Prediction And Allocation Of Live To Virtual Communication Bridging Resources

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PREDICTION AND ALLOCATION OF LIVE TO VIRTUAL COMMUNICATION
BRIDGING RESOURCES

by

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Major Professor: Linda C. Malone
ABSTRACT

This document summarizes a research effort focused on improving live-to-virtual (L-V) communication systems. The purpose of this work is to address a significant challenge facing the tactical communications training community through the development of the Live-to-Virtual Relay Radio Prediction Algorithm and implementation of the algorithm into an Integrated Live-to-Virtual Communications Server prototype device. The motivation for the work and the challenges of integrating live and virtual communications are presented. Details surrounding the formulation of the prediction algorithm and a description of the prototype system, hardware, and software architectures are shared. Experimental results from discrete event simulation analysis and prototype functionality testing accompany recommendations for future investigation.

If the methods and technologies summarized are implemented, an estimated equipment savings of 25%-53% and a estimated cost savings of $150,000.00 - $630,000.00 per site are anticipated. Thus, a solution to a critical tactical communications training problem is presented through the research discussed.
This dissertation is dedicated to my husband Christopher, and to my brothers Luke and Michael.
Completion of this dissertation is the realization of one of my life-long academic goals. It could not have been achieved without the encouragement and contribution of many. First, I would like to thank my family. My loving husband Christopher supported my efforts from the start of this journey. I am grateful to my parents, Robert and Mary Thompson, for providing the academic foundation which ultimately led me to this moment.

I would like to recognize my dissertation committee members: Linda Malone, Charles Reilly, Denise Nicholson, Kay Stanney, and David Kotick. My committee Chair, Linda Malone, was the catalyst of this pursuit. Her unwavering support made this achievement possible. I will be forever grateful for her vision, passion, and perseverance. Without the guidance of Charles Reilly, I may not have found the field of Industrial Engineering. His input and analytical expertise impacted the core of this research effort. Denise Nicholson mentored my early research efforts, provided valuable insight that ultimately shaped this body of work, and enabled me to continue my academic growth. Kay Stanney’s commitment to advancing the state of the science motivated me to push my research deeper than I could have imagined. Finally, I would like thank David Kotick for facilitating the development of the topic researched. His expertise in the field of virtual communications was crucial to the success of this work.

I also wish to thank Christopher Sprague and Jonathan Harris. Their efforts to support this body of research were outstanding. I could not ask for better team members.

Thank you all for your belief in me.
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LIST OF ACRONYMS/ABBREVIATIONS

API          Application Programming Interface
AWSIM       Air Warfare Simulation
CIC          Combat Information Center
COMSEC      Communications Security
DES          Discrete Event Simulation
DESMO-J     Discrete Event Simulation Modeling - Java
DIS         Distributed Interactive Simulation
DoD         Department of Defense
FST          Fleet Synthetic Training
GUI          Graphical User Interface
HLA         High Level Architecture
HPSM        Human Performance System Model
I/O          Input / Output
ILVCS       Integrated Live-to-Virtual Communications Server
JSAF        Joint Semi-Automated Forces
L-V          Live-to-Virtual
LRB          Live Radio Bridge
LVC          Live, Virtual, Constructive
MUTTS       Multi-Unit Tactical Training System
NCTE        Navy Continuous Training Environment
NETWARS     Network Warfare Simulation
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<td>One Semi-Automated Forces</td>
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<tr>
<td>OPAL</td>
<td>Open Pool Australian Light</td>
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<td>PTT</td>
<td>Push-to-Talk</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>SAF</td>
<td>Semi-Automated Forces</td>
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<td>SINCGARS</td>
<td>Single Channel Ground and Airborne Radio System</td>
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<td>TACDEW</td>
<td>Tactical Advanced Combat Direction and Electronic Warfare</td>
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<td>UML</td>
<td>Unified Modeling Language</td>
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<td>V-L</td>
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CHAPTER ONE: INTRODUCTION

Effective communication among military forces during combat is universally regarded as the key to a mission’s success. One of history’s most noted and studied military strategists, Sun Tzu, recognized the power of tactical communications. In his celebrated military treatise, *The Art of War*, he advised, “When there are means of communication on all four sides, the ground is one of intersecting highways,” (Galvin, 2003). Today, the importance of tactical communications remains at the forefront of the United States military planning and success. The U.S. Secretary of Defense called for the armed forces to harness technological advantages in order to enable the various branches of the military to fight jointly in the *2004 Annual Defense Report to the President and the Congress* (Rumsfeld, 2004). Capabilities supporting command, control, computers, communications, and intelligence (C4I) are specifically cited as supporting the emergence of formalized joint operations. The term “joint operations” describes military actions conducted by two or more Military Departments operating under a single joint force commander (Joint Chiefs of Staff, 2001). While cooperation among branches of the U.S. military is not uncommon, the recent focus on joint operations reveals enhanced challenges on the battlefield, and as a result, impacts challenges faced by the training community.

A key component of service level and joint military training is tactical communication. As military training environments increase in complexity, the methods, networks, and devices employed to address tactical communication training objectives follow suit. One approach to mitigating these challenges is to incorporate modeling and
simulation tools. A current strategy merges live training elements with virtual or simulated training devices. Thus, integrating live and virtual components is particularly important to the tactical communications training domain.

The intent of this research effort is to address a tactical communications training problem through the development of a method that improves live-to-virtual (L-V) communication bridging techniques. The effort discussed specifically focuses on reducing the amount of operational hardware required to support tactical communications during L-V training, and is presented in an alternative dissertation format. Following an introduction to the research, the dissertation includes a series of self contained journal papers discussing essential elements of the research effort.

The first article, “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments,” introduces a heuristic method for aiding decision makers in the assessment of communication resource requirements within tactical training environments. Existing approaches fall short of current training requirements and may significantly impact future L-V training architectures and implementations in a negative way. Methods rooted in telephony theory that serve as the foundation for the L-V Relay Radio Prediction Algorithm are presented. The algorithm developed is discussed in detail and is followed by a discussion of experimental results. Extensive discrete event simulation (DES) analyses provide confidence in the prediction algorithm and supply quantifiable results and recommendations. Finally, the paper explores potential applications of the current research and recommendations for future refinement of the heuristic.
The next article, “Blending Systems Engineering Principles and Simulation Based Design Techniques to Facilitate Prototype Development: A Case Study,” summarizes the research and developmental process. The purpose of this paper is to convey the approach used to implement the L-V Relay Radio Prediction Algorithm into a prototype device. The paper provides a review of systems engineering approaches, and describes the approach applied to this research effort in detail. A summary of prior work that applied modeling, simulation, and analysis techniques within the tactical communications realm is given and serves as the foundation upon which a tactical communications network DES was developed. DES analysis results contributed to the development of a prototype device that implements the L-V Relay Radio Prediction Algorithm.

The implementation of the prototype device, the Integrated Live to Virtual Communications Server (ILVCS) is captured in the third paper, “Managing Communication Resources in Live, Virtual, and Constructive Training Environments.” Insight is offered into the application of the ILVCS prototype as a solution to the emerging military and crisis event training challenges. The article includes an overview of military simulation and training tools, and the definition of key terms. Historical context, pertinent terminology, and technical challenges associated with bridging L-V communications follows. Existing tactical voice communication training methods are reviewed. The prototype ILVCS design features and system test results are reported. Suggestions for future research provide the community with a path toward fully integrated L-V communication capabilities.

After presentation of the three papers, experimental results, recommendations for future research, and conclusions drawn from this research are summarized.
REFERENCES


CHAPTER TWO: PREDICTING RESOURCE REQUIREMENTS FOR BRIDGING LIVE-TO-VIRTUAL COMMUNICATIONS IN TACTAL TRAINING ENVIRONMENTS

Abstract

The purpose of this paper is to introduce a heuristic method for assisting decision makers in the determination of communications resource requirements within tactical training environments. This important topic is motivated by challenges facing the military training community and recent technological advances in bridging live and virtual communication networks. Results from this research have direct applicability to modern training systems and provide a path forward for future development.

This paper opens with a discussion of the tactical communications training environment. Background, terminology, and valuable insight into the current training environment, methods, and challenges are provided. A statement of the problem from a tactical perspective leads to a discussion of telephony theory and techniques that serve as the foundation for the resource prediction algorithm derived. The algorithm developed is presented in detail and is followed by a discussion of potential applications and recommendations for future research.

Tactical Communications Training

The ability to bridge live and virtual radio networks is of particular interest to the military training community. Previous efforts that integrated live-to-virtual (L-V)
communications include the Tactical Advanced Combat Direction and Electronic Warfare (TACDEW) trainer device, Coalition Readiness Management System, and the Combined Arms Staff Training Upgrade System. These systems are currently in use by the U.S. Navy and Marine Corps, as well as Coalition Forces.

In general, these systems are characterized by three components: live communication devices, virtual communication devices, and a means to bridge voice and data links between live and virtual communication devices (Figure 2-1). Live participants engage in a training exercise using the operational communications equipment (e.g. tactical radios) used during combat. Virtual radio equipment may also be used to train command and control skills, and is typically housed within a training facility. If a training exercise requires operators of live and virtual radios to communicate, a set of the communication circuits is dedicated for that purpose. Other circuits may be defined for transmissions among exclusively live or exclusively virtual radios.
Live radios typically operate over radio frequencies (RF), whereas virtual radios communicate digitally over a wide area network (WAN). Each circuit dedicated to L-V communications is linked by a relay radio and a Live Radio Bridge (LRB). The relay radio transmits and receives data. The LRB converts voice data signals from analog to digital, and vice versa, as required. See Figure 2-2.
Another way to visualize this type of configuration is in terms of a system architecture. Some number of live radios is allocated for use by trainees in the field, and some number of virtual radios is allocated for use by participants in a training facility. The links between them require the allocation of a relay radio for each dedicated L-V circuit. The LRBs are essentially the software interfaces that allow each relay radio to appear to be a virtual radio on the WAN (Legan & Kotick, 2005). See Figure 2-3.
The benefits of the current LRB configuration include increased communications capabilities within live, virtual, and constructive (LVC) exercises, however deficiencies still exist. The current capability requires a one-to-one mapping of a relay radio resource to each L-V circuit that is bridged. Each live radio residing in the “relay radio bank” represents operational equipment that is unavailable for use by a trainee or deployed marine/soldier. The current state of military deployment exerts a strain on all resources including radio equipment and hardware. As a result, the number of radios that can be
spared for bridging or relay purposes often determines the number of circuits that can be bridged during LVC exercises.

The operational components of the relay radio bank represent a significant cost for each LVC training facility. The acquisition cost of radio equipment adhering to military specifications ranges from tens of thousands to hundreds of thousands of dollars per unit. These estimated figures exclude personnel costs associated with hardware maintenance, repair, operation, and storage.

Finally, the current L-V communication configuration is static by nature. Relay radios must be tuned to their assigned L-V circuit prior to exercise execution, and cannot be reconfigured without human interaction. This limits the level of realism injected into tactical communications training events. Current LRB configurations address a subset of the LVC communication requirements, but present difficulties that impact resource availability, cost, and training realism.

**Telephone Network Traffic**

The reduction of relay radios provides a solution to a tactical problem; however, the method by which this is achieved poses a compelling theoretical question. Techniques exist to predict and manage traffic capacity that are based upon teletraffic engineering, and have also been applied to road and air traffic, manufacturing, service systems (International Teletraffic Conference, 2005), local area networks, database structures, mobile radio and broadband packet networks (Kelly, 1991). The following is
an exploration of a classic telephony traffic capacity forecasting method, never before applied to the field of L-V communications.

