constrained by range, bandwidth, and power requirements and limitations. "The DOD supports strategic communication by maintaining a robust network of terrestrial and satellite communications, spanning the electromagnetic spectrum from [extremely low frequency] to [extremely high frequency], that supports survivable command and control, worldwide, of U.S. military forces" (Stine & Portigal, 2004). However, much of the DOD's strategic radio communication is conducted on military and commercial satellite services (Stine & Portigal, 2004). Additionally, the DOD employs radio communications for command and control and passage of information amongst its tactical units to support their warfighting functions (Stine & Portigal, 2004). However, the land-based (tactical) waveforms generally reside in the radio segment of the electromagnetic spectrum and are limited to a designated frequency range of 3 megahertz (MHz) to 2 gigahertz (GHz) and space-based wave forms (strategic) generally range from 3 to 30 GHz (Stine & Portigal, 2004). Each segment of the electromagnetic spectrum maintains relative advantages and disadvantages regarding maximum transmission range, bandwidth and data rate capacity, power requirements, antenna dimension requirements, and node service capacity. These requirements are critical to the evaluation of the suitability and feasibility during employment to support DMO in EABO.

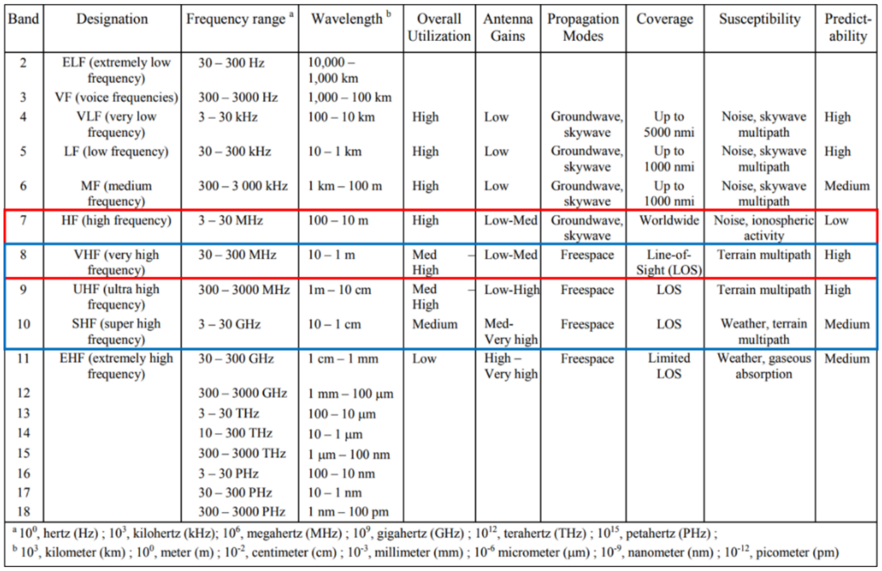
a. DOD Waveforms and Frequency Bands

The DOD employs many different waveforms which range the electromagnetic spectrum to support strategic, operational, and tactical operations. Each waveform maintains unique characteristics which provide critical capabilities to its users; however, each waveform is also subject to limitations which may not be suitable or feasible for every environment. Per the 2020 DOD Communication Waveform Inventory, there are 65 unique waveforms employed by the DOD. Despite the robust number of waveforms, each one falls within a particular frequency band on the electromagnetic spectrum. Table 1 provides a summary of characteristics of each frequency band employed by the DOD. As displayed, the majority of the ground-based or terrestrial communication waveforms reside between the 3 MHz to 2 GHz frequency range, while satellite and space-based waveforms reside between 2–75 GHz range. As discussed, performance is based on the characteristics of waveforms produced at each frequency band and relative to requirements and capabilities needed to support operations. According to the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021), planners supporting EABO and operating in contested environments must meet specific requirements to ensure they employ and execute an effective, resilient, and scalable communication network.

The red box in Table 1 indicates the communication bands typically in use by tactical-level units (under the regimental level, to be defined which is a term described in detail later in this study). In the researchers' experience, tactical-level units are limited to primarily high frequency (HF) and very-high frequency (VHF) assets due to scarcity of ultra-high frequency (UHF) and super-high frequency (SHF) SATCOM (1/6, 2020). These SATCOM assets are necessary for extending communications beyond the line of sight: currently, tactical units need more plentiful, long range communication assets, while satellite communications remain limited.

The blue box in Table 1 indicates the communication bands typically utilized by higher and strategic-level assets above the digital divide: high throughput communications suites, strategic UAS, and other strategic assets are most often used by higher level entities where UHF and SHF SATCOM resources are more available.

Table 1. Frequency Bands Characteristics Employed by DOD. Adapted from Stine and Portigal (2004).



Band	Designation	Frequency range [a]	Wavelength [b]	Overall Utilization	Antenna Gains	Propagation Modes	Coverage	Susceptibility	Predict-ability
2	ELF (extremely low frequency)	30 – 300 Hz	10,000 – 1,000 km						
3	VF (voice frequencies)	300 – 3000 Hz	1,000 – 100 km						
4	VLF (very low frequency)	3 – 30 kHz	100 – 10 km	High	Low	Groundwave, skywave	Up to 5000 nmi	Noise, skywave multipath	High
5	LF (low frequency)	30 – 300 kHz	10 – 1 km	High	Low	Groundwave, skywave	Up to 1000 nmi	Noise, skywave multipath	High
6	MF (medium frequency)	300 – 3 000 kHz	1 km – 100 m	High	Low	Groundwave, skywave	Up to 1000 nmi	Noise, skywave multipath	Medium
7	HF (high frequency)	3 – 30 MHz	100 – 10 m	High	Low-Med	Groundwave, skywave	Worldwide	Noise, ionospheric activity	Low
8	VHF (very high frequency)	30 – 300 MHz	10 – 1 m	Med – High	Low-Med	Freespace	Line-of-Sight (LOS)	Terrain multipath	High
9	UHF (ultra high frequency)	300 – 3000 MHz	1m – 10 cm	Med – High	Low-High	Freespace	LOS	Terrain multipath	High
10	SHF (super high frequency)	3 – 30 GHz	10 – 1 cm	Medium	Med-Very high	Freespace	LOS	Weather, terrain multipath	Medium
11	EHF (extremely high frequency)	30 – 300 GHz	1 cm – 1 mm	Low	High – Very high	Freespace	Limited LOS	Weather, gaseous absorption	Medium
12		300 – 3000 GHz	1 mm – 100 µm						
13		3 – 30 THz	100 – 10 µm						
14		10 – 300 THz	10 – 1 µm						
15		300 – 3000 THz	1 µm – 100 nm						
16		3 – 30 PHz	100 – 10 nm						
17		30 – 300 PHz	10 – 1 nm						
18		300 – 3000 PHz	1 nm – 100 pm						

[a] 10^0, hertz (Hz) ; 10^3, kilohertz (kHz); 10^6, megahertz (MHz) ; 10^9, gigahertz (GHz) ; 10^{12}, terahertz (THz) ; 10^{15}, petahertz (PHz) ;

[b] 10^3, kilometer (km) ; 10^0, meter (m) ; 10^{-2}, centimeter (cm) ; 10^{-3}, millimeter (mm) ; 10^{-6} micrometer (µm) ; 10^{-9}, nanometer (nm) ; 10^{-12}, picometer (pm)

(1) Ground Based Wave Forms

Single Channel Ground and Airborne Radio System (SINCGARS) operate between 30 MHz to 87.975 MHz and remains in extensive use throughout tactical North Atlantic Treaty Organization organizations (Withington, 2017).

Very High Frequency Line-of-Sight (VHF LOS), primarily supports LOS communications between operating units at ranges over 15–20 km over flat, open terrain (Pike & Sherman, 1999).

Ultra High Frequency Line-of-Sight (UHF LOS) is employed by tactical units to transmit and receive information (both voice and data) in the UHF range (300 MHz - 3 GHz) and "is capable of operating in either the UHF LOS or UHF Satellite Communications (UHF SATCOM) mode" (Pike & Sherman, 1999). UHF LOS is frequently used by airborne assets, as they generally operate at altitudes which negate LOS obstacles. The effective range of UHF LOS is generally 45–50 km over flat, open terrain.

(2) Satellite/Space Based Waveforms

Ultra-High Frequency Satellite Communications (UHF SATCOM) systems provides SATCOM communication links between mobile and land-based terminals. "The UHF SATCOM system also provides multichannel satellite transmission and reception, and is comprised of two distinct, but related, subsystems: UHF SATCOM receiving set, and UHF SATCOM transceivers and UHF Demand Assigned Multiple Access (DAMA) equipment" (Pike & Sherman, 1999). These terminals provide strategic access and critical distribution and reporting channels to support C2 of operations. These communication channels support a significant increase in range and bandwidth capabilities, as well as higher data capacity and faster transmissions. However, these benefits lead to increased demand beyond available resources. UHF SATCOM capabilities can be distributed to the tactical level to support strategic objectives; however, these cases are rare.

The Extremely High Frequency Satellite Communications (EHF SATCOM) system is one of three SATCOM systems which operates in the EHF range (30-300 GHz) (Pike & Sherman, 1999), and is well suited for general-purpose satellite communications that emphasize jam-resistance, low probability of interception, and secure voice, teleprinter and data communication (Pike & Sherman, 1999). EHF SATCOM similarly offers increased range and bandwidth capabilities but is a scarce resource.

The Super High Frequency Satellite Communications (SHF SATCOM) system operates in the range of 3–30 GHz, SHF range. SHF SATCOM supports satellite communication links between mobile and land terminals. SHF SATCOM systems, using crosslink capabilities create a large, mobile networks which can provide significant bandwidth capacity, and can be used as communication relays as well as telemetry, tracking, and control functions, for users and administrators. This network supports communication and data links for tactical, operational, and strategic operations (Pike & Sherman, 1999). "Shipboard SATCOM configurations vary in size and complexity and dependent upon the message traffic level, types of communications and operational missions of the ship" (Pike & Sherman, 1999). Additionally, SHF SATCOM communication is resistant to jamming and direction finding, which is significant for process operating within adversaries' engagement zones (Pike & Sherman, 1999).

b. EABO Communication Network Requirements

As part of a strategic vision to counter adversaries' anti-access area denial (A2AD) capabilities, the DOD is focused on developing "a networked security architecture capable of deterring aggression, assuring, and enhancing allies and partners, maintaining stability, and ensuring free access to common domains" (HQMC, 2021, p. 1-2). The evolving capabilities of adversaries in the Pacific arena challenge DOD operations in littoral regions. To support this endeavor, the DOD must employ a resilient, effective, and efficient communication network which has a low probability of detection and interception. "[Current] A2AD systems credibly threaten vessels in close and confined seas relatively near to adversary territory" (HQMC, 2021, p. 1-3). Thus, employing contemporary forces and capabilities based on the conventional C2 topologies and assumptions of uncontested naval, air, and communications superiority are challenged and potentially invalid. "The impending challenge is significant and cannot be met by merely refining current methods and capabilities" (HQMC, 2021, p. 1-2). In other words, EABO will require innovative and novel approaches to achieving C2, which allow friendly forces to communicate effectively, even within the reach of enemy lethal and nonlethal capabilities. “It is critical that the composition, distribution, and disposition of forces executing EABO limit the adversary’s ability to target them, engage them with fires and other effects, and otherwise influence their activities” (HQMC, 2021, p. 1-4). These critical requirements present significant challenges for the DOD, many of which cannot be addressed using conventional C2 topologies supported by traditional communication networks. The DOD must explore agile, low profile, and resilient C2 constructs and networks to support persistent EABO in contested environments. The researchers focused on identifying detailed requirements and potential C2 topologies, supported by a BSMN, which fulfill specific requirements for successful employment of EABO in contested environments.

(1) Resiliency

Resilient communication networks are critical to DOD’s C2 infrastructure. The ability to employ reliable, effective and efficient communication networks that directly support C2 functions are vital to continuous operations and mission success. A resilient communication network is one that can mitigate and withstand potential disruptions of service. As such the DOD prioritizes EM signature management as a measure of force protection and spectrum management to support operations and reduce risk to force and risk to mission.

RF transmissions emit energy across the electromagnetic spectrum which can be detected, collected, and analyzed by passive signals intelligence (SIGINT) systems. These systems can listen to radio and radar frequencies or observe heat signatures of personnel, missiles, aircraft, artillery, and vehicles (Congressional Research Service [CRS], 2020). The intelligence produced from the SIGINT capabilities are then exploited through the employment of electronic warfare (EW) capabilities. “SIGINT capabilities allow military forces to understand where adversary forces are located as well as what frequencies they use for communications and radars” (CRS, 2020, p. 2). Knowing the location and frequencies of a target, in turn, allows a military force to disrupt the enemy, either in the electromagnetic spectrum, or physically (CRS, 2020). In response, the DOD intends to develop techniques to protect themselves by reducing RF signatures to decrease the probability of detection, commonly referred to as low probability of detection (LPD)/low probability of intercept (LPI). LPI/LPD is desirable for its ability to make U.S. forces and their electromagnetic communications more difficult to disrupt, and as a force protection measure against conventional, kinetic attacks" (CRS, 2020).

Low probability of incapacitation (LPI) and detection (LPD): the principal goal or function of a communication system to minimize the risk of interception and/or detection, respectively, of the communication transmission by anyone other than the intended recipient. LPI and LPD are referred to in this study as a singular concept (i.e., LPI/LPD) (Sklar, 2017).

(2) Range

Range of current communication systems present significant challenges while operating in the India Pacific Command (INDOPACOM) area of responsibility (AOR). As noted, VHF and UHF have published theoretical ranges of 15–20 km and 45–50 km, respectively, over flat terrain. Due to their LOS requirements, VHF and UHF waveforms work over water and flat terrain, however, they are generally ineffective in dense, tropical vegetation and require relays or retransmission nodes to support communications over mountainous terrain, much of which makes the INDOPACOM AOR. These challenges are magnified while operating on island chains over medium to short distances as both VHF and UHF waveforms require users to extend elevated antennas above the canopy, or even employ relay/ retransmission nodes to support communications over vertical terrain to meet the LOS requirements. These additional resources increase potential identification by adversaries due to large physical footprints (i.e., large antenna pole or extra personnel which may not blend into the natural environment. Although VHF and UHF waveforms can be employed in an EABO environments, questions regarding their reliability make it not ideal for DMO in contested environments.

(3) Satellite Communications

Satellite communications (SATCOM) are better suited for DOD operations in the INDOPACOM AOR. Although SATCOM networks are LOS, their mobile antennas maintain a lower profile, and the relay/retransmission node is extra-terrestrial, which is makes it difficult to detect by adversaries. Also, the data capacity of SATCOM network is larger than VHF and some UHF networks, which provides more robust capabilities for the DOD. However, the current demand within the DOD for SATCOM capabilities significantly outpaces the available resources, making it difficult to gain and maintain continuous access to SATCOM networks. Additionally, many SATCOM mobile terminals require a minimum of 5–10-watt power output to establish a reliable SATCOM link. Although relatively small for radio communications, the power requirements can create long term logistical challenges regarding power generation and sustainment while conducting EABO and DMO in the INDOPACOM AOR. To address these challenges, the researchers propose evaluating the potential employment of BSMN to alleviate the pressure and demand for limited SATCOM resources while providing a feasible resilient communication network for tactical units.

c. Potential Bursty-Signal Modulation Solutions

(1) Chirp Spread-Spectrum Modulation

Chirp spread-spectrum (CSS) is a signal modulation technique that encapsulates information through the use of wideband frequency chirp pulses (IEEE, 2007). A chirp, or sweep signal, is a sinusoidal signal whose frequency increases or decreases over time; the rate at which the frequency changes is referred to as the chirp rate (IEEE, 2007). The carrier signals are resistant to detrimental effects, such as channel noise, in-band and out-of-band interferences, multipath fading, and Doppler effects within the mobile radio channel (IEEE, 2007). These characteristics of are critical to resilient, effective, and efficient transmission of data of RF communication networks. CSS uses the entire, predetermined, bandwidth to broadcast a signal, making it robust to channel noise, resistant to multi-path fading even while operating at very low power relying on the linear nature of the chirp pulse. These advantages make CSS suitable for organizations which desire secure communication networks and resistance to noise, jamming, detection prevention, and low power requirements and have potential to serve as modulation techniques which support BSMNs.

(2) Long Range Frequency Modulation

Long Range (LoRa) is a Semtech proprietary frequency modulation scheme and is considered a derivative of CSS which employs orthogonal spreading factors to exchange data rate for, sensitivity (signal-to-noise ratio [S/N]), signal efficiency, range, and power within a fixed channel bandwidth (Semtech, 2013). The physical layer is based on CSS modulation techniques using one or more channels for a given frequency band. LoRa itself is a Layer One implementation, however, when incorporated with the LoRa Wide Area Network (LoRaWAN), it interfaces with additional layers, with the potential and capability of implementation at all protocol layers (Semtech, 2013). This allows LoRa to communicate and operate with existing network architectures. LoRaWAN is the backbone of the CubeSat technology communication network which supports the low-power data transfer from nodes/endpoints via satellite communications to a network gateway. Although LoRa signal modulation requires LoRaWAN gateways for the execution of the mobile networks, this study evaluates the foundational modulation scheme as a potential concept which would support the employment of BSMNs (Semtech, 2013).

5. Literature Summary

Overall, the literature available to the authors was adequate for the narrow and preliminary nature of this study. However, the literature is ultimately inadequate for both developing a thorough understanding of the Navy and Marine Corps’ construct of DMO and EABO and the nature of C2 in these contexts, to the extent that other operating concepts and their C2 constructs are understood. Literature concerning DMO and EABO is limited because the concepts themselves, at the time of the conduct of this research, are still in development. Literature regarding C2 in EABO contexts was limited due both to the relative scarcity of exercises based on developing concepts, and due to a lack of access, as these documents are typically unpublished or classified. Furthermore, literature concerning BSMN was also limited due to the technology being relatively novel. The rectification of this study using more robust literature is included in the recommendations for future research.

D. RESEARCH DESIGN AND METHODOLOGY

1. Research Questions

a. What are the optimal characteristics of the C2 structure for EABO, and how is this structure distinct from that of conventional operations?

b. How does the EABO environment, as it relates to C2, create risks to force and mission?

c. What potential technical capabilities are provided by a bursty-signal mesh network to support C2 infrastructures in EABO environments? Can these capabilities be feasibly applied to support EABO command, control, and communications' frameworks?

d. What potential operational capabilities are provided by employing bursty-signal mesh network to support C2 infrastructures in EABO?

e. What fiscal requirements are associated with supporting current command structure?

f. What fiscal requirements and financial characteristic associated with development, procurement, implementation, and maintenance of a bursty-signal mesh network to support C2 infrastructures in EABO environments?

g. What is the cost-benefit analysis of employing a bursty-signal mesh network to support C2 infrastructures in EABO environments over current structures?

2. Research Design

This research is principally composed of three separate parts. The first part of this research consists of case studies of recent Marine Corps exercises in the EABO context. These case studies examine both the qualitative and quantitative aspects of C2. The researchers will use these case studies to establish conceptual and technical characteristics against which to assess the suitability of BSMN technology.

The second principal part of this research is a quantitative analysis, accomplished through *conceptual technical modeling* (i.e., conceptual modeling composed of technically derived data) (Tatomir et al., 2018). The researchers intend to use this modeling analysis to generate the theoretical quantitative data, including technical capabilities and limitations, which can be compared to the findings of the case studies: this comparison will indicate whether BSMN is theoretically suitable for use in support of C2 in EABO.

The third principal part of this research is an analysis of the financial requirements of acquiring, developing, and deploying one CubeSat with one terrestrial, shore-based transceiver. Costs will initially be calculated based on the development of the software and hardware costs of developing the payload, space allocation on the transport vehicle, and launch requirements. This study will seek to determine the financial viability of developing and employing BSMNs using CubeSat technology in support of EABO.

The final analysis of the research will compare the three principal studies: the requirements of the EABO construct identified in part one will be compared with the capabilities of the technology in question identified in part two; finally, the resulting suitability of the technology in question for future naval operations will be measured against the financial viability of its development and acquisition. The end-state of this research is to test the hypothesis: that bursty-signal mesh network technology is a suitable and viable solution for resilient communications in future naval operations. Figure 1 illustrates the overall design of this thesis.

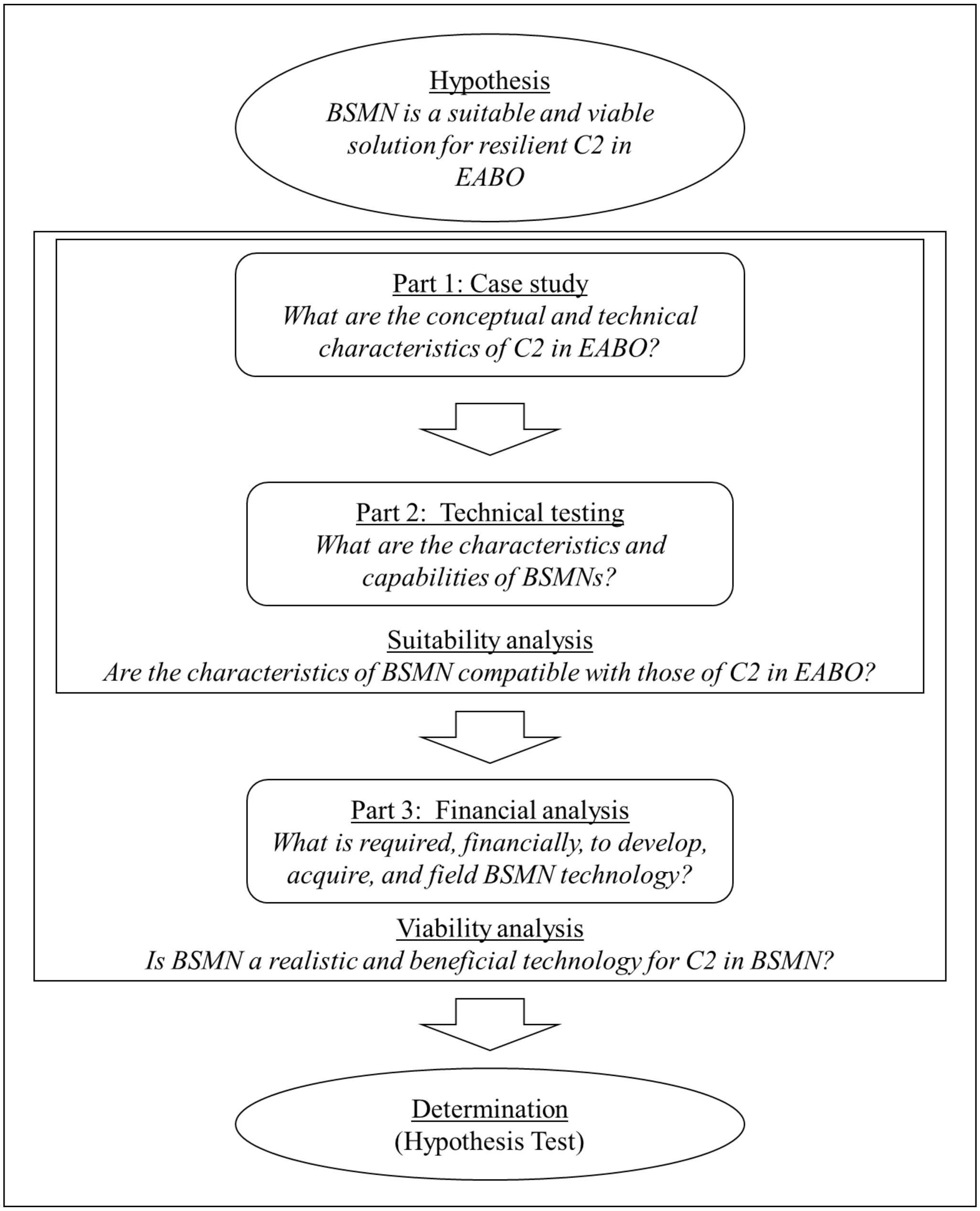


Figure 1. Research Design Illustration

3. Research Methods

This study utilized a convergent parallel mixed method design, in which both qualitative and quantitative data is collected and analyzed separately, and then compared and interpreted (Creswell, 2014). This mixed methods study will ultimately be used to evaluate the suitability of a BSMN in supporting C2 in EABO, and the financial viability of its procurement, development, and fielding to U.S. naval forces.

The qualitative portion of this researchers consisted of case studies of recent Marine Corps exercises, with a focus on analyzing and characterizing the conceptual and technical aspects of C2 in an EABO context. In parallel, the researchers conducted a quantitative analysis BSMN technology through modeling in order to characterize the technical capabilities and limitations of BSMN technology. The results of these qualitative and quantitative analyses were then combined and compared in order to determine the suitability of BSMN technology for use in C2 systems for EABO.

Finally, with the suitability of BSMN for C2 in EABO determined, the researchers conducted a quantitative financial cost-benefit analysis of BSMN in order to evaluate the viability of procuring, developing, and employing BSMN for EABO naval forces.

E. STAKEHOLDER ANALYSIS

1. Stakeholder Identification

The stakeholders of this study were broadly identified as both DOD services and commercial industries. U.S. naval forces engaged in DMO, and U.S. Marine Corps forces engaged in EABO are the primary DOD service stakeholders for this study, though the applications of the hypothesized resilient, low power, and stealthy communications of BSMN have wide DOD application. Commercial industries which can develop and provide BSMN capabilities and services to the DOD are the commercial industry stakeholders.

