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INCORPORATING RADIO FREQUENCY MESH NETWORKS TO LINK LIVE, VIRTUAL, CONSTRUCTIVE TRAINING

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THESIS

INCORPORATING RADIO FREQUENCY MESH NETWORKS TO LINK LIVE, VIRTUAL, CONSTRUCTIVE TRAINING

by

Lauren J. McCann

June 2020

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Given the importance of modeling and simulation (M&S) for creating realistic training environments and employing or developing tactical systems for warfighters, the Department of Defense is turning toward live, virtual, constructive (LVC) simulations as a means to prepare and equip our military for the next war. M&S offers a unique competency for modeling emergent enemy behaviors in constructive simulations on virtual battlefields across the globe. Transferring these dynamic tactical actions to live command and control (C2) systems used during training can create decision-making opportunities for distributed units to react to and act upon. The research conducted in this thesis assessed, developed, and implemented an appropriate LVC environment that can be used in training for tactical convoy operations in the Marine Corps. We developed a robust mesh network connected to a personal computer running a constructive simulation to create dynamic tracks on handheld, Android-based C2 systems. Using low-bandwidth radios to create the network, we were able to create a rich, tactically realistic training environment while minimally increasing the combat load of our Marines. The system we created has the same functionality of the blue force tracker (BFT). Because the BFT is no longer funded, we recommend the LVC solution we created for this thesis as a potential replacement with embedded training capabilities.

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INCORPORATING RADIO FREQUENCY MESH NETWORKS TO LINK LIVE, VIRTUAL, CONSTRUCTIVE TRAINING

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ABSTRACT

Given the importance of modeling and simulation (M&S) for creating realistic training environments and employing or developing tactical systems for warfighters, the Department of Defense is turning toward live, virtual, constructive (LVC) simulations as a means to prepare and equip our military for the next war. M&S offers a unique competency for modeling emergent enemy behaviors in constructive simulations on virtual battlefields across the globe. Transferring these dynamic tactical actions to live command and control (C2) systems used during training can create decision-making opportunities for distributed units to react to and act upon. The research conducted in this thesis assessed, developed, and implemented an appropriate LVC environment that can be used in training for tactical convoy operations in the Marine Corps. We developed a robust mesh network connected to a personal computer running a constructive simulation to create dynamic tracks on handheld, Android-based C2 systems. Using low-bandwidth radios to create the network, we were able to create a rich, tactically realistic training environment while minimally increasing the combat load of our Marines. The system we created has the same functionality of the blue force tracker (BFT). Because the BFT is no longer funded, we recommend the LVC solution we created for this thesis as a potential replacement with embedded training capabilities.

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LIST OF ACRONYMS AND ABBREVIATIONS

5G-ATW	Fifth Generation – Advanced Tactical Waveform
AAR	After Action Report
AFB	Air Force Base
AFRL	Air Force Research Lab
AMIE	Architecture Management Integration Environment
AO	Area of Operations
AOR	Area of Responsibility
ATAK	Android Tactical Assault Kit
BFT	Blue Force Tracker
C2	Command and Control
C2PC	Command and Control Personal Computer
CBP	Customs and Border Patrol
CC	Convoy Commander
CCS	Combat Convoy Simulator
CLB	Combat Logistics Battalion
CNA	Computer Network Attack
COA	Course of Action
COC	Combat Operations Center
COP	Common Operational Picture
CoT	Cursor – on – Target
DAGR	Defense Advanced Global Positioning System Receiver
DES	Discrete Event Simulation
DIS	Distributed Interactive Simulation
DHS	Department of Homeland Security
DOD	Department of Defense
DU	Display Unit
ESPDU	Entity State Protocol Data Unit
EUD	End User Device
EWTGPAC	Expeditionary Warfare Training Group Pacific
FOM	Federation Object Model

GUI	Graphical User Interface
HHQ	Higher Headquarters
HIMARS	High Mobility Artillery Rocket System
HITL	Human in the loop
HLA	High Level Architecture
HMMWV	High Mobility Multipurpose Wheeled Vehicle
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineers
JBC - P	Joint Battle Command – Platform
JCATS	Joint Conflict Tactical Simulation
JDLM	Joint Deployment Logistics Model
JLTV	Joint Light Tactical Vehicle
JTAC	Joint Tactical Air Controller
KU	Keyboard Unit
LOC	Logistics Officer Course
LOS	Line of Sight
LVC	Live, Virtual, Constructive
LVC-IA	Live, Virtual, Constructive – Integration Architecture
LVC-TE	Live, Virtual, Constructive – Training Environment
MACE	Modern Air Combat Environment
MAGTF	Marine Air Ground Task Force
MCC	Movement Control Center
MCWL	Marine Corps Warfighting Lab
MEF	Marine Expeditionary Force
MFOC	Mounted Family of Computer Systems
MOS	Military Occupational Specialty
M&S	Modeling and Simulation
MTVR	Medium Tactical Vehicle Replacement
MTWS	MAGTF Tactical Warfare Simulation
NGTS	Next Generation Threat System
NPS	Naval Postgraduate School
OneSAF	One Semi-Autonomous Forces

PDU	Protocol Data Unit
PLI	Position Location Information
PU	Processing Unit
RF	Radio Frequency
RTI	Runtime Infrastructure
SA	Situational Awareness
SDK	Software Development Kit
SDR	Software Defined Radio
SIMNET	Simulator Networking
SISO	Simulation Interoperability Standards Organization
SLATE	Secure LVC Advanced Training Environment
SOP	Standard Operating Procedure
TENA	Testing and Training Enabling Architecture
TSOA	Tactical Services Oriented Architecture
TTP	Tactics, Techniques, and Procedures
T&R	Training and Readiness
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
USMC	United States Marine Corps
VBS2	Virtual Battlespace 2
VR	Virtual Reality
VRSG	Virtual Reality Scene Generator
XML	Extensible Markup Language

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I. INTRODUCTION

On July 16, 2007, a congressional resolution recognized modeling and simulation (M&S) as a national critical technology. "Historically, a National Critical Technology is one that has particular value to the national security of the United States and/or significant impact on the country" (Tolk & Oren, 2017, p. 356). Given the importance of M&S in determining our path forward in this time of geopolitical uncertainty, the Department of Defense (DOD) is turning toward live, virtual, constructive (LVC) simulations as a means to train and equip our forces for the next war. Little is known about what that will be, but our nation cannot stand by and wait, or it will be too late, therefore, LVC training environments will be able to quickly adapt to multiple environments.

M&S offers a unique competency in modeling emergent enemy behaviors on virtual battlefields across the globe. Transferring these dynamic tactical actions to command and control (C2) systems used during live training can create decision-making opportunities for our distributed units to react to and act upon. Integration of simulation data into C2 systems during training is supposed to be a hallmark of LVC environments which requires interoperable systems and simulations. Wide-scale implementation has not been realized because it is difficult and costly, however, cost savings will occur in the long run. Under the current fiscal constraints, the DOD must implement and design training exercises using the existing tactical systems and architectures already in place to create the live, virtual, constructive – training environment (LVC–TE) so our warfighters can prepare for the next global conflict, wherever it may be.

A. CURRENT STATE OF THE ART IN LVC TRAINING WITHIN THE DOD

In early January 2019, Air Force and Navy officials declared "success for a joint technology demonstration that tied jet fighters in the air with pilots operating simulators on the ground, who could all fly against computer-generated adversaries" (Magnuson, 2019, para 1). The program, called SLATE, or Secure LVC Advanced Training Environment, was led by Dr. Wink Bennett with the Air Force's 711th Human Performance Wing of the Airman Systems Directorate, Warfighter Readiness Research Division at

Wright Patterson Air Force Base. Tested in December 2018 at Nellis Air Force Base (AFB), SLATE included a Fifth Generation Advanced Tactical Waveform (5G-ATW) developed at Massachusetts Institute of Technology Lincoln Labs. In addition, the operators also used Link-16 and ultra-high frequency/very high frequency voice communications. The 5G-ATW was used to pass simulation data to live aircraft "untethered," meaning no direct physical connection was needed, during the exercise. The data transmitted to the live aircraft was done so via compressed protocol created by constructive simulations on the ground. For aircraft to receive this data, all were required to deploy a tactical communications pod shown in Figure 1.

Figure 1. USAF F-16 with the SLATE 5G -ATW pod deployed at Nellis AFB, NV. Source: Magnuson (2019).

During the demonstration, "pilots could actually fly to the edge of the training range and 'see' computer-generated aircraft far beyond the base's boundaries, thus expanding the range virtually" (Magnuson, 2019, para 13). This is a key benefit of LVC simulations and a concept that SLATE was able to exhibit, opening the door to any number of relevant tactical scenarios to enhance training. With unlimited possibilities in this emerging domain, it will be critical for the services to understand the military skill sets that require training. In typical DOD fashion though, SLATE was targeting the training requirements for the aviation community only. However, there are a broad range of military specialties that could benefit from the dynamic environments made possible through simulation interoperability. This thesis will specifically investigate the use case of motor transportation operations and the duties and responsibilities of a Convoy Commander (CC) in order to expand the LVC environment training capability. Appendix A contains the United States Marine Corps (USMC) Convoy Commander Checklist, which is a detailed list of tasks he or she must complete to ensure successful mission execution.

B. VISION FOR LVC TRAINING IN THE MARINE CORPS

The USMC published their Science and Technology Strategic Plan in 2018 in which the benefits and future concepts for LVC integrated training are outlined. It states "the Live Virtual Constructive-Training Environment (LVC-TE) will provide the means to conduct realistic, collaborative training and exercise of warfighting functions across the full range of military operations" (USMC, 2018b). As expected, system interoperability between many C2 and simulation systems will be critical. Across the services and within various units, different computer-based systems are used to provide an exercise common operational picture (COP) during live operations and in training. Inputs for these systems come in the form of data from sensor systems and surveillance reports from tactical units. Normally, sensor data populates into a C2 system real-time, whereas surveillance reports are manually entered via a graphical user interface (GUI). Integration of simulation data differs slightly in that it can be processed real-time for display on C2 systems or manually entered based on the outcomes displayed visually in a constructive simulation. These actions and processes form the construct of LVC training. Although the process seems simple, we have yet to adopt a service-wide approach to training our forces using this technology. To offer a potential methodology, we will create a feasible LVC-TE with the programmed systems and architectures that currently connect our forces today.

C. LIVE VIRTUAL CONSTRUCTIVE SIMULATIONS DEFINED

"The Marine Corps is investing in a suite of virtual and constructive training systems, augmented reality googles, and other emerging technologies to give Marines more repetitions, and in some cases, more authentic experiences during training" (Eckstein, 2018, para 1). To create this authenticity, virtual and constructive simulations stimulate C2 systems used in live training environments to create decision-making opportunities for staffs and unit commanders. These decisions start the formation of tactical plans to employ real units and systems on live training ranges. Adding realism to these training events is a top priority for the Marine Corps as they want "to allow for cross-community training events—fire support teams talking to artillery units, forward air controllers talking to pilots, ground combat units talking to logistics teams that support them, and so on" (Eckstein, 2018, para 2). To best understand this domain, we must first define live, virtual, and constructive simulations.

- **Live simulations** involve "real people operating real systems. Military training events using real equipment are live simulations. They are considered simulations because they are not conducted against a live enemy" (DOD, 2011a, p. 119).

- **Virtual simulations** involve "real people operating simulated systems. Virtual simulations inject human-in-the-loop in a central role by exercising motor control skills (i.e., flying an airplane), decision skills (i.e., committing fire control resources to action), or communication skills (i.e., as members of a C4I team)" (DOD, 2011a, p. 159).

- **Constructive simulations** include "simulated people operating simulated systems. Real people stimulate (make inputs) to such simulations but are not involved in determining the outcomes. A constructive simulation is a computer program. For example, a military user may input data instructing a unit to move and to engage an enemy target. The constructive simulation determines the speed of movement, the effect of the engagement with the enemy and any battle damage that may occur" (DOD, 2011a, p. 85).

As singular entities, these simulations are effective in achieving the intended outcome for testing, training, analysis, or assessment, but our leadership, as outlined in the 38th Commandants Planning Guidance (USMC, 2018a), has a greater vision. Interoperable simulations will create an end-to-end training solution. The tools are available, but they have not been aligned and synchronized in the proper way. To enable connectivity between simulations and C2 systems there are some baseline protocols and architecture that need to be described first. Some of these will be used in this thesis to create the LVC architecture we propose.

1. Simulation Interoperability and the Supporting Protocols and Architectures

The foundation for the LVC-TE are the simulation interoperability standards which have been in use for decades. In 1983, the Defense Advanced Research Projects Agency initiated the concept of simulation interoperability through the Simulator Networking (SIMNET) program (Cosby, 1995). "SIMNET objectives were to bring armor, mechanized infantry, helicopters, artillery, communications, and logistics components together into a common, situated virtual battlefield" (Tolk, 2018, sec. 2.1, para. 1). The vision for SIMNET was to have crews "observe each other, communicate via radio channels, and observe each other's effects" (Tolk, 2018, sec. 2.1, para. 1). The early successes of SIMNET were noticed by the DOD and Industry and it led to the development of the Distributive Interactive Simulation (DIS) Protocol, which is still in use today and was the primary simulation protocol used for this work.

a. Distributive Interactive Simulation

To ensure standardization across disparate simulations, DIS was developed to be "easy to understand, easy to implement, and open for future developments" (Tolk, 2018, sec. 2.1, para. 2). Managed and modified through the Simulation Interoperability Standards Organization (SISO) formed in 1989, the Institute of Electrical and Electronics Engineers (IEEE) standard 1278 was created based on Protocol Data Units (PDUs) that capture and share data between autonomous simulation systems. In the current DIS version 7, there are 72 different PDU types organized into 13 different families: Entity Information/Interaction, Warfare, Logistics, Simulation Management, Distributed Emission Regeneration, Radio Communications, Entity Management, Minefield, Synthetic Environment, Simulation Management with Reliability, Live Entity, Non-Real Time and Information Operations (IEEE, 2012).

This diverse set of PDUs enables simulators to operate on their own; however, there are many requirements to consider when working with interoperable simulations. Some that were overlooked in the development of DIS are described in the next paragraph.

Many simulations use their own "visual representation of their perception and compute their own effects" (Tolk, 2018, sec. 2.1, para 3). During development of DIS, it was assumed that each simulation would share a common understanding of terrain and other features, but this concept was not enforced leading to the 'unfair fight' problem and "the systematic advancements of one sim over another" (Tolk, 2018, sec. 2.1, para. 3). DIS tried to ensure "unambiguous situations by clearly distributing responsibilities for the distribution of computational effects" (Tolk, 2018, sec. 2.1, para. 4). For example, if an effect occurs between two simulations, "the initiating simulation is responsible to calculate the location of the effect, and the receiving simulation computes the effect" (Tolk, 2018, sec. 2.1, para. 4). Unfortunately, it was found to be very difficult to consistently represent effects on simulators and rules could not be enforced. SISO had to resort to outside the core standard solutions. This issue remains today but DIS is still widely used as it is an extremely effective data transfer standard.

b. High-Level Architecture

To address the limitations of DIS, the DOD established the Architecture Management Group in 1995 to develop High Level Architecture (HLA). The first version released was HLA 1.3 and it was intended to be a general-purpose simulation interoperability standard. Over time lessons were learned and the architecture was improved to the IEEE 1516–2000 HLA and later the IEEE 1516–2010 HLA.

The architecture was essentially

> a set of 10 rules governing interplay composition of participating simulation systems, the so-called federation, and each individual simulation system,

> the so-called federates. These rules define how to exchange information, who is responsible for the object and interactions invoking the information exchange, and other high-level rules. A second part of the standard defines the details of the interface between the so-called Runtime Infrastructure (RTI) and federates. (Tolk 2018, sec. 2.2, para. 4)

The RTI provides services supporting the federation to include "management of the federation, declaration, object, ownership, time, and data distribution" (Tolk, 2018, p. 682).

IEEE 1516 also defines an Object Model Template, which "provides a means to define persistent objects with their attributes as well as transient interactions with their parameters" (Tolk, 2018, sec. 2.2, para. 6). "The Object Model Template provides a set of tables that allow to unambiguously define all the data necessary for the definition of data types, transportation constraints, and even a lexicon for all terms utilized" (Lutz et al., 1998, p. 404).

> The standard differentiates between the definition of the information exchange that can be supported by a single federate (the simulation object model), support of the information exchange within the composition (the federation object model (FOM)), and the standardized management object model that provides information objects needed for all the services provided by the RTI. (Tolk, 2018, sec. 2.2, para. 6)

Given the popularity of IEEE 1278, the simulation community created a common representation of DIS PDUs in the HLA format called the Realtime Platform Reference Federation Object Model. The Realtime Platform Reference Federation Object Model was "used as a foundation for many follow-on activities, as it combined the flexibility of HLA with the well-known information exchange objects of DIS" (Moller et al. 2014, para. 1).

2. C2 System Interoperability and the Supporting Schemas and Architectures

For data transfer between a simulation and C2 system, a data gateway translator is required, and these normally come embedded within specific constructive simulations. For example, the Marine Corps Air Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS) has a data translation application that converts DIS version 7 to the specific data format required to display tracks on the Command and Control Personal Computer (C2PC). On a larger scale, the Marine Corps currently uses the Tactical Services Oriented

Architecture (TSOA) to bridge to C2PC and other C2 systems including the Global Command and Control System – Joint. To pass data, it employs a service-oriented infrastructure schema that enables data transfer to and from the TSOA servers. This framework will enable a collapse of the current disparate information technology construct and create a Net-centric environment where authorized personnel employ user-centered applications that access required information from the TSOA, an overview is displayed in Figure 2 (Marine Corps Systems Command, 2018).

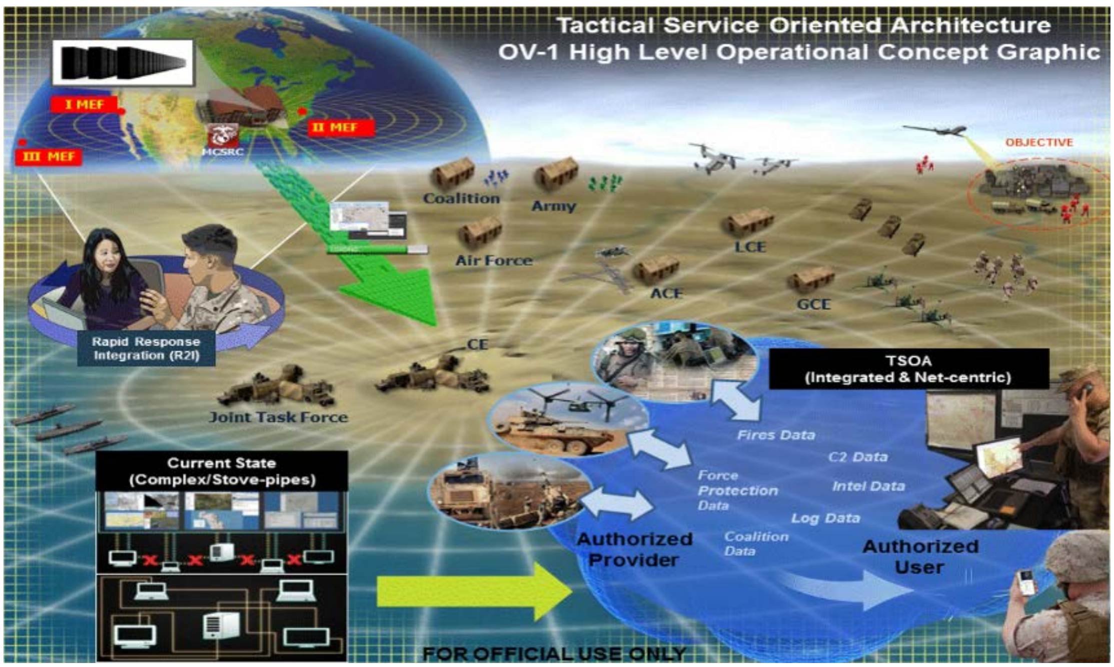

Figure 2. Operational overview of the TSOA. Source: Marine Corps System Command (2018).

In the M&S domain across the services, other integration architectures exist to enable the flow of simulation data to and from C2 systems and between various simulations. One example is the U.S. Army's LVC-Integration Architecture (LVC-IA). Although the Army is planning to replace this architecture with the Synthetic Training Environment, the Marine Corps has adopted the LVC-IA for use within the LVC-TE. Like the TSOA, the LVC-IA uses applications to serve as data gateway translators to process the data. In the LVC-IA, the Joint Simulation Bus performs that function. Given that the

LVC-IA and TSOA perform similar functions, it could be conceivable that tactical networks could host the LVC-TE for specific training events.