Traffic capacity is the maximum traffic per unit of time that a communications network or system can successfully carry under specified conditions (American Telecommunications Industry Solutions, 2001). If the level of traffic exceeds the system’s capacity, an incoming call will be denied service (e.g. busy signal) or placed in a queue to wait for service (Parkinson, 2005). “Blocking” is the term used to describe the denial of service (American Telecommunications Industry Solutions, 2001) and is due to lack of available servers or resources (International Teletraffic Conference, 2005). It is expressed as a percentage of denied calls (Parkinson, 2005). Since calls that are blocked are lost, such systems are termed “loss-systems” (International Teletraffic Conference, 2005). A blocking probability of 1-2% is traditionally deemed an adequate Quality of Service (QoS) for loss-systems (Viterbi, A.M. & Viterbi, A.J., 1993).

For mathematical or simulation modeling purposes, call arrivals are typically assumed to follow a Poisson process and call holding times are routinely represented by an exponential distribution (Erlang, 1917; Ramjee, Towsley, Nagarajan, 1997; Parkinson, 2005). Poisson arrival processes assume the following (Law & Kelton, 2000): 1) calls arrive one at a time, 2) the number of arrivals in any time interval is independent of the number in previous time intervals, and 3) the arrival rate is independent of the time of day. Although many real world arrival processes violate the third assumption (Law & Kelton, 2000), traffic capacity analyses often focus on a peak performance period (International Teletraffic Conference, 2005). Law and Kelton (2005) acknowledge that the arrival rate for a peak demand period is reasonably constant for many situations.
Properties of the exponential distribution present some conveniences when modeling call duration or holding time. The term “holding time” in this situation indicates the amount of time the communications resource (e.g. server, circuit, wireless frequency, etc.) services the user (Erlang, 1917). Holding time may also include any overhead or queuing time (Parkinson, 2005). Holding time is also referred to as call length in the literature.

The exponential distribution assumes that the mean and variance are equal which simplifies analysis, but may introduce inaccuracy (Iversen & Mirtchev, 1996). The exponential distribution is the only continuous statistical distribution characterized by a memoryless property (Evans, Hastings & Peacock, 2000). In essence, individual call lengths are independent of previous call lengths. The memoryless property is a powerful assumption that aptly describes typical commercial telephone traffic.

Another important feature of conventional commercial telephone traffic is bi-directional communication between users. Multiple users may speak, even at the same time, and be heard simultaneously.

**Methods for Predicting Traffic Capacity**

Forecasting techniques aimed at predicting traffic capacity for commercial wireline (Baccelli, Blaszczyszyn, Karray, 2005) and wireless (Mitchell & Sohraby, 2001) telephony systems have successfully applied the concepts introduced by Agner Erlang (1878-1929) in the early 20th century (Brockmeyer, Holstrøm and Jensen, 1948; Krarup, 2004). Erlang demonstrated the validity of representing teletraffic arrivals with a Poisson
process (Erlang, 1909) and call durations with an exponential distribution (Erlang, 1920). His conceptual development of statistical equilibrium, led Erlang to derive his famous loss formula (Kelly, 1991) (see Equation 2-1).

\[
E_n(\alpha) = \frac{\alpha^n}{n!} \sum_{i=0}^{n} \frac{\alpha^i}{i!}
\]

(Eqn. 2-1)

Where \( E_n(\alpha) \) = percent of calls lost due to lack of availability
\( \alpha \) = traffic intensity
\( n \) = number of resources

(adapted from Harris, 2005)

Equation 2-1, also known as the Erlang B formula, applies to loss-systems and assumes a Poisson arrival process, constant or exponential call lengths (Erlang, 1917, 1920), and an infinite number of available sources (Parkinson, 2005). However, the Erlang B formula was proven to be robust with respect to call lengths that vary from Erlang’s original assumptions (Kelly, 1991). The principle use of the Erlang B formula is to determine trunk resource requirements. Expansions of the model include the Extended Erlang B formula, which was developed to account for callers attempting to retry upon hearing a busy signal. The Erlang C formula accommodates system architectures that delay, rather than block service, when demand exceeds maximum traffic capacity (Parkinson, 2005 and International Teletraffic Conference, 2005).
The literature suggests that crisis and tactical communications differ from commercial telephony traffic. Brodeen, Brand, and Santos (2001) leveraged the work of Kaste, Brodeen, and Broome, (1992), and hypothesized that the performance of tactical communication networks and civilian, or commercial, communication networks differ significantly. Aschenbruck, Frank, Martini, and Tolle (2005) demonstrated that attributes of voice messages and transmissions within crisis communications differ from public telephony systems in duration and frequency. Based upon statistical analysis of a real disaster event, Achenbruck’s team fit theoretical distributions to interarrival times and durations of calls. Their results differ from the telephony assumptions defined above (Aschenbruck, et al., 2005).

A key difference between teletraffic and crisis/tactical communication events is that telephone conversations are bi-directional and tactical communications are unidirectional. In telephony systems, each communication event represents a bi-directional conversation between users. Within tactical environments, a communication event equates to a single transmission sent by one user. A conversation is comprised of an arbitrary number of transmissions between multiple users (Aschenbruck, et al. 2005).

Theoretically, the uni-directional communications within tactical environments violate the independence assumption of Poisson arrival processes. If a conversation consists of multiple transmissions, then the number of transmissions in a given time interval is not independent. For example, some tactical maneuvers require more intense coordination, and thus more frequent communication between users.
Examination of communications data collected during multiple LVC military exercises echoed the findings in the literature by consistently revealing significant autocorrelation between the arrival times of transmissions (see Figure 2-4.)

![Autocorrelation Function for Arrival Time - Ex 040218](image1)

![Autocorrelation Function for Arrival Time - Ex 040123](image2)

**Figure 2-4. Sample Autocorrelation Plots of Transmission Arrival Times**

Autocorrelation suggested, and discrete event simulation (DES) output confirmed a significant difference between model performance when using input models derived from empirical data and input models based upon a Poisson arrival process. The 95% confidence interval resulting from the comparison of the maximum number of simultaneous transmissions for the two alternative arrival processes was (3.9692, 4.6941). A statistical test for the difference in means yielded a p-value of 0.000 at an α level of 0.05. These findings correspond with findings of Aschenbruck, et al. (2005).

The motivation for transmitting messages also contributes to disparities. Catalysts for message transmissions involve disaster and combat events that are inherently more stressful than typical telephone conversations (Aschenbruck, et al., 2005). Aside from behavioral characteristics of voice transmissions, QoS standards impact logistical constraints of LVC training environments. The nature of LVC training
introduces the possibility of physical harm to participants. QoS standards are mandated
to not only facilitate effective training, but to ensure the greatest level of safety for all
participants involved. Loss of transmissions due to “trunk” resource availability is
unacceptable.

Communication traffic during crisis and tactical events is significantly different
from commercial telephony environments. The core characteristics of tactical
communications that impact DES input models are the uni-directional nature of
transmissions, the motivation for transmissions, and QoS criteria. These differences call
into question the ability to extend the application of classic telephony forecasting
techniques to a new field: tactical communications training in LVC environments. The
next section addresses this question in detail.

A Method for Determining L-V Communication Resource Requirements

Reducing the total number of relay radios required to support a given LVC
training event requires a balance between predicting traffic capacity, and minimizing the
possibility of transmission loss. Figure 2-5 provides a conceptual model of the algorithm
developed.
The first step is to predict the traffic capacity required. Figure 3 depicts the current L-V communication network architecture. The role of relay radios in the architecture is similar to trunk lines within a telecommunications network. Erlang’s loss formula affords insight into the minimum number of relay radios required to accommodate the maximum number of simultaneous transmissions during a LVC exercise.

A convenient recursive adaptation of the Erlang B loss formula is given by Equation 2-2 (Harris, 2005). For the derivation of Equation 2, see Appendix A.
By creating a traffic capacity table using Equation 2 above, the number of resources, \( N \), required to meet the QoS criterion may be developed. The traffic intensity, \( \alpha \), results from the product of the arrival rate of transmissions, \( \lambda \), and the mean transmission length, \( m \). Arrival rate is calculated by dividing the number of transmissions, \( x \), by the length of the peak performance period, \( t \). Table 2-1 reflects the loss incurred for the number of relay radios indicated assuming 10,000 transmissions over a four hour period (14,400 seconds), and a mean transmission length of 4.5 seconds. For example, the table indicates that using two relay radios results in a loss of 49.7% of the transmissions entering the systems, but no loss of transmissions if 13 relay radios are used. As shown in Table 2-1, the loss estimate is rounded to five decimal places. The decision to round to 5 decimal places was based upon a comparison of precision gained when rounding to 2, 3, 4, 5, and 6 decimal places.
In order to predict the resource requirements for a particular LVC training event, the mean transmission length, duration of peak performance, and expected number of transmissions are used to create a traffic capacity table. Requesting a user to predict the mean length of a transmission is unreasonable. Therefore, the mean transmission length is based upon data collected during various tactical training events and is held constant at 4.5 seconds. The duration of the peak period is solicited from the user in addition to the number L-V bridges. A regression equation is used to predict the number of transmissions for a particular exercise given the length of the peak period and the number of bridged circuits. Equation 2-3, the regression model, is derived from communications data collected during nine military training exercises. For a detailed summary of the regression analysis, see Appendix B.
\[ y = -4706 + 1122x_2 + 0.000033x_1^2 - 0.0655x_1x_2 \]  
(Eqn. 2-3)

Where \( y \) = number of transmissions  
\( x_1 \) = duration of peak performance period  
\( x_2 \) = number of L-V bridges

Model adequacy testing involved thirty replications of the DES for the following number of L-V communications bridges: 10, 15, 20, 30, 40, 50, and 60. At each level, peak period durations 2, 3, 4, 5, and 6 hours were investigated. The experimental conditions were chosen based upon what is typically observed in LVC training events. Extreme levels were added to stress the system in order to ascertain the feasible region of application for the L-V Relay Radio Prediction Algorithm. Erlang B traffic capacity predictions and the number of simultaneous transmissions observed during DES experimentation were compared. A statistical test of the means revealed a 95% confidence interval of (-1.4783, 4.7908) and a p-value of 0.29 at an \( \alpha \) level of 0.05.

\textit{Spare Capacity}

Once the number of relay radio resources required is estimated, spare capacity requirements are calculated. Spare capacity is vital to maintaining the QoS requirement of 0% loss, and is motivated by safety concerns. Providing spare relay radios, and thus, spare input/output (I/O) capacity in addition to the number recommended by Erlang’s loss calculation ensures sufficient access to communication resources.

Previously developed military trainers have encountered a similar need for spare communication capacity. The E-6 Mercury is an aviation asset that serves as a
communication relay for strategic intelligence. Its mission is to provide, “survivable, reliable, and endurable airborne command, control, and communications between National Command Authorities and U.S. strategic and non-strategic forces,” (Naval Aviation Systems Command, 2006). The E-6B represents the most recent upgrade to the E-6 fleet. A component of the E-6B training system is the E-6B Weapons System Trainer (WST). Performance specifications for the communication system within the E-6 WST stipulates at least 20% spare I/O capacity (Naval Air Systems Command, 2003).

The performance specifications for the MH-53E Operational Flight Trainer, contain similar spare communication requirements. The MH-53E is a rotary wing asset. Its primary objective is to support airborne mine countermeasures. Additional mission tasks include air-to-air refueling, search and rescue, and external cargo transportation, within land and sea environments (Federation of American Scientists, 1999). Performance specifications for the MH-53E training system require 30% spare audio channel capacity.

Outside the military domain comparable spare I/O requirements are specified. Australia’s newest nuclear reactor, the Open Pool Australian Light-water (OPAL) reactor, asserts the incorporation of the world’s best safety and technology features (Australian Nuclear Science and Technology Organisation, 2006). The OPAL safety analysis report sites a minimum of 20% I/O spare capacity (Investigacion Aplicaciones, 2004).
Spare I/O capacity requirements for high risk operational environments typically ranges from 20-30%. Analysis of a verified DES model representing a L-V communications network, revealed that similar I/O requirements would be sufficient to provide the specified communications QoS level for LVC training environments. The method consistently overestimated the number of relay radios required to support the anticipated number of simultaneous transmissions.