2. Stakeholder Needs

Both DOD and industry stakeholders require an informed indication that BSMN is, or is not, a worthwhile technology to pursue for use in EABO. Such an indication would help to build a case for, or against, future investments of time and resources for developing the technology in question for use in operations in the Pacific theater.

F. DEFINITIONS

Anti-Access Area Denial (A2AD): the emergent techniques and technologies which seek to deny adversary maritime and littoral freedom of movement through the employment of long range, precision anti-ship missiles (HQMC, 2021).

Bandwidth: the difference between the greatest and lowest (i.e., range) of frequencies in the electromagnetic domain, measured in Hertz, available for use by a communication system, or by that system in a particular task (Cambridge University Press, n.d.).

Bursty-Signal Mesh Network (BSMN):

Bursty-signal: signals in which data is sent in relatively short, sudden timeframes (Cambridge, n.d.).

Mesh network: a variety of mobile ad hoc network (MANET) in which nodes dynamically self-organize grants indiscriminate, high bandwidth access for a high quantity of users (McTasney et al., 2009, pp. 379–380).

Command: the lawful authority afforded to a military commander to direct the actions of subordinates according to the commander's rank and assignment (JCS, 2021).

Command concept theory: first postulated in *Command Concepts* (Builder et al., 1999), and adopted by the researcher's for the purpose of this study, command concept theory postulates that optimal command and control is characterized by three essential qualities: first, optimal command and control provides information necessary for a commander to build a clear pre-conceived vision of the environment, the enemy, and their desired course of action in accomplishing a given mission; optimal command and control enables a commander to monitor and realize their vision in execution, and if their vision is incongruent with reality, to find and correct the faults in their vision; and finally, optimal command and control systems sufficiently and exclusively transmit information relevant to build, convey, or alter the commander's vision (Builder et al., 1999).

Command and control (C2): the process by which a commander is made to understand a particular environment and enemy situation and directs subordinates to act to achieve the commander's intent in accomplishing their mission (JCS, 2021; Builder et al., 1999).

Command and control system: the sum of all people, physical objects, and intangible processes and procedures by which command and control is achieved (JCS, 2021).

Digital divide: the recommended conceptual delineation in command and control, below which units bear a reduced burden to develop and transmit data rich messages and signals (3dMARDIV, 2019).

Distributed Lethality (DL): the U.S. Navy's organizational and operational principle of improving the individual lethality of all warships, distributing offensive capabilities over wider physical areas, and improving multi-domain force protection for naval forces. (COMNAVSURFOR, 2017)

Distributed Maritime Operations (DMO): the emerging naval operating concept being developed in the continuum of the Distributed Lethality principle (CNO, 2018; Eyer & McJessy, 2019).

Expeditionary Advanced Base Operations (EABO): "the employment of mobile, low-signature, persistent, and relatively easy to maintain and sustain naval expeditionary forces from a series of austere, temporary locations ashore or inshore within a contested or potentially contested maritime area in order to conduct sea denial, support sea control, or enable fleet sustainment" (HQMC, 2021, pp. 1–3)

Information Preparation of the Battlespace (IPB): the analysis of the environment, enemy, time, and terrain in which military operations are anticipated. IPB methodology assists in defining the operational environment, describing the battlefield's effect on friendly and enemy forces, evaluating the enemy threat, and determining potential enemy courses of action (HQMC, 2021).

Link Budget Equation: the equation used to estimate the quantitative factors that govern electromagnetic communication, i.e., $\frac{E_b}{N_0} = P_t G_t \left(\frac{1}{\alpha}\right) \left[\frac{\lambda^2}{(4\pi d)^2}\right] \left(\frac{1}{L_1}\right) * \frac{1}{kR} \times \frac{G_r}{T}$ (Sklar, 2017, p. 270).

Littoral: the operational environment consisting of both seaward and landward components to the extent that they are operationally relevant to each other (i.e., the areas of the ocean that are within the operational reach of landward forces, and land that is conversely within the operational reach of seaward forces) (HQMC, 2021).

Littoral Combat Team (LCT): the component of the MLR task-organized around an infantry battalion, with long-range anti-ship missile, aircraft forward arming and refueling, and intelligence/surveillance/reconnaissance capabilities (Eckstein, 2020).

Low probability of incapacitation (LPI) & detection (LPD): the principal goal or function of a communication system to minimize the risk of interception and/or detection, respectively, of the communication transmission by anyone other than the intended recipient. LPI and LPD are referred to in this study as a singular concept (i.e., LPI/LPD) (Sklar, 2017).

Marine Littoral Regiment (MLR): the emergent naval expeditionary force formation based on ongoing Deputy Commandant for Combat Development and Integration (DC CD&I) analysis in support of DMO. The MLR could potentially require the principal reorganization of III MEF into task-organized regimental-level formations suitable for DMO (CNO, 2020). Early iterations of the MLR are manned to 1,800 to 2,000 Marines (in contrast to the 3,400 Marines of 3d Marine Regiment, for example) and consist of three principal components: the Littoral Combat Team, Littoral Anti-Air Battalion, and Littoral Logistics Battalion (Eckstein, 2020).

Maritime: “the oceans, seas, bays, estuaries, islands, coastal areas, and the airspace above these, including the littorals” (HQMC, 2021, pp. F-6). See also: littorals.

Mission command: the model/method of directing the actions of a force by communicating the commander’s intent and desired end-state, leaving subordinates to exercise creativity and initiative as to how precisely they will seek to achieve that intent. This contrasts with *detailed command*, which dictates explicit and precise instructions as to the actions of subordinates in pursuit of the commander’s intent. (See also: *mission tactics* and *mission command and control*) (HQMC, 2018).

Node: a point in a communication network which serves either as a junction for network communication, or the destination of the network traffic (IBM Cloud Education, 2021).

Throughput: the rate at which a communication system can transmit digital data, measured in bits per second (bits/s) (see also: data rate) (Sklar, 2017).

THIS PAGE INTENTIONALLY LEFT BLANK

II. CASE STUDIES

A. CASE STUDY ORIENTATION

1. Case Study Purpose, Method, and End-State

a. Purpose

Evaluating the suitability of BSMN for C2 in EABO requires characterization EABO's C2 qualities and features. By studying recent Marine Corps exercises related to and/or modeled after EABO, the researchers intend to characterize both its qualitative and quantitative factors as they relate to C2.

b. Method

To characterize the qualities and characteristics of C2 in the context of EABO, the researchers sought to analyze a sample set of exercises resembling EABO with a focus on C2. Due to access constraints, this study was limited solely to unclassified sources entirely available from the repository of AARs at the MCCLL website. Note: recommendation for future research (Chapter VI, Section C, Paragraph 1) address the potential for future research on the topic with more comprehensive material.

c. Desired End-State

The researchers sought to establish conceptual and technical criteria by which to evaluate the potential viability of BSMN technology for use in C2 for EABO.

2. Case Study Design

Scope. For the cases studied, the researchers examined C2 in EABO-related exercises under two distinct paradigms: conceptual and technical. While the overall purpose of the thesis study concerned BSMN's viability as a technical solution to support C2 in EABO, the researchers contended that a wholistic evaluation of both conceptual and technical aspects of C2 was necessary. A comprehensive evaluation of C2 in EABO not only established if BSMN supports C2 as it is currently designed, but rather, if it supports C2 as it could, or should be designed. For example, if the existing C2 model requires digital bandwidth and throughput to support a certain volume or type of information flow, but it is demonstrated that such a volume or type of information is not ultimately beneficial to the exercise of C2 in EABO, the researchers could more accurately assess the impact of BSMN's ability or inability to support such communication.

Selection Criteria. With the intent of evaluating C2 in a context as close as possible to that of anticipated EABO, the following criteria were used in selecting cases to study.

- Timeframe: 2017-Present. The researchers sought cases recent enough to accurately reflect contemporary technology capabilities and requirements, and the publication of the EABO concept (COMNAVSURFOR, 2017; CMC, 2019; HQMC, 2021).

- Environment: Pacific Littoral Environment. Cases were chosen which occurred, or were simulated to occur in, Pacific littoral environments similar to those anticipated in DMO (COMNAVSURFOR, 2017) to minimize potential environmental or physical variables.

- Context: Expeditionary Advanced Base Operations. Cases were chosen which explicitly reflect EABO in some capacity (COMNAVSURFOR, 2017; CMC, 2019; HQMC, 2021). In particular, the researchers sought to study exercises in which participants were task-organized, physically distributed, and tasked to perform functions explicitly reflecting anticipated EABO.

- Participants: United States Marine Corps Units. Cases in which U.S. Marine Corps units were the primary training audience were chosen in order to limit variables of communication technology, techniques, regulations, and policies, etc., from other services or nations.

3. Selected Cases

Due to time and resource constraints, the researchers limited the study to three cases. These cases spanned over two years and involved several Marine Corps units across I and III Marine Expeditionary Forces (MEF), as well as U.S. 3d Fleet, and Army Special

Operating Forces (SOF). The cases selected provide a variation in the echelon of command and function of training audience, from the battalion to MEF level, as well as a variety of elements of the Marine Air Ground Task Force (MAGTF) (i.e., the Command Element, Ground Combat Element, Air Combat Element, and Logistics Combat Element). The following is a summary of the selected cases.

- <u>1st Battalion, 6th Marines Exercise Northern Apache (July 2020)</u>. Exercise Northern Apache was a battalion-level force-on-force field exercise hosted by 1st Battalion, 6th Marine Regiment from 13–19 July 2020 in Northern Training Area, Okinawa, Japan. Exercise Northern Apache was designed as an experiment in "Distributed Maritime Operations (DMO) employment concepts with similar capabilities outlined in the Marine Littoral Regiment (MLR) force design" specifically relating to tactical considerations for company-level operations (1/6, 2020, p. 1). This exercise incorporated a wide variety of fire support, intelligence, reconnaissance, special forces, logistics, and aviation units, and provides valuable insight into C2 at and below the battalion level.
- <u>III Marine Expeditionary Force Exercise (2019)</u>. III MEF's Marine Expeditionary Force Exercise 2019 (MEFEX-19) provided an opportunity to examine a MEF-level simulation of C2 in an EABO context. MEFEX-19 was hosted by the Marine Air Ground Task Force Staff Training Program (MSTP) in Okinawa, Japan from April 29 to 10 May 2019 (3dMARDIV, 2019). This case provided insight into the type and nature of communication at the MEF level in the context of EABO operations.
- <u>I Marine Expeditionary Force & 3rd Fleet Joint Exercise Pacific Blitz (March 2019)</u>. The case of Exercise Pacific Blitz 2019 examined a MEF/Fleet level joint exercise in which Marine Corps and Navy forces worked in highly integrated teams to exercise various Expeditionary Advanced Base (EAB) concepts (1st Marine Division [1stMARDIV], 2019; Marine Aircraft Group 39 [MAG-39], 2019). This case provided valuable

insight into complications in unity of command associated with DMO's joint construct (COMNAVSURFOR, 2017; CMC, 2019).

4. Conceptual Study

Definition of Conceptual Study. The *conceptual study of C2* is defined herein as the study of abstract aspects of decision making and communication by which a military unit achieves C2 (HQMC, 2018): it includes the study of the mechanisms by which a commander can understand the situation at hand and influence subordinates to accomplish the commander's will (e.g., task organization and chain of command, communication procedures, reporting requirements).

Conceptual C2 Model. The researchers will conduct the conceptual C2 study using an adaptation of the theoretical model posited in a 1999 RAND Corporation study by Builder, Bankes, and Nordin, entitled *Command Concepts—A Theory Derived from the Practice of Command and Control*. This theoretical model for evaluating the conceptual aspects of C2 in military operations was chosen for use in this study because it both addresses the subject of conceptual C2 precisely and succinctly, and because it has previously been utilized as a valid and useful model for evaluating the subject matter by the Department of Defense (DOD).

Command Concept Theory's Foundations. *Command Concepts* (Builder et al., 1999), and this study by extension, use the *Department of Defense Dictionary of Military and Associated Terms* (JCS, 2021) definitions for *command*, *command and control*, and *command and control systems*:

> *Command: 1. The authority that a commander in the armed forces lawfully exercises over subordinates by virtue of rank or assignment….*
>
> *Command and control: The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Also called C2.*
>
> *Command and control system: The facilities, equipment, communications, procedures, and personnel essential for a commander to plan, direct, and control operations of forces pursuant to the missions assigned. (p. 40)*

In this study, as in *Command Concepts* (1999), these definitions bear stating explicitly to point out that while C2 certainly has a crucial material aspect, it is arguably more of a conceptual, human endeavor, and is ultimately dependent on the cognition and motive force of the commander (Builder et al., 1999; Allard, 1996). Put differently, Weaver (1949) might recognize the ability of the commander to precisely express their meaning and the ability of subordinates to receive and act on that meaning (the Level B and Level C problems) as being equally important as the capability of a C2 system to faithfully transmit symbols (the Level A problem).

In *Command Concepts* (1999), Builder et al. go even further in specifying the cognitive burden on the commander, and the timeframe in which that burden must be primarily carried: not only must a commander build clear visions of the environment, the enemy, and their own intentions for what is to be done, and communicate these visions clearly to subordinates; but further, all of these actions must take place well before the actual engagement with the enemy, and not immediately prior to or during the engagement. Thus, successful command concepts can be recognized by minimal communication traffic during the engagement with the enemy, as the commander's intent is well understood and units are equipped to independently act upon it (Builder et al., 1999).

5. Command Concept Theory

Optimal C2 bears the following principal characteristics (Builder et al., 1999):

- Commanders have a clear pre-conceived vision of the environment, the enemy, and what ought to be done about them.
- Commanders are able to monitor the realization of their vision in execution, and if their vision is incongruent with reality, are able to find and correct the faults in their vision.
- The C2 systems transmit only the information that is relevant to build, convey, or alter the commander's vision.

The researchers examined the conceptual C2 characteristics in each case in direct reference to each of these three principles, hereafter referred to as Command Concept

Theory. The researchers then drew key points and conclusions relative to this optimal C2 model. Using this theory as a lens for this study, the researchers did not seek to scrutinize or second-guess the motivations or cognitive performance of the commander in each case. Rather, the researchers sought to simply understand each commander's principal vision, the ability of the C2 construct in informing and reforming the vision, and the qualities of the information transmitted.

The researchers suspected that this theory would prove profoundly useful in the broader evaluation of BSMN's suitability for EABO, as it explicitly rejects the notion that the mere capability to transmit more information is necessarily better. Thus, by evaluating EABO exercises, the researchers could plausibly argue what information should be required in EABO, and then evaluate if BSMN would be suitable.

Conceptual Study Metrics. In accordance with the three-point statement of Command Concept Theory above, the researchers developed the following metrics to measure the cases studied relative to an ideal C2 construct:

Concerning the commander's vision of the enemy and corresponding intent:

- What was the commander's pre-conceived understanding of the enemy's disposition and intent? What signals/intelligence offered this understanding?
- What was the commander's intent in relation to the mission from higher and their understanding of the enemy? How was this intent communicated to subordinates? Was this intent reasonable given the forces and resources at hand?
- What was the commander's understanding of the environment in which their intent would be executed?

Concerning the commander's ability to and adjust the execution of their intent:

- By what means did the commander monitor the execution of their intent, and did that apparatus provide the commander with sufficient and crucial information necessary to realize that intent in reality?

- Did indications of incongruity between the commander's vision and reality presented themselves? How quickly and precisely was the commander made aware of these incongruities?
- If an incongruity between the commander's vision and reality presented itself, how did the commander react? If changes to their original intent were made, how did the commander communicate the new intent to subordinates?

Concerning the C2 systems and the information transmitted:

- What was the volume of communications passed during execution of the exercise relative to the volume of information passed prior to execution of the exercise? Was there any indication of insufficient or superfluous flow of information during the exercise?
- What sort of information was transmitted during the exercise? Was the information passed during the exercise crucial in confirming or denying the commander's original vision?
- Were the C2 systems able to transmit information in sufficient fidelity to pass the meaning of the information accurately? Were there any indications that transmissions suffered meaningfully from a loss in fidelity?

To note, while the researchers seek to answer all the questions posed above, insight into each question in not necessarily provided in each case. With the case material at hand, the researchers hope to be able to generally answer the questions posed in a cumulative manner. Future studies of more comprehensive material using these metrics is recommended at the end of this study.

Special considerations for conceptual study case material. Studying training scenarios requires certain special considerations when compared to the study of real-life scenarios if *Command Concepts* (Builder et al., 1999).

Real-World vs. Training Evaluation. Training scenarios are innately artificial, and these artificialities must be considered when evaluating the nature of C2 in that exercise. For example, while understanding the "enemy" in a training scenario is no less important than, the enemy is inherently artificial and cannot truly reflect a real-world adversary due to safety and resource constraints. In these points of inherent artificiality, the researchers exercised their best judgement to extrapolate the point in question to its likely real-world effect. To note, the researchers originally intended to use the same ten-point metric for the cases as that found in *Command Concepts* (Builder et al., 1999), but the incongruities between training and real-world scenarios rendered the metrics incompatible.

Case Resource Constraints. The specific cases in this study are derived from AARs, which are relatively incomprehensive when compared to the well documented cases in *Command Concepts* (Builder et al., 1999). The researchers examined the cases according to the determined criteria to the best of their ability but recommend further study with more robust documentation in this study's conclusion.

6. Technical Study

Definition of Technical Study. *Technical characteristics of C2* are defined herein as the quantitative, measurable aspects by which the military unit achieves command and control, particularly concerning communication via the electromagnetic spectrum (HQMC, 1998a): it includes the physical factors of the communication system, including power output, transmission range, etc. These physical factors contribute to what Weaver (1949) might characterize as the level-A problem (i.e., the system's capacity to accurately transmit communication symbols).

Technical Study Metrics. The physical factors measured in the technical portion of these case studies were derived from elements of the *link budget equation.* The link budget equation is "a balance sheet of gains and losses" (Sklar, 2017, p. 243) to quantitatively estimate the overall effect of hardware, environment, and electromagnetism on the communication system (Sklar, 2017, p. 270). The specific expression of the link budget below pertains to digital systems, and accounts for the physical aspects of the transmitter and receiver, the transmitting medium, and the means of encoding and modulation utilized to transmit data.

$$\frac{E_b}{N_0} = P_t G_t \left(\frac{1}{\alpha}\right)\left[\frac{\lambda^2}{(4\pi d)^2}\right]\left(\frac{1}{L_1}\right) * \frac{1}{kR} \times \frac{G_r}{T}$$

Such that:

$$\frac{E_b}{N_0} = Normalized\ signal\ to\ noise\ ratio$$

$$E_b = Energy\ per\ bit\ of\ data\ (Joules\ or\ Watt * seconds)$$

$$N_0 = \ Noise\ spectral\ density\ \left(\frac{Watts}{Hertz}\right) = kT$$

$$k = Boltzman's\ constant = \ 1.38 * 10^{-23}\ \frac{Watts}{Hertz\ {}^{\circ}Kelvin}$$

$$T = Temperature\ ({}^{\circ}Kelvin)$$

$$P_t = \ Power\ transmitted\ (Watts)$$

$$G_t = \ Gain\ of\ the\ transmitter\ (ratio) = \frac{\pi^2 \eta D^2}{\lambda^2}$$

$$\eta = Antenna\ efficiency\ (ratio)$$

$$D = Antenna\ size\ (meters)$$

$$\lambda = Wavelength\ of\ the\ EM\ signal\ (meters)$$

$$\alpha = Atmospheric\ attenuation\ (ratio)$$

$$\lambda = Wavelength\ of\ the\ EM\ signal\ (meters)$$

$$d = Distance\ transmitted\ (kilometers)$$

$$\boldsymbol{L_s = \frac{(4\pi d)^2}{\lambda^2} = Free\ space\ loss\ (ratio)}$$

$$\boldsymbol{L_I = Receiver\ loss\ (ratio)}$$

$$\boldsymbol{R = Data\ rate\ \left(\frac{bits}{second}\right)}$$

$$\boldsymbol{G_r = \ Gain\ of\ the\ receiver\ (ratio)}$$

$$T = Receiver\ system\ noise\ temperature\ (Kelvin)$$

$$\boldsymbol{\frac{G_r}{T} = Receiver\ sensitivity}$$

The elements of the data link budget equation above (S. Tackett, PowerPoint Slides, October 2020) in ordinary type are those that are environmental or otherwise outside of the influence of the communicators: the elements in bold are variables within EABO forces' influence to realistically effect.

An additional variable of concern to digital mesh networks not otherwise named in the link budget equation is the number of nodes served in a communication system. A *node* is defined as a point in a communication network which serves either as a connection/conduit for that network's communication (e.g., switches and routers), or as the terminal destination of the network traffic (e.g., a computer or phone) (IBM Cloud Education, 2021; Srivathsan et al., 2009, p. 225).

Having defined the logical framework for the technical evaluation, the researchers sought to measure the following variables quantitatively in the cases studied in order to characterize the physical/technical characteristics of EABO as they occurred.

- Maximum transmission range: what was the furthest range in which the exercise force communicated within the scenario?
- Bandwidth and data rate requirement/constraint: based on the specific software and hardware systems used in the scenario, what was the

maximum bandwidth and data rate required and/or achievable by the exercise force?

- Power requirement/constraint: how much power could the communication power sources at hand produce, or how much power was required to operate the most capable communication systems?
- Antenna dimension requirement/constraint: based on both man-portable and ground vehicle-mounted communication assets, what is the maximum length of antenna EABO utilized in these scenarios?
- Number of nodes served: approximately how many radios, computers, or other information systems were used in the communication network during these scenarios?

Because much of the technical information sought was not immediately available or explicitly stated, some deduction and estimation is required, with the methods for that deduction noted in the table. Further research with precise historical data from EABO exercises could better characterize these technical aspects of C2 in EABO.

B. CASE STUDIES

1. 1st Battalion, 6th Marine Regiment: Exercise Northern Apache 2020

a. Summary of Events

From 13 to 19 July 2020, 1st Battalion, 6th Marine Regiment (1/6) planned and executed Exercise Northern Apache (1/6, 2020), a battalion-level force-on-force field exercise aboard the Northern Training Area of Okinawa, Japan. The exercise was designed as an experiment in company-level EABO concepts and techniques, with battalion-level goals of refining the battalion C2 standard operating procedures, thus establishing best practices for EABO exercise design and control and provide higher feedback regarding MLR design (1/6, 2020). The training audience for this exercise consisted of Joint Forces from all elements of the MAGTF, including the following, with reinforcements indicated as applicable:

- Headquarters Company, 1/6
- Fire Direction Center (FDC), 3d Battalion, 12th Marine Regiment (3/12)
- Reconnaissance Operations Center (ROC), 3d Reconnaissance Battalion (3d Recon).
- Company A, 1/6
- Motorized Section, Heavy Machine Platoon, Weapons Company, 1/6
- Operational Detachment Alpha (ODA) 1125, 1st Battalion, 1st Special Forces Group (SFG)
- A section of High Mobility Artillery Rocket System (HIMARS), 3/12 (i.e., (1) HIMARS launcher with crew)
- 4th Platoon, Company A, 3d Recon
- Combat Logistics Detachment (CLD), 3d Transportation Support Battalion (3d TSB)
- 3d MEF Information Group (MIG) Ground Sensor Platoon (GSP)
- Marine Medium Tiltrotor Squadron-265 (VMM)

The adversary force for this exercise consisted of the Anti-Armor Platoon, 1/6, and 4th Platoon, Company B, 3d Recon.

b. Conceptual Study

(1) The Commander’s Vision

The Exercise Northern Apache Road-to-War (RTW) brief, provided as an addendum to the AAR (1/6, 2020, pp. 26–76) is an example of the quality of intelligence that was available to the battalion and company commanders, and appeared to the researchers to be a reasonably realistic resource from which to build the respective commanders’ visions of the enemy and environment. Specifically, background information on current events with the notional enemy on a broader strategic scale and recent operational-level intelligence of enemy actions in the region were sufficient to build a vision of the lower-level enemy's intent in the immediate fight. The researchers found the artificial enemy scenario to be realistically presented, with fidelity similar to that of RTWs experienced during real-world military operations. The source of the information in the RTW was not explicitly stated, but the researchers assumed that strategic-level intelligence services would be required to collect and process this information.

During the exercise, intelligence of the enemy's tactical disposition was provided by the Marines from 3d Recon (supporting both Company A and 1/6 Battalion HQ), GSP, and 1125th ODA Soldiers, in addition to reports from the force's maneuver elements (1/6, 2020). Overall, the intelligence apparatus would seem to be sufficient for the task at hand at the company level, though the battalion (and company, to a lesser degree) would also likely have an additional intelligence, surveillance, and reconnaissance (ISR) capability in a real-world scenario.

In the exercise warning order (1/6, 2020, p. 12), the exercise force was given an explicit statement of their higher commander's intent. Furthermore, while there was not a full operation order (OPORD) from this notional higher commander available to researchers in this case, the researchers assert that the exercise force likely executed the training scenario from OPORDs from respective higher commanders: it is highly unlikely that a real-world scenario like this would be executed without detailed and explicit orders, confirmation briefs, and rehearsals (CNO, 2018). Specifically, in this case, the exercise force was informed that the higher notional commander's intent was to deny the enemy use of the islands that constituted the exercise force's area of operations (AO) as their EAB, and ultimately to degrade the enemy's ability to influence the notional allied nation's territorial waters. This scenario's context and the commander's intent are plausible, though the size of the enemy force opposing the EAB force is questionable. By the researchers' estimation, an enemy platoon-sized element, alone on an EAB, may be smaller than what would likely be encountered in real life.