D. LVC EVENT DESIGN: TOP-DOWN APPROACH

The Marine Corps Training and Education Command has adopted a top-level interoperability approach when it comes to the design of LVC training events. Although difficult to execute, it considers all aspects of training to include requirements, objectives, and overall effectiveness. Figure 3 shows the process broken down into three distinct phases resulting in the implementation of a specific training event. In this thesis we will use this process to assess the applicability of low bandwidth radio frequency (RF) radios to train for convoy operations in a LVC environment. Figure 3 outlines our approach and this section describes a plan for each chapter as we perform this assessment of mesh networks and their integration into the LVC-TE.

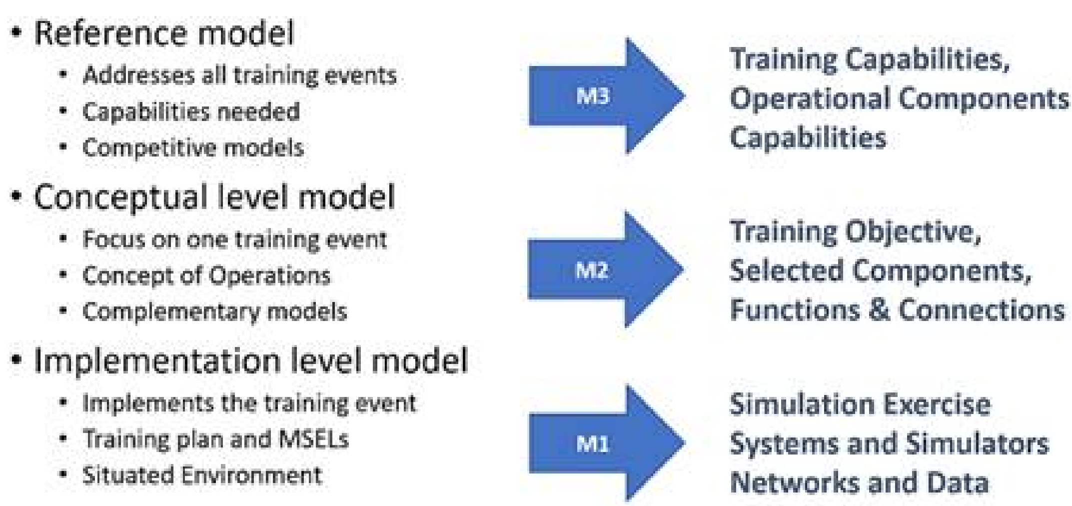

Figure 3. Top-level interoperability LVC event design. Source: A. Tolk (personal communication, Apr. 22, 2020).

1. Reference Model

In Chapter II, we will begin by defining a reference model. In this context, "our reference model will describe all training capabilities needed in the form of operational view like artifacts" (A. Tolk, personal communication, April 22, 2020). The training capabilities will include all options possible to support convoy testing, training, analysis, etc. The capabilities we describe will be all inclusive meaning we will account for all simulation and non-simulation training tools available for Logistics units in the Marine Corps. We anticipate "there will be some overlap in the capabilities, but this will only serve to benefit us during exercise design as the systems can be competitive and provide alternative viewpoints" (A. Tolk, personal communication, April 22, 2020). Overall, the reference model we will present is a collection of the knowledge about the training domain.

2. Conceptual-Level Model

In Chapter III, we will focus on "a concrete training event where the training objectives are used to tailor the reference architecture to a required and consistent set of components that are conceptually aligned with the training objective, and that are technically interoperable" (A. Tolk, personal communication, April 22, 2020). The resulting artifact is a conceptual model. While "the reference model is complete, but likely inconsistent, the conceptual model must be consistent to be executable by computer simulations, but is incomplete" (A. Tolk, personal communication, April 22, 2020). However, it is complete regarding the mission that fulfils the training objective.

To apply an operational context to this research, we will investigate the execution of motor transportation operations and specifically focus on the duties and responsibilities of the CC. Considering the CC checklist contained in Appendix A, we will look at each task and determine what components from the conceptual model could help meet the particular training objectives we identify.

At present, DOD units use the Blue Force Tracker (BFT) to track and command vehicles and embarked forces during tactical motorized movements. This system allows for the display of known friendly and enemy units on a detailed geospatial display. For mission communication, it allows for text messages to be sent between vehicles and a

Combat Operations Center (COC). In addition, it allows units and users to share points of interest specific to the tactical operation. Given these capabilities, we are seeking to identify an interoperable system under test that is capable of simulating a dynamic red force to stimulate C2 systems and training during a LVC convoy training event. The system under test we have identified is a low bandwidth RF mesh network with connected Android Tactical Assault Kits (ATAKs) with the display shown in Figure 4.

Figure 4. ATAK showing an overhead geospatial display. Source: Release APK (2020)

3. Implementation-Level Model

In Chapter IV, we will specifically investigate the mission engineering of the interoperable system we seek to create. The system will fulfill a capability gap in LVC training incorporating communication abilities to the lowest levels, in this instance a convoy. The system will also connect the lowest level to adjacent units, i.e., supporting units.

In this case, the conceptual model can be instantiated by selecting the best components, information exchange protocols, and networks. After conducting a thorough analysis that is expounded upon in Chapter II, the created system uses DIS protocols, a GoTenna Pro X, and ATAK to link the various types of simulations. In remaining with the concept of using equipment and software already fielded to units, multiple units such as 1st EOD and 1st Battalion 4th Marines have already begun using and experimenting with ATAK and the GoTenna Pro in real world environments. Units such as Marine Corps Warfighting Lab (MCWL) have begun implementing these components in their training environments.

The technical work and potential LVC-TE RF mesh network solution will be described in detail in Chapter IV with recommendations for future work in Chapter V.

E. PROBLEM STATEMENT

The BFT is a computer based C2 system deployed aboard tactical vehicles giving commanders situational awareness of friendly and enemy unit locations while also forming a robust communications network within an area of operations. It is a family of systems that includes the Joint Battle Command – Platform (JBC – P) software. The BFT has undergone many system upgrades over the years in which hardware was improved, the GUI was preformatted with messages, and a new terrestrial communication capability to enable communications when satellite communications are degraded. At present, the BFT only operates on live missions and there is a shortage of BFTs in the Marine Corps. In addition, the Marine Corps is looking for an alternative to the currently fielded system.

F. RESEARCH QUESTIONS

- Can currently fielded Android-based C2 systems provide the same tactical fidelity and functionality as the BFT?
- Do the RF mesh network bandwidth limitations affect tactical situational awareness when used to share data across a tactical network?

- Are the messaging architectures for the BFT and other Android-based C2 systems capable of supporting the detailed simulation protocol data produced by constructive simulations used for LVC training?
- Are communication systems used in a simulation environment capable of operating in and supporting live operations?

G. REQUIREMENT FOR ALTERNATIVE BFT

The Marine Corps has been operating on the current communication architecture that has incorporated the BFT for decades. Recently the Commandant of the Marine Corps eradicated the JBC-P asking CD&I to come up with an alternative communication system. The proposed courses of action (COAs) will be discussed later.

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II. REFERENCE MODEL FOR CONVOY OPERATIONS

When performing a top-level interoperability analysis for LVC training of motor transportation operations, careful consideration must be given to understanding the tools and equipment that must be integrated. In addition, to stimulate the Marine Corps Planning Process, the exercise designer must be knowledgeable on the capabilities and limitations of all available assets in order to create the interactions and decision points that challenge the training audience with the event. There is a certain balance between training transfer and event difficulty that all planners must meet to ensure effective training occurs. The planning of the use case in this thesis will be outlined in this chapter and will lay the foundation for the effective construct of a LVC training event and overall logistics unit training plan.

To begin, we will briefly define the training challenges associated with operational tasks we hope to train for. This starts our definition of the reference model. Adding to that, we will then assess all training tools available, specifically the virtual and constructive simulations used to drive the enemy activities and adjacent unit support during the training exercise. To be thorough, we will also identify the non-simulation equipment available to create the targeted LVC event. Essentially, this chapter is an exhaustive review of assets available to Logistics units in the Marine Corps leading to the development of their own LVC convoy training operation. This is the first step in the process.

A. CHALLENGES IN IMPLEMENTATION OF MOTOR TRANSPORTATION OPERATION TRAINING

Motor transportation operations are critical to the overall success of MAGTF operations as it enables management of the four principle logistics concerns: time, space, consumption rates, and resources. For logistics staff training, it is critical to stimulate the training audience to make decisions and employ assets to ensure resources are maintained in balance with consumption rates while they also manage time and space effectively to distribute the resources (Thomerson, 2019).

In the Marine Corps motor transport operations for logistics C2 training comes with many challenges due to three primary reasons: cost, secondary effects, and priority of training. "First, the cost of distributing resources in mass across a space is disproportional to the training value gained by a logistics C2 watch floor. Second, using live units gives no room for error. If the logistics C2 training audience fails, the secondary effects degrade the operational units. Finally, due to the nature of military organization, ground units should and will always take priority; thus, once a ground unit is introduced, logistics is no longer the primary focus of the training. Ultimately, live logistics C2 training is only appropriate as a secondary benefit in support of larger scale training" (Thomerson, 2019, p. 22).

These issues can be addressed through the use of well-designed LVC training. To design an effective exercise, we first need to understand the tools available to construct a tactical event. The next five sections describe those tools. Some descriptions are provided in greater detail as they are the solutions selected for the implementation model described in Chapter IV.

B. TACTICAL VEHICLES AND SYSTEMS

1. Medium Tactical Vehicle Replacement

In the LVC training event we propose, we anticipate using actual combat vehicles to drive to and from local tactical ranges utilizing the military base infrastructure and roadways. Considering this, we will employ Medium Tactical Vehicle Replacement (MTVR), which is a family of military vehicles used to conduct various logistics operations. They are the replacement for the Vietnam-era 5-ton trucks. With enhanced capabilities, the MTVR has a payload of "7.1 tons off road and 15 tons on-road" (Oshkosh, 2014, p. 3). There are several mission-specific variants "including a cargo variant in both standard and extended-length wheelbase configurations, dump truck, wrecker and tractor. The dump and wrecker variants maintain maximum commonality with the basic MTVR cargo chassis while performing unique missions. The tractor variant serves as the prime mover for the Marine Corps' MK 970 5,000-gallon aviation and bulk-haul refueling trailer. The High Mobility Artillery Rocket System (HIMARS) resupply vehicle is an MTVR extended-length wheelbase cargo variant that was procured with an associated trailer as part of the HIMARS artillery resupply system" (USMC, 2020c, para 2). Specifically, the MTVR family of vehicles come in the following variants:

- MK23 Standard Cargo Truck
- MK25 Standard Cargo Truck
- MK27 Extended Cargo Truck
- MK28 Extended Cargo Truck
- MK29 Dump Truck
- MK30 Dump Truck
- MK31 Tractor
- MK36 Wrecker
- MK37 HIMARS Resupply Vehicle
- HIMARS
- 4x4 Short Bed Cargo Truck
- LHS 9-ton, 6x6 (Load Handling System)
- LHS 16.5-ton, 8x8 (Load Handling System)
- Global 8x8 Heavy Load Handling System
- MAS (MTVR Armor System)
- MTVR OBVP (On-Board Vehicle Power) (Oshkosh, 2014)

Given the Marine Corps recently extended the service life of the MTVR from 2024 to 2042, it is imperative that we develop a robust training program for its employment. The top-level interoperability analysis will allow us to train in a LVC environment while addressing the concerns covered in Section A. Figure 5 is an image displaying the MTVR family of vehicles.

Figure 5. MTVR family of vehicles. Source: Oshkosh (2014).

2. Joint Light Tactical Vehicle

The Joint Light Tactical Vehicle (JLTV), shown in Figure 6, is a joint U.S. Army and Marine Corps program designed to replace the aging High Mobility Multipurpose Wheeled Vehicle (HMMWV) (USMC, 2020a). It was specifically designed to enhance the light tactical vehicle fleets across the services based on the lessons learned in Iraq and Afghanistan. Those operations revealed that our warfighters need a mobile, survivable vehicle to enable expeditionary operations. The JLTV provides that exact capability.

The JLTV

> minimizes maintenance costs through increased reliability and provides increased fuel efficiency over the current light tactical vehicle. JLTVs are configured to support multiple mission packages, derived from two base vehicle configurations, the four-door Combat Tactical Vehicle and two-door Combat Support Vehicle. The commonality of components, maintenance procedures, and training among all vehicle configurations minimizes total ownership costs. (USMC, 2020a, para 1)

Figure 6. JLTV on off-road terrain. Source: Oshkosh (2017).

Employing the JLTV on convoy operations would provide the staff under training an ability to provide enhances protection for the movement of MTVRs. The JLTVs could serve as route reconnaissance and given their enhanced C4ISR capabilities, they could enable engagement with tactical aircraft and helicopters providing surveillance and potentially close air support. In a LVC environment, we could use virtual flight simulators to provide the close air support and route reconnaissance. In addition, it is possible to use a constructive simulation connected to a virtual simulation to produce a live video feed of tactical enemy behaviors executed in real-time. This concept has been proven at the Air Force Research Lab (AFRL) and the Expeditionary Warfare Training Group Pacific (EWTGPAC) using the Joint Tactical Air Controller (JTAC) simulator, the Modern Air Combat Environment (MACE) and X-Plane. The JTAC simulator is shown in Figure 7. In addition, the concept of providing real-time video for display on Android devices was shown in the Android Virtual Environments for Live Training program developed at the Modeling, Virtual Environments and Simulation Institute.

Figure 7. JTAC simulator at EWTGPAC at NAB Coronado. Source: VRSG (2001).

C. COMMUNICATIONS SYSTEMS

1. AN/PRC 117G(V)1(C) Multiband Networking Manpack Radio

The AN/PRC-117G man-packable software defined radio (SDR) developed by L3 Harris combines both high wideband data speeds with legacy narrowband performance to support beyond line of sight communications on the battlefield. Many units have this capability within their communications inventory, but the true capabilities have not been explored as there is limited expertise in their deployment. “When paired with L3Harris RF-7800B Broadband Global Area Network terminals, the manpack delivers automatic SATCOM beyond line of sight range extension along with Internet and remote private network access” (L3Harris, 2019, para 2). This specific capability would enable the federation or connection of simulations using HLA or DIS respectively.

Considering the current level of expertise in deploying this technically challenging system, the concept of using them for training to enable tactical communicators and networking personnel to deploy these systems on a regular basis is appealing. This would enable units to do testing on the systems by scaling the amount of data simulations might provide for a LVC training event. Units would be able to experiment with the real capabilities of SDRs and expand their knowledge of employment.

The AN/PRC-117G is also the only tactical radio with “NINE Suite B encryption, allowing sovereign nations to securely interoperate with the U.S., NATO and regional tactical partners” (L3 Harris, 2019, para 1). This would alleviate the cost and time required to deploy two separate radio systems during coalition LVC operations. In addition, the AN/PRC-117G is voice and data secure up to the TOP SECRET level making it applicable to integrate signals intelligence and cyber injects into tactical LVC events. By using multiple radios in disparate locations along a convoy route or within tactical military operations on urban terrain ranges, it would be possible to model a dense, noisy RF environment deployed to train signals intelligence operators on tactical geo-location. Another consideration for using the AN/PRC-117G would be the ability to model various communications between COCs using the capabilities of DIS Voice. This would allow for the modeling of a virtual kill chain during convoy operations.

2. Silvus Radio

The Silvus radio is another capable SDR that could be an option for integration into LVC training events as it has already been used by MCWL for manned-unmanned teaming events in Muscatatuck, IN. It uses a mobile networking multiple input multiple output waveform to create a mobile ad hoc network to enable high-bandwidth communications in dense RF environments (Silvus, 2020a). A key component of the Silvus radio system is that its network is self-forming and self-healing meaning “radios can join or leave the network at any time. The network will then continuously adapt its topology as nodes move in relation to one another” (Silvus, 2020b). This capability would be critical to a dynamic LVC environment as the battlespace and force structure can continually expand and contract based on the decisions made by the training audience. One drawback regarding these radios is that they are relatively costly at $12,000 per radio which could be prohibitive to field service wide or even for specific units.

D. COMMAND AND CONTROL SYSTEMS

1. Joint Battle Command Platform/Blue Force Tracker

The BFT is the compilation of multiple systems in order for forces to be able to navigate, communicate, track unit positions, and mark important locations on the map. The current BFT is comprised of a display unit (DU), a processing unit (PU), a keyboard unit (KU), and a removable hard drive disk cartridge as seen below in Figure 8.

Figure 8. BFT components. Source: MCCSSS (2016, p. 7).

The DU can be either a 10 or 12-inch monitor that is sunlight readable with a color display. It is touch screen capable and also has ports on the left side to be able to connect the KU and PU. The main features of the DU are the function keys along the left side. The locations of the buttons are depicted in Figure 9 with their functions listed below in Figure 10.

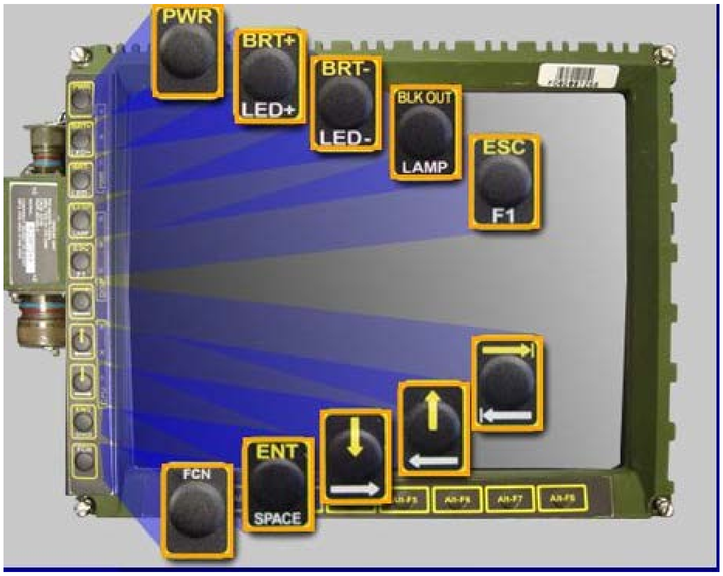


Figure 9. BFT function buttons. Source: MCCSSS (2016, p. 8).

Button	**Action**	**With Function Button Pressed**
PWR	Power	N/A
BRT +	Bright Intensity	LED Intensity increase
BRT -	Bright Intensity	LED Intensity decrease
BLK OUT	Black Out the	Lamp Test
ESC	Escape feature	F1 Map Control
Right Arrow	Right Arrow Tab	Jumps to left stop
Marall6mark	Up One Space	Moves one space left
Down Arrow	Down One Space	Moves one space right
ENT	Enter	Adds space in text
FCN	Function	N/A

Figure 10. BFT function commands. Source: MCCSSS (2016).

In addition to the above system components there are two components that are needed for the BFT to work; they are the MT2011 transceiver and the Defense Advanced Global Positioning System Receiver (DAGR). The equipment is pictured below; the transceiver in Figure 11 and the DAGR in Figure 12.

Figure 11. MT2011 transceiver. Source: MCCSSS (2016, p. 27).

Figure 12. DAGR. Source: MCCSSS (2016, p. 12).

The BFT system works by taking the position location information (PLI) data generated by the DAGR and via the MT2011 transceiver sends the information to a satellite which then sends the information down to the BFT Network Operations Center and updates the COP. This communication link also works in reverse, the Network Operations Center will compile all the PLI data all the units and send it back out via the satellite and then the MT2011 transceiver in order to update the DU in the vehicle. In regards to a ground unit's PLI data it will be updated every five minutes or 800 meters while an air unit's PLI data will update every minute or 2300 meters. Figure 13 shows an overall example of the communication structure.