Based upon the results of the DES analysis, spare I/O capacity requirements for similar systems, and safety concerns inherent to live tactical training, the spare capacity of up to 30% is recommended for L-V communication bridging.

Model Applicability

DES analysis confirmed the prediction heuristic’s adequacy and demonstrated the boundaries within which it can be feasibly applied. The number of L-V bridges and the peak period duration are important in the determination of relay radio resource
requirements. Simulation results indicated the feasible use cases for the prediction heuristic summarized in Table 2-2.

Table 2-2. Feasible Use Cases for the L-V Relay Radio Prediction Algorithm

<table>
<thead>
<tr>
<th>Peak Period Duration (hours)</th>
<th>Number of Bridged Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 - 10</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Key:
- ◊ Number of relay radios = number of L-V bridges
- Use 3 hour prediction values
- Traffic capacity calculation only
- Traffic capacity calculation + 30% spare capacity
- Use 4 hour prediction values

1) The diagonal stripe region indicates when the number of relay radios recommended equals the number of bridged circuits. This situation arises if 10 or fewer L-V bridges are required.

2) For an exercise with a peak period duration of less than three hours, it is recommended that the 3 hour prediction values be used. This case applies if between 11 and 40 bridges are required and is indicated by the dotted section of the table. For a situation where 21-30 bridges are required for a 2 hour exercise, the prediction value for 3 hours and 21-30 bridges should be used.

3) The solid white area represents the region where only the traffic capacity calculation is recommended. DES experimentation showed
that the Erlang B formula overestimated the number of simultaneous
transmissions by approximately 20-30% for these cases given the
current input data. This is the case if the number of L-V bridges is
between 11 and 40 and the peak period duration is between 3 and 4
hours.

4) The solid gray region indicates when 30% spare capacity is to be
   included in a recommendation for the number of relay resources
   required, and occurs if between 11 and 40 bridged circuits are required
   and the peak period is at least 4 hours but less than 5 hours.

5) The region covered by horizontal stripes indicates when the predictions
   from 4 hour peak periods should be substituted for 5 and 6 hour peak
   periods. For example, the prediction from 4 hours and 21-30 bridged
   circuits should be substituted for the prediction from 6 hours and 21-30
   bridged circuits. DES experimentation showed that this strategy
   supported a 20-30% spare capacity capability. This result proved
   interesting, and upon closer inspection reasonable. The raw data
   analyzed was comprised of training exercises with peak period
durations of less than 5 hours even when the full exercise length was
24-48 hours.

6) For situations requiring greater than 40 bridges, it is recommended to
   partition the number of required bridges into subgroups. Each subgroup
   should include no more than 40 bridged circuits. The number of
instructor circuits should be evenly distributed across subgroups. Apply the L-V Relay Radio Prediction Algorithm to each partition.

7) For conditions outside the above description, the heuristic is not recommended.

Potential Applications of the Heuristic

Various military applications of the heuristic defined above exist. Training exercises involving command and control environments are of specific interest. In addition to individual service exercises, Joint and Coalition force exercises may be served. This approach to predicting relay radio resources would benefit distributed exercises that require multiple sites to communicate over L-V circuits.

Crisis event training involving law enforcement and emergency services can also benefit. Examples of emergency response requiring coordination during natural disasters include simulated hurricane, wild fire, and earthquake scenarios. Another potential application would be rehearsal and preparation for hostile actions against civilian populations such as terrorist attacks and hostage situations.

The L-V Relay Radio Prediction Algorithm presented above can be applied to determine the relay radio resource requirements for environments that share the following characteristics: live and virtual communications are bridged, transmissions are unidirectional, transmission loss is unacceptable, and the motivation for communicating is of a critical nature.
Tables 2-3 and 2-4 summarize the estimated savings offered by the prediction heuristic. In Table 3, savings are represented as the percent reduction in the number of operational radios required for L-V relay purposes. Alternatively, Table 4 presents the cost savings assuming the average procurement cost of a relay radio is $30,000. Depending upon the nature of the exercise, a 25 - 53% reduction in relay radios may be realized. As a result, an estimated $150,000.00 - $630,000.00 savings in relay radio procurement costs per training site. The estimates provided are based upon the DES experimentation and output modeling used to verify the adequacy of the prediction algorithm.

Table 2-3. Estimated Percent of Reduction in the Number of Relay Radios

<table>
<thead>
<tr>
<th>Peak Period (hours)</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>30%</td>
<td>40%</td>
<td>48%</td>
</tr>
<tr>
<td>3</td>
<td>30%</td>
<td>40%</td>
<td>48%</td>
</tr>
<tr>
<td>4</td>
<td>25%</td>
<td>43%</td>
<td>53%</td>
</tr>
<tr>
<td>5</td>
<td>25%</td>
<td>43%</td>
<td>53%</td>
</tr>
<tr>
<td>6</td>
<td>25%</td>
<td>43%</td>
<td>53%</td>
</tr>
</tbody>
</table>

Table 2-4. Estimated Cost Savings Offered by Prediction Heuristic (in hundreds of thousands of dollars)

<table>
<thead>
<tr>
<th>Peak Period (hours)</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$180K</td>
<td>$360K</td>
<td>$570K</td>
</tr>
<tr>
<td>3</td>
<td>$180K</td>
<td>$360K</td>
<td>$570K</td>
</tr>
<tr>
<td>4</td>
<td>$150K</td>
<td>$390K</td>
<td>$630K</td>
</tr>
<tr>
<td>5</td>
<td>$150K</td>
<td>$390K</td>
<td>$630K</td>
</tr>
<tr>
<td>6</td>
<td>$150K</td>
<td>$390K</td>
<td>$630K</td>
</tr>
</tbody>
</table>
Conclusions

The relay radio prediction heuristic developed in this research paper pairs traditional telephone capacity forecasting strategies with spare capacity estimation methods. An estimated savings of 25 - 53% in required hardware results in an estimated cost savings of $150,000.00 - $630,000.00 per training site. The method presented requires minimal input from a user by relying upon regression modeling and extensive analysis of tactical communications during multiple military training exercises. DES input modeling played a key role in the development of the prediction heuristic. Confidence in the prediction method and verification of model adequacy was provided by DES output analysis.

Further refinement of the L-V Relay Radio Prediction Algorithm will require a greater quantity of data in order to leverage the DES model developed. The heuristic is applicable within the boundaries defined. In order to apply this resource prediction method to exercises characterized by peak periods longer than six hours or that include fewer than ten and greater than 40 bridged circuits, data must be collected for these specific use cases. In addition, features of any data collection events such as mission objective (e.g. close air support, urban warfare, emergency response) and type of scenario events (e.g. call for fire, insurgent response activities, nature of emergency) should be added. Incorporating such features into DES input data and model features may enhance prediction capability. Improvement in the quality of data collected should also be pursued. Reduction of false triggers and other anomalies that may corrupt communications data should be a priority.
APPENDIX A: DERIVATION OF EQUATION 2-2
Harris (2005) provides the following derivation of the recursive form of Erlang’s Loss Formula.

Consider:

\[
E_n(A) = \frac{A^n}{n!} \left( \sum_{i=0}^{n-1} \frac{A^i}{i!} \right) = \frac{A}{n} \cdot \frac{A^n}{(n-1)!} \left( \sum_{j=0}^{n} \frac{A^j}{j!} \right) = 1 + \frac{A}{n} E_{n-1}(A) + \frac{A}{n} E_{n-1}(A)
\]

Thus:

\[
E_n(A) = \frac{AE_{n-1}(A)}{n + AE_{n-1}(A)}
\]
APPENDIX B: REGRESSION ANALYSIS OF THE NUMBER OF TRANSMISSIONS THAT OCCUR DURING LIVE, VIRTUAL, AND CONSTRUCTIVE TRAINING EVENTS
1. Hypothesized Model

Originally, the hypothesized model for the number of transmissions that occur during an LVC training event is given by the full second order model:

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \]

where, \( x_1 \) and \( x_2 \) represent the exercise length and the number of LRBs, respectively.

The final model takes the form:

\[ y = \beta_0 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_5 x_1 x_2 \]

2. Parameter Estimation

The Minitab 14 statistical software toolset was used to conduct the following analysis.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-4706.0</td>
<td>848.3</td>
<td>-5.55</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Num LRBs</td>
<td>1122.2</td>
<td>168.2</td>
<td>6.67</td>
<td>0.001</td>
<td>173.6</td>
</tr>
<tr>
<td>Ex Length_sq</td>
<td>0.00003289</td>
<td>0.00000669</td>
<td>4.92</td>
<td>0.004</td>
<td>12.9</td>
</tr>
<tr>
<td>Ex Length * Num LRBs</td>
<td>-0.06552</td>
<td>0.01228</td>
<td>-5.34</td>
<td>0.003</td>
<td>246.8</td>
</tr>
</tbody>
</table>

\( S = 453.163 \) \( R-Sq = 98.8\% \) \( R-Sq(adj) = 98.1\% \)

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>87444989</td>
<td>29148330</td>
<td>141.94</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>5</td>
<td>1026784</td>
<td>205357</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>88471772</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure A-1. Minitab Session Window Output

Note: Data collection events were focused on the peak period of transmission activity. Exercise length equals the duration of peak periods and is represented in seconds.

3. Assessment of Model Adequacy

a. Hypothesis

\( H_0: \beta_0 = \beta_2 = \beta_3 = \beta_5 = 0 \)

\( H_1: \text{at least one } \beta \neq 0 \)
b. F-Test
   From the analysis above F = 141.94, with a p-value of 0.000.

   For this model, $v_1 = k = 3$ degrees of freedom for the numerator – mean
   square of the model, and $v_2 = n – (k + 1) = 9 – (4) = 5$. Therefore, $F_{0.05} = 5.41$ as given the F Distribution Table (Mendenhall and Sincich, 1995, P1104). ($k =$ number of coefficients, $n =$ number of data points)

   Since $F > F_{0.05}$ and the p-value = 0.000, reject $H_0$. At least one of the model parameters differs from 0.

c. Test Individual $\beta$’s
   i. P-values
      Due to high p-values the exercise length and the squared number of
      LRBs terms were omitted. The terms were removed one at a time to
      understand the impact each term had on the model.

      ![Residuals Versus the Fitted Values Plot](image)

      Figure A-2. Residuals Versus Fits Plot

      The standard deviation given by Minitab $S = 453.163$. No points lie
      outside $3S = 1359.489$.

   ii. Trend over time – Residuals v. order
       1. This type of analysis is not applicable since the data are not
          time sensitive.
4. Residual Analysis  
   d. Error Assumption 1: Mean of the probability distribution for $\varepsilon = 0$ or Model Misspecification

![Scatterplot of RESI3 vs Ex Length](image1)

**Figure A-3. Residuals v. $x_1$ (Exercise Length)**

The graph above may indicate that there is a relationship between the exercise length and the residuals. No other indicators of model misspecification appear in the analysis. Data transformations do not result in a better model fit.

![Scatterplot of RESI3 vs Num LRBs](image2)

**Figure A-4. Residuals v. $x_2$ (Number of LRBs)**

The graph above may indicate that there is a relationship between the number of LRBs and the residuals. No other indicators of model misspecification appear in the analysis. Data transformations do not result in a better model fit.
e. Error Assumption 2: Variance of the probability distribution of $\varepsilon$ is constant
   The residuals graphs may indicate that the variance decreases as $x_1$ and $x_2$ increase. The potential relationships revealed by the residual plots may be due to the small number of data points available for analysis.

f. Error Assumption 3: Probability distribution of $\varepsilon$ is normal

![Figure A-5. Normality Plot of Residuals](image)

The normality plot above indicates the residuals are normally distributed. This assessment is supported by the Kolmogorov-Smirnov test results $KS = 0.182 < $ critical value of 0.895. The associated $p$-value is $> 0.15$ for $\alpha = 0.05$. In addition, the mean is estimated to be 0.

g. Error Assumption 4: Errors associated with any two different observations are independent
   These regression data do not represent a phenomenon that takes place over time, therefore correlation errors are assumed not to exist.

