



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

**INCREASED EFFECTIVENESS OF THE JOINT FIRE'S
KILL CHAIN VIA IMPROVEMENTS IN COMMAND
AND CONTROL RESPONSIVENESS FOR
BETTER COOPERATIVE ENGAGEMENT CAPABILITY**

by

Kelly P. Haycock, Lance Kerestes, Brenda Menees,
and Axel E. Rodriguez-Negron

September 2020

Advisor:
Co-Advisors:

Eugene P. Paulo
Paul T. Beery
Anthony G. Pollman
Wayne Porter

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2020	3. REPORT TYPE AND DATES COVERED Systems Engineering Capstone Report	
4. TITLE AND SUBTITLE INCREASED EFFECTIVENESS OF THE JOINT FIRE'S KILL CHAIN VIA IMPROVEMENTS IN COMMAND AND CONTROL RESPONSIVENESS FOR BETTER COOPERATIVE ENGAGEMENT CAPABILITY			5. FUNDING NUMBERS	
6. AUTHOR(S) Kelly P. Haycock, Lance Kerestes, Brenda Menees, and Axel E. Rodriguez-Negron				
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 system of interest (SOI) for this research centers on the mission of a friendly Blue Force (BF) controlling the enemy Red Force's (RF) influence on a strategic, bottleneck trade route and the execution of the kill chain functions performed by the BF during the conflict that ensues. The kill chain function of "finding the RF threat" is conducted by the BF's Intelligence Surveillance Reconnaissance (ISR), the function of "targeting the RF threat" is performed by the BF's decision maker, and the function of "engaging the RF threat" is conducted by the BF's shooter. There are multiple messages exchanged between the BF's ISR, decision maker, and shooter during execution of the kill chain functions and a recognized need to improve the command and control (C2) responsiveness while performing cooperative engagements to ensure overmatch of a near peer enemy by 2030, when naval unmanned surface vessels are predicted to join the fleet.				
14. SUBJECT TERMS joint fires, command and control, C2, link-16, distributed maritime operations, littoral combat ship, multi-domain, unmanned aerial vehicles, unmanned ground vehicles, adaptive force package, carrier strike group, close air support, weapons release authority, data, decision, expeditionary, artillery, missiles, kill chain, system of interest, SOI, cooperative engagement capability, air defense mission, strike mission, Intelligence Surveillance Reconnaissance, ISR			15. NUMBER OF PAGES 115	
			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	

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

**INCREASED EFFECTIVENESS OF THE JOINT FIRE'S KILL CHAIN
VIA IMPROVEMENTS IN COMMAND AND CONTROL RESPONSIVENESS
FOR BETTER COOPERATIVE ENGAGEMENT CAPABILITY**

Maj Kelly P. Haycock (USMC), Lance Kerestes, Brenda Menees,
and Axel E. Rodriguez-Negron

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN ENGINEERING SYSTEMS

and

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
September 2020**

Lead Editor: Brenda Menees

Reviewed by:

Eugene P. Paulo
Advisor

Paul T. Beery
Co-Advisor

Anthony G. Pollman
Co-Advisor

Wayne Porter
Co-Advisor

Accepted by:

Ronald E. Giachetti
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The system of interest (SOI) for this research centers on the mission of a friendly Blue Force (BF) controlling the enemy Red Force's (RF) influence on a strategic, bottleneck trade route and the execution of the kill chain functions performed by the BF during the conflict that ensues. The kill chain function of "finding the RF threat" is conducted by the BF's Intelligence Surveillance Reconnaissance (ISR), the function of "targeting the RF threat" is performed by the BF's decision maker, and the function of "engaging the RF threat" is conducted by the BF's shooter. There are multiple messages exchanged between the BF's ISR, decision maker, and shooter during execution of the kill chain functions and a recognized need to improve the command and control (C2) responsiveness while performing cooperative engagements to ensure overmatch of a near peer enemy by 2030, when naval unmanned surface vessels are predicted to join the fleet.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	BACKGROUND	1
B.	DISTRIBUTED MARITIME OPERATIONS.....	2
C.	SCENARIO OVERVIEW	3
D.	RESEARCH OBJECTIVES	3
E.	SYSTEMS ENGINEERING PROCESS.....	4
II.	LITERATURE REVIEW	5
A.	BACKGROUND	5
B.	DATA COLLECTION AND ANALYSIS	5
III.	OPERATIONAL CONCEPT	13
A.	GENERAL OPERATIONAL ENVIRONMENT	13
B.	SPEEDING UP THE DECISION CYCLE.....	19
C.	LETHAL TRIAD: ROLES THAT COMPRISE JOINT CEC	24
D.	PRIMARY FUNCTIONS THAT COMPRISE A JCEC	28
E.	MESSAGING PROTOCOLS.....	30
F.	REQUIRED COMMUNICATIONS CAPABILITIES	31
IV.	PROPOSED SYSTEM ARCHITECTURE.....	39
A.	SYSTEM OF INTEREST (SOI).....	39
B.	JF PROPOSED IMPROVEMENTS.....	42
C.	CAPABILITY MODELS OF CURRENT & IMPROVED JCEC C243	
D.	FUNCTIONAL MODELS OF PROPOSED IMPROVEMENTS	48
V.	JOINT FIRE DMO SIMULATION.....	61
A.	SIMULATING THE JF'S DMO KILL CHAIN.....	61
B.	SIMULATION APPROACH AND PURPOSE	62
VI.	EFFECTIVENESS AND PERFORMANCE	71
A.	MEASURES OF EFFECTIVENESS AND PERFORMANCE.....	71
B.	DATA ANALYSIS AND RESULTS	73

VII. CONCLUSIONS AND RECOMMENDATIONS.....	85
A. CONCLUSIONS	85
B. RECOMMENDATIONS.....	87
C. FURTHER RESEARCH.....	87
LIST OF REFERENCES	89
INITIAL DISTRIBUTION LIST	95

LIST OF FIGURES

Figure 1	A Tailored System Engineering Process. Source: Blanchard and Fabrycky (2011, 36).	4
Figure 2.	Network Architectures: Centralized, Decentralized, and Distributed. Source: Bach, Brier, and McNeil (2019).....	10
Figure 3.	Region of Interest within the Scenario Space.	14
Figure 4.	Scenario Space’s Major Shipping Lanes	15
Figure 5.	Red Force Military Base Locations	16
Figure 6.	BF versus RF, First Phase Concept of Operations.....	17
Figure 7.	BF Offensive Fires Concept of Operations.....	19
Figure 8.	Example of Internally Integrated Combat Systems	21
Figure 9.	Joint Force Commander’s Fire Cell, Externally Integrated.....	22
Figure 10.	Example of CEC Using F-35 and Aegis	23
Figure 11.	Externally Integrated Joint Platforms Emulating Internally Integrated C2 via CEC	24
Figure 12.	Lethal Triad Potential Platforms	27
Figure 13.	CEC Exchanges among the ISR, Decision Maker, and Shooter.....	30
Figure 14.	System of Interest—JF Kill Chain’s Increased Effectiveness	39
Figure 15.	Shortening of the Kill Chain to Find, Target, Engage. Source: Popa et al. (2018).	41
Figure 16.	Modified Kill Chain Applicable to JF’s Research. Source: Popa et al. (2018).	41
Figure 17.	Capability Model for Current JF Kill Chain	44
Figure 18.	Capability Model for Improved JF Kill Chain.....	46
Figure 19.	Operational / Functional Model for Improved JF Kill Chain	49
Figure 20.	Operational / Functional Model for Finding of Threats via BF ISR.....	52
Figure 21.	Operational / Functional Model for Fixing, Tracking, and Assessing via BF ISR.....	53
Figure 22.	Operational / Functional Model for Targeting of Threats via BF DM	55

Figure 23.	Operational / Functional Model for Engaging Threats via BF Shooter.....	57
Figure 24.	IDEF0 of Improved JF Kill Chain	59
Figure 25.	Proposed Lethal Triad JCEC C2 Kill Chain Execution Thread	61
Figure 26.	Establishing the Red Force (RF) and the Blue Force (BF).....	65
Figure 27.	Allocated Munitions to RF and BF Platforms	66
Figure 28.	Locations for Land-Based Platforms	66
Figure 29.	Assigning Location to RF and BF Platforms.....	67
Figure 30.	Dynamic Interplay of RF & BF Platforms and Munitions	67
Figure 31.	BF Platforms Killed	75
Figure 32.	BF Mean % Survivability	75
Figure 33.	BF Mean % Survivability for Excursions	79
Figure 34.	Additional BF AMD Munitions Available and Spent	80
Figure 35.	Additional BF AMD Munitions Available and Spent for Excursions.....	81
Figure 36.	Additional RF Munition Neutralized	82
Figure 37.	Additional RF Munition Neutralized with Excursions.	84

LIST OF TABLES

Table 1.	Proposed JCEC C2 Interoperability Improvements.....	42
Table 2.	Comparison of Current and Improved JCEC C2 for JF Kill Chain.....	47
Table 3.	RF and BF Munition Parameters. Source: Popa et al. (2018).....	63
Table 4.	RF Platform Parameters. Source: Popa et al. (2018).	64
Table 5.	BF Platform Parameters and Sensors. Source: Popa et al. (2018).	64
Table 6.	Blue Force Platform Capability Categories	68
Table 7.	Simulation Input Timing.....	70
Table 8.	2030 JF MOE & MOPs.....	72
Table 9.	Simulation Output Parameters that Relate to JF MOPs.....	74
Table 10.	BF Mean % Survivability	76
Table 11.	DM Options in Timing for Excursions from Table 7, Column 2. Source: Moon, Carley, and Kim (2013).	77
Table 12.	Explanation of SQ0, JCEC1, SQ2, JCEC3, SQ4, JCEC5.....	77
Table 13.	BF Mean % Survivability for Excursions.....	78
Table 14.	Additional BF AMD Munitions Available and Spent	80
Table 15.	Additional BF AMD Munitions Available and Spent for Excursions.....	82
Table 16.	Additional RF Munitions Neutralized	83
Table 17.	Additional RF Munitions Neutralized with Excursions.....	84
Table 18.	BF Mean % Survivability Analysis Summary.....	85
Table 19.	Additional BF AMD Munitions Available and Spent Summary.....	86
Table 20.	Additional RF Munitions Neutralized Summary	86

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AEGIS	Advanced Electronic Guided Interceptor System
AFP	Adaptive Force Package
AMD	Air Missile Defense
ANOVA	Analysis of Variance
AO	Area of Operations
BACN	Battlefield Airborne Command Nodes
BF	Blue Force
C2	Command and Control
C3	Command, Control, and Communications
CA	Complex Adaptive
CASOS	Complex Adaptive Systems of Systems
CCDR	Combatant Commander
CEC	Cooperative Engagement Capability
CIWS	Close in Weapon System
CMN	Concurrent Multi-Netting
CNV	Nuclear Powered Aircraft Carriers
CSG	Carrier Strike Group
CWC	Composite Warfare Commander
DOE	Design of Experiments
DMO	Distributed Maritime Operations
EMCON	Emissions Control
ESG	Expeditionary Strike Group
F2T2EA	Find Fix Track Target Engage Assess
GATOR	Ground/Air Task Oriented Radar
HIMARS	High Mobility Artillery Rocket System
HVP	Hyper Velocity Projectiles
ISR	Intelligence Surveillance Reconnaissance
JCEC	Joint Cooperative Engagement Capability
JCS	Joint Chiefs of Staff
JF	Joint Fire

JTF	Joint Task Force
JTRS	Joint Tactical Radio System
LCS	Littoral Combat Ship
LHD/LHA	Amphibious Assault ships
LUSV	Large Unmanned Surface Vessels
MADL	Multifunction Advanced Data Link
MCDP	Marine Corps Doctrinal Publication
MIDS	Multifunction Information Distribution System
MOC	Maritime Operations Center
MOE	Measures of Effectiveness
MOP	Measures of Performance
MUSV	Medium Unmanned Surface Vessels
NIFC-CA	Naval Integrated Fire Control-Counter Air
NTTP	Naval Tactics Techniques and Procedures
NWDC	Navy Warfare Development Command
NWP	Naval Warfare Publication
OTC	Officer in Tactical Command
PLA-N	Peoples Liberation Army - Navy
RF	Red Force
Rx	Receiving
SEA	Systems Engineering Analysis
SoS	System of Systems
SQ	Status Quo
TTP	Tactics Techniques and Procedures
Tx	Transmitting
U.S.	United States
WEZ	Weapon Engagement Zone

EXECUTIVE SUMMARY

This capstone examines the combination of an improved cooperative engagement capability (CEC) and command and control (C2) for an adaptive force package (AFP) operating within a Distributed Maritime Operation's (DMO) location. This research examines four important entities of the CEC. First, a complete CEC has an observer capable of identifying the precise location of a potential target. In the missile threat environment, the precision of location detail must be extremely high and updated many times per second. This functional element will be categorized as the observer/ISR or sensor function. Second, a complete CEC has the capability to exchange this high-fidelity, target-quality data from the Observer/ISR platform to other participating platforms. Third, a complete CEC has a firing platform with a munition capable of successfully prosecuting the observed target. Fourth, a complete CEC has a decision support/decision making capability where the human decision maker interfaces with the system and expresses his or her weapons release authority. The combination of the observer/ISR, decision maker, and shooter will be referred to throughout the paper as the lethal triad.

This research centers on the mission of a friendly Blue Force (BF) controlling the enemy Red Force's (RF) influence on a strategic, bottleneck, trade route and the execution of the kill chain functions performed by the BF during the conflict that ensues. The kill chain functions of finding, targeting, and engaging the threat are conducted, respectively, by the BF observer, decision maker, and shooter. There are multiple messages exchanged between the lethal triad during execution of the kill chain functions and a recognized need to increase the C2 responsiveness while performing CEC to ensure overmatch of a near peer enemy by 2030 when naval unmanned surface vessels are predicted to join the fleet.

Proposed lethal triad interoperability improvements for shortening current C2 cycles during the kill chain execution include digitization of typically analog messages relayed between the lethal triad, radio messaging translation from one protocol to another, automation of the best solution for the lethal triad and incorporation of MADL-like communications similar to that used on the F-35. The implementation of these

improvements on every platform should allow for the creation of a distributed, AFP, ad-hoc mesh.

Of utmost importance are the effects that shortening the C2 cycle should have on the kill chain and the outcome of a battle. The kill chain benefits should include faster, less jammable communication between the lethal triad; more responsive, reliable decision making in a highly contested environment; and improved matching of weapon systems to threats which should culminate in a more appropriate and effective ad hoc, self-forming AFP.

Capability and functional models of the proposed improvements have been developed along with a simulation of the mission scenario using various combinations of the BF lethal triads attacking and defending against the enemy RF weapon systems with realistic weapon system parameters incorporated including unmanned. The simulation data collection and analysis results indicate a 5.9 % to 6.4% increase in survivability of the BF while implementing the proposed JCEC C2 interoperability improvements with the greatest improvements due to automated decision making. Additional data also indicates that accelerating the kill chain via JCEC C2 improvements allows for as many as 12 additional BF munitions to become available for fire and for 4.6 additional RF munitions to be destroyed, thus acting as a form of BF multiplier. BF losses are also reduced by 12.6%.

These results indicate that by improving interoperability among the lethal triad and by improving human decision making through automation, war fighter lives can be saved because less BF platforms are lost and overmatch against a near peer enemy in 2030 is maintained. The analysis supports that the single most significant factor the JF is facing is the mismatch between human cognitive response time and the speed at which future enemy hyper velocity projectiles (HVPs) may travel. The data indicates that human decision makers introduce significant delays into the command and control system that could hinder the ability of the JF to promptly react and defend their platforms in future conflicts. The JFs of 2030 should consider pursuing artificial intelligence and machine learning algorithms to greatly reduce the C2 cycle times and data exchange delays of the JCEC C2, thereby increasing the chances of neutralizing newly developed and faster incoming threats.

ACKNOWLEDGEMENTS

Many thanks to our advisors, Professors Paul Beery, Eugene Paulo, Anthony Pollman, and Wayne Porter, for the many lessons learned from years of their cumulative experience. Special thanks to our teammate, Major Kelly Haycock, USMC, for his relentless insistence on tackling this subject and imparting his knowledge as a communications officer to his teammates. Thanks to all for staying well during the COVID-19 pandemic and for planning and preparing for the inevitable. Be steadfast and courageous, for good things are conceived from many weekends of revisions.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

On 13 September 2016, an F-35 and an Aegis combat system demonstrated a cooperative engagement capability (CEC) where the Aegis platform successfully engaged and destroyed an incoming enemy missile that was beyond its detection range through the high-fidelity tracking data provided by the sensors on the F-35 (Lockheed Martin Newsroom 2019). This required a highly integrated command and control (C2) system between the F-35 and the Aegis combat system that included sensors, data processors, and high-data rate radio transmissions to find, target, and coordinate engagement of the missile prior to entering the friendly Aegis platform's sensor range. This was a pivotal, yet incremental step in the futuristic Navy concept of Naval Integrated Fire Control-Counter Air (NIFC-CA) where the fleet's mission effectiveness in a contested environment relies on the extended range of airborne and surface-based sensors and a very rapid find-target-engage cycle among its distributed components to interdict incoming missile threats. While a single enemy missile does not usually present an unmanageable threat with the Aegis combat system in defense of the platform, the future threat environment predicts a speed and volume of missile fire that would overwhelm the Aegis combat system if it was left to operate alone. In distributed maritime operations (DMO), the naval force may be configured into custom task organizations known as adaptive force packages (AFPs) where there may only be a single Aegis combat system close enough to affect the outcome of such engagements.

While the F-35 acted as a sensor, the pilot acted as a decision maker, and the Aegis combat system acted as a shooter in the find-target-engage cycle, this is a very novel combination of platforms that require a large number of very specific situational circumstances to align in order to be effective. In this research project, the team explores ways to expand the number of platforms capable of participating in the cooperative engagement capability desirable in both NIFC-CA (air and missile defense) and surface and strike warfare through inclusion of joint platforms like the Patriot missile battery, AN/TPS-80 GATOR radar alongside naval platforms such as the guided missile destroyer,

littoral combat ship (LCS), F-35, large unmanned surface vessel (LUSV), and medium unmanned surface vessel (MUSV).

B. DISTRIBUTED MARITIME OPERATIONS

As adversary, sea denial tactics increasingly threaten the Navy fleet with cruise and ballistic missiles, so too are Navy fleet tactics evolving to address them. In order to conduct freedom of navigation operations and exert sea control over important maritime regions while allowing the highest value platforms to maintain appropriate standoff distances from adversary threats, it may be appropriate to distribute the naval force into task elements smaller than a traditional carrier strike group (CSG) or expeditionary strike group (ESG) while still being able to conduct surface warfare, anti-submarine warfare, air & missile defense, and strike warfare. These are components of the composite warfare commander (CWC) concept (Navy Warfare Development Command (NWDC) 2015a). The task elements organized from their parent CSGs, ESGs, or other maritime groups or squadrons will be formed into mission-tailored threat-informed AFPs to enter the adversary's weapon engagement zone (WEZ) and conduct sea control operations (NWDC 2015b). Because of the potential absence of high-value platforms such as nuclear-powered aircraft carriers or amphibious helicopter ships, the AFP must be able to conduct many of the same warfare functions that previously were centered on a capital ship while operating without the traditional cover associated with a CSG or ESG. Being able to divide the friendly naval force into AFPs allows it to conduct DMO.

DMO is smaller-sized AFPs with commensurately scaled-down air and missile defense, surface and strike warfare capabilities tailored to be a subset of a larger force. The F-35 and Aegis combat system CEC previously discussed is a prime example of how reach and firepower can be scaled down and distributed. Distributed platforms are more difficult for the enemy to find, classify, target, and hit than their high-value counterparts. This is a far less favorable cost equation for the enemy.

However, distributing the lethality among many smaller platforms and accepting a higher risk for their expendability does not guarantee robust CEC. The desired effectiveness of DMO can only be realized with a sufficiently robust C2 system.

C. SCENARIO OVERVIEW

The timeframe is 2030, and the friendly Blue Force (BF) has unmanned, autonomous surface ships to deploy that will lower the risk to manned platforms. The Red force (RF) threat is projecting power to control a highly coveted, narrow strait through which global trade flows to Red and Blue partner nations. Whoever controls the strait will most likely win the conflict because they will choke the opponent's supply line. Both Red and Blue Forces have partner nations in the area and are building coalition forces to protect their assets along the strait.

D. RESEARCH OBJECTIVES

The current Navy C2 capabilities must be capable of supporting an advanced CEC like that demonstrated between the F-35 and the Aegis. Distributed lethality platforms depend upon robust and timely C2 to exercise an effective CEC. There is an urgent need to develop a systems architecture that standardizes and speeds C2 interoperability to improve the overall joint force effectiveness in air and missile defense, naval surface, and air strike warfare by bringing platforms together in a joint CEC (JCEC). The focal point of this research is to understand the increased effectiveness of the kill chain by implementing shorter C2 cycles between 1) the observer conducting intelligence, surveillance, and reconnaissance (ISR); 2) the shooter; and 3) a more empowered, forward weapons release authority also known as the decision maker (DM). This will depend upon improved CEC interoperability and implementation of a CEC mesh network.

E. SYSTEMS ENGINEERING PROCESS

The Joint Fires (JFs) team follows a tailored system engineering process as shown in Figure 1 (Blanchard and Fabrycky 2011). The process begins by analyzing the stakeholder's objectives to ensure correct interpretation of the problem. The next step translates the user's required capabilities into requirements via the use of operational scenario. The requirements decompose into major functions which in turn drive the development and selection of Measures of Effectiveness (MOEs) and Measures of Performance (MOPs). The simulation and back of the envelope calculations support the MOEs and MOPs.

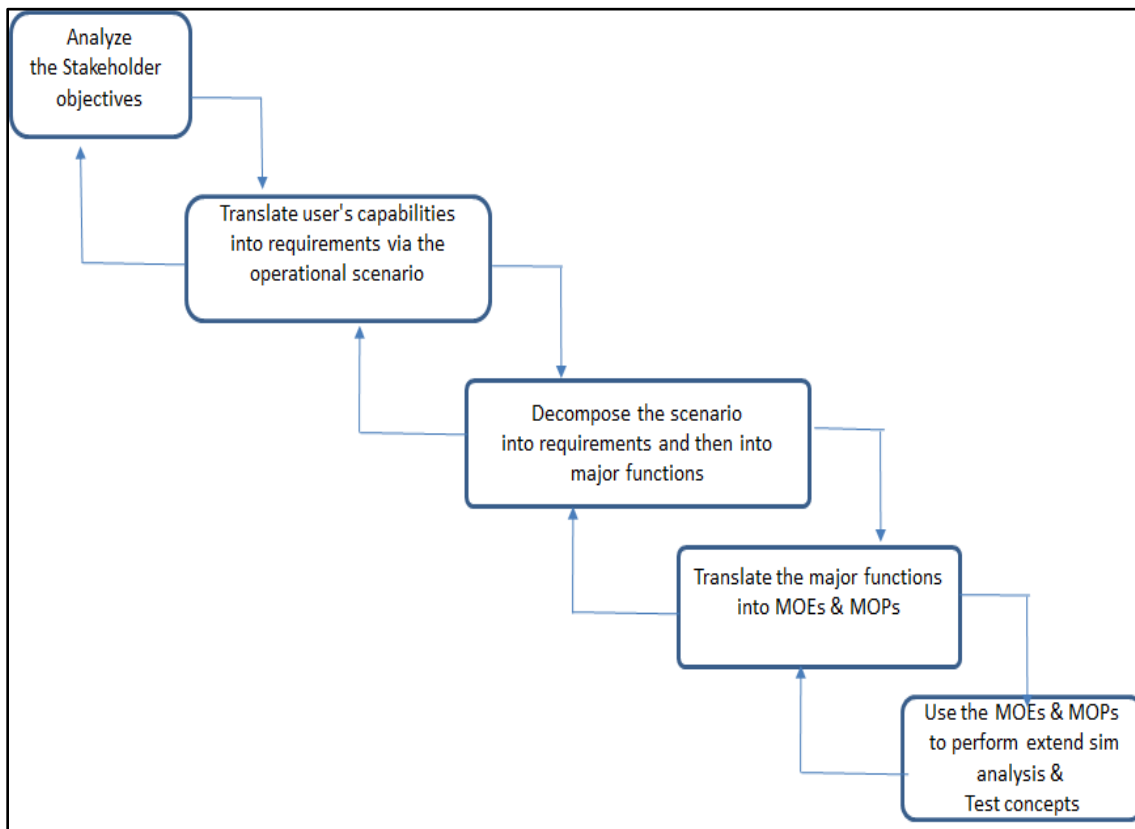


Figure 1 A Tailored System Engineering Process.
Source: Blanchard and Fabrycky (2011, 36).

II. LITERATURE REVIEW

A. BACKGROUND

In general terms, the JFs team was asked the following question: “What can be done to improve the operational effectiveness for manned and unmanned joint fires capabilities in the maritime operational environment?” This question can be decomposed into many parts that require an understanding of operations in the maritime operational environment and DMO, manned and unmanned naval and joint fires, and what constitutes high and low operational effectiveness. Decomposing these topics even further reveals the sub-topics of operational and tactical doctrine, specific manned and unmanned joint platforms and their respective capabilities, tactics, techniques, and procedures (TTPs), enemy doctrine and capabilities, and the command and control theory and architecture that make all friendly action possible and effective. A review of previous literature reveals both general background and context on these topics as well as related research.

B. DATA COLLECTION AND ANALYSIS

1. Operational and Tactical Doctrine

To develop an understanding of distributed maritime operations, operations in the maritime operational environment, and naval and joint fires, and to establish a basic vocabulary on the topic, the JF team reviewed a wide range of doctrinal publications. The most valuable references were those related to organization and employment of naval forces in the maritime environment and related to naval and joint fires. This list of key doctrinal references includes NWCD Navy Warfare Publication (NWP) 3–56: Composite Warfare: Maritime Operations at the Tactical Level of War (NWDC 2015a); Navy Warfare Publication 3–10: Navy Expeditionary Combat Command Forces (NWDC 2015b); Joint Publication 3-09: Joint Fire Support (Joint Chiefs of Staff (JCS) 2019); Navy Warfare Publication 3–09: Navy Fire Support (NWDC 2011); Joint Publication 3-60: Joint Targeting (JCS 2013); and Naval Tactics Techniques and Procedures (NTTP) 3–32.1: Maritime Operations Center (DON 2013a). Other doctrinal publications were referenced but excluded from this list because they did not provide substantive information upon

which to base theories that address what can be done to improve the operational effectiveness of joint fires capabilities in the maritime operational environment or aid in proving or disproving them. Through this research on operational and tactical doctrine, the team assembled the following shared vocabulary of key terms:

Adaptive Force Package: “A non-standard unit, task organized to meet a specific operational requirement, as opposed to standard force packages that are comprised of task organized naval units that routinely train together and deploy in support of combatant commander (CCDR) operations such as a CSG” (NWDC 2015b).

Distributed Maritime Operations: “The integration of a diversity of communications, sensors, and weapons platforms within an area of operations grid to form a real-time configurable Adaptive Force Package to counter the enemy” (DON 2019). For our research we have added that, “in a DMO environment, AFPs are geographically dispersed while still operating as a united, fighting, and lethal force” (Geiss 2019).

Joint Fires: “Joint fire support is joint fires that assist air, land, maritime, space, cyberspace, and special operations forces to move, maneuver, and control territory, airspace, space, cyberspace, the electromagnetic spectrum, and key waters and to influence populations” (JCS 2019). This research focuses on joint fires that assist air, land, maritime, and special operations force to move, maneuver, and control territory, airspace, and key waters.