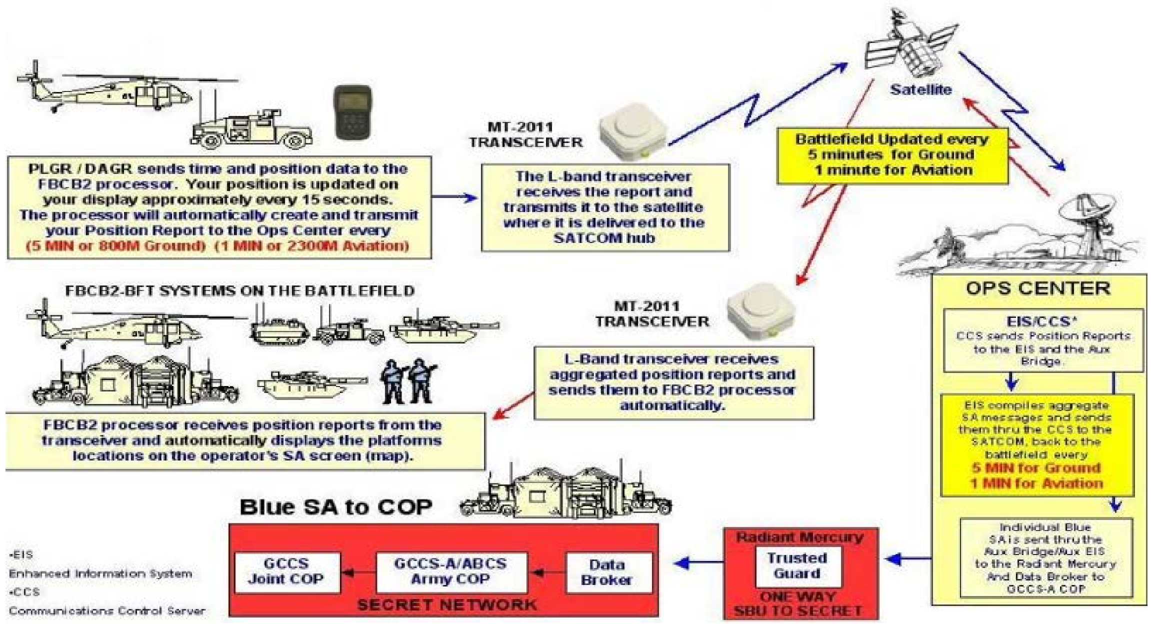


Figure 13. BFT communication diagram. Source: MCCSSS (2016, p. 18).

The BFT systems are in a multitude of Marine Corps vehicles. Some of the various vehicles include the HMMWVS, Mine resistant ambush protected vehicles, tanks, rotary and fixed wing aircraft. By the variety of vehicles, the BFT is in, it is utilized on multiple types of missions. Some examples include supply runs, troop transport, tank operations, and operations with close air support.

The current BFT is an expensive system and not every tactical vehicle that needs a BFT has one. In addition, the security of the BFT communication has been compromised which led to the Commandant looking for an alternative as previously stated.

2. Command and Control Personal Computer

The Joint Tactical Common Operational Picture Workstation is a Windows based system that "provides a framework for enhanced systems interoperability and commonality between MAGTF Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems" (USMC, 2020b, para 1). Within the Joint Tactical Common Operational Picture Workstation is the C2PC, which is a geospatial C2 system that presents live tracks based on inputs from surveillance assets and user inputs from tactical reports. With its robust user interface, users can plan routes and integrate tactical overlays, such as unit boundaries and fire support plans. In addition, C2PC can embed word, power point and sound files for sharing between users on the same tactical network.

In a LVC environment, stimulating C2 systems is critical to provide an overall picture to the training audience as to the red and blue force laydown. In addition, integration of a C2 networks using simulations expands the training to include network engineers making cross unit collaboration during training more worthwhile.

3. Android Tactical Assault Kit with GoTenna Pro X Radio

The system this thesis is exploring makes use of a combination of the application of ATAK and the GoTenna Pro. The components of the system on the vehicles will consist of an Android Tablet and a GoTenna Pro while a computer located in the COC or HHQ, depending on the operating intent, will be running the software.

The communication of this system will be managed by the GoTenna Pro X, depicted below in Figure 14.

Figure 14. GoTenna Pro X. Source: GoTenna (n.d.).

The GoTenna Pro X will provide an adhoc mesh network within the local area. The antenna is very lightweight and compact, weighing 2.8 ounces and measuring 5.3 by 1 by 0.7 inches. The GoTenna Pro X also features a rechargeable battery that can approximately last up to 30 hours depending on its usage. In regards to data transfer, the user is able to set how many times per minute the PLI data should be transmitted. The antenna also features its own sets of encryption.

Next in the system is the Android Tablet. Used in this thesis is the Samsung Galaxy Tab S5e tablet. The tablet is also lightweight and compact at 5.5mm thin and weighing 400 grams. It is a 10.5 inch display screen that still can be seen in all types of light. The tablet has the capability for microSD cards to be used to increase its memory capacity. It is capable of fast charging should the tablet not always be plugged into a power source, making the device more mobile. The tablet is all touchscreen; however, it has the capability to attach keyboards or pens via Bluetooth.

The laptop component will be located in the HHQ or COC. The laptop can be any make or model but must have Python Coding Application installed, Virtual Reality (VR) Forces, and the application Gulliver. In a simulation training environment, this will be located near the personnel developing the scenario for the unit in training, the simulation manager. The simulation manager can have multiple roles such as aiding the commanding officer to allow them to make decisions based on the scenario developments or can be interjecting items into the scenario, such as Improvised Explosive Devices (IEDs), that the convoy has to react to for their training.

a. Marine Corps Warfighting Lab

MCWL conducted an exercise to experiment with different force capabilities and testing different means of communication. This thesis will specifically discuss the findings of ATAK on a tablet or cell phone as the means of communication. The experiment was called Project Metropolis II and it was conducted from 1–30 August 2019 at the Muscatatuck Urban Training Center in Indiana. The exercise consisted of exercise forces divided into a blue cell (friendlies), a red cell (the adaptive threat force), and a white cell (exercise control personnel).

Throughout this exercise, all cells communicated via ATAK. As stated in the Project Metropolis II after action report (AAR), "ATAK allowed for a decentralized command architecture that increased the exercise force's decision cycle and execute commander's intent without micromanagement, ultimately resulted in a lower electronic signature" (Houston, 2019).

The use of ATAK tablets is important because it allowed for more communication assets to be utilized in the exercise. Every platoon was able to have a tablet which allowed for positions to be plotted down to the squad-level. This is very important when trying to maintain situational awareness (SA) of the battlefield. Some capabilities that ATAK demonstrated during the exercise were that the Marines were capable of "mapping, publishing, and coordinating scheme of maneuvers in conjunction with fires plans in real time distributed position" (Houston, 2019), which allowed the units to maintain a low electronic signature while they established link up points to further continue the mission.

During the exercise there were also some communication issues. However, the Marines were still able to use ATAK to effectively update unit positions and pertinent information such as sectors of fire, allowing the development of a company fire plan sketch. To reiterate, the direct impact of the use of ATAK is to allow the Marines to maintain a high level of SA to operate effectively and efficiently on the battlefield.

b. 1st Battalion, 4th Marines Border Patrol

ATAK was used in another situation with 1st Battalion 4th Marines during southwest border mission tactical assault kit integration in 2019. The unit had successful integration with ATAK, and all its capabilities previously mentioned. The goals of this mission were to

- "enhance the shared SA between Marines, Soldiers, and Customs and Border Patrol (CBP) agents
- establish and maintain a common tactical picture for DOD and Department of Homeland Security (DHS) enabled through end user device (EUD) Global Positioning System via the TAK server
- utilize the capability to develop and share common map overlays, digitally report activities (point drops) and text-based chat between devices

- conduct secure TAK server management between EUDs over commercial ISP or LTE cellular networks. (Lejeune, 2019)

The identified integration goals mentioned above were successfully completed. However, this was only tested in a limited scale with 5 EUDs. It appears that most of the limitations in this test were due to bandwidth and server capabilities, not the capabilities of ATAK functioning as needed. Depicted in Figure 15 are the various locations that the Marines, CBP, and DHS agents were operating by the areas marked connected EUD close to the Mexico border.

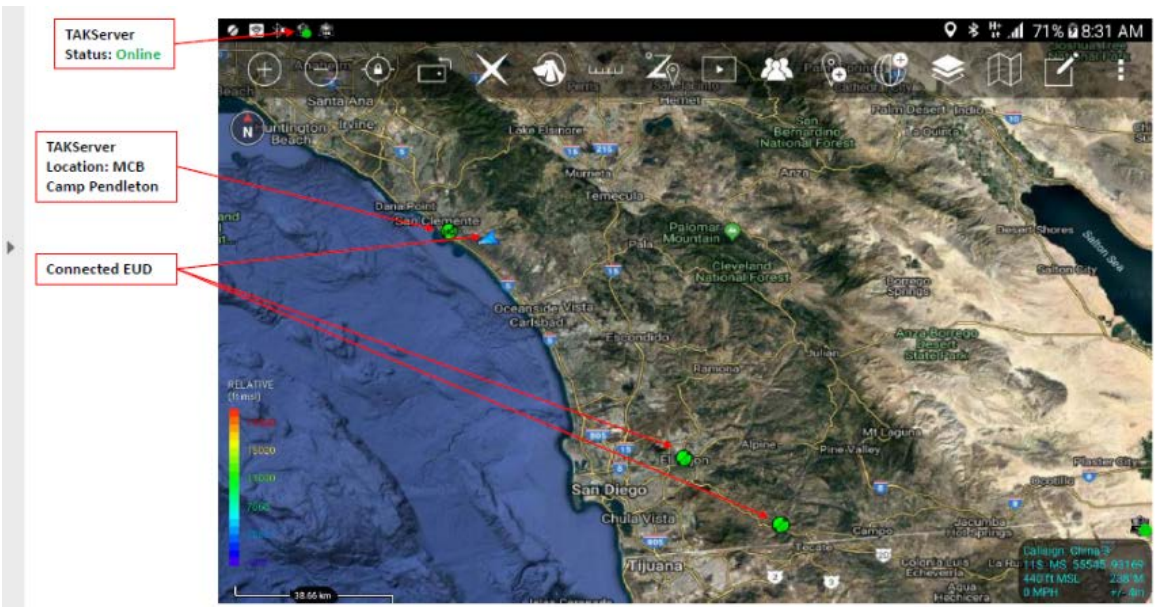


Figure 15. Border patrol locations. Source: Lejeune (2019).

c. Exercise Information Warrior 18 and Exercise Joint Warrior 18

MarWorks Information, a technology company working with the Royal Navy, conducted trials of the GoTenna Pro and ATAK during Exercise Information Warrior 18 and Exercise Joint Warrior 18 located in the United Kingdom in two training areas; Dartmoor Area, consisting of rural and rolling hills terrain, and Plymouth Area being an urban environment. Within each training area, different capabilities were tested.

In the Dartmoor Training, "the GoTenna Pro was trialed as a linear network for range extension as a point-to-point and relayed link between 2 users with the aim of this trial to investigate the feasibility for GoTenna to act as a range extension node for SA via the use of ATAK" (Davies, 2018). The layout of the Dartmoor Training Area is shown in Figure 16.

Figure 16. Dartmoor training area. Source: Davies (2018).

The Plymouth Area "was trialed within a static, mobile and elevated mission profile. The GoTenna Pro was elevated at a static location to a height of 200 feet, providing a tri-mesh network of 3 nodes for 3 users. GoTenna was also trialed as a mesh network within separate multi-floor buildings, comprising of 20 in stone walls, and rooms that are above and below surface" (Davies, 2018). The Plymouth Training Area is shown below in Figure 17.

Figure 17. Plymouth training area. Source: Davies (2018).

The Dartmoor training area results concluded that by using a third-party device such as a HeliKite to elevate an antenna to 250 feet, it enabled a line of sight (LOS) connection for all the units traversing the hills. The HeliKite was located at Point A on Figure 16. The units were able to communicate out to a range of 16 kilometers when it was a point to point communication which is depicted by the x-axis boundaries on Figure 18. Continuing to look at Figure 18 it is shown that the signal strength between both points varies over different elevations. The trails were also able to establish communications out to a range of approximately 3 kilometers while maneuvering in the undulating terrain. It also confirmed that the signal was stronger at higher elevations than it was at lower elevations.

Figure 18. Dartmoor elevation and distance with signal strength. Source: Davies (2018).

During the trials in the Plymouth Training Area, the GoTenna Pro was tested by elevating the antenna in a static location, depicted by point A in Figure 17, to a height of 8m. In this trial, communications were able to be established out to 30 kilometers and a strong connection was maintained out to at least 6.8 kilometers in order to send PLI and messages. While testing the capabilities of the network, they also screened the active user between buildings and bridges and there was no impact on the strength of the network. The signal strength is depicted in Figure 19. It is noted in this use case that the GoTenna Pro network outperformed the radios currently used.

Figure 19. Plymouth elevation and distance with signal strength. Source: Davies (2018).

4th ANGLICO, an air naval gunfire liaison company unit in the Marine Corps, also conducted trials of the GoTenna Pro used with ATAK during Exercise Joint Warrior 18. This test included the use of six GoTenna Pros and five Samsung Galaxy phones/tablets and one Google Pixel phone. The unit tested GoTenna in the dense urban environment of Edinburgh City Center, Scotland. The units patrolled on foot throughout the Area of Operations (AO) towards specific checkpoints. The GoTennas that were in closer proximity to each other were able to gain a better signal strength, however, the maximum range achieved with all units still connected was 1,074 meters while the maximum distance achieved between any two units was 2,160 meters. The Edinburgh Training Area is shown in Figure 20.

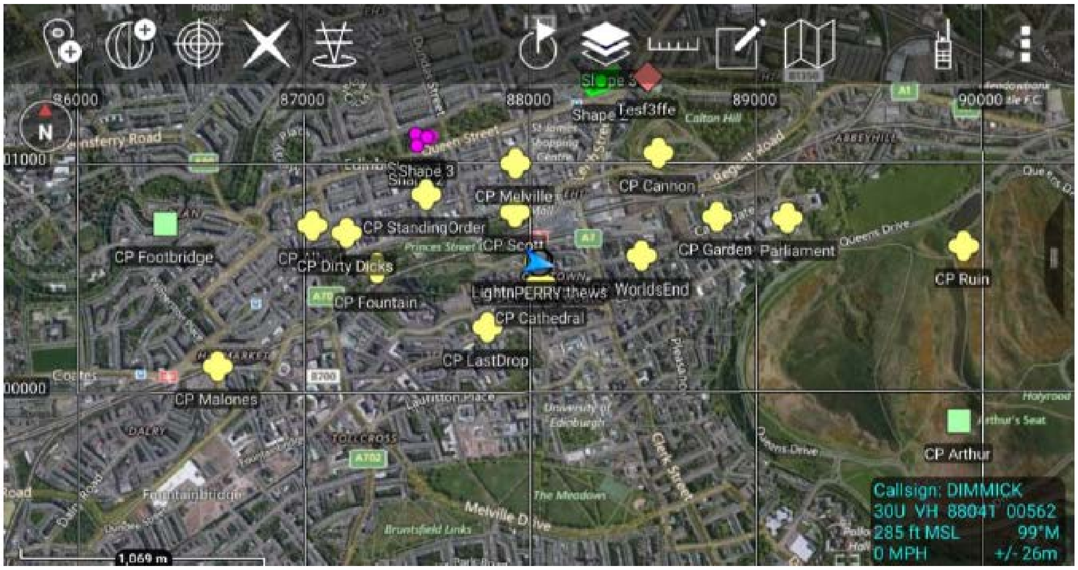


Figure 20. Edinburgh city center. Source: Perry (2018).

d. System Limitations

Current limitations of the GoTenna and Android-based system include data sending rate and range of transmissions. The system is limited by the number of messages per minute that can be sent without loss of data. While one can set the rate for PLI information to be transmitted to whatever number one wants, the more messages sent increases the risk of some messages being lost. Although 100% message traffic received is ideal, in the reality of the situation, no unit will be moving fast enough that lag time for updating correct unit locations displayed on the tablet should not be an issue.

The other system limitation of range can have a high impact on mission performance. As stated above in the AARs the furthest the system has currently been successful is at 30 kilometers. In the specific use case of convoys utilized in this thesis range can be very limiting as a convoy itself could span miles; without a LOS connectivity, the relaying of the antennas for communications could be limiting. However, the system's range can easily be extended by raising an antenna on a pole, as done in the Plymouth Training Area or by having an antenna in an aircraft flying overhead.

e. Integration with Simulations

This system originally will be integrated with constructive simulations, in this particular case, VR Forces. VR Forces outputs DIS data. This is where the integration of the app Gulliver is crucial. The app is able to take the DIS data and convert it to Cursor on Target (CoT), or extensible markup language (XML) schema, in order for ATAK to be able to process the information and be able to display the data on the screen.

f. Future Plans

As multiple units across the Marine Corps have already started to tap into the capabilities of the GoTenna Pro X and ATAK for training purposes, the next step is to verify its encryption capabilities and make any adjustments necessary as well as integrate it with simulations to further expand the LVC community.

MCWL used the GoTenna Pro and ATAK for white cell communications during a training exercise and was impressed with the ability it had to communicate and update personnel's position. MCWL would like to expand the use and test the capabilities and limitations of the system by having the red or blue force use it during an exercise.

E. SIMULATIONS

1. Constructive Simulations

a. MAGTF Tactical Warfare Simulation

"MTWS is the Marine Corps only constructive, aggregate resolution simulation system used to support the training of Marine commanders and their battle staffs in MAGTF warfighting principles/concepts and as well as associated command and control procedures" (USMC C & P, n.d., para. 1). The simulation was designed by CESI as a full member of the J7 JLVC federation to support staff training for battalion level and above and is maintained as a Marine Corps program of record (Thomerson, 2019). MTWS is a combat simulation that represents friendly, enemy, and neutral units across land, air, and maritime operations (USMC C & P, n.d.). MTWS is currently in use at each of the Marine Expeditionary Force (MEF) Simulation Centers and also at the MAGTF Staff Training

Program, where MAGTF Commanders are trained on managing all of the elements of a Marine Expeditionary Unit or MEF in the execution of an expeditionary operation.

MTWS is DIS and HLA capable and is used as a human in the loop (HITL) simulation. To conduct a training event, simulation managers, also called "pucksters," are instrumental in creating the behavior inputs for an event as decisions are made by the training audience. This requirement for "pucksters" normally scales up as the size of the exercise increases. There is a steep learning curve to operate MTWS, but it has been an effective system for simulation events since 1995. MTWS has not been used to drive entity behaviors for LVC events, although the system is used to train Combat Logistics Battalion (CLB) staffs at the Marine Corps Logistics Operations Group.

b. Joint Conflict Tactical Simulation

Joint Conflict Tactical Simulation (JCATS), also a member of the JLVC federation, differs from MTWS in that it is an entity level simulation. Developed at Lawrence Livermore National Labs, JCATS is widely used across the DOD and internationally including 30 allied nations (LLNL, 2018). At the Marine Corps Tactics and Operations Group, it is used to train Marine Corps Infantry Battalion Operations Officers on how to direct their staffs during combat operations. It is a HITL simulation and as the same as MTWS, it requires "pucksters" to create and execute tactical behaviors in real-time as decisions are made by the training audience. Figure 21 displays an image of the JCATS user interface and graphics display.