Regarding the communication of the intent, however, there appeared to be deficiencies during Exercise Northern Apache (1/6, 2020, p. 3). While the intent of the commander, generally, was simple and appeared to have been well understood, the intent for the internal structure of the exercise force and in what manner it would operate (e.g., what the internal responsibilities for support were) were unclear. While the concept of the MLR was referenced in the 1/6 AAR (1/6, 2020), the command and support relationships within the MLR for the performance of essential warfighting functions (e.g., logistics, fires) were not clear to the exercise force. Specifically, the operating force was unclear about: who commanded the EAB, and whom the EAB supports; what forces necessarily constitute the EAB; where the EAB's logistical support lies; and who has the authority concerning essential EAB functions (tasking authority of sensors, fires approval, etc.). The Exercise Northern Apache AAR recommends the refinement of the basic structure of the EAB and the manner in which EABs fit into EABO, and DMO in general (1/6, 2020). In addition to the recommendation that Headquarters Marine Corps continue to develop, refine, and solidify the MLR construct, the researchers assert that the commander in this case could have reasonably made the intent for the inner workings of the organization known well before the execution of the exercise. The researchers offer this observation with the obvious caveat that EABO and the MLR are concepts in development, and that some lack of precision regarding particular information like task organization is to be expected.

This exercise scenario provided a realistic and largely sufficient evaluation of the environment in which the exercise force would operate (DON, 2020a, p. 27). As a doctrinal step in preparatory planning, the exercise force produced an Information Preparation of the Battlespace (IPB) report, which among other things, defines the operational environment and describes the battlespace effects (DON, 2018b, p. 2–2). That is, the 1/6 battalion staff evaluated such physical aspects of the environment as terrain, vegetation, meteorological forecasts, avenues for vehicle traffic, clearings for use as airfields, etc. The IPB further describes how the environment will affect operations and evaluates which terrain is key to the operation (DON, 2020a). The understanding of the terrain given in this exercise is derived from geospatial sources (e.g., satellite imagery) and ground-level intelligence: both the sources and quality of information about the environment are realistic and plausible relative to a real-world scenario as experienced by the researchers. The only thing missing from the evaluation of the environment is an assessment of the disposition of the local population and infrastructure: the absence of this information is likely due to the intentional limitation of the scope of the exercise (i.e., no civilian population was depicted in this scenario). Thus, the researchers would not attribute this to absence in the IPB to a deficiency in planning or intelligence resources.

(2) Execution of the Commander's Vision

In this scenario, as is generally the case, the commander was made aware of events on the battlefield through reporting from sources organic to the task organization of the unit. Specifically, reports came from both the supporting reconnaissance, intelligence, and SOF elements, and the maneuver forces themselves. While there was no indication that maneuver or intelligence forces failed to provide the commander with sufficient information concerning the execution of their intent, the exercise AAR did state that both organizational and technical communication shortfalls prevented information from reaching the commander in a timely or complete manner (1/6, 2020, p. 9). Some re-organization of support units (i.e., moving the GSP monitoring station into the Company Command Operations Center (COC)) was necessary to overcome technical limitations and streamline the process by which the commander and higher headquarters understood the environment, with some success. To this point, the exercise force described the available communication systems (High Frequency Tactical Chat [HF TAC Chat]) as wholly inadequate for transmitting information to confirm or deny the commander's intent during execution. Specifically, there were not an appropriate number of nets to support separate functions per Marine Corps communication doctrine (i.e., intelligence reports had to be sent over the battalion tactical direction net instead of the doctrinal intelligence net) (1/6, 2020, p. 9; HQMC, 1998a). The exercise force further asserted that, even if satellite communications (SATCOM) were available, there were insufficient quantities of SATCOM assets (PRC-117Gs) and access to support anything more than the battalion headquarters (HQ) element and a single EAB (1/6, 2020, p. 9).

(3) The C2 Systems and Information Transmitted

While the previously identified deficiency in communication resources carries a negative connotation, this point illustrates a positive aspect of C2 in Northern Apache: the exercise force appeared to the researchers to be ultimately successful in their principal objective of taking and holding the EAB while suffering from constraints in the communication volume between the company and battalion. This indicates that the battalion commander's C2 construct did not suffer from superfluous communication volume. While the Northern Apache AAR (1/6, 2020) indicated the desire for higher communication volume between battalion and company elements in order to achieve doctrinal communication standards, the apparent success of the exercise brings into question the need for such higher volume of communications.

With HF TAC Chat named as a primary means of communicating between the company and the battalion, simple plain text appeared to be the primary type of transmission by which the battalion commander confirmed and altered their intent in this exercise. While not specifically stated, it is presumed that VHF communications were utilized at the company level. In the AAR for Exercise Northern Apache (1/6, 2020), and while relegated primarily to text in HF TAC Chat, there were no indications that the medium lacked fidelity in transmitting information to and from the battalion commander.

(4) Key Conceptual C2 Observations

Sustain MAGTF-style task organization at battalion level. Task organization and distribution of authorities and responsibilities requires further refinement. Because of the explicit emphasis on tempo in seizing and displacing from EABs, and the wide physical displacement of EABs per the *38th Commandant's Planning Guidance* (CMC, 2019), the researchers recommend a task organization for battalions and below similar to 1/6's in this exercise, with a complete MAGTF-like construct (i.e., a command, ground, air, and logistics capability) and authorities to utilize all assets at hand as it relates to operating EABs and conducting A2AD. Doing so will further alleviate the burden and hazards associated with long range communications. The greatest challenge to this recommendation will likely come from resource constraints in logistical and aerial assets.

Decentralize EAB fire support authority. Authority to use resources, and particularly fire support assets, should be vested in the lowest level in which each respective echelon of forces is expected to influence. This means the HIMARS, and aerial fire support assets needed to mutually support EABs and conduct A2AD should have approval authority vested at the battalion or regimental level, as opposed to the division level as in previous operations in the Middle East. Company EAB forces should continue to maintain authority to coordinate fires organic to the EAB force, such as mortars and apportioned Close Air Support (CAS) affecting targets within the EAB's immediate vicinity.

Battalion EABO operations require more plentiful, low power, stealthy communications. Throughout Exercise Northern Apache, the requirement for resilient, stealthy, and long-range communications first identified in the *38th Commandant's Planning Guidance* (CMC, 2019) is echoed at the tactical level. Given the principle that optimal C2 requires minimal communication during execution (Builder et al., 1999), the researchers contend that the information that confirms or denies the commander's vision during execution should be streamlined to its minimal form, and potentially to the size and volume supported by existing high frequency (HF) assets. What cannot be contended, however, is the lack of capacity for doctrinal communication nets that the exercise force identified (HQMC, 1998a). Further research using documentation indicating how many different nets were used during this type of exercise could illuminate how many nets BSMN might need to support.

c. Technical Study

Table 2 summarizes key technical aspects of C2 as observed or surmised from Exercise Northern Apache.

Table 2. Exercise Northern Apache Technical Characteristics

Criteria	Observation	Comments
Maximum Transmission Range	30 mi (48 km)	VHF communications unable to range battalion-to-EAB communications: HF and SATCOM were required.
Bandwidth (BW), Data Rate (DR) Requirement/ Constraint	BW: < 60 MHz DR: < 9.6 kbps	Voice and/or HF TAC Chat and similar simple text protocols characterize the type of message traffic observed, and the bandwidth and data-rate benchmark. Bandwidth and data rate are based off advertised PRC-150 HF Radio capabilities in support of HF TAC Chat (Harris, 2005).
Power Requirement/ Constraint	Vehicle: 50 W Man-pack: 20 W	Power requirements are consistent with those of typical, currently issued equipment. Minimal power requirement is explicitly named as a priority due to logistical constraints (1/6, 2020, p. 4). Vehicle-power for issued radios (e.g., AN/VRC-103(v2) for PRC-150 and PRC-117G) (Harris, 2007). BA-5590/BB-2590 Batteries for man-packed communications systems. Between 10–20 Watts in 1dB increments is listed as the standard power output (Harris, 2007).

Criteria	Observation	Comments
Antenna Dimension Requirement/ Constraint	Vehicle: < 32 ft Man-pack: < 35 ft	Vehicle mounted and man-packed radio systems typical to ground combat element Tables of Equipment (T/E) characterize the antenna size limitations in this case's EAB. Vehicle mounted antenna size is based on the current mountable whip antennas (Harris, 2007); man-portable radio antenna maximum size is based on the current OE-254 Antenna Group (Headquarters Army, 1991).
Number of Nodes/Users Served	40 ≤ x ≤ 121 nodes	Per estimations made in similar Mobile Ad hoc Network (MANET) research (Nicholas et al., 2013), there can be as few as 40 and as many as 121 nodes in an infantry battalion. While this is clearly over estimation for this case, with a single company and battalion headquarters, the addition of the overall task force elements leads the researchers to estimate that this estimation is valid, though approximate, for the force at hand. To note, the research by Nicholas et al. is based on the echelons of leadership between the battalion commander and infantry fire team leader level (2013): future research can better approximate the number of radio nodes for this scenario by using a current table of equipment (T/E), which was not available to the researchers in this case.

While the technical burden on communications would appear to be light and resulted, arguably, in sufficient C2 for the execution of the mission, the need for logistically modest and spectrally stealthy communications was emphasized in the Exercise Northern Apache AAR (1/6, 2020). Furthermore, the lack of channels with which to control and monitor doctrinal communications nets should also be observed as a deficiency in the number of nodes operating: this precise sort of deficiency in scalability makes BSMN a compelling technical solution for C2 in EABO, should BSMN prove effective (Bordetsky et al., 2014).

d. Conclusion

Exercise Northern Apache, while relatively small in scale compared to other cases in this study, provided valuable insight into the unique considerations and challenges faced by the lowest tactical-level warfighters in EABO. The observations made in this case reinforce the need for the development of communication capabilities that are stealthy (i.e., low probability of detection and intercept), and that are sensitive to the relatively limited logistical and sustainment capabilities of EAB forces (i.e., low power requirement) (1/6, 2020).

While Exercise Northern Apache was explicitly intended to serve as a testbed for battalion level C2 and EAB operations (1/6, 2020), the researchers believe that the task-organization of the EAB forces is sound, with the potential need for additional enablers, like an engineer support element. As previously concluded in the conceptual study, once the task-organization is solidified, the researchers recommend that all authorities for such activities as fire support be vested in the lowest level possible to minimize the burden and hazards of long-range communication, and to increase operational tempo in accordance with the principles of mission command (HQMC, 2018): such decentralization of authority will require training and deliberate emphasis on understanding of the higher commander's intent prior to the commencement of hostile engagement with the enemy (Builder et al., 1999).

2. III Marine Expeditionary Force: Marine Expeditionary Force Exercise 2019

a. Summary of Events

From 26 April to 10 May 2019, the MAGTF Staff Training Program (MSTP) hosted MEFEX-19 at Marine Corps Base Butler in Okinawa, Japan (3dMARDIV, 2019). MEFEX-19 served as a rehearsal of MEF-level amphibious operations (MASS-6, 2019) with III MEF as the primary training audience and major subordinate units in supporting roles. Because MEFEX-19 was a simulated exercise (3dMARDIV, 2019), little insight is offered in the way of real-world communications. This case does, however, provide valuable insight into the nature and substance of information in MEF-level EABO.

b. Conceptual Study

(1) The Commander's Vision

In terms of the commander's vision of the enemy, understanding of the environment, and vision for action, the documentation for this case offers little insight. The one aspect of the pre-fight vision that is clear, however, is the commander's intent for their organization at the top level to be tightly integrated: this vision was manifested in the extensive and effective use of liaison officers (LNOs) between the III MEF staff and subordinate/supporting units. LNOs were exchanged, reciprocally, between MEF headquarters, 3d Marine Division (MARDIV), 1st Marine Air Wing (1st MAW), 3d Marine Logistic Group (3d MLG), the MEF Information Group (MIG) Detachment, and the Civil Military Operations detachments (3dMARDIV, 2019). Further socialization of LNOs across subordinate organizations also proved key to a mutual understanding of the enemy, environment, and the means to achieving the commander's vision, particularly in the case of the integration of MIG and fire support organizations (3dMARDIV, 2019, p. 11). Such a vision for the integration of the force was a valuable point to take away from this case.

(2) Execution of the Commander's Vision.

The question of which information, and in what form, was used to update the commanders about the state of the battle and the condition of their visions was addressed by 3dMARDIV with an observation about the digital communications, and audio-visual information, specifically (3dMARDIV, 2019). While some forms of digital communications are rich in information and formatted for ease of use by the consumer, such productions can also be both time consuming and resource intensive to make and transmit. Furthermore, the communication apparatus needed to transmit resource intensive digital information often requires static command posts with robust antennas and power resources (3dMARDIV, 2019). Thus, 3dMARDIV recommended a delineation between the level of commands that can and cannot sustain the requirements for audio-visual information: they call this limit the “digital divide” (3dMARDIV, 2019, p. 2). Defining the digital divide could help to temper expectations for digital communication and products and shape the way in which the higher headquarters expects to understand the environment. Due to the constant maneuver of regimental-level units/task forces in MEFEX-19, 3dMARDIV ultimately recommended that the digital divide lie between the regimental and division level (3dMARDIV, 2019, p. 2). This delineation would relieve 3dMARDIV’s subordinate units from the burden of digital C2 productions and transmissions.

(3) The C2 Systems and Information Transmitted

In an effort to build the commander’s situational awareness, 3dMARDIV staff recognized a superfluous volume of MEF Priority Information Requests (PIRs), to the point that the requests came to resemble Requests for Information (RFIs) more closely in their broad and numerous nature (3dMARDIV, 2019). The observation that information requirements, deemed critical by the higher commander/staff, appeared to lack focus indicates that exactly which information is critical is either ill-defined or unknown. Additional consideration and guidance from the commander may be required to simply identify and communicate what information is critical for confirming and modifying the commander’s vision to its absolutely essential elements.

While an abbreviated list of the types of software and communications systems that were utilized in MEFEX-19 is located in the technical portion of this case study, one application of interest, due to its high digital resource requirement, was Secure Video Teleconference (SVTC) (3dMARDIV, 2019; Defense Information Systems Agency [DISA], 2014, p. 15). 3dMARDIV staff recognized the need for a robust SVTC capability and recommended the development of the capacity to support several SVTC stations simultaneously (3dMARDIV, 2019). Per the AAR comments from 3dMARDIV, the value of face-to-face communications at and above the division level is considered one of the more potent, if technologically burdensome, means of communicating the commander’s vision and making the commander aware of how their vision is playing out in reality.

(4) Key Conceptual Observations

Emphasis on the importance of LNOs. The recognition of the importance of LNOs in enabling C2 in the case of MEFEX-19 is in alignment with the principles of Command Concept Theory, namely, that the bulk of communication must happen before the engagement, and that a successful C2 construct is evident by minimizing information that must be passed during the engagement. In the case of LNOs, this early and intrinsic communication is achieved through the organic placement of individuals with relevant information. The researchers second the motion that LNOs be used to the greatest degree possible, both vertically and horizontally in the EABO task organization.

The digital divide. The digital divide's principal reduction of burden, both on the time and effort of units below the division level, and on their communication and logistical resources, is considered by the researchers to be a valid recommendation that is aligned with Command Concept Theory (3dMARDIV, 2019; Builder et al., 1999): the researchers will adopt this recommendation for an optimal EABO C2 design.

UAS as C2 enabling nodes. A point of this case not previously addressed indicated the exercise force's desire to utilize unmanned aerial systems (UAS) as retransmission nodes for C2: resources for retransmission sites required during MEFEX-19 were recognized as lacking, and specifically, the manpower required to safeguard retransmission sites was a limiting factor (3dMARDIV, 2019). UAS retransmission capabilities were posited to establish retransmission nodes without requiring manpower to maintain security around that node. To the researchers, the inclusion of UAS retransmission nodes indicated a need for a communication system that is scalable and dynamic: both these qualities are advertised benefits of mesh networks (Srivathsan et al., 2009), which the researchers will seek to evaluate in BSMN.

c. Technical Study

Table 3 summarizes key technical aspects of C2 as observed or surmised from MEFEX-19. Though MEFEX-19 was a simulated exercise, many technical criteria were still observable.

Table 3. MEFEX-19 Technical Characteristics

Criteria	Observation	Comments
Maximum Transmission Range	NA (Simulation)	3d MEF and 7th Communication Battalion tested the Free Space Optics (FSO) IR communication system at a range of approximately 1 km (Camp Hansen to Camp Courtney (3dMARDIV, 2019; Valero & Kindo, 2018). The desire to achieve distances of 15 km was expressed, as well. Given the simulated nature of this exercise, these distances are not considered to accurately reflect operational transmission range samples or requirements.
Bandwidth, Data Rate Requirement/ Constraint	DR: 1 Gbps	FSO averaged data rates of 30 Mbps, with 70 Mbps peaks. Other services, like Cypher Block Systems (CBS), were recommended to upgrade to a 1 Gbps capacity (3dMARDIV, 2019). Bandwidth and data rates were required to utilize the following programs: MCEN services (NIPR and SIPR); VOIP; SQL; SolarWinds; Openfire (XMPP Chat); SharePoint; Wave/TRICS; JADOCS; C2PC Gateway; CLC2S; TCPT; Transverse; VLC; and SVTC (3dMARDIV, 2019).
Power Requirement/ Constraint	NA	Power to communications systems is deemed unconstrained due to the infrastructural and expeditionary resources available to operation centers at the MEF and division levels.
Antenna Dimension Requirement/ Constraint	113ft (34.7 m)	MEF level forces are presumed to have a more robust antenna-size capacity than EABs: estimations are based on dimensions of TEAMS antenna (Contact Corporation, n.d.).

Criteria	Observation	Comments
Number of Nodes/Users Served	> 1500	There were an estimated 1,500 users across all platforms and functions of enterprise services at the division level during MEFEX-19 (3dMARDIV, 2019; MASS-6, 2019). While the researchers assume that the MEF-level would have a greater number of functions served, they also draw a distinction between platforms served and nodes required to establish a link between distinct units and locations. Further study is required to determine the precise number of nodes served at the MEF level.

d. Conclusion

This case, while a simulation, provided valuable insight into the type of information that is appropriate for each echelon of command, particularly above the division level. This study is a prime example of the balance that must be struck between an organization's appetite for communication that aids in C2 (e.g., SVTC), and the need to limit communication in pursuit of mission command principles. The difficulty in this case to clearly define priority information suggests that the force requires focus on the disciplined streamlining of information at this level of warfare, rather than merely adding technological C2 capacities.

3. I Marine Expeditionary Force & U.S. 3rd Fleet: Exercise Pacific Blitz 2019

a. Summary of Events

From 25 February to 11 April 2019, I MEF, U.S. 3rd Fleet, and major subordinate units conducted Exercise Pacific Blitz 2019 (PB-19). The objective of PB-19 was to integrate Navy and Marine Corps teams, and exercise C2 over both maritime and amphibious forces engaged in "Advanced Naval Base Operations," which the researchers interpret to be synonymous with EABO (1stMARDIV, 2019, p. 1). The exercise force, task-organized into a Littoral Combat Force (LCF) with aviation combat element (MAG-29), ground combat element (1stMARDIV), and maritime combat element (3d Expeditionary Strike Group (ESG-3)), established four uniquely tasked EABs ashore with MEF-level support (MAG-39, 2019). This case provided valuable insight into the particulars of current task organization issues within the LCF (MAG-39, 2019) and above, as well as C2 related to Joint Navy and Marine Corps operations (Fuentes, 2019).

b. Conceptual Study

(1) The Commander's Vision

The researchers assert that this case is most valuable for its illustration of the dynamic of task organization and its effect on the actualization of the commander's vision. All other things being equal, the manner in which a military unit is organized can alter its effective resources, tempo, and potency (HQMC, 2018). Several different AAR points suggest that PB-19's force structure suffered from a lack of unity and clear lines of authority, which ultimately inhibited the execution of the commander's vision.

Even prior to the execution of the commander's vision in PB-19, 1stMARDIV Staff Judge Advocates identified the benefit of adding a law enforcement capability to EABO task organizations, as this provides the commander with additional options in creating and achieving a vision for action. As DMO will require Navy and Marine Corps forces to interact with "nontraditional naval forces or flagless vessels" (1stMARDIV, 2019, p. 11), the addition of a maritime law enforcement capability through a Coast Guard element could be useful in DMO operations, particularly in regarding to abiding by and leveraging international law.

Several references indicate that the commander's vision of the environment was derived through the ordinary IPB process (CNO, 2018; 1stMARDIV, 2019). However, 1stMARDIV staff were critical of the IPB provided, and the lack of focus on domains other than physical (e.g., the cultural domain): a key source of this insufficiency was a stated failure to integrate all intelligence assets across the Navy and Marine Corps team. This point further emphasizes the need for Navy and Marine Corps unity of effort, at the highest levels as well as the lowest, which includes the pooling of resources and sharing of data (1stMARDIV, 2019).

(2) Execution of the Commander’s Vision

Along with ordinary reporting (presumed by the researchers, as there is little insight into this in the source material), the 1stMARDIV AAR (1stMARDIV, 2019) identified a missed opportunity for the use of I MEF Communications Strategy & Operations (COMMSTRAT) to provide the commander the division and fleet commanders with an audio-visual representation of current events from the EABs. In the case of this exercise, this data was collected and disseminated, but only after the data was physically returned to the commanders’ location, and not in real time. 1stMARDIV staff suggested the Mobile User Objective System (MUOS), which was able to transmit data to and from naval vessels at a rate of 3 MBps, as a solution to allow for this real-time visual information transfer. However, the researchers question the necessity of real-time audio-visual information to confirm the commander’s vision at-and-above the division level, particularly considering the burden it would place on communication systems: the researchers recommend further study in this regard.

Some incongruities between the commander’s vision and reality were manifested in the inner workings of the commander’s organization, particularly regarding authorities. One such example at the highest levels of the PB-19 exercise was recognized by participants from 1stMARDIV (1stMARDIV, 2019): several principal channels existed between the Navy and Marine Corps forces for the tactical tasking of aircraft, including Fragmentary Orders (FRAGOs), Air Tasking Orders (ATOs) and Navy Daily Intention Messages (DIMs). This sentiment was brought forward by MAG-39, which served as an attached Air Combat Element (ACE) to the LCF: because the Task Elements (TE) charged with the principle task of establishing EABs were subordinate to the LCF, and some EAB tasks were predominantly ACE missions (e.g., establishing and executing forward air refueling points), the ability of MAG-39 to task TEs was inhibited, and instead, MAG-39 had to work through the LCF (MAG-39, 2019).

Regarding all TEs, not just those concerning the ACE, 1stMARDIV recognized that they maintained too much centralized control, as they became the primary planners of tactical tasks that should be the domain of MLRs, LTC or even the EAB forces themselves (e.g., planning forward arming and refueling FARPs, HIMARS sites, etc.) (1stMARDIV, 2019). This is an indication that mission command is not being properly exercised, but rather, higher commands are micro-managing subordinate operations. As the AAR suggests, this could have been an artificiality of the training scenario as MLRs (along with subordinate Littoral Combat Teams (LCTs) and EAB) were not fully staffed or represented, but still indicates that tactical direction of EABs needs to be the domain of units below the division level.

Upon later receipt and review of the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021), the problem of task organization and authority for aviation-related units and capabilities is addressed through the integration of aviation capabilities into the force, specifically, the Littoral Logistics Battalion (LLB) as it relates to establishing and running the FARP. It appears to the researchers that some of the issues experienced in this exercise as it relates to aviation capabilities may have been mitigated in a real-life operation through the existence and support of the LLB, which was beyond the scope and/or capacity of PB-19. Further research is recommended to confirm this assumption.

(3) The C2 Systems and Information Transmitted

While the volume of communications themselves is not addressed directly in the case material for PB-19, certain AAR points further reinforced both the need for low probability of interception/detection (LPI/LPD) communication technology, and the exercise of mission type orders as the primary means of communicating the commander's intent (vice continuous and immediate directions from the higher commander) (1stMARDIV, 2019). Denial of communications was a point of concern in the *38th Commandant's Planning Guidance* (2019): an evaluation of the exercise force's electronic protection procedures by an Electronic Warfare Support Team identified vulnerability in this exact regard, and specifically the denial of UHF satellite communications.

(4) Key Conceptual Observations

Increase emphasis on joint unity of command and inter-force coordination of resources. Unity of command between Navy and Marine Corps units, and internally to Marine Corps units, is a consistently addressed issue (1stMARDIV, 2019). Fully integrated and/or organic ACE forces within the appropriate elements of the MLR, rather than as an attachment to the LCF, could assist in establishing a clear line of authority and tasking. The researchers recommend exploring options for a more unified command of the LCF and MLR, like a single commander of the ground, maritime, and air elements under a LCF command element similar to the MAGTF construct (HQMC, 1998b). The management of warfighting resources, like intelligence apparatus, may also be improved through their consolidation under a unified command structure. Regarding joint command, the addition of U.S. Coast Guard elements to the LCF can provide capabilities below the threshold of violence and with non-combatant interactions.