Other key terms include Officer in Tactical Command (OTC), Composite Warfare Commander (CWC), Air and Missile Defense (AMD), Surface Warfare, and Strike Warfare.

The study of operational and tactical doctrine will help ensure the findings of this research will fit reasonably well within the existing naval and joint operational framework. Proposed adjustments to the way forces are task organized and commanders are delegated decision-making authority must be workable within that framework.

2. Related Research

The Literature Review also includes a previously developed body of research with findings that share at least one main component with the Joint Fires in DMO research. Key shared areas of this research included command and control of forces during DMO,

command and control of manned and unmanned systems, and networked manned and unmanned air and missile defense, surface, or strike warfare systems.

a. Theoretical Basis

The most significant body of research that impacts Joint Fires does so by providing an evidenced foundational theory of fast command and control in a complex and dynamic environment. This research is presented in the form of the 2019 doctoral dissertation entitled, “Summary of a Framework for Engineered Complex, Adaptive (CA) System of Systems (SoS)” (Johnson 2019). Of particular interest for Joint Fires in DMO, this research illustrated the value of engineering complex adaptive combat systems of systems capable of displaying emergent behavior to outpace the enemy decision cycle by networking friendly force platforms with embedded intelligent agents and decision makers in a way that makes rapid self-organization, distributed decision making, and cooperative engagement possible. In this Capstone Project, the Joint Fires in DMO team attempts to apply Johnson’s findings to answer the following two questions: 1) “What are the requirements for an engineered C2 system that can interconnect friendly force platforms and decision makers in a way that makes rapid self-organization, distributed decision making, and cooperative engagement possible?” and, 2) “Can the inclusion of joint manned and unmanned platforms in the scenario space further improve the results?”

b. Integration of Manned and Unmanned in Support of C2

The next body of research that relates to the JF’s research topic is the 2019 thesis entitled, “Analysis of Unmanned Surface Vessel Employment in Distributed Maritime Operations” (Geiss 2019). This research shares the foundational concept that improved effectiveness can be facilitated by increased speed of command and control and employment of distributed manned and unmanned platforms. The assertion that improved effectiveness can be facilitated by increased speed of command and control is supported by discrete events modeling employed in Johnson’s dissertation. The Geiss research topic also focuses on the application of fast command and control enabling distributed cooperative engagement between manned and unmanned surface platforms conducting the air and missile defense mission. It answers the question, “What is the optimal mix (considering capability and cost) of manned and unmanned surface vessels which share a

cooperative engagement capability to improve the operational effectiveness of the adaptive force package in distributed maritime operations?” The Geiss research also provides key friendly and enemy order of battle and capability information. The primary point departure of the JF’s research topic from the Geiss research topic is the question of joint platform inclusion and effectiveness in surface or strike warfare that constitutes the focus of this research.

The next reference that addresses the JF’s research topic is the 2018 capstone report entitled, “Distributed Maritime Operations and Unmanned Systems Tactical Employment” (Popa et al. 2018). This research shares the underlying concept of employing fast command and control to improve operational effectiveness of the friendly force in distributed maritime operations as presented by Johnson. This paper explores the use of novel organizations, tactics, and C2 architecture of manned and unmanned systems to improve the speed and effectiveness of command and control in DMO. Popa further focuses on the improved mission effectiveness of the friendly naval force when employing larger numbers of distributed manned and unmanned air and missile defense platforms in conjunction with counter targeting tactics. While this paper uses modeling support to assess improved operational effectiveness of manned and unmanned fires capabilities in the maritime environment, it does not factor in joint platforms or provide significant evidence supporting improved effectiveness in surface or strike warfare which constitute this capstone’s joint fires objectives.

The final research paper that relates to the JF’s capstone topic is the 2017 “Command and Control for Distributed Lethality” (Corbett et al. 2017). This addresses the exchange of command and control information between weapon system platforms and decision makers conducting manned and unmanned cooperative engagement. This contributes to the concepts being explored by the JF’s capstone.

c. DMO Network Architecture Options

The next research paper relevant to the JF’s research project is the 2019 capstone report entitled, “Systems Engineering Approach to Determining the Suitability of Wireless Mesh Networks for Joint-Fires in Distributed Maritime Operations” (Bach, Brier, and McNeil 2019). Command and control network architectures are reflections of the way

decision makers exert command and control over subordinate commands or systems. For rigidly hierarchical command and control architectures, subordinate commands or systems are dependent on the presence of a higher echelon to coordinate their interactions. When all coordination must be facilitated by a single, central hub or top-level decision maker, to facilitate the exchange of information, it is known as a star or hub-spoke network architecture. Loss of that central node (hub) would mean that no two subordinate elements would be able to connect.

A decentralized command and control hierarchy allows decision making to be delegated from the top decision maker down one or more levels. This is a standard approach to military command and control. Major units are organized into subordinate units that routinely train and operate together. An example of this is when the officer in tactical command delegates the surface warfare function to a surface warfare commander responsible to coordinate the activities of subordinate task elements related to surface warfare. A corresponding network architecture allows for all subordinates of that surface warfare commander to interconnect directly with the surface warfare commander.

However, in general, if a surface warfare subordinate needed to coordinate with an air and missile defense platform, the coordination between them would be made at a higher level of command (i.e., composite warfare commander). This is representative of a decentralized network architecture where networked nodes must connect with a higher echelon to exchange information laterally.

Finally, a distributed command and control architecture is where the authority to make decisions is delegated to the lowest level possible. Adjacent units can form into teams as necessary to create the desired effects and self-organize the decision cycle as necessary to respond to emerging problems. Distributed command and control architectures, conducive to rapidly forming and operating are not optimal with centralized or decentralized network architectures. A network architecture that reflects the distributed command and control architecture must be able to connect all nodes with minimal time lost to reconfiguration. Therefore, a non-hierarchical mesh, or ad-hoc network architecture is ideal. These three network architecture options are depicted in Figure 2.

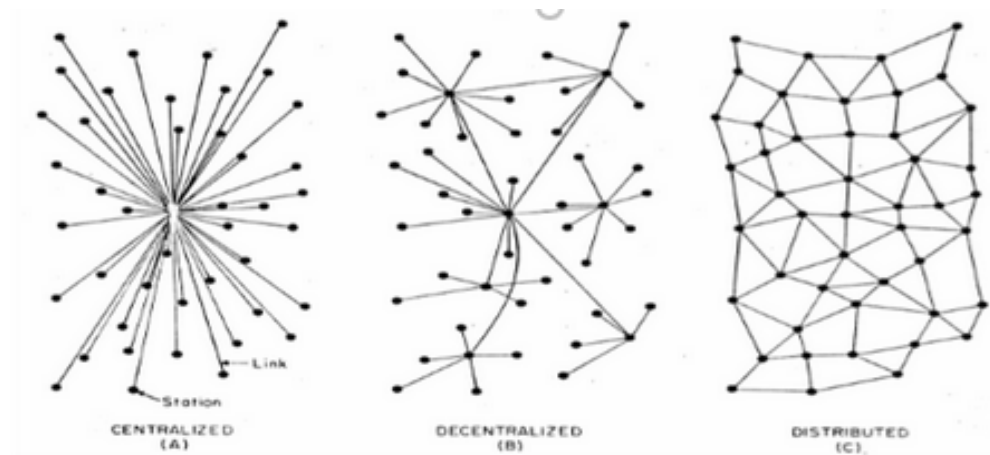


Figure 2. Network Architectures: Centralized, Decentralized, and Distributed. Source: Bach, Brier, and McNeil (2019).

The report, “Systems Engineering Approach to Determining the Suitability of Wireless Mesh Networks for Joint-Fires in Distributed Maritime Operations,” (Bach, Brier, and McNeil 2019) provides evidence to support the claim that wireless mesh communications architectures are more effective than star or hierarchical networks for connecting weapons systems and decision makers in the distributed maritime operational environment. This topic is explored further in the JF’s capstone.

3. Cooperative Engagement Capability (CEC)

The other key source of information on operational effectiveness when implementing CEC is provided by recent technology experiments and the work of capability integrators. It is evident that in September 2016, according to the U.S. Naval Institute, a break-through cooperative engagement technology was demonstrated between the F-35B and the Aegis combat system that accomplished many of the goals of the aforementioned doctrinal publications and lends weight to the assertions and findings of past researchers (Lockheed Martin Newsroom 2016). The report of this accomplishment provides sufficient confidence that this technology is mature enough to build upon within the scope of the JF’s capstone research.

In December 2017, the Army Fires Bulletin published an article describing the significant potential to be gained by integrating the F-35’s sensors directly with the M142

HIMARS weapon system so that the sensing functions in one could inform the targeting and firing of the other without the aid of a coordinating agent (Russo 2017). This is one of many use cases central to the JF's capstone project. Finally, to provide context to the desired operational effectiveness of the JF's research proposal, it is noted that in November 2019, U.S. military service chiefs came together to agree on a strategy of incorporating the joint manned and unmanned CEC (Hitchens 2019).

THIS PAGE INTENTIONALLY LEFT BLANK

III. OPERATIONAL CONCEPT

A. GENERAL OPERATIONAL ENVIRONMENT

A friendly, joint Blue Force (BF) is tasked with maintaining freedom of navigation and sea control against a near peer, adversarial Red Force (RF) in the south Pacific region. The area of operations includes friendly and neutral nations that desire safe passage of air and maritime shipping to ensure continued conditions favorable to trade and economic growth. The battlespace consists of open ocean, sea lanes, and land masses that range in size from small shoals to that of continents.

During routine operations, the friendly, joint BF operates in the contact layer, where naval forces transit sea lanes and aid in enforcement of elements of international law related to protection of allied regional interests. Amphibious, land, air, and special forces conduct theater security cooperation exercises to develop stronger ties with allied militaries and provide nation building aid where possible (DOD 2018).

During periods of escalated tensions, the BFs must rapidly reorganize and refocus to deter or prevent conflict escalation at the blunt layer. This means that some military action, usually lethal, is required at a level below full-scale war. Naval, amphibious, land, air, and special forces assigned to the theater task organize into a joint task force adapted to create the desired military effects (Colby 2019).

As the need may arise for the friendly joint BF to commit to full scale war against a major regional maritime power, the force must have the flexibility to reorganize and surge, as necessary. This means that the friendly nation and allies mobilize reserve forces and bring them to bear against their regional adversary.

During this scenario, the friendly BF begins operation at the contact layer and must escalate its posture to support blunt layer and surge layer operations. A friendly, joint BF consists of a carrier strike group and an amphibious ready group conducting freedom navigation and theater security cooperation or contact layer operations (Colby 2019). When transiting sea lanes, the maritime force observes a peer competitor force conducting maritime operations meant to deter friendly, BF from transiting by the most economical

route through international waters. The near peer, adversarial RF is asserting new claims of ownership over the waterways including natural resources.

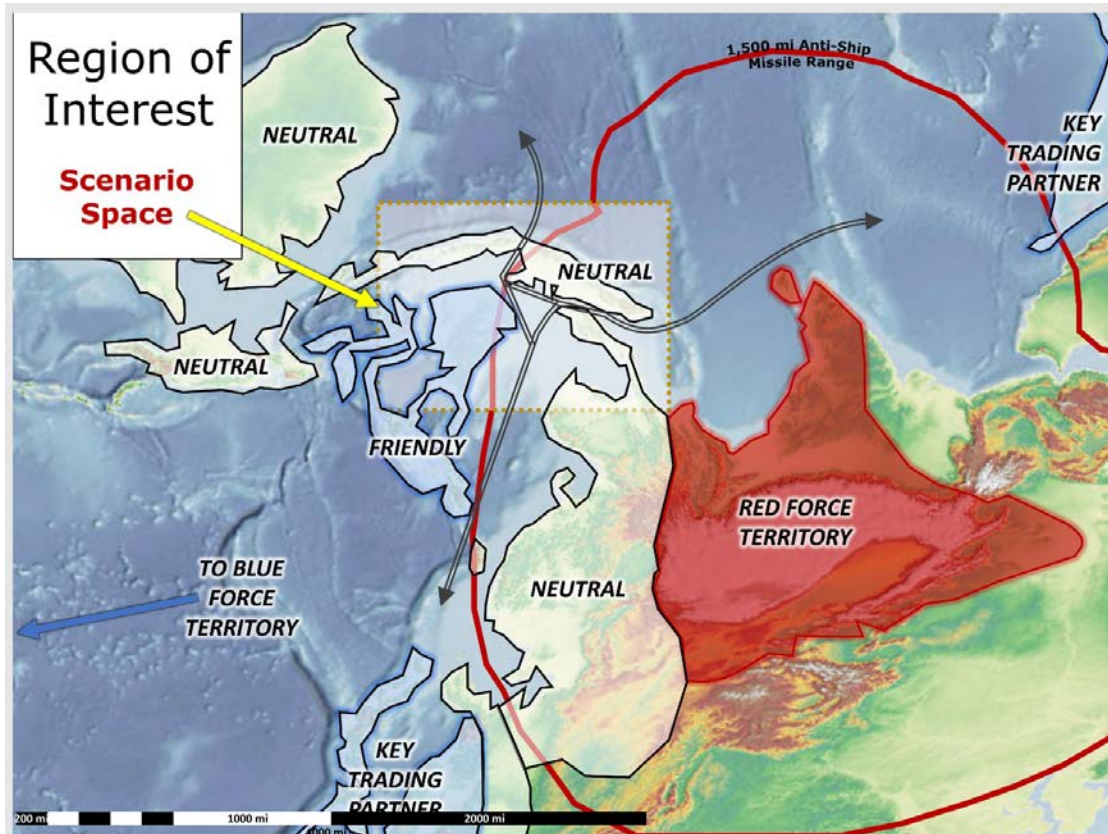


Figure 3. Region of Interest within the Scenario Space.

The RF territory is situated in a manner that allows it to reach 1,500 miles or greater with its anti-ship missile capability placing key waterways under direct threat of attack. The operational scenario takes place in a focal point of a region. A major chokepoint for regional shipping is indicated with the brown dotted line box as shown in Figure 3.

Figure 4 depicts a scenario space with its designated shipping lanes. This possible DMO scenario begins when multi-source intelligence assets observe the adversary RF, employing medium range surface to surface missiles, striking, and sinking a commercial vessel from a partner nation in international waters.

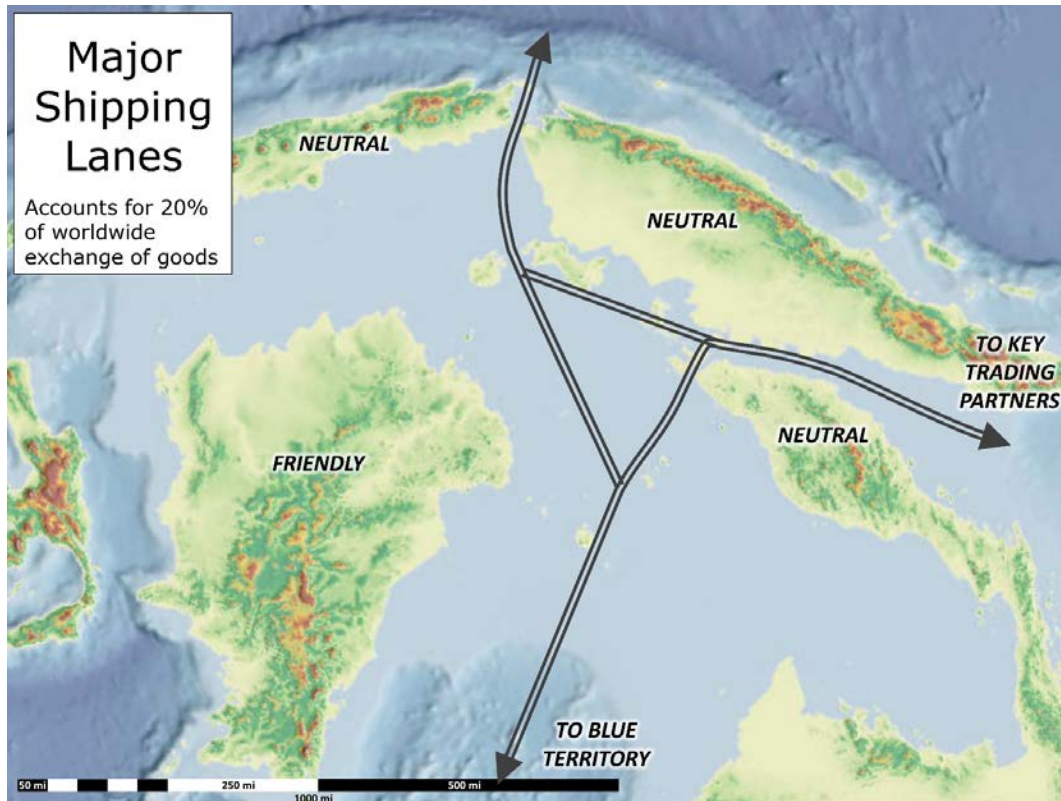


Figure 4. Scenario Space's Major Shipping Lanes

The joint, BF commander directs the maritime force to neutralize the RF platforms that sank the partner nation's vessel and threaten free navigation of key waterways. The RF platform's possible locations are displayed in Figure 5. The friendly BFs conducting contact layer operations are distributed throughout the region. Based on their understanding of the enemy strength, disposition, and capabilities, the combatant commander and navy component commander task-organize a small adaptive force package (AFP) from the available naval, amphibious, land, air, and special operations resources appropriate to prosecute the RF platforms. The adaptive force package is placed under a single joint task force (JTF) commander and will begin conducting blunt layer operations.

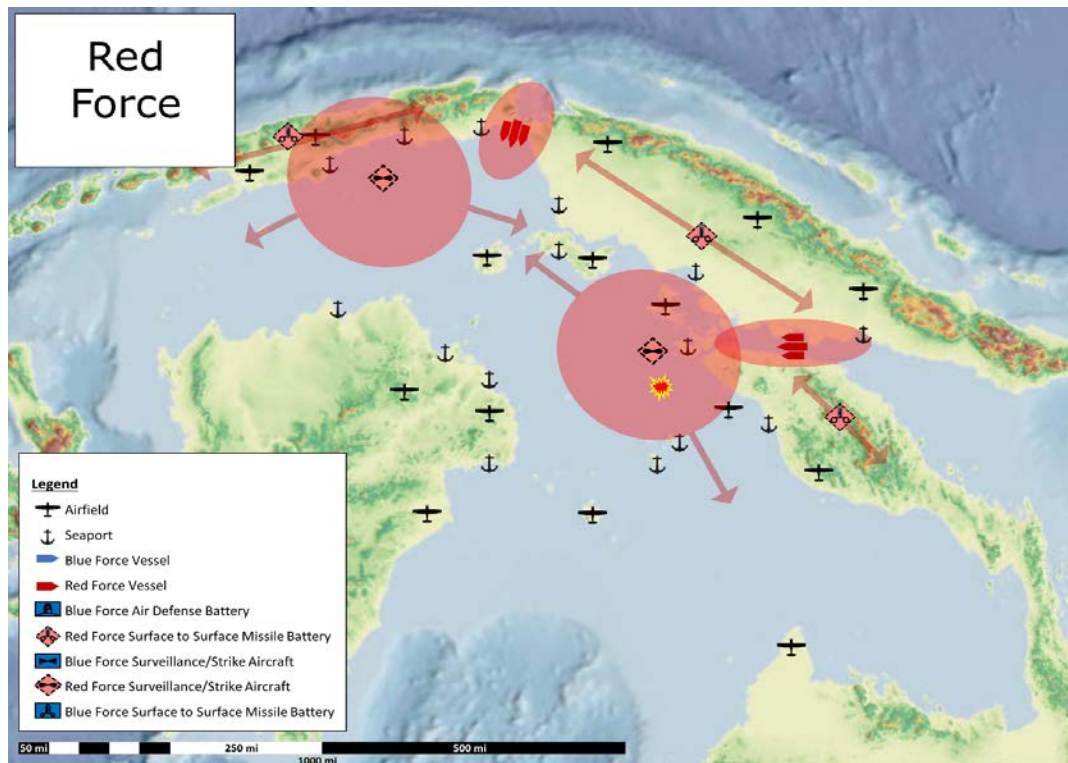


Figure 5. Red Force Military Base Locations

This adaptive force package is relatively small consisting of three to five manned and unmanned surface and subsurface vessels, four to eight manned and unmanned aircraft, and ground combat units capable of conducting air and missile defense and medium range rocket attack. The supported JTF commander will also serve as the joint maritime component commander, and officer in tactical command (OTC), as outlined in the CWC concept (NWDC 2015a). However, because of the unknown extent of the enemy's response, the Navy's component commander will mitigate risk by maneuvering the naval force to be able to influence the AFP's operating area with reinforcing fires.

The objective is to find and neutralize the naval platforms from which the adversary missiles were launched. However, to do so, the AFP will have to enter the adversary weapons engagement zone populated by hidden surface to surface missile platforms, safe harbors for gunboats, and airfields for strike aircraft. The AFP may need to mitigate a wide spectrum of threats while in pursuit of the objective.

This scenario is divided into two phases. First the AFP will transit to the objective area across open ocean, inside of the adversary's integrated air and surface defensive weapons engagement zone, in which friendly use of fires is characterized as defensive in nature. During this phase, fires must neutralize threats from adversary strike aircraft, anti-ship, cruise missiles, or hyper velocity projectiles in flight, and any submarines or gunboats with which the enemy may attempt to gain an asymmetric advantage. Threats identified during this phase can be mitigated through radar and integrated surface and air defense, patrolling manned and unmanned aircraft, surface, or subsurface vessels, and theater aerial or space-based surveillance. This scenario concept of operations is depicted in Figure 6.

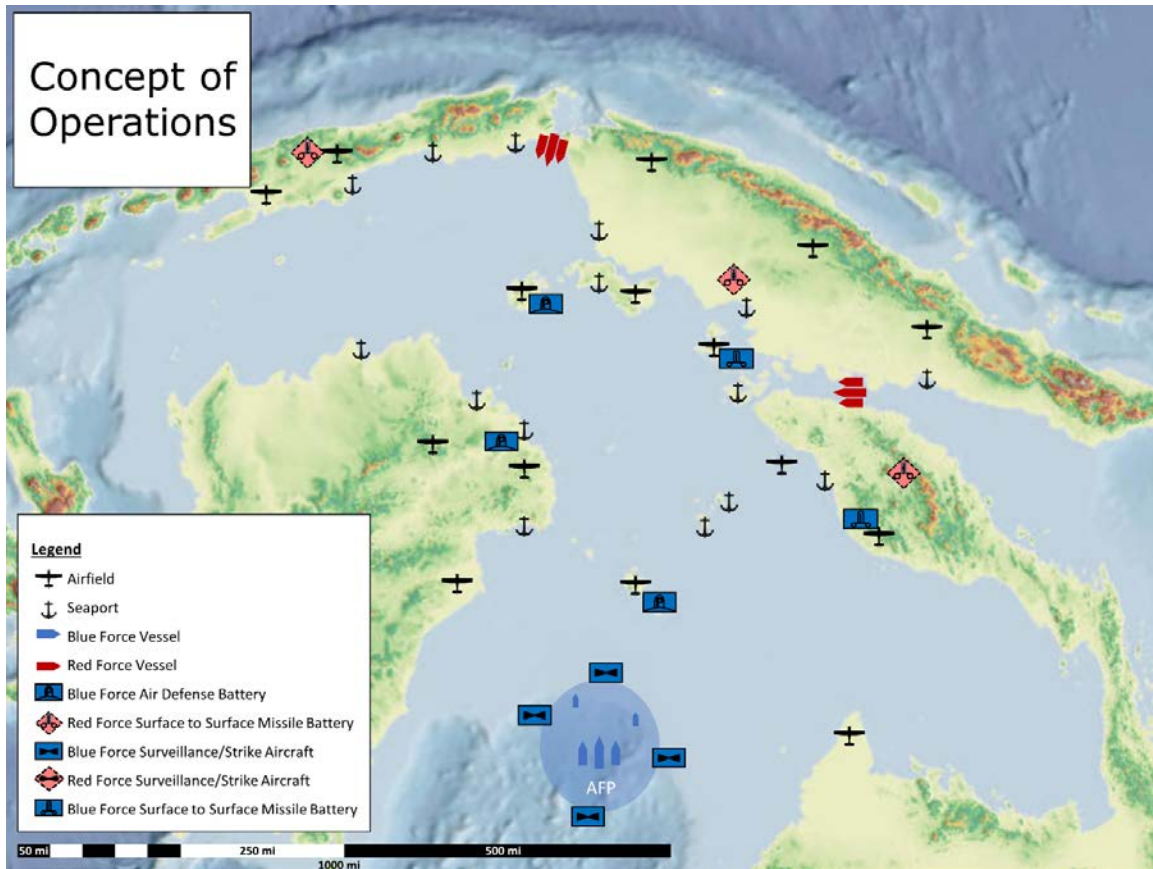


Figure 6. BF versus RF, First Phase Concept of Operations

As the friendly BF transits the open ocean to close with the area of operations (AO), the joint force commander should seek to bring joint force capabilities to the defense of the

AFP. In doing so, the joint special operations force or maritime component commander provides covert units to seize advanced expeditionary airfields in the vicinity of the enemy force, and the joint force air component commander provides rapidly deployable strategic airlift capabilities to covertly transport and deploy land air search and air and missile defense (AMD) passive sensors or active radars as the situation and threat demands. Also, in this outer sensor ring, medium displacement unmanned surface vessels, unmanned aerial systems, and F-35s are interconnected with the ground sensors to exchange target-quality data. However, they will exercise coordinated emissions control (EMCON) until the decisive point is cued by theater intelligence, surveillance, and reconnaissance (ISR). In a defensive ring closer to the AFP, the C-17s covertly land Air Defense Artillery platforms (i.e., Patriot Batteries) that can be linked to, and coordinated with, other integrated counter-air fire control systems and firing platforms to include other medium displacement unmanned surface vessels, unmanned aerial systems, and manned platforms.

The second phase will be characterized by the integration of offensive fires. As the AFP closes with the adversary RF, the RF will reveal its full defensive capabilities. For the AFP to survive, the transit to the objective area must identify, target, and employ fires to neutralize the threats. RF threats can be identified by electromagnetic or electro optical observation of inbound missiles, high velocity projectiles, or missile batteries or by electromagnetic detection of enemy targeting radars. RF threats can then be cooperatively engaged and neutralized by fires from a wide range of joint distributed lethality platforms available to the AFP. These AFPs include, but are not limited to, manned and unmanned strike aircraft, manned and unmanned surface and subsurface missile platforms, artillery, or missile-capable land forces. They can be maneuvered to adjacent landmasses by air or surface connectors and can target with long-range land-based conventional ballistic missiles. Finally, joint fires will be used for accomplishment of the objective to neutralize the enemy, RF targets. In Figure 7, the integration of offensive fires concept of operations is depicted.