It is important to note that Mendenhall and Sincich (1995) state that, “in actual practice, the assumptions need not hold exactly for the least squares method estimators and test statistics to possess the measures of reliability that we would expect.”
h. Multicollinearity

![Scatterplot of Num LRBs vs Ex Length](image)

Figure A-6. Correlation Test

The Pearson correlation value of the two independent variables is 0.87 with a p-value of 0.02. Multicollinearity may exist.

The Variance of Inflation Factors of the coefficients are higher than the classically recommended, but not rarely seen, value of 10. The potential presence of multicollinearity may not adversely affect the model performance due to the results of the F-Test for model adequacy.

5. Model Use
   i. The model will be used to predict the number of transmission for a given LVC exercise based upon the length of the exercise (peak performance period) and the number of LRBs specified in the communications plan.


CHAPTER THREE: BLENDING SYSTEMS ENGINEERING PRINCIPLES AND SIMULATION BASED DESIGN TECHNIQUES TO FACILITATE PROTOTYPE DEVELOPMENT: A CASE STUDY

Abstract

A logical step in the advancement of live-to-virtual (L-V) communications is the development of a device capable of merging, managing, and allocating multiple requests for live radio resources in a dynamic live, virtual, constructive (LVC) configuration. The paper “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments” summarized the algorithm derived to determine the number of relay radios resources required to support a given LVC training event. The purpose of this article is to discuss the implementation of the prediction algorithm developed in the referenced article into a prototype Integrated Live-to-Virtual Communications Server (ILVCS).

This paper begins with a summary of systems engineering approaches and previous applications of simulation to tactical communication systems. Next, specific challenges identified during the initial phases of the development of a Live-to-Virtual Communications Server are given. A detailed description of the systems engineering approach and discrete event simulation (DES) techniques applied to address these challenges follows. Finally, the results of this effort and the products developed are discussed.
Systems Engineering Approaches

The waterfall method was once the most commonly used systems engineering approach applied to major acquisition projects (Defense Acquisition University, 2001). This approach involves a series of steps completed in succession (see Figure 3-1).

![Figure 3-1. Typical Waterfall Systems Engineering Phases](Schaeffer, 1998)

Typical steps in this approach include: requirements definition, design, build, test, and deploy. A review of project progress and requisite documentation after each step determines whether the project is ready to move forward, but minor overlap may occur. While this method was effectively applied to many large-scale development efforts, clear
drawbacks to this method exist when applied to concept formulation and initial development. It fails to allow for a prototyping phase, nor does it accommodate new requirements (Sommerville, 2001). Additionally, by its nature it is time consuming and costly (National Office for Integrated and Sustained Ocean Observations, 2005).

The classic waterfall method was formerly employed by the Department of Defense (DoD), but gave way to a new method termed the spiral approach (Defense Acquisition University, 2001). Several years ago, the DoD implemented a new systems engineering approach based upon a recursive process. This method provides a comprehensive approach that is applied sequentially by integrated teams (see Figure 3-2).

(Defense Acquisition University, 2001)

Figure 3-2. DoD Systems Engineering Process

Process input consists of user needs, objectives, requirements, and project constraints. Requirements analysis translates the process inputs into functional and
performance requirements. Functional analysis decomposes the requirements identified above into lower-level functions. Design synthesis defines physical and software elements required to create the product. Each element must support at least one functional requirement.

If the functional analysis indicates a need to revisit requirements, then the requirements loop is followed. The design loop provides a means to revisit the functional analysis phase if necessary. The verification loop assesses whether the results of the design satisfy the original requirements. System analysis and control provides balance to the system. This module is responsible for decisions based upon tradeoff analyses, development of schedules, and ensures that the required technical disciplines are integrated into the effort.

Ultimately, the process output for each cycle depends upon the level of development, but includes the system decision database, the system architecture, baselines, and specifications (Defense Acquisition University, 2001).

The DoD spiral approach provides an analysis phase prior to each developmental and testing phase, and allows for both changing requirements and prototyping. The full implementation of this method, including progress reviews and documentation, is intended for large-scale development projects.

A third method, based upon the spiral approach, is the Human Performance System Model (HPSM) (Human Performance Center, 2003). This method involves four phases that are intended to be applied in succession as many times as required. The four phases include define requirements, define solutions, develop components, and execute and measure (see Figure 3-3).
Phase I, defines requirements by gaining knowledge about the system and specifying performance and functional requirements. The next phase defines solutions by generating the system design based upon the requirements from Phase I. The system design then drives the development of components in Phase III. Finally, Phase IV evaluates the performance of the components developed by comparing the actual system performance to the predefined performance specifications (from Phase I). Insight gained from each model iteration is leveraged into the next cycle.

This method offers the benefits of the DoD systems engineering approach, but is more applicable to smaller projects and research efforts. The HPSM provides structure
and accounts for the four basic systems engineering phases. However, it reduces the complexity of model execution compared to a large-scale spiral process. The concise nature of the four quadrant model lends itself to adaptation for smaller efforts. Thus, HPSM offers flexibility that is beneficial to prototype development.

**Application of Simulation Techniques to Tactical Communication Systems**

Historically, the military has used modeling and simulation to test new tactical communications system configurations (Baker, Hauser & Thoet, 1988). Baker, et al., (1988) discuss the importance of understanding the performance of underlying radio networks that support tactical radio communications in order to facilitate prototype development. Their distributed simulation and prototyping test bed provided a more realistic environment for the design and testing of computer communication networks. Simulation analyses for the purpose of facilitating design decisions and prototype development is also discussed by Kolek, Rak and Christensen (1998). The Battlefield Communications Network and Tactical Engagement Simulation program demonstrated how simulation could be applied to performance analysis of radio networks (Kolek, et al., 1998). This work demonstrates the ability of simulation to compare alternative configurations during research, development, and prototyping efforts.

Network analysis is another military application of simulation described in the literature. The US Army developed the Information Flow Design and Evaluation Tool that provides prioritization, allocation, planning, and management of division-level tactical network resources (Hill, Surdu, Carver, Vaglia & Pooch, 2001). At the core of
this tool, is a DES capable of representing a communications system for various
operating conditions. Visualization tools allow for inspection and analysis of bandwidth
saturation and bottlenecks in a tactical data network with greater ease than previously
available. Uses of this system include training, design of experimental networks, and
rapid decision-making support (Hill, et al., 2001). The Information Flow Design and
Evaluation Tool provides an example of a communications management product that is
driven by a DES engine.

The Network Warfare Simulation (NETWARS) program aims to model military,
federal, state, and local civilian agencies to improve planning and decision processes
during a large-scale crisis event (Murphy & Flournoy, 2002). NETWARS, a network-
modeling tool for the U.S. armed forces, provides tools to model, analyze, and assess
network traffic and information flow. It is intended to support contingency planning,
war-gaming and evaluation of emerging technology by extending the capabilities of the
commercial product OPNET Modeler (Murphy & Flournoy, 2002).

Simulation has proven its value to tactical communications technology developers
and decision makers. During research and development of emerging communications
technology, simulation can be used to support design efforts and component
development. Simulation engines have also been used to drive network analysis and
operational planning tools. Modeling and simulation techniques have application to the
full range of design, development, and deployment of tactical communications tools.
Developmental Challenges

Although countless challenges face any research effort, five fundamental challenges arose during the initial phases of the ILVCS development. First, since the system in this case encompassed the entire L-V communication network, the level of system complexity was extremely high. Inserting an additional subsystem into the architecture required a thorough investigation of the component subsystems and their interactions. Second, no persistent system of the communications network under investigation is in existence. No test-bed exists that would support experimentation on the scale required, and experimentation during actual training events was not feasible. Due to the lack of a persistent system, there was a lack of doctrinal requirements and design documentation, and a shortage of available data. This third challenge led to a desire for clear documentation and the establishment of extensible prototype software and hardware that would facilitate future development and production. Finally, cost and schedule constraints demanded a prudent approach to accomplish the research and development goals. Identification of the ILVCS developmental challenges motivated the pursuit of a process to maintain balance between technical goals, cost, and schedule constraints. The following section details the process implemented.

Developmental Approach

The methodology employed was based upon a systems engineering approach implemented by the U.S Navy’s Human Performance Center. Figure 3-3 depicts the HPSM (Human Performance Center, 2003) adapted for this effort. Three iterations of
this model were necessary to complete the proposed research. Spiral 1 focused on the simulation of the existing system. Spiral 2 redirected the simulation focus to alternatives to the existing system configuration. The third spiral developed a prototype device based upon the outcomes of the previous spirals. See Figure 3-4 for a graphical representation of the development spirals.

Figure 3-4. ILVCS Research and Development Process
Spiral 1: Simulated Live Radio Bridge (LRB) Configuration

The first spiral simulated the existing LRB configuration. Requirements derived in this spiral drove the efforts during the three development spirals. The requirements included the definition of a use case that was based upon exercise and communication plans from various LVC training events. An exercise length of four hours and a total of 40 bridged circuits were defined for this use case. For this configuration, it is important to note that each bridged circuit required an operational radio resource. Communications in this environment were uni-directional and zero loss of transmissions was strictly enforced.

Following the use case development and requirements definition, an object-oriented DES was designed to model the current LRB capability. Unified Modeling Language (UML) tools were utilized to support the design of the DES. Creation of class and state diagrams facilitated the development of the DES software design by clarifying component interactions and life cycle processes of entities.

DES development included extensive input modeling. Nine sets of communications data collected during military training exercises were available for analysis. Eight out of the nine data sets were analyzed to gain insight into the characteristics of tactical voice communications. The remaining data set was reserved for model verification purposes.

In addition to the number of transmissions passing over each circuit, transmission lengths and interarrival times were of particular interest. The analysis of military communications data provided insight into the attributes of transmissions passing through
the LRB system. Input models developed in Spiral 1 were leveraged for all simulation models analyzed during the ILVCS research effort.

Programming of the DES was based upon the design defined in Phase 2 of Spiral 1. Java served as the programming language and the model integrated the Discrete Event Simulation MOdeling – Java (DESMO-J) application programming interface (API).

Model verification included informal peer reviews by the original developers of the LRB technologies. Structured model comparisons were based upon DES output analysis. Thirty replications of the DES using the input models developed were compared to the model performance using the reserved data set. No significant difference was indicated. Upon model verification, the LRB DES served as the baseline for alternative comparisons.

Spiral 2: Simulated ILVCS Configuration

Spiral 2 simulated the ILVCS configuration. One feature of the use case was modified for Spiral 2: the number of relay radio resources within the system. The requirement of the ILVCS system was to reduce the number of resources without reducing the quality of service (zero loss of transmissions). This single change significantly impacted the DES design of the alternative ILVCS system(s).

In order to reduce the number of relay radios, a mechanism for detecting transmissions over live radio frequencies (RF) had to be provided. Multiple alternative configurations were considered, but two were deemed feasible. The first alternative involved creating a bank of scanning radios that monitor subsections of the RF spectrum
in addition to maintaining a bank of relay radios for signal transmission. The second option sought to identify a device that would monitor a defined portion of the RF spectrum in order to detect live RF transmissions.

Each alternative design was based upon the design in Spiral 1 and modified as required. The modified designs generated in Spiral 2 and input models developed during Spiral 1 served as the foundation for simulation development and programming. The ILVCS simulation models leveraged the LRB DES previously programmed in Java using the DESMO-J API.