Mission type orders and execution. An earlier observation reinforced the need for LPI/LPD communication technology in response to potential enemy communication denial attacks. While a technological solution that would allow for continuous and discrete communications is clearly desirable, Builder et al. (1999) asserted that successful C2 is characterized by minimal communication during execution. In other words, the intent of the commander, optimally communicated, rehearsed, and resourced prior to execution would require no additional direction to subordinates during execution (Builder et al., 1999, p. xvi). In terms of the manner in which the commander’s vision is communicated, the circumstances and hazards of denied communication in the EABO place additional emphasis on the prior communication and understanding of the commander’s vision, and the proper resourcing and empowering of subordinates to carry out that vision absent of the commander’s constant direction. Such a reinvigoration of mission command could mitigate the need for the communication of robust data (e.g., streaming audio-visual data).

c. Technical Study

Table 4 summarizes key technical aspects of C2 as observed or surmised from PB-19. The real-execution of EABO with a division-level force provided valuable technical data for both the higher headquarters and EAB forces within the broader EABO context (1stMARDIV, 2019).

Table 4. Exercise Pacific Blitz Technical Characteristics

Criteria	Observation	Comments
Maximum Transmission Range	150 km	Liberal estimations of maximum ranges are based on the following reported participant locations for PB-19 (Fuentes, 2019): • Marine Corps Base Camp Pendleton • Marine Corps Air Station Miramar • Naval Air Station Point Mugu • Naval Surface Warfighting Center Port Hueneme • San Clemente Island (EAB)
Bandwidth, Data Rate Requirement/ Constraint	DR: 3MBps	Mobile User Objective System (MUOS) transmitted imagery at 3 MBps (1stMARDIV, 2019). Services used between Marine and Navy forces included MCEN (13 NIPR & 9 SIPR servers), MUOS, VOIP, (3dMARDIV, 2019; MASS-6, 2019; 1stMARDIV, 2019; 9th Communications Battalion [9th Comm], 2019)

Criteria	Observation	Comments
Power Requirement/ Constraint	Vehicle: 50 W Man-pack: 20 W	Power to communications systems at the MEF and division levels is deemed unconstrained due to their infrastructural and expeditionary power resources. Power constraints for EABs are based on typical issued vehicle and man-portable communication power sources: • Vehicle-power for issued radios (e.g., AN/VRC-103(v2) for PRC-150 and PRC-117G) (Harris, 2007) • BA-5590/BB-2590 Batteries for man-packed communications systems. (Harris, 2007)
Antenna Dimension Requirement/ Constraint	113ft (34.7 m)	MEF level forces are presumed to have a more robust antenna-size capacity than EABs: estimations are based on dimensions of TEAMS antenna (Contact Corporation, n.d.).
Number of Nodes/Users Served	Unknown	Researchers were unable to estimate the number of nodes used in PB-19.

d. Conclusion

Exercise PB-19 provided the most insight out of any case reviewed into the internal mechanics that will be required for EABO, with the key lessons summarized in the word "unity." Particularly when dealing with a joint naval force (i.e., Navy, Marine Corps, and Coast Guard team), the need for a unified command structure and more flexible, streamlined sharing of resources is well illustrated in this case. In much the same manner as MEFEX-19, PB-19 also draws questions about the type and volume of data desired in EABO (e.g., real-time audio-visual data) and whether such expectations for data sharing are congruent with adherence to the principals of mission command doctrine (HQMC, 2018; 9th Comm, 2019).

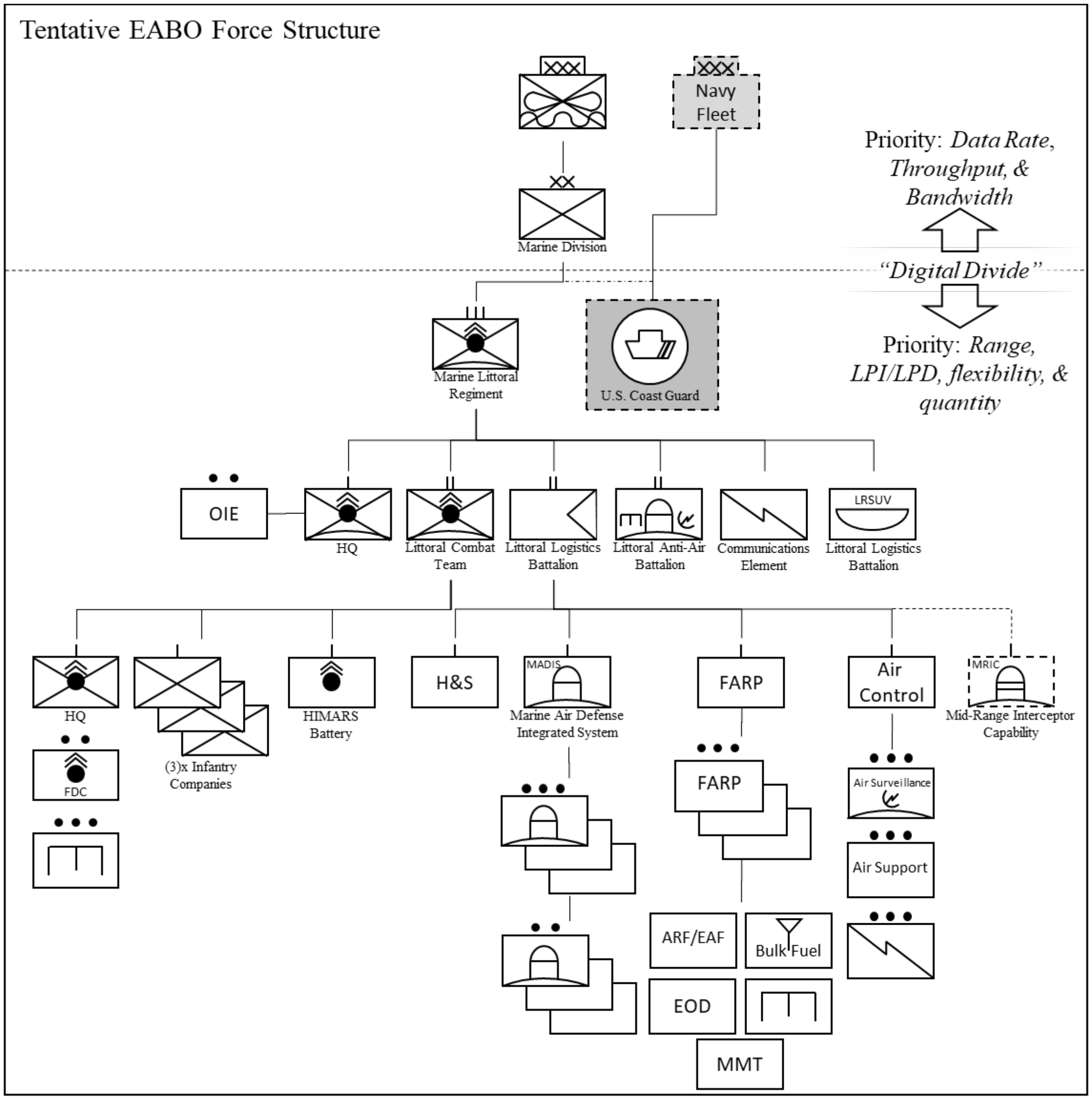
4. Case Study Final Conclusion and Recommendations

a. Future Case Study Recommendation

A common theme throughout the cases studied in this research is the desire for more detailed and comprehensive case material. In choosing the source documents of these case studies, the researchers were prohibitively limited in access, both to source documentations of a more substantial nature, and to the participating units for interview and clarification (attempts to reach and interview units in this study proved unsuccessful). As such, many of the observations and recommendations are made to the best of the researchers' ability, but more liberally than they would have preferred. The researchers assert that the most valuable aspect of this study is the model by which aspects of C2 were analyzed: the insights into C2 itself are sufficient for a preliminary examination of the suitability of BSMN, but a much more thorough analysis of EABO exercises is necessary to confirm or deny the conclusions drawn in this study. Recommendations for future study are detailed following the conclusion of this research.

b. Organizational Observations and Recommendations

Figure 2 depicts the conceptual composition and arrangement of the EABO force at and below the MEF level. It includes recommendations for aspects of authority and task organization within the EABO.



The U.S. Coast Guard element, increased Navy integration, and BSMN interoperability are outlined above in gray, and are recommended additions to the proposed task organization found in Appendix A of Tentative Manual for Expeditionary Advanced Base Operations (HQMC, 2021). Adapted from Tentative Manual for Expeditionary Advanced Base Operations (HQMC, 2021).

Figure 2. Notional EABO Task Organization with Recommendations

(1) Additional U.S. Coast Guard Element, Navy Integration, and BSMN Interoperability

One capability specifically addressed in the case studies is the law enforcement and sub-lethal operating capacity the Coast Guard could bring to EABO (1stMARDIV, 2019).

The same sentiment is echoed in the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021), but is not specifically addressed in the tentative force structure model. The researchers recommend that a U.S. Coast Guard element with a habitual support relationship to the Marine Division or MLR (i.e., direct, or general, support) be an explicit element of the EABO task organization.

In the same vein, tight integration of U.S. Navy forces is an explicit feature of EABO (CMC, 2019; HQMC, 2021). The exact nature of this integration is unclear to the researchers, though higher-level guidance about EABO and DMO generally suggests this integration would occur down to the EAB element level (CNO, 2018; CMC, 2019). Further research and/or clarification of the joint aspect of EABO would benefit C2 research. As it relates to the suitability of BSMN, the researchers assert that any technical solution for C2 in EABO will have to be designed and implemented with joint interoperability in mind (i.e., the system will have to be made compatible with the systems of the naval force and other joint actors).

(2) Decentralization of Authorities

As illustrated in Exercise Norther Apache, EAB forces desire authorities for activities like fire support to increase their flexibility and negate the need for communication with distant, higher level commands (1/6, 2020). In respect to this, and after review and apparent concurrence of the *Tentative Manual for Expeditionary Advanced Base Operations* echelon tasking (HQMC, 2021, appx B), the researchers recommend that authorities for aviation and surface fires be vested at the LCT-level.

(3) Two separate communication models in EABO

Based on the stratification between tactical EABs and MEF-level units studied, the researchers recognize two distinct communications system environments in EABO, with the separation occurring at the digital divide (1stMARDIV, 2019). Below the digital divide, communication needs prioritize LPI/LPD, lower power requirements, longer transmission ranges, higher scalability (Wang et al., 2009, pp. 1–30), and more plentiful channels (1/6, 2020). Above the digital divide, both studies of MEF-level exercises illustrate the continued desire for high capacity (i.e., throughput and bandwidth) communications systems (MASS-6, 2019; 1stMARDIV, 2019). A more precise characterization of the separate needs for communication systems in EABO is provided below in the combined technical observations paragraph.

c. Institutional observations and recommendations

(1) Strategic Authorities for Tactical Level Commanders and Adherence to Mission Command

Marine Corps Doctrinal Publication 1–2, *Campaigning* (1997) defines the full spectrum of military actions in pursuit of national objectives in three stratifications: the strategic level of warfare is the broadest and encompasses the design and pursuit of national military objectives (HQMC, 1997, p. 9); the tactical level of warfare encompasses the actual conduct of battle, or engagement of the enemy (HQMC, 1997, p. 100); and the operational level of warfare concerns the art and science of accomplishing strategic military objectives through the planning and influence of tactical engagements (in a sense, the operational level of warfare is the figurative middle-ground between strategy and tactics) (HQMC, 1997, p. 100).

With the levels of warfare thus defined, EABO's principal function of placing dispersed tactical naval units with long-range fire support assets to deny freedom of maneuver to enemy strategic naval forces in designated littoral zones (HQMC, 2021) presents a unique stratification of the levels of warfare in this specific context, which is illustrated in Figure 3. The nature of strategic enemy targets and the extended range of tactical fire support assets means that tactical level units will interface with strategic objectives: this is a departure from previous engagements between opposing infantry/insurgent combatants, for example. Such engagements underscore the relatively higher importance of pronouncing clear guidance for tactical commanders, and particularly in cases where communications are limited. While technological solutions, like those sought in this study, could assist in overcoming environmental and enemy challenges to communication, the principles of *Command Concepts* (1999) still promote minimal communication as a sign of successful command and control. Mission command, expressed clearly, remains a critical requirement for the careful and effective application of tactical force in potentially strategic outcomes (CNO, 2018). In doing so, authority for the use of fire support assets can be delegated to a level at or below the MLR, alleviating burdens for long-haul communication and allowing the tactical force to engage enemies in a timelier manner. This contrasts with more recent conflicts where authority to launch HIMARS resided at the division level, being that HIMARS served as a reinforcing or general support asset at the MEF or division level (in the researchers' experience).

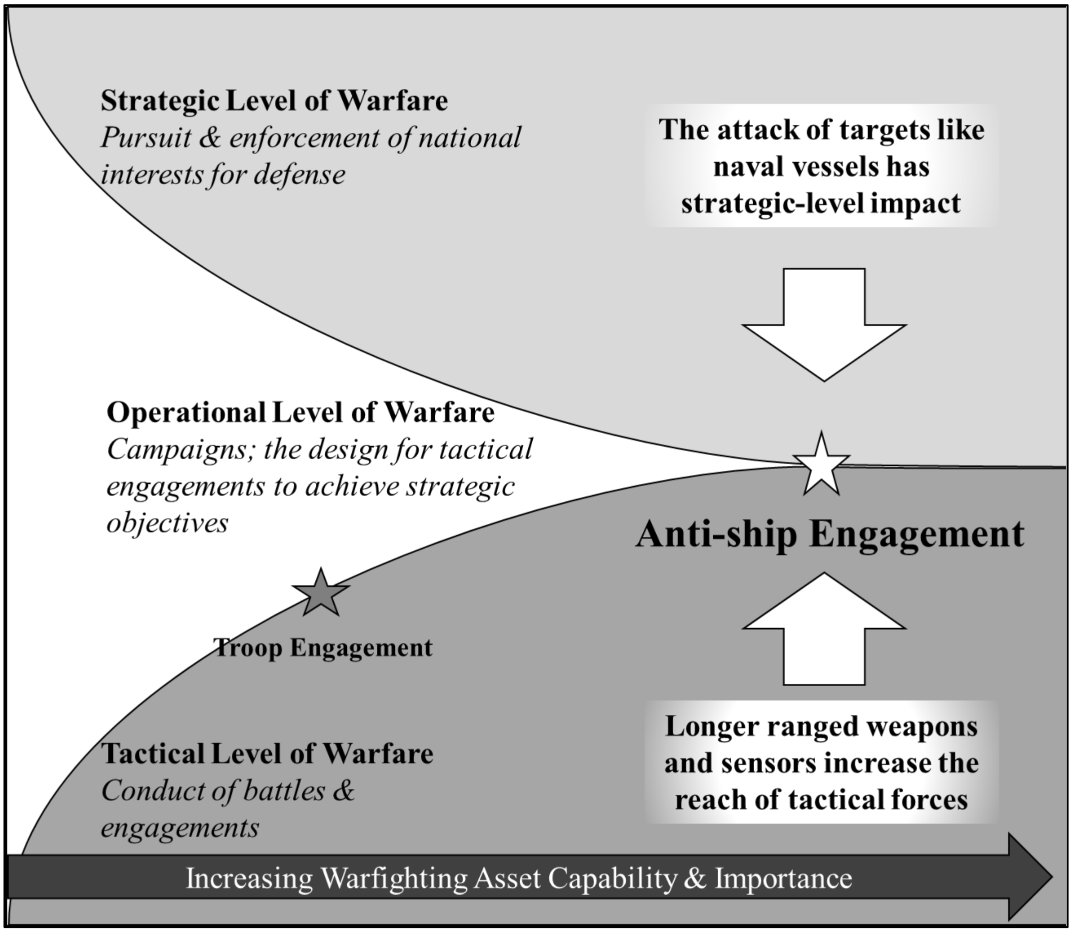


Figure 3. Illustration of Strategic, Operational, & Tactical Warfare Destratification in EABO

Such decentralization of authority for the use of this tier of fire support assets means that these commanders must now be trained and empowered as such, with emphasis on the potentially strategic-level consequences of engaging an enemy naval ship. Furthermore, commanders at the EAB require the intelligence and communication apparatus necessary to positively identify their targets and prevent the negligent engagement of civilian vessels.

(2) Renewed Focus on Mission Type Orders

The long distance between dispersed EABs is both an intended feature of EABO and a burden for communications and logistics systems needed for operations. To act dynamically in EABO, subordinates at the tactical level must be empowered to act without having to wait for communications from higher command outside of the enemy weapon engagement zone (WEZ). In the case of EABO, this will not only be time and resource intensive, but may be challenged past the point of feasibility (CMC, 2019; HQMC, 2021).

Therefore, the naval force must emphasize mission command in EABO, and empower tactical leaders to act within mission command. The empowerment includes: the timely and simple articulation of their respective commander's intent; the provision of resources with which to act effectively (e.g., intelligence and fire support assets); and vestment with the authority required take tactical action that may have strategic impact. Any technical solution offered by BSMN for communications should be implemented in a way to increase the capacity for mission command, and not enable continuous and cumbersome detail command. *MCDP-6: Command and Control* [HQMC, 2018, p. 4] gives a fictional example of just such potential for advances in C2 technology inhibiting effective mission command).

(3) The bursty rhythm of C2

The researchers have thoroughly defined and stressed the importance of mission command up to this point in the study (HQMC, 2018). Without contradicting this notion, the researchers and this study's advisor also recognize the logical correlation between the pace at which information is exchanged in a C2 system, and the tempo with which an organization is able to operate. This correlation, and particularly in the context of EABO, presents a notion which the advisor for this study, Alex Bordetsky, coined as the "bursty rhythm of C2" (email to authors, May 26–27, 2021). Thus far, the researchers have discussed bursty communications in a digital context, in which the timeframe for the transmission of information is in fractions of a second (Semtech, 2013). When considering

C2 in the EABO and in the mission command context, there is the potential for a similar phenomenon, but on a longer scale: EAB units could potentially operate within an enemy WEZ for an extended period of time (CMC, 2019; HQMC, 2021). When these units do eventually communicate with their higher headquarters, it logically follows that they would use the opportunity to transmit most of the necessary information, and particularly, the commander's updated intent. Timeframes for these broader communication bursts could be on the order of hours, days, or even weeks.

Thus, the researchers and Alex Bordetsky assert that the battle rhythm of EABO units would correlate to the bursty rhythm of C2 they are able to achieve (email to authors, 26–27 May, 2021). A higher bursty rhythm of C2 (i.e., more frequent communications of essential information like the commander's intent) are desirable to increase the tempo of operations. Again, the researchers would stress that the nature of information being passed in bursts should adhere to the nature of mission command, and because bursts are inherently intermittent, subordinates must be equipped to act in the absence of communication.

(4) Increased Billets for Liaisons

In the researchers' experience, the emphasis placed on providing liaison to external units is not uniform, but rather depends on the unit and activity in question. While some organizations only put forth their best Marines for liaison billets, as that Marine will be a representative for the unit and warfighting community, others prefer to keep their most talented and proficient Marines employed within their unit. Given not only the wide variety of occupational specialties that are likely to interact within EABO units, but the intrinsically joint nature of EABO, researchers recommend more emphasis be placed on providing knowledgeable liaisons between units and echelons of an organization. Doing so will decrease requirements for communication between units (3dMARDIV, 2019).

d. Combined Technical Observations

Table 5 combines the technical observations made in all three cases studied and is generally divided between activities above and below the aforementioned digital divide. Due to the comparatively limited information related to the technical aspects of C2 in the cases studied, the following observations should be verified through future analysis and technical study of C2 in EABO.

Table 5. Combined Technical Study Observations

Criteria	Below the Digital Divide	Above the Digital Divide
Maximum Transmission Range	30-90mi (50-150km)	90mi (150km)
Bandwidth, Data Rate Requirement/ Constraint	BW: < 60MHz DR: < 9.6kbps	DR: 3MBps - 1Gbps
Power Requirement/ Constraint	Vehicle: 50W Man-pack: 20W	Infrastructural/Unlimited
Antenna Dimension Requirement/ Constraint	Vehicle: < 32ft (10m) Man-pack: < 35ft (11m)	113ft (34.7m)
Number of Nodes/Users Served	40 ≤ x ≤ 121 nodes	> 1500 nodes

THIS PAGE INTENTIONALLY LEFT BLANK

III. TECHNICAL TESTING

A. TECHNICAL STUDY INTRODUCTION

Having characterized the key conceptual and technical aspects of C2 in EABO, the researchers then sought to identify the technical aspects of BSMN through technical modeling to compare BSMN's characteristics to the needs and limitations of C2 in EABO. While the researchers originally intended to analyze BSMN through its use with a miniaturized satellite (CubeSat) in low-earth orbit (LEO), complications with the payload hardware and delays in the launch of the transport rocket caused the researchers to opt, instead, to use conceptual modeling to analyze BSMN. This model is based on the operational communication requirements established in the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021), identified in Section II, Paragraph 5 of this study as transmission range, bandwidth, data rate capacity, power, antenna size, and number of nodes on a BSMN. A *conceptual technical model* is a theoretical composition of multiple concepts to represent the abstract relationship and interaction between technical theories to describe, explain, and illustrate a particular idea (Tatomir et al., 2018).

1. Technical Study Purpose

The purpose of the technical study is to observe and record the capabilities of BSMN relative to its use in a C2 system in a EABO environment. As discussed, the researchers seek to understand BSMN's characteristic maximum transmission range, bandwidth and data rate capacity, power requirements, antenna dimension requirements, and node service capacity.

2. Technical Study Method

This study will provide quantitative data of potential signal modulation schemes for comparison with BSMN based on operational requirements. The technical capabilities and limitations of the potential signal modulation schemes will be evaluated in terms of conceptual experimentation using small satellite link budget calculations. The evaluation criteria of potential modulation techniques will be established using a controls and variables method to determine relative correlation to performance. This experiment will help characterize elements critical to communication networks which can feasibly support EABO.

3. Technical Study End-state

The researchers sought to understand the technical characteristics of BSMN in order to compare these capabilities and requirements against the C2 capabilities and requirements of EABO, as derived from case studies.

B. TECHNICAL STUDY DESIGN

1. Overview

The scope of this technical evaluation will cover the baseline characteristics, and fixed operational capacity of two separate signal modulation techniques: Chirp Spread Spectrum (CSS) and Long Range (LoRa). The baselines used for the evaluation will be based on the published performance parameters of CSS and LoRa signal modulation techniques. However, due to the limited resources allocated for this study, the specific variables evaluated will be limited to power, data capacity, and range. Both CSS and LoRa modulation techniques have published characteristics which include favorable LPI/LPD to EABO requirements. Additionally, to limit the number of variables, this study will use published antenna performance data as a control throughout the experiment. Lastly, this study will limit the experiment to point-to-point communication observations.

2. Chirp Spread Spectrum Characteristics

As previously discussed, CSS is a spread spectrum signal modulation technique that uses wideband linear frequency modulated chirp pulses to encode information (IEEE, 2007). Employing CSS signal modulation techniques requires an assigned broad spectrum which is occupied for modulating information. Below, Ouyang and Zhao (2016) offer the mathematical representation of CSS modulation using Fresnel transform, phase, and chirp frequency as a function of time. It also depicts the bandwidth of the chirp signal and, inversely, the processing gain.

> *Most applications consider the frequency modulated (chirp) signal whose frequency evolves linearly or equivalently whose phase quadratically over time,*
>
> $$\psi(t) = e^{j\left(\pi\alpha t^2 + \varphi_0\right)},$$
>
> *where* α *is the chirp rate and* φ_0 *is an initial phase. Its instantaneous frequency is,*
>
> $$f(t) = \frac{1}{2\pi}\frac{\mathrm{d}}{\mathrm{d}t}\left[\pi\alpha t^2 + \varphi_0\right] = \alpha t.$$
>
> *If the chirp signal is temporally limited within some period T, the bandwidth of the chirp signal B is determined by the chirp rate α and the period T, i.e.,*
>
> $$B \propto (\alpha / T).$$
>
> *The time-bandwidth product* $\alpha \propto B \times T$ *indicates the processing gain of a chirp signal.*
>
> *Source: Ouyang, Zhao, (2016)*

These equations are critical in determining bandwidth, or spectral efficiency, which refers to the capacity or data rate which can be transmitted over a given bandwidth. “It is a measure of how efficiently a limited frequency spectrum is utilized by the physical layer protocol, and sometimes by the medium access control” (Miao et al., 2016, p. 124). A disadvantage of using CSS signal modulation is that it sacrifices spectral efficiency for higher processing gains. Regardless, a CSS modulated signal is appealing in cases where reliable, resilient communication is a priority, while capacity is not.

3. LoRa Modulation Characteristics

The intention of LoRa modulation is to establish a long-range network in which high data rate requirements are traded for range, signal integrity, and energy improvements. “The LoRa modulation is based on CSS scheme that uses wideband linear frequency-modulated pulses whose frequency decreases or increases over a specific amount of time based on the encoded information” (Semtech, 2013, p. 67). LoRa modulation defines the first layer in which established local area network (LAN) technologies, using mesh network architecture, increases the communication range and cell size of the network. In terms of Layer One, LoRa is a frequency (FM) modulation scheme in which end devices detect, transmit, receive, and identify manipulated radio waves with encoded information using a chirped, multi-symbol format (Ray, 2018). Additionally, the systems that support the modulation, including LoRa chips and gateways, help make up the physical layer.

LoRa nodes are the sensors or application where sensing and control takes place. These nodes are often placed remotely (e.g., sensors, tracking devices, etc.) (3GLTEinfo, 2016). These devices can be physically wired to a gateway host; however, they are generally designed to use radio communications to communicate with a gateway host for WAN communications.