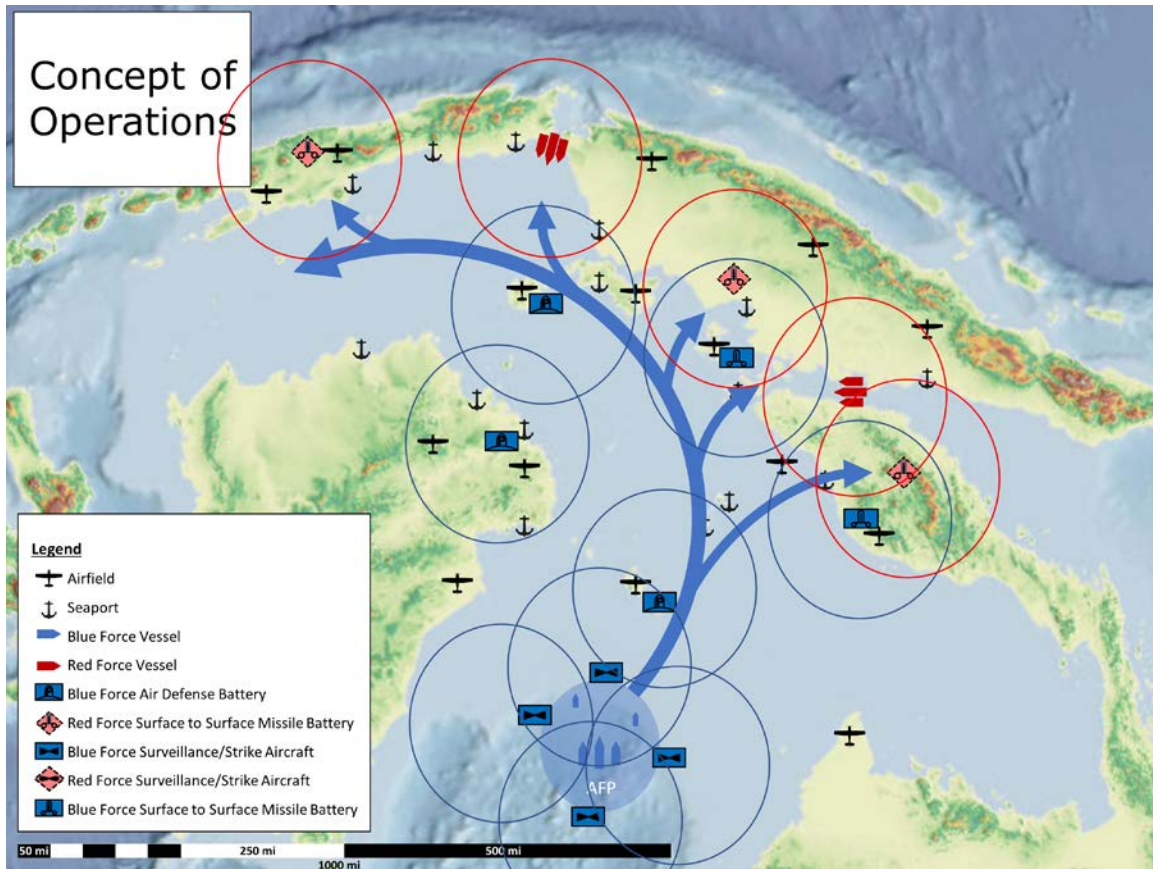


Figure 7. BF Offensive Fires Concept of Operations

It is important to note that both phases of the scenario bear some risk to non-combatant vessels, though significantly more when operating in the littoral environment or among sea lanes. Increased use of semi-autonomous or fully autonomous portions of the kill chain must not infringe on the necessary weapons release authority delegated to the AFP's OTC.

B. SPEEDING UP THE DECISION CYCLE

The following quote from the Marine Corps doctrine emphasizes the criticality of speed in warfare.

Speed is a weapon. In war, it is relative speed that matters rather than absolute speed. Superior speed allows us to seize the initiative and dictate the terms of action, forcing the enemy to react to us. Speed provides security. It is a prerequisite for maneuver and for surprise. Moreover, speed is necessary to concentrate superior strength at the decisive time and place.

(Marine Corps Doctrinal Publication (MCDP) 1997) To generate the tempo of operations we desire and to best cope with the uncertainty, disorder, and fluidity of combat, command and control must be decentralized. We must not try to maintain excessive control over subordinates since this will necessarily slow our tempo and inhibit initiative. (MCDP 1997)

Within the scope of AFP operations, there are two primary command and control problems to solve. The first is the enemy missile barrage problem which poses a threat that centralized command and control struggles with, at least in a hierarchical model reliant on the cooperation of multiple echelons of command and control agencies. The second problem is conducting surface and strike warfare quickly enough to preemptively neutralize enemy weapon platforms or to stop them from posing a continued threat. However, the ranges of the various platforms in the AFP are finite and do not, individually, cover the entire scenario battlespace. To dominate in the battlespace, the AFP must make use of coordinated fires, where systems and platforms come together to perform the functions of the targeting cycle. This consists of finding, targeting, and engaging the enemy. AFP assets must also iterate through this coordinated targeting cycle faster than the adversary can react. There are two basic paradigms for coordinated fires: internally integrated and externally integrated.

Internally integrated fires systems would include the Aegis combat system or the Patriot anti-air missile battery. An internally integrated fires system is very fast because all sensors and weapons systems wait in a high state of readiness for the threat to appear, and when the threat appears within the engagement zone and engagement criteria (set by the rules of engagement and the commander's intent) are met, then only a single human is required to authorize the release of lethal munitions. That human may be aided by other humans or decision support systems, but if the authority has been granted, and the decision maker is trained on correct employment, then no higher or adjacent coordination needs to be sought.

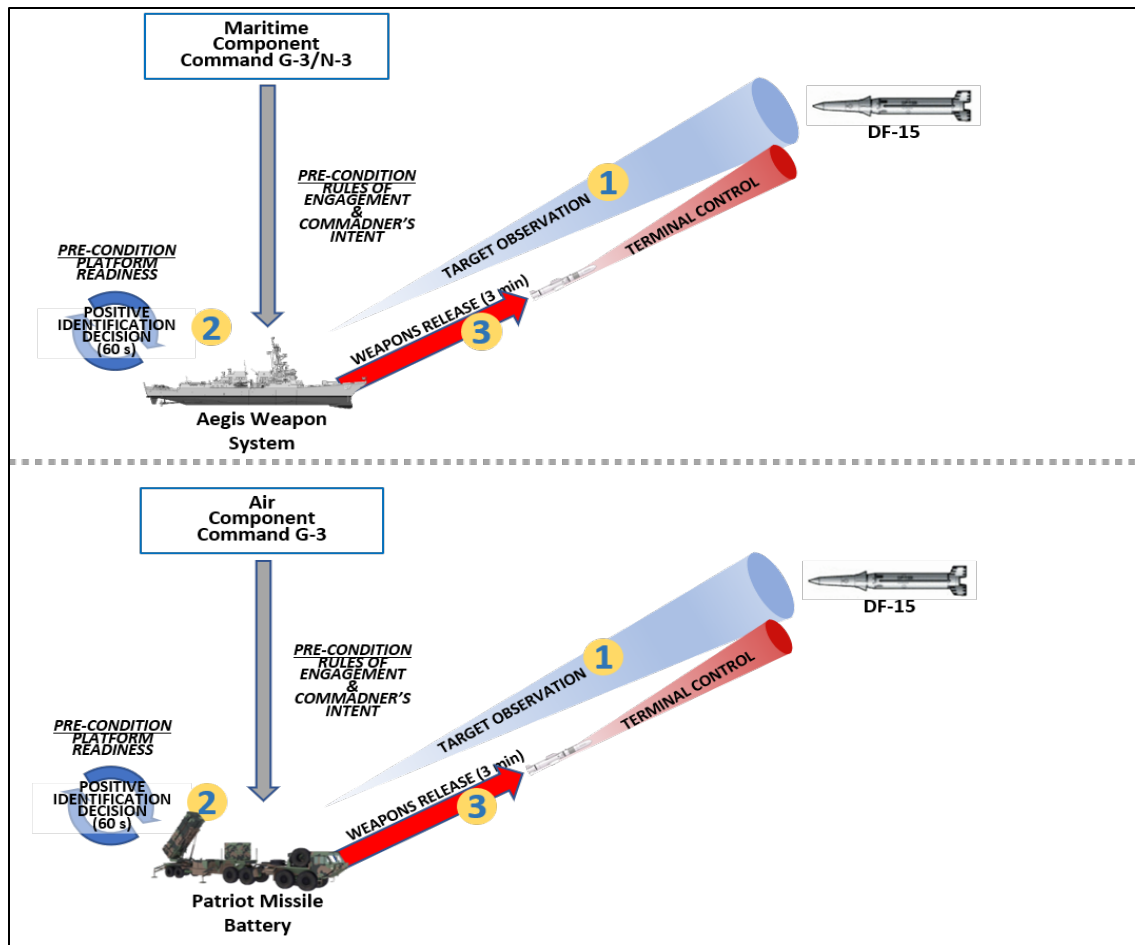


Figure 8. Example of Internally Integrated Combat Systems

With an internally integrated combat system like the Aegis combat system, as depicted in Figure 8 (top), where the AN/SPY-1 radar is operating, the weapons are armed and ready, and a means of positive identification is active, the time from detection to launch should be less than one minute. The Patriot missile battery, as depicted in Figure 8 (bottom), is a combat system with similar internal integration.

Conversely, especially within the joint environment, external organizations rarely form at the tactical level. Usually, a Joint Force Commander is appointed and acts as the coordinating authority for joint fires (JCS 2019). This generally means that for a Navy platform to provide fires against a target identified by an Army platform, detailed target coordination, including weapons release authority, would be requested up or tasked down several echelons in a chain of command all the way up to the Joint Force Commander's

fires cell, see Figure 9. In a joint force, it may take as long as 20 minutes for the force to engage an unexpected target of opportunity because of centralized control exerted over joint fires which are externally integrated.

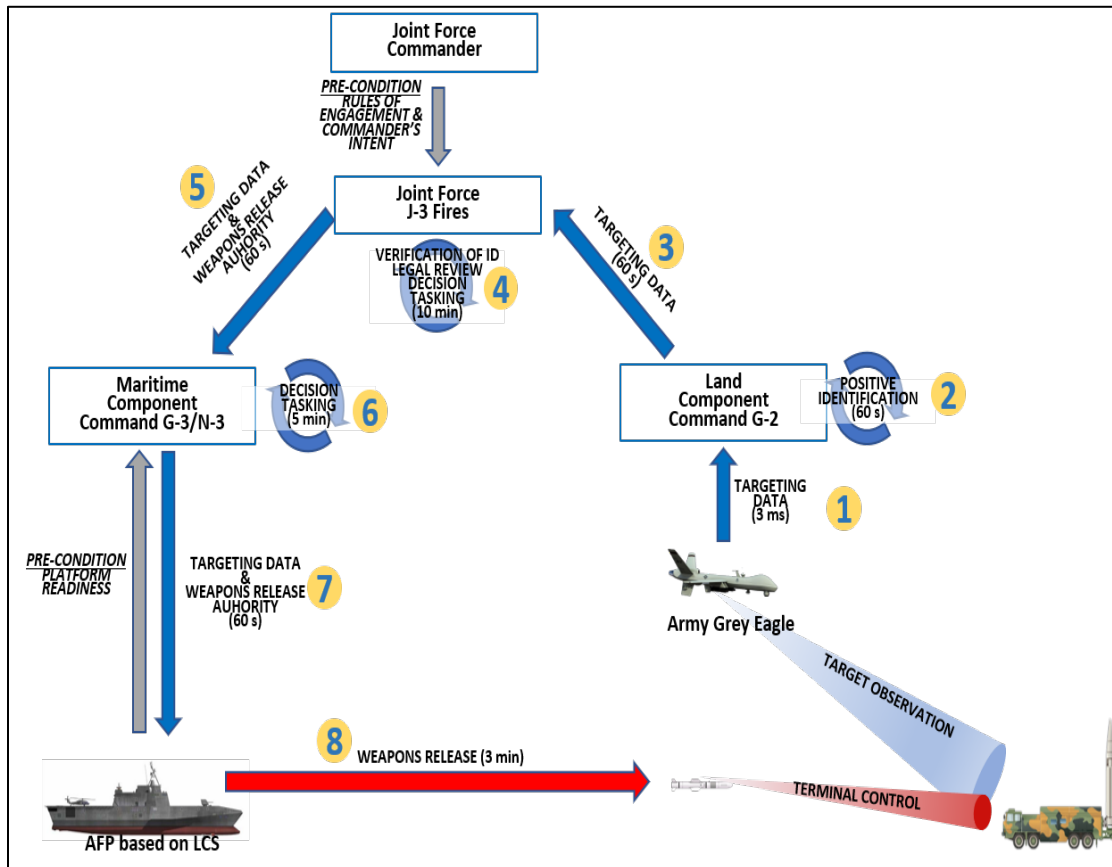


Figure 9. Joint Force Commander's Fire Cell, Externally Integrated

In September 2016, an F-35 demonstrated its CEC by passing missile tracking data to the Aegis combat system that then successfully engaged the incoming missile while it was outside the Aegis system's radar range (Lockheed Martin Newsroom 2016). The missile was destroyed just as it entered the Aegis system's radar range (Lockheed Martin Newsroom 2016). The primary example of CEC by means of a C2 system that interconnected the F-35 in an observer role and the Aegis combat system in a shooter role, as depicted in Figure 10, increased the effective range of the Aegis combat system and thus eliminated several minutes which the missile would have spent closing the distance toward the friendly force.

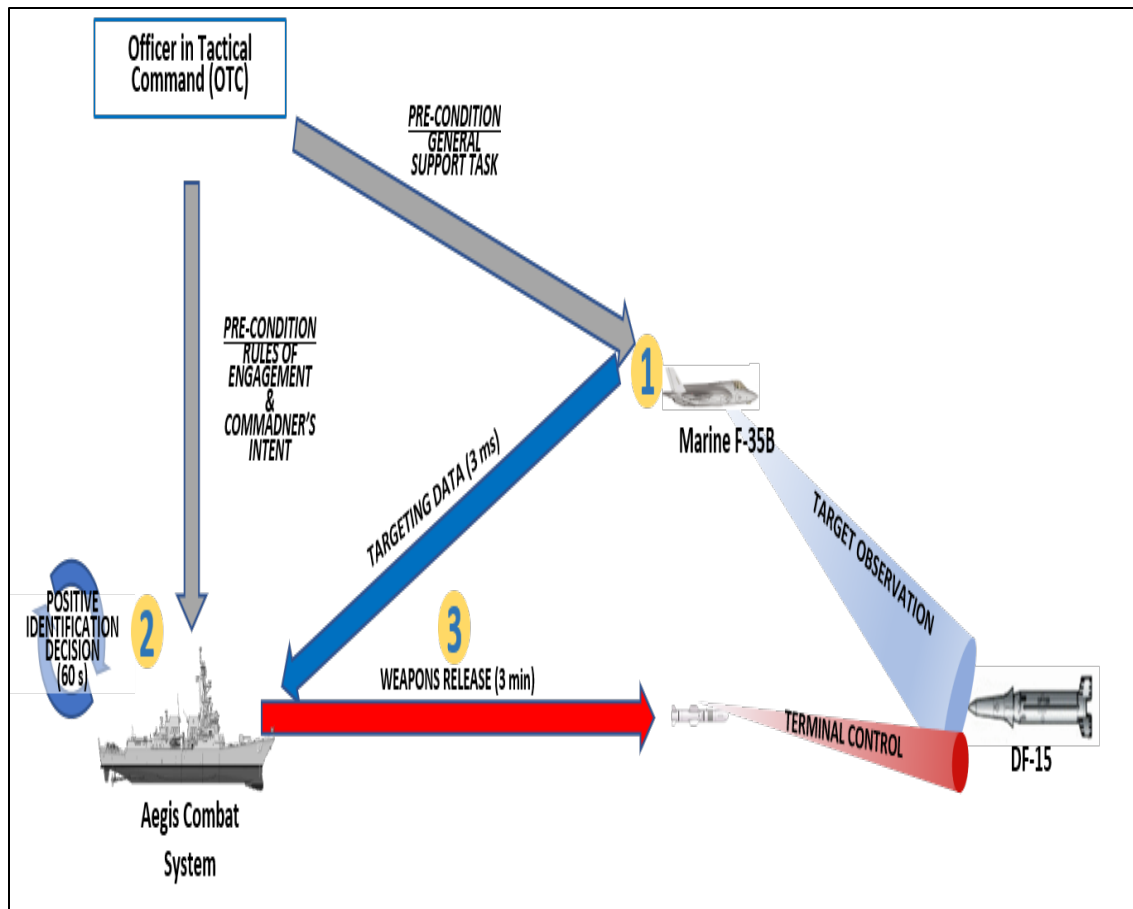


Figure 10. Example of CEC Using F-35 and Aegis

In order for joint CEC to emulate the speed of an internally integrated combat system (like the Aegis or Patriot missile battery), participating joint platforms must be directly connected, and command and control authority must also be delegated to the lowest level possible. If the observer platform (e.g., Army Grey Eagle) is interconnected with all of the potential shooter platforms in the area (e.g., Littoral Combat Ship), and weapons release authority is delegated to the shooter platform, the amount of time it takes to complete the targeting cycle may be reduced as shown in Figure 11. Externally integrated joint platforms may emulate internally integrated C2 systems to reduce target cycle time through CEC.

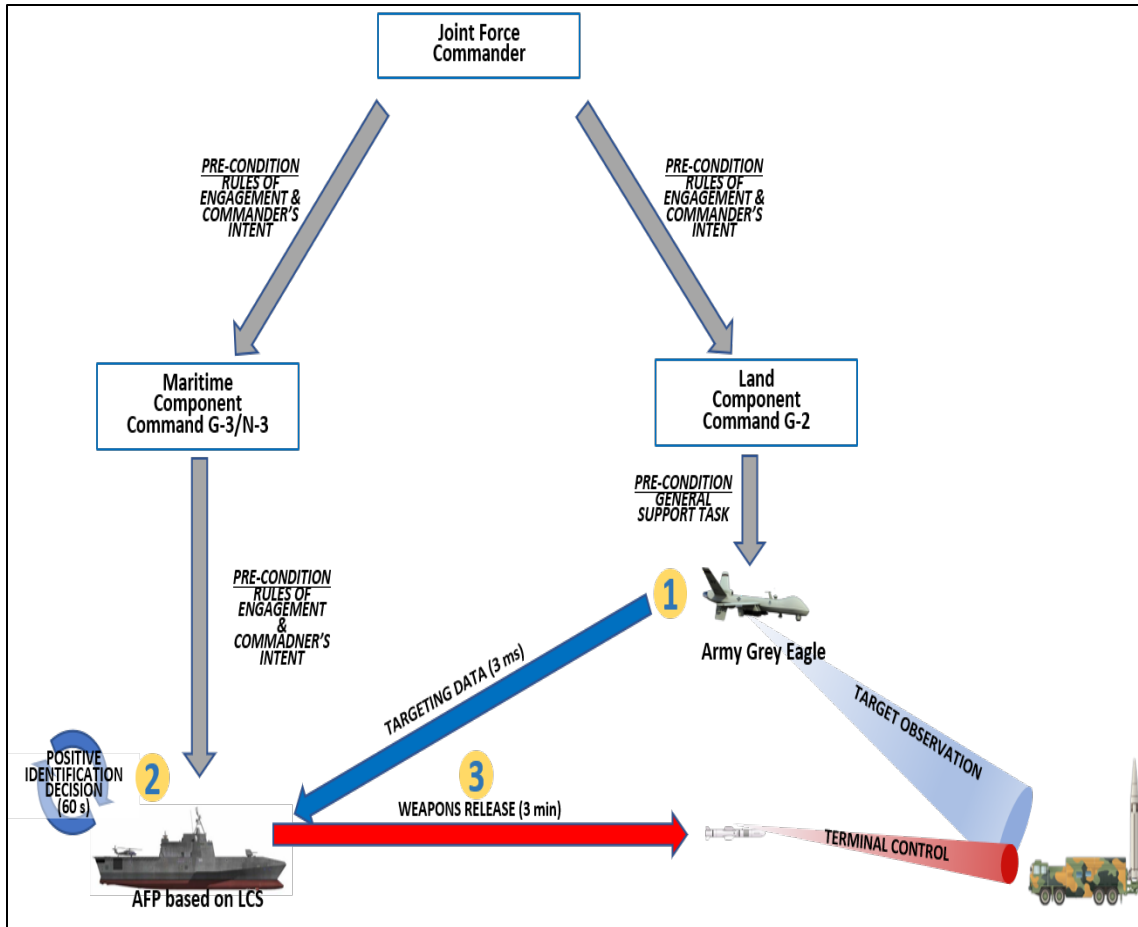


Figure 11. Externally Integrated Joint Platforms Emulating Internally Integrated C2 via CEC

C. LETHAL TRIAD: ROLES THAT COMPRISE JOINT CEC

In order to establish common terminology that is agnostic to specific platforms, and in consideration of the preference to distribute command and control down to the lowest level, the JFs team has decomposed the CEC into a bare minimum organization. Three roles are needed: a platform capable of observing joint fires; a platform capable of firing munitions; and a platform with weapons release authority. These three roles will be hereafter referred to as the ISR/Observer role, the Shooter role, and the Decision Maker (DM) role.

The ISR/Observer role takes the name of ISR to denote that the platform's primary role in this case is intelligence, surveillance, and/or reconnaissance. This applies to many

manned and unmanned aviation or surface platforms. However, since many platforms that can perform ISR have additional capabilities such as air search, surface search, airspace control, or fires support the name Observer may be used interchangeably with ISR. It is also possible that an ISR/Observer platform needs to be directed to a location by cueing from another ISR asset. For example, a search radar identifies a contact, but the fidelity of the search radar's data is not high enough to target the contact. The data from the search radar cues the platform with a better radar to collect targeting-quality data. Other sources of cueing might be ground-based or satellite-based. It is important to note that the ISR/Observer platform does not need to be manned. On the other hand, unless the decision is made to pursue artificial intelligence and/or fully automated weapons release by the Shooter, targeting data must make its way to a platform capable of positive identification, which can only be performed by a human decision maker.

The Shooter role refers to a platform that has the capability to fire munitions to engage a target. Not all shooters can engage all targets and many platforms discussed in this research can perform the roles of both Shooter and ISR/Observer. Examples include the F-35 cited earlier. In a few cases, the shooter does not have its own internal 'ISR/Observer' capability. The M142 HIMARS is an example of a shooter platform that relies on calls for fire from forward observers to provide fire control information. It is important to note that a Shooter platform may require human interaction to bring the system into a state of readiness according to the tasking and the threat. However, for the fastest joint cooperative capability, the platform should be able to fire immediately upon remote triggering by the decision maker WITHOUT another human in the loop.

The decision maker role refers to the only necessary human in the loop. With an ISR/Observer platform providing targeting-quality data and a Shooter platform that has been placed into a state of readiness for remote triggering, the DM is responsible for C2, including launch authority. The DM must consider the rules of engagement and commander's intent, whether the target has been positively identified as a threat, and whether an appropriate Shooter can adequately and proportionally engage the target. If these criteria are met, the DM authorizes weapons release and remotely triggers firing of munitions to engage the target. In delegating decision authority to the lowest level, the DM

must ideally be the lowest echelon in the tactical chain of command that can receive and process sufficient information to authorize weapons release. The DM must therefore have access to a decision support system that processes, correlates, and simplifies the many aspects of the threat and defensive capabilities available.

This capstone argues that the more an AFP is networked and equipped to connect its various ISR/Observer, Shooter, and DM platforms into a joint CEC (JCEC) (as it does with the F-35 and the Aegis combat system), the better it will be able to rapidly execute the find-target-engage kill chain cycle in response to dynamic missile threats or targets of opportunity. The future fight is joint in nature and will benefit greatly from the inclusion of manned and unmanned joint platforms engineered as complex adaptive systems of systems. This will require the integration of a common JCEC into a much wider range of joint platforms (Johnson 2019). This capstone research explores the benefit of interconnecting the sea-based, land-based, or aviation-based, manned, or unmanned platforms in the joint inventory in the battlespace to make this JCEC possible. According to the principles of complex adaptive systems of systems (CASoS), the force would then be able to self-organize in response to changes in the threat environment to display emergent behavior of the sensor, shooter, and DM, also referred to as the lethal triad, in the rapid and decentralized prosecution of enemy targets.

A lethal triad consists of one or more sea surface-, ground surface-, or aviation-based, manned, or unmanned platforms in the joint inventory which, together, are able to perform all three of the ISR/Observer, Shooter, and DM roles. Figure 12 depicts potential ISR/Observer platforms on the right, Shooters on the left, and DMs at the top.

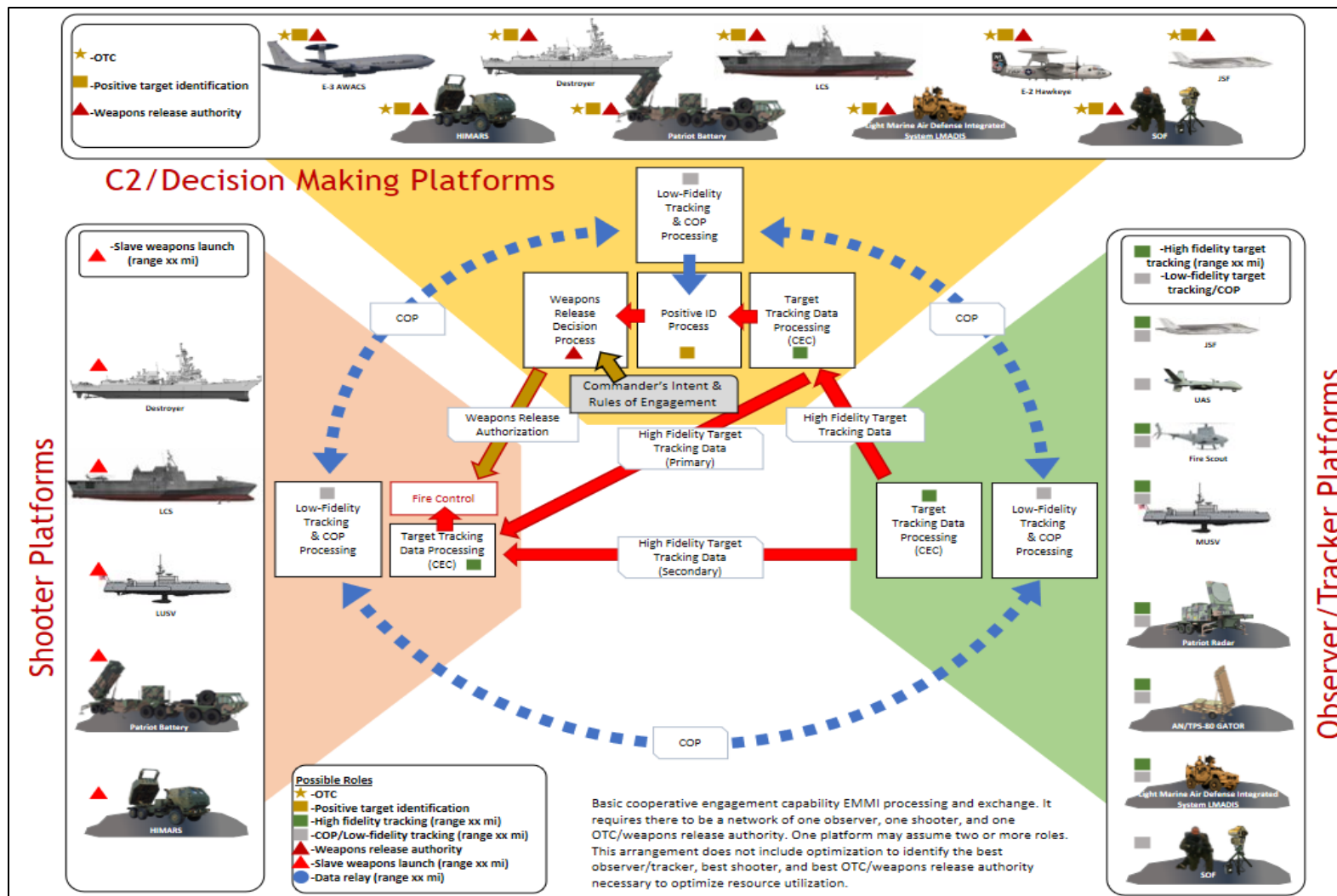


Figure 12. Lethal Triad Potential Platforms

D. PRIMARY FUNCTIONS THAT COMPRISE A JCEC

With the understanding of what constitutes a cooperative engagement capability, we can decompose the capability into its constituent functions and organize them into four basic functional elements. First, like any joint fire's capability, a complete CEC has an observer capable of identifying the precise location of a potential target. In the missile threat environment, the precision of location detail must be extremely high and updated many times per second. Platforms capable of this high-fidelity target-quality data include the Aegis combat system (specifically the SPY-1 radar), the F-35, the AN/TPS-80 GATOR radar, the Patriot battery radar, and many others.