Model verification was conducted in the same manner as Spiral 1 for each ILVCS configuration. No significant difference was indicated between the performance of the either simulated ILVCS configuration using the input models developed in Spiral 1 and the reserved data set. Verification was followed by a scenario comparison of the alternative configurations in order to assist in determining which ILVCS design to implement. Using common random numbers for the DES input, ensured that the same random numbers were used for the exact same purpose in each alternative. Thus, the observed differences between models were not due to variance in transmission attributes, rather differences between model configurations (Law & Kelton, 2000). No significant difference was indicated between the two configurations. However, due to reduced system complexity and cost, the second alternative was chosen for prototype development. In essence, the monitor configuration was a more elegant and cost effective solution.
For the defined use case, experimental results indicated that the proposed ILVCS-Monitor configuration may significantly reduce the number of relay radios required to support the use case defined in the requirements specification from Spiral 1.

**Spiral 3: ILVCS Prototype Device**

Finally, the third spiral of the systems engineering process resulted in the design and development of a prototype ILVCS device. This prototype is capable of determining the number of relay radios required to support the defined use case, and dynamically allocating those resources during a LVC training event.

The requirements from Spiral 2 were leveraged. Additional requirements for a decision support component used to determine the number of relay radios required were derived from the research results described in the article “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments.” The system architecture and the software and hardware designs were based upon the design defined in Spiral 2.

Leveraging existing LRB software source code and hardware components facilitated the development of the ILVCS prototype software and hardware. Modifications to the components leveraged were made as required to support the prototype device development.

Testing and evaluation of the prototype verified device functionality and performance. The ILVCS was shown to sufficiently meet the use case requirements within a laboratory setting.
Results

The systems engineering method described above provided structure to the analysis of a highly complex system, and led to the development of a new subsystem. By dividing the effort into three spirals, the current system capabilities were clearly defined and alternative configurations could be considered. The phases within each spiral added another level of organization to the effort, and provided a way to assess and convey progress toward technical, cost, and schedule goals.

While the adaptation of the HPSM provided a systems engineering blueprint for the overall effort, DES techniques made significant contributions. Without an existing system, analysis and experimentation were not possible. DES provided a means to demonstrate subsystem interactions and to experiment with various configurations. The DES input modeling process led to the use case definition and added much needed insight to the nature of tactical communications. By simulating the tactical environment, a deeper understanding of tactical communications resulted in the refinement of system requirements, design recommendations, and served as the foundation for the prototype developed.

By drawing upon the strengths of DES to reduce technical risks, cost and schedule risks were also mitigated. Simulation based design allowed for comparison of multiple alternative configurations prior to hardware procurement and assembly. The results from the DES study influenced procurement choices, and provided an opportunity for “what-if” analysis prior to construction. It is estimated that the utilization of DES analysis techniques afforded a cost savings of 33% in hardware procurement, 46% in software
development, and 75% in system analysis. Without an existing system to use for experimentation, system analysis would have been severely impaired. The durations of the first and second spirals were reduced by approximately 50% and 80%, respectively. Utilizing DES to fill the need for an experimental system supported prototype development within a constrained schedule. DES significantly contributed to reducing technical, cost, and schedule risks.

The products (see Table 3-5) of this effort are available for future use. The products include requirements specifications, system design documentation, DES tools, and prototype hardware and software. Research results in the area of input modeling for tactical communications, and an innovative algorithm for predicting resource requirements are available for emerging development efforts and operational experimentation.

Table 3-1. Products Resulting from Each Spiral of the System Engineering Process

<table>
<thead>
<tr>
<th>Phase</th>
<th>Spiral 1</th>
<th>Spiral 2</th>
<th>Spiral 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define Requirements</td>
<td>• LRB system requirements</td>
<td>• LVCS system requirements</td>
<td>• Prototype HW &amp; SW requirements</td>
</tr>
<tr>
<td></td>
<td>• DES input models</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Define Solutions</td>
<td>• LRB DES design</td>
<td>• LVCS DES design</td>
<td>• Prototype design</td>
</tr>
<tr>
<td>Develop Components</td>
<td>• LRB DES</td>
<td>• LVCS DES</td>
<td>• Prototype LVCS</td>
</tr>
<tr>
<td>Evaluate &amp; Measure</td>
<td>• Model verification</td>
<td>• Experimental results</td>
<td>• Experimental results</td>
</tr>
<tr>
<td></td>
<td>• Initial LVCS recommendations</td>
<td>• Refined prototype LVCS</td>
<td>• Recommendations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• LVCS recommendations</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

Applying systems engineering principles and simulation based design techniques benefits prototype development. They are particularly adept at addressing issues found in complex systems and their associated subsystem components. Based upon the developmental challenges identified at the beginning of this effort, the application of a systems engineering approach was a natural choice. The three spirals defined provided structure to the overall effort. The phased approach (requirements definition, design specification, component development, and performance measurement) within each of the three spirals provided continuity throughout the entire development cycle. Incorporating DES techniques assisted in the conceptualization of the system under investigation, the derivation of functional requirements, and comparison of design alternatives. This case study is a testament to the application of systems engineering principles and simulation based design techniques for prototype development in advanced research initiatives.
REFERENCES


CHAPTER FOUR: MANAGING COMMUNICATION RESOURCES IN LIVE, VIRTUAL, AND CONSTRUCTIVE TRAINING ENVIRONMENTS

Abstract

Due to the increasing complexity of the operational environment, the military training community is compelled to advance the science of training and simulation technologies. Tactical communications represent one of the focus areas currently under development. Efficiently bridging tactical communications between live and virtual domains remains one of the key challenges to the simulation and training community. Emerging methodologies and recent technological developments have led researchers to the development of prototype capabilities aimed at improving techniques for bridging live and virtual communications.

The paper begins with an overview of military simulation and training tools, and the definition of key terms. A brief history of simulation and training systems specifically focused on tactical communications follows. Current tactical voice communication training practices are summarized. A research and development prototype technology that addresses key challenges faced by the current practice is discussed in detail. System, hardware, and software architectures presented are illuminated by a use case description. The results of laboratory integration and testing are provided. Finally, the potential impact of this device and recommendations for future work are offered.
Military Training Tools

The military training community relies on modeling and simulation tools to provide solutions to training challenges that cannot be mitigated by other means. Simulation and training tools are categorized by the level and type of human interaction required. The three categories are live, virtual, and constructive (LVC). Live simulations involve real humans operating real systems (Defense Simulation Modeling Office, 2005). For example, the U.S. Naval Strike Warfare Center in Fallon, Nevada, provides Air Wing training that involves operational equipment such as aircraft, weapons, and communications devices. All trainees, instructors, and opposing force roles are fulfilled by live human participants. Alternatively, virtual simulations consist of a human interacting with a computer simulation system rather than operational (live) equipment (Defense Simulation Modeling Office, 2005). The U.S. Marine Corps’ Combined Arms Staff Trainer in Twentynine Palms, California, provides trainees with an environment to train combat tasks using computer simulated radios. Participants interact with virtual radios in lieu of operational equipment to complete command and control training missions and build tactical communications skills. Lastly, constructive simulations simulate combatants, civilians, and vehicles by automated or semi-automated means (Defense Simulation Modeling Office, 2005). Joint Semi-Automated Forces (JSAF), One Semi-Automated Forces (OneSAF), and Air Warfare Simulation (AWSIM) provide environments where virtual platform simulators may interact with simulated forces driven by automated model logic. Fleet Synthetic Training (FST) events, directed by U.S. Fleet Forces Command, have utilized multiple semi-automated force (SAF) applications,
including JSAF, OneSAF, and AWSIM to generate simulated or synthetic entities to replicate geography, vehicles, and individual combatants. Integration of LVC simulation tools attracts the military training community due to the long-term cost savings and increased scenario flexibility. Table 4-1 lists examples of LVC tools and technologies currently in use.

Table 4-1. Examples of LVC Simulation Tools and Technologies

<table>
<thead>
<tr>
<th>Simulation Categories</th>
<th>Example Technologies and Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live</td>
<td>Naval Strike Air Warfare Center</td>
</tr>
<tr>
<td></td>
<td>Military Operations in Urban Terrain: Combat Towns</td>
</tr>
<tr>
<td></td>
<td>Operational vehicles, aircraft, ships, weapons</td>
</tr>
<tr>
<td></td>
<td>Communication devices</td>
</tr>
<tr>
<td></td>
<td>Instructors</td>
</tr>
<tr>
<td></td>
<td>Role-players portraying friendly forces, enemy forces, and civilians</td>
</tr>
<tr>
<td>Virtual</td>
<td>Conning Officer Virtual Environment</td>
</tr>
<tr>
<td></td>
<td>Combined Arms Staff Trainer</td>
</tr>
<tr>
<td></td>
<td>CAVE Automated Virtual Environment</td>
</tr>
<tr>
<td></td>
<td>Virtual Environment Landing Craft Air Cushioned</td>
</tr>
<tr>
<td></td>
<td>Marine Corps Digital Voice Simulated Communications</td>
</tr>
<tr>
<td></td>
<td>Close Combat Tactical Trainer</td>
</tr>
<tr>
<td></td>
<td>MicroSimulations</td>
</tr>
<tr>
<td></td>
<td>Tactical Decision-making Simulations</td>
</tr>
<tr>
<td></td>
<td>America’s Army Video Game</td>
</tr>
<tr>
<td>Constructive</td>
<td>Modular Semi-Automated Forces</td>
</tr>
<tr>
<td></td>
<td>Joint Semi-Automated Forces</td>
</tr>
<tr>
<td></td>
<td>One Semi-Automated Forces</td>
</tr>
<tr>
<td></td>
<td>Air Warfare Simulation</td>
</tr>
<tr>
<td></td>
<td>Vehicle, aircraft, ship, weapon, and communications models</td>
</tr>
<tr>
<td></td>
<td>Human behavior representations, cognitive models, and intelligent agents</td>
</tr>
</tbody>
</table>
Facilitating Tactical Communications in a LVC Training Environment

The Tactical Advanced Combat Direction and Electronic Warfare (TACDEW) training system, dating back to the late 1970’s, was the one of first large scale training systems to integrate LVC components. The purpose of this system was, and is, to allow shipboard operators within Combat Information Centers (CIC) to interact with tactical equipment during a simulated training exercise such that crews on multiple ships may train together regardless of the physical distance between them (Kotick, 2005). For example, one crew aboard a ship docked in Jacksonville, Florida, may train with a crew aboard a ship docked in Norfolk, Virginia, and a team housed in a simulated onshore CIC also located in Norfolk, Virginia. Despite the distance between the groups, they all operate in the same simulated battle space, perhaps, off the coast of California.

The pier side CICs represent live components with live humans interacting with operational equipment. The virtual ship platforms represent the virtual components as live humans interact with computer simulations of shipboard equipment. The constructive piece is currently brought to bear through the use of a SAF engine, which provides the simulated battle space and specifies entities (Kotick, 2005).

The TACDEW training device provides task force and team training capable of driving up to 22 separate shipboard CIC mockup systems. Simulated exercises are exported to ships at pier side via the Multi-Unit Tactical Training System (MUTTS) (Human Performance Center, 2004). In this system, data are partitioned into three categories: tactical voice, link data, and scenario information. Tactical voice is comprised of voice communications between participants. Link data typically represent
text messages and data exchanges. Scenario information, in this case, includes information about the simulated battle space and the entities, which populate that battle space. Tactical voice, data links, and scenario information are passed between the onshore virtual ship simulators and MUTTS retransmission centers using a WAN. Transmission of scenario information is exchanged between MUTTS and pier side CICs over a WAN connection. Tactical voice and link data are transmitted locally over radio frequencies (RF). See Figure 4-1.