LoRa nodes/end-points are the sensors or application where sensing and control takes place. These nodes are often placed remotely (e.g., sensors, tracking devices, etc.) (LoRaWAN Tutorial, n.d.). These devices can be physically wired to a gateway host (critical to LoRaWAN), however, is generally designed to use radio communications to communicate with a gateway host for WAN communications.

a. LoRa Data Rate

"LoRa provides bidirectional communication which operates in the sub-GHz unlicensed frequency bands" (Liberg, 2018). "The channel bandwidth is mainly 125 kHz for European spectrum bands, and 125 or 500 kHz for U.S. spectrum bands" (Liberg, 2018). Although LoRa sacrifices some data transfer capacity when compared to Frequency-shift Keying (FSK), it ultimately is more efficient in data transmission as it is less sensitive to noise interference during transmission and reception. LoRa uses three different bandwidth frequency bands: 125 kHz, 250 kHz, and 500 kHz (Liberg, 2018). LoRa symbols are modulated over an up-chirp frequency bandwidth and reciprocal down chirp. Additionally, it uses different orthogonal spreading factors (i.e., the rate at which the signal increases/decreases frequency) to differentiate between channels on a given bandwidth range.

As depicted in the Table 6, the data transfer rate is proportional to the spread factor (SF), which is directly corelated to the sensitivity to noise, distance a signal can be transmitted, and energy consumptions. The lower the spread factor, the higher the data transfer rates, the more sensitive it is to noise, and the more power required to complete the transmission.

$$Data\ Rate = \boldsymbol{R_b} = \boldsymbol{SF} \times \frac{\mathbf{1}}{\left(\frac{\mathbf{2^{SF}}}{\boldsymbol{BW}}\right)}\ Where{:}\ Rb = Bit\ Rate$$

Source: Semtech (2013).

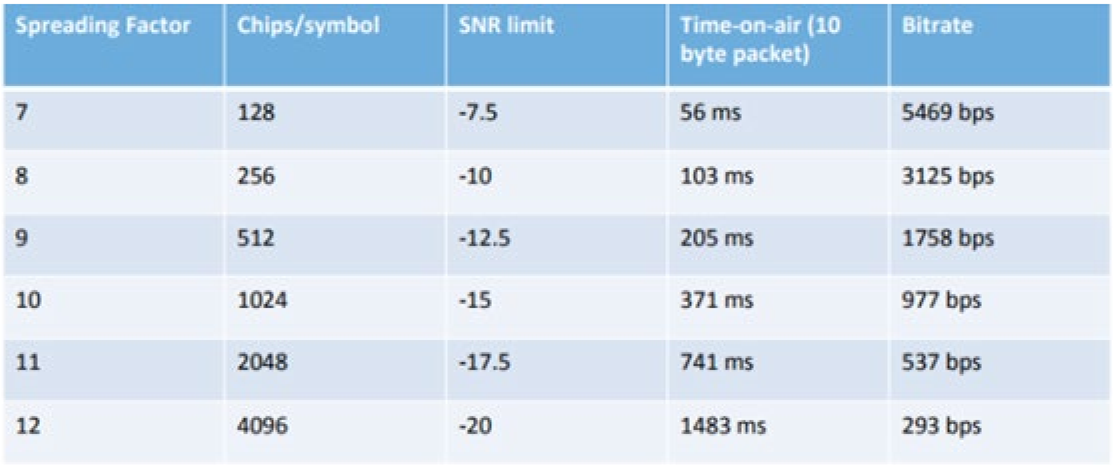
$$SF = spreading\ factor\ (7..12)$$

Source: Semtech (2013).

$$BW = Bandwidth\ (Hz)$$

Source: Semtech (2013).

Table 6. LoRa Spreading Factors at 125 kHz . Source: Semtech (2013).



Spreading Factor	Chips/symbol	SNR limit	Time-on-air (10 byte packet)	Bitrate
7	128	-7.5	56 ms	5469 bps
8	256	-10	103 ms	3125 bps
9	512	-12.5	205 ms	1758 bps
10	1024	-15	371 ms	977 bps
11	2048	-17.5	741 ms	537 bps
12	4096	-20	1483 ms	293 bps

b. LoRa Communication Channel and Signal Transmission

LoRa nodes have established chirp rates and spread factors for their transmission which are published throughout the LoRa network infrastructure. The LoRa endpoints are designed to detect specific chirp rates at specific SFs/slopes. These predetermined settings are what establishes the layer communication channel between the nodes/endpoints at the gateways. The nodes/endpoints transmit a preamble, "which can be set as a variable number of 'symbols,' which are just the number of chirps" (Ray, 2018). If there is a constant chirp at the right frequency and at the right chirp rate, a LoRa endpoint sends a reciprocal chirp, and will demodulate the signal with the encoded message. Figure 4 depicts the establishment of the LoRa layer one communication channel.

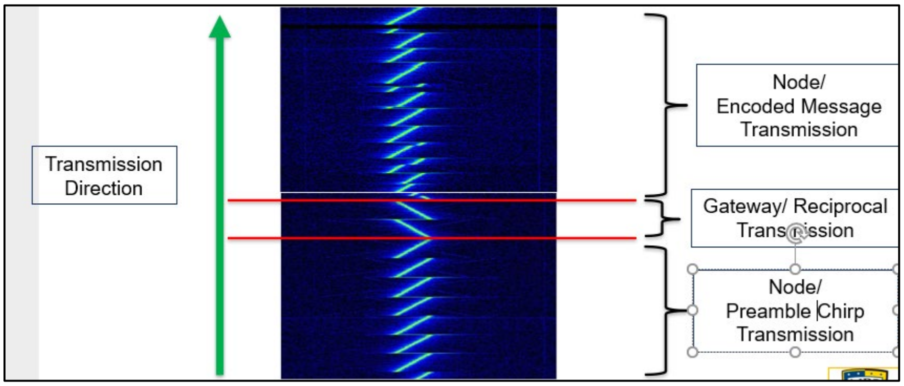


Figure 4. Illustration of LoRa Layer One Communication Channel. Source: Ray (2018).

Once the LAN is established, the LoRaWAN, defined as the system architecture and communication protocol, is responsible for implementation of functionality of remaining layers.

4. Antenna Characteristics

Antenna characteristics are critical to the functionality and performance of satellite communications. The two critical properties involved in this study are antenna gain and antenna efficiency. These two elements directly affect the link budget/link margin and are crucial in determining the S/N ratio of a communication link.

Antenna gain, the measure of input power, is transferred and concentrated through the antenna, to propagate a signal in a predetermined direction (Wayana Software, 2015). Antenna gain is represented in the following equation where η is the antenna efficiency, D is the diameter of the antenna, and λ is the wavelength of the signal:

$$G_t = \eta(\pi D/\lambda)^2$$

Source: Wayana Software (2015).

Antenna efficiency is the ratio of the amount power output from an antenna to the amount of power input to the antenna (Bevelacqua, 2016).

$$\eta = \text{antenna efficiency (unitless)} = P_{output}/P_{input}$$

Source: Bevelacqua (2016).

"An ideal antenna has 100% antenna efficiency (i.e., it transmits all the power fed to it). But in the real world, a good antenna radiates only 50 to 60% of power supplied to it" (everythingRF, 2018). As such, this study incorporates a randomly generated antenna efficiency from 50 to 60% as represented in the graph below for a center frequency of 920 MHz. Figure 5 depicts the relationship between antenna gain, efficiency, and the frequency of transmission.

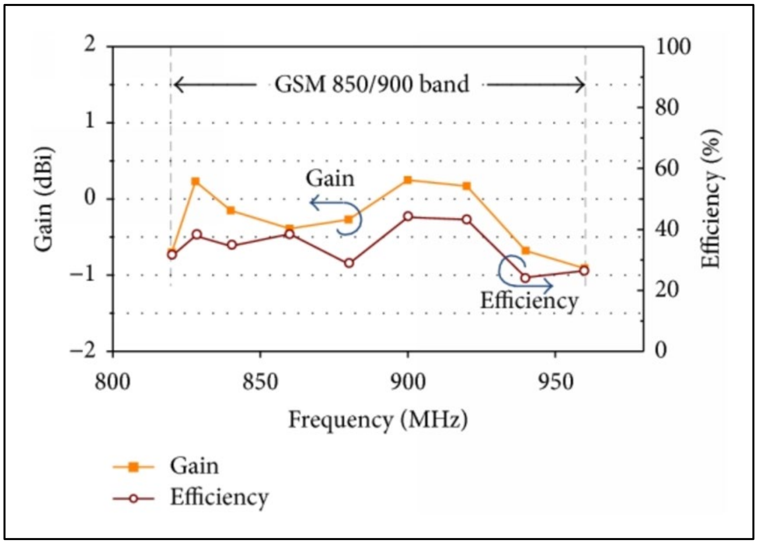


Figure 5. Antenna Efficiency, Gain, & Frequency Relationship.
Source: Hong et al. (2014).

5. Link Budget Evaluations

To evaluate both CSS and LoRa signal modulations as viable techniques to support BSMNs, we must establish common controls, and dependent and independent variables.

Since LoRa is a derivative of CSS, the researchers evaluated both modulation schemes under the same circumstances to determine effectiveness and applicability of supporting point-to-point communications. In this scenario, a ground-to-ground terminal, or a ground-to-airborne terminal (high altitude), are synonymous with point-to-point communications. Additionally, both terminals are considered stationary and are the only two nodes of communication on the established link. Lastly, the following variables were held in constant throughout the evaluations:

- Transmitter Power: 0.5 W for CSS and 0.158 Watts (Maximum Power output for LoRa devices) for LoRa
- Bandwidth: 125 kHz. Minimum bandwidth design for LoRa devices
- Center Frequency: 920 MHz
- Antenna Efficiency: 0.5-0.6
- Antenna Size: 2 meters
- Receiver Sensitivity: -137 dB
- Noise Floor: 6 dB

Holding these elements in constant allowed the researchers to determine how range (independent variable) effects the feasibility of establishing a viable communication link in terms of link budget/link margin, and S/N ratio (dependent variables).

- Range (Independent Variable)
- Link Budget/Link Margin (Dependent Variable)
- Signal to Noise (S/N) Ratio (Dependent Variable)
- Data Capacity (Dependent Variable)

To complete the evaluation, the researchers established six benchmarks for the independent variable at 1, 25, 50, 100, 400, and 500 kilometers to determine the impacts on Link Budget/Link Margin, S/N ratio, and data capacity. The first benchmark (1 km) is used to demonstrate the functionality of the communication link at near ideal conditions.

The next three benchmarks (25, 50, and 150 km) were established in Table 4, Combined technical study observations, as maximum transmission ranges of current forces, using traditional communication network topologies and equipment, while operating below the digital divide. The last two benchmarks (400–500 km) were established as required operating ranges above the digital divide, as well as being the altitude above the earth's surface at which LEO satellites operate in orbit. As the range between communication nodes increases, communication links start to succumb to external factors, like atmospheric attenuation, physical obstacles, free space loss, noise and other signal interference, which degrade signal propagation. These degradations become more significant at greater ranges and create significant challenges for the propagated signal to overcome and have been built into the testing models for both CSS and LoRa signal modulation schemes.

The following equations have been established to determine the S/N involved with propagating a CSS modulated signal. First, the researchers determined the antenna gains for both the transmitter and receiver. For initial testing, researchers recommended using the same antenna settings to ensure consistent performance and maintain experiment controls. As previously discussed, the equation for antenna gain is:

$$Gt = \eta(4\pi A/\lambda^2) = \eta(\pi D/\lambda)^2$$

$$\eta = \text{antenna efficiency (unitless)} \rightarrow 0.5\text{ -}0.9 \text{ typical}$$

$$A = \text{area of antenna (meters}^2\text{)}$$

$$D = \text{diameter of antenna (meters)} \rightarrow \text{circular areas only}$$

$$\lambda = \text{wavelength of signal (meters)}$$

Also, the researchers needed to determine the wavelength of the propagated signal. Since they have established a center frequency of 920 MHz, the researchers used the following equation to determine wavelength:

$$f = c/\lambda$$

$$c = \text{speed of light} = 2.98 \text{ x } 10^8 \text{ m/s}$$

$$\lambda = c/f$$

$$\lambda = (2.98 \text{ x } 10^8 \text{ m/s})/920\text{MHz}$$

$$\lambda = 0.324 \text{ m}$$

Next the researchers accounted for free space loss, which is the diminishing signal strength as it travels between two antennas (Bevelacqua, 2016). Free space loss is determined by the distance between two antennas, which the researchers varied among the six established benchmarks to determine the effect range has on signal propagation. The researchers used the following equations for free space loss:

$$Lfs = (\lambda/4\pi R)^2$$

$$R = \text{distance between antennas}$$

Lastly, the researchers used the following equation to determine the strength of the propagated signal:

$$\text{Signal (in dB)} = P_t + G_t + \text{Line Loss}_t + G_r + \text{Line Loss}_r + L_{fs} + \text{Attenuation}$$

$$P_t = \text{Power at the transmitter}$$

$$G_t = \text{Antenna gain at the transmitter}$$

$$\text{Line Loss}_t = \text{Line loss at the transmitter}$$

$$G_r = \text{Antenna gain at the receiver}$$

$$\text{Line Loss}_r = \text{Line loss at the receiver}$$

$$L_{fs} = \text{free space loss}$$

Attenuation

Applying the established controls (a consistent power of 0.5 W, antenna diameter of 0.5 meters, transmitter/receiver line loss of 0.9 dB each, and attenuation of -0.1 dB), the researchers were able to determine a CSS propagated signal strength.

The last step is determining the S/N ratio, which required the researchers to determine the noise for each scenario of the experiments. Once determined, the researchers maintained a constant noise level throughout the experiment. The following equation was used to determine noise:

$$N \text{ in dB} = 10 \text{ x } \log_{10} (kTB)$$

$$k = \text{Boltzmann's constant} = 1.38 \text{ x } 10\text{–}23 \text{ Joules/K}$$

$$T = \text{temperature in Kelvin}$$

$$B = \text{bandwidth of receiver in Hz}$$

$$N = 10 \text{ x } \log_{10} (1.38 \text{ x } 10\text{–}23 \text{ Joules/K}) \text{ x } (305.37 \text{ K}) \text{ x } (125{,}000{,}000 \text{ Hz})$$

$$N = -122.78 \text{ dB}$$

For the temperature in Kelvin, the researchers used a constant 305.37 degrees K as it converts to 90 degrees Fahrenheit, which is similar to conditions in the INDOPACOM AOR. Additionally, the constant bandwidth of 125 MHz was applied. As a result, the consistent noise level for this experiment was -122.78 dB.

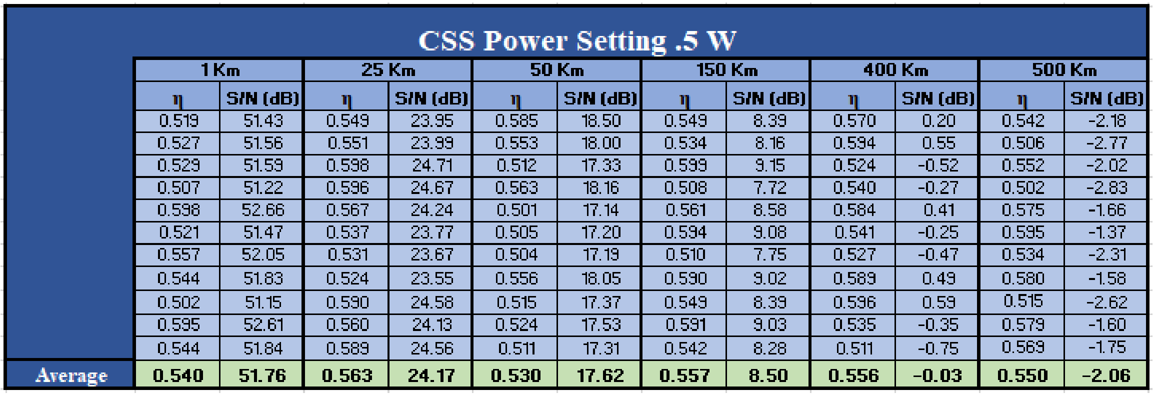
To complete the S/N ratio assessment, the researchers then subtracted the calculated noise from the calculated propagated signal to determine the S/N ratio per range, given a randomized antenna efficiency between 0.5 and 0.6.

To determine a S/N ratio for LoRa modulation, the researchers conducted the same process as CSS, however, included a change in power output, reducing it from 0.5W for

CSS to 0.158W for LoRa as it is the published maximum power output for LoRa nodes/devices.

C. TECHNICAL STUDY OBSERVATIONS AND FINDINGS

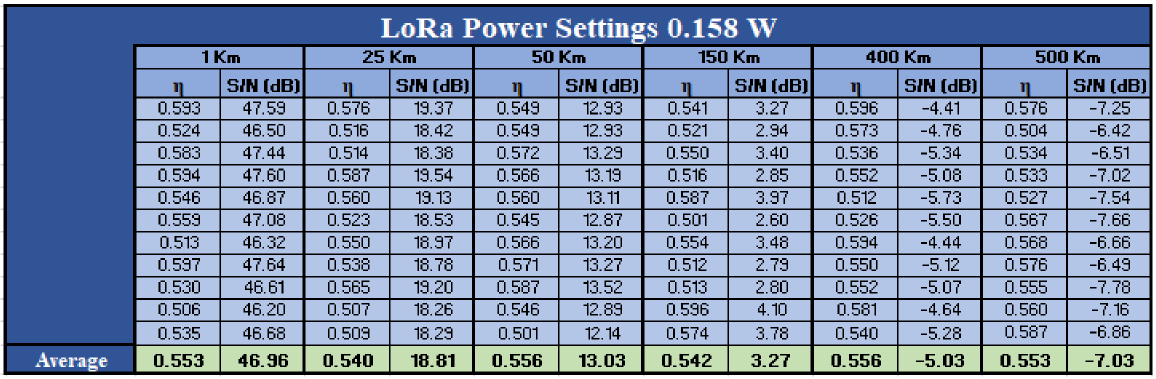
The researchers model included a total of 500 observations per established range benchmark, given a randomized antenna efficiency to determine an average S/N ratio. These observations were conducted for both CSS modulation with 0.5W and LoRa modulation with 0.158W of power output, respectively. Figure 6 is an excerpt from the model tables demonstrating variation and averages of antenna efficiency and S/N ratio for CSS at 0.5 W of output power, while Figure 7 depicts a LoRa power output of 0.158 W.



CSS Power Setting .5 W

	1 Km		25 Km		50 Km		150 Km		400 Km		500 Km	
	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)
	0.519	51.43	0.549	23.95	0.585	18.50	0.549	8.39	0.570	0.20	0.542	-2.18
	0.527	51.56	0.551	23.99	0.553	18.00	0.534	8.16	0.594	0.55	0.506	-2.77
	0.529	51.59	0.598	24.71	0.512	17.33	0.599	9.15	0.524	-0.52	0.552	-2.02
	0.507	51.22	0.596	24.67	0.563	18.16	0.508	7.72	0.540	-0.27	0.502	-2.83
	0.598	52.66	0.567	24.24	0.501	17.14	0.561	8.58	0.584	0.41	0.575	-1.66
	0.521	51.47	0.537	23.77	0.505	17.20	0.594	9.08	0.541	-0.25	0.595	-1.37
	0.557	52.05	0.531	23.67	0.504	17.19	0.510	7.75	0.527	-0.47	0.534	-2.31
	0.544	51.83	0.524	23.55	0.556	18.05	0.590	9.02	0.589	0.49	0.580	-1.58
	0.502	51.15	0.590	24.58	0.515	17.37	0.549	8.39	0.596	0.59	0.515	-2.62
	0.595	52.61	0.560	24.13	0.524	17.53	0.591	9.03	0.535	-0.35	0.579	-1.60
	0.544	51.84	0.589	24.56	0.511	17.31	0.542	8.28	0.511	-0.75	0.569	-1.75
Average	0.540	51.76	0.563	24.17	0.530	17.62	0.557	8.50	0.556	-0.03	0.550	-2.06

Figure 6. CSS Modulation with a 0.5-Watt Power Output



LoRa Power Settings 0.158 W

	1 Km		25 Km		50 Km		150 Km		400 Km		500 Km	
	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)	η	S/N (dB)
	0.593	47.59	0.576	19.37	0.549	12.93	0.541	3.27	0.596	-4.41	0.576	-7.25
	0.524	46.50	0.516	18.42	0.549	12.93	0.521	2.94	0.573	-4.76	0.504	-6.42
	0.583	47.44	0.514	18.38	0.572	13.29	0.550	3.40	0.536	-5.34	0.534	-6.51
	0.594	47.60	0.587	19.54	0.566	13.19	0.516	2.85	0.552	-5.08	0.533	-7.02
	0.546	46.87	0.560	19.13	0.560	13.11	0.587	3.97	0.512	-5.73	0.527	-7.54
	0.559	47.08	0.523	18.53	0.545	12.87	0.501	2.60	0.526	-5.50	0.567	-7.66
	0.513	46.32	0.550	18.97	0.566	13.20	0.554	3.48	0.594	-4.44	0.568	-6.66
	0.597	47.64	0.538	18.78	0.571	13.27	0.512	2.79	0.550	-5.12	0.576	-6.49
	0.530	46.61	0.565	19.20	0.587	13.52	0.513	2.80	0.552	-5.07	0.555	-7.78
	0.506	46.20	0.507	18.26	0.546	12.89	0.596	4.10	0.581	-4.64	0.560	-7.16
	0.535	46.68	0.509	18.29	0.501	12.14	0.574	3.78	0.540	-5.28	0.587	-6.86
Average	0.553	46.96	0.540	18.81	0.556	13.03	0.542	3.27	0.556	-5.03	0.553	-7.03

Figure 7. LoRa Modulation with a 0.158-Watt Power Output

As depicted, for both CSS and LoRa modulations, there is an inverse relationship between transmission range and S/N ratio: as the range of transmission increases, the S/N ratio decreases. There are multiple factors which can be attributed to this relationship, however, for this study the researchers focused on power output. Also, depicted in Figure 8, at each respective range the S/N ratio of the CSS modulation technique is slighter higher than the LoRa modulation.

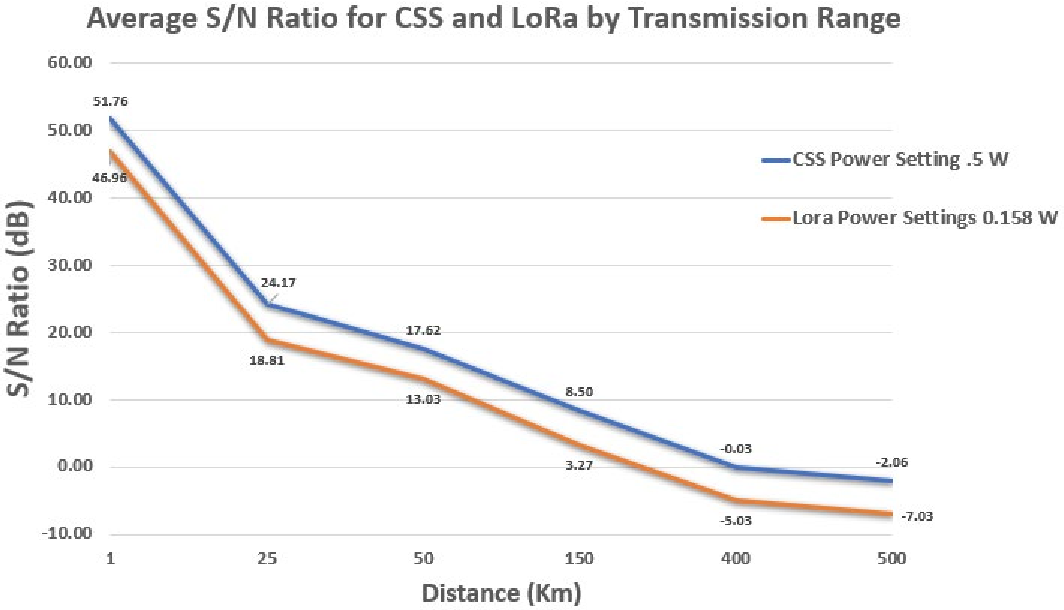


Figure 8. Average S/N Ratio for CSS and LoRa Modulations by Transmission Range

For this experiment, the researchers have attributed this effect to the higher power output of CSS versus LoRa. However, these results do not infer that CSS is more effective or appropriate. Since LoRa is a derivative of CSS, the researchers deduct that both CSS and LoRa have similar characteristics, and that given the same power output, theoretically, should produce similar S/N ratio.

Using the established noise floor constant of 6 dB, being the level at which the propagated signal can no longer be detected, received, demodulated, and decoded appropriately due to noise interference, this evaluation demonstrates that the theoretical effectiveness of CSS modulation technique can support signal propagation up to approximately 150 km. LoRa modulation, however, can support approximately 125 km. Regardless, both modulation techniques can only support signal propagation below the established digital divide. However, as the transmission range extends over 100 km and approaches the noise floor, it is a reasonable assumption that loss of transmission signal due to movement of antennas, atmospheric attenuation, change in atmospheric temperature, interference, absorption, terrain, signal diffraction, etc., is likely, and the successful transmission and receipt of the propagated signal is diminished. These are all areas in which further research and field testing is required to determine the practicality of each propagation technique to support the employment of BSMNs in EABO.

D. SUITABILITY ANALYSIS OF BSMN FOR C2 IN EABO

The purpose of this study was to determine the feasibility of employing a low power, LPI/LPD BSMN to support C2 of EABO in the INDOPACOM AOR. Using the guidance established in this study, DOD forces are mandated to diligently manage their EM signature in support of force protection and survivability. As demonstrated, CSS and LoRa modulation techniques provide potential solutions to difficult C2 and communication topology challenges presented by EABO.