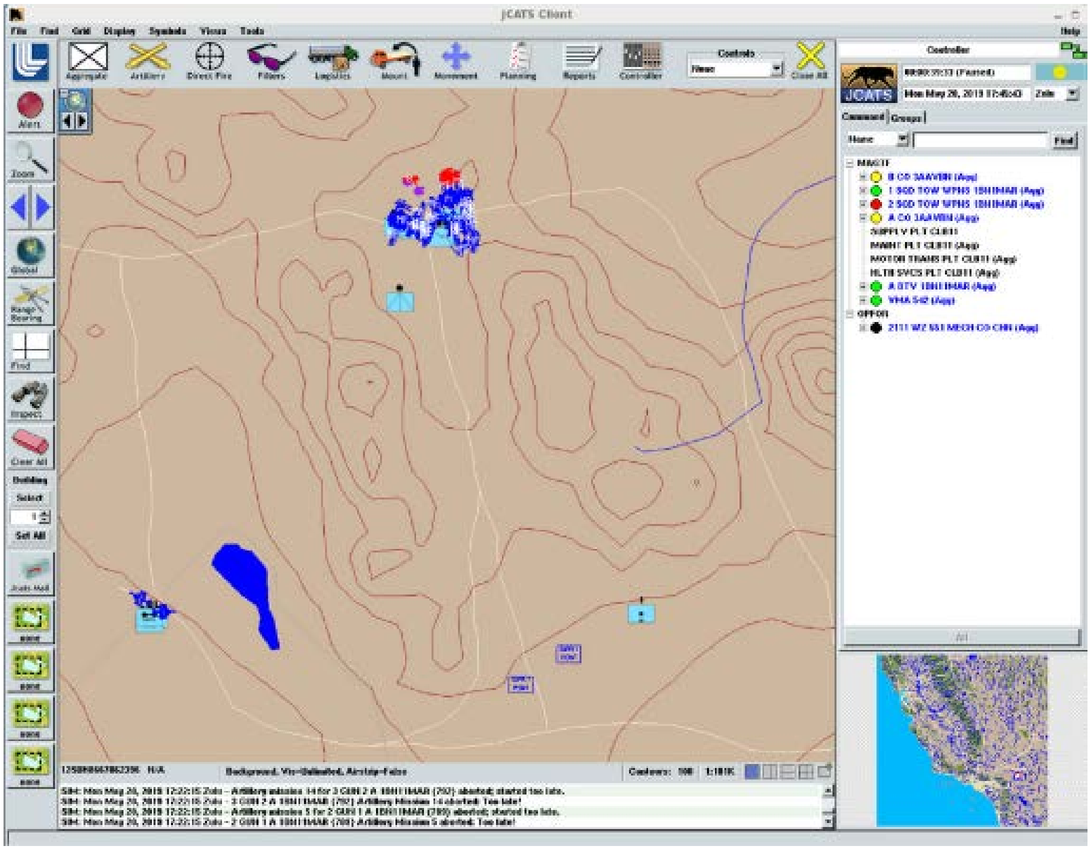


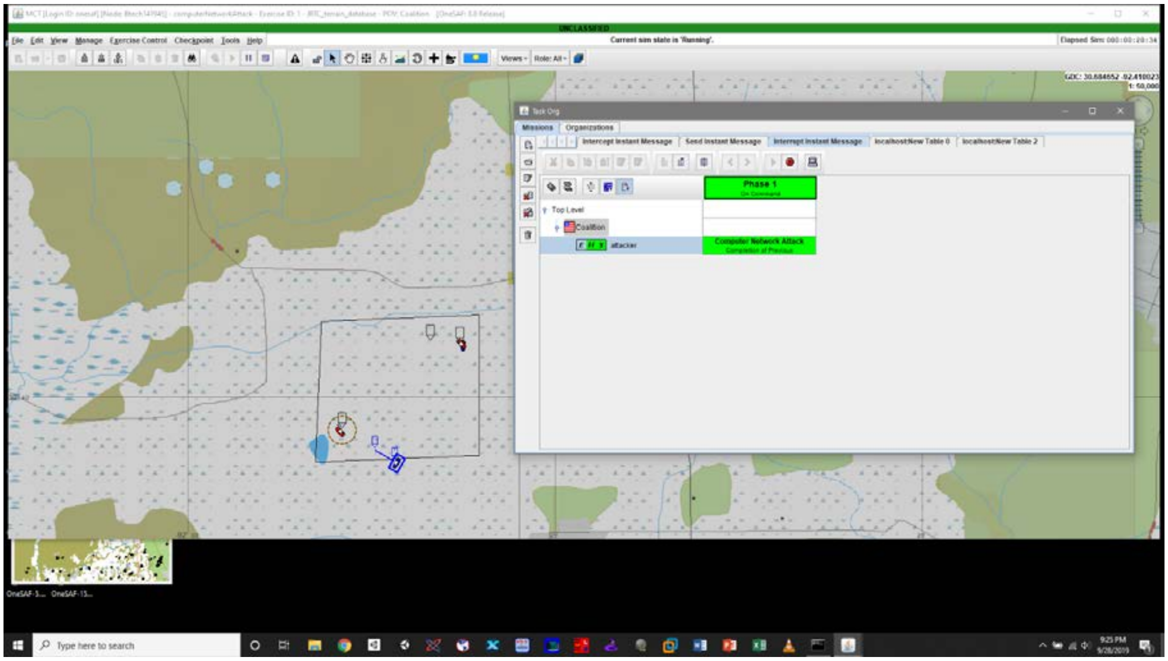
Figure 21. JCATS user interface and graphic display. Source: Thomerson (2019).

Recently, JCATS has been upgraded to include a robust logistics capability. This included management of maintenance and treatment of battlefield injuries. This enhanced capability complements the Joint Deployment Logistics Model (JDLM) making the federation between the two simulations a viable solution for convoy operations training. JCATS runs on Red Hat Linux 7.6 and can be easily run on a suite of laptops which make it ideal for tactical environments and quick deployment.

c. One Semi-Autonomous Forces

One Semi-Autonomous Forces (OneSAF) is an entity-based, computer generated forces simulation managed at Program Executive Office, Simulation, Training, and Instrumentation in Orlando, FL. It models "behaviors that are both semi-automated and fully automated" (PEO STRI, 2020, para 3). Marketed as a cross-domain simulation, OneSAF supports the "training, testing, evaluation, analysis, intelligence, acquisition and experimentation communities by providing the latest physics-based modeling and data collection, and reporting capabilities" (PEO STRI, 2020, para 3). It is also used to drive virtual simulations, specifically the Combat Convoy Simulator (CCS), which will be described in the next section. Using the behaviors modeled in OneSAF, the CCS displays a realistic battlefield environment using Virtual Battlespace 2 (VBS2) and entity activity and position data is passed via DIS. The capability to drive entities semi-autonomously or autonomously is a powerful capability in terms of conducting future LVC events.

Recently, OneSAF began upgrading its capabilities as well to model the insertion of cyber effects into the tactical environment. This application within OneSAF is called CyberSAF. Some of the effects include computer network attack (CNA) and infiltration of supervisory control and data acquisition systems. An example of this is shown in Figure 22. These capabilities could expand convoy training where a commander would have to consider the security of his networks and COC as he/she plans the logistics movement. As a CNA could make the route available to enemy forces for potential ambush while enroute.



Scenario developed in OneSAF at NPS

Figure 22. Coalition force executing a CNA on a red force to determine his location

d. Virtual Reality Forces

VT Mäk's VR Forces is an entity or aggregate level simulation system with an intuitive user interface to create autonomous behaviors or HITL executed behaviors. The platform has multiple simulation views including a 2D plan view option using MIL STD-2525 symbology and a 3D Stealth View option where scenarios are visible from multiple perspectives as controlled by the user. The simulation has access to a global terrain database called "VR the World" making modeling scenarios in any location around the globe possible. The simulation is DIS capable and HLA compliant. For federations, VT Mäk provides their own RTI for use.

The simulation models synthetic environments "with urban, battlefield, maritime and airspace activity" (VT Mäk, 2020, para 1). It comes will hundreds of 3D models for more realistic view in the Stealth Mode. In addition, the model comes with a scripting capability using Lua, where a user can essentially program any robust behavior methodology desired. Based on the ease of use and robust modeling capability, it is recommended that VR Forces be used for building LVC environments for convoy operations training.

e. Next-Generation Threat System

Next-Generation Threat System (NGTS) has been used for aircraft system testing and evaluation at NAVAIR 5.4 on Naval Air Station Paxtuxent River, MD. Using the Architecture Management Integration Environment (AMIE), DIS data from NGTS can be converted to MIL-STD 6016 in order to be detected on various aircraft systems on naval aircraft. NGTS has been used specifically to test aircraft electronic warfare systems. However, recent programs including the Distributed Experimentation Environment has expanded NGTS' capabilities to include surface operations and maneuvers in littoral regions. Although NGTS is DIS capable and HLA compliant, it would not be an ideal simulator for the creation of a LVC event for convoy operations because its current aviation focus. It would have potential in modeling a combat air patrol; however, it is unlikely that a fixed wing aircraft would be selected and tasked for such an operation. NGTS would have limited applications in our work.

f. Modern Air Combat Environment

MACE is "a physics-based, many-on-many simulation and threat environment with a large order of battle, ideally suited for both standalone mission rehearsal and distributed mission simulation" (BSSim, 2020, para 1). Like NGTS, MACE has a robust electronic warfare modeling capability and when used with the Virtual Reality Scene Generator (VRSG), the system is capable of aircraft route planning and visualization in challenging tactical environments where various integrated air defense systems are deployed to defend an area. MACE can also execute "9-lines" as programmed by the user. It can model pattern of life for vehicles and human entities to insert noise into the environment. Aside from being DIS capable and HLA compliant, MACE also has a CoT schema plug-in that enables visualization of scenario data onto ATAK if operating on the same WiFi network.

Similar to VR Forces, MACE has an intuitive user interface and currently drives the JTAC simulator. This would be of potential interest for a Logistics Convoy Commander as he/she may have an Air Officer assigned to them to assist with coordinating tactical aircraft. Considering the robust capabilities of MACE, it would be a viable option to integrate into a convoy operations LVC event.

2. Virtual Simulations

a. Combat Convoy Simulator

The Marine Corps owns seven CCS systems; two located on Camp Pendleton, California, one on Kaneohe Bay, Hawaii, two on Camp Lejeune, North Carolina, one on 29 Palms, California and one on Camp Hansen, Okinawa. Each CCS has five major components: CCS Suite, Student Station Vehicles, Simulated Weapon System, Instructor Operator station, and AAR. A photo of a Student Station Vehicle is in Figure 23 and each major component is described in Table 1.

Figure 23. Combat convoy simulator. Source: Scanlan (2013).

Table 1. CCS major components. Source: FAAC Incorporated (2019).

CCS Item	Description
CCS Suite (Standard Configuration)	A standard suite contains six training bays (four (4) HMMWVs, two (2) MTVRs and one (1) IOS. Camp Pendleton (CPEN) and Camp Lejeune (CLNC) each consists of two suites, labeled CCS 1 and CCS 2, which are designed to work together to allow up to twelve vehicles in a single convoy.
Student Station Vehicles	Replicates the combat vehicles, including items such as seats, doors, hood, controls and indicators, communications/navigation, drivers' controls, and other subsystems. The CCS supports a set of unique vehicle student stations that include the following: • Four (4) High Mobility Multipurpose Wheeled Vehicles (HMMWVs) with M1151 configuration • Two (2) Medium Tactical Vehicle Replacements (*MTVRs*) with a Marine Armor Protection Kit configuration
Simulated Weapon System	The CCS provides small arms and weapons training to generate realistic convoy training to the troops. Wireless weapons provide warriors more freedom to move into and out of the vehicles, and to feel the rifle recoil of "rounds fired."
Instructor Operator Station (I/O)	The Instructor Operator (I/O) directs exercise scenarios using an IOS and, in conjunction with the unit Subject Matter Experts, provides training for the Marines scheduled to attend training. The IOS can create convoy training experienced that is adaptive to the training needs and skill-level of each crew. As the training exercise proceeds, the I/O can inject different threats and situations to stress the crews undergoing training.
After Action Review (AAR)	An AAR capability provides the means to debrief and reinforce exercise instruction by replaying all or part of the recorded training session. During the AAR, the I/O has the ability to select the viewpoint of any student station involved in the training exercise for playback. AARs is a professional discussion of an event, focused on performance standards, that enables Marines to discover for themselves what happened, why it happened, and how to sustain strengths and improve on weaknesses.

A majority of the CCS locations do not have an operational BFT in the simulation. Some of the CCS locations have a BFT that will allow the assistant driver to send messages, however, the messages do not automatically update the COC or other vehicles in the simulation. The simulation manager must send the messages to vehicles individually. In the upgrades that are currently in the works for the CCS, one of the new pieces of equipment that will be introduced is the BFT with the JBC-P software. Introducing this capability will make the training conducted with the CCS more realistic and get the Marines used to using the equipment they would need to use in a real-world environment.

Prior to the instruction from the Commandant the Army and Marine Corps were looking to update the technology and software used in the BFT system. Now the specific proposed courses of actions are:

- COA A: Repurpose the mounted family of computer systems (MFoCS) and continue using JBC-P in a Type I terrestrial network configuration
- COA B: Repurpose the MFoCS and use a different software that meets the requirement in a Type I terrestrial network configuration
- COA C: Dispose of the entire material solution of JBC-P and leverage tactical tablets and Type I encrypted radios. (CE-IWD, 2019)

b. Prepar3D

Developed by Lockheed Martin, Prepar3D is a visual flight "simulation platform that allows users to create training scenarios across aviation, maritime and ground domains. Prepar3D engages users in immersive training through realistic environments" (Lockheed Martin, 2020). Prepar3D has models for over 40 high detailed cities and models approximately 24,900 airports. It also produces DIS data for transfer onto the network (if using the Professional Edition). This simulator has been used extensively at AFRL to model F-22 flights in support of tactical operations, depicted in Figure 24. It has also been used with the JTAC simulator to fly "9-lines." For an LVC event supporting a convoy, Prepar3D could be used to virtually fly an armed reconnaissance mission in a fixed winged aircraft. This would allow a Convoy Commander to train his Air Officer in employing air assets to provide route security for the operation. For LVC training, Prepar3D provides "virtual reality (VR) support for the HTC Vive, Oculus Rift, Varjo VR-1, and other headsets compatible with SteamVR" (Lockheed Martin, 2020, sec. "Features"). This might be an option for logistics units to integrate VR headsets into their LVC training.

Figure 24. F-22 ready for take-off on a runway at Eglin AFB in Prepar3D. Source: Lockheed Martin (n.d.).

c. X-Plane

X-Plane is another virtual flight simulator with similar capabilities and fidelity to Prepar3D. It offers a robust data transfer capability; however, the data is not transferred in the DIS format, but rather its own proprietary format via the User Datagram Protocol (UDP). This requires processing via an interoperability architecture described in Section F and an example of the data output is shown in Figure 25. This virtual simulation was also used for virtual kill chain research at AFRL as described in Section B.2. of this chapter.

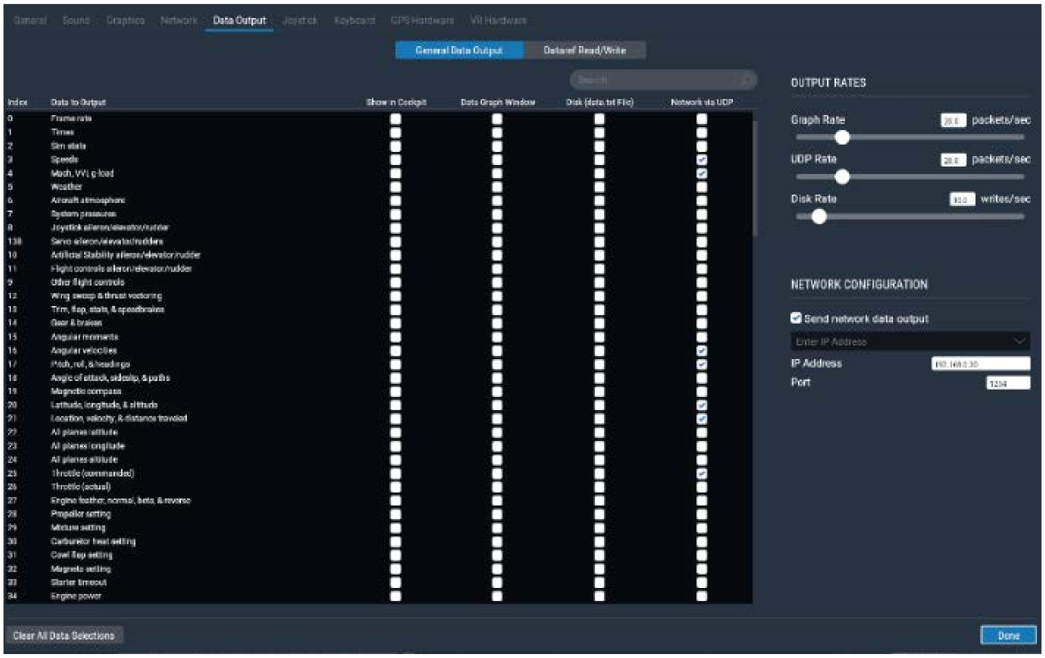


Figure 25. X-Plane 11 data output and selection interface. Source: XPlane 11 (n.d.).

F. INTEROPERABILITY ARCHITECTURES AND SOFTWARE

1. Architecture Management Integration Environment

AMIE is "a common, non-proprietary method of integrating models and simulations that will 'create the battlespace.' AMIE is a cost effective open-architecture that allows multiple models to be in one location, making it more practical to test with live assets and threats in a joint environment" (NAVAIR, 2016, para. 1). In LVC environments, this capability can be critical in the conversion of various simulation formats into formats required for tactical mission systems. We anticipate using AMIE to convert DIS data into the CoT format similar to the application in MACE. The following plugins are available with AMIE:

- DIS Version 6 and 7
- DIS CAFDMO
- HLA NASMP
- TENA
- Joint Integrated Mission Model
- Joint Range Extension Applications Protocol

2. Test and Training Enabling Architecture

The OSD's Test Resource Management Center seeks to ensure that all within the DOD have the right test and evaluation infrastructure to accomplish the system assessment mission (TRMC, 2020). To do this, they have created the Test and Training Enabling Architecture (TENA) Software Development Activity to ensure interoperability between ranges, facilities, and simulations. Although TENA is similar to AMIE, it is another architecture we may use in the development of LVC events to ensure data transfer between all participating systems and software tools.

G. OTHER CONSIDERATIONS

When considering a reference model to conduct a top-level interoperability, one must carefully consider the capabilities of competing systems and make the appropriate judgement as to what solution provides the best training available for the training audience. We may need to revisit the assessment of this tools as we further understand the specific training objectives. We may also add to this list as capabilities emerge. Top-Level Interoperability analysis to conduct LVC training on a grand scale is a continuous process.

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III. CONCEPTUAL-LEVEL MODEL FOR CONVOY OPERATIONS

In continuing with our top-level interoperability event design, we next define the conceptual model that allows us "to identify any concepts that are important for the simulation experiment that may be hidden for the user, but may lead to inconsistencies within a composition" (Tolk, 2018, p. 685). For example, in training for convoy operations, using constructive enemy agents displayed on live C2 systems must be coordinated exactly with all other participants to include live enemy role-players if utilized. Although this is a minute detail, if overlooked and discrepancies are detected, it could result in negative training. To ensure consistency, relevance and realism within a LVC training event, the designer must have a thorough understanding of his or her training audience and their objectives while also mapping those to the capabilities LVC could provide. This thesis recommends building the conceptual level model through detailed task analysis and understanding of the specific training objectives contained in the Marine Corps' Training and Readiness (T&R) manuals for convoys.

A. TRAINING

1. Individual Training

There are various Military Occupational Specialties (MOS's) in the Marine Corps, however, this thesis will focus on the logistics domain, looking at the pipeline of the Logistic Officers and the Motor Transport Operators.

First the pipeline of the logistician. After completion of The Basic School the logisticians head to Camp Johnson in North Carolina to attend the Logistics Officer Course (LOC) for 3 months. In this time, they are taught a plethora of information involving the functions of logistics, however, the main focus of the course and the culminating event pertains to convoys. Subject matter experts in motor transportation go through all of the components and control factors of a convoy in class setting. Upon completion, they are then tasked to execute a tactical convoy as a CC during a week-long field exercise.

The Motor Vehicle Operator starts at the Motor Vehicle Operator course. "The purpose of the Motor Vehicle Operator Course is to train entry level Marines the basics of operating equipment, preventative maintenance checks, emergency procedures, cargo loading, ground guide procedures, and operating a load handling system" (MTIC, n.d.). It provides them with the "core specialty skills and technical ability to perform the duties of a basic motor transport equipment operator of light, medium, and heavy wheeled vehicles under varying garrison and field conditions" (MTIC, n.d.).

Progressing in the pipeline, Marines may attend the Semitrailer Refueler Operator Course. "The purpose of the Semitrailer Refueler Operator Course is to train qualified Marines to operate and maintain the MK31 tactical tractor and the MK970 Semitrailer refueler in support of ground and aviation equipment during combat and garrison operations" (MTIC, n.d.).

Finally, a Marine may attend the Vehicle Recovery Course. The Vehicle Recovery Course provides "the core specialty skills and technical ability to perform the duties as a motor transport vehicle recovery operator using medium and heavy tactical wreckers under varying garrison/field conditions" (MTIC, n.d.). In this course, "instruction is concentrated toward vehicle recovery, flat tow, lift towing, oxyacetylene cutting, crane operations, basic issue items, operator/crew preventative maintenance checks, and emergency procedures on both medium and heavy tactical wreckers" (MTIC, n.d.).

Between LOC and the various courses of the Motor Transport Operators, the Marines are taught about the important details in section B of this chapter. In their pipelines they have many in classroom hours reviewing the material as well as multiple live training events in order to reinforce what they were taught.

2. Unit Training

The next step is to train as a unit to solidify tactics, techniques, and procedures (TTPs), as well as to train to the unit's standard operating procedure (SOP) to ensure if any changes are needed they are changed and practiced prior to deployment. In the fleet, units will conduct live and simulated training. Due to possible restraints on live training such as resources, financial constraints, weather, range availability, units may train using available convoy simulators. Through their use, Marines are able to interact in different scenarios to challenge their decision-making capabilities, communication TTPs, and maintain proficiency on the current TTPs and SOP in place by their unit.

B. LEARNING MATERIALS

In the logistics schoolhouses, the learning objectives go through specific elements pertaining to convoys to ensure mission success. This thesis will define and explain the role and importance of these elements as they will guide LVC training event design.

1. Tactical Convoy

"A tactical convoy is a deliberate planned combat operation to move personnel and/or cargo via ground transportation in a secure manner under the control of a single commander. Tactical convoys must have access to the current COP and maintain an aggressive posture that is both agile and unpredictable" (ALSA, 2009, p. 1). The execution first begins with a warning order which includes. "the general purpose, the destination, the type of movement, and the approximate schedule of the convoy" (USMC, 2001). From there, it will develop into a movement order which is comprised of, "the current situation, the mission and purpose, the concept of operations, the applicable administrative and logistics procedures and responsibilities, and the command, control, and communication assignments and techniques that will be employed during the convoy" (USMC, 2001). All of the information provided by the two orders is essential data that feeds into mission planning.