Bridging communications devices across the live and virtual domains (see Figure 4-1), requires a dedicated operational/military radio and Live Radio Bridge (LRB) software interface for each circuit bridged. Such a requirement results in the architecture
depicted in Figure 4-2. Within this architecture, an arbitrary number of live radios in the field or offshore may communicate with an arbitrary number of virtual radios within a training facility over a specified number of bridged circuits. Unfortunately, the number of circuits and level of training realism may be negatively impacted by a lack of available operational resources. Rather than building a communications infrastructure upon training objectives, the communications plan may be altered to accommodate resource availability.

The architecture depicted in Figure 4-2 has significant implications for current and future LVC training exercises. The TACDEW philosophy and its LVC applications
evolved into the current FST-Joint (FST-J) events and are supported by the Navy’s Continuous Training Environment (NCTE) architecture. FST-J events extend the number of exercise participants and distributed sites to include the U.S. Navy, Army, Marine Corps, Air Force, Coast Guard, and foreign military forces. FST-J events currently integrate multiple sites across the U.S. (Figure 4-3) and some foreign military sites. Integration of additional U.S. (Figure 4-4) and international (Figure 4-5) sites are planned for future exercises.

(Seeland, 2005)

Figure 4-3. Current U.S. Sites
Expanding the number of FST-J training sites will significantly impact the NCTE communications infrastructure (Figure 4-6). Further complications will arise as
Homeland Defense components such as local law enforcement, emergency, and intelligence services are integrated into large domestic and global synthetic training events. In order to support the increased number of training sites and the resulting enhancement of infrastructure complexity, current LRB methods will require hundreds, perhaps thousands, of relay radios. Allocating sufficient resources may be infeasible.

There is sufficient evidence to suggest that a dynamic, reconfigurable Integrated Live-to-Virtual Communications Server (ILVCS) will advance the state of the science of live radio bridging by reducing the number of relay radios required to conduct LVC training exercises. This research will alleviate communication resource allocation issues experienced by the local, Joint, and global training community as FST progresses and the NCTE architecture expands.
(Seeland, 2006)

Figure 4-6. NCTE Infrastructure
Meeting the Challenge: Prototype Integrated Live-to-Virtual Communications Server

A prototype ILVCS device was developed that applies the Live-to-Virtual (LV) Relay Radio Prediction Algorithm detailed in the paper “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments.” The ILVCS allows a user to determine the number of relay radios required to support a given LVC training event. By implementing the L-V Relay Radio Prediction Algorithm and leveraging previous bridging methods, the ILVCS advances the science of L-V communication in order to meet the challenges described above.

Fusing existing technologies and emerging methodologies offers the opportunity to revise the LRB architecture. The conceptual ILVCS architecture is depicted in Figure 4-7.

![Figure 4-7. ILVCS Conceptual Architecture](image)
As discussed in the paper, “Blending Systems Engineering Principles and Simulation Based Design Techniques to Facilitate Prototype Development: A Case Study,” the prototype development followed a spiral approach. The first spiral analyzed current L-V communications practices and the LRB configuration. The next spiral simulated ILVCS alternatives, and resulted in the system design developed in the final spiral. The outcomes of the final spiral and a description of the ILVCS system level design, hardware configuration, and software architecture are discussed below.

The high level ILVCS system design is depicted in Figure 4-8. The “live side” of the communications network is comprised of operational or “live” military radios that serve as relays between the training range and the ILVCS. They are tethered to the ILVCS so that they may be controlled (e.g. frequency tuning) and monitored (e.g. radio performance and health) through the ILVCS graphical user interface (GUI). Virtual radios communicating over a WAN and using Distributed Interactive Simulation (DIS) protocols reside on the “virtual side” and use Ethernet connections to link to the ILVCS. High Level Architecture (HLA) protocols can be supported through a DIS/HLA gateway. The ILVCS translates digital and analog messages so that transmissions may be bridged between the live and virtual domains.
A closer look at the ILVCS hardware configuration is provided by Figures 4-9 and 4-10. The prototype includes a monitoring receiver that is used to scan the RF spectrum. Dual Ethernet cards provide isolated connection to the simulation network and control of the receiver. Audio and control signals pass to and from the relay radios via an input/output (I/O) panel specifically designed for the ILVCS. This panel contains circuitry which routes various signals between the digital signal processors and high speed serial cards. Each relay radio connects to the I/O panel via a newly designed interface cable. With the exception of power, this cable is the only connection required to interface with the relay radios.
The underlying control mechanisms of the ILVCS are software driven (see Figure 4-11). The main program, the *Smart Radio Manager*, enables transmission routing.
through high level control processes. The *Comms* class initiates the *DIS Network Sniffer* in order to detect the arrival of virtual radio transmissions. The *Radio I/O* thread coordinates the functions between a specific live and virtual radio pair to facilitate message management. A component titled *Instructor Station* was adapted from existing LRB technology and serves as the software interface, the bridge, for live and virtual audio data. The *Live Monitor* class launches the *Live Monitor UDP Sniffer* in order to notify the *Smart Radio Manager* of the arrival of a live radio transmission. Finally, the *Smart Radio Manager GUI* supplies the user interface to the ILVCS.

![Image of ILVCS Software Architecture](image)

**Figure 4-11. ILVCS Software Architecture**
The following example illustrates the functions of the ILVCS. Prior to an exercise, a user will connect the ILVCS to the simulation WAN in order to provide connectivity to virtual radios. The ILVCS GUI is then used to input or create a communications plan that lists the frequencies to be bridged from the live side to the virtual side. Once the communications plan is created, the Smart Radio Manager (see Figure 4-12) must be launched. The user will input the exercise length, the number of frequencies dedicated to instructor use, and the number of frequencies used by students. The Smart Radio Manager will determine the number of relay radios to recommend based upon the L-V Relay Radio Prediction Algorithm. Other inputs (e.g. Squelch, Network Setup, and CommPlan) are user defined.

Figure 4-12 ILVCS Smart Radio Manager Configuration GUI
Once the number of relay radios is determined, the user connects the relay radios to the ILVCS unit via cabling provided with the device. Due to safety regulations and in addition to the spare relay radio capacity calculated by L-V Relay Radio Prediction Algorithm, the ILVCS conducts a reliability analysis of the relay radios tethered to it (see Figure 4-13). A reliability assessment is conducted on each relay radio connected to and controlled by the ILVCS. Assessment consists of built-in-testing that is standard issue for military radios and includes testing of electronics, circuitry, and radio software functionality. Guidance provided by the ILVCS if a failure is detected (see Figure 4-14), otherwise, the user is prompted to the next section. The user is responsible for replacing faulty radio(s) before proceeding to the next step.

![Reliability Analysis](image)

Figure 4-13. ILVCS Relay Radio Reliability Analysis Initiation Dialogue
The Smart Radio Manager initializes the relay radios and prepares them for bridging during the exercise. During the set up procedure, the GUI is updated and can be monitored by the Smart Radio Manager GUI shown in Figure 4-15. The radio indicators cycle from red signifying that the radio is not working or not activated, to green when it is activated, then to yellow which represents that radio setup in progress, and finally to green indicating the radio bridge is ready. When the set up bar reaches 100% completion, all relay radios are configured for the exercise and the L-V communications bridges are in place and ready for training.
Once the ILVCS Smart Radio Manager and the bank of relay radios are configured, L-V communications can be bridged. During the exercise the ILVCS will detect transmissions via the monitor/receiver (see Figure 4-9). The monitor/receiver scans the frequencies specified in the communications plan, alerts the Smart Radio Manager when a transmission commences, and on which frequency. The Smart Radio Manager searches the relay radio bank for an available radio and tunes it to the appropriate frequency, if necessary. The tuned radio receives the analog signal
transmission and passes it to the Smart Radio Manager. The signal is then digitized and
the translated transmission is forwarded to the WAN. Virtual radios tuned to the
equivalent virtual frequency will receive the digitized audio.

The routing of a transmission from the virtual side to the live side is similar.
Rather than relying upon the monitor/receiver to detect the occurrence of a transmission,
virtual radios provide an indicator via a push-to-talk (PTT) signal. In order for a user to
activate a virtual radio and transmit, a PTT device is engaged by depressing a button, soft
switch, or foot pedal. That signal alerts the Smart Radio Manager of a transmission
occurrence and the respective frequency. The message is translated from a digital to an
analog signal by Digital Signal Processors, and the Smart Radio Manager allocates a
relay radio for broadcast on the equivalent live frequency. Live radios in the field that
are tuned to that frequency will receive the bridged transmission.

The process of bridging transmissions allows for the recording of all bridged
messages. Upon exercise completion, the ILVCS may provide audio data to support after
action review purposes. The data recorded can also facilitate performance assessment of
the communications network. Source and destination data, transmission length and
arrival time are available for all recorded transmissions. Such data facilitates statistical
analysis of tactical communications characteristics and could be leveraged to enhance the
existing L-V Relay Radio Prediction Algorithm or other L-V communication research
efforts.

Laboratory testing was conducted to confirm the ILVCS functionality. The
driving force behind the ILVCS, the L-V Relay Radio Prediction Algorithm, was
rigorously tested through the use of discrete event simulation analysis and is documented
in the paper, “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments.” Other software functions and the hardware components were tested using the following method.

Twenty four operational radios were made available for ILVCS verification testing. Fifteen served as relay radios, and eight filled the role of field radios. The experimental design was influenced by the availability of military equipment, and is scalable for future testing that would involve a greater number of live radios. First, the ILVCS was configured with a communications plan that included fifteen bridged frequencies that were carefully chosen to avoid utilization conflicts with outside entities. The ILVCS was then configured to include eight virtual radios and fifteen relay radios. The eight field radios were located between 150 and 400 feet from the relay radio bank to reduce the possibility of intermodulation.

Intermodulation is a type of RF interference that can occur when live radios are physically located too close to one another. The introduction of intermodulation had the potential of negatively impacting the validity of the ILVCS test results. Intermodulation may cause detection of false positives and would unnecessarily consume relay radio resources. Figure 4-16 details the testing topology.
Following the system configuration, testing of serial transmissions commenced. Two important purposes were served. Serial transmission testing ensured that all live and virtual radios could successfully transmit and receive voice data. It also confirmed that the ILVCS could successfully bridge transmissions on all frequencies specified in the communications plan as expected. During this portion of the system test, one operator would transmit a known but variable test count on a specified frequency. All frequencies were tested in this manner for both L-V and virtual-to-live (V-L) routes.
The ILVCS demonstrated the ability to successfully bridge 100% of the serial voice transmission data between the live and virtual domains. During this testing phase one of the frequencies stipulated in the communications plan experience unanticipated activity from an external source. For this reason, the faulty frequency was removed from the communications plan one of the relay radios was removed from the ILVCS configuration. All testing involving this frequency was ceased. The loss of the data that would have been collected on this one frequency did not significantly or negatively impact the final analysis of ILVCS effectiveness.

The next and most critical testing phase focused on simultaneous transmissions. The inherent danger in reducing the number of radios in the relay bank is the loss of transmissions due a lack of resource availability. Safety regulations within the scope of this effort require 0% loss of transmissions due to the ILVCS. For this reason a carefully constructed experimental approach was followed to determine whether the ILVCS could meet this criterion. This phase tested the ILVCS performance under the following conditions: two, four, eight, and fourteen simultaneous transmissions. For the first three levels, one live radio and one virtual radio were tuned to equivalent frequencies. Operators transmitted a known but variable test count upon hearing a synchronized start signal. Round one of each test involved only L-V transmissions, and round two of each test was comprised solely of V-L transmission.

Fourteen messages were transmitted using a mixture of L-V and V-L. The Smart Radio Manager GUI was used to confirm the transmissions. Testing two, four, and eight simultaneous transmissions allowed for the detection of false transmissions to be allocated to a spare relay radio. The final level, fourteen simultaneous transmissions, did
not. If for some reason a false transmission due to interference occurred, there was a clear potential for loss of an actual transmission. This test exhausted the system’s relay radio resources and provided useful stress testing.