Using this model and the demonstrated positive effects that power output has on S/N ratio, the researchers believe that CSS and LoRa modulation techniques employed in a BSMN are potential solutions to support C2 and communication topologies while conducting DMO and EABO. Although this study demonstrated that CSS and LoRa modulation techniques were effective below the digital divide (150 km), it may be possible to support communications above the digital divide by simply increasing power output. The researchers recommend caution in interpreting this as a viable solution to support communication above the digital divide as it contests operational guidance from the DOD. By increasing power output by as little as 5 Watts, the S/N would meet the requirement to support communications up to 500 km. However, at 5 Watts, transmitters also become more susceptible to signal and physical detection by adversarial forces through use of EM signature detection capabilities and direction finding. Once located, adversarial forces can target friendly forces to disrupt operations. This is concerning as it directly impacts force protection efforts and increases risk to force and risk to mission while conducting EABO.

Additionally, DMO and EABO require efficient use of limited resources, one of which is power and power generation. By increasing power output, forces would decrease their power resources, and require additional logistical support and additional resupply efforts. This too increases risk to force and risk to mission as more movements create greater opportunity for adversaries to track, locate, and target DOD forces.

This study has identified specific performance characteristics of CSS and LoRa signal modulation techniques which are effective below the digital divide (<150 km), however, both CSS and LoRa modulation techniques require further modification, amplification, and testing to determine their suitability above the digital divide (> 150 km). This study is the first iteration of a larger research effort to research and develop suitable signal modulation techniques to create an effective BSMN using land-based, mobile, and space-based terminal. This study has demonstrated the theoretical point-to-point communication link (land-based and mobile terminals); however, follow-on study will be required to research the viability of including spaced-based terminal in the current BSMN topology.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. FINANCIAL ANALYSIS

A. FINANCIAL STUDY INTRODUCTION

1. Financial Study Purpose

The purpose of the financial study is to determine the financial viability of BSMN technology for use as a broader C2 system. In particular, the researchers seek to determine the financial requirements and feasibility of acquiring, developing, deploying, and maintaining the software and hardware required to establish a space-based terminal to include in a BSMN topology.

2. Financial Study Method

This study will use open-source cost structures of three commercial space development and launch companies to provide quantitative data for cost comparison and estimation. The researchers will use these results will help create a model to estimate a CubeSat program life cycle cost structure. The projected program cost estimates will be compared to current space-based programs to determine relative cost in reference to established satellite program budgets.

3. Financial Study End-state

The researchers seek to understand the total costs and budget requirements of acquiring, developing, deploying, and maintaining the software and hardware required to include space-based terminals to support a BSMN topology.

4. Financial Study Design

The previous chapters presented a possible low power, efficient modulation scheme as foundation to the employment of a BSMN in support of EABO. Ultimately, this research is to evaluate the feasibility of a BSMN through the employment of a CubeSat constellation, whose infrastructure id low-cost, low maintenance, while maintaining its global effectiveness. This chapter will analyze the cost for acquiring, developing, deploying, and maintaining the software and hardware required to establish a space based

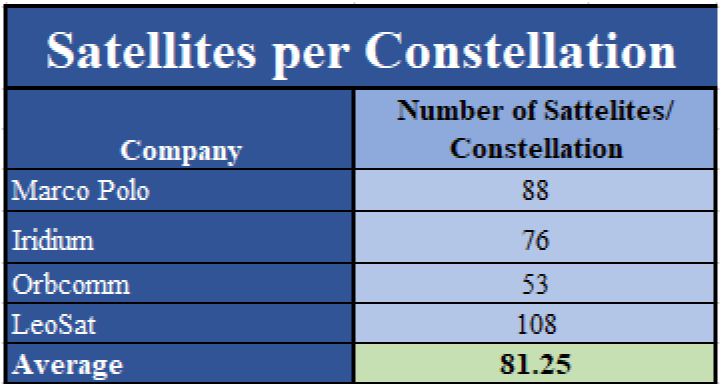
BSMN terminals. Cost estimates and budgets will be based on commercial satellite industry standards from spaceflight development companies' published pricing schedules. An average of those pricing schedules will be used to create an acquisition model and propose a program life cycle for space-based terminals to support BSMNs.

Size of Bursty-Signal Mesh Network. This study will include projected costs of a 100-satellite constellation to support large scale coverage to multiple AORs across the globe. Since the projected CubeSat constellation will be deployed in a LEO orbit (approx. altitude 400–500 km), the orbital period of a satellite, which is the time it takes make one revolution around the earth, will be between 92–94 minutes and will be traveling at approximately 7.7 km/s.

These characteristics effect the maximum communication interval, which is the time a ground terminal can communicate with the satellite while it passes overhead. Generally, a satellite at LEO must be a minimum of 15 degrees above the horizon, horizontal plane, from the ground station in order to establish a LOS communication link (Cakaj et al., 2014). However, due to high rate of travel of a LEO satellite, the communication interval is very minimal (e.g., 3–5 minutes on average for altitudes of 400–500 km) per orbital period (Dredge & Timmins, 2017).

To mitigate the gap between satellite communication intervals, organizations must deploy a multi-satellite constellation to maintain a continuous communication link. The required number of satellites to support continuous coverage depends on the orbital characteristics of the constellation, however, commercial industry has provided a benchmark in which the researchers determined a projected number of satellites to support the constellation by average current commercial LEO constellations.

This study referenced four commercial spaceflight and satellite companies which operate multi-satellite LEO constellation with global coverage. Although, there are many of companies which are currently operating, or intend to operate mega constellations with hundreds and thousands of CubeSats at LEO, this study focused on balancing costs and functionality of a space-based terminals to support a BSMN. As a result, the researchers focused on minimum number of satellites required to support such priorities. Represented in Figure 9, the average number of satellites required for global coverage is 81.25. Accounting for maintenance issues, loss of functionality, and required redundancy, the researchers used determined that developing 100 CubeSats was a realistic requirement for this study. This number will be used to support the cost estimation of the payload and launch requirements of the CubeSat constellation.



Satellites per Constellation

Company	Number of Sattelites/ Constellation
Marco Polo	88
Iridium	76
Orbcomm	53
LeoSat	108
Average	**81.25**

Adapted from Marco Polo (2020), Iridium Satellite Communications (2021), ORBCOMM (2021), and LeoSat (2021).

Figure 9. Average Number of Satellites in LEO Constellations

B. COST COMPONENTS AND ESTIMATION

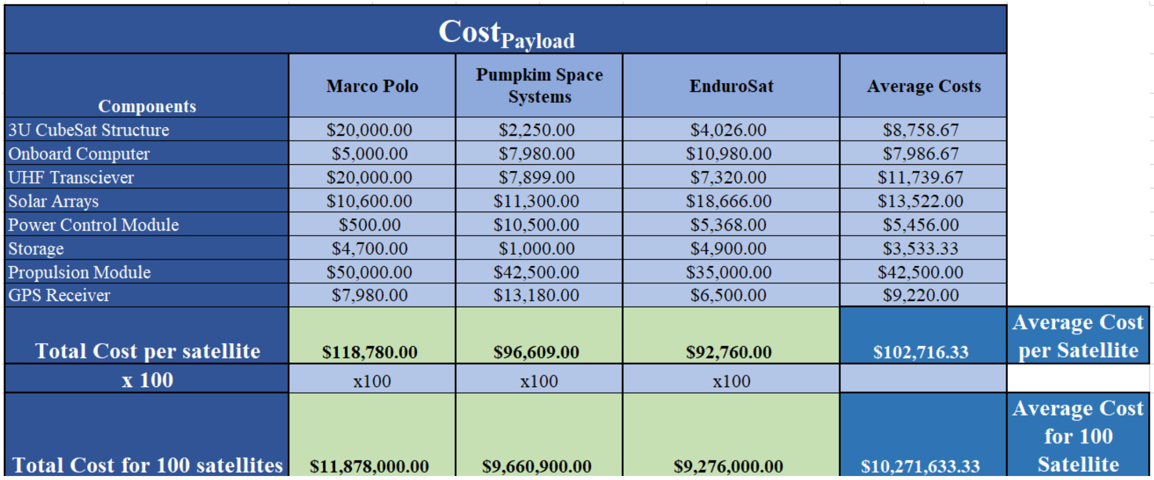
Cost components for a space-based satellite program are generally made up of four sections of development: 1) payload, 2) ground stations, 3) personnel, operations, and maintenance, and 4) launch. The sum of the costs of each section makes up the total cost of a space-based satellite program. As such the following equation can be used to demonstrate total costs of the program (Heyman, 2009):

$$Cost_{Total} = Cost_{Payload} + Cost_{GroundStation} + Cost_{PO\&M} + Cost_{Launch}$$

Using this cost equation, the researchers can develop projected estimations for each of the four sections. Each section contains several components which will be identified, and cost averaged per industry standards. Figure 10 depicts the average of three commercial spaceflight companies and their published pricing schedules. Using these pricing schedules, the researchers can develop a model to depict the total cost of a CubeSat constellation to support a BSMN.

1. Cost of Payload Development

Cost of payload development is the first element is the cost structure equation. The researchers evaluated and averaged the costs of critical components of three commercial satellite development companies. Figure 10 demonstrates the required components and average associated costs with regard to development and construction of a one 3U CubeSat. “U” stands for unit, which is a common unit of measure describing size of a CubeSat. The dimensions of one “U” are equal to 10cm x 10cm x 10cm cube (NASA, 2017). Thus, the 3U satellite used for this study is equivalent to 10cm x 10cm x 30cm structure. A 3U is required to maintain all the physical components of a designed CubeSat listed in Figure 10. Since the projected constellation consists of 100 CubeSats, the researchers multiply the average cost by 100.



$\text{Cost}_{\text{Payload}}$

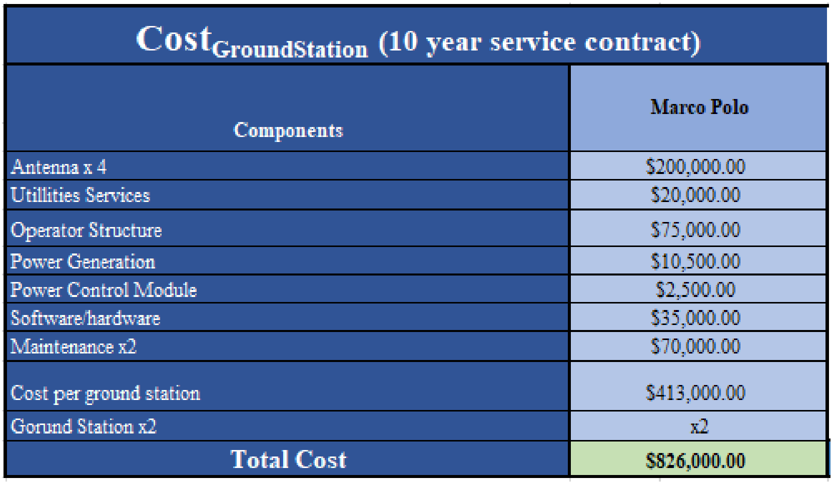
Components	Marco Polo	Pumpkim Space Systems	EnduroSat	Average Costs	
3U CubeSat Structure	$20,000.00	$2,250.00	$4,026.00	$8,758.67	
Onboard Computer	$5,000.00	$7,980.00	$10,980.00	$7,986.67	
UHF Transciever	$20,000.00	$7,899.00	$7,320.00	$11,739.67	
Solar Arrays	$10,600.00	$11,300.00	$18,666.00	$13,522.00	
Power Control Module	$500.00	$10,500.00	$5,368.00	$5,456.00	
Storage	$4,700.00	$1,000.00	$4,900.00	$3,533.33	
Propulsion Module	$50,000.00	$42,500.00	$35,000.00	$42,500.00	
GPS Receiver	$7,980.00	$13,180.00	$6,500.00	$9,220.00	
Total Cost per satellite	**$118,780.00**	**$96,609.00**	**$92,760.00**	**$102,716.33**	**Average Cost per Satellite**
x 100	x100	x100	x100		
Total Cost for 100 satellites	**$11,878,000.00**	**$9,660,900.00**	**$9,276,000.00**	**$10,271,633.33**	**Average Cost for 100 Satellite**

Adapted from Marco Polo (2020), Pumpkin Space Systems (2021), and EnduroSat (2021).

Figure 10. Average Payload Development Costs

2. Cost of Ground Station Development

The second cost component is the ground station development. The ground station is required to communicate with and control the operational functions of the CubeSat constellation. A constellation requires multiple ground stations, while each ground station requires a minimum of four antennas to handle to communication load of the constellation (Marco Polo, 2020). Figure 11 depicts the cost components of developing and maintain a ground station for a period of ten years. Since two ground stations are required, the total cost figure list in Figure 11 includes costs per each ground station.



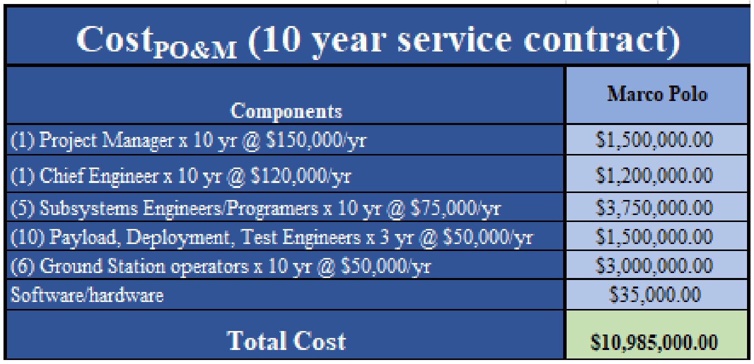
$\text{Cost}_{\text{GroundStation}}$ (10 year service contract)

Components	Marco Polo
Antenna x 4	$200,000.00
Utilities Services	$20,000.00
Operator Structure	$75,000.00
Power Generation	$10,500.00
Power Control Module	$2,500.00
Software/hardware	$35,000.00
Maintenance x2	$70,000.00
Cost per ground station	$413,000.00
Gorund Station x2	x2
Total Cost	**$826,000.00**

Figure 11. Ground Station Development and 10-Year Service Cost. Source: Marco Polo (2020).

3. Cost of Personnel, Operations, and Maintenance

The personnel and labor associated with the development, operations, and maintenance of the CubeSat constellations are the costliest component of the project. Personnel are responsible for the design, manufacturing, assembly, launch support, monitoring, operation, and maintenance of every CubeSat launched into orbit. As depicted on Figure 12, the costs associated with personnel are generally salary over a ten-year service contract, which accounts for a 2% percent performance raise each year. Additionally, the costs associated with the hardware/software upgrades throughout the life of the program are listed.



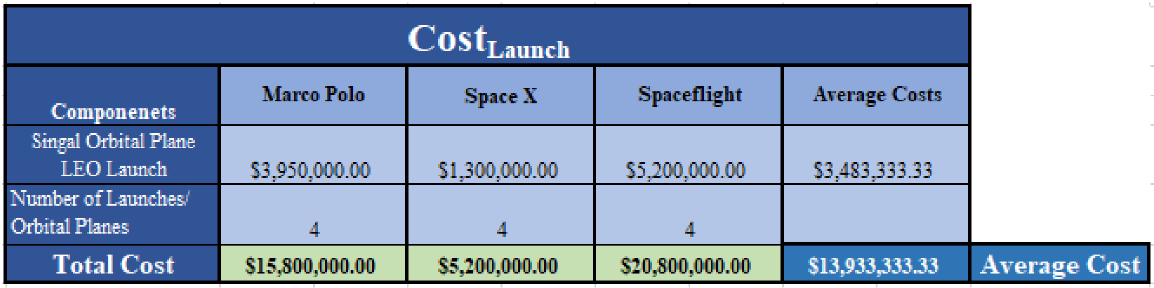
$\text{Cost}_{\text{PO\&M}}$ (10 year service contract)

Components	Marco Polo
(1) Project Manager x 10 yr @ $150,000/yr	$1,500,000.00
(1) Chief Engineer x 10 yr @ $120,000/yr	$1,200,000.00
(5) Subsystems Engineers/Programers x 10 yr @ $75,000/yr	$3,750,000.00
(10) Payload, Deployment, Test Engineers x 3 yr @ $50,000/yr	$1,500,000.00
(6) Ground Station operators x 10 yr @ $50,000/yr	$3,000,000.00
Software/hardware	$35,000.00
Total Cost	**$10,985,000.00**

Figure 12. Personnel, Operations, and Maintenance Cost. Source: Marco Polo (2020).

4. Costs of Constellation Launch

The fourth and final component is the costs associated with launching the payload into orbit. This is contracted through commercial spaceflight companies which have developed ride share programs which serve multiple customers and multiple payloads who share the same launch timeline and orbit altitude. The rideshare programs have significantly decreased the cost of launching payloads into space as the total launch costs are spread throughout all customers and is relative to payload size. For this study, the researchers referenced the price schedules of three commercial companies for a single orbital plane, LEO launch. To service the largest area possible with a BSMN, the constellation will operate on multiple orbital planes. As such, each orbital plane requires a separate launch vehicle as each vehicle is schedule to achieve a predetermined altitude to deploy its payload. This designated altitude cannot be altered or deviated from post-launch. Thus, for this study, the researchers have separated the constellation into four separate orbital planes, which will require four separate launches containing 25 CubeSats scheduled for each launch. As depicted in Figure 13., this study has calculated an average total cost of a four-launch schedule.



$Cost_{Launch}$					
Componenets	**Marco Polo**	**Space X**	**Spaceflight**	**Average Costs**	
Singal Orbital Plane LEO Launch	$3,950,000.00	$1,300,000.00	$5,200,000.00	$3,483,333.33	
Number of Launches/ Orbital Planes	4	4	4		
Total Cost	**$15,800,000.00**	**$5,200,000.00**	**$20,800,000.00**	**$13,933,333.33**	**Average Cost**

Adapted from Marco Polo (2020), Space X (2021), and Spaceflight (2021).

Figure 13. Average Launch Cost

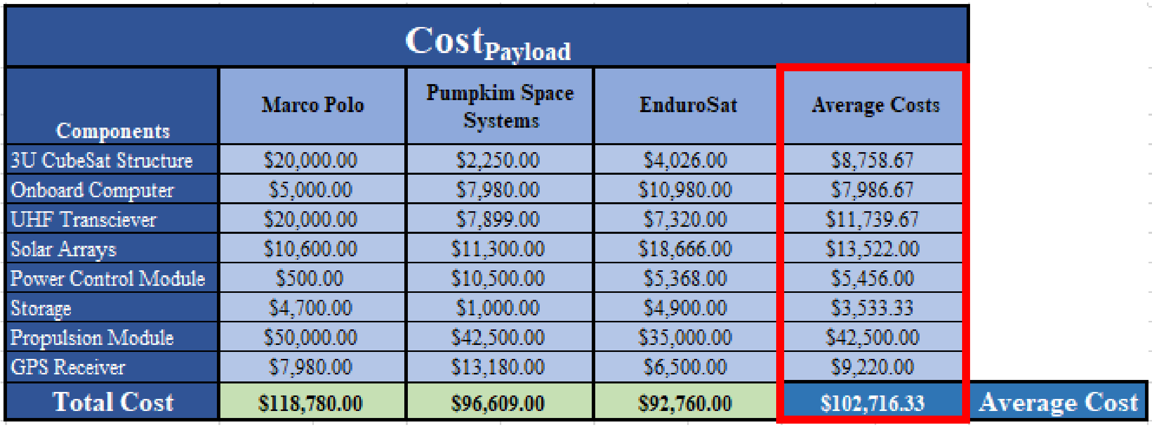
C. TOTAL COMPONENT COSTS

Using the equation presented in Section B.2 in this chapter (Heyman, 2009),

$$Cost_{Total} = Cost_{Payload} + Cost_{GroundStation} + Cost_{PO\&M} + Cost_{Launch}$$

we can present estimated total cost of acquiring, developing, deploying, and maintaining the software and hardware required for space-based terminals. The estimated total cost of the 100 CubeSat constellation is: $36,011,966.33. However, this is a very small data sample does not provide much confidence in the financial data presented as it does not account for many variances of potential pricing changes. As a result, the researchers developed a cost forecasting model to add confidence to the dataset and into the financial analysis.

Cost Forecasting Model. Since there is limited data regarding industry pricing schedule surrounding each of the four cost components for $Cost_{Total}$, this study presents a forecasting model to help build confidence and identify variance within industry pricing to support this research. To establish the model, the researchers started by building a robust the data set. The researchers created a formula to simulate the average cost of production of each component and subcomponent of the $Cost_{Total}$ formula. This calculation required the average costs of each subcomponent, highlighted in the red box depicted in Figure 14, to incur a randomized 1–15 percent increase in production costs. These average costs were used for each of the four cost components.



$\text{Cost}_{\text{Payload}}$

Components	Marco Polo	Pumpkim Space Systems	EnduroSat	Average Costs	
3U CubeSat Structure	$20,000.00	$2,250.00	$4,026.00	$8,758.67	
Onboard Computer	$5,000.00	$7,980.00	$10,980.00	$7,986.67	
UHF Transciever	$20,000.00	$7,899.00	$7,320.00	$11,739.67	
Solar Arrays	$10,600.00	$11,300.00	$18,666.00	$13,522.00	
Power Control Module	$500.00	$10,500.00	$5,368.00	$5,456.00	
Storage	$4,700.00	$1,000.00	$4,900.00	$3,533.33	
Propulsion Module	$50,000.00	$42,500.00	$35,000.00	$42,500.00	
GPS Receiver	$7,980.00	$13,180.00	$6,500.00	$9,220.00	
Total Cost	**$118,780.00**	**$96,609.00**	**$92,760.00**	**$102,716.33**	**Average Cost**

Adapted from Marco Polo (2020), Iridium Satellite Communications (2021), ORBCOMM (2021), and LeoSat (2021).

Figure 14. Average Payload Development Costs

The following equation was used to simulate average cost of production:

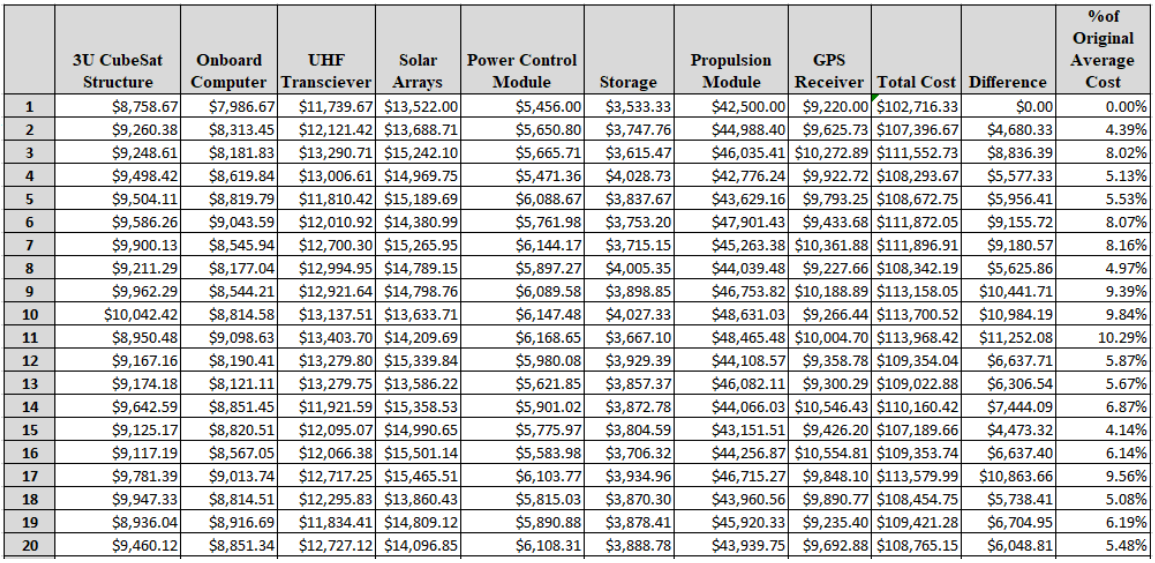
Total Average $\text{Cost}_{\text{subcomponent}}$ =

(Average $\text{Cost}_{\text{subcomponent}}$ x Rand(1-15%) + Average $\text{Cost}_{\text{subcomponent}}$)

Example:

- Average $\text{Cost}_{\text{subcomponent}}$: $8,758.67
- Randomized function produces: 7%
- Total Average $\text{Cost}_{\text{subcomponent}}$ =
    - ($8,758.67 x 0.07) +$8,758.67 = $9,371.78

This study conducted 1000 iterations of this equation for each cost subcomponent to simulate cost variances. Then the researchers used the produced data set to calculate average cost over the 1000 interactions. The average cost of each subcomponent was then added together to produce an average total cost for each cost component (i.e., $\text{Cost}_{\text{Payload}}$; $\text{Cost}_{\text{GroundStation}}$; $\text{Cost}_{\text{PO\&M}}$; $\text{Cost}_{\text{Launch}}$). Figure 15 depicts portion of the data set produced for the $\text{Cost}_{\text{Payload}}$ subcomponents. Finally, the average total of the $\text{Cost}_{\text{Payload}}$ was used to build the forecasting model.