Second, a complete CEC has the capability to share this high-fidelity target-quality data from the Observer/ISR platform with other participating platforms. Within the Aegis combat system, the SPY-1 radar communicates this data internally via its tightly integrated internal fire control network. Between the F-35 and the Aegis platform, this exchange of targeting data occurs over a tightly integrated, jam-resistant, high-data rate, radio network like the multifunction advanced data link (MADL). Also, the ability to seamlessly enter into a CEC network with any platform from the joint force is desirable. It is feasible that a ubiquitous, open standard means of secure communication of targeting and fire control data can be replicated and integrated into new combinations (*USNI NEWS* 2016).

Third, a complete CEC has a firing platform with a munition capable of successfully prosecuting the observed target. In the missile threat environment, this munition can be any of the joint inventory of guided anti-air missiles such as SM-2, SM-3, SM-6, PAC-3, and AIM-9 Sidewinder. The firing platforms must be able to receive a stream of high-fidelity, target-quality data which updates many times per second. Once launched, the anti-air missile must rely on this stream of target-quality data until it is close enough to the target for internal guidance systems to acquire the target and perform terminal control. Also, to intercept incoming enemy missiles, a platform launching guided anti-air missiles must respond very quickly to launch commands. Human actuation of firing mechanisms must be minimal or non-existent after the decision to launch has been made, else critical moments in the CEC response time will be wasted. It is for this purpose that

any CEC firing platform is recommended to have a slave mode of operation. Once the human operator has configured the firing platform for the air and missile defense mission, a distant decision maker with training and authority can trigger the munition's launch remotely. In strike or surface warfare, this munition can be any of the joint inventory of surface to surface missiles. While less critical for surface or strike warfare, the high speed of the surface to surface missile response is also necessary for the successful engagement of fleeting targets of opportunity. Therefore, a slave mode of operation could be employed for surface-to-surface engagements as well. These munitions-firing functions will be categorized as the shooter functional element.

Fourth, a complete CEC has a decision support/decision making capability where the human decision maker interfaces with the system and authorizes weapons release. The weapons release decision is informed by a combination of commander's intent related to fires objectives and rules of engagement, a fires-related decision support system identifying the available and optimal munitions for each target, and other sources of shared situational awareness. This weapons release decision is communicated in the form of an execution command that activates the slave-mode munition capable of prosecuting the observed target. This decision support and promulgation function will be categorized as the C2 functional element. The CEC exchange of data as described above is shown in Figure 13.

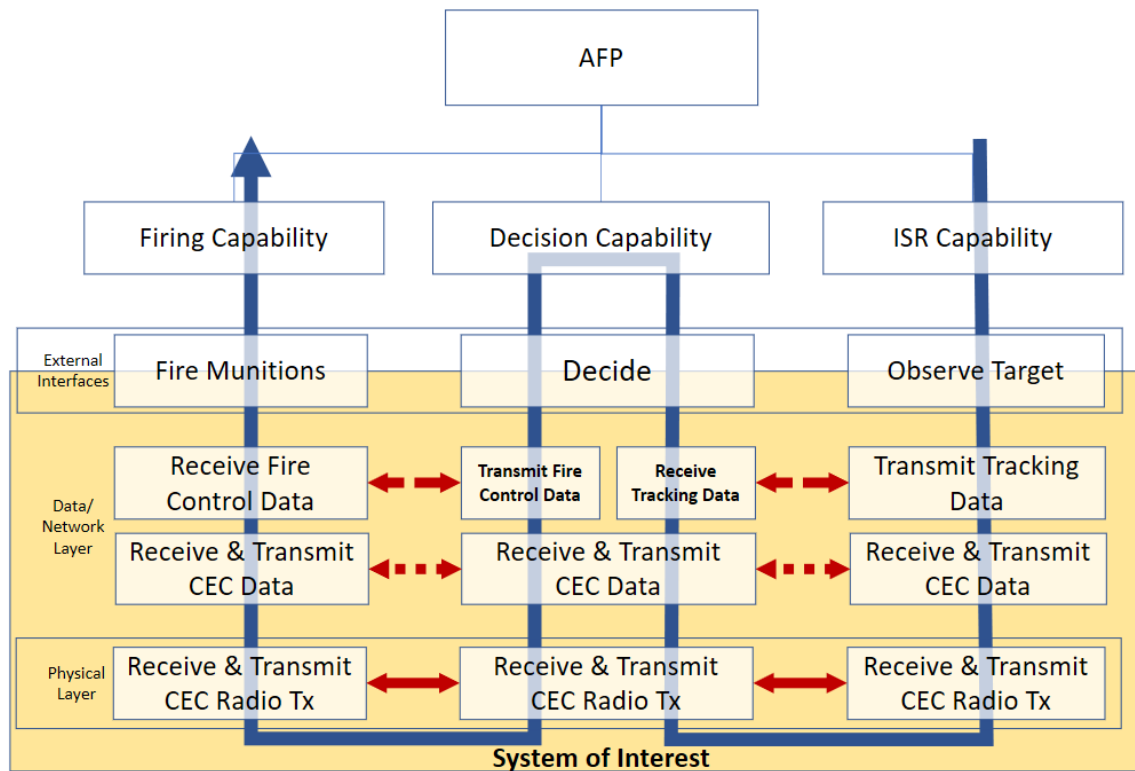


Figure 13. CEC Exchanges among the ISR, Decision Maker, and Shooter

E. MESSAGING PROTOCOLS

Digital fires-related C2 information is exchanged between systems based on the United States and North Atlantic Treaty Organization (NATO) standardized messaging protocols defined by MIL-STD-6016 and STANAG 5516 (Hura et al. 2000). Messages related to precise participant location and identification (PPLI) of friendly and surveilled enemy platforms, weapons coordination, platform system and status, tasking, control, and network management are all defined according to the standardized Tactical Digital Information Link (TADIL) J-series message format (DOA 2000). Several communications systems have been developed over many years to support transmission of these digital J-series messages, or the near-real-time exchange of J-series messages among tactical data systems. Each such system is specified by hardware/software characteristics as well as by message and protocol standards (Hura et al. 2000).

A complete CEC will continue to make use of standardized J-series messages to remain interoperable with the joint force at the digital level regardless of which radio waveform, modulation schemes, rates, or transmission media are used. There are many systems currently fielded which interoperate at the digital level because they use J-series messages. This includes Joint Range Extension Application Protocol (JREAP) which can travel over radio signals, telephone lines, and internet connections (DON 2013b) as well as Link-16.

“Link-16 is an encrypted, jam-resistant, tactical digital data link network established by communication terminals that transmit and receive standardized J-series data messages” (Hura et al. 2000). In the United States, Link-16 generally refers to the J-series message processor and the L-band, UHF radio that transmits and receives them. In general, NATO recognizes Link-16 as the capability to process J-series messages while each particular type of Link-16-capable radio system is defined by its characteristics of frequency, size, weight, power, hopping algorithm, compatible platform etc. It is useful in this research to separate these two aspects of digital message exchange. Hereafter, the important aspect of Link-16 which will be carried forward into the proposed system of interest will be the J-series messaging protocol and capability of processing or translating it. However, this research will challenge a few aspects of the common approach to the radio transmissions of Link-16 including frequency and directionality. The strengths, weaknesses, and conclusions about JCEC radio capabilities will be elaborated in the next section.

F. REQUIRED COMMUNICATIONS CAPABILITIES

a. Transmission Rate and Responsiveness

Entering and exiting a Joint CEC network must be seamless to allow the rapid formation of a complete CEC assembled from whichever distributed lethality platforms are present in the time and location of the enemy attack. To be fast enough to start engaging an enemy missile barrage early enough to survive, the first platform to observe the enemy missiles must be able to immediately feed the closest firing platform’s fire control system with targeting data. This is delayed if the participating platforms first need to enter a

different radio network than each is currently monitoring. If a verbal command and the re-configuration of radios is first required to enter the network, then additional response time is wasted. If the ideal observer and shooter platforms do not even share compatible radio protocols between them, then a third-party platform with radio cross-banding or protocol translation would be required before cooperatively engaging the target. Those more centralized (versus distributed) communications architectures may be inadequate for C2 situations that require a high degree of responsiveness (Corbett et al. 2017). At a minimum, a mesh network where any member can exchange data with any other member is preferred over a star/hub-spoke/centralized network topology (Bach, Brier, and McNeil 2019).

The two-part Link-16 capability, including J-series message processing and anti-jam radio transmission, is implemented on various joint platforms as variations and improvements upon the Joint Tactical Information Distribution System (JTIDS). The following is a direct quotation from Navy Tactics Techniques and Procedures.

JTIDS (AN/URC-107 series systems) and Multifunctional Information Distribution System (MIDS) (AN/USQ-140 series systems) are high-capacity, time division multiple access (TDMA) systems that provide integrated communications, navigation, and identification of friend or foe (IFF) capabilities. They provide electronic counter-counter measure (ECCM) capabilities such as spread spectrum and frequency hopping for aircraft and surface ships, extended range of communications, and over-the-horizon communications for surface ships with an airborne relay platform. The maximum transmission rate with full anti-jam and error detection and correction is 59.5 kbps with an effective data throughput of 26.8 kbps. Data throughput of 107.5 kbps is attainable but with a sacrifice of some anti-jam and error detection and correction capability. Timeslots are preassigned for transmission, which eliminates the need for a net control station. Air and surface tracks are nominally updated once every 12 seconds. Land tracks are reported less frequently than air tracks (nominally at 48 seconds). Tracks are reported in latitude, longitude, and height coordinates, which allows for reporting of tracks anywhere on Earth. (DON 2005)

In general, 12 seconds between transmissions is too slow to effectively update precise target locations many times per second as required in a joint CEC.

The legacy MIDS Link-16 construct are improved upon with recent development of the MIDS Joint Tactical Radio System (JTRS) per the following quote.

When integrated into a host platform, MIDS JTRS provides Link 16 digital datalink, Link 16 digital voice communications, and Tactical Air Navigation (TACAN) capabilities, plus three additional programmable channels capable of hosting additional JTRS compliant waveforms in the 2 Megahertz to 2 Gigahertz radio frequency band. In addition, MIDS JTRS provides the capability for Link 16 enhanced throughput and Link 16 frequency re-mapping. (DOTE 2012)

These aspects of Link-16 are better suited for the dynamic cooperative engagement capability and spectrum denied environment. Of specific interest to this research, “MIDS JTRS terminals have been developed to conduct Concurrent Multi-Net Reception using four-channel Concurrent Multi-netting with Concurrent Retention Receive. This provides improved digital receivers, improved buffering, and faster processors to allow host aircraft to receive more Link 16 messages during periods of high message exchange demand” (DOTE 2012). This makes it possible to essentially quadruple the number of terminals that can participate in the otherwise fixed-size network and can make it reasonable to assign individual sensor or shooter platform with multiple time slots, so that time between transmissions can be shorter intervals than 12 seconds (DOA 2019). However, it is unclear if this decrease in time between time slot allocations will lead to operational improvements to friendly naval forces when applying CEC.

b. Resistance to Electromagnetic Interference

Further, the cooperative engagement capability demonstrated by the F-35 and Aegis combat system was designed to resist a significant amount of electromagnetic interference. The proprietary multi-function advanced data link (MADL) fulfills the requirement for high data throughput and high resilience to electromagnetic interference (Lockheed Martin Newsroom 2019). While the MADL’s proprietary characteristics are not available for this research, principles of communications engineering reveal what a hypothetical high-data-rate, jam-resistant radio protocol might look like.

Spot Jamming is jamming technique that causes overwhelming interference to a single frequency (DOA 2019a). “Frequency hopping is the repeated switching of frequencies during radio transmission” and minimizing unauthorized interception or jamming of single frequency radio transmissions (DON 2013b). “The overall bandwidth required for frequency hopping is much wider than that required to transmit the same

information using only one carrier frequency” (DON 2013b). This is also a form of what is known as “spread spectrum.”

A minimally effective jam-resistant radio protocol is identified by its ability to hop between many frequencies far enough apart from each other that the enemy cannot use simple narrowband (spot) jamming techniques. This research assumes that narrowband (spot) jamming capabilities are available to any individual or nation-state actor that may be found in the battlespace. Further, the hopping algorithm should be unpredictable to the enemy to avoid allowing the enemy to establish a time-sync with the friendly radios thereby predicting the next frequency in the hopping algorithm, and jamming each frequency before it can be used to transport friendly information. Many amateur radio enthusiasts, and certainly industrialized nations can obtain the ability to observe a range of frequencies and use computer software to decipher the hopping algorithm and jam specific frequencies (Schweizer 2017).

Many industrialized nations can likely also employ high-power broad-spectrum interference signals (known as barrage jamming) to jam all frequencies in an adversary’s hopping algorithm at the same time (DOA 2019a). While more difficult, it is reasonable to expect that peer nation states can produce high-power, barrage jamming signals against a moving target from a long range for a long enough period of time to interfere with the friendly find-target-engage fires cycle.

Frequency hopping alone is not enough to mitigate the effects of enemy jamming. In order to best mitigate threats to enemy jamming, a joint CEC radio should also be directional (DOA 2019a). Many current MIDS/Link-16 systems employ omni-directional antennas and are therefore susceptible to jamming effects from any direction. Directional antennas close the window of opportunity for enemy jamming down to the minimum size possible according to the limits of physics (Johnson 1993). Minimum beam size in a dynamic mobile environment equates to minimal time of exposure as well. Communicating over directional antennas requires geometric alignment of the transmitter and receiver (Johnson 1993). Any misalignment will result in radiated electromagnetic energy failing to reach its intended destination. This cannot be overcome by extra power and better frequency tuning.

Directional antennas require the members of the network to be geospatially self-aware and able to communicate their three-dimensional position information to all other members of the network to generate useful antenna orientation information. However, if the system of interest is designed with directional antenna coverage pointed to and from the front, rear, left, right, top, and bottom of a platform (aerial platform in this case), the platform gains the ability to direct its radio signals to any other available platform within signal range. Further, given equal input power, a directional antenna provides radio signals and data rates that are orders of magnitude higher than their omnidirectional counterparts (Johnson 1993). This means that, should the enemy attempt broad-spectrum jamming, the desired friendly signal would likely still be stronger than the jamming signal or have only a momentary impact because of the constant change in relative position between the friendly receiver and the enemy jammer. Phased array radio frequency transceivers are found on many military platforms and have many benefits over omnidirectional or mechanically steerable antennas (Ong 2004). While heavier and more complex than their parabolic counterparts, phased array transceivers can be designed to fit any candidate CEC platform including the F-35 (Ong 2004).

When aggregating these various assured, high-data rate radio communications factors, unifying theory of jam-resistance emerges based on low probabilities. When frequency hopping and directional (phased array) antennas are combined to produce a highly jam-resistant radio capability, an increasingly rare set of circumstances would be required for the enemy to create an effective jamming signal. For instance, the jammer and the friendly receiver would need to be geometrically aligned due to the requirement for directionality. Further, the jamming platform would need to observe and record the full hopping algorithm, decipher it, and produce a stronger interference signal in time-sync with a friendly signal. It would also have to employ a higher degree of directionality than the friendly platform, which is likely closer to, and receiving pointing information from, the friendly radio at the distant end. The jamming platform may alternatively attempt to jam the entire range of frequencies in the hopping algorithm, which is again extraordinarily difficult against a moving target, even more so when the friendly radios are already in closer proximity to each other and are using location-informed, auto-tracking, high power

directional antennas. If the combination of the above conditions were to exist, they would likely only exist momentarily because of the constant change in relative position and attitude among the various moving friendly and enemy platforms.

Finally, a sub-system could be designed that automatically nulls the receiving antenna when a desired radio signal does not carry an encrypted authentication code, indicating that it is a jamming signal. If one face of the phased array antenna is receiving a signal that is determined to be a jamming signal that face of the antenna could simply be turned off. The remaining antenna panels, assuming they are facing friendly forces in a distributed network architecture and have radio-relay abilities like the MIDS JTRS, will provide alternative radio pathways for the platform. In this way, any jamming signal that does not overcome all the above conditions, would be ineffective.

As of this research, fielded MIDS terminals do transmit and receive on phased array or flat-panel directional antennas. As long as the four way concurrent multi-netting (CMN-4) MIDS JTRS time slots are allocated in a way that increases message exchange between observer, ISR, and DM platforms to the high rate necessary to update dynamic CEC tracking information, the CMN-4 MIDS JTRS network may be sufficient. However, this research assumes that this is not yet the case. This research offers the alternative possibility that an ad hoc frequency hopping point-to-point network be established between every two platforms which are in range of each other that would overall constitute a full, force-wide, distributed mesh architecture.

Also, truly seamless entry into the JCEC network requires that every potential participant can enter and interoperate without any user adjustment to configurations or verbal relay of messages. The CMN-4 MIDS JTRS still relies on pre-planned addressing of all nodes in the network each time the network is re-formed. This suggests that a JCEC network requires each participant platform in the joint force be issued a globally unique address and authentication code that allows for automatic entry into the network regardless of which component of the joint force or originating base, the platform came from.

Based on recent developments where the F-35 and Aegis or F-35 and HIMARS were paired together to execute missions, this capstone proposes an engineered J-series

message processing system like a MIDS terminal to be integrated on the various joint forces platforms using a new MADL-like open-standard radio protocol which can be designed by 2030. This system would have high-data rate and jam-resistance capabilities while also hosting an addressing schema favorable to seamless entry by any joint distributed lethality platform for enhanced, joint fires cooperative engagement.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. PROPOSED SYSTEM ARCHITECTURE

A. SYSTEM OF INTEREST (SOI)

The system of interest (SOI), shown in Figure 14, centers on the mission of a friendly, Blue Force (BF) controlling the enemy, Red Force's (RF) influence of a strategic, bottleneck, trade route and the execution of the kill chain functions performed by the BF during the conflict that ensues. The kill chain function of finding the RF threat is conducted by the BF ISR, the function of targeting the RF threat is performed by the BF decision maker, and the function of engaging the RF threat is conducted by the BF shooter. There are multiple messages exchanged between the lethal triad during execution of the kill chain functions and a recognized need to shorten the C2 cycle, improve interoperability between the lethal triad platforms while performing CEC, and therefore increase the effectiveness of the kill chain to ensure overmatch of a near peer enemy by 2030 when naval unmanned surface vessels are predicted to join the fleet.

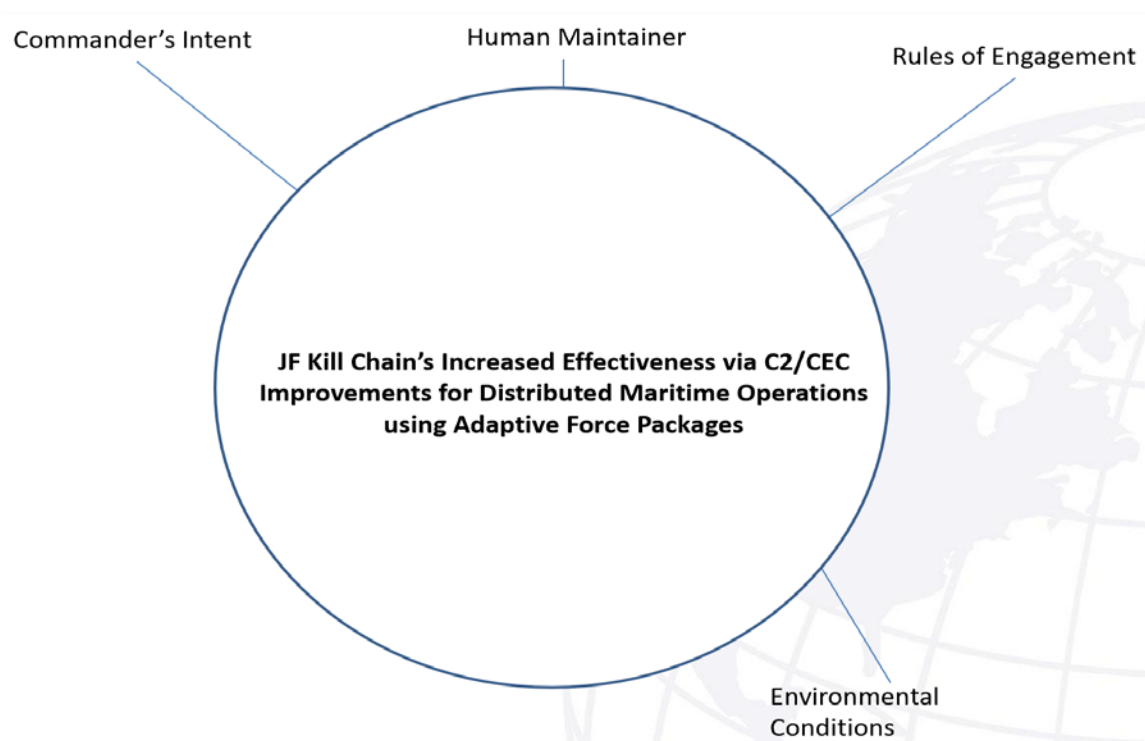


Figure 14. System of Interest—JF Kill Chain's Increased Effectiveness

Based on previous research by the SEA 27 capstone group in 2018, as captured in Figure 15, the kill chain functions were shortened from find, fix, track, target, engage, and assess (F2T2EA) to find, target, and engage (FTE) due to the modernization of weapon systems which now perform multiple functions simultaneously (Popa et al. 2018). The ISR platform performs the find role by collecting location information about the threat and maintaining track (Popa et.al. 2018). The decision maker performs the targeting role by determining the resources available, prioritizing the threats, developing the options, selecting the methods, and deciding to further engage by allocating the resources (Popa et al. 2018). The shooter performs the engage role by striking the threat (Popa et al. 2018).

For the purposes of this research, however, the JF team has chosen to modify the SEA 27's groupings to those shown in Figure 16 by moving the ordering of engagements and transmitting of orders to the decision maker's targeting activities as indicated by the yellow highlights. Further, the assess function will be considered part of the ISR's finding functions as indicated by the blue highlights.

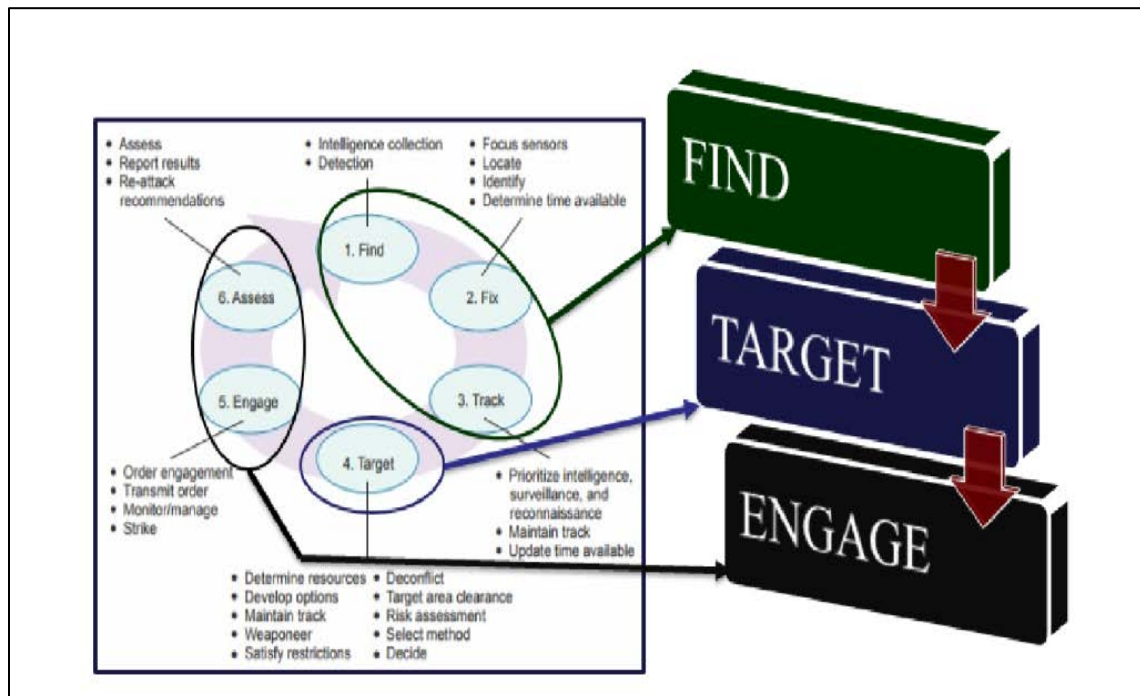


Figure 15. Shortening of the Kill Chain to Find, Target, Engage. Source: Popa et al. (2018).

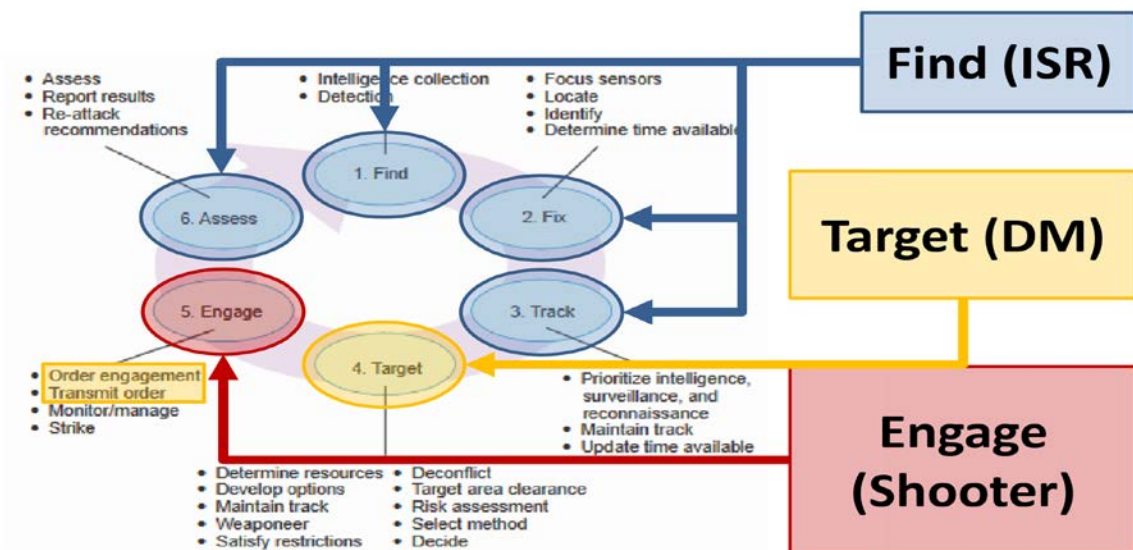


Figure 16. Modified Kill Chain Applicable to JF's Research. Source: Popa et al. (2018).