2. Convoy Mission Planning

The task organization of a convoy will depend on the specific mission. In general, they will typically consist of a, "transport element, escort or security element, various support elements, and command and control elements" (USMC, 2001). An example of the composition of a convoy is shown in Figure 26.

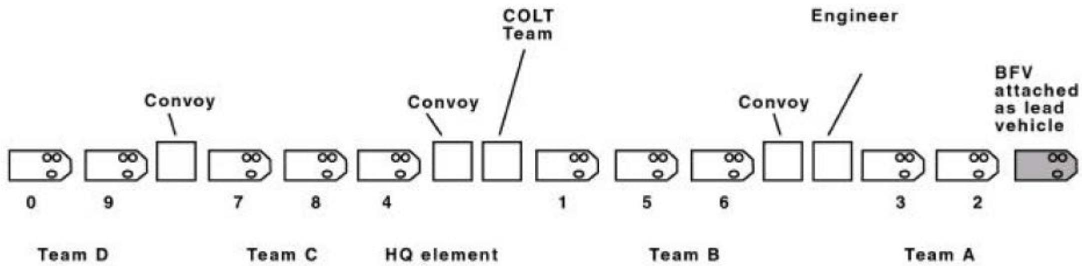


Figure 26. HMMWV scout platoon escorting convoy. Source: USMC (2001).

Considering the mission objectives, the unit will have to determine route selection, intervals, rate of speed, and types of formation. These factors will be unique across different mission sets and will have a direct impact on the efficiency and effectiveness of the mission.

The routes are broken into three types: type x, type z, and type z. “Type x is an all-weather route that is passable throughout the year. Type y is a limited, all weather route that can be open in all-weather but is sometimes limited to traffic capacity, and finally type z is a fair-weather route that becomes impassable in adverse weather” (USMC, 2001).

Determining the intervals or spacing in between each vehicle is important in minimizing attacks but also maintaining mutual support. Fifty (50) to 100 meters is usually ideal as, “mine damage can be limited, and the effectiveness of air attacks minimized” (USMC, 2001). Rate of speed is closely aligned with intervals as at times the rate will fluctuate above or below the planned speed in order to maintain the necessary spacing between vehicles while encountering new terrain or situations.

Intervals and spacing also affect the formation type. There are 3 types of formation: open column, close column, and infiltration column. “The open column is normally used during daylight with a dispersion of 50–100 meters between vehicles. The close column is usually used in darkness or limited visibility with the distance between vehicles around 25 meters. Lastly, infiltration is the movement of dispersed, individual units or vehicles at irregular intervals” (USMC, 2001).

3. Convoy Movement Controls

In order to effectively maneuver during motor operations, there are multiple movement controls including distance, time, rate of movement, critical points, and intervals. A convoy with varying missions such as delivering supplies or personnel transportation needs these critical measures for effective C2 and safe and successful completion of the mission. Each movement control is described below.

When referring to distance, it is the total distance the convoy has to travel. It is important for planning halts, intervals, and logistic support such as fuel.

Time is the amount of time that it will take the convoy to complete the trip. This enables tracking of the mission and provides the supported unit with an expectation of arrival. Should a convoy not arrive near the expected time or miss prior coordinated arrival times set at critical points, it may indicate an unplanned event, maintenance issue, or an ambush.

Rate of movement refers to the ratio of distance to time. It is defined by three terms: speed, pace, and rate of march. Speed is how fast the vehicle is traveling, depicted by the speedometer in the units of miles per hour. Pace is “the regulated speed of a column or element as set by the lead vehicle, the pacesetter” (USMC, 2001). The pace can be adversely impacted by inclement weather or rough terrain. Rate of march is defined as “the average number of miles traveled in any specific time period” (USMC, 2001).

Critical points are landmarks along the route that could limit the movement of the convoy. “Any road structure or feature that limits road width, overhead clearance or vehicle load class, as well as any feature that interferes with the meeting or crossing of two or more streams of traffic” (USMC, 2001) are a few examples.

Intervals refer to the distance between each vehicle on the convoy and is critical to overall security. The spacing varies in multiple conditions; however, it must be balanced with the necessary security measures employed. The interval should not be so small that if the convoy hits an IED more than one vehicle is damaged. On the contrary, the interval should not be so large that the vehicles cannot support each other with firepower in the event of an ambush.

Each control is an important consideration during planning, and they can vary between specific convoys due to impacts caused by terrain, mission type, weather conditions, etc. For example, if operating in the desert, as the vehicles are moving, they will create dust clouds limiting visibility, creating a need to increase spacing between each vehicle so that there is enough time for the dust to settle. This will enable the next vehicle to pass without an obstructed view, but also maintain convoy security. All factors need to be carefully balanced.

Figure 27 displays a graphical example of the different convoy control measures. Displayed is the interval between vehicles, the distance that the convoy occupies, and the distance of the mission.

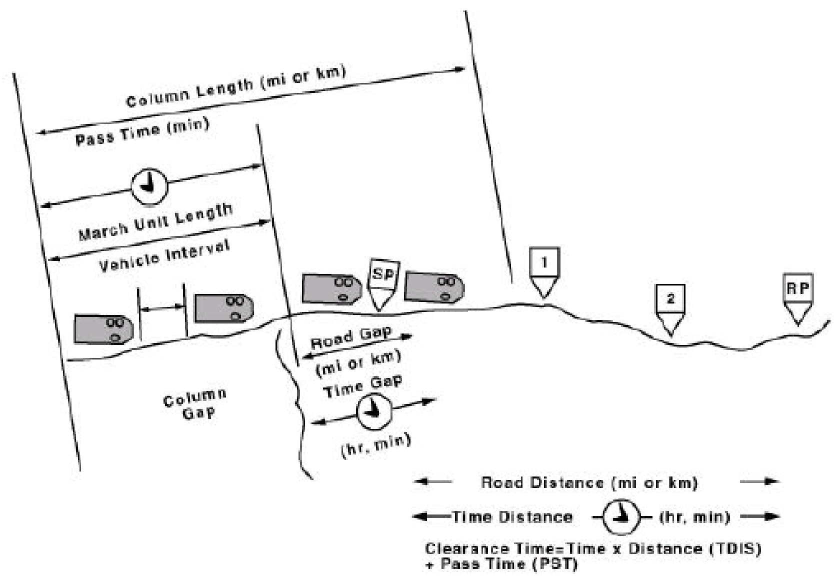


Figure 27. Clearance time picture. Source: USMC (2001).

4. Convoy Operations C2

Similar to any other military mission, there are multiple layers of leadership for a convoy. The leaders range from the MAGTF Commander all the way down to the Vehicle Commander. This thesis will go over some of the key roles of a Convoy and Vehicle Commander and the importance of why they need reliable communications. Figure 28 shows one version of the force breakdown of a Motor Transport Company.

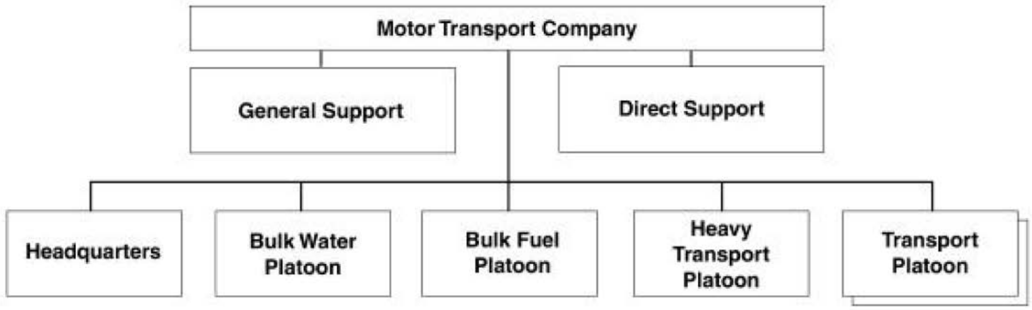


Figure 28. Motor transportation company command Structure. Source: USMC (2016).

a. *Convoy Commander*

For planning, the CC must at a minimum coordinate with the "Higher Headquarters (HHQ) Movement Control Center (MCC), units located where the convoy will traverse, units being moved, supporting units, units at the convoy destination, and military police" (USMC, 2001). Coordination with HHQ prior to movement is critical in determining the correct route to travel. Sometimes HHQ will mandate which route to take, while other times it will be up to the CC to determine how to get to the destination. The CC also, "must receive route clearance prior to movement" (USMC, 2001). Remaining in contact with HHQ during the convoy will also be critical to receive updates on possible threats and unit movements in the AO and to request support or assistance if needed.

The CC must "coordinate with friendly units enroute, control and coordinate actions in response to enemy action, request and control supporting arms fires, request casualty evacuation, and report progress of the convoy" (USMC, 2001). All play a vital role in supporting the convoy should they need assistance. Specifically, the CC needs to accurately navigate the planned route and have awareness of their exact location during movement. This PLI data will be one of the critical pieces of information that will be needed to pass to units outside the convoy as well as within should support be required at any time.

Coordination with other units along the route is critical to avoid fratricide and create opportunities for mutual support if a tactical need arises. For example, another unit in the

AO might have engineering assets that could assist in clearing a road. This might allow the CC to modify his or her vehicle selection in deployment of the convoy. In addition, the CC needs to liaison with personnel at the destination to coordinate logistics support such as fuel, chow, and berthing. During movement, the CC needs to remain in contact with personnel at the destination to provide and receive status updates. Continuous communication is absolutely critical to react and prepare for the unexpected.

b. Vehicle Commander

Ultimately the Vehicle Commander is responsible for the individual actions of their vehicle and the internal status of their personnel. At all times, he or she needs to maintain communications with the CC. Should the vehicle need to adjust any of the movement controls as previously discussed, they need to inform the CC. In addition, the Vehicle Commander needs to let the entire convoy know should they perceive any threats, i.e., a possible IED or obstacle. The entire convoy will then have to communicate and take the appropriate immediate actions. The convoy also needs the ability to be able to mark the location of any threats or obstacles to enable supporting units to mitigate the threat once on scene. Figure 29 depicts an example of a convoy's actions should they reach an obstacle.

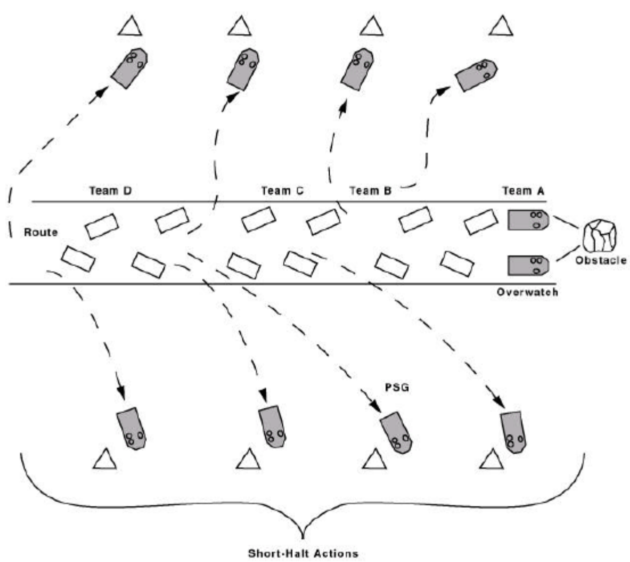


Figure 29. Short halt actions. Source: USMC (2001).

C. TASK ANALYSIS: CONVOY COMMANDER

Since the ultimate responsibility of the success of the convoy falls upon the CC, we will look at the task analysis from their perspective in detail.

> Task analysis is the analysis of how a task is accomplished, including a detailed description of both manual and mental activities, task and element durations, task frequency, task allocation, task complexity, environmental conditions, necessary clothing and equipment, and any other unique factors involved in or required for one or more people to perform a given task. (Kirwan & Ainsworth, 1992)

The CC checklist contained in Appendix A outlines each specific task relative to the training event that make up the graded elements contained in the T&R standards. Evaluators make assessments on performance of the graded elements to determine the proficiency of the performer. Before an end-state evaluation though, a performer must be given the opportunity to demonstrate and practice the skills listed on the T&R standards. As there are complexities in each task, obtaining immediate proficiency is unrealistic. Performing a top-level interoperability assessment will allow for extraction of the most complex tasks to enable the training event designer to present the most difficult skills from various perspectives to maximize learning. In addition, LVC offers repeatability of specific instances within the training evolution to allow the performer additional time and practice to master the skills being assessed. Ultimately, the T&R standards are designed so that upon the successful completion of an event, the Marine should be able to perform that task proficiently. Since reaching proficiency assumes completion of a training regimen, LVC environments offer a unique capability to align training tasks with the performer’s growing level of proficiency and improvement.

Below we begin our task analysis for the nine (9) areas of responsibility for a CC. As stated, the areas of responsibility were extracted from the Convoy Commander Checklist contained in Appendix A. The checklist is a compilation of planning tasks that are required before the conduct of an actual convoy. Since this is an exhaustive list of the commander’s responsibilities, our task analysis will select a few items from each area and define the decision or task that maybe be required for mission planning or execution. We will then make a recommendation of what type of training simulation may be best to train for that decision or task.

1. Mission Requirements

In Mission Requirements among many other areas of responsibility, the CC is expected to train and prepare for the current intelligence situation, pre-mission vehicle tasking and expected lighting/blackout conditions. Specifically considering these within the conceptual level model, we may be able to apply the capabilities and systems defined in our reference model in Chapter II to meet training objectives. The question still remains, will LVC environments to expand or enhance training for each area of responsibility?

First, training for the decisions and assessments required in understanding the current intelligence situation could be enhanced using both constructive and virtual simulations. As an example, AFRL uses MACE, described in Chapter II.E.1.f, and X-Plane to model unmanned aerial vehicle (UAV) operations in an area of responsibility (AOR). Since some UAVs, including Scan Eagle in the Marine Corps, are controlled by humans, it is feasible to have a human-in-the-loop using X-Plane to model activities of airborne reconnaissance assets to provide a real-time intelligence estimates. Using those same simulations to model pre-mission reconnaissance, a CC could also request to visualize their planned convoy routes using an image generator. AFRL uses the VRSG for this purpose. Greater fidelity intelligence available in training will create decision-making opportunities during planning for the CC as he or she determines how to best conduct their convoy safely. Figure 30 is an image of a UAV in MetaVR’s VRSG.

Figure 30. UAV flying over terrain in MetaVR's VRSG. Source: Rees (2014).

The current intelligence assessment continues when the CC decides on what assets to deploy on his or her convoy to include security, C2, and maintenance vehicles. The same training approach could be used as described above by deploying virtual UAVs, but it could be expanded with the use of constructive simulations. For example, within them developers could create dynamic red force behaviors in the context of a tactical scenario that mirrors a live training event. This enables visualization of the capabilities and force construct of the simulated red forces within the training AO. Here, the CC could be challenged in deciding what forces he or she should deploy and also determine whether or not supporting assets should be requested prior to moving to the objective. In addition, the interoperability of constructive simulations with C2 also enables the MCC to see the same events unfold from a higher echelon of command and potentially re-task the convoy based on the dynamic events unfolding pre-mission due to the integration of the constructive simulations.

Finally, constructive simulations can also be helpful in demonstrating the effectiveness of battlefield illumination during reduced lighting or blackout conditions. Constructive simulations can be used to plan for these changing environmental conditions and offer capabilities to enable the CC to better assess their operations in the AO. At a minimum, constructive simulations can model time of day, inclement weather, change of seasons, and lunar illumination. To account for the environmental difficulties, most constructive simulations can fire illumination rounds to improve visibility during low light level operations. Figure 31 depicts an illumination round fired over an urban range on Camp Pendleton. The illumination enables an infantry squad to use robotic systems to track enemy movements on the western side of the range. The illumination rounds are visible in the center of Figure 31 providing clear visibility along all routes in the AOR. Modeling this type of tactical activity may expose the CC to assets previously thought as unavailable within the mission. Simulations in this instance would expand the CC's knowledge of the tactical environment and supporting assets available.

Scenario developed in VT Mak's VR Forces at NPS (MV4503 Course)

Figure 31. Illumination rounds over urban training range on Camp Pendleton, CA

2. Reconnaissance

Under reconnaissance, the CC is expected to analyze maps and other photographic evidence of the tactical environment to evaluate the physical conditions of the convoy route. This assessment will reveal potential obstacles and rough terrain guiding the decisions the CC makes for overall vehicle employment. In this area of responsibility, virtual and constructive simulations could provide the most unique training inputs creating the need for the CC to re-evaluate aspects of his or her plan to carry out mission tasking. The simulations could be used in the exact same manner as they were used above in the

Mission Requirements section. To expand on that though, live simulations could also be used to make the training environment more realistic by adding live subordinate units to conduct reconnaissance and intelligence collection. In addition, adding live elements may inform and scope how we want to create the implementation model to be described in Chapter IV.

Using live assets to conduct reconnaissance patrols real-time along the convoy route creates opportunities to expand collaboration between organic sections in the unit and subordinate units. A supporting reconnaissance patrol could be a squad sized element that moves in a clandestine fashion along the convoy route seeking to collect intelligence on enemy activities. Integration of constructive simulations with handheld C2 systems carried by a live patrolling element could create an environment where supporting units would be providing real-time intelligence reporting. In this case LVC would be conducted in a distributed environment requiring the set-up and deployment of communication networks and a COC for the training event. Implementation of LVC quickly expands the size of the training audience in a realistic way. Here, the operations department in a logistics unit would need to work closely with the unit communications officer, S-6, and Information Technology section to create an environment that connects the CC to the live reconnaissance patrol supporting the training event and the HHQ element tracking the mission as well. The data collected in this area would then lead into the next CC task: route selection.

3. Route Selection

For route selection, there is one area where constructive simulations could enhance training not previously discussed. It would be in modeling of dynamic terrain selection for a blue reconnaissance element to inform the CC of the emerging enemy situation along the route. Dynamic terrain selection has been integrated into many existing combat simulations to create more realistic reactions to red forces along a mission route. To avoid enemy engagements, it is typically used with an agent's observe capabilities. For example, if a blue agent is traversing a route to reach a goal point or objective location, it could be programmed to re-plan that route based on the observation of a red entity or unit on the pre-planned route. Dynamically, the blue force would then change its routing to the objective until the next threat is encountered. Constructive simulations can be very effective in modeling a lead reconnaissance element of the convoy. Through dynamic blue entity behavior development, the CC could observe a simulated forward element execute the pre-planned route. Based on the lead element's goal to avoid interaction with red forces, the reconnaissance element could then provide intelligence causing the CC to make a change to the plan. Again, creating a challenging decision making opportunity for the CC through the utilization of constructive simulations.

4. Liaison and Coordinate

Coordinating with subordinate, adjacent, and higher-level units during training events has been made more accessible through the implementation of LVC. Critical to establishing this capability is the federation of various simulations together. This enables an event designer to leverage specific capabilities of different simulations to create a more robust training environment. For example, JDLM can be used to model several logistics capabilities to include vehicle maintenance, medical care, mortuary affairs, and unit resupply. Federating JDLM with a combat simulation can create an environment where logistics units can train with a virtual combat unit to provide logistics support as needed based on a tactical scenario. In many cases, logistics training is often overlooked as most services tend to focus on training their warfighting elements. If resupply of a warfighting element fails during live training, negative training would occur, and training time and dollars would be wasted.

Using federated combat and logistics simulations together allows for logisticians including a CC to fail in the execution of their training event while not impacting another training unit. LVC allows the operator under training to explore the results of his or her decisions. They can fail, reset the event, and then re-perform the task once more to create an active learning environment. The training evaluators can also replay specific events to reinforce learning and provide relevant after action feedback. The capability to reset events, allows the CC to rethink his or her decisions and make changes based on feedback received real-time. Creating a federation is another capability that simulations provide to effectively train a broad range of units within one specific training event. With the ability to program red and blue behaviors, a logistics unit could potentially train with a MAGTF that does not need to be physically present. This alone makes implementation of LVC training absolutely critical within the Marine Corps.

5. Convoy Organization

The main purpose for training is to exercise decision making and rehearse TTPs and SOPs so that the time to make a decision and execute in a high stress environment is reduced. By integrating simulations and live training we are able to exercise these components between the various levels: convoy personnel, CC, and HHQ Commander at the COC. To execute training within convoy organization, simulations can be integrated to plan for movement controls including the type of column, operating gaps, positions of security and supporting units, and positions of control. Simulations in this case can give the CC and other operators more "sets and reps" in a variable environment without using resources such as fuel and unit funds to relocate units to different training areas.