	3U CubeSat Structure	Onboard Computer	UHF Transciever	Solar Arrays	Power Control Module	Storage	Propulsion Module	GPS Receiver	Total Cost	Difference	%of Original Average Cost
1	$8,758.67	$7,986.67	$11,739.67	$13,522.00	$5,456.00	$3,533.33	$42,500.00	$9,220.00	$102,716.33	$0.00	0.00%
2	$9,260.38	$8,313.45	$12,121.42	$13,688.71	$5,650.80	$3,747.76	$44,988.40	$9,625.73	$107,396.67	$4,680.33	4.39%
3	$9,248.61	$8,181.83	$13,290.71	$15,242.10	$5,665.71	$3,615.47	$46,035.41	$10,272.89	$111,552.73	$8,836.39	8.02%
4	$9,498.42	$8,619.84	$13,006.61	$14,969.75	$5,471.36	$4,028.73	$42,776.24	$9,922.72	$108,293.67	$5,577.33	5.13%
5	$9,504.11	$8,819.79	$11,810.42	$15,189.69	$6,088.67	$3,837.67	$43,629.16	$9,793.25	$108,672.75	$5,956.41	5.53%
6	$9,586.26	$9,043.59	$12,010.92	$14,380.99	$5,761.98	$3,753.20	$47,901.43	$9,433.68	$111,872.05	$9,155.72	8.07%
7	$9,900.13	$8,545.94	$12,700.30	$15,265.95	$6,144.17	$3,715.15	$45,263.38	$10,361.88	$111,896.91	$9,180.57	8.16%
8	$9,211.29	$8,177.04	$12,994.95	$14,789.15	$5,897.27	$4,005.35	$44,039.48	$9,227.66	$108,342.19	$5,625.86	4.97%
9	$9,962.29	$8,544.21	$12,921.64	$14,798.76	$6,089.58	$3,898.85	$46,753.82	$10,188.89	$113,158.05	$10,441.71	9.39%
10	$10,042.42	$8,814.58	$13,137.51	$13,633.71	$6,147.48	$4,027.33	$48,631.03	$9,266.44	$113,700.52	$10,984.19	9.84%
11	$8,950.48	$9,098.63	$13,403.70	$14,209.69	$6,168.65	$3,667.10	$48,465.48	$10,004.70	$113,968.42	$11,252.08	10.29%
12	$9,167.16	$8,190.41	$13,279.80	$15,339.84	$5,980.08	$3,929.39	$44,108.57	$9,358.78	$109,354.04	$6,637.71	5.87%
13	$9,174.18	$8,121.11	$13,279.75	$13,586.22	$5,621.85	$3,857.37	$46,082.11	$9,300.29	$109,022.88	$6,306.54	5.67%
14	$9,642.59	$8,851.45	$11,921.59	$15,358.53	$5,901.02	$3,872.78	$44,066.03	$10,546.43	$110,160.42	$7,444.09	6.87%
15	$9,125.17	$8,820.51	$12,095.07	$14,990.65	$5,775.97	$3,804.59	$43,151.51	$9,426.20	$107,189.66	$4,473.32	4.14%
16	$9,117.19	$8,567.05	$12,066.38	$15,501.14	$5,583.98	$3,706.32	$44,256.87	$10,554.81	$109,353.74	$6,637.40	6.14%
17	$9,781.39	$9,013.74	$12,717.25	$15,465.51	$6,103.77	$3,934.96	$46,715.27	$9,848.10	$113,579.99	$10,863.66	9.56%
18	$9,947.33	$8,814.51	$12,295.83	$13,860.43	$5,815.03	$3,870.30	$43,960.56	$9,890.77	$108,454.75	$5,738.41	5.08%
19	$8,936.04	$8,916.69	$11,834.41	$14,809.12	$5,890.88	$3,878.41	$45,920.33	$9,235.40	$109,421.28	$6,704.95	6.19%
20	$9,460.12	$8,851.34	$12,727.12	$14,096.85	$6,108.31	$3,888.78	$43,939.75	$9,692.88	$108,765.15	$6,048.81	5.48%

Figure 15. Portion of the $\text{Cost}_{\text{Payload}}$ Simulated Data Set

Once all the data was compiled for the forecasting model, which used the 1000 iterations of simulated historical data to produce data for the forecasting model. The researchers used the forecasting function within Microsoft Excel which uses the produced historical data and AAA version of the Exponential Smoothing (ETS) algorithm to predict future values. The forecasting model was used with the following parameters:

- Confidence Interval: 95%
- Seasonality: None
- Predicted Value Range: 250 predicted values

Once compiled, the researchers then calculated the average total forecasted Cost$_{\text{Payload}}$ from the 250 forecasted. Each of the forecasted Cost$_{\text{Payload}}$ total was then compared to the initial Average Cost$_{\text{Payload}}$ from Figure 16 and determined the difference. The researchers then determined the mean and standard deviation of the of the difference of the forecasted totals and the original average total.

Example:

- Original Average Cost$_{\text{Payload}}$: \$102,716.33
- Forecasted Cost$_{\text{Payload 1}}$: \$108,728.52
- Difference: \$6,012.19

The calculated data for Cost$_{\text{Payload}}$ is depicted below:

- Original Cost Average:102,716.33
- Mean of the Difference of Forecasted Total Cost$_{\text{Payload}}$: \$5,789.10
- Standard Deviation of the Difference of Forecasted Total Cost$_{\text{Payload}}$: \$1,011.27

This same procedure was also conducted for the remaining three cost components: (Cost$_{\text{GroundStation}}$; Cost$_{\text{PO\&M}}$; Cost$_{\text{Launch}}$). Below are the forecasted data:

- Cost$_{\text{GroundStation}}$:
    - Original Cost Average: \$826,000
    - Mean of the Difference of Forecasted Total Cost$_{\text{Payload}}$: \$56,362.91

    - Standard Deviation of the Difference of Forecasted Total $\text{Cost}_{\text{Payload}}$: \$570.67
- $\text{Cost}_{\text{PO\&M}}$:
    - Original Cost Average: \$10,895,000.00
    - Mean of the Difference of Forecasted Total $\text{Cost}_{\text{Payload}}$: \$640,755.19
    - Standard Deviation of the Difference of Forecasted Total $\text{Cost}_{\text{Payload}}$: \$100,450.77
- $\text{Cost}_{\text{Launch}}$:
    - Original Cost Average: \$13,933,333.33
    - Mean of the Difference of Forecasted Total $\text{Cost}_{\text{Payload}}$: \$621,401.30
    - Standard Deviation of the Difference of Forecasted Total $\text{Cost}_{\text{Payload}}$: \$108,474.16

This data can now be used to estimate the mean $\text{Cost}_{\text{Total}}$ by combining the original Cost Average with the calculated mean difference of forecasted components plus or minus the standard deviation of the difference of the forecasted component cost.

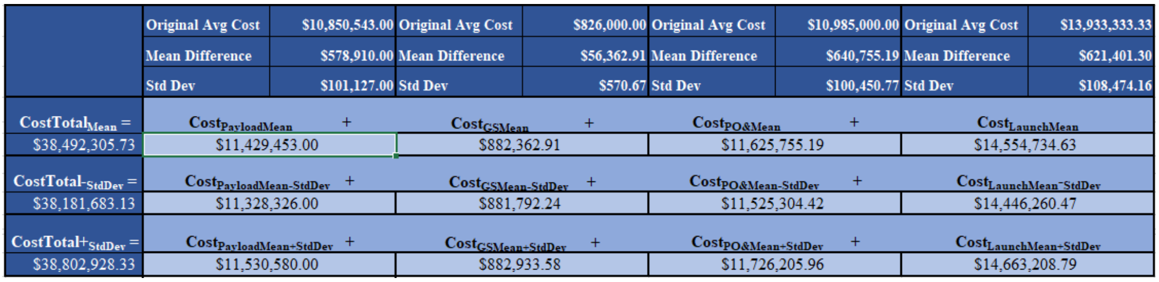
As a result, this study has produced the following three equations:

$$Cost_{TotalMean} = Cost_{PayloadMean} + Cost_{GroundStationMean} + Cost_{PO\&M\ Mean} + Cost_{LaunchMean}$$

$$Cost_{TotalMean\text{-}StdDev} = Cost_{Payload\ Mean\text{-}StdDev} + Cost_{GroundStation\ Mean\text{-}StdDev} + Cost_{PO\&M\ Mean\text{-}StdDev} + Cost_{Launch\ Mean\text{-}StdDev}$$

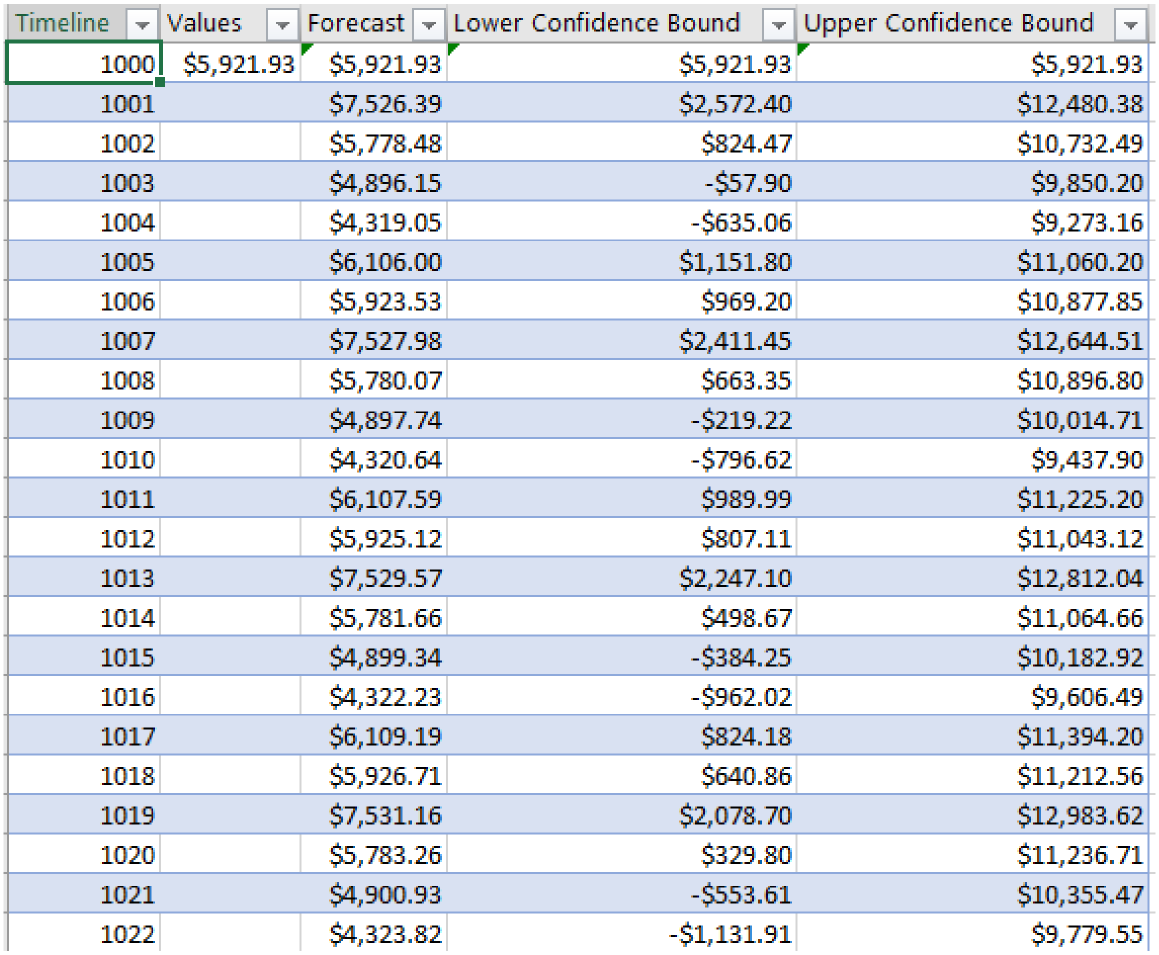
$$Cost_{Total\ \ Mean+StdDev} = Cost_{Payload\ \ Mean+StdDev} + Cost_{GroundStation\ Mean+StdDev} + Cost_{PO\&M\ Mean+StdDev} + Cost_{Launch\ Mean+StdDev}$$

Using these equations, the $\text{Cost}_{\text{Total}}$Mean, $\text{Cost}_{\text{Total-StdDev}}$, and $\text{Cost}_{\text{Total+StdDev}}$ can be computed. These values are listed in Figure 16 which depicts that the low-end project estimation is \$38,181,683.13, while the high-end estimation is \$38,802,928.33, and the mean estimation is \$38, 492,73. Figure 17 further lists a portion of the forecasted $\text{Cost}_{\text{Payload}}$ data set, with the same data set graphed in Figure 18.



	Original Avg Cost	\$10,850,543.00	Original Avg Cost	\$826,000.00	Original Avg Cost	\$10,985,000.00	Original Avg Cost	\$13,933,333.33
	Mean Difference	\$578,910.00	Mean Difference	\$56,362.91	Mean Difference	\$640,755.19	Mean Difference	\$621,401.30
	Std Dev	\$101,127.00	Std Dev	\$570.67	Std Dev	\$100,450.77	Std Dev	\$108,474.16
$\text{CostTotal}_{\text{Mean}}$ =	$\text{Cost}_{\text{PayloadMean}}$ +		$\text{Cost}_{\text{GSMean}}$ +		$\text{Cost}_{\text{PO\&Mean}}$ +		$\text{Cost}_{\text{LaunchMean}}$	
\$38,492,305.73	\$11,429,453.00		\$882,362.91		\$11,625,755.19		\$14,554,734.63	
$\text{CostTotal-}_{\text{StdDev}}$ =	$\text{Cost}_{\text{PayloadMean-StdDev}}$ +		$\text{Cost}_{\text{GSMean-StdDev}}$ +		$\text{Cost}_{\text{PO\&Mean-StdDev}}$ +		$\text{Cost}_{\text{LaunchMean-StdDev}}$	
\$38,181,683.13	\$11,328,326.00		\$881,792.24		\$11,525,304.42		\$14,446,260.47	
$\text{CostTotal+}_{\text{StdDev}}$ =	$\text{Cost}_{\text{PayloadMean+StdDev}}$ +		$\text{Cost}_{\text{GSMean+StdDev}}$ +		$\text{Cost}_{\text{PO\&Mean+StdDev}}$ +		$\text{Cost}_{\text{LaunchMean+StdDev}}$	
\$38,802,928.33	\$11,530,580.00		\$882,933.58		\$11,726,205.96		\$14,663,208.79	

Figure 16. $\text{Cost}_{\text{Total}}$ with Standard Deviation Included



Timeline	Values	Forecast	Lower Confidence Bound	Upper Confidence Bound
1000	\$5,921.93	\$5,921.93	\$5,921.93	\$5,921.93
1001		\$7,526.39	\$2,572.40	\$12,480.38
1002		\$5,778.48	\$824.47	\$10,732.49
1003		\$4,896.15	-\$57.90	\$9,850.20
1004		\$4,319.05	-\$635.06	\$9,273.16
1005		\$6,106.00	\$1,151.80	\$11,060.20
1006		\$5,923.53	\$969.20	\$10,877.85
1007		\$7,527.98	\$2,411.45	\$12,644.51
1008		\$5,780.07	\$663.35	\$10,896.80
1009		\$4,897.74	-\$219.22	\$10,014.71
1010		\$4,320.64	-\$796.62	\$9,437.90
1011		\$6,107.59	\$989.99	\$11,225.20
1012		\$5,925.12	\$807.11	\$11,043.12
1013		\$7,529.57	\$2,247.10	\$12,812.04
1014		\$5,781.66	\$498.67	\$11,064.66
1015		\$4,899.34	-\$384.25	\$10,182.92
1016		\$4,322.23	-\$962.02	\$9,606.49
1017		\$6,109.19	\$824.18	\$11,394.20
1018		\$5,926.71	\$640.86	\$11,212.56
1019		\$7,531.16	\$2,078.70	\$12,983.62
1020		\$5,783.26	\$329.80	\$11,236.71
1021		\$4,900.93	-\$553.61	\$10,355.47
1022		\$4,323.82	-\$1,131.91	\$9,779.55

Figure 17. Portion of Forecasted $\text{Cost}_{\text{Payload}}$ Data Set

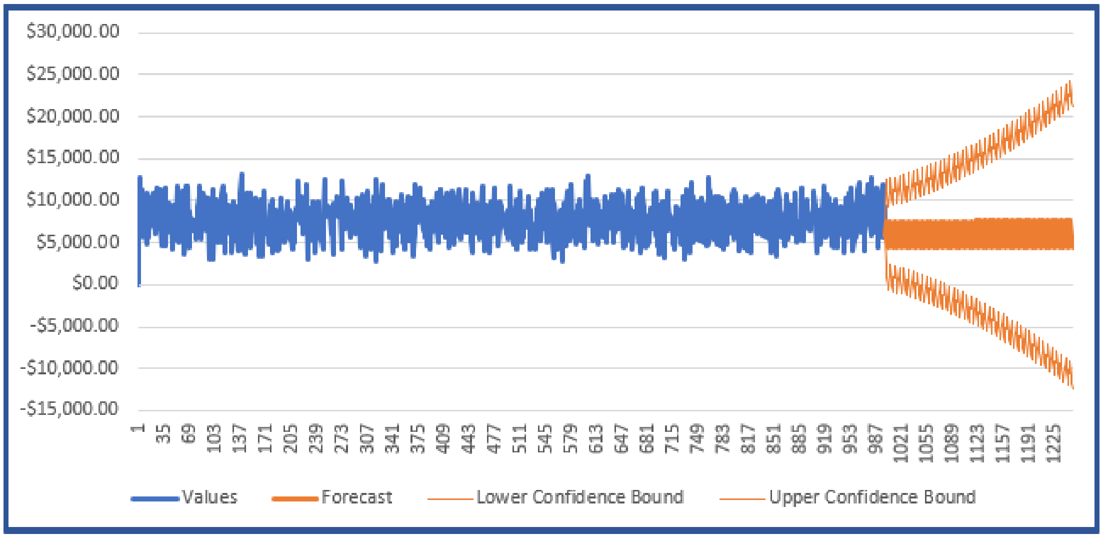
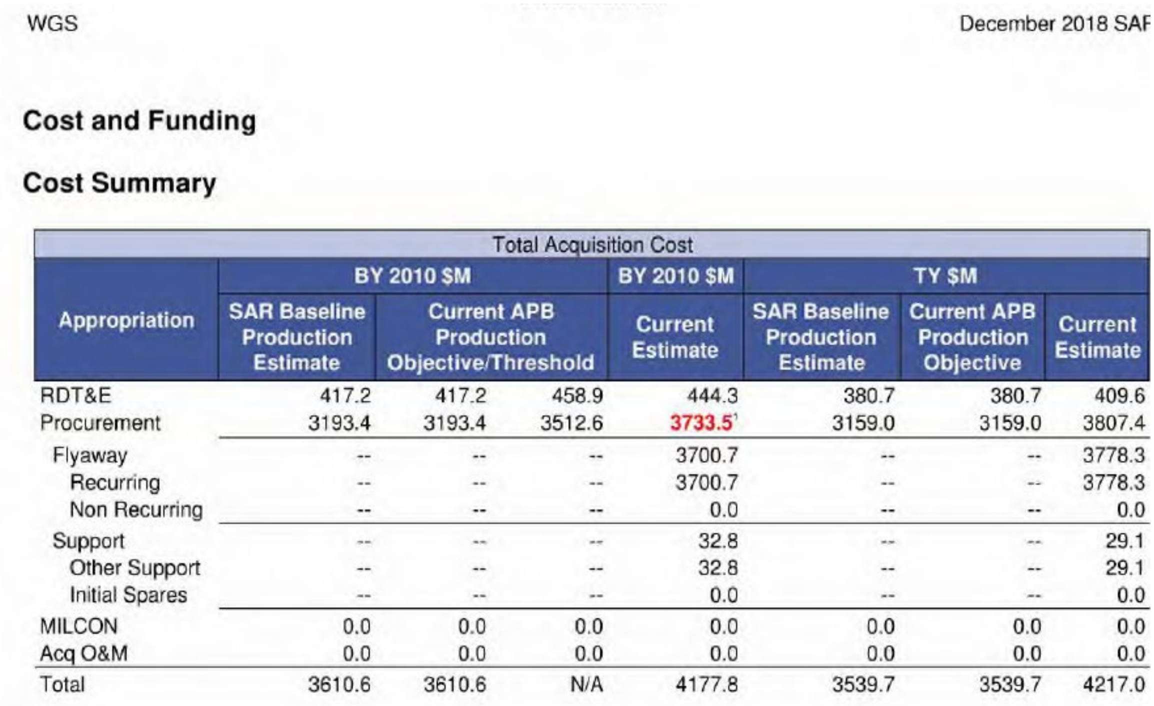


Figure 18. Graph of Forecasted Cost$_{\text{Payload}}$ Data Set

D. FINANCIAL STUDY OBSERVATIONS, FINDINGS AND VIABILITY OF BSMN FOR C2 IN EABO

When comparing the estimations demonstrated in the previous section with funding for current DOD satellite programs we can determine the viability of acquiring, developing, deploying, and maintaining the software and hardware required to establish a space-based terminals to include in a BSMN topology.

Listed below is the FY2019 Selected Acquisition Report covering the Wideband Global SATCOM (WGS) System. Figure 19 depicts the Acquisition Program Baseline (APB) which started in 2010 and is current today. This APB depicts the estimated total cost for the entire WGS is over four billion dollars (Global Broadcast Service [GBS], 2014).



WGS December 2018 SAR

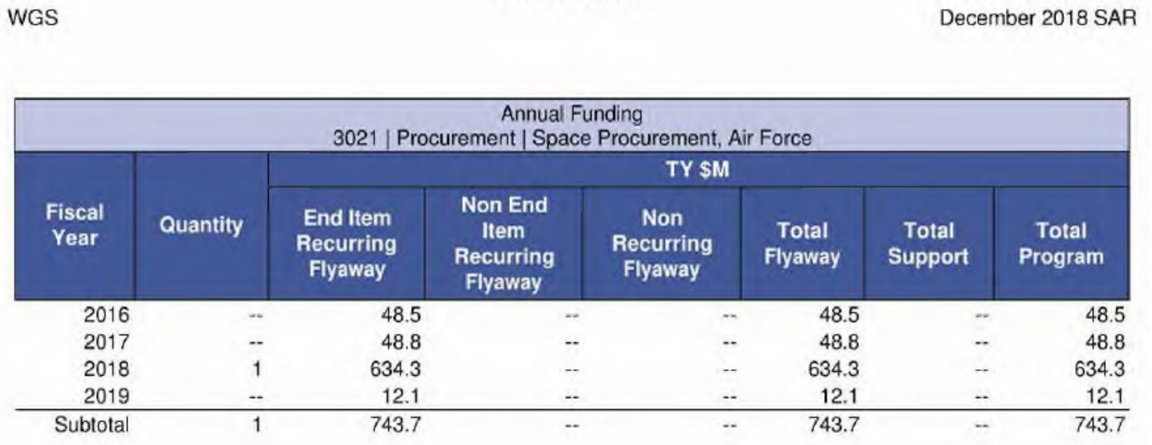
Cost and Funding

Cost Summary

Total Acquisition Cost							
Appropriation	BY 2010 $M			BY 2010 $M	TY $M		
	SAR Baseline Production Estimate	Current APB Production Objective/Threshold		Current Estimate	SAR Baseline Production Estimate	Current APB Production Objective	Current Estimate
RDT&E	417.2	417.2	458.9	444.3	380.7	380.7	409.6
Procurement	3193.4	3193.4	3512.6	3733.5[1]	3159.0	3159.0	3807.4
Flyaway	--	--	--	3700.7	--	--	3778.3
Recurring	--	--	--	3700.7	--	--	3778.3
Non Recurring	--	--	--	0.0	--	--	0.0
Support	--	--	--	32.8	--	--	29.1
Other Support	--	--	--	32.8	--	--	29.1
Initial Spares	--	--	--	0.0	--	--	0.0
MILCON	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Acq O&M	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	3610.6	3610.6	N/A	4177.8	3539.7	3539.7	4217.0

Figure 19. Acquisition Program Baseline (APB) 2010. Source: GBS (2018).

Additionally, Figure 20 depicts the Annual Space procurement funding for the Air Force which FY 2016, 2017, and 2018 were each attributed at least $48 million for the WGS program.



WGS December 2018 SAR

Annual Funding 3021 | Procurement | Space Procurement, Air Force							
Fiscal Year	Quantity	TY $M					
		End Item Recurring Flyaway	Non End Item Recurring Flyaway	Non Recurring Flyaway	Total Flyaway	Total Support	Total Program
2016	--	48.5	--	--	48.5	--	48.5
2017	--	48.8	--	--	48.8	--	48.8
2018	1	634.3	--	--	634.3	--	634.3
2019	--	12.1	--	--	12.1	--	12.1
Subtotal	1	743.7	--	--	743.7	--	743.7

Figure 20. Annual Funding, Air Force WGS Program. Source: GBS (2018).

Both figures demonstrate the large amounts of money allocated yearly, and throughout the life cycle of a space-based satellite program. When comparing to estimated total cost of the BSNM constellation of approximately $39 million dollars, the researchers deduct that it is very feasible, from a financial perspective, to acquire, develop, deploy, and maintain the software and hardware required to establish a space-based terminals to include in a BSMN topology. This estimated cost is less than 1% of the total APB of the WGS program. With the potential benefits produced by BSMNs, it is reasonable to argue that the financial commitment would benefit the DOD.