B. JF PROPOSED IMPROVEMENTS

The proposed improvements for shortening the Joint Fires kill chain's C2 responsiveness include improving interoperability between the lethal triad and creating an effective, distributed, ad-hoc mesh network, like that shown in Figure 2, by integrating the following on all JF platforms by 2030 for platform commonality:

Table 1. Proposed JCEC C2 Interoperability Improvements

Improvement	Description
JCEC C2 Message Exchanges	Incorporate high speed digital interoperability among the lethal triad, rather than the analog voice method, and automate the selection of the most effective combination of lethal triad for a given threat for the decision maker.
MADL-like Communications	Incorporate anti-jamming capabilities, seamless ad-hoc participation entry via improved addressing schema, radio translation capability from one protocol to another, and high-speed transmission data rates for multi threat tracking and common situational awareness.

The substantiation for the proposed improvements in the C2 cycle are developed from the examples given in Figures 8–11 in section III-B and from the writings given in sections III-C through F. Incorporation of these proposed improvements are found at the lowest levels of the proceeding capability and functional models in Figures 17–23 as indicated.

The benefits of creating and using a distributed, mesh network to quickly reconfigure dynamic, self-organizing, ad-hoc AFPs for effectiveness have been discussed previously in Section II's DMO Network Architecture Options paragraphs. It is highly plausible that a joint force warfighting scenario will be complex, dynamic, and have the potential for confusion with its many participants. A distributed mesh network is an optimal architecture for both communications and C2 for any joint force. It allows for the connection of all nodes with minimal time lost to reconfiguration due to jamming or as

participants join and detach from the AFP for whatever reason. In addition, long C2 cycles can take several minutes and diminish the effectiveness of a dynamic, quick reactionary AFP. These C2 cycles must traverse each service's own decision maker before moving onto the higher echelon's, joint force decision maker, as discussed in Section III.

While the recommended improvements in Table 1 do not change the kill chain functions, they do improve the way in which the lethal triad conducts JCEC C2 by improving interoperability through MADL-like communications and JCEC C2 message exchanges. Of utmost importance are the effects that shortening the C2 cycle should have on the kill chain and the outcome of a battle. The kill chain benefits should include faster, less jammable communication among the lethal triad; more responsive, reliable decision making in a highly congested environment; and improved matching of weapon systems to threats which should culminate in a more appropriate and effective ad-hoc, self-forming AFP.

C. CAPABILITY MODELS OF CURRENT & IMPROVED JCEC C2

The current JF kill chain's capability model is shown in Figure 17, and the improved JF kill chain's capability model is shown in Figure 18. Table 2 offers a comparison of current capabilities versus improved capabilities based on Table 1's proposed improvements. Figure 17 shows the first two layers as the JF kill chain which decompose into three major capabilities: 1) finding of threat capabilities, 2) targeting threat capabilities, and 3) engaging threat capabilities which decompose into the BF ISR, BF decision maker, and BF shooter capabilities, respectively. The BF ISR decomposes into 1) finding the RF threat, 2) fixing the RF threat, 3) tracking the RF threat, and 4) assessing battle damage of RF threats. The BF decision maker decomposes into the follow/target capabilities. The BF shooter decomposes into the strike/engage threat capabilities. Embedded within each of the BF ISR, BF DM, and BF Shooter capabilities are the capabilities of performing JCEC C2 interoperability which then decomposes into 1) performing non MADL-like communications and 2) performing analog C2 messaging as highlighted by colors at the lowest level of Figure 17.

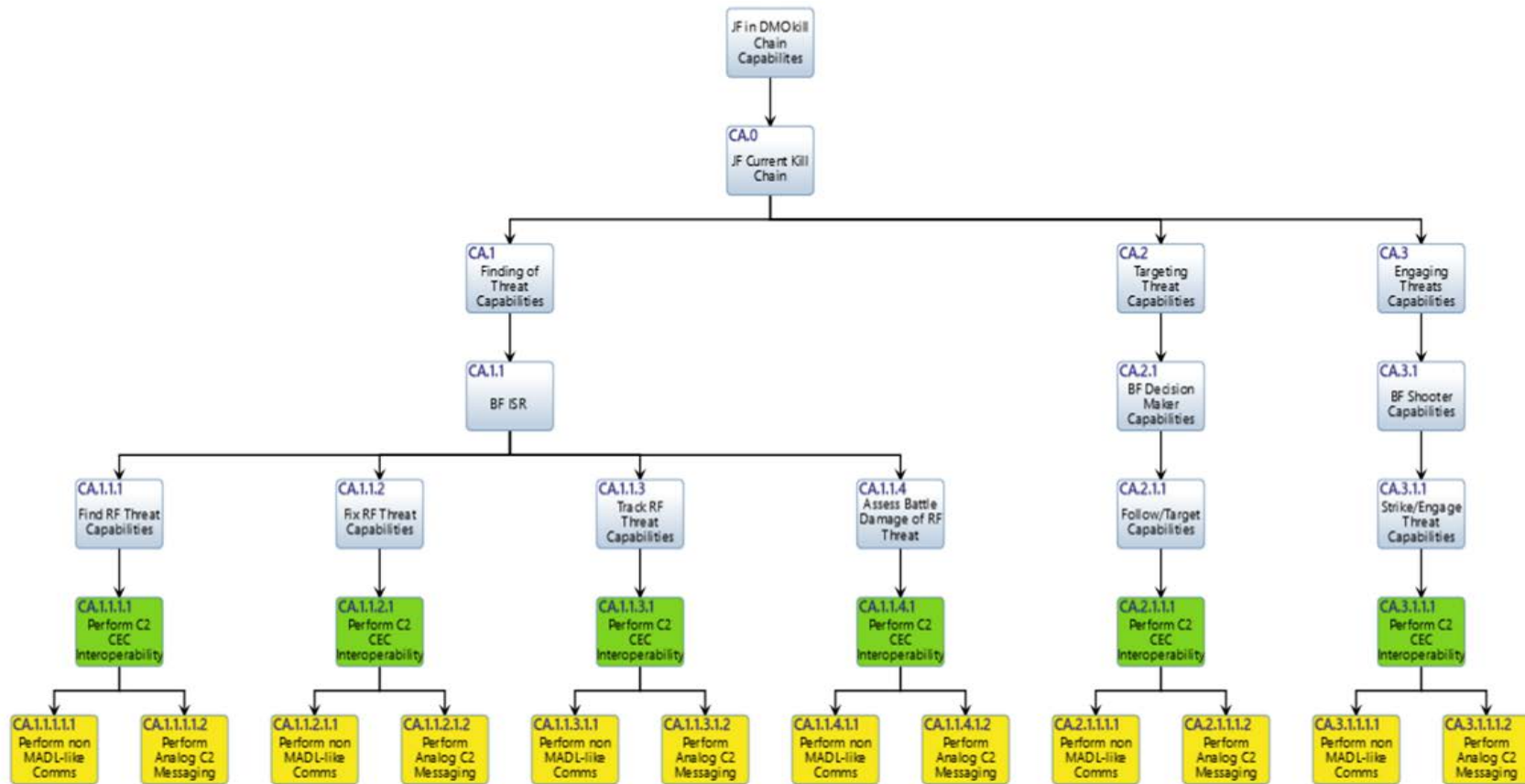


Figure 17. Capability Model for Current JF Kill Chain

The Joint Fires kill chain's improved capability model is shown in Figure 18 which is built from the current kill chain functionality shown in Figure 16. Figure 18 shows the proposed improvements from Table 1, which are MADL-like communications and improved JCEC C2 message exchanges, and are incorporated in the last two, colored layers. Figure 18 does not change the kill chain capabilities, but it does improve the way in which the lethal triad conducts JCEC C2 while performing the kill chain functions by improving interoperability. The first two layers of Figure 18 indicate the JF DMO Kill Chain, the third layer is composed of the 1) finding the threat, 2) targeting threats, and 3) engaging the threats. These decompose into the fourth layer of 1) BF ISR capabilities, 2) BF decision maker capabilities, and 3) BF shooter capabilities. These are the platforms executing the kill chain and have their inputs defined in the simulation per Table 7. The fifth layer represents the kill chain capabilities which each platform performs and maps to the colored bubbles in Figure 16. Each of these capabilities is further decomposed into performing improved JCEC C2 interoperability on the sixth layer which then decomposes into 1) performing MADL-like communications capabilities and 2) performing improved JCEC C2 capabilities on layer seven.

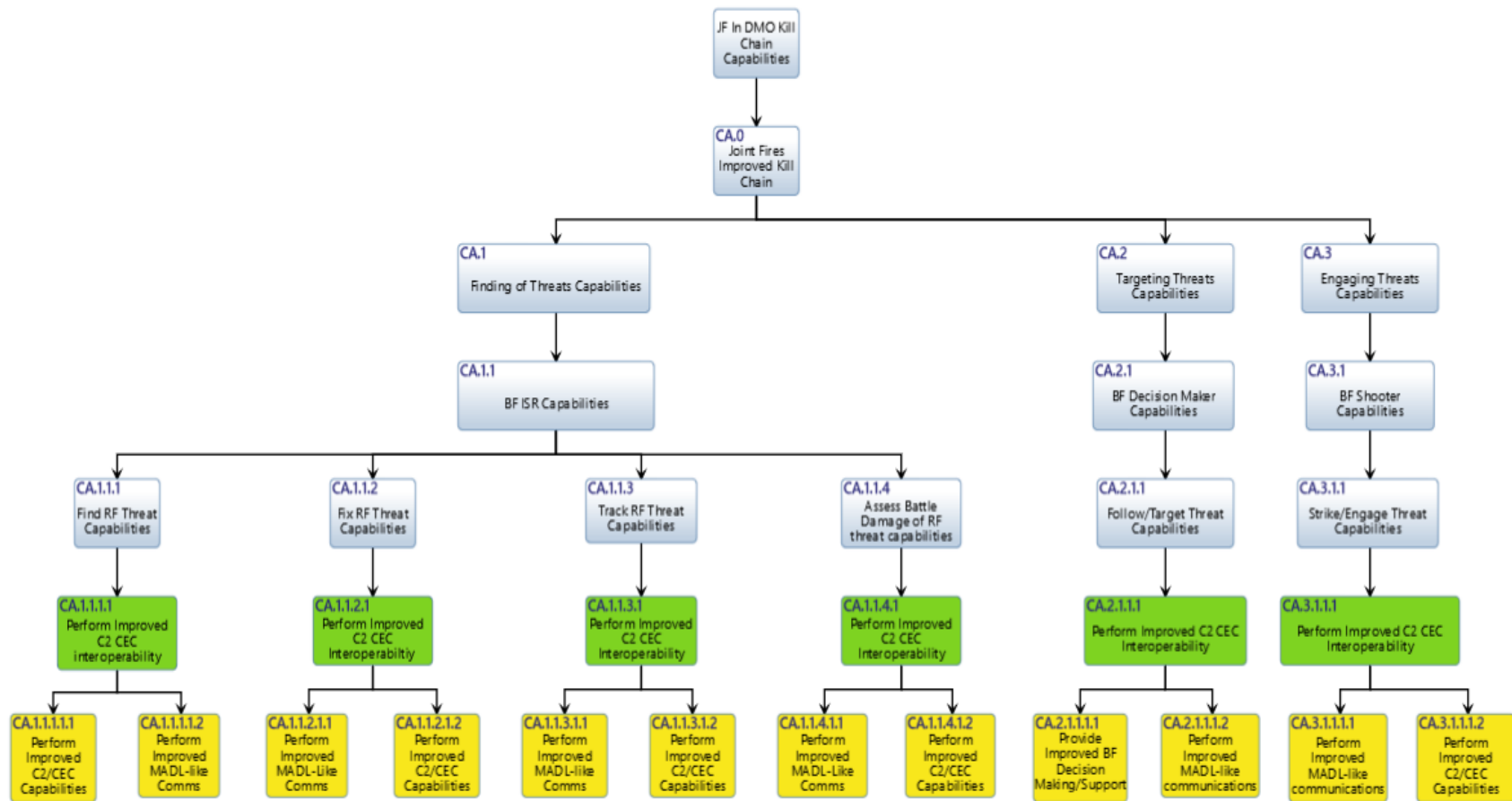


Figure 18. Capability Model for Improved JF Kill Chain

Table 2. Comparison of Current and Improved JCEC C2 for JF Kill Chain

JCEC C2 Capabilities for JF Kill Chain	Current	Improved
CA.1 Finding of Threats Capabilities	Standard	Standard
CA.1.1 BF ISR Capabilities	Standard	Standard
CA.1.1.1 Find RF Threat Capabilities	Standard	Standard
CA.1.1.1.1 Perform Improved C2 CEC Interoperability	Standard	Improved
CA.1.1.1.1.1 Perform Improved C2 CEC Capability	Standard	Improved
CA.1.1.1.1.2 Perform Improved MADL-like Comms	Not Supported	New
CA.1.1.2 Fix RF Threat Capabilities	Standard	Standard
CA.1.1.2.1 Perform Improved C2C CEC interoperability	Standard	Improved
CA.1.1.2.1.1 Perform Improved MADL-Like Comms	Not Supported	New
CA.1.1.2.1.2 Perform Improved JCEC C2 Capabilities	Standard	Improved
CA.1.1.3 Track RF Threat Capabilities	Standard	Standard
CA.1.1.3.1 Perform Improved C2 CEC interoperability	Standard	Improved
CA.1.1.3.1.1 Perform Improved MADL-Like Comms	Not Supported	New
CA.1.1.3.1.2 Perform Improved JCEC C2 Capabilities	Standard	Improved
CA.1.1.4 Assess Battle Damage of RF threat capabilities	Standard	Standard
CA.1.1.4.1 Perform Improved C2 CEC interoperability	Standard	Improved
CA.1.1.4.1.1 Perform Improved MADL-Like Comms	Not Supported	New
CA.1.1.4.1.2 Perform Improved JCEC C2 Capabilities	Standard	Improved
CA.2 Targeting Threats Capabilities	Standard	Standard
CA.2.1 BF Decision Maker Capabilities	Standard	Standard
CA.2.1.1 Follow/Target Threat Capabilities	Standard	Standard
CA.2.1.1.1 Perform Improved C2 CEC Interoperability	Standard	Improved
CA.2.1.1.1.1 Provide Improved BF DM/Support Capabilities	Standard	Improved
CA.2.1.1.1.2 Perform Improved MADL-like comms	Not Supported	New
CA.3 Engaging Threats Capabilities	Standard	Standard
CA.3.1 BF Shooter Capabilities	Standard	Standard
CA.3.1.1 Strike/Engage Threat Capabilities	Standard	Standard
CA.3.1.1.1 Perform Improved C2 CEC Interoperability	Standard	Improved
CA.3.1.1.1.1 Perform Improved MADL-Like comms	Not Supported	New
CA.3.1.1.1.2 Perform Improved JCEC C2 Capabilities	Standard	Improved

D. FUNCTIONAL MODELS OF PROPOSED IMPROVEMENTS

The Joint Fires kill chain's improved functional model is composed of the proceeding Figures 19–23 which represent the kill chain functionality shown in Figure 16. Figure 19 represents the overall functional model for the proposed improvements and is nine layers deep although only seven layers are shown for readability. The proposed functional improvements are derived from Table 1 and begin at the sixth layer with JCEC C2 interoperability, shown in color. While Figure 19 does not change the kill chain functions, it does improve the way in which the lethal triad conducts JCEC C2 by improving interoperability through MADL-like communications and JCEC C2 message exchanges.

The first two layers of Figure 19 indicate the JF kill chain, the third layer is composed of: 1) finding the threat functions, 2) targeting the threat functions, and 3) engaging the threat functions which decompose into: 1) performing BF ISR functions, 2) performing BF decision maker functions, and 3) performing BF shooter functions, respectively. and correspond to the high-level boxes on the right side of Figure 16. These are also the platforms executing the kill chain in the simulation with their inputs in Table 7. The fifth layer represents the kill chain functions which each platform performs and maps to the colored bubbles in Figure 16. The sixth layer is where the improvements from Table 1 are incorporated. Each of these functions is decomposed into performing improved JCEC C2 interoperability which then decomposes into 1) performing MADL-like communications functions and 2) performing improved JCEC C2 functions on layer seven. Functions of layers eight and nine will be explained in greater detail in the following Figures 20–23.

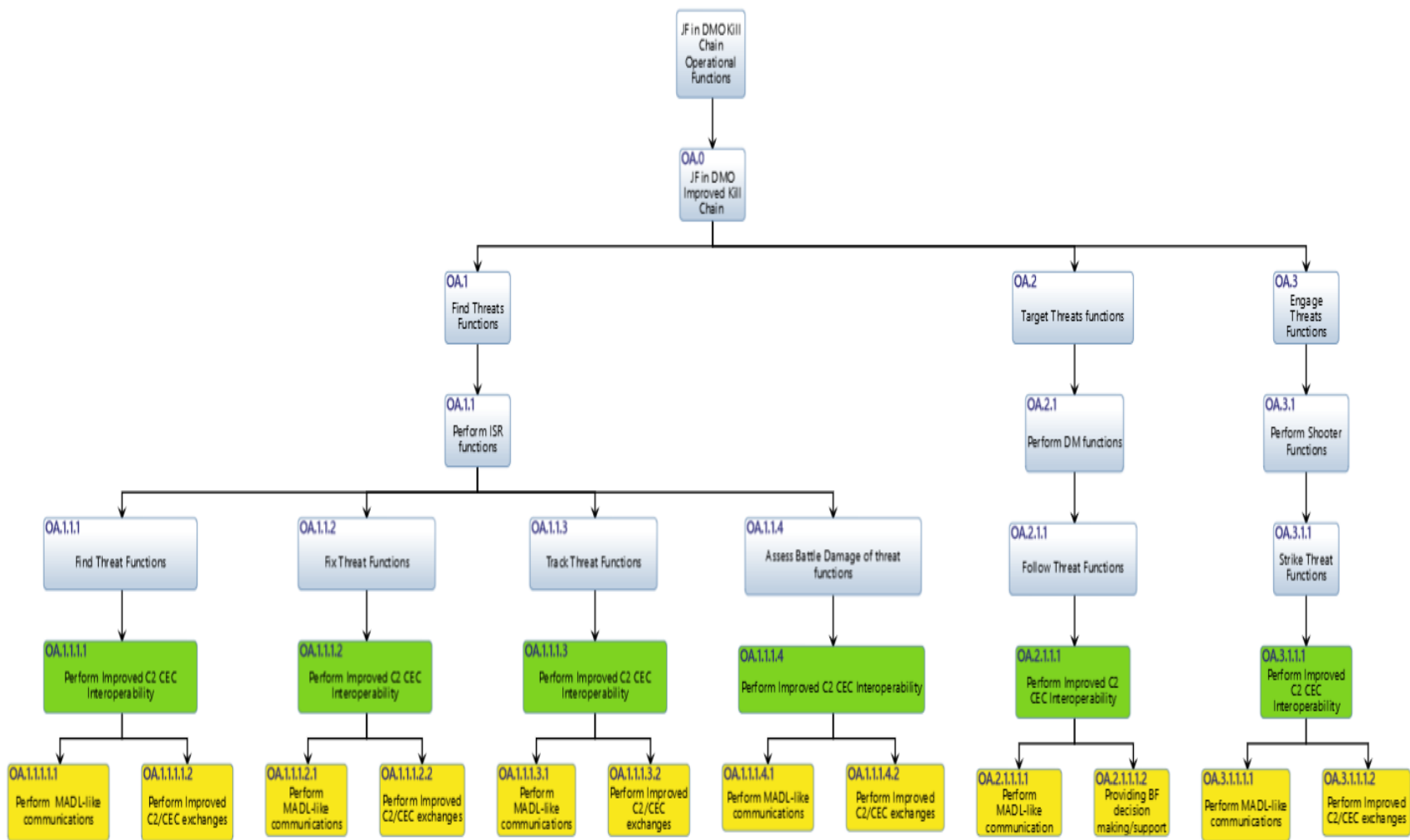


Figure 19. Operational / Functional Model for Improved JF Kill Chain

Figure 20 represents the finding threat functions of the overall model in Figure 19. Performing BF ISR functions decomposes into performing the four major functions of 1) finding the threat, 2) fixing the threat, 3) tracking the threat, and 4) assessing the threat. Figure 20 only represents one of the four functions mentioned previously for readability. These four major functions correspond to the four blue bubbles in Figure 16. Each of these four major functions is decomposed into performing improved JCEC C2 interoperability which then decomposes into the proposed improvements of 1) performing the functions of improved MADL-like communications and 2) performing the functions of improved JCEC C2 exchanges. In Figure 20, JCEC C2 functions, derived from Table 1, decompose into 1) converting analog voice to digital data, 2) transmitting digitized readiness signal to the DM, and 3) transmitting digitized location data to the DM and shooter.

The MADL-like communication functions, as derived from Table 1, will repeat across all four major functional areas under BF ISR but will only be decomposed and discussed in detail once while JCEC C2 will change across the four major functional areas based on the types of messages being exchanged. Proposed functional improvements for MADL-like communication decomposes into 1) performing BF anti-jamming, 2) implementing addressing schema to allow ad hoc joining of participants to the AFP, 3) receiving, transmitting, and updating high speed multi threat tracking data for common situational awareness, and 4) translating radio messages from one protocol to another. Providing BF anti-jamming decomposes into 1) transmitting directionally, 2) frequency hopping, and 3) nulling threat signals on receive.

Figure 21 shows the major functions of 1) fixing the RF threat, 2) tracking the RF threat, and 3) assessing the RF threat from layer 5 of the Figure 19. Fixing the threat decomposes into improving the JCEC C2 interoperability which then decomposes into 1) performing MADL-like communications, and 2) performing improved JCEC C2. In this case the JCEC C2 functions, as derived from Table 1, decompose into 1) converting analog voice to digital data and 2) transmitting digitized CEC threat location updates to the shooter and DM.

Figure 21 further shows the major function on layer five of the functional decomposition as tracking the RF threat which decomposes into improving the JCEC C2 interoperability and then into 1) performing MADL-like communications, and 2) performing improved JCEC C2. The JCEC C2 functions, as derived from Table 1, decompose into 1) converting analog voice to digital data and 2) transmitting digitized CEC threat location updates to the shooter and DM.

The last major function shown in Figure 21 on layer five is assessing battle damage of the RF threat. Assessing battle damage functions, which are derived from Table 1, decomposes into improving the JCEC C2 interoperability and then decomposes into 1) performing MADL-like communications and 2) performing improved JCEC C2. In this case performing JCEC C2 decomposes into 1) converting analog voice into digital messages to the DM and ISR and 2) transmitting and receiving digitized BDA to and from the DM and shooter.

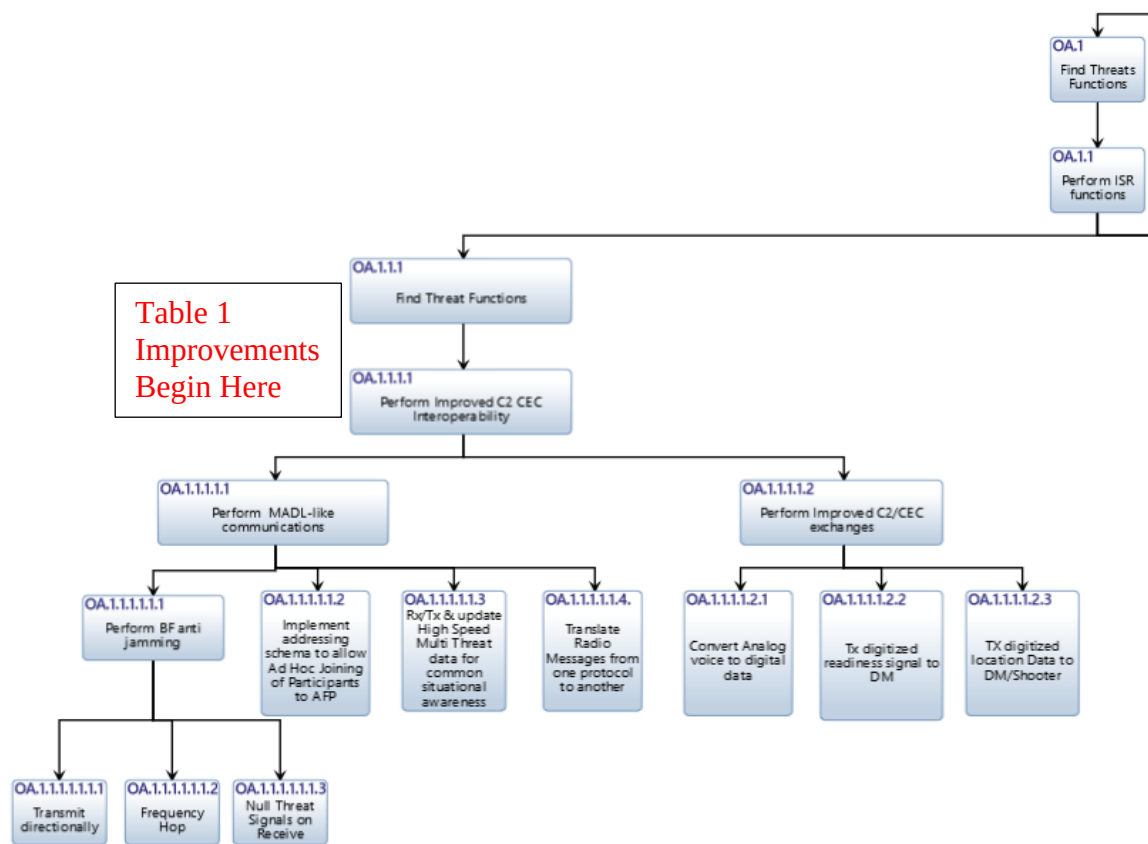


Figure 20. Operational / Functional Model for Finding of Threats via BF ISR

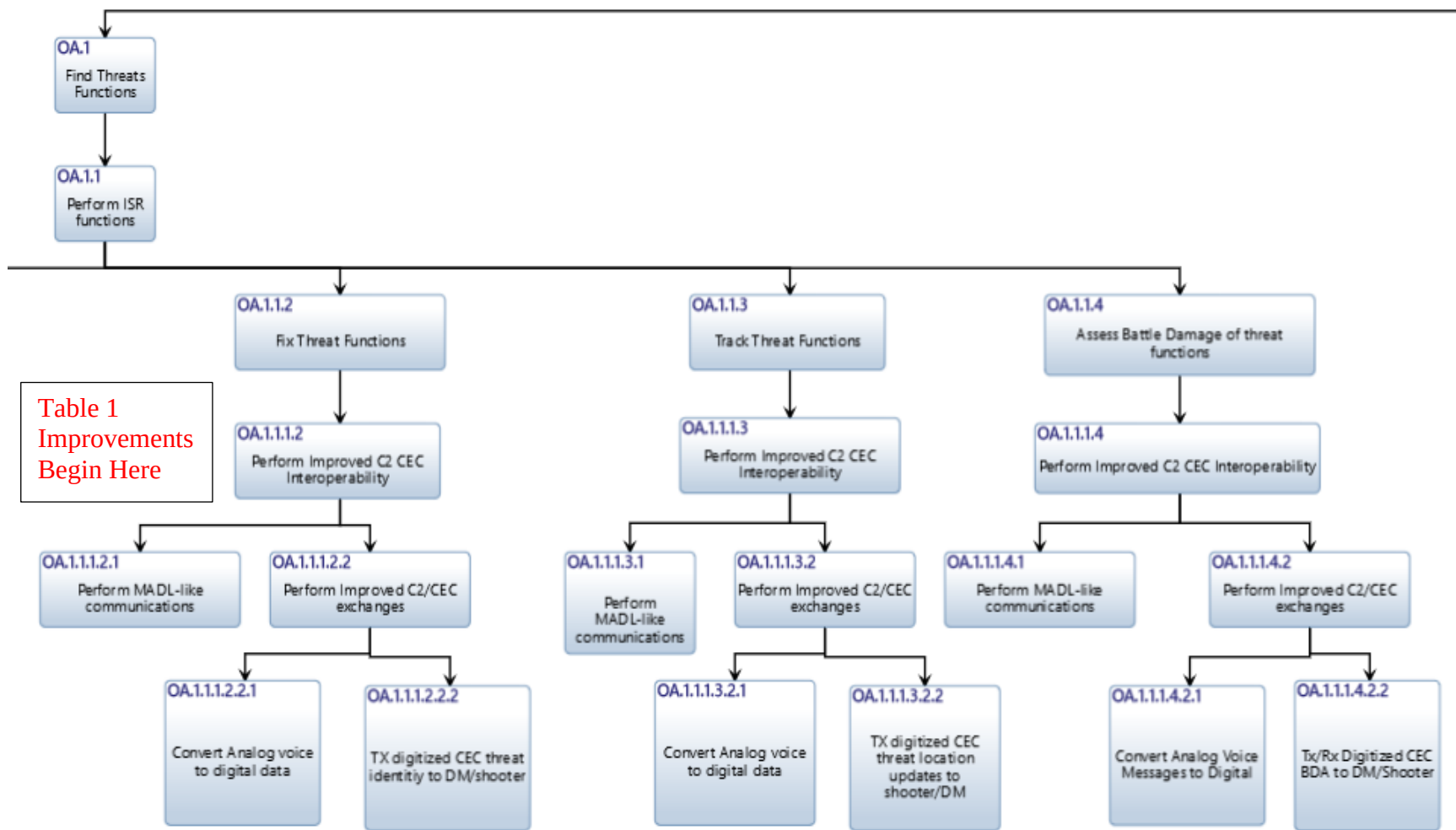


Figure 21. Operational / Functional Model for Fixing, Tracking, and Assessing via BF ISR

Figure 22 is a representation of targeting the threat which is the second major function on the third layer of the overall functional model in Figure 19. Targeting the threat decomposes into the performing improved BF DM functions. This in turn decomposes into follow/target threats and represents the yellow bubble shown in Figure 16. Figure 22 decomposes into improving the JCEC C2 interoperability which decomposes into 1) performing MADL-like communications functions and 2) providing BF decision making/support functions.