For the types of columns and operating gaps, using constructive simulations can be used to evaluate the overall impact of formation adjustments made as simulations can execute them in multiple configurations in the context of a tactical scenario. The same can be said for the types of formations: file, staggered or offset. Using constructive simulations enables testing of each formation in different physical environments as well as their reactions to different critical points. The reaction to the physical environment is how the formation stands up against different changes in the terrain. Consider a convoy attempting to go through a narrow mountain pass. If the pass was too narrow to maintain a diamond formation, the vehicles would be stopped in close proximity to each other creating a greater potential for them to be ambushed. These are critical insights that a constructive simulation could provide during the planning phase of a training event.

In terms of the operating gaps, the intervals between vehicles, a constructive simulator is also able to enact different scenarios within varying terrain to see what the impact would be due to greater spacing. The CC will be able to see how much the increased in interval distance impacts the convoy's ability to mutually support each other, or maybe it did not have an impact and the CC can allow for a greater distance than they originally thought possible. The simulator can also add the effects of weather in this case. For example, if there are icy conditions, the interval will again increase to avoid collisions but it will enable the CC to see how different situations, ambushes or IEDs, are effected by the reaction times of the convoy due to the physical environment conditions.

6. Movement Plan and Security Enroute

To conduct training for the movement plan and security enroute areas of responsibility for the CC, we recommend the use of the CCS, described in Chapter II.E.2.a. This virtual simulator uses OneSAF and Virtual Battlespace 2 to create an immersive environment where vehicle operators can conduct hands-on training with pneumatic weapons (no projectiles) on a mock tactical vehicle in a realistic virtual environment. In this system, the CC and vehicle operators will be networked and sharing tactical C2 information displayed on their internal BFT. During the training and similar to an actual convoy operation, the commander and crew will need to maintain their situational awareness and balance combat tasks with tactical communications. Within the environment, the CC will be able to evaluate the crew’s performance of immediate action drills following an ambush. In addition, the unit will be able to replay these drills with different formations, intervals, and vehicle ordering.

Using OneSAF within this virtual simulator will enable the training event designer to stress the crews through the execution of virtual red force air, artillery, ground, and sniper attacks. If an attack should happen, it is essential for the CC to be able to communicate their PLI data to HHQ and surrounding units. The passing of PLI data will allow other units, air, or ground, to aid the convoy through a joint tactical air request or the use of a quick reaction force. Both require coordination with HHQ in the MAGTF and will create realistic training for the CLB command staff supporting the tactical convoy.

7. Service Support and Communication

The final two areas of responsibility to address are service support and communication. These two areas are mutually supporting and require interaction with HHQ via tactical communications links. Integration of requests for fuel or servicing during convoy operations can allow a MCC to exercise their unit support processes to ensure administrative requirements to track these events does not impact timely execution. This type of training is best executed via live simulation to ensure support personnel are aware of the coordination process and unit SOPs set up to provide real-time support requests. Constructive simulations can also be used in the event that live training cannot occur. For example, if a convoy ambush is modeled in a federation with JDLM, the specific vehicle damage will be registered in the simulation causing the MCC to need to coordinate for a specifically trained mechanic with select parts required for replacement. This integration of constructive simulations could test a logistics units' overall readiness to support operations.

8. Integration with Service T&R Manuals

Simulators have been used successfully in the aviation communities across the services. This can be attributed to detailed integration of simulations into their initial, continuous and sustainment training programs. For sustainment, pilots can log simulator flight hours monthly to maintain their 30/60/90-day currency. This same type of integration needs to be implemented in the logistics community. As LVC environments are enhanced, their training value also increases making simulations a viable solution to consistently train our force. Integration of the simulation training approaches detailed in this section into the T&R manuals within ground units will increase usage for training throughout the ranks.

D. EVALUATION

Coinciding with the CC checklist are the requirements of the T&R standards. The T&R standards evaluate Marines on an individual basis as well as evaluate certain larger scale functions that a unit must be able to perform.

> T&R Manuals are organized in one of two methods: unit-based or community-based. Unit-based T&R Manuals are written to support a type of unit (Infantry, Artillery, Tanks, etc.) and contain both collective and individual training standards. Community-based are written to support an Occupational Field, a group of related MOSs, or billets within an organization (EOD, NBC, Intel, etc.), and can contain both collective and individual training standards. (DOD, 2011b, p. 1-4)

T&R events have a specific identifier code to show the community being trained and at what level. Figure 32 and Figure 33 show how the code is broken down.

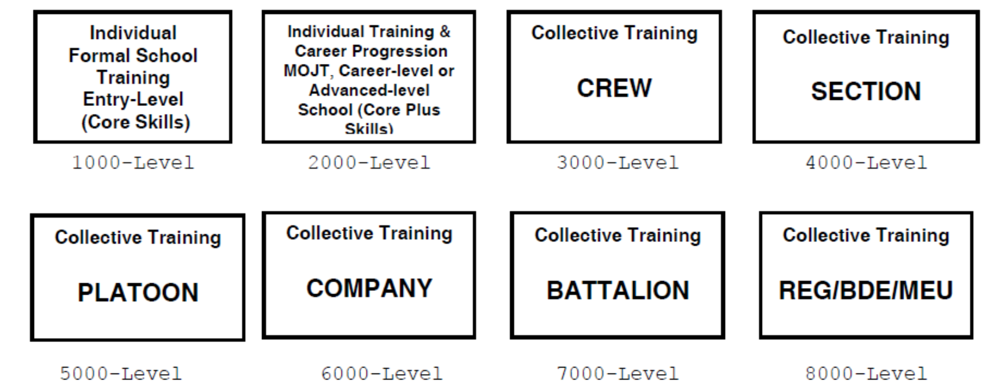


Figure 32. T&R event coding. Source: Department of Defense (2011, p. 1-5).

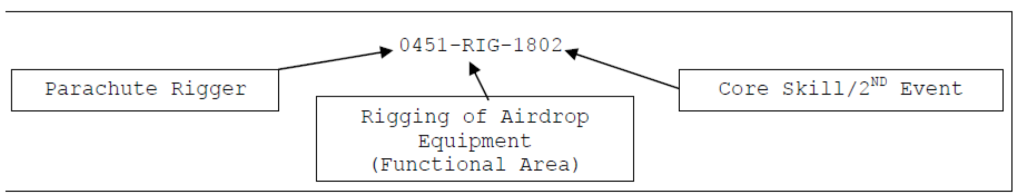


Figure 33. T&R event coding example. Source: Department of Defense (2011, p. 1-5).

1. Motor Transportation, 3531, T&R

The Motor Vehicle Operator's T&R Standards manual is comprised of multiple events starting at the lowest levels. A few important events to focus on will be shown in this thesis. Appendix B outlines the T&R event of transport 3531-OPER-2205: Conduct convoy operations. This event is a training requirement for individuals in the MOS of 3531, specifically for the billets of the Assistant Convoy Commander and CC. The standard is "arriving at a determined location with all required equipment and personnel" (DOD, 2012, p. 9-18). The event performance steps outline what is needed to fulfill the task correctly which correlates with the individual actions taught in the MOS courses.

Considering the task analysis performed in Section C above, the CC checklist is much more general than the T&R event described in 3531-OPER-2205. In this section, we will focus on how specific skills within this event could benefit from the use of LVC training environments. Those events include; direct the movement of a convoy using navigational devices, direct the movement of a convoy using communication equipment, and conduct a post mission AAR (DOD, 2012, p. 9-18).

Directing the movement of a convoy using navigational devices can be rehearsed in the CCS. As discussed in Chapter III.C.6, the CCS has an embedded BFT which contains the DAGR to update PLI data and the DU to show the geo-referenced PLI data collected within the AOR. Using the navigation capabilities of the BFT and aligning it the VBS2 virtual environment, a motor transport operator could track a convoy's exact location real-time for reporting to the CC. This training would be effective as the operator would be working simultaneously on navigation, communication, and systems usage skills through virtual training in a LVC environment with their unit.

The next performance step is directing the movement of a convoy using communication equipment. Similar to the previously mentioned performance step, again using the CCS, allows the convoy personnel to train on the real-world equipment and see how it is impacted in different situations and environments. By using the simulator, it allows the unit to be able to train in these various environments without spending the money or other resources transporting the unit to other locations.

Finally, the performance step of preparing a post mission AAR. Using a simulator, whether virtual or constructive, is very simple and beneficial to the unit. The simulators are able to record and then replay specific instances from the operation for the unit to be able to discuss what went well, what went wrong, and what they can improve upon.

2. Community-Based Logistics

In Appendix C is the T&R event LOG-OPS-5002: Conduct convoy operations. This T&R standard applies to a platoon size unit for evaluation and is under the logistics community T&R events. The standard of this event is, "in order to support movement timeline, maintaining safety and accountability" (DOD, 2011b, p. 3-45). Some of the event components that can benefit and expand the training experience for the Marines are; conduct cross boundary coordination, employ crew-served weapons from motorized platforms, direct the defense of the convoy, conduct escalation of force, react to enemy contact, supervise limited driving operations, and send and receive required reports (DOD, 2011b, p. 3-45).

First, expanding upon the communications necessary during a convoy; conduct cross boundary coordination and send and receive required reports. Using a constructive simulator as an overall picture of the AOR can show commanders how important it is to cross coordinate as culminating points could occur due to no coordination. Different units can also use a constructive simulator, such as VR Forces, and plan a mission, lay down their forces based on their missions, and see how they interact with each other. In addition, it is necessary for commanders to send and receive required reports. Simulators have the capability to force scenarios. Examples of specific situations that require reporting are ambushes, MEDEVACS, or IEDS. By the simulator forcing these scenarios onto the trainees, they are able to rehearse passing the required information and when to pass the information so that it does not impede on current operations.

The event component of employing crew served weapons from motorized platforms can be rehearsed in the CCS. When operating weapon systems, it is important to know how to operate the weapon and weapon corrective actions should the weapon system malfunction. In some of the vehicle suites of the CCS are vehicle mounted crew-served weapons. This enables personnel to get more hands-on experience with the weapon system in a safe controlled environment.

Finally, the performance events of direct the defense of the convoy, conduct escalation of force, and react to enemy contact are all TTPs that should be covered in the unit's SOP. By rehearsing these scenarios in the CCS, the personnel are shortening their reaction times on how to execute the proper response to a certain scenario, as well as, emphasizing how to execute these tasks in multiple environments. By controlling the scenario in a simulator, the scenario can be made more difficult and fluctuate according to the reaction of the personnel, making it a more dynamic and adaptive training tool.

IV. IMPLEMENTATION-LEVEL MODEL FOR CONVOY OPERATIONS

The final step in our top-level interoperability analysis is the development of the implementation level model. Based on our detailed assessment of the tools and systems available for convoy training and the training objectives we seek to meet, we have developed a RF mesh network connecting handheld ATAKs distributed across the training audience to allow for the real-time integration of simulated, dynamic red forces into the live training event. Since our goal was to implement this solution while minimally increasing the load requirements on Marines, we selected the lightweight GoTenna Pro X radios as the communications capability to enable the passage of simulation data between all subordinate, adjacent, and HHQ units. While the system is running, there are multiple forms of PLI data transmitted across the network to populate the COP on the ATAKs. The data takes the form of DIS, UDP, text string, COT, and XML through its life cycle. Our system ensures the timely and accurate transfer of the red force PLI data as it is intended to stimulate tactical decisions, operational maneuver, and force employment during the planning and execution phases of LVC convoy training. (Note: Although not specifically tested in this implementation level model, our system can also support the integration of virtual simulations.)

A. HIGH-LEVEL SYSTEM OVERVIEW

There are a few important features to highlight prior to describing the systems as a whole; the GoTenna Pro X radios create their own mesh network while none of the other components of the system are connected to any type of wired or wireless network, the GoTenna Pro X Radio connects to the laptop running the constructive simulation via USB, the GoTenna Pro X Radio connects to the tablet via Bluetooth; the application we created to pass COT schema data to the ATAK has been named "Gulliver," and the code we wrote is in Python and Kotlin.

Figure 34 shows the data flow in our implementation model. Point A is the GoTenna Pro X radio tethered to the laptop running a constructive simulation, which for our work is VT Mäk's VR Forces. When we run the tactical scenario created for convoy training, the DIS PDUs containing red force maneuver data are passed via the localhost to port 5006 as configured in the simulation menu shown in Figure 35.

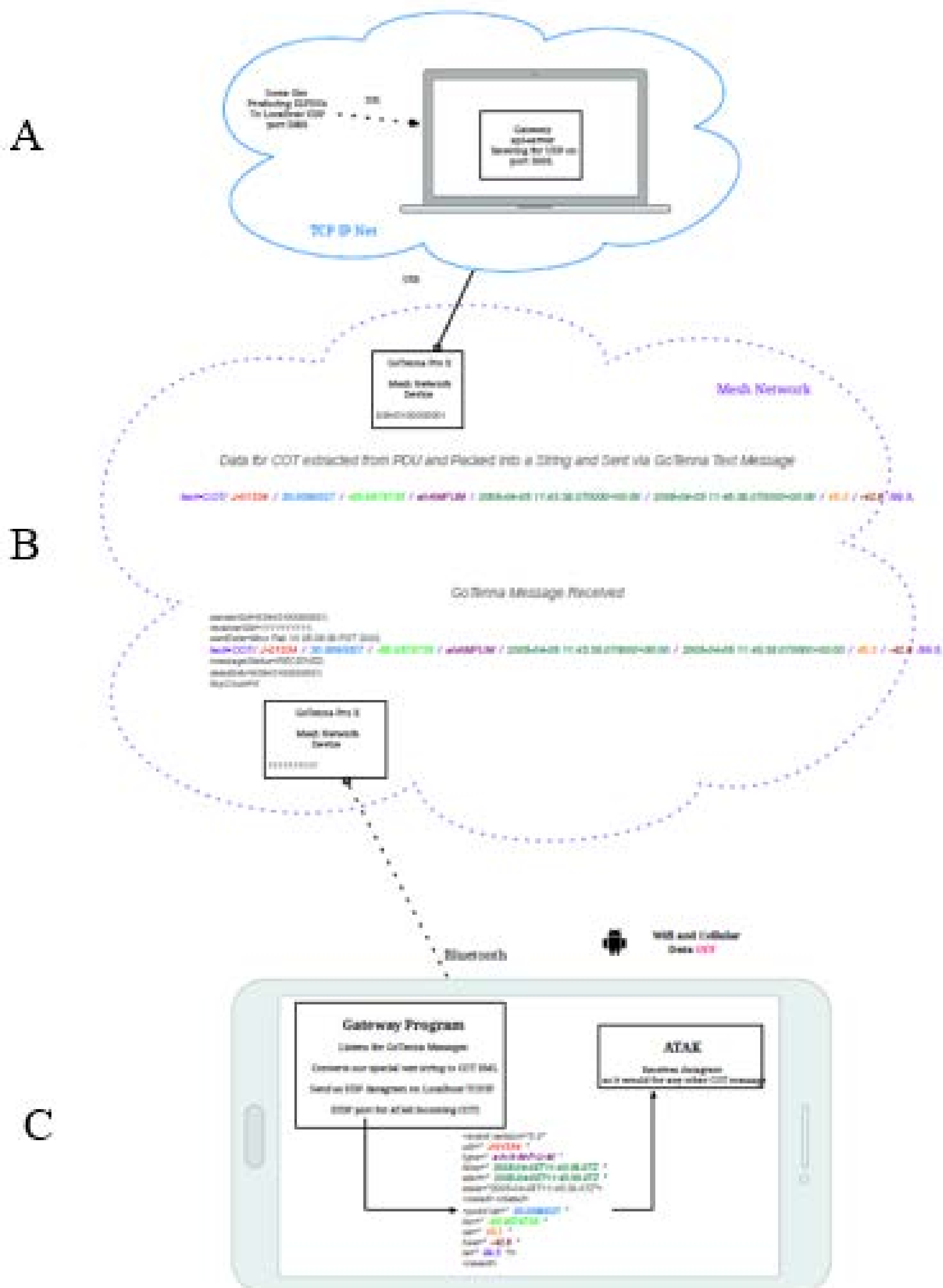


Figure 34. Gulliver data flow

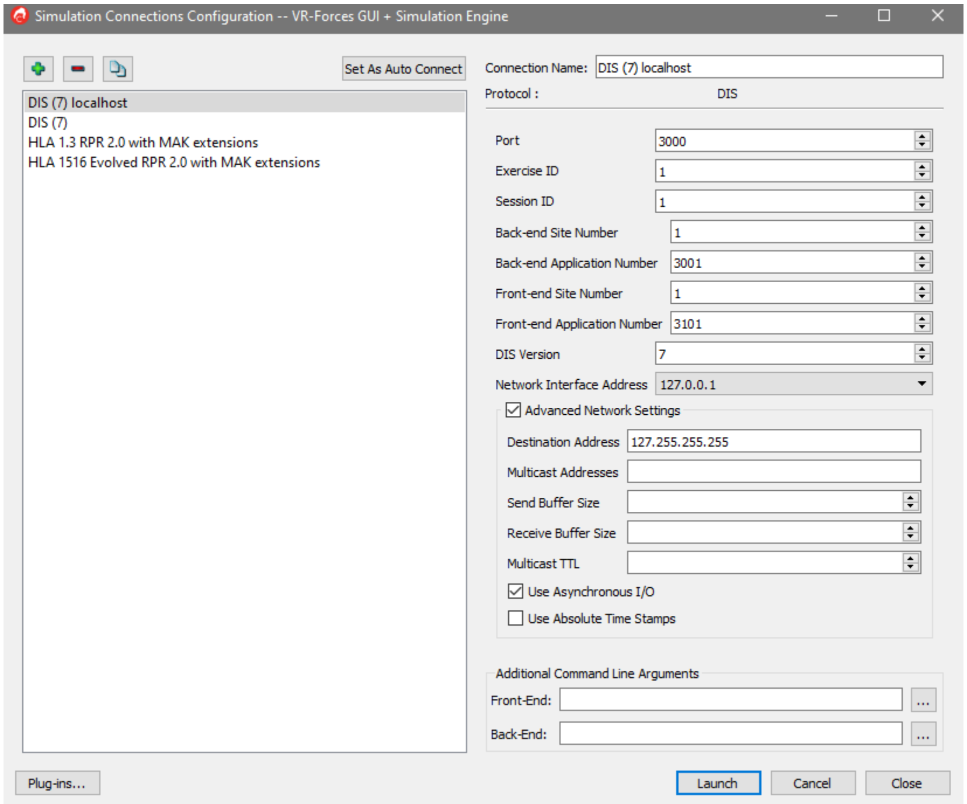


Figure 35. The simulation interoperability menu on VT Mäk's VR Forces. Source: VT Mäk (2020).

We then run the tactical convoy scenario shown in Figure 36. DIS PDUs are transmitted continuously for the entities modeled in the scenario. That data is extracted from the data packets and packed into a String. Then, the message is broadcast to the RF mesh network as a GoTenna Text Message and eventually is received by all other GoTenna Pro X radios in that network including the one schematically represented as Point B in Figure 34. At point C, the GoTenna Pro is connected via Bluetooth to "Gulliver" on the tablet where the message is received and converted and then passed as a COT message to be displayed as a track on ATAK.

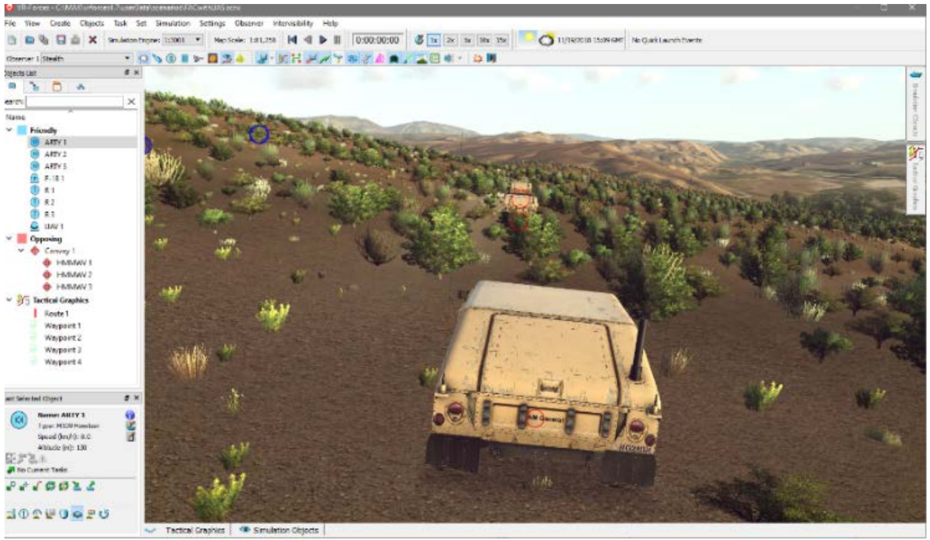


Figure 36. VR Forces convoy scenario. Source: VT Mäk (2020).