For all three levels and for all three transmission scenarios (i.e. L-V, V-L, mixture of L-V and V-L), the ILVCS successfully bridged 100% of the voice transmission data. The following appendix provides a sample of the ILVCS testing procedure and evaluation form.

### Conclusion

The prototype ILVCS represents the embodiment of emerging L-V bridging methodologies such as the L-V Relay Radio Prediction Algorithm through innovative technological development. This capability addresses key challenges facing the military training community. The impact of this work is both technical and financial. The ILVCS supports increased training realism by providing the opportunity to bridge more L-V tactical communications circuits, but with fewer resources. Integration of the ILVCS will also facilitate after action review and network analysis activities.

Looking to the future, expanded testing is recommended. Testing of the prototype ILVCS device within a LVC training environment under controlled circumstances, and subsequently during a training exercise, will provide further performance assessment opportunities. The ILVCS prototype provides a path forward for the improvement of tactical communications resource allocation and management.
APPENDIX: ILVCS SAMPLE TESTING PLAN
Description:

This testing procedure is designed to test the operational status of the ILVCS.

System Operation:

A minimum of 23 radios will be used for the testing of the ILVCS. 15 Harris 5800 tactical radios must be used to test the bridging of simultaneous transmissions. All ILVCS tests will be conducted with unclassified, unencrypted, communications. The Harris 5800 radios are not COMSEC equipment. Eight additional 5800 radios are required to act as live side transmitters for the test. Eight virtual radios will also be required to test virtual side communications. Antenna farm testing will require the additional use of a Harris PRC-117 COMSEC radio and three PRC-119 SINCgars radios. All antenna farm testing will be conducted with unclassified, unencrypted, communications.

Purpose:

The purpose of the testing procedures below is to verify the functionality of the hardware and software components within the ILVCS server, and to augment discrete event simulation testing of the L-V Relay Radio Prediction Algorithm. This testing procedure does not test the suitability of the ILVCS for use in an exercise, or verify its ability to operate beyond the capabilities tested. The test is designed for unclassified communications. The testing procedure has been designed to scale to higher numbers of radios and relays. The tests below can be modified for higher relay counts by simply
repeating the individual testing for each individual radio and conducting simultaneous transmission tests for the available number of relays.

**Setup:**

Choosing a communications plan for the exercise is the first step. The server will be configured to bridge 30 nets (1 Instructor and 29 Student Nets). It is important that the communications plan chosen is suitable for the radios used and the surrounding RF environment.

First, 30 frequencies must be chosen that are within the frequency capabilities of the radios used. Second, the location for the test must be monitored for activity on the chosen frequencies. It is important that all the frequencies in the communications plan are clear and open for use. If it is found that a chosen frequency is noisy or in use, it is important that it is replaced with another. Finally, each individual frequency in the communications plan should be at least 25 KHz apart. Try to choose frequencies with 1 MHz or greater separation. The initial testing communications plan is shown in table one. Frequencies may change as necessary to remove unwanted interference.

<table>
<thead>
<tr>
<th>Net:0</th>
<th>302678000</th>
<th>Net: 10</th>
<th>334156000</th>
<th>Net:20</th>
<th>363856000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net:1</td>
<td>304722000</td>
<td>Net:11</td>
<td>337155000</td>
<td>Net:21</td>
<td>366695000</td>
</tr>
<tr>
<td>Net:2</td>
<td>307504000</td>
<td>Net:12</td>
<td>341948000</td>
<td>Net:22</td>
<td>369783000</td>
</tr>
<tr>
<td>Net:3</td>
<td>311427000</td>
<td>Net:13</td>
<td>342695000</td>
<td>Net:23</td>
<td>372264000</td>
</tr>
<tr>
<td>Net:4</td>
<td>315548000</td>
<td>Net:14</td>
<td>345471000</td>
<td>Net:24</td>
<td>374384000</td>
</tr>
<tr>
<td>Net:5</td>
<td>319425000</td>
<td>Net:15</td>
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<td>Net:25</td>
<td>379388000</td>
</tr>
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<td>322684000</td>
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<td>350492000</td>
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<td>Net:17</td>
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<td>Net:27</td>
<td>384626000</td>
</tr>
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<td>Net:18</td>
<td>359167000</td>
<td>Net:28</td>
<td>386704000</td>
</tr>
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<td>Net:9</td>
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<td>Net:19</td>
<td>361695000</td>
<td>Net:29</td>
<td>388595000</td>
</tr>
</tbody>
</table>
Next, connect the ILVCS hardware, relay radios, and virtual simulation network as directed in the ILVCS installation manual. Position the 8 live side radios a minimum of 300 feet from the ILVCS relay radios. Figure one illustrates the layout topology. The ILVCS will be setup in the loading dock area of the Deflorez Building with field radios located a minimum of 300 feet away in the line of sight of the ILVCS. There are three power supplies, each capable of powering 6 relay radios. The power supplies will need to be located centrally to the relays so as to allow for the powering of the whole set. A fourth power supply will be used to power 6 of the eight field radios with the two remaining running off of battery power. The radios will be operated in low power – one Watt output.
Arrange the relay radios in a star topology around the ILVCS and operate the relays with the attached antennas. Power the system and wait for the Smart Radio Manager setup to load. Set the configuration options as needed including the communications plan you have chosen and begin the initialization process. Consult the user’s guide for assistance configuring the ILVCS software. The Smart Radio Manager setup software will perform a reliability analysis and built-in self tests on the relay radios during initialization. If the operational status of the field radios is not known, consult the Harris manual for instructions on testing the radios. Configure the virtual side simulation with eight virtual radios. The ILVCS software should proceed to initialize the 15 connected relays and begin bridging communications.
Testing Process

Serial Transmissions:

First make sure all virtual radios are listening to all of the frequencies in the communications plan. Have an operator transmit a test count to ten on one of the live radios starting on Net 0 and continuing to Net 30 in the communications plan. Verify that all virtual radios can hear the transmissions.

Repeat the sequence on a single virtual radio and have a live radio operator verify that the virtual to live transmission is heard on the live side as well. Repeat with the other live radios until all nets have been tested individually. Since 8 live and 8 virtual radios are available, retune the radios as needed to test all 30 nets. Additional hand held radios operating outside the communications plan should be used to facilitate ease of communication between live side and virtual side operators.

During the test, observe the radio activity in the smart radio manager (SRM) during a transmission. The active radio should change colors from green to blue while actively transmitting and receiving.

Simultaneous Transmissions:

Two Simultaneous Transmissions

Tune one live radio to net 0 and another to net 1. Tune a virtual radio to listen to net 0 and another to listen to net 1. Have both live side operators simultaneously transmit a test count to 10. Verify that both transmissions are heard by the virtual operators. Be sure to note any mixing or bleeding of audio between channels. Repeat the simultaneous
test for virtual to live side transmissions and verify. If necessary, repeat this test for each net in the communications plan.

**Four Simultaneous Transmissions**

Tune one live radio to net 0, another to net 1, a third to net 2, and a fourth to net 3. Tune three virtual radios to net 0, net 1, net 2, and net 3 respectively. Have the three live side operators simultaneously transmit a test count to 10. Verify that the associated virtual operators are all able to hear the test count. Be sure to note any mixing or bleeding of audio between channels. Repeat the simultaneous test for virtual to live side transmissions and verify. If necessary, repeat this test for each net in the communications plan by retesting with nets 3,4,5 and then 6,7,8, etc...

**Eight Simultaneous Transmissions**

This simultaneous test will simulate the maximum simultaneous transmissions expected during a typical 30 Net exercise. Tune eight live radios to nets 0 through 7. Tune eight virtual radios to the same nets. Have the eight live side operators simultaneously transmit a test count to 10. Verify that the associated virtual operators are all able to hear the test count. Be sure to note any mixing or bleeding of audio between channels. Repeat the simultaneous test for virtual to live side transmissions and verify. If necessary, repeat this test for each net in the communications plan by retesting with different nets.

**Maximum Server Load Test**

This will test that the server can handle the extreme case where every relay radio connected must transmit or receive simultaneously – thus leaving no radios open for additional bridging. Using the virtual radios, transmit simultaneously, using unique
frequencies. This will occupy 8 of the 15 relay radio resources available to the ILVCS. Additionally, initiate 7 transmissions from the field radios. REMINDER: Make sure every transmission source, virtual or live, is transmitting on a unique frequency. At this moment, the ILVCS will be actively bridging transmissions bidirectionally with 100% resource utilization. Monitor the software error window for errors messages. If the live and virtual radio resources exist, one could also monitor the active live and virtual nets for transmission bridging verification.

At this point you have verified that the ILVCS can bridge live to virtual and virtual to live side transmissions on any net in the communications plan simultaneously. The following steps are designed to test the fault handling responses of the ILVCS.

**Fault Testing:**

**Reliability Analysis Test**

The purpose of this test is to determine the functionality of the reliability analysis and built in self test feature within the ILVCS. First, turn off the odd numbered relay radios and startup the ILVCS. After the setup procedure, the reliability analysis tool will begin. After detecting that the radios are not functioning, a message box should pop up informing the user of the error. Verify that the radios that were turned off did not pass the test. Before choosing retry, turn on the relay radios and allow them to boot up. Select retry and verify that the tool continues to retest and proceed to the main smart radio manager with no errors.
Heartbeat test

Properly configure the ILVCS once again and wait for it to begin bridging communication traffic. While idle, the heartbeat feature of the smart radio manager software periodically checks the status of a radio when not in use. Every 10 seconds, the heartbeat will attempt to verify the operational status of a relay. If the relay radio is not detected, the respective light on the smart radio manager panel will turn from green to red. To test this feature, perform the following steps. While the system is sitting idle, turn off the odd numbered radios and observe their heartbeat status. Once all odd radios are off and the respective indicators in the GUI are red, turn the radios back on and observe the status change back to green.

Flutter Test

This test is designed to test the scanners ability to deal with multiple transmitters from different locations. This is a fault case where two field operators accidentally talk on the same frequency at the same time. With the ILVCS configured and operational, locate two field radios on opposite sides of the ILVCS maintaining the minimum 100 foot clearance. Tune both field radios to the first frequency in the communications plan. Proceed to have both field radio operators transmit simultaneously on the same net. Observe the audio on the virtual side and monitor the ILVCS for errors.

Realistic Load Testing

This test will test the ILVCS switching under the load of a realistic exercise. Using the CDIL record playback tool and radio emulators, playback a recorded 30 net exercise on the virtual network. The ILVCS will bridge the real traffic. Although it will
not be possible to observe the transmissions in the live realm, use this test to observe the ILVCS for error messages and faults. Allow the exercise to run for the complete 4 hours.

**Longevity Testing**

Configure the ILVCS with 15 relays in the lab and allow it to operate for 24 Hours. Verify proper functionality after 24 hours by performing a single live to virtual and virtual to live transmission. Be sure to note any noticeable performance degradation or error messages.
Operational Risk Management Identification of Hazards

Basic Testing Steps

1) Pre-Brief to core test team (participants will receive an introduction to the testing process and proper testing procedures)

2) Setup of the ILVCS test system (test equipment will be pre-configured and setup for the test team by qualified technicians)

3) Requirement tests (performed by the test team according to the published test plan)

4) Disassemble the ILVCS system (test equipment will be disassembled and returned to the lab by qualified technicians)

5) Post- Brief to core test team (participants will review any and all concerns during the testing process to the test lead)

Preliminary Hazard Analysis

Table A-2. Hazard Analysis

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personnel slip/fall hazard</td>
<td>Wet Ground - Moisture</td>
</tr>
<tr>
<td>Electric shock hazard</td>
<td>Plugging in power supplies incorrectly or mishandling batteries.</td>
</tr>
<tr>
<td>Back or muscle strain hazard</td>
<td>Improperly carrying heavy equipment.</td>
</tr>
<tr>
<td>RF Energy hazard</td>
<td>Proximity to RF energy / Pacemaker interference</td>
</tr>
<tr>
<td>Environmental hazard</td>
<td>Lightning in proximity to antennas</td>
</tr>
</tbody>
</table>
## Assessment of Hazards

### Table A-3. ILVCS Field Test Risk Matrix

<table>
<thead>
<tr>
<th>Mission: ILVCS Field Test</th>
<th>Date Worksheet Prepared: 9/18/06</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step 1. Identify Hazards</strong></td>
<td><strong>Step 2. Assess Hazards</strong></td>
</tr>
<tr>
<td><strong>Operation Phases</strong></td>
<td><strong>Hazards</strong></td>
</tr>
<tr>
<td>Operational steps 2-4</td>
<td>Personnel slip/fall</td>
</tr>
<tr>
<td>Operational steps 2-4</td>
<td>Electric shock</td>
</tr>
<tr>
<td>Operational steps 2 &amp; 4</td>
<td>Back or muscle strain</td>
</tr>
<tr>
<td>Operational step 3</td>
<td>RF Energy</td>
</tr>
<tr>
<td>Operational step 3</td>
<td>Environmental</td>
</tr>
</tbody>
</table>

**Recommend Accept Risks:** Yes

Note: For more information on the safe use of the commercial equipment utilized in this test - Refer to appendix A, B and C.
### Table A-4. Risk Matrix

**Risk Matrix**

<table>
<thead>
<tr>
<th>Severity</th>
<th>Probability A</th>
<th>Probability B</th>
<th>Probability C</th>
<th>Probability D</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>III</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>IV</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*Risk Assessment Code*

1 = Critical  
2 = Serious  
3 = Moderate  
4 = Minor  
5 = Negligible

### Table A-5. Risk Matrix Definitions

**Probability**

- **A** - Likely to occur immediately or within a short period of time.
- **B** - Probably will occur in time.
- **C** - May occur in time.
- **D** - Unlikely to occur.

**Severity**

- **I** - May cause death, loss of facility/asset.
- **II** - May cause severe injury, illness, property damage.
- **III** - May cause minor injury, illness, property damage.
- **IV** - Minimal threat.
ILVCS Test Checklist

Radio 1 Bridge Test
☐ Single Transmitter Bridged (Live to Virtual)
☐ Single Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Radio 2 Bridge Test
☐ Single Transmitter Bridged (Live to Virtual)
☐ Single Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Radio 3 Bridge Test
☐ Single Transmitter Bridged (Live to Virtual)
☐ Single Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
Radio 4 Bridge Test

☐ Single Transmitter Bridged (Live to Virtual)

☐ Single Transmitter Bridged (Virtual to Live)

Failures:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

Radio 5 Bridge Test

☐ Single Transmitter Bridged (Live to Virtual)

☐ Single Transmitter Bridged (Virtual to Live)

Failures:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

Radio 6 Bridge Test

☐ Single Transmitter Bridged (Live to Virtual)

☐ Single Transmitter Bridged (Virtual to Live)

Failures:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________
Radio 7 Bridge Test
☐ Single Transmitter Bridged (Live to Virtual)
☐ Single Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Radio 8 Bridge Test
☐ Single Transmitter Bridged (Live to Virtual)
☐ Single Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

2 Simultaneous Transmissions Bridge Test
☐ Simultaneous Transmitter Bridged (Live to Virtual)
☐ Simultaneous Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
4 Simultaneous Transmissions Bridge Test
☐ Simultaneous Transmitter Bridged (Live to Virtual)
☐ Simultaneous Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

8 Simultaneous Transmissions Bridge Test
☐ Simultaneous Transmitter Bridged (Live to Virtual)
☐ Simultaneous Transmitter Bridged (Virtual to Live)

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

15 Simultaneous Transmissions/Receptions Bridge Test
☐ 100% Load Software Success

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
Reliability Analysis Testing
☐ Full Malfunction Test

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Heartbeat Testing
☐ Full Heartbeat Test

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Flutter Testing
☐ Flutter Test

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Realistic Load Testing
☐ Recorded Exercise Test

Failures:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
Longevity Testing

☐ Longevity Test Performed

Failures:

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

NOTES:

________________________________________________________________________
________________________________________________________________________
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REFERENCES


CHAPTER FIVE: SUMMARY OF RESULTS

The aim of this body of research was to establish a method for reducing communication resources within the tactical training environment and to develop a prototype device implementing that method. Several significant contributions to the literature and the tactical training environment are offered by this research effort. This section of the dissertation summarizes the experimental results and contributions of each paper. The overall significance of this work is also reviewed.

The purpose of the first article, “Predicting Resource Requirements for Bridging Live-to-Virtual Communications in Tactical Training Environments,” was to detail the development of a novel method for determining the number of relay radios required to support a LVC training event. Current practice requires a relay radio to be statically allocated for each circuit that is bridged between the live and virtual communications assets. Traditional “trunking” methods from telephony theory have been applied to a multitude of domains in the past. However, the nature of tactical communications violates a core assumption to the historic telephony trunking forecast method, the Erlang B loss formula.

A primary assumption of the Erlang B loss formula is that transmission arrivals follow a Poisson process. Tactical communications are shown in this research to fail the independence assumption of a Poisson arrival process. The applicability of telephony methods to the tactical training environment was called into question by the violation of Poisson assumptions and other significant differences between tactical/crisis communications and commercial telephone traffic. A comparison of Erlang B loss
formula predictions and tactical communication traffic observed during DES experimentation revealed no significant difference. A statistical test of the means revealed a 95% confidence interval of (-1.4783, 4.7908) and a p-value of 0.29 at an $\alpha$ level of 0.05.

The second component of the L-V Relay Radio Prediction Algorithm, spare capacity, was also confirmed through DES experimentation. Typical communication spare capacity requirements for military training systems and other high risk environments range from 20-30%. Spare capacity of up to 30% was found to be sufficient to address the 0% loss QoS requirement for tactical communication networks.

The principal contribution of this research article is the L-V Relay Radio Prediction Algorithm. In addition to providing the motivation for the work and a detailed description of the algorithm’s creation and verification, this paper clearly defines the feasible region within which its application is recommended. The L-V Relay Radio Prediction Algorithm is intended to be used for exercises requiring up to 40 bridged circuits and characterized by peak period durations of between 2 and 6 hours. Recommendations are given for cases where more than 40 circuits are to be bridged. Estimated resource and cost savings are also provided. An estimated 25-53% reduction in hardware is coupled with an estimated $150,000.00 - $630,000.00 cost reduction per site.

Another significant contribution resulted from the application of the Erlang B loss formula. The formula requires the number of transmissions as an input. A regression model was formulated to estimate the number of transmissions likely to occur during a
training exercise. The output of the model is based upon the peak period length and number of bridged circuits.

The paper, “Blending Systems Engineering Principles and Simulation Based Design Techniques to Facilitate Prototype Development: A Case Study,” provides insight into the methods and processes leveraged by this research effort. Application of the HPSM reflects the model’s ability to facilitate development of emerging technologies. This work is a testament to the utility of the HPSM as a systems engineering platform for research, development, and prototyping.

Another element that was critical to the success of this research and development effort was DES modeling and analysis. The DES model developed for this effort provided key insight into the nuances of tactical communication networks and served as an experimental environment. Without the development of the simulation model, the research would have been severely impaired due to the lack of a physical communication system to analyze. The DES developed was used to verify the L-V Relay Radio Prediction Algorithm and to define the feasible region of its application. Alternative system design comparisons were conducted through simulation output analysis. Ultimately, the value of the DES can be measured by the estimated reduction in developmental costs and schedule. It is estimated that DES analysis resulted in a cost savings of 33% in hardware procurement, 46% in software development, and 75% in system analysis. The overall savings in production time due to the use of the DES is 43%. Thus, this research effort exemplifies how modeling and simulation techniques can significantly reduce technical, cost, and schedule risks.
This article offers three key contributions. The first is a viable systems engineering process, rooted in HPSM methodology that has delivered the technical foundation upon which to build future research and production efforts. The second is a verified DES capable of modeling the behavior of a L-V communications network that is based upon empirical data collected during real-world LVC training exercises. Finally, an artifact of the development of the above simulation model is a deeper insight into the underlying characteristics of tactical/crisis communications traffic than previously documented in the literature.

The third and final paper, “Managing Communication Resources in Live, Virtual, and Constructive Training Environments,” shares designs and experimental results related to the ILVCS prototype device developed. Motivation for the implementation of the L-V Relay Radio Prediction Algorithm via the ILVCS is documented in a brief history of L-V communications bridging and a description of the future vision of L-V communications within the NCTE. A multitude of ILVCS system and architectural designs are given, and include: conceptual model, high-level software design, high-level hardware design and configuration, hardware interface architecture, and functional testing topology. A description of the intended use of the ILVCS is explored through an illustrative example; images from the graphical user interface are provided for clarity.

In addition to the detailed discussion of the ILVCS design and implementation, experimental results are also disclosed. Functional testing results report 0% loss for both serial and simultaneous transmission due to the availability of L-V relay radios. A stress test comprised of stimulation of the system with prerecorded data verified the ILVCS performed as designed.
The overarching contribution of the research is the improvement of LVC training methodology and practice. Specifically, this effort advances the state of science of L-V communication resource allocation and addresses current and emerging needs of the tactical/crisis training community. The two core components include an innovative method for predicting communication resource requirements and a prototype device implementing the L-V Relay Radio Prediction Algorithm. As a result of this work, requirements specifications, design specifications, and experimental results are available for use by future research and production efforts aimed at bridging live and virtual communications. It is intended that the products of this research effort serve as a catalyst for further innovation in the field of L-V bridging.
CHAPTER SIX: RECOMMENDATIONS AND CONCLUSIONS

Ultimately, the legacy of this body of research is a strong foundation upon which to build. Products of the effort include innovative theoretical advancement, a prototype device, and the associated design documentation and experimental results. However, subsequent L-V bridging research is recommended. Refinement of the L-V Relay Radio Prediction Algorithm requires additional data analysis in order to expand the applicability of the heuristic. Ideally, additional data collection should consist of a variety of exercise conditions such as varying length and number of bridged circuits. Other important data features to pursue include mission objectives and details of specific scenario events. Reduction of false triggers and other anomalies that corrupt data will improve the quality of observational data.

Similarly, enhancement of the DES based upon the results of the additional and improved data collection as described above is a logical next step. Advancement of the DES to include globally distributed operations would provide tools to assess requirements and impact designs of future development efforts. Leveraging of the DES developed under this research is recommended for developmental efforts aiming to reduce technical, cost, and schedule risks.

The prototype device capabilities may be extended in a number of ways, but additional testing of the ILVCS device is recommended. Extensive laboratory testing of the underlying prediction and relay radio control algorithms was completed by this research. Experimentation within a controlled LVC training environment, and ultimately during a training exercise is advised. The nature of the ILVCS lends to integration of
after action review tools and Scenario Based Training capabilities. Expansion of the data
types supported could encompass text and digital communications, for both classified and
unclassified communications.

The benefits rendered by the application of the L-V Relay Radio Prediction
Algorithm and the integration of the ILVCS technology have been documented. Gains
afforded by these two core research contributions do not require a tradeoff in
performance, rather they are specifically designed to maintain and improve training
realism. This body of work determined that telephony forecasting methods were
applicable to L-V communication networks. The feasibility of significantly reducing the
number of relay communications resources within a L-V environment was substantiated.
Benefits of applying the HPSM as a systems engineering approach and DES analysis
techniques for prototype technology development were confirmed. Finally, laboratory
testing indicated that the ILVCS