Proposed functional improvements, which are derived from Table 1, for MADL-like communication decomposes into 1) performing BF anti-jamming, 2) implementing addressing schema to allow ad hoc joining of participants to the AFP, 3) receiving, transmitting, and updating high speed multi threat tracking data for common situational awareness, and 4) translating radio messages from one protocol to another. Providing BF anti-jamming decomposes into 1) transmitting directionally, 2) frequency hopping, and 3) nulling threat signals on receive.

Providing BF decision making/support functions, also derived from Table 1, decompose into 1) converting analog voice to digital data, 2) receiving readiness signals from all the ISRs and shooters, 2) sending and receiving digitized CEC messages including shooter engagement orders, 3) processing shooter availability and inventory, and 4) automatically optimizing and selecting the best combination of ISR/DM/Shooter for a given threat.

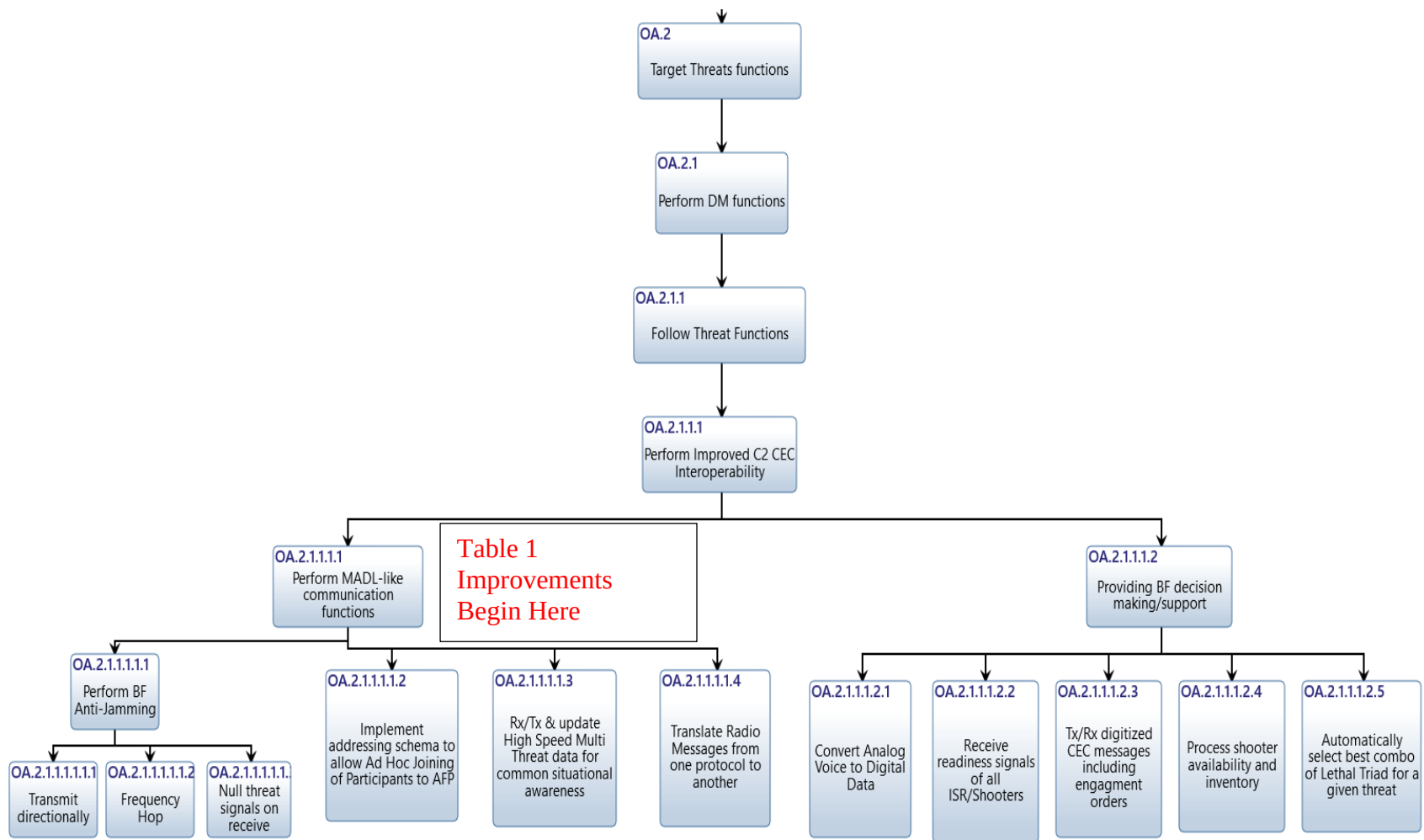


Figure 22. Operational / Functional Model for Targeting of Threats via BF DM

Figure 23 is a representation of engaging the threat functions which is the last major function on the third layer of the overall functional model in Figure 19. Engaging the threat decomposes into the performing BF shooter functions. This in turn decomposes into striking and engaging threats. Striking and engaging threats decomposes into improving JCEC C2 interoperability which in turn decomposes into the proposed functional improvements of 1) performing MADL-like communications and 2) performing improved JCEC C2.

Proposed functional improvements which are derived from Table 1, for MADL-like communications, decompose into 1) performing BF anti-jamming, 2) implementing addressing schema to allow ad hoc joining of participants to the AFP, 3) receiving, transmitting, and updating high speed multi threat tracking data for common situational awareness, and 4) translating radio messages from one protocol to another.

Providing BF anti-jamming decomposes into 1) transmitting directionally, 2) frequency hopping, and 3) nulling threat signals on receive. Performing improved JCEC C2 functions, as derived from Table 1, decomposes into 1) converting analog voice into digital data, 2) transmitting readiness signals to all DMs and ISRs, 3) receiving digitized fire control data from the DM, and 4) transmitting digital engagement status to ISR and DM.

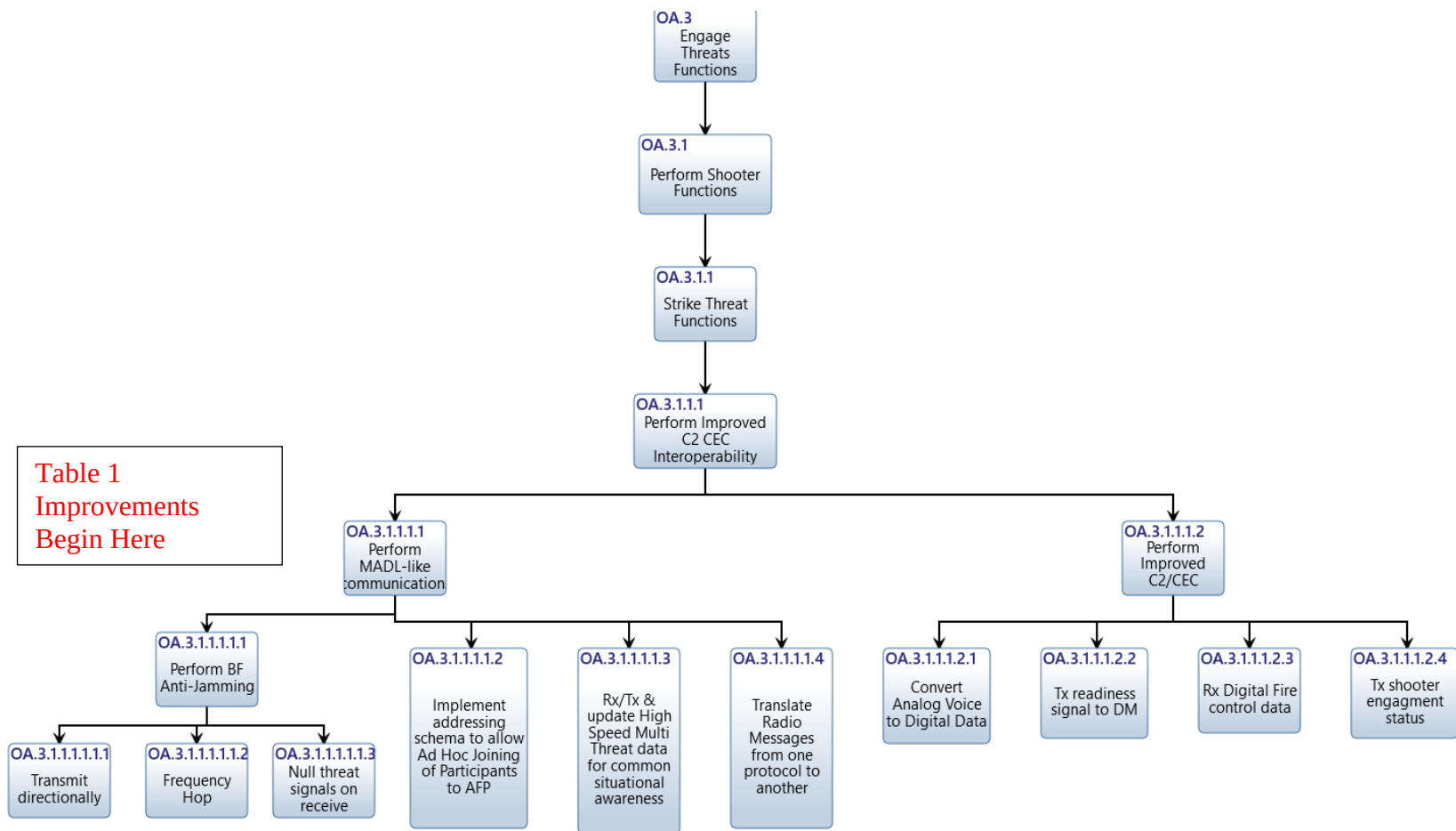


Figure 23. Operational / Functional Model for Engaging Threats via BF Shooter

The IDEF0 diagram for the improved JF's kill chain is shown in Figure 24. The proposed JCEC C2 interoperability improvements from Table 1, are shown as part of the mechanisms of the IDEF0. The proposed improvements increase the responsiveness of the lethal triad as they conduct their interoperability functions when executing the kill chain, but they do not change the kill chain functions. The diagram has three major functions which match the kill chain functions of find, target, and engage. The inputs are on the left and include the red force threats coming into the find threats function using the BF ISR, along with the proposed JCEC C2 improvements as the mechanisms. Target location data is passed from the find threats function to the target threats function where the BF DM, along with the proposed JCEC C2 improvements as the mechanisms, decides whether to engage the red force threat based on controls like rules of engagement and commander's intent. The fire control command is passed from the target threat function to the engage threat function where a BF shooter, along with the proposed JCEC C2 improvements as the mechanisms, engages with the red force threat if so directed. The outputs are the JF MOPs listed in Table 8, which include, but are not limited to, the number of BF missiles launched at the RF targets and the number of RF targets destroyed or disabled. The inputs, outputs, controls, and mechanisms directly relate to the simulation.

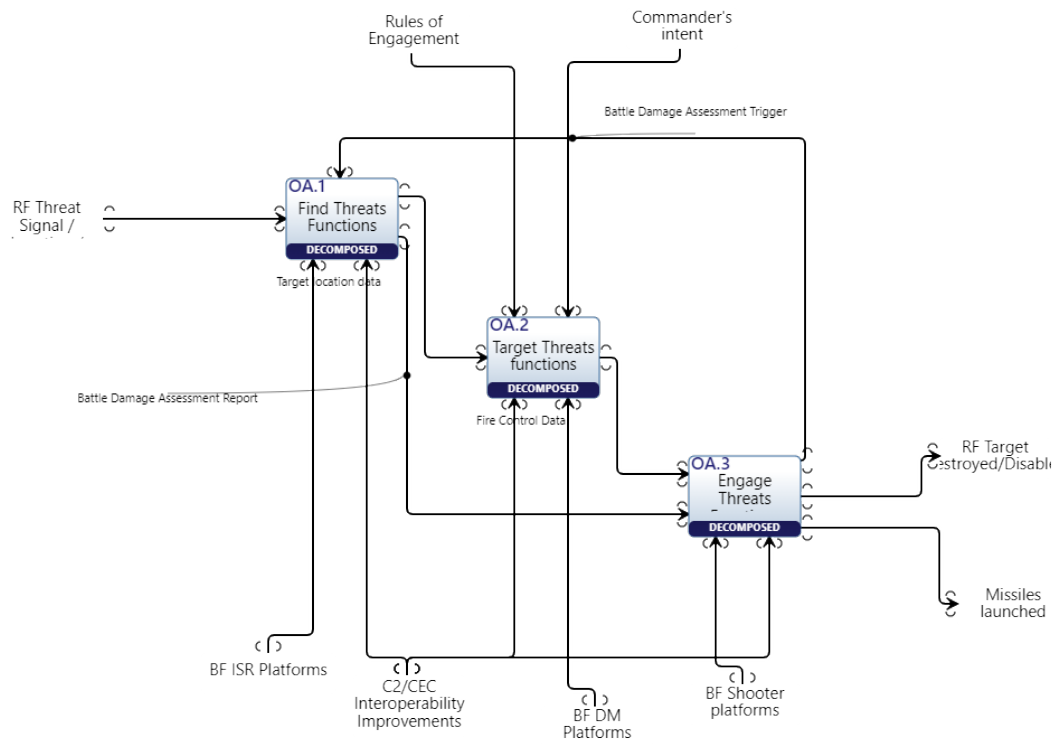


Figure 24. IDEF0 of Improved JF Kill Chain

THIS PAGE INTENTIONALLY LEFT BLANK

V. JOINT FIRE DMO SIMULATION

A. SIMULATING THE JF'S DMO KILL CHAIN

The interactions during an engagement scenario between the RF threat and the BF lethal triad platforms, which have integrated the JCEC C2/MADL functionality on every platform to create a distributed mesh, are shown in Figure 25.

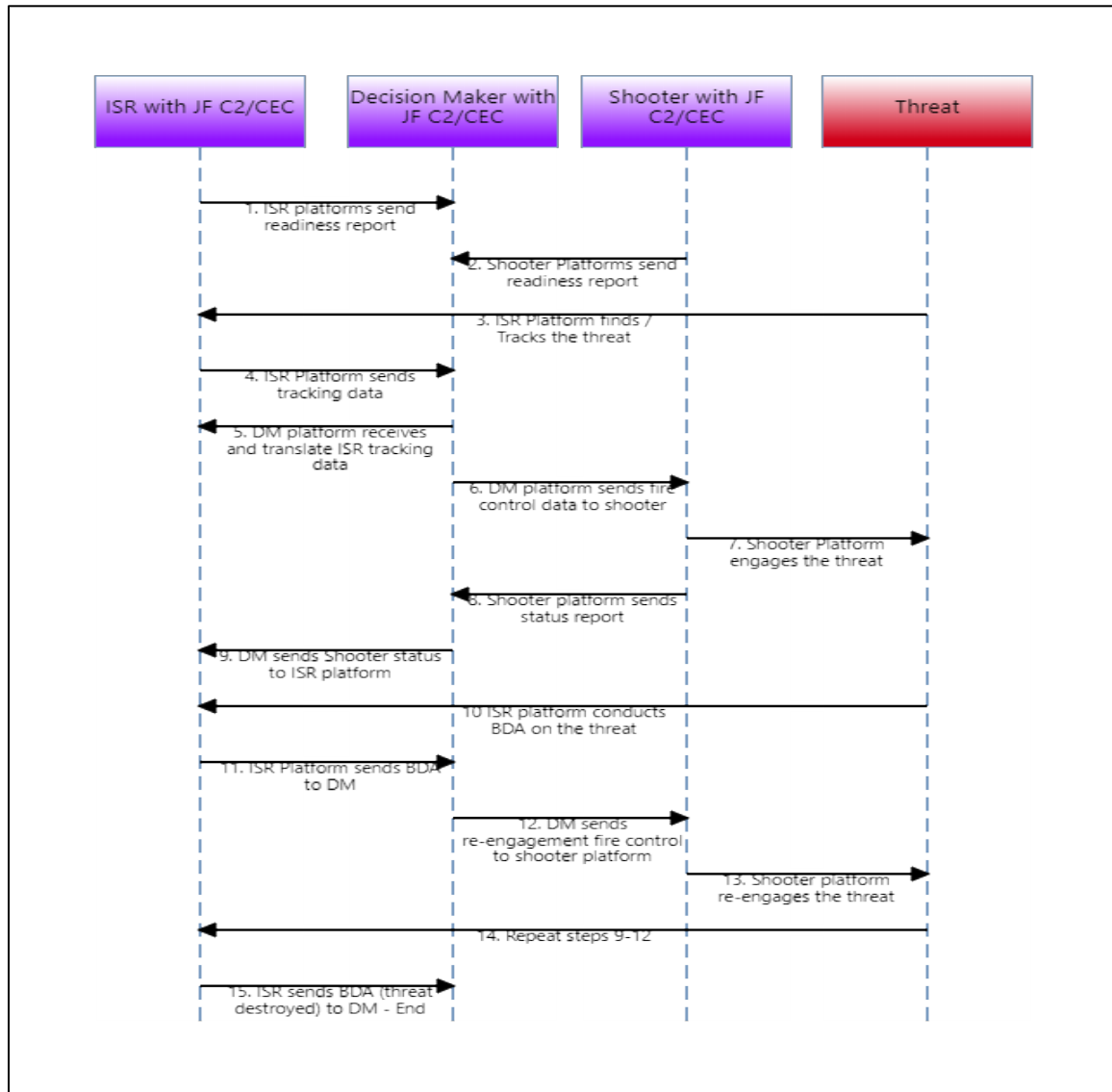


Figure 25. Proposed Lethal Triad JCEC C2 Kill Chain Execution Thread

The scenario begins with shooter and ISR platforms sending their readiness signals to the DM. The ISR's threat location information is then transmitted to the DM. The ISR platform identifies the threat, tracks the threat, and transmits the tracking data to the DM for automatically selecting the best combination of lethal triad based on its effectiveness against the threat. Based on the ISR information about the threat, the decision maker transmits a fire control decision to the shooter which then engages the threat. The ISR transmits a battle damage assessment report back to the shooter and decision maker for reengagement purposes.

B. SIMULATION APPROACH AND PURPOSE

The modeling and simulation approach is to use ExtendSim 10. This is a software tool that allows the team to create a force on force model to simulate different scenarios for exercising the assumptions and concepts of operations for an AFP. The scenario to be simulated is as described in the Operational Concept in section III with both the RF and BF locations as shown in Figures 3–7. The simulation will show the results of the BF engaging with the RF in both a defensive and offensive posture. The simulation should determine the kill chain's percentage of increased BF survivability while comparing the baseline runs of current JCEC C2 implementation with the Table 1 recommended improvements for JCEC C2 runs.

Simulation assumptions include the expectation that the BF will have superior range for detecting, finding, targeting, tracking, and engaging the RF because of the connectedness of remote observers. Further simulation assumptions include expectations that the BF platforms are better organized and trained in the cooperative engagement capabilities. The exact RF employment of capabilities is unknowable unless informed by intelligence. The BF will use notional ISR to place its platforms in locations not occupied by the RF. The BF is limited to identified detection ranges of its platforms.

The platforms and munitions selected for employment by BF are current U.S. Navy ships and weapon systems, while RF platforms and munitions are based upon the current unclassified PLA-N Naval Order of Battle. Platforms are integrated based on certain characteristics of surface, air, and ground attributes. Platforms included primary strike

munitions, if capable, as well as primary air defense munitions, if capable. Each platform from both forces will employ one type of strike warfare munition and one type of AMD warfare munition, if able. The RF ability to defend against BF strike warfare is not measured. The RF has sufficient observation capability over the scenario space and will engage the BF with strike warfare munitions at their longest engagement ranges. There are no RF MOPs associated with their ability to coordinate strike warfare. These parameters are detailed in Tables 3–5.

Table 3. RF and BF Munition Parameters. Source: Popa et al. (2018).

Red Force Munitions	Velocity (MPH)	Engage Range (mi)	Blue Force Munitions	Velocity (MPH)	Engage Range (mi)
DF-21D	7618	920	SM-2	2647	69
DF-26	9114	1991	SM-3	7618	1151
FN-6/16	1277	4.6	SM-6	2647	288
HQ-10	1530	75	LRASM	748	345
HY-2	621	144	Tomahawk	748	115
YJ-100	535	495	Harpoon	541	75
YJ-12	2279	247	ESSM	3027	13.8
YJ-18	2281	334	Sidewinder (AIM-9)	1899	21
YJ-62	535	247	Hellfire	994	4.6
YJ-83C/C-803	691	115	AMRAAM	3027	86
HHQ-9	3194	186	HARM	1381	92
CJ-10	614	930	ATACMS	2284	190
HQ-16	3188	75	PAC-3	3045	43
PL-12	3021	69			
PL-9	2647	14			
YJ-91	3453	75			

Table 4. RF Platform Parameters. Source: Popa et al. (2018).

Red Force Platforms	Strike Munition	Strike Munition Capacity	AMD Munitions	AMD Munitions Capacity
DF-21 Launcher	DF-21D	8		0
DF-26 Launcher	DF-26D	4		0
DH-10 / CJ-10 Launcher	CJ-10	3		0
H-6K	YJ-100	6		0
H-6K	YJ-12	6		0
Houbei	YJ-83	6FN-6/16		2
HY-2 Launcher	HY-2	4		0
J-11		0PL-9		4
J-15	YJ-91	2PL-9		4
J-15	YJ-83C/C-803	2		0
J-16	YJ-12	3PL-12		6
Jiangkai	YJ-83	6HQ-16		18
Luyang	YJ-83	10HQ-16		10
Nanchang Q-5	YJ-12	4PL-12		4
Renhai	YJ-18	20HQ-16		20
YJ-62 Launcher	YJ-62	8		0
Z-18	YJ-83C/C-803	2		0

Table 5. BF Platform Parameters and Sensors. Source: Popa et al. (2018).

Platform	Strike Munition	Strike Munition Capacity	AMD Munitions	AMD Munitions Capacity	Sensor Name	Sensor Range
DDG-1	MST Tomahawk	8	SM-2	32		
DDG-2	LRASM	8	SM-3	5		
F-35	Hellfire	4	Sidewinder (AIM-9)	9	Array Radar	62
F-35	Hellfire	4	Sidewinder (AIM-9)	2	ECCM	62
F-35	AMRAAM	2	Sidewinder (AIM-9)	9	ESM	172
HIMARS	ATACMS	6	0	0	ESM	62
LCS	Harpoon	4	ESSM	21	Phased	
LUSV	Harpoon	4	ESSM	21	Array Radar	207
LUSV	SM-2	4	ESSM	21		
MQ-8	Hellfire	2	0	0		
MQ-9	Hellfire	2	0	0		
MUSV	Harpoon	4	ESSM	21		
Patriot		0	PAC-3	16		

Figures 26–30 show how the RF and BF are established in the simulation, how they are assigned munitions, the steps involved in physically placing them in the battlespace, and finally the dynamic interplay of platforms from both forces. The RF resource pool is put through a randomizer to select an aircraft, ship, or ground force. The RF platforms are assigned a longitude and latitude. The RF platforms target BF strike platforms based on proximity to each target and the distances identified. Next, the RF platforms have their defense munition and capacity identified. The final attribute assigned to the RF platform is the targeting of a BF air target. The distance to the BF air target is identified. This assignment process creates the RF baseline. It does this for the RF aircraft, sea, and ground locations. Once the RF platforms have locations, they get their assigned BF targets and the distance to the target. The attributes of the RF platform will be assigned to the munition. The munition will be assigned the platform’s location.

The BF platforms and munitions will go through a similar process as the RF platforms and munitions. The BF will choose available locations from the remaining 150 available locations. The BF platforms will receive sea, air, and ground locations. The BF platforms will be given a certain number of strike and air defense munitions based on their capacities. At the end of the setup phase, RF platforms will have assigned targets with associated distances. The RF munitions will be designated with range, velocity, probability of kill, strike target, and distance to target. The BF platforms have the same parameters assigned.