B. IN-DEPTH DATA FLOW INFORMATION

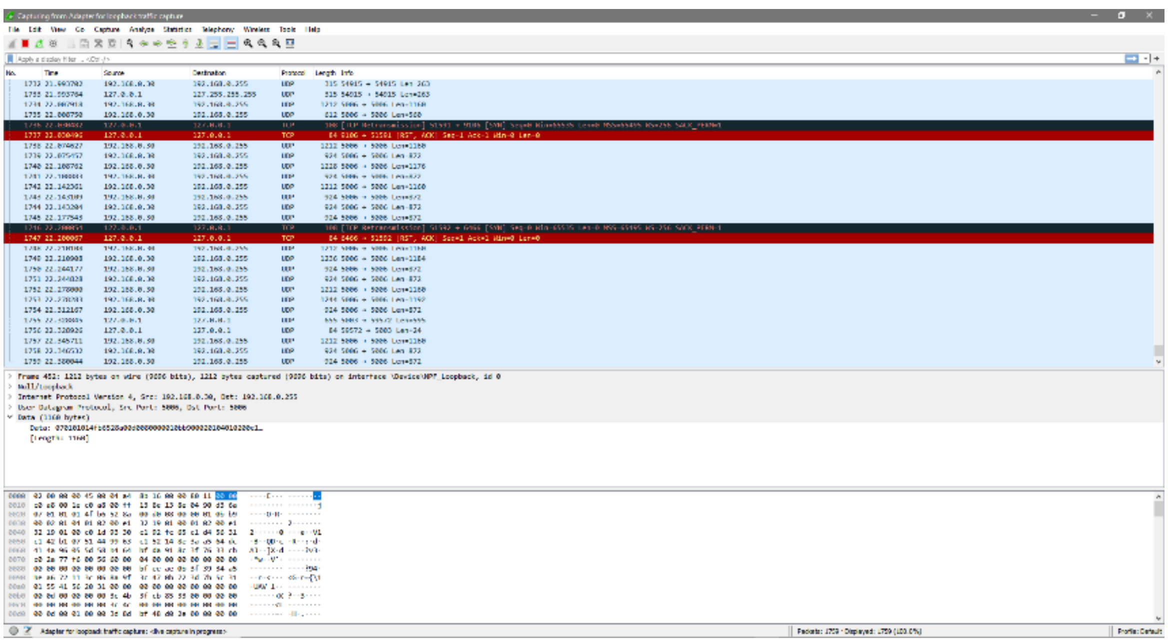
DIS Entity State Protocol Data Units (ESPDUs) are designed to provide ground truth information with enough resolution that different simulations and systems can rectify entities in their own local representation from a data stream. How that data stream is generated is of no concern to the receiving system. This is a hallmark of simulation interoperability. The system we developed is such a system, our local representation is track data represented in the COT data format.

GoTenna provides Software Development Kits (SDK) for several platforms; this supports developing software that communicates with the device hardware (via Bluetooth for Android and iOS, and via USB on other devices using Python). To broadcast and receive messages, our code makes use of the SDK’s data structures and commands.

The data structure of interest here is the message, and the message payload type defined in the SDK (Location Payload). We selected the most general message type offered by the SDK, which allows for an arbitrary text string to be transmitted along with the location. This message’s complete payload consists of location and time data, several fields used internally by the GoTenna mesh protocol, and our message. We use data contained in an ESPDU produced by our simulation in Figure 34, Part A, to fill in time and location fields; the other data needed to create COT is derived from the PDU and encoded into a string that is placed in the text field.

1. Part A

For our work in this section, we used Wireshark to capture the ESPDUs being transmitted on the loopback address (127.0.0.1) to port 5006 to determine if our initial data source was passing the appropriate information. Figure 37 is an actual Wireshark screen capture taken during system development. Figure 37 shows the ESPDU sizes ranging from 1160 bytes to 1192 bytes, which far exceeds the data transfer capabilities of the GoTenna Pro X radio at ~250 bytes. This was our first major hurdle in the development of the implementation model.



Screenshot of Wireshark Screen running at NPS

Figure 37. Wireshark screen capture used to assess ESPDU size

To address this issue, we used Wireshark to perform comparative analysis between the data contained in the ESPDUs and the requirements for “Gulliver” to create a COT XML message to pass to ATAK. Since ATAK is a tactical system, it does not understand DIS. Instead, it understands the world in terms of track reports. Specifically, it is able to display basic COT XML messages shown later in Figure 43. Understanding this compatibility issue, we had to decide where the best place would be to translate the entity state data into track data. We selected the PC for this because track data is closely aligned to how data is formatted and expected for processing within the GoTenna SDK. In addition, as shown in Figure 38, there is a lot of extraneous data in an ESPDU that can be easily filtered on a PC to fit the message size constraints of the GoTenna Pro X radio.

```
# The tree-like structure of contained classes in this representation is useful, but
keep in mind
# the wire protocol for DIS is flat, just read the fields in order.
# For example, nothing in the wire-protocol corresponds to  "entityId", there is just
# the three fields shown here as fields of "enitityID"

protocolVersion: int
exerciseID: int
pduType: int
protocolFamily: int
timestamp: int
length: int = 0
pduStatus: int = 0
padding: int = 0
protocolFamily: int = 1
entityID:
    siteID: int
    applicationId: int
    entityId: int
forceId: int
numberOfVariableParameters: int
entityType:
    entityKind:
    domain: int
    country: int
    category: int
    subcategory: int
    specific: int
    extra: int
alternativeEntityType:
    entityKind: int
    domain: int
    country: int
    category: int
    subcategory: int
    specific: int
    extra: int
entityLinearVelocity: tuple
entityLocation: tuple
entityOrientation:
    psi: float
    theta: float
    phi: float
entityAppearance: int
deadReckoningParameters:
    deadReckoningAlgorithm: int
    parameters: List[float]
    entityLinearAcceleration: tuple
    entityAngularVelocity: tuple
marking:
    characterSet: int
    characters: List[int]
capabilities: int
variableParameters: List
```

Figure 38. ESPDU code model

Once the ESPDU is established it is stored on the localhost of the computer for the next step in the system to access it.

2. Part B

A close-up image of Part B in the diagram is displayed in Figure 39.

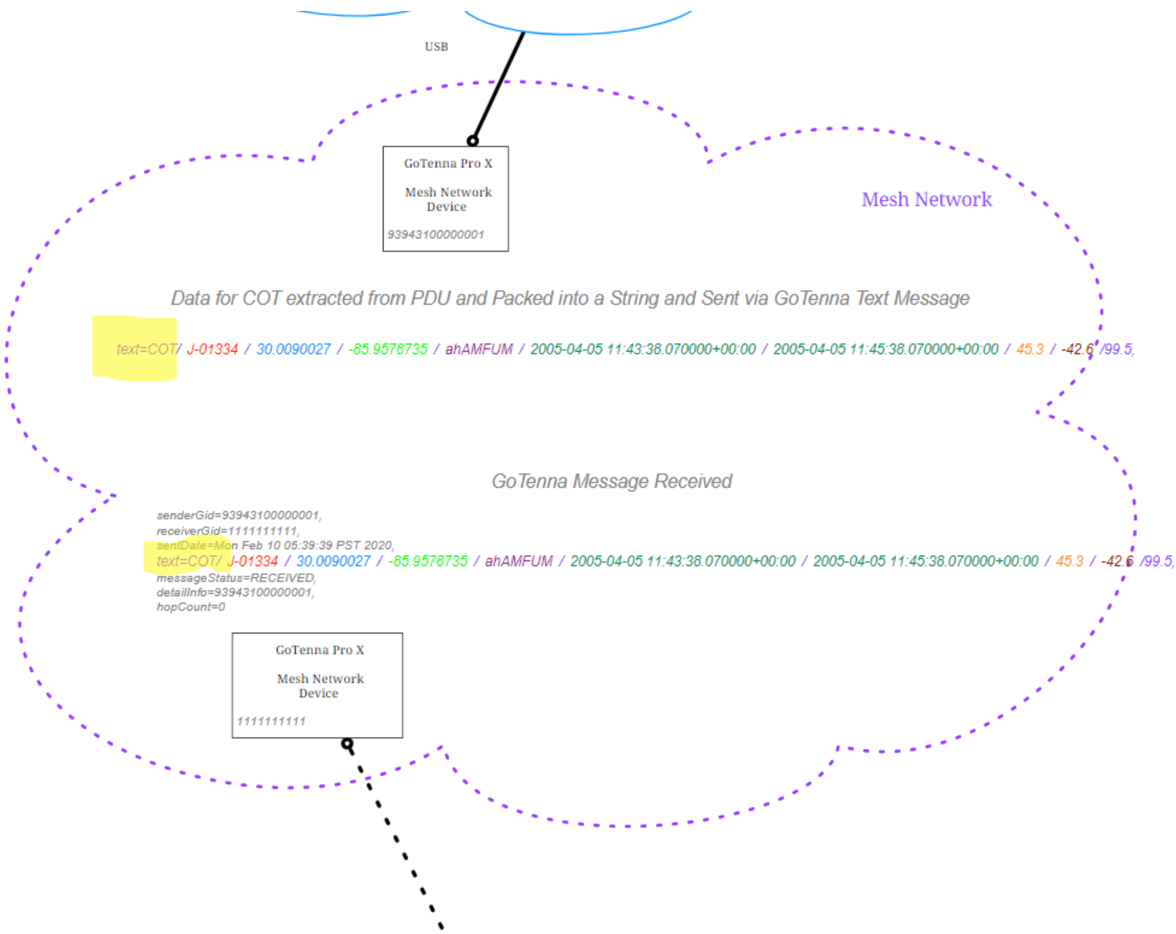


Figure 39. Part B

Part B of our system again makes use of the GoTenna SDK, this time receiving notifications from the device driver that the device has received a message. We must inspect each message and determine if it is of the type that could contain our encoded COT string, and if it is, then attempt to decode that string to build a string in the COT XML data format. This conversion from GoTenna payload to COT XML is discussed in Part C.

That information from the EDPDS will populate the constructor titled CotEvent, shown in Figure 40.

```
class CotEvent(BaseModel):
    version: float = 2.0
    uid: str
    type: str
    time: struct_time
    start: struct_time
    stale: struct_time
    point:
        lat: float
        lon: float
        ce: float
        hae: float
        le: float
    detail: Optional[dict] = None # Could put dead reckoning data here, maybe
```

Figure 40. CotEvent code

The information from CotEvent is then used to populate the fields in the GoTenna message payload data structure provided by the SDK. In Figure 39, there is a line that states text=COT, it is highlighted in yellow for easy distinction, that shows that the ESPDU data has successfully been converted into a COT text format that is being transmitted over the RF mesh network created by the GoTenna.

3. Part C

Figure 41 displays Part C of the system diagram.

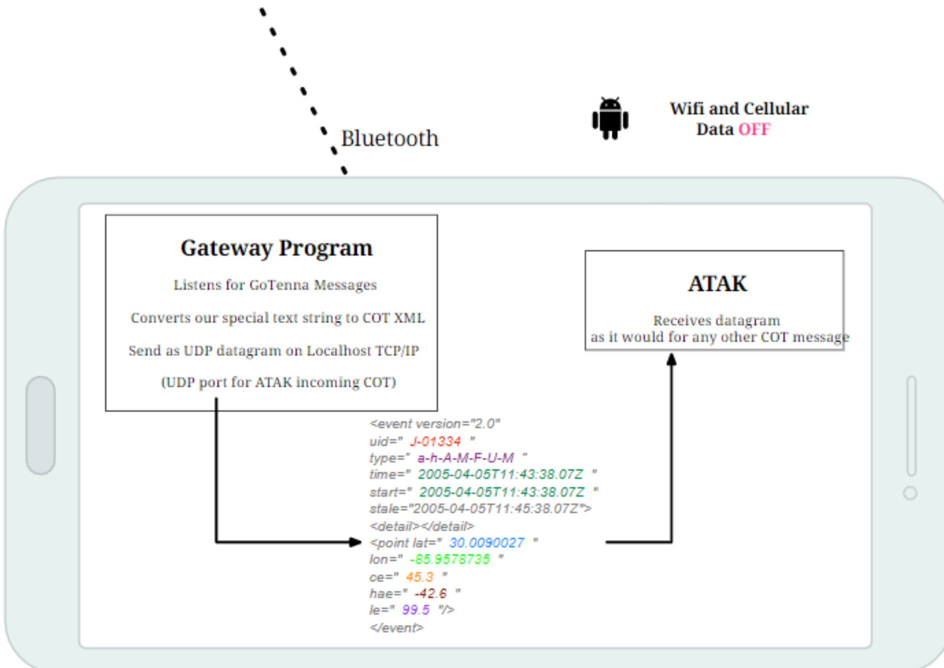


Figure 41. Part C

Part C is the Android tablet with Gulliver and ATAK installed. As far as GoTenna is concerned, our program, "Gulliver" does two things: (1) it manages pairing and unpairing of the GoTenna via Bluetooth, and (b) registers with the GoTenna SDK to receive notification of message receipt. When the device receives a message, it calls the registered callback function of all registered "listeners," passing the message data as an argument.

When Gulliver's callback is invoked by the SDK, the argument is a structure depicted in Figure 42. Gulliver then processes the message payload using the function, cotFromMessage, which will look at the text field of the message to see if it begins with "COT/." If it does, then the code will parse the text of the message to extract COT data. An example of what this data model looks like is in Figure 43.

```
Message(
    senderGid=93943100000001,
    receiverGid=1111111111,
    sentDate=Mon Feb 10 05:39:39 PST 2020,
    text=COT/J-01334/30.0090027/-85.9578735/ahAMFUM/2005-04-05
11:43:38.070000+00:00/2005-04-05 11:45:38.070000+00:00/45.3/-42.6/99.5,
    messageStatus=RECEIVED,
    detailInfo=93943100000001,
    hopCount=0
)
```

Figure 42. Representation of the GoTenna message payload passed to Gulliver's callback function

From the parsed message in Figure 42, the code will convert it into XML format which looks like Figure 43.


```
<event version="2.0"
   uid="J-01334"
   type="a-h-A-M-F-U-M"
   time="2005-04-05T11:43:38.07Z"
   start="2005-04-05T11:43:38.07Z"
   stale="2005-04-05T11:45:38.07Z">
<detail></detail>
<point lat="30.0090027"
       lon="-85.9578735"
       ce="45.3"
       hae="-42.6"
       le="99.5"/>
</event>
```


Figure 43. XML data model

Figure 44 shows a breakdown of the data in the COT data model, specifically the type of entity. Analyzing Figure 43, the type would be atom, hostile, air, based on the information shown in Figure 44. Specific information on the type of system modeled is contained in MIL-STD-2525.

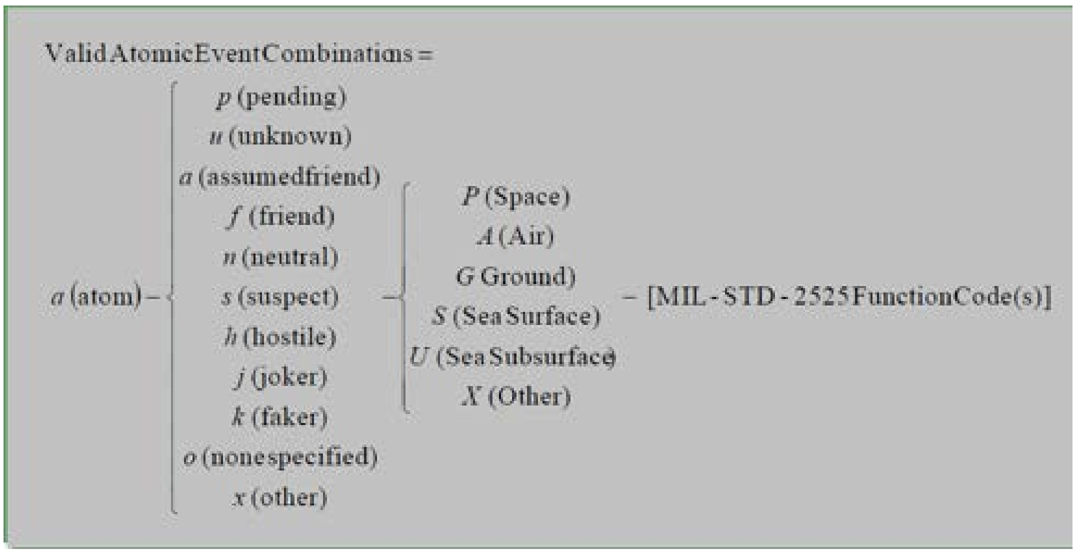


Figure 44. XML breakdown. Source: Kirstam et al. (2009, p. 2-4).

The XML from Figure 43 is then put onto the Android's local network as a UDP datagram, which ATAK will receive on the configured COT UDP multicast port. Figure 45 shows the user interface on the Gulliver application.

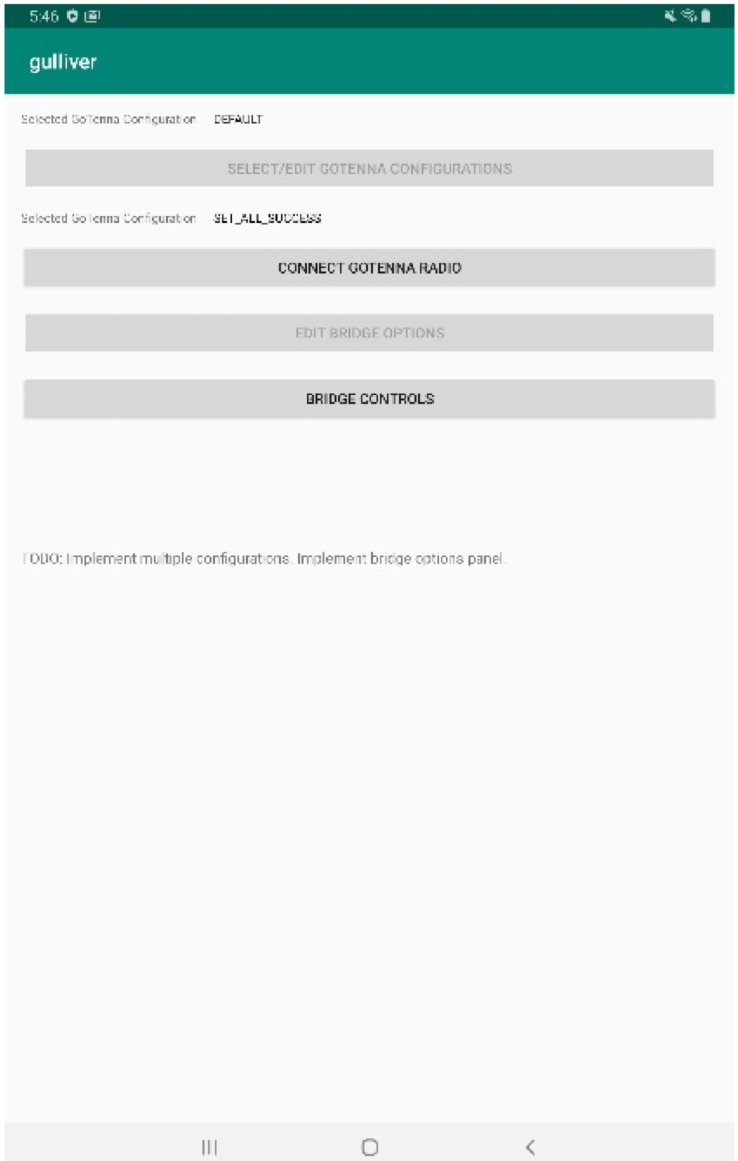


Figure 45. Gulliver UI on the Android tablet

This chapter went through the specifics of the code necessary to transform the data into the required formats to be able to transmit. There are other code intricacies that are discussed in Appendix D that are needed to run Gulliver.

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V. CONCLUSION, FINDINGS AND FUTURE WORK

A. CONCLUSION

In the performance of a top-level interoperability analysis to conduct tactical convoy training in the Marine Corps, this thesis created a unique technical solution to better enable dynamic LVC training at the small unit level. Through the implementation of a robust mesh network consisting of a constructive simulation and multiple, handheld Android-based C2 systems, we created an interconnected training solution to stimulate decision making at all echelons of command within a logistics unit, such as a CLB or a Transportation Support Battalion. Figure 46 is an image of our system in action. The reality, with geopolitical conditions constantly in a state of flux, military training needs to be more dynamic to prepare our Marines for the asymmetric threats they will face on future battlefields. The research questions posed in Chapter I led us down the path to building this implementation level model. Now that we are complete, we will review and assess those questions to identify future research in this area.

Figure 46. Gulliver system running

(1) Can currently fielded Android-based C2 systems provide the same tactical fidelity and functionality as the BFT?