E. FINANCIAL ANALYSIS SUMMARY

Through gathering of open-source information from commercial satellite and spaceflight companies, the researchers were able to develop a financial forecasting model which referenced average components costs related to the development, manufacturing, operation, and maintenance of a LEO constellation. These are based on current industry standards regarding pricing for each cost component (payload, ground station, personnel, operations and maintenance, and launch) and then were simulated over 1000 interactions to build simulated historical information. Using the simulated historical information, the researchers built a forecasting model which provided the mean, and higher and lower levels of total cost of all components regarding the development, manufacturing, operation, and maintenance of a LEO constellation to support BSMNs.

Upon processing the information and making a comparative analysis of the current WGS program, the researchers deduct that since the total component costs are less than one percent of the WGS APB, it is reasonable and financially viable to acquire, develop, deploy, and maintain the software and hardware required to establish a LEO satellite constellation to support a BSMN topology.

V. CONCLUSION

A. SUMMARY OF FINDINGS

1. Hypothesis Test

The researchers hypothesized that BSMN is a suitable technological solution to provide both the resilience and stealth for C2 required by the EABO construct, and that BSMN is a financially viable technology to develop and acquire for use in EABO C2.

Creating a BSMN, based on CSS and LoRa modulation techniques, as a technical solution for C2 in EABO demonstrated significant potential to support communications below the digital divide (<150 km).

Regarding the viability of developing and acquiring BSMN for C2 in EABO, the researchers that it is reasonable and very viable to provide the financial support to acquire, develop, deploy, and maintain the software and hardware required to establish a space-based terminal to include in a BSMN topology.

2. Answers to Research Questions

All answers to research questions below were offered with a repetition of the researchers' previously expressed caveats: more research, using more robust case study source and models/simulations, are necessary to answer these questions in a more reliable and rigorous manner. Having said this, the researchers answered the following questions as accurately and thoroughly as possible with the resources and methods available.

- What are the intended/optimal characteristics of the C2 structure for EABO, and how is this structure distinct from that of conventional operations?
    - EABO commanders should place increased emphasis on: building and maintaining a clear pre-conceived vision of the environment, the enemy, and actions to address the situation; monitoring the realization of their vision in execution, and if their vision is incongruent with reality, find and correct the faults in their vision; and constrain their C2 apparatus to

exclusively transmit information that is relevant to build, convey, or alter their vision (Builder et al., 1999).

    - Conceptually, an optimal C2 system makes known the commander's intent well before the engagement in question and is characterized by minimal communication during execution (Builder et al., 1999).
    - The researchers assert that C2 systems for use below the digital divide, (e.g., MLRs and EABO TEs), prioritize stealth (i.e., LPI/LPD), lower power consumption, smaller size, and lower weight, longer range, and greater flexibility/scalability.
    - The researchers assert that C2 systems above the digital divide prioritize throughput and bandwidth necessary to support data rich communications.

- How does the EABO environment, as it relates to C2, create risks to force and mission?
    - <u>Logistical limitations</u>: austere AOs to support EABs lack infrastructure and require naval forces to operate in a self-contained and self-sustained manner: due to the nature and locations of prospective EABs, logistical resources are a limiting constraint to which C2 systems are viable and the manner in which C2 systems can operate (HQMC, 2021).
    - <u>Contested electromagnetic communication</u>: the ability of enemy forces to detect, intercept, and/or target the sources of electromagnetic radiation (i.e., our communication systems) for kinetic and non-kinetic attack places EABO forces and mission at risk (Office of the Secretary of Defense [SecDef], 2017; HQMC, 2021).
    - <u>Long transmission range</u>: the essential nature of EABO puts certain forces within an enemy WEZ, while other forces operate from outside the WEZ (HQMC, 2021). This creates the potential requirement for long-range

    communication (the researchers estimate upwards of 150 km), which if not supported, presents a risk to mission.

  - Operational scalability: EABO employs widely dispersed and expeditionary forces to counter enemy A2AD threats. Many EABO forces are mobile, and EABs are established and disestablished rapidly to prevent targeting by the enemy (HQMC, 2021). This implies that a C2 system that is unable to rapidly scale itself to support communications from more or fewer nodes is insufficient to enable C2, and potentially endangers the mission.

- What potential technical capabilities are provided by BSMN to support C2 infrastructures in EABO environments? Can these capabilities be feasibly applied to support EABO command, control, and communications' frameworks?

  - This study established a total of six range (1 km, 25 km, 50 km, 150 km, 400 km, 500 km) benchmarks in which the researchers evaluated the effectiveness of establishing a communication link using CSS and LoRa modulation techniques. Through multiple model iterations, CSS and LoRa modulation techniques proved to be theoretically effective in establishing a communication link below the digital divide (<150 km), while generating an unfavorable S/N ratio above the digital dive (>150 km). As such, the researchers argue that CSS and LoRa modulation techniques are potential capabilities which would support the establishment of BSMNs to support C2 infrastructure in EABO environments.

- What potential operational capabilities are provided by employing bursty-signal mesh network to support C2 infrastructures in EABO environments? How does BSMN support or increase the bursty rhythm of C2 in EABO?

  - This study identified how power output at the transmitter can effectively increase the link margin and create a favorable S/N ration. By increasing the power output to 5 Watts, the researchers determined that both CSS and

    LoRa modulation were able to create a successful communication link above the digital divide (>150 km); specifically at ranges of 400 and 500 km, respectively. As such, this study had demonstrated the theoretical viability of a BSMN to support low-power, limited data rate UHF SATCOM communication links. This capability can supplement and augment current UHF SATCOM resources which are deficient with respect to the demand for UHF SATCOM capabilities. BSMN support or increase the bursty rhythm of C2 in EABO?

- What fiscal requirements and financial characteristics are associated with development, procurement, implementation, and maintenance of a bursty-signal mesh network to support C2 infrastructures in EABO environments?
    - This study identified the financial and budget requirement involved with included space-based terminals in a BSMN. The researchers determined that in order to be operationally and cost effective, a multi-year CubeSat program would have to be established to ensure the proper acquisition development, deployment, and maintenance of the software and hardware required for a space based BSMN terminals. This program of record would have strategic level impacts regarding budgetary discourse and would require significant attention and support from the DOD to be successful.
    - Overall, the program cost of a LEO BSMN constellation would be approximately $38,802,928.33 over ten years. This amount of funding is not too significant that it makes this program unfeasible, however, it is large enough that funding would have to increase significantly to support a space-based satellite program for BSMN.
- What is the cost-benefit analysis of employing a bursty-signal mesh network to support C2 infrastructures in EABO environments over current structures?

- The estimated cost of the program would be \$38,802,928.33, which is a significant portion of the DOD’s UHF LOS satellite communication budget. Unless strategic leaders decide to create additional funding for the new program of record, the DOD would have to reallocate limited resources to fund this project. If this is the case, the DOD is essentially transitioning critical strategic level resources to tactical level units to support operations. However, as previously discussed, the current DOD SATCOM resources are already over-tasked and underfunded as it is, thus creating further operating deficiencies across the department. Instead, the DOD should look to expanding funding for this program as it would not only increase capabilities across tactical and operational levels of war, but it will also relieve some of the strain and tasking of current DOD SATCOM capabilities.

B. ADDITIONAL RESEARCH RECOMMENDATIONS

iv. The researchers originally sought to conduct the case studies for this research using more detailed and comprehensive documents that could potentially reveal more about the characteristics of C2, i.e., complete OPORDs with annexes and appendices. These documents, as well as requests for interviews with Marines familiar with the exercises for amplifying information, were ultimately unavailable for this research. The researchers recommend that future studies seeking information similar to this study (i.e., research involving the characterization of C2 in particular operating models) would benefit from access to these comprehensive documents.

v. Much of the research conducted in this study was built on the principle understanding that a C2 system can suffer from too much information: specifically, there are volumes and types of information that do not meaningfully enhance a commander’s ability to understand the critical aspects of the enemy and environment, and that do not meaningfully inform a commander of a need to alter their vision of action in pursuit of a shared goal.

In the PB-19 case study, the question of whether audio-visual information from COMMSTAT (previously known as Combat Camera) was needed in real-time from EABs (3dMARDIV, 2019). A more precise study that seeks to answer how much and what type of audio-visual information is truly beneficial to the formation of the commander's vision would be worthwhile to inform studies like this one.

vi. Exercise PB-19 brought into question the integration and line of authority of aviation units and capabilities in EABO (1stMARDIV, 2019). Upon review of the *Tentative Manual for Expeditionary Advanced Base Operations* (HQMC, 2021), the researchers assumed that many of the issues faced in PB-19 were due to artificial limitations of the exercise, and specifically, the absence of an LLB that would have made those relationships and authorities clearer. However, the researchers recommend further analysis of the dynamic of aviation units and capabilities in the MLR, specifically, as they relate the EAB mission sets of the LCT that relate to aviation operations (e.g., establishing FARPs).

vii. The technical research identified many areas which fell outside the scope of this study. Although the researchers identified and employed controls in term theoretical antenna characteristics, the following antenna design characteristics should be evaluated for applicability and appropriateness: confirm, modify, deny antenna efficiency, size, shape, and type established in this study through field testing. Additionally, further research should explore other antenna parameters outside those established in this study.

viii. Researchers recommend evaluating the effects of antenna height during point-to-point communication and it affects the communication link. Additionally, the researchers recommend further investigation regarding the how antenna height will affect signal propagation, as well as, how height impacts atmospheric attenuation, change in atmospheric temperature, interference, absorption, terrain, signal diffraction during transmission.

ix. This study established and constant of 0.158 and 0.5 Watts of power consumption at the transmitters. The researchers recommend further investigation regarding the impacts on signal propagation of CSS and LoRa modulation techniques with varying power settings. Additionally, any investigation of power consumption should include the logistical support requirements for established power setting and correlate the impact of power generation resources.

x. This study evaluated point-to-point communication links involving two nodes. The researchers recommend further research to include more than two nodes and evaluate to feasibility of a multi-node BSMN and the impacts on transmission range, performance, capacity, and efficiency.

xi. One element of the point-to-point communication link established in this study was the stationary nature of the nodes. The researchers recommend evaluating the impact mobile nodes have on the transmission range, performance, capacity, and efficiency of the communication link.

xii. This study conducted an initial financial analysis regarding the feasibility of acquiring, developing, deploying, and maintaining the software and hardware required to establish a space-based terminal to include in a BSMN topology. The researchers recommend a more robust financial analysis study to further evaluate the feasibility of developing other aspects of a BSMN such as acquiring, developing, deploying, and maintaining the software and hardware required to establish a land and mobile terminals to include in a BSMN topology.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

1st Battalion, 6th Marine Regiment. (2020, July 7). *1st Battalion, 6th Marines expeditionary advanced based operations exercise after action report (AAR)*. Department of the Navy. Forward Deployed Battalion-East, 3d Marine Division. https://eis.usmc.mil/sites/mccll/LLDocuments/1-6_EABO_FEX20_AAR.pdf#search=northern%20apache

1st Marine Division. (2019, May 5). *Exercise Pacific Blitz 2019 (PB-19) after action report*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/1st%20MarDiv%20PACIFIC%20BLITZ-19%20AAR%20190505-FILEID-45435.pdf#search=pacific%20blitz

3d Marine Division. (2019). *After action report for III Marine Expeditionary Force Exercise (MEFEX), 29 April 2019 through 10 May 2019*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/3d%20MARDIV%20MEFEX-19%20AAR%20190603-FILEID-43626.pdf#search=MEFEX%2D19

3GLTEinfo. (2016). *LoRa Architecture - LoRaWAN Tutorial*. https://www.3glteinfo.com/lora/lora-architecture/

9th Communications Battalion. (2019). *Pacific Blitz 19: I MEF flat enterprise domain*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/9th%20Comm%20Pacific%20Blitz%20%20Final%20Report-I%20MEF%20Flat%20Domain%20190802-FILEID-43723.pdf#search=Pacific%20Blitz%2019

Allard, K. (1996). *Command, control, and the common defense* [E-reader version]. Institute for National Strategic Studies. Washington, DC. Internet Archive. https://archive.org/details/commandcontrolth00alla/page/16/mode/2up

Bevelacqua, P. (2016). *Antenna efficiency*. https://www.antenna-theory.com/basics/efficiency.php

Bordetsky, A., Benson, S., & Hughes, W. (2016, June 1). Hiding comms in plain sight. *Signal*. https://www.afcea.org/content/?q=Article-hiding-comms-plain-sight

Builder C., Bankes S., & Nordin R. (1999). *Command concepts: a theory derived from the practice of command and control*. RAND. https://www.rand.org/pubs/monograph_reports/MR775.html

Cakaj, S., Kamo, B., Lala , A., & Rakipi, A. (2014). *The coverage analysis for low earth orbiting satellites at low elevation*. P.4. The Science and Information (SAI) Organization. https://thesai.org/.

Cambridge University Press. (n.d.). Bursty. In *Cambridge dictionary*. https://dictionary.cambridge.org/dictionary/english/bursty

Commandant of the Marine Corps. (2019). *38th Commandant's planning guidance*. Headquarters, Marine Corps. Department of the Navy. https://www.hqmc.marines.mil/Portals/142/Docs/ 38th Commandant's Planning Guidance_2019.pdf?ver=2019-07-16-200152-700

Commandant of the Marine Corps. (2020, March). *Force design 2030*. Headquarters, Marine Corps. Department of the Navy. https://www.hqmc.marines.mil/Portals/142/Docs/CMC38%20Force%20Design%202030%20Report%20Phase%20I%20and%20II.pdf?ver=2020-03-26-121328-460

Commander, Naval Surface Forces. (2017). *Surface force strategy: return to sea control.* Department of the Navy. https://media.defense.gov/2020/May/18/2002302052/-1/-1/1/SURFACEFORCESTRATEGY-RETURNTOSEACONTROL.PDF

Congressional Research Service. (2020, 9 December). Defense primer: military use of the electromagnetic spectrum. *In Focus*, IF11155 (version 10). https://crsreports.congress.gov/product/pdf/IF/IF11155

Contact Corporation. (n.d.). *USMC TEAMS; tactical elevated antenna mast system* [Fact sheet/brochure]. https://contactcorp.net/images/teams%20brochure.pdf

Creswell, J. (2014). *Research design: qualitative, quantitative, and mixed methods approaches* (4th ed.). Sage.

Defense Information Systems Agency. (2014, February 7). *Video teleconference security technical implementation guide (STIG) overview* (version 1, release 2). DISA Field Security Office. https://secureswitch.com/pdf_files/U_Video_Teleconference_V1R2_STIG_Overview.pdf

Dredge, K., & Timmins, I. (2017). *LEO constellations and tracking challenges*. Satellite Evolution. https://www.satelliteevolutiongroup.com/articles/LEO-Constellations&Tracking.pdf.

Eckstein, M. (2020, June 4). Marine testing regiment at heart of emerging island-hopping future. *USNI News*. https://news.usni.org/2020/06/04/marines-testing-regiment-at-heart-of-emerging-island-hopping-future

Eyer, K. & McJessy, S. (2019, March 19). Operationalizing Distributed Maritime Operations. *Center for International Maritime Security* (CIMSEC). Retrieved from https://cimsec.org/operationalizing-distributed-maritime-operations/39831

EverythingRF. (2018, Jan 3). What is antenna efficiency? https://www.everythingrf.com/community/what-is-antenna-efficiency

Fuentes, G. (2019, March 26). Pacific Blitz tests how Navy, Marines could fight the next island campaign. *USNI News*. https://news.usni.org/2019/03/26/pacific-blitz-tests-navy-marines-fight-next-island-campaign

GBS Joint Program Office. (2018, December). *Selected acquisition report (SAR): Global broadcast service (GBS) as of FY 2016 President's Budget.* P17-26 Department of the Air Force. https://www.hsdl.org/?view&did=815116

Harris. (2005). *AN/PRC-150(C) radio system* [Handbook]. https://www.armyproperty.com/Resources/Catalogs/Harris-AN-PRC-150C-Applications-Handbook.pdf

Harris. (2007). *AN/PRC-117F(C) multiband multimission radio* [Handbook]. http://www.railce.com/cw/casc/harris/HB-AN-PRC-117FC.pdf

Headquarters, Army. (1991). *Technical manual for antenna group OE-254* (TM 11–5985-357-13) [Technical manual]. Department of the Army. http://www.radiomanual.info/schemi/Surplus_Accessories/OE-254_antenna_serv_user_TM11-5985-357-13_1991.pdf

Headquarters, Marine Corps. (1997, August 1). *Campaigning* (MCDP 1-2). Department of the Navy. https://www.marines.mil/Portals/1/Publications/MCDP%201-2%20Campaigning.pdf

Headquarters, Marine Corps. (1998a, November 16). *Communications and information systems* (MCWP 6-22). https://www.globalsecurity.org/military/library/policy/usmc/mcwp/6-22/mcwp6-22.pdf

Headquarters, Marine Corps. (1998b, April 16). *Expeditionary operations* (MCDP-3). Department of the Navy. https://www.marines.mil/Portals/1/Publications/MCDP%203%20Expeditionary%20Operations.pdf?ver=2012-10-11-164103-873

Headquarters, Marine Corps. (2018). *Command and control* (MCDP-6). Department of the Navy. https://www.marines.mil/Portals/1/Publications/MCDP%206.pdf?ver=2019-07-18-093633-990

Headquarters, Marine Corps. (2021, February). *Tentative manual for expeditionary advanced base operations*. Department of the Navy. https://intelshare.intelink.gov/sites/mcwl/TMEABOAssessment/Current%20Manual/TM%20EABO%20-%20First%20Edition%20Rev%2020210211.pdf

Heyman, J. (2009, October). *FOCUS: CubeSats — A costing + pricing challenge*. SatMagazine. http://www.satmagazine.com/story.php?number=602922274.

Iridium Satellite Communications. (2021). *Truly Global Communications*. https://www.iridium.com/#:~:text=Offering%20voice%20and%20data%20connectivity,the%20air%2C%20or%20at%20sea.

Hoehn, J. C., Gallagher, J.C., & Sayler, K. M. (2021). *Overview of Department of Defense use of the electromagnetic spectrum.* (CRS Report No. R46564). Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R46564

Hong, Y., Tak, J., Baek, J., Myeong, B., & Choi, J. (2014). Design of a multiband antenna for LTE/GSM/UMTS band operation. *International Journal of Antennas and Propagation, 2014*(article ID 548160), 1–9. https://www.hindawi.com/journals/ijap/2014/548160/

IEEE Computer Society. (2007, 31 August). *IEEE Standard 802.15.4a-2007*. New York, NY.

Jackson, K., Scobell, A., Webber, S., & Ma, L. (2020). *Command and control in U.S. naval competition with China*. RAND. https://www.rand.org/pubs/research_reports/RRA127-1.html

Joint Chiefs of Staff. (2018). *Description of the national military strategy of the United States of America 2018*. https://www.jcs.mil/Portals/36/Documents/Publications/UNCLASS_2018_National_Military_Strategy_Description.pdf

Joint Chiefs of Staff. (2021, January 21). *Department of Defense dictionary of military and associated terms*. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/dictionary.pdf

L3Harris Technologies. (2019). *L3Harris Falcon III AN/PRC-117G(V)1(C)* [Fact sheet]. Melbourne, FL. https://www.l3harris.com/sites/default/files/2020-07/cs_tc_datasheet_an-prc-117g-multiband-networking-manpack-radio.pdf

Law, K. (2009). Chapter 10: Transport protocols for wireless mesh networks (pp. 255–276). In S. Misra, S. C. Misra, I. Woungang (Eds.), *Guide to wireless mesh networks* (1st ed.). Springer.

LeoSat. (2021). *LeoSat Enterprisises*. LeoSat. https://www.leosat.com/to/about-us/.

Liberg, O., Sundberg Mårten, Wang, E., Bergman, J., & Sachs, J. (2018). *Cellular internet of things: technologies, standards, and performance*. Amsterdam. Academic Press.

Marine Air Support Squadron 6. (2019). *After action report for III MEF MEFEX for the period of April–May/2019*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/MASS-6%20III%20MEF%20MEFEX%20AAR%20190522-FILEID-43327.pdf#search=MASS%2D6

Marine Aircraft Group 39. (2019, April 22). *MAG-39 after action report for exercise Pacific Blitz 2019*. Department of the Navy. https://eis.usmc.mil/sites/mccll/LLDocuments/MAG-39%20Exercise%20PACIFIC%20BLITZ%202019%20AAR%20%20190422-FILEID-43175.pdf#search=pacific%20blitz

Marco Polo. (2020). Budget. http://propagation.ece.gatech.edu/ECE6390/project/Sum2015/team5/budget.html.

McTasney, R., Grunwald, D., & Sicker, D. (2009). Chapter 15: Low latency in wireless mesh networks (pp. 379–424). In S. Misra, S. C. Misra, & I. Woungang (Ed.)*,* *Guide to wireless mesh networks*. Springer.

Miao, G, Zander, J. Sung, K., & Slimane, B. (2016*). Fundamentals of mobile data networks*. Cambridge University Press.

NASA CubeSat Launch Initiative, California Polytechnic State University, & San Luis Obispo (Cal Poly) CubeSat Systems Engineer Lab, CubeSat101 Basic Concepts and Processes for First-Time CubeSat Developers4–4 (2017). https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf

Nicholas, P., Pepper, J., Weaver, C., Gibbons, D., & Muratore, M. (2013). Simulation and analysis of mobile ad hoc network technology in the U.S. Marine Corps infantry battalion. *Military Operations Research, 18(4)*, 19–35. http://mason.gmu.edu/~pnichol6/docs/manet_2013.pdf

Office of the Chief of Naval Operations. (2018, December). *A design for maintaining maritime superiority* (ver 2). Department of the Navy. https://media.defense.gov/2020/Jul/23/2002463490/-1/-1/1/A%20DESIGN%20FOR%20MAINTAINING%20MARITIME%20SUPERIORITY_2.0.PDF

Office of the Secretary of Defense. (2017). *Annual report to Congress: Military and security developments involving the People's Republic of China 2017*. Department of Defense. https://media.defense.gov/2020/Sep/01/2002488689/-1/-1/1/2020-DOD-CHINA-MILITARY-POWER-REPORT-FINAL.PDF

Ong, P. (2020, November 24). Black Sea drill again validates HIMARS as an anti-ship weapon system. *Naval News*. https://www.navalnews.com/naval-news/2020/11/black-sea-drill-again-validates-himars-as-an-anti-ship-weapon-system/

ORBCOMM. (2021). *ORBCOMM OG2 Next-Generation Satellite Constellation*. https://www.orbcomm.com/en/networks/satellite/orbcomm-og2.

Ouyang, X., & Zhao, J. (2016). Orthogonal chirp division multiplexing. *IEEE Transactions on Communications, 64*(9) 3946–3957. Doi: 10.1109/TCOMM.2016.2594792.

Pike, J., & Sherman, R. (1999). *Radio communications system*. Radio Communications System (RCS). https://fas.org/man/dod-101/sys/ship/weaps/radio.htm#:~:text=The%20Extremely%20High%20Frequency%20Satellite,(30%2D300%20GHz).

Ray, B. (2018, June 26). What is LoRa? A technical breakdown. *Lab Links.* Retrieved from https://www.link-labs.com/blog/what-is-lora

Secretary of Defense. (2018). *Summary of the 2018 national defense strategy of the United States of America*. Department of Defense. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf

Semtech. (2013, July 1). *LoRa modem design guide* (SX1272/3/6/7/8: AN1200.13). https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R0000001OK4/K1xBJSCPflEbqU03CfABAjL29tRKA9KsdAdTIsWBA8s

Sklar, B. (2017, January 2). *Digital communications: fundamental and applications* (2nd ed.). Prentice Hall.

Srivathsan, S., Balakrishnan, N., & Iyengar, S. S. (2009). Chapter 13: Scalability in wireless mesh networks (pp. 325–348). In S. Misra, S. C. Misra, & I. Woungang (Ed.), *Guide to wireless mesh networks*. Springer.

Stine, J., & Portigal, D. (2004). Spectrum 101: an introduction to spectrum management. 220. *National Aeronautics and Space Administration Spectrum*. https://www.nasa.gov/sites/default/files/atoms/files/spectrum_101.pdf

Tatomir, A., McDermott, C., Bensabat, J., Class, H., Edlmann, K., Taherdangkoo, R., & Sauter, M. (2018). Conceptual model development using a generic Features, Events, and Processes (FEP) database for assessing the potential impact of hydraulic fracturing on groundwater aquifers. *Advances in Geosciences*. https://adgeo.copernicus.org/articles/45/185/2018/

Walkenhorst, B. (2020, September 24). The impact of LPI/LPD waveforms and anti-jam capabilities on military communications. *The Modern Battlespace*. https://modernbattlespace.com/2020/09/24/impact-lpi-lpd-waveforms-anti-jam-capabilities-military-communications/#.YHJ1sqySmUn

Wayana Software. (2015). *Antennas for satellite communications*. http://www.geosats.com/antennas.html

Weaver, W., & Shannon, E. (1949). *Recent contributions to mathematical theory of communication*. Chicago, IL. University of Illinois Press.

White House. (2017). *National security strategy of the United States of America*. National Security Council, White House. https://www.whitehouse.gov/wp-content/uploads/2017/12/NSS-Final-12-18-2017-0905.pdf

Withington, T. (2017). *Waveform resilience improvements*. Waveform Resilience Improvements—Mönch Verlagsgesellschaft mbH. https://www.monch.com/mpg/news/c5i/2173-waveform-resilience-improvements.html

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California