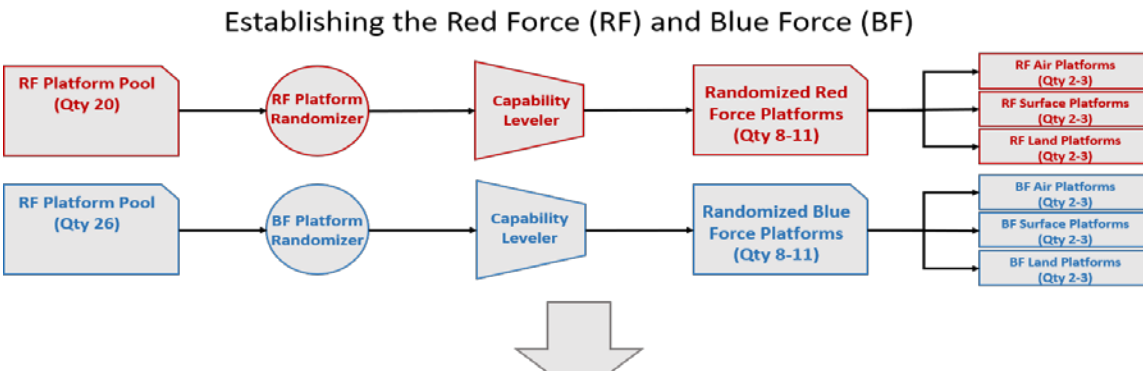


Figure 26. Establishing the Red Force (RF) and the Blue Force (BF)

Allocating Munitions to RF & BF Platforms

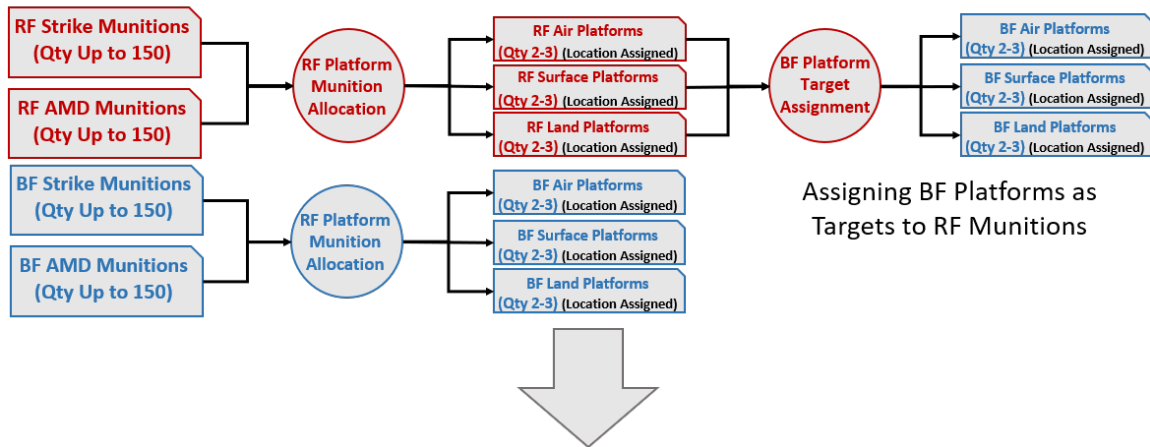


Figure 27. Allocated Munitions to RF and BF Platforms

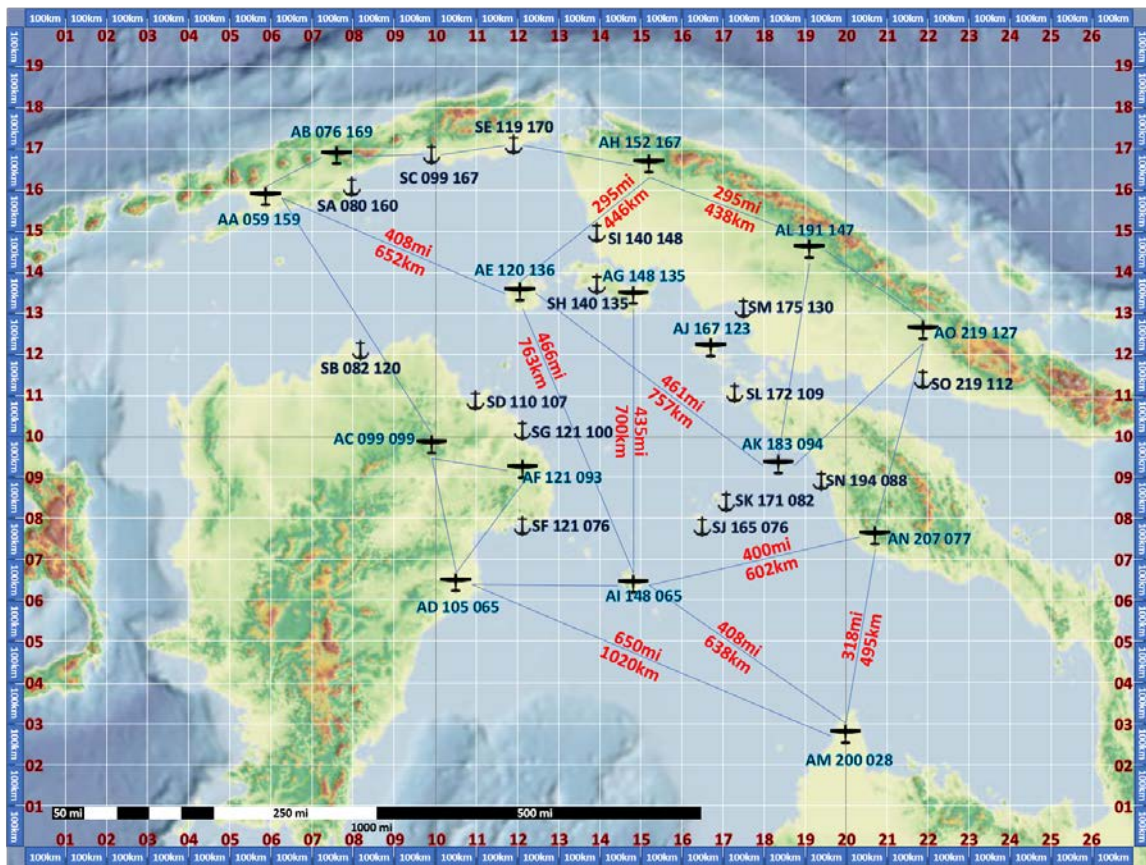


Figure 28. Locations for Land-Based Platforms

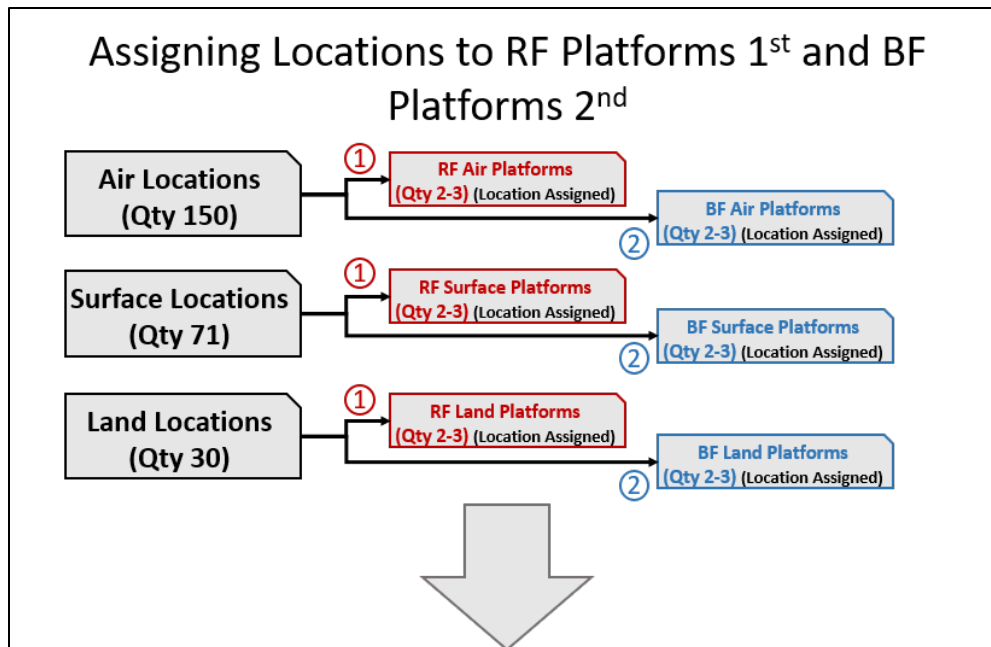


Figure 29. Assigning Location to RF and BF Platforms

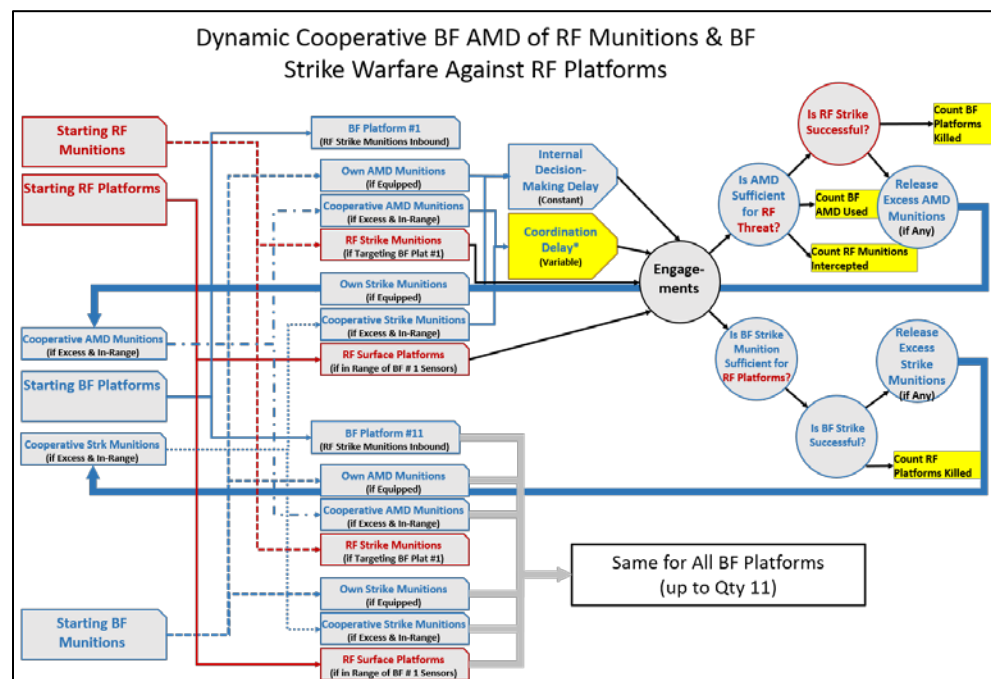


Figure 30. Dynamic Interplay of RF & BF Platforms and Munitions

The engagement phase has process markers used in the lethal triad kill-chain algorithm. It begins with RF munitions receiving targets assigned. This begins the calculation of the RF travel time in which it is the actual movement of the RF munition at a BF target. The BF munitions have munitions with targets assigned. There is an additional attribute of calculating communication time between platforms. The BF platforms engage targets following the JF kill chain's proposed improvements from Table 1. The BF platforms have five possible capability categories and are listed in Table 6.

Table 6. Blue Force Platform Capability Categories

Blue Force Platforms Capability Categories
Sensor /Shooter/DM
Sensor/DM
Shooter / DM
Sensor/Shooter/Unmanned
Sensor/Unmanned

The Sensor-Strike-DM, for example, engages when it can sense, strike, and provide strike decision-making against the target. This engagement design is robust enough to incorporate additional platforms' capability categories for future modeling and simulation. Based on the BF platform roles, there are process time delays outlined in Table 7.

The simulation of BF munitions targeting automates the process for the DM issue weapons release decisions. Again, it is important to note in this model that all the BF and RF platforms are static. However, the BF and RF munitions have a designated velocity. Munition travel times and delays are based on time, distance, and proximity. This is addressed in a BF platform capability combination that is delineated in Table 7. The simulation will first perform baseline engagement scenarios using the timing in Table 7, column two, plus the addition of either the current JCEC C2 estimated timing shown in column three or the addition of improved JCEC C2 timing shown in column four.

Sharif H. Calfee and Neil C. Rowe, while researching at The Institute for Modeling, Virtual Environments, and Simulation (MOVES), modeled the cognitive responses of the team members of the Combat Information Center performing air defense operations for a U.S. Navy battle group (Calfee and Rowe 2004). This study surveyed many operators and averaged their inputs (Calfee and Rowe 2004). The study found that the decision process could take up to 30 seconds per individual making decisions when the situation is not of high alert, 20 seconds when the situation is balanced, and 10 seconds when the situation is highly stressful (Calfee and Rowe 2004).

I.C. Moon, K.M. Carley, and T.G. Kim studied fleet success in air and missile defense and the impacts of human decision makers in stressful environments (Moon, Carley, and Kim 2013). Their research indicated that typical C2 decision making delays range from 40 to 60 seconds (Moon, Carley, and Kim 2013). This was incorporated into the JF simulation by using these decision times as a normal distribution with a sample mean $\bar{X} = 50$ seconds and a sample standard deviation $\sigma = 3.25$ seconds, as shown below in Table 7's column two, with the additions of columns three or four as appropriate.

To represent the traditional C2 fires coordination cycles among various echelons of the joint force, an estimate for the delays caused by this coordination was set at $\bar{X} = 400$ seconds and a sample standard deviation $\sigma = 100$ seconds as shown in Table 7, column three. In contrast, given basic calculations for radio signal transmission at the speed of light within the scenario space and negligible processing times for computer and networking systems within the system of interest, the JF team used a much smaller coordination delay time for corresponding joint CEC exchanges of information implementing Table 1 improvements. After the decision maker has authorized weapons release, there are no more humans in the loop, and slave mode munitions can be actuated remotely. This delay time is estimated at $\bar{X} = .04$ seconds with a sample standard deviation of $\sigma = 0.01$ seconds as shown in Table 7, column four.

Table 7. Simulation Input Timing

Platform Capabilities	Baseline/SQ Human Decision-Making Time	Status Quo Estimated JCEC C2 Cycle Times	Proposed Improved JCEC C2 Cycle Times
Sensor /Shooter/DM	Norm.dist(50,3.25) secs	Add Norm.dist(400,100) secs	Add Norm.dist(0.04,0.01) secs
Sensor/DM	N/A	Add Norm.dist(400,100) secs	Add Norm.dist(0.04,0.01) secs
Shooter / DM	Norm.dist(50,3.25) secs	Add Norm.dist(400,100) secs	Add Norm.dist(0.04,0.01) secs
Sensor/Shooter/Unmanned	N/A	Add Norm.dist(400,100) secs	Add Norm.dist(0.04,0.01) secs
Sensor/Unmanned	N/A	Add Norm.dist(400,100) secs	Add Norm.dist(0.04,0.01) secs

VI. EFFECTIVENESS AND PERFORMANCE

A. MEASURES OF EFFECTIVENESS AND PERFORMANCE

The SOI is shown in Figure 14 (Chapter IV, Section A) and focuses on the JF kill chain's increased effectiveness via the proposed improvements from Table 1 (Chapter IV, Section B), for improving current C2 responsiveness during the kill chain execution. Of utmost importance are the effects that shortening the C2 cycle could have on the kill chain and the outcome of a battle. The kill chain benefits should include faster, less jammable communication between the lethal triad; more responsive, reliable decision making in a highly contested environment; and, improved matching of weapon systems to threats which should culminate in a more appropriate and effective ad hoc, self-forming BF AFP. These improvements are modeled in the simulation via the timing in Table 7 (Chapter V, Section B) by adding columns two and four together. The measures of effectiveness (MOEs) and measures of performance (MOPs) for the BF defensive and offensive warfare scenarios, as described in Chapter III's Operational Concept, are shown in Table 8.

Table 8. 2030 JF MOE & MOPs

Scenario Objective	AFP Function	MOE	MOPs
Conduct Blue Force (BF) DMO via an AFP to effectively control a strategic strait access by controlling the Red Force Platforms			
	Employ effective joint fires during dynamic interplay of defensive and offensive warfare	BF Survivability and RF Survivability	
			The number of RF threats destroyed
			The number of BF platforms destroyed
			The number of RF munitions neutralized
			The number of BF AMD munitions spent
			The number of BF strike munitions spent
			The number of RF platforms that escape
			The number of RF hits but not kills on BF
			The number of RF munitions remaining

B. DATA ANALYSIS AND RESULTS

The data analysis was conducted using MS Excel and JMP. The JMP analysis of the simulation output data is shown in Figures 31–37 and represents analysis of variance (ANOVA) of the mean for a significant statistical difference. The data was collected using the ExtendSim10 write-to-database or information blocks. The simulation was run one thousand times for the baseline or Status Quo (SQ) configuration using inputs from Table 7, column two added to column three and then again for the improved JCEC configuration using inputs from Table 7, column two added to column four. The simulation was configured such that the BF is slightly more capable than the RF. This is an important assumption the JF team made which directly relates to the belief that the U.S. JF has and will have better capabilities than any near peer adversary in the 2030 timeframe.

The input parameters for the simulation were as follows: 1) the JCEC C2 cycle timing from Table 7 depending on the configuration; 2) the number of BF platforms that are created along with the weapons load for each platform; and, 3) the number of RF platforms that are created. The simulation output parameters which relate to the MOPs in Table 8 are shown in Table 9.

Table 9. Simulation Output Parameters that Relate to JF MOPs

MOP	Note
1) the number of BF platforms killed	This MOP directly relates to the overall survivability of the BF platforms that represented the AFP in each configuration.
2) the number of RF platforms killed	This MOP directly relates to the overall survivability of the RF platforms.
3) the number of RF munitions neutralized	
4) the number of BF AMD munitions spent	This MOP may be significant as each platform forward deployed can only carry a limited amount of munitions.
5) the number of BF strike munitions spent	This MOP allowed the JF team to simulate CEC with ground or air platforms from the joint forces.
6) the number of RF platforms that escape	
7) the number of RF hits on BF but not kills	This MOP was captured to represent possible significance of some of the BF platforms, although being targeted and hit, still are able to defend themselves and continue with the mission.
8) the number of RF munitions remaining	

The following are the detailed findings from the simulation.

a. Finding A: Bf Mean % Survivability

The increase in the overall BF Platforms survivability is the result of improving the kill chain, via the implementation of the JCEC improvements from Table 1, using the C2 cycle timing from Table 7. The JF team expected to see that as the kill chain was accelerated by reducing the JCEC C2 cycle times, the overall BF platform's survivability would increase. Figure 31 represents the BF Platforms Killed versus the SQ (0) run and

the improved JCEC (1) run which incorporate no further decision-making improvements as explained in Table 12. Figure 32 represents the BF Mean % Survivability versus the SQ (0) run and the improved JCEC (1) run. The mean results from the figures are transcribed to Table 10.

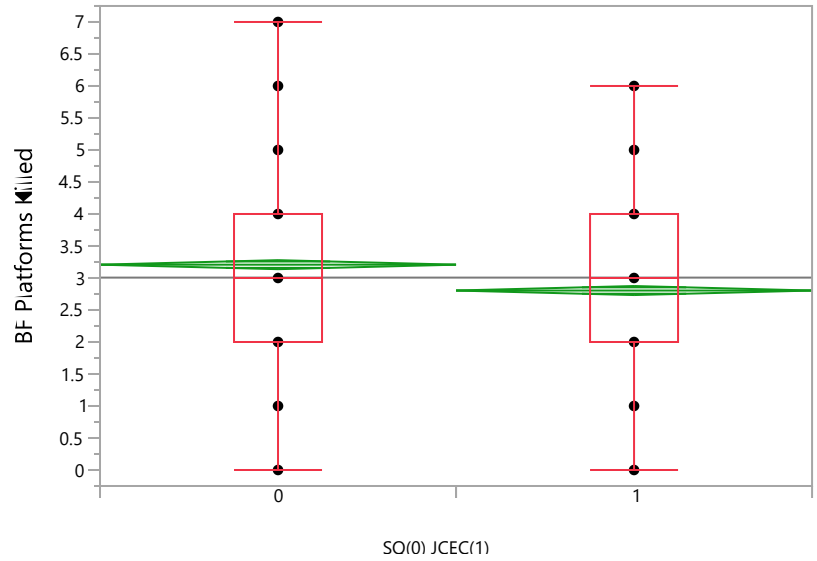


Figure 31. BF Platforms Killed

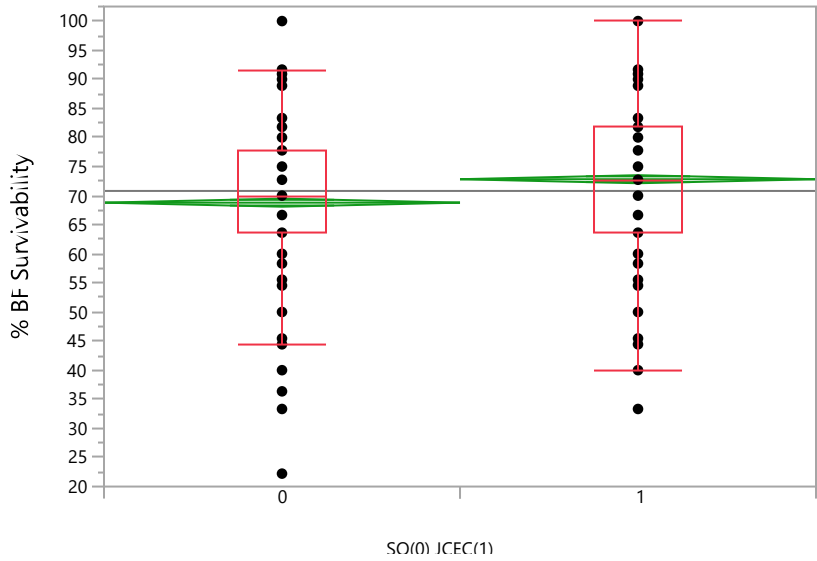


Figure 32. BF Mean % Survivability

The overall BF Mean % Survivability in Table 10 is calculated using Equation 1 below:

Equation 1. BF Mean % Survivability = $[(\text{Mean BF initial platforms} - \text{Mean BF Killed}) / \text{Mean BF initial platforms}] \times 100$

The JF team calculated a decrease in BF losses of 12.6 % and an overall 5.9% improvement in BF Mean % Survivability, as indicated in the Table 10. These results represent a significant savings in lives and costly platforms. Increased effectiveness of the BF kill chain thus represents a more survivable BF.

Table 10. BF Mean % Survivability

1000 runs each	SQ(0) (mean)	Improved JCEC(1) (mean)	% Difference Using Eq 1.
Mean BF Platforms created	10.4	10.4	0.44
Mean BF Platforms Killed	3.2	2.8	12.6
BF Mean % Survivability	68.8	72.8	5.9

The JF team decided to simulate two different excursions with C2 cycle time improvements to measure the effects on the overall BF Mean % Survivability. The first improvement is shown as Excursion 1 in Table 11 and is representative of what could be achieved with extensive training of the human decision maker in order to reduce the C2 cycle times (Calfee and Smith 2016). The second improvement shown as Excursion 2 in Table 11 represents what could be achieved if the JFs implemented automation using artificial intelligence and machine learning algorithms to accelerate the C2 cycles. The simulation's input SQ decision-making timing from Table 7's column 2, is changed per Table 11 for Excursion 1 and then again for Excursion 2, for a total of six runs as shown

in Table 13 and Figure 33 and indicated by the nomenclature SQ (0), JCEC (1), SQ (2), JCEC (3), SQ (4), and JCEC (5), as explained in Table 12.

Table 11. DM Options in Timing for Excursions from Table 7, Column 2.
Source: Moon, Carley, and Kim (2013).

1000 runs each	Excursion 1- SQ Human Decision-Making Time with Training	Excursion 2-SQ Human Decision-Making Time with Automation
Cycle Time Mean Xbar	20 seconds	0.04 seconds
Cycle time Std. Dev σ	10 seconds	0.01 seconds

As shown in Table 12, the baseline scenario uses SQ (0) and JCEC (1) which represent Table 7, column 2 decision-making input timing without training or automation. Excursion 1 uses SQ (2) and JCEC (3) which incorporate improvements in decision-making timing with training of the decision maker. Excursion 2 uses SQ (4) and JCEC (5) which incorporate improvements in decision-making timing with automation implemented.

Table 12. Explanation of SQ0, JCEC1, SQ2, JCEC3, SQ4, JCEC5

Human Decision-Making Configuration & Timing	Status Quo JCEC Configuration & Timing	Improved JCEC Configuration & Timing
Status Quo (SQ) DM, (See Table 7, Col 2)	SQ (0)	JCEC (1)
Trained DM, (See Table 11, Excursion 1)	SQ (2)	JCEC (3)
Automated DM, (See Table 11, Excursion 2)	SQ (4)	JCEC (5)

The differences in various mean results from Table 13 and Figure 33 offer three important findings. First, a near instantaneous, improved JCEC (5) capability, with

automated decision making, results in a 6.4% increase in survivability over the SQ (0) configuration with no JCEC or decision-making improvements. This represents the maximum improvement that could be realized in any of the configurations. Second, the near instantaneous, improved JCEC (5) configuration, with automated decision making, results in a 2.4% increase in survivability compared to the baseline, improved JCEC (1) configuration with no improvements in decision making. This represents the maximum improvement that could be realized with improved JCEC capability and automation. Finally, SQ (4) configuration with automated decision-making results in a 2.1% increase in survivability compared to the baseline SQ (0) configuration. This suggests that there is an approximately 2% improvement in survivability that can be realized via automation of just the decision-making process, without the implementation of further JCEC improvements.

Table 13. BF Mean % Survivability for Excursions

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
SQ (0)	1000	68.9	0.35	68.1	69.5
JCEC (1)	1000	72.8	0.35	72.1	73.5
SQ (2)	1000	70.9	0.35	70.2	71.6
JCEC (3)	1000	75.0	0.35	74.3	75.7
SQ (4)	1000	71.0	0.35	70.4	71.8
JCEC (5)	1000	75.3	0.35	74.6	75.9

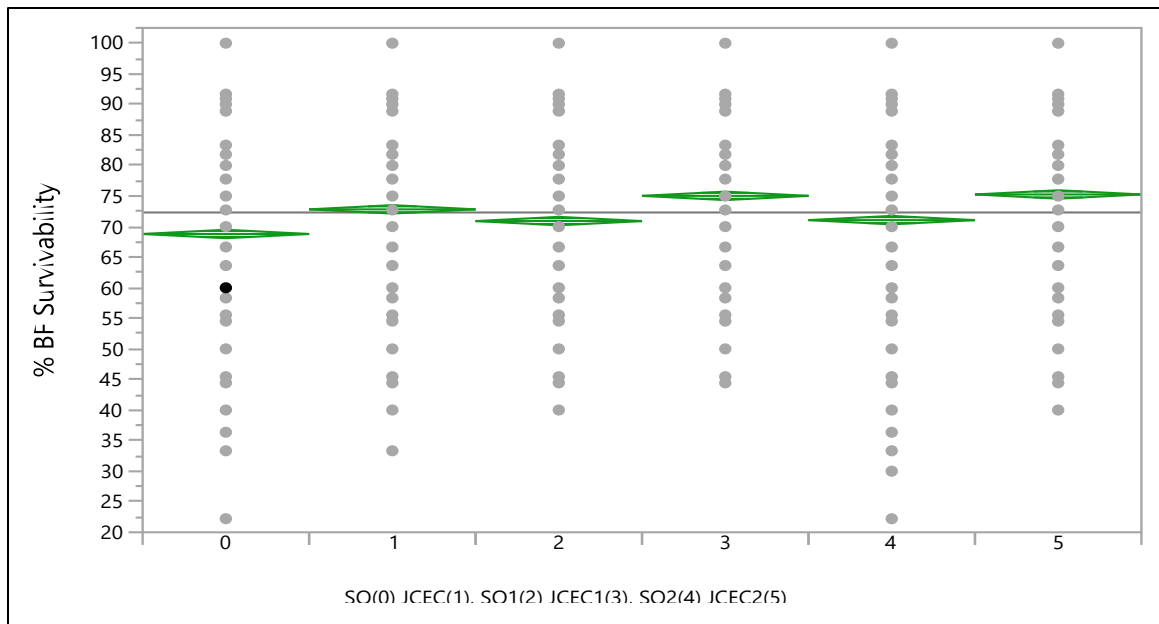


Figure 33. BF Mean % Survivability for Excursions

b. Finding B: Additional Bf amd Munitions Available

Faster C2 cycles should allow the BF to be able to fire more AMD Munitions to defend its platforms. The difference in the mean shown in Figure 34 and transcribed to Table 14 indicates that faster C2 cycle times allow the BF in the improved JCEC (1) configuration to fire a mean of 50.7 missiles, which is approximately 6 additional missiles available and fired than the SQ (0) configuration, without improvements. JCEC C2 improvements which accelerate the kill chain, would allow for additional BF munitions to be available for fire, thus acting as a form of BF multiplier.