Yes. The most critical functions of the BFT are message transmission and geospatial situational awareness. This capability was proven in many live demonstrations that happened to use some of the same components that made up our system. MCWL was able to use the systems as communications for their white cell during Project Metropolis II. In addition, troops were also using this system architecture during Exercise Information Warrior 18 and Exercise Joint Warrior 18, proving that this system is capable of acting like a BFT in a tactical environment. The only limitations discovered are possible range issues, that were also improved upon by elevating one GoTenna to act as a relay and improve the range of the network.

(2) Do the RF mesh network bandwidth limitations affect tactical situational awareness when used to share data across a tactical network?

Considering this in a tactical, real world environment, the answer is no. The number of messages sent per minute can be adjusted and there have not been any reported issues of any bandwidth limitations on a real-world tactical network. However, when we switch to the LVC network developed in this thesis there may be bandwidth issues as the size and complexity of the training event increases in scope. Based on analysis of DIS PDU transmission rates in the execution of a constructive simulation, data packets are sent every 1/10 of a second. This is to ensure accuracy between interoperable simulations. This level of accuracy is not necessarily needed in the conduct of LVC training events. Thus, we can develop filters to minimize the amount of traffic on the network. When processing DIS PDUs into the COT format on the PC during our implementation, we were able to significantly reduce the load on the network by removing extraneous data in the PDUs. A more sophisticated filter would be required as LVC events increase in scale. A possible filter suggestion to be considered for future work is described in Section B of this chapter.

(3) Are the messaging architectures for the BFT and other Android-based C2 systems capable of supporting the detailed simulation protocol data produced by constructive simulations used for LVC training?

Yes, the systems are capable, specifically the Android based C2 system, ATAK. During our research we discovered, there was a method that had previously been used on the BFTs to integrate constructive simulations. It involved personnel riding in the back of the vehicle with another computer system that was connected to the BFT in the front. Minimal information about this system was available as it was an old practice and very cumbersome, so it was hardly used. In addition, since the guidance came out to find an alternative to the BFTs, it seemed practical to not focus on that system and to work on the Android-based systems that are starting to become more prominent in the military. The Android-based C2 system developed in this thesis is capable of supporting the detailed simulation protocol data produced by constructive simulations. As discussed in Chapter IV, there was a lot of data structure manipulations that had to be done to convert the data into the correct format to be transmitted over the network, due to required methods used by the devices that were used in this system. There is the possibility to further analyze and test other antennas that produce an RF mesh network or their own WiFi network to ease some of the computational effort of the system.

(4) Are communication systems used in a simulation environment capable of operating in and supporting live operations?

Determining if "Gulliver" is capable of this is still a work in progress. We know that when used solely in the realm of live training that this system works. We also know that when integrating live and constructive simulations that this system is able to pass PLI data. However, that data passage is currently only one way, from the constructive simulation to the live tablet. In order to determine if the communication system will act correctly in the simulation world, we must first be able to add more devices and have them communicate device to device as well as simulator to device before we can fully answer this question.

B. FUTURE WORK

1. Integration of Discrete Event Simulation

As this system stands it creates a LVC environment. However, there are a few known ways to improve the system. Before the system becomes more adaptable and a greater number of components can be joined to the network it must first have discrete event simulation (DES) calculations incorporated versus the current time step method associated with DIS. By integrating DES, it would essentially act as a filtering system for the data being transmitted over the network. It is important to integrate a filter due to the vast number of messages LVC events produce. With that, the potential for message collisions increases thus, a loss of information.

DES is defined as a combination of dead reckoning and a time-stamped location. Dead reckoning is determining an entity's location by using known information such as previous course and speed. When DES becomes integrated into the system, the dead reckoning capability would register the entity's current state, such as current state and speed, and determine the entity's location. This would be done with minimal messages and a new message would only be transmitted if a state of that entity should change, consequently altering the previous dead reckoning course. For example, a vehicle in the convoy is continuing along the route but has engine problems and needs to stop. The system would produce an original message with the information that this vehicle is moving with course and speed data. Then, when the vehicle's speed changes, in this case goes to zero, a new message will be transmitted for the system to update the location of the entity. With messages being filtered to only being sent when a state change occurs, less of the bandwidth is being used, creating better communications.

2. Two-Way Communications

A further addition to the system is to make it a two-way interaction. As of now the data is only sent one way, from the constructive simulation to the live simulation feed on the tablet. The next step is to now take the data from the live component, the tablet, and be able to populate the constructive simulation with live data. Ultimately, virtual simulations would be populated and populating the other simulations as well. As the number of components that can be connected to the system increases, it will be easier to manage the bandwidth limitations if the DES method is already functioning

3. Expanding to Virtual Simulations

Further expanding this system to also include virtual systems, such as a flight simulator, enables a more realistic and robust training environment to be created. By data populating from a live component, such as a convoy, a virtual component, such as a flight simulator, and a constructive component, such as VR Forces, a unit will be able to train all levels of leadership and all levels of communication that take place on a mission.

C. FINAL CONCLUSION

This thesis focused on one specific use of LVC. Continued adjustments need to be made as already stated in order to allow for more robust and larger scale exercises to be conducted. However, by using LVC, the scenarios and training that can be conducted is limitless. Based on the work this thesis was able to produce, the Marine Corps should continue testing the capabilities of this system architecture but also push the limits of the system. This thesis was just one aspect of how the system can be incorporated into live and training scenarios. With further exploration the Marine Corps could potentially find a new light weight communication system that is dual purpose and also allows them to integrate simulation training effortlessly.

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APPENDIX A. CONVOY COMMANDER CHECKLIST

This Appendix contains the Convoy Commander Checklist taken from *MCRP 4–11.3f Convoy Operations Handbook* (USMC, 2001).

Mission Requirements

- Current Intelligence/Situation
- Task Vehicles: Type and Quantity
- Personnel
- Cargo by Type, Class, and Size
- Security Vehicles: Type and Quantity Maintenance Vehicles
- Materials Handling Equipment
- Command and Control Vehicles: Type and quantity Lighting/ Blackout Conditions/NVGs

Reconnaissance

- Map and Photo
- Physical

Route Selection

- Road
- Bridges and Tunnels
- Grades and Curves
- Traffic Density
- Requirements for Route Preparation or Repair

Liaison and Coordinate

- Units along Route
- Units Being Moved
- Supporting Units
- Highway Control Agencies/ Movement
- Control Centers
- Shippers/Cargo Handlers
- Engineer/explosive ordnance disposal requirements

Convoy Organization

- Size of Serials/March Units
- Type of Column
- Operating Gaps
- Serials/March Units
- Vehicles
- Positions of Security and Supporting Units
- Positions of Control Personnel/ Escorts Guides
- Organization for Command
- Vehicle Marking

Movement Plan

- Controlled Route
- Convoy Clearance/Movement Credit
- Road Movement Table
- Special Permits or Authorization
- Distance, Time, and Rate of Movement
- Trip Distance
- Required Start Time
- Column Length
- Slowest Vehicle
- Required Delivery Time
- Rate of Movement/Speed (Speedometer Multiplier) Maximum Catch-up Speed

- Loading
- Time and Place
- Report to
- Type/Class Cargo
- Outsize Loads
- Materials Handling Equipment Required Blocking, Bracing, and Cargo Restraints
- Staging
- Location
- Vehicle Checks
- Cargo Checks
- Time to Start Point
- Operator Briefing
- Start Point
- Location/Grid Coordinates
- Identification Characteristics
- Checkpoints
- Locations/Grid Coordinates
- Identification Characteristics/ Alphanumeric Designators
- Guides and Markers
- Positions
- Posting and Pickup
- Halts
- Purpose
- Time Duration
- Locations
- Maintenance
- Trail
- Enroute Support
- Medical Support
- Organic Capability
- Evacuation
- Release Point
- Location/Grid Coordinates Identification Characteristics
- Report Requirements
- Control of Vehicles and Operators Unloading
- Time and Place
- Report to HHQ at Destination
- Materials Handling Equipment Required
- Backload and Turn Around

Security Enroute

- Action in Event of Attack
- Air Attack
- Artillery Attack
- Ground Attack
- Sniper
- Air Support Procedures
- Fire Support Procedures
- Use of Lights/Blackout Restrictions

Service Support

- Fuel
- Location/Times
- Types and Quantity Accompanying Convoy
- Messing/Rations
- Locations/Times
- Units on Route
- Prescribed Loads

Communications

- Convoy Control Net
- Serial/March Unit Commanders Parent Unit/Headquarters
- Alert/Broadcast Net
- Security/Tactical Nets
- Fire and Air Support Nets Medical Evacuation
- Visual Signals
- Sound Signals
- Interpreter Requirements

Convoy Commander After Action Report

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APPENDIX B. T&R EVENT 3531-OPER-2205: CONDUCT CONVOY OPERATIONS

This Appendix shows an example of a T&R event, specifically to Conduct Convoy Operations taken from the *NAVMC 3500.39B motor t T&R manual* (DOD, 2012, p. 9-18).

3531-OPER-2205: Conduct Convoy Operations

EVALUATION-CODED: No **SUSTAINMENT INTERVAL**: 12 months

MOS PERFORMING: 3531

BILLETS: Assistant Convoy Commander, Convoy Commander

GRADES: CPL, SGT

INITIAL TRAINING SETTING: FORMAL

CONDITION: Given references vehicles, personnel, required tools, cargo and equipment.

STANDARD: Arrival at determined location with all required equipment and personnel.

PERFORMANCE STEPS:

1. Analyze the order
2. Organize the convoy in march order.
3. Identify classifications for routes.
4. Identify defense requirements
5. Identify convoy communication
6. Inspect cargo loads
7. Direct the movement of a convoy using navigational devices.
8. Direct the movement of a convoy using communications devices.
9. Conduct a convoy mission brief.
10. Conduct a post mission debrief.
11. Prepare a post mission After Action Report (AAR).

REFERENCES:

1. FM 21-305 Manual for Wheeled Vehicle Driver
2. FM 55-30 Army Motor Transport Units and Operations
3. MCRP 3–40-3A Multi-Service Communications Procedures and Tactical Radio Procedures in a Joint Environment
4. MCRP 4–11.3F Convoy Operations Handbook

5. MCRP 4–11.3H Multi-service Tactics, Techniques and Procedures for Tactical Convoy Operations
6. MCRP 4–11.4A Recovery and Battle Damage Assessment and Repair
7. MCWP 3-17.1 Combined Arms Gap-Crossing Operations
8. MCWP 4-1 Logistics Operations
9. MCWP 4-11 Tactical-Level Logistics
10. MCWP 5-1 Marine Corps Planning Process (MCPP)
11. MSTP PAM 4-0.1 Movement Control
12. NAVSEA OP 5 VOL 1 Ammunition and Explosives Ashore Safety Regulation (ESQD Information)
13. NAVSEA OP 5 VOL 2 Ammunition and Explosives Ashore Safety Regulation
14. NAVSEA SWO20-AF-ABK-010 Motor Vehicle Driver and Shipping Inspector's Manual for Ammunition, Explosives, and Related Hazardous Materials
15. NAVSEA SWO20-AG-SAF-010 Navy Transportation Safety Handbook for Ammunition, Explosives, and Related Hazardous Materials
16. TM-09880C-0R Operator's Guide, DAGR Operator's Pocket Guide
17. TM 11240-OD_ Principal Technical Characteristics of U.S. Marine Corps Motor Transport Equipment

APPENDIX C. T&R LOG-OPS-5002: CONDUCT CONVOY OPERATIONS

This Appendix shows an example of a community-based T&R event, taken from *NAVMC 3500.27B logistics training and readiness (T&R) manual* (DOD, 2011b, p. 3-45).

LOG-OPS-5002: Conduct convoy operations

SUPPORTED MET(S): None

EVALUATION-CODED: NO **SUSTAINMENT INTERVAL:** 12 months

DESCRIPTION: This event is for any platoon-sized unit tasked to conduct convoy operations.

CONDITION: Given a mission, personnel and equipment.

STANDARD: In order to support movement timeline, maintaining safety and accountability.

EVENT COMPONENTS:

1. Receive/review intelligence reports.
2. Determine lift requirements.
3. Conduct route reconnaissance.
4. Task organize.
5. Develop a movement plan.
6. Submit movement plan to higher headquarters.
7. Coordinate cas/medevac support procedures.
8. Direct loading operations.
9. Issue order to all organic, attached, and supporting units.
10. Conduct pre-combat actions, checks/inspections.
11. Establish convoy communication.
12. Direct the movement of the convoy.
13. Conduct cross-boundary coordination.
14. Employ current technology and equipment (eg., comm, BFT, CREW).
15. Employ crew-served weapons from motorized platforms.
16. Direct the defense of the convoy.
17. Conduct escalation of force.
18. React to enemy contact (e.g., IED, small arms, complex ambush).
19. Supervise vehicle fording operations.
20. React to a vehicle roll over.
21. Supervise vehicle recovery operations.
22. Supervise field expedient repairs.
23. Supervise limited visibility driving operations.
24. Send and receive required reports.
25. Conduct convoy debrief with convoy personnel.

26. Conduct mission debrief with appropriate staff.
27. Prepare mission after-action brief.

REFERENCES:

1. FM 20-22 Vehicle Recovery Operations
2. FM 20-30 Battlefield Damage Assessment and Repair
3. FM 55-15 Transportation Reference Data
4. MCRP 4–11.3 Transportation Operations
5. MCRP 4–11.3F Convoy Operations Handbook
6. MCWP 4-11.3 Transportation Operations
7. Unit SOP

APPENDIX D. OTHER CODING INTRICACIES

There are many unique aspects of the way in which this code had to be designed in order to integrate the GoTenna SDK and all the data types. This appendix goes over more code intricacies such as how to connect the system as well as shows more coding from the system.

A. GOTENNA SDK

1. Encryption

In order to be able to use the services provided by the GoTenna SDK, a static global configuration with the GoTenna Pro SDK must be done first. This configuration sets up the crypto key used by the device firmware and is required before the SDK will connect to the device. The key is applied to the GoTenna device itself when paired via Bluetooth or when using a USB connection. Only antennas with the same application token can interpret the mesh communications from other antennas using that token. The device cannot have more than one token configured at a time, therefore all applications on the Android or computer using the SDK that want to have simultaneous access to the antenna must use the same token. Tokens are issued by the GoTenna manufacturer to ensure that developers all have their own, unique, tokens. This prevents developers from interfering with each other, but it also prevents the simultaneous use of applications developed by different developers with a single GoTenna. (It is possible, however, to have more than one GoTenna paired at a time. In this case, the application from each developer would access only one of the GoTennas).

2. Gulliver Python Application (PC. Raspberry Pi, etc.)

Within the GoTenna SDK there are a wide range of classes with different functions, we are calling them “services.” In order to be able to use these services, you must instantiate each as a singleton.

> A singleton is a class that allows only a single instance of itself to be created and gives access to that created instance. It contains static variables that can accommodate unique and private instances of itself. It is used in scenarios

when a user wants to restrict instantiation of a class to only one object. This is helpful usually when a single object is required to coordinate actions across a system. (Techopedia, 2011)

Most of these objects are designed such that you register handlers that you want to be called when certain events take place on the GoTenna device. Figure 43 is an example of a handler that was created to listen for UDP datagrams.

```
async def start(self):
    self._loop = asyncio.get_running_loop()
    print(f"Starting DIS listener from anywhere on port 5006")
    await self._loop \
        .create_datagram_endpoint(self.make_dis_protocol_handler(self._queue),
local_addr=('0.0.0.0', 5006))
```

Figure 47. Handler listening to UDP datagrams

Figure 44 is the code that returned a handler class.

```
def make_dis_protocol_handler(self, queue: Queue): ①

    class DisProtocol(asyncio.DatagramProtocol): ②
        def __init__(self):
            super().__init__()

        def connection_made(self, transport):
            self.transport = transport

        def datagram_received(self, data, addr): ③

            # Use open-dis to parse the datagram into the open-dis model of a PDU.
            pdu = createPdu(data)

            gps = GPS() # used to convert DIS x,y,z to lat, lon, elevation
            d = gmtime() # a timestamp used in various date/time fields of the COT
data model

            # We immediately drop any Pdu that isn't an open-dis EntityStatePdu
            # Note that the open-dis pdu type does not numerically line up with the
SISO
            # standard, where Entity State Pdus are PDU type 67,

            if pdu.pduType is 1:

                # Code to convert data from the pdu is elided for brevity
                lat = #...
                lon = #...
                hae = #...

                pdu_model: EntityStatePdu = espdu_to_model(pdu) ④

                # Use data in our DTO to construct the values needed for the COT data
format

                site_id = pdu.entityID.siteID
                app_d = pdu.entityID.applicationID
                ent_id = pdu.entityID.entityID

                # We build the COT uid field from the PDU's identifying data.
                # The simulation site id, application id and entity id

                uid = f"{site_id}-{app_d}-{ent_id}"

                # Build  the COT Point model from pdu data

                cot_point = CotPoint(lat=lat, lon=lon, ce=0.0, hae=hae, le=0.0)

                # Build the COT Event model

                cot_event = CotEvent(
```

Figure 48. Return of a handler class

```
                uid=uid,type=type_string, time=d,
                start=d, stale=d, point=cot_point
            )

            # and finally the whole COT data model

            cot: Cot = Cot(event=cot_event)

            go_tenna.broadcast_cot(cot) ⑤

            # command messages for the ASGI Queue are elided
            # The queue messages are used to push data to the local
            # websocket for the UI to display and could be used for
#           # logging or storage to some persistence layer.

    return DisProtocol
```

Figure 48. (con't) Return of a handler class

On the right side of the code in Figure 44, there are red numbers in circles to explain different components of the code.

1. Factory to create an instance of a custom subclass of ayncio.DatagramProtocol. This is called to provide the handler class to the create_datagram_endpoint factory method of the ayncio library.
2. Start the subclass definition
3. Template method called by asyncio whenever a UDP datagram is received
4. Build our own pydantic data model of an ESPDU. This is a data transfer object we can pass around in asyncio queue messages. There's no queue messaging here right now because those message's purpose is driving the local web UI and logging, etc, which isn't really implemented yet.
5. Send out COT data model to a service function that knows how to send a GoTenna message.

The pydantic data model referenced in step 4 is a python library. More information and help about this library can be found through the pydantic website (Pydantic, n.d.).

B. GULLIVER ANDROID APPLICATION

When the Gulliver application is started, it sets up the GoTenna SDK with critical values such as our unique application token and a GID and username for the device. The token is common with the one used in the python application on the PC. It is a method to ensure that only our applications are the ones communicating with each other. The GID is a unique identifier for a device within the namespace established by the token. While the username is intended to be a friendly name representation of the GID for display purposes. Next, the application starts the GoTenna SDK in the background to handle events created by the GoTenna, i.e., incoming messages. Figure 45 shows the steps Gulliver takes in detail.

1. Initialize the SDK as described above. This sets the application token, and is performed in the Android `Application` subclass called `GulliverApp` so that it is performed as early as possible in the application lifecycle.
2. Initialize all the needed GoTenna service modules (from the SDK) using a dependency injection framework, KOIN (Each of these classes has some minimal documentation in the GoTenna documentation and javadocs):
    1. Create a `UserDataStore`
    2. Create a `BluetoothAdapterManager`
    3. Create a `GTConnectionManager`
    4. Create a `GTCommandCenter`
    5. Create a `SetFrequencySlotInfoInteractor`
3. Perform checks on the SDK to determine if everything is ready for Bluetooth pairing of the GoTenna, and activate or deactivate UI elements as appropriate.

Figure 49. Gulliver detail

After pressing the connection button, the user will be given the option to connect to the same GoTenna or to a new one. Upon selecting a choice, an asynchronous described below is initiated:

- The MainActivity initiates the Bluetooth scan with the SDK method scanAndConnect, called on the singleton instance of GTConnectionManager that was set up in the module configuration. If this process results in a connection, the SDK will call all registered event handlers for connection state change events.

- Since the Android MainActivity had previously registered with the SDK to handle connection state change events (during its onCreate life cycle), its registered callback, MainActivity.onConnectionStateUpdated will be called.

- When the SDK calls MainActivity.onConnectionStateUpdated with state CONNECTED, then the app knows it can finish the GoTenna configuration steps tha require an actual device, which it does by calling MainActivity.configureGoTenna.

Finally, the GoTenna configuration performed by MainActivity.configureGoTenna is as follows:

- Setting the frequency slot value in the SDK singleton instance of SetFrequencySlotInfoInteractor. This is an asynchronous call that requires a callback, which is provided inline as a Kotlin lamda. Currently all we do in the callback is publish the state into a LiveData field that is displayed in the UI.

- Set the GoTenna GID by calling setGoTennaGID on the singleton instance of GTCommandCenter. This too is an async call, so we provide a lambda callback that simply prints the response code when called.

- Finally, the application's MainViewModel is registered as a handler for incoming messages by calling setMessageListener on the singleton instance of GTCCommandCenter.

Now that all of the necessary connections and initializations have been established between all of the equipment and software, the system will be able to perform as described in Chapter IV.A and Chapter IV.B

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