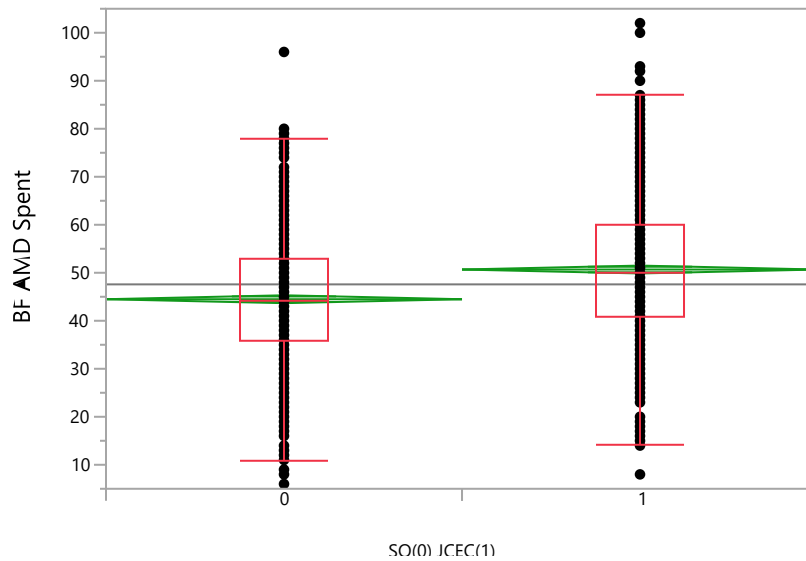


Figure 34. Additional BF AMD Munitions Available and Spent

Table 14. Additional BF AMD Munitions Available and Spent

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
SQ (0)	1000	44.5	0.42	43.7	45.3
JCEC (1)	1000	50.7	0.42	49.9	51.5

Figure 35 and Table 15 indicate the results for the number of additional BF AMD munitions available and spent during the simulated C2 cycle time improvements while implementing Excursions 1 and 2 using the mean and standard deviations shown in Table 11. The difference in mean results, indicates that the improved JCEC (5) with automated decision- making, represents approximately 6 additional BF AMD munitions available and fired when compared to an improved JCEC (1) with no decision-maker automation or training. This suggests that if the JF implemented artificial intelligence and machine learning algorithms by the year 2030, it would be able to fire on average 56.4 AMD munitions.

The difference in mean results also indicates that the improved JCEC (5) with automated decision-making represents approximately 12 additional BF AMD munitions available and fired when compared to the current SQ (0) configuration with no improvements. JCEC C2 improvements which accelerate the kill chain, would allow for additional BF munitions to be available for fire, thus acting as a form of BF multiplier.

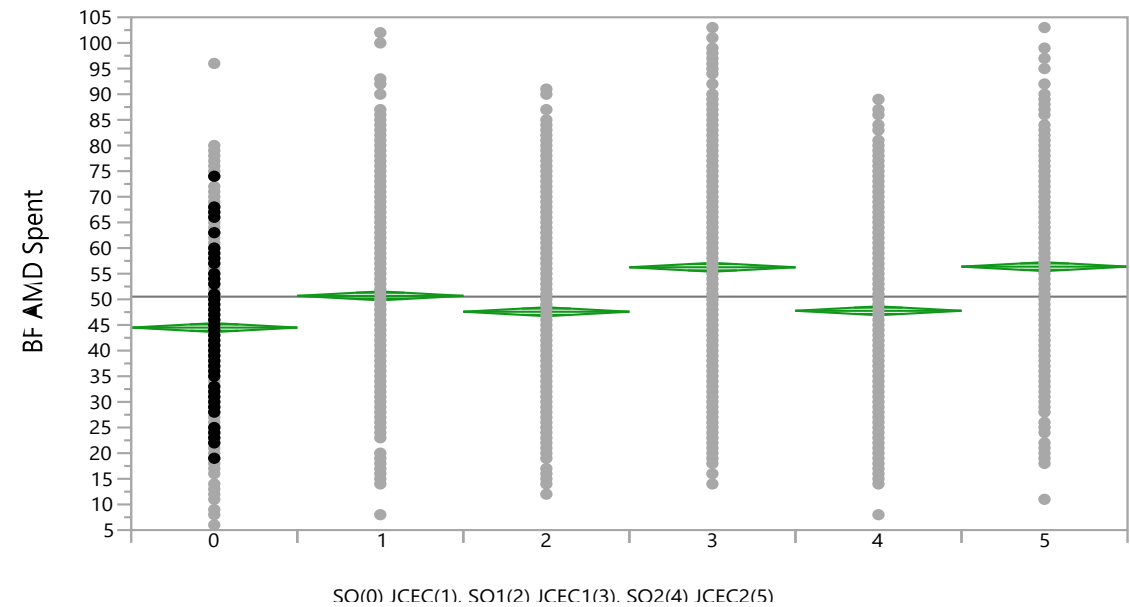


Figure 35. Additional BF AMD Munitions Available and Spent for Excursions

Table 15. Additional BF AMD Munitions Available and Spent for Excursions

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
SQ (0)	1000	44.5	0.4	43.6	45.4
JCEC (1)	1000	50.7	0.4	49.8	51.5
SQ (2)	1000	47.6	0.4	46.7	48.4
JCEC (3)	1000	56.3	0.4	55.4	57.1
SQ (4)	1000	47.8	0.4	46.9	48.6
JCEC (5)	1000	56.4	0.4	55.5	57.2

c. **Finding C: Additional Number of Rf Munitions Neutralized**

Faster C2 cycles improve the kill chain and allow the BF to be able to neutralize more RF munitions. More enemy RF munitions destroyed, results in a more favorable outcome for the BF in terms of less casualties and less damage to costly platforms. The differences in the mean values of Figure 36 and Table 16 below indicate the improved JCEC (1) configuration, with no improvements in decision making, results in approximately 4.6 more RF munitions destroyed than the SQ (0) configuration with no improvements. Faster C2 cycles shorten the kill chain and allow the BF to defend its platforms more promptly.

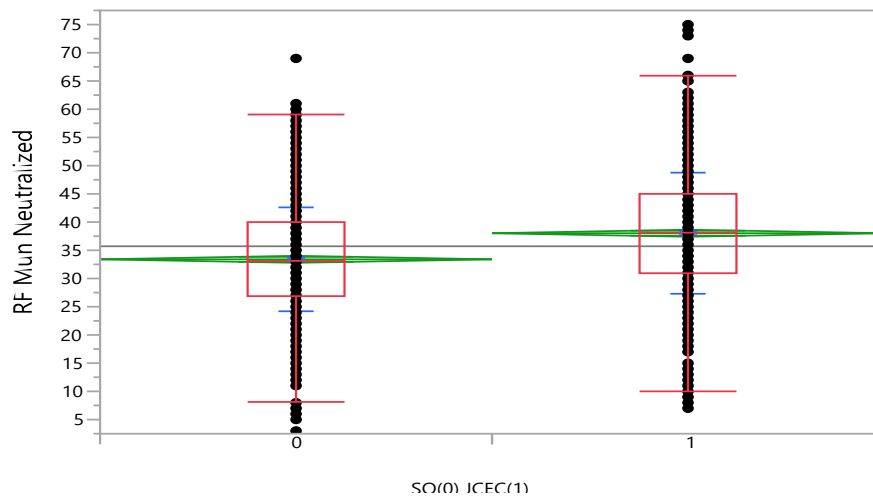


Figure 36. Additional RF Munition Neutralized

Table 16. Additional RF Munitions Neutralized

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
SQ (0)	1000	33.4	9.2	0.3	32.8	33.9
JCEC (1)	1000	38.0	10.7	0.3	37.4	38.7

Figure 37 and Table 17 indicate the results for the number of additional RF munitions destroyed during the simulated C2 cycle time improvements while implementing Excursions 1 and 2 using the mean and standard deviations shown in Table 11. The difference in mean results, indicates that the improved JCEC (5) with automated decision-making, represents destruction of approximately four additional RF munitions when compared to an improved JCEC (1) with no decision-maker automation or training. The difference in mean results also indicates that the improved JCEC (5) with automated decision-making, represents approximately 8.7 additional RF munitions destroyed when compared to the current SQ (0) configuration with no improvements. JCEC C2 improvements which accelerate the kill chain, would allow for additional RF munitions to be destroyed, thus acting as a form of BF multiplier.

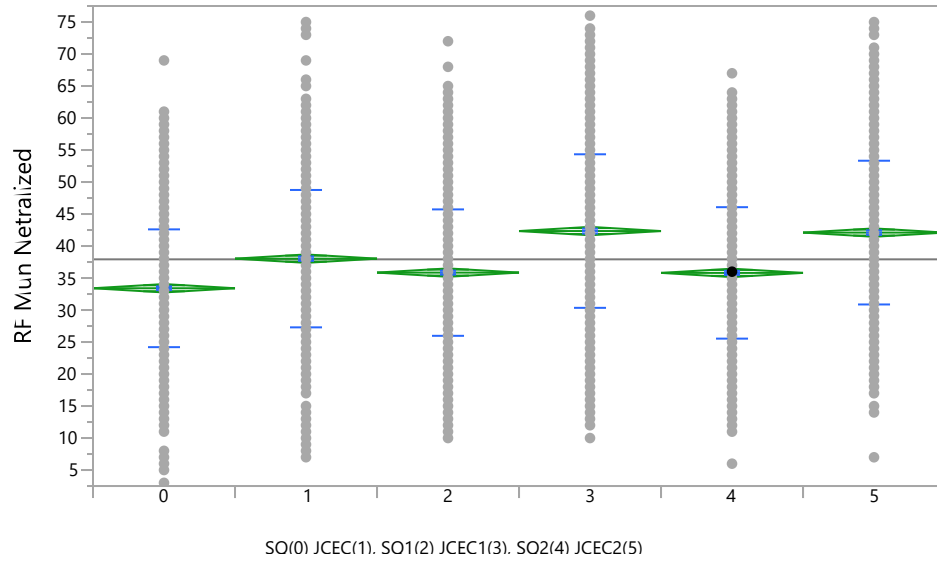


Figure 37. Additional RF Munition Neutralized with Excursions.

Table 17. Additional RF Munitions Neutralized with Excursions

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
SQ(0)	1000	33.4	9.2	0.3	32.8	33.9
JCEC(1)	1000	38.0	10.7	0.3	37.4	38.7
SQ(2)	1000	35.8	9.9	0.3	35.2	36.5
JCEC(3)	1000	42.3	11.9	0.4	41.6	43.1
SQ(4)	1000	35.8	10.3	0.3	35.2	36.4
JCEC (5)	1000	42.1	11.2	0.4	41.4	42.8

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The focal point of this research is evaluating the implementation of a shorter C2 cycle between the lethal triad to speed the kill chain. The Joint Fires team modeled the Table 1 improvements for shortening the JF kill chain's JCEC C2 responsiveness, via the simulation input timing in Table 7 with additional improvements in human decision-making timing further explored as excursions using training and automation as described in Table 11. The simulation results and analysis conclude that the proposed improvements to the JCEC C2 cycle, increase the BF kill chain effectiveness.

The simulation results and analysis for the BF Mean % Survivability are shown in Table 18 with explanations of the SQ0, JCEC1, SQ2, JCEC3, SQ4 and JCEC5 in Table 12.

Table 18. BF Mean % Survivability Analysis Summary

Without Excursion Timing	With Excursion Timing
5.9% increase in BF Survivability when comparing SQ0 to JCEC 1	6.4% increase in BF survivability when comparing SQ0 to JCEC5
12.6% decrease in BF loses when comparing SQ0 to JCEC 1	2.4% increase in BF survivability when comparing JCEC5 to JCEC1
	2% increase in BF survivability when comparing SQ4 to SQ0

The simulation results and analysis for the additional BF AMD munitions are shown in Table 19 with explanations of the SQ0, JCEC1, SQ2, JCEC3, SQ4 and JCEC5 in Table 12.

Table 19. Additional BF AMD Munitions Available and Spent Summary

Without Excursion Timing	With Excursion Timing
6 additional BF munitions available when comparing SQ0 to JCEC1	6 additional BF munitions available when comparing JCEC 5 to JCEC 1
	12 additional BF munitions available when comparing JCEC 5 to SQ0.

The simulation results and analysis for the additional RF munitions neutralized are shown in Table 20 with explanations of the SQ0, JCEC1, SQ2, JCEC3, SQ4 and JCEC5 in Table 12.

Table 20. Additional RF Munitions Neutralized Summary

Without Excursion Timing	With Excursion Timing
4.6 additional RF munitions destroyed when comparing SQ0 to JCEC1	4 additional RF munitions destroyed when comparing JCEC 5 to JCEC 1
	8.7 additional RF munitions destroyed when comparing JCEC 5 to SQ0.

From the analysis it is evident that JCEC C2 improvements, which allow for the acceleration of the kill chain, act as a form of BF multiplier because they allow for additional BF munitions to be available for fire and cause additional RF munitions to be destroyed. The simulated data collection suggests that training individual decision-makers to achieve shorter C2 cycle times does improve JF kill chain responsiveness. However, the data shows that human decision-makers introduce significant delays into the command and control system that could hinder the ability of the JF to promptly react and defend their platforms in future conflicts, particularly against the predicted speeds of hyper velocity projectiles (HVP). Therefore, automating human decision making is recommended and supported by the analysis in Tables 18–20.

B. RECOMMENDATIONS

The JF Team recommends pursuing the proposed improvements from Table 1 for shortening the JF kill chain's C2 responsiveness which include improving interoperability among the lethal triad, adding automation to the human decision-making process, incorporating MADL-like communication, and creating a distributed, ad-hoc mesh network by integrating the improvements on all JF platforms by 2030. Of utmost importance are the effects that shortening the C2 cycle should have on the kill chain and the outcome of a battle. The kill chain benefits should include faster, less jammable communication between the lethal triad; more responsive, reliable decision making in a highly contested environment; and improved matching of weapon systems to threats which should culminate in a more appropriate and effective ad hoc, self-forming AFP.

Human decision making is the bottleneck of the JCEC C2 and implementation of artificial intelligence and machine learning algorithms which can aide and expedite the human decision-making process should be explored. The JF team further recommends that the joint forces carefully consider using mission engineering principles to better plan forward deployed force munitions loadouts for conflicts and engagements with a near peer adversary which has access to a shortened supply chain.

C. FURTHER RESEARCH

The JF team believes that more research is needed for the development and integration of JCEC. There is also further research needed in ad-hoc networks and connectivity of the joint forces. There is an urgent need for more research in artificial intelligence, machine learning algorithms and their integration into the command and control systems. Research and development are needed to explore Adaptive Force Package configurations that include joint forces capable of extending the tactical span of control and effective mission range of the Carrier Strike Group.

Further classified research should be conducted for a comparison effort of the MIDS JTRS, Link 16 versus MADL-like communications and the use of MADL for the creation of a JF common situational awareness. MADL-like communication may require

the upgrade of outdated mission processors and displays to handle the increases in information which MADL can provide. If cost is the prohibitive factor, then more platforms should be considered for implementation as Battlefield Airborne Command Nodes (BACN) (Burns, Kevin R. and Smith, Keith. 2016). There are opinions that satellites can be used to create communication links, determine adversary locations, and create a common situational awareness for JF, but what is the contingency plan if those satellites are jammed or destroyed as was the case when the South Koreans complained to the United Nations that North Korea was jamming its Global Positioning System (GPS) satellites as early as 2016 (Nichols 2016). Furthermore, evidence exists of peer adversary testing of a new anti-satellite weapon and of disruption of military and commercial navigation (Coggins 2020). However, the U.S. Space Force is working on mitigation of space satellite threats with the successful testing of the “Mitigation and Anti-Jam Enhancement” (MAJE) program (Strout 2020). Also the work being done by the Space Development Agency concerning the “Joint All-Domain Command and Control” (JADC2) mesh network will further strengthen our confidence in space satellite use (Strout 2020a). However, its incorporation of Link 16 versus MADL-like communications is an area worthy of further research.

Research efforts concerning the speed of command, control, and communications needed for weapons engagement against adversarial hyper velocity projectiles is also another area of future concern. In a 2018 article written by Sydney Freedberg, the Pentagon’s Strategic Capabilities Office was approaching the testing of a newly developed, ballistic, HVP which could travel at 5600 miles per hour, or Mach 7.6 (Freedberg 2018). In a joint fires scenario, if a non MIDS, JTRS, version of Link 16 messaging is implemented with the slowest frame rates between messages, and if command and control cycles are on the order of minutes, speed could become a limiting factor in the effectiveness of defending against such weapons.

LIST OF REFERENCES

- Bach, Peter A., Shawn Brier, and Lauren E. McNeil. 2019. "Systems Engineering Approach to Determining the Suitability of Wireless Mesh Networks for Joint-Fires in Distributed Maritime Operations." Master's thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/63484>.
- Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*, 5th ed. Upper Saddle River: Prentice-Hall.
- Burns, Kevin R and Smith, Keith. 2016. "Battlefield Airborne Communications Node (BACN), Realizing the Vision of the Aerial Layered Network (ALN)." American Institute of Aeronautics and Astronautics, Inc, <https://arc.aiaa.org/doi/pdf/10.2514/6.2016-0574>.
- Calfee and Rowe 2004. "Multi-Agent Simulation of Human Behavior in Naval Air Defense." Journal Article, Navy Engineers' Journal. Pages 53–64.
- Coggins, Kevin. 2020. "Deploying a Backup to GPS will protect the U.S. and Spur Innovation." 19 August 2020. <https://www.c4isrnet.com/opinion/2020/08/19/deploying-a-backup-to-gps-will-protect-the-us-and-spur-innovation/>.
- Colby, Elbridge A., 2019. "Testimony Before the Senate Armed Services Committee Hearing on Implementation of the National Defense Strategy." January 29, 2019. https://www.armed-services.senate.gov/imo/media/doc/Colby_01-29-19.pdf.
- Corbett, Logan, Michael Enloe, William Jankowski, Erik Kelly, Gerald Kummer, Keren Kummer, Sarah Smith, and Scott Watson. 2017. "Command and Control for Distributed Lethality." Master's thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/55534>.
- Department of the Army (DOA). 2000. Introduction to Tactical Digital Information Link J and Quick Reference Guide. NWP 6-02.5, Washington, DC: DOA. <https://www.globalsecurity.org/military/library/policy/army/fm/6-24-8/index.html>.
- . 2019a. Electronic Warfare Techniques. ATP 3-12.3. Washington, DC: DOA. https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/ARN18105_ATP%203-12x3%20FINAL%20WEB.pdf.
- . 2019b. *Multi-Functional Information Distribution System (MIDS) Joint Tactical Radio System*. Washington, DC: Operational Test and Evaluation.

- Department of Defense (DOD). 2018. Summary of the National Defense Strategy of the United States of America. DOD. Washington, DC: DOD.
<https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf>.
- Department of Defense Operational Test and Evaluation Directorate. 2012 Report on DOD Operational Testing “Multi-Functional Information Distribution System (MIDS) Joint Tactical Radio System (JTRS).” DOD. Washington, DC: DOTE
<https://www.dote.osd.mil/Portals/97/pub/reports/FY2012/dod/2012mids.pdf?ver=2019-08-22-111645-127>.
- Department of Navy. 2005. *C4I Infrastructure*. NTTP 6–02. Washington, DC: DON. January 2005. <https://docplayer.net/30152726-C4i-infrastructure-nttp-6-02.html>.
- . 2013a. *Maritime Operations Center*. NTTP 3–32.1. Washington, DC: DON. April 2013. [https://www.navybmr.com/study%20material/NTTP_3-32-1_MOC_\(Apr_2013\).pdf](https://www.navybmr.com/study%20material/NTTP_3-32-1_MOC_(Apr_2013).pdf).
- . 2013b. *Multi-Service Tactics, Techniques, and Procedures for Tactical Radios*. NTTP 6–02.72. Washington, DC: DON <https://www.marines.mil/portals/1/MCRP%203-40.3A%20z.pdf>.
- . 2015. *A Cooperative Strategy for 21st Century Sea power*. DON Instruction. Washington, DC: DON. <https://www.navy.mil/local/maritime/150227-CS21R-Final.pdf>.
- . 2019. *Resources and Requirements Review Board and Naval Capabilities Board*. OPNAV Instruction 5420.117. Washington, DC: DON.
<https://www.secnav.navy.mil/doni/Directives/05000%20General%20Management%20Security%20and%20Safety%20Services/05-400%20Organization%20and%20Functional%20Support%20Services/5420.117.pdf>.
- Freedberg, Sydney J. 2018. “\$86,000 + 5600 MPH= Hyper Velocity Missile Defense.” <https://breakingdefense.com/2018/01/86000-5600-mph-hyper-velocity-missile-defense/>.
- Geiss, Elizabeth A. 2019. “Analysis of Unmanned Surface Vessel Employment in Distributed Maritime Operations.” Master’s thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/64162>.

- Headquarters, United States Marine Corps. 1997. *Warfighting*. MCDP-1. Washington, DC: Department of the Navy. <https://www.marines.mil/Portals/1/Publications/MCDP%201%20Warfighting.pdf>.
- Hitchens, Theresa. 2019. "Exclusive Navy, Air Force Chiefs Agree to Work on all Domain C2." *Breaking Defense*, November 12, 2019. <https://breakingdefense.com/2019/11/exclusive-navy-air-force-chiefs-agree-to-work-on-all-domain-c2/>.
- Hura, Myron, Gary W. McLeod, Eric V. Larson, James Schneider, Daniel Gonzales, Daniel M. Norton, Jody Jacobs et al. 2000. *Interoperability: A Continuing Challenge in Coalition Air Operations, CH 9 Tactical Data Links*. RAND, pg. 108. https://www.rand.org/pubs/monograph_reports/MR1235.html.
- Johnson, Bonnie W. 2019. "A Framework for Engineered Complex Adaptive Systems of Systems." Master's thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/63463>.
- Johnson, Richard C. 1993. *Antenna Engineering Handbook, Third Edition*. Georgia Institute of Technology, 1993 http://seklad69associates.com/seklad69associates.com/EEG_808_and_815_files/Antenna%20Engineering%20Handbook.pdf.
- Joint Chiefs of Staff. 2013. *Joint Targeting*. JP 3-60. Washington, DC: Joint Chiefs of Staff. https://www.justsecurity.org/wp-content/uploads/2015/06/Joint_Chiefs-Joint_Targeting_20130131.pdf.
- . 2016. *Department of Defense Dictionary of Military and Associated Terms*. JP 1-02. Washington, DC: Joint Chiefs of Staff. https://fas.org/irp/doddir/dod/jp1_02.pdf.
- . 2017. *Doctrine for the Armed Forces of the United States*. JP 1. Washington, DC: Joint Chiefs of Staff. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp1_ch1.pdf.
- . 2018. *Joint Maritime Operations*. JP 3-32. Washington, DC: Joint Chiefs of Staff. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_32.pdf?ver=201903-14-144800-240.
- . 2019. *Joint Fire Support*. JP 3-09. Washington, DC: Joint Chiefs of Staff. https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_09.pdf.

- Lockheed Martin Newsroom. 2016. "F-35 And Aegis Combat System Successfully Demonstrate Integration Potential in First Live Missile Test" Published 13 September 2016. <https://news.lockheedmartin.com/2016-09-13-F-35-and-Aegis-Combat-System-Successfully-Demonstrate-Integration-Potential-in-First-Live-Missile-Test>.
- Marine Corps Doctrinal Publication. 1997. *Warfighting*. MCDP-1. Washington, DC: USMC. <https://www.marines.mil/Portals/1/Publications/MCDP%201%20Warfighting.pdf>.
- Moon IC., Carley K.M., Kim T.G. 2013. "Modeling and Simulating Command and Control for Naval Air Defense Operation." In: *Modeling and Simulating Command and Control*. Springer Briefs in Computer Science. Springer, London. https://doi.org/10.1007/978-1-4471-5037-4_3.
- Navy Warfare Development Command. 2011. *Navy Fire Support*. NWP 3-09. Washington, DC: Department of the Navy. October 2011. https://nps01.sharepoint.com/sites/tpo2020/axel.rodriagueznegron/My%20Files/Capstone/Reference%20Material/Navy%20Warfare%20Doctrine/NWP_3-09%20Navy%20Fire%20Support.pdf.
- . 2015a. *Composite Warfare: Maritime Operations and the Tactical Level of War*. NWP 3-56. Washington, DC: Department of the Navy. December 2015. https://nps01.sharepoint.com/sites/tpo2020/axel.rodriagueznegron/My%20Files/Capstone/Reference%20Material/Navy%20Warfare%20Doctrine/NWP_3-56%20Composite%20Warfare%20-%20Maritime%20Operations%20at%20the%20Tactical%20Level%20of%20War.pdf.
- . 2015b. *Navy Expeditionary Combat Command Forces, Chapter 5. Adaptive Force Packaging and the Navy Expeditionary Combat Force*. NWP 3-10. Washington, DC: Department of the Navy. September 2015. https://nps01.sharepoint.com/sites/tpo2020/axel.rodriagueznegron/My%20Files/Capstone/Reference%20Material/Navy%20Warfare%20Doctrine/NWP_3-10%20Navy%20Expeditionary%20Combat%20Command%20Forces.pdf.
- Nichols, Michelle. 2016. "South Korea tells UN that North Korea GPS jamming threatens boats, planes." <https://www.reuters.com/article/us-northkorea-southkorea-gps/south-korea-tells-u-n-that-north-korea-gps-jamming-threatens-boats-planes-idUSKCN0X81SN>.
- Ong, Chin. 2004. "Digital Phased Array Architectures for Radar and Communications Based on Off-the-Shelf Wireless Technologies" Master's thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/1245>.

- Popa, Christopher H., Sydney P. Stone, Ee Hong Aw, Choon Pei Jeremy Teo, Licun Edwin Cai, Wai Hoe Chong, Rachel Cline, Jiesheng Jackson Hong et. al. 2018. "Distributed Maritime Operations and Unmanned Systems Tactical Employment." Master's thesis, Naval Postgraduate School. <http://hdl.handle.net/10945/59587>.
- Richardson, J. M. 2018. "A Design for Maintaining Maritime Superiority." Official memorandum. Washington, DC: DON. https://www.navy.mil/navydata/people/cno/Richardson/Resource/Design_2.0.pdf.
- Russo, Joe. 2017. "A lethal combination F-35 Joint Strike Fighter and M142 HIMARS sensor-to-shooter integration." *Army Fires Bulletin*, November-December 2017.
- Schweizer, Andreas. 2017. "On Developing a Wideband BLE Sniffer." Classy code (blog), June 5, 2017 <https://blog.classycode.com/on-developing-a-wideband-ble-sniffer-part-1-5db2a6a0193e>.
- Strout, Nathan. 2020. "U.S. Space Force Tests New Anti-Jamming Capability." 26 August 2020. https://www.c4isrnet.com/battlefield-tech/c2-comms/2020/08/26/space-force-tests-new-anti-jamming-capability/?utm_source=clavis.
- . 2020a. "Space Development Agency orders its first satellites." 31 August 2020. <https://www.c4isrnet.com/battlefield-tech/space/2020/08/31/space-development-agency-orders-its-first-satellites/>.
- USNI NEWS. 2016. "Successful F-35, SM-6 Live Fire Test Points to Expansion in Networked Naval Warfare." Video, September 13, 2016. <https://news.usni.org/2016/09/13/video-successful-f-35-sm-6-live-fire-test-points-expansion-networked-naval-warfare>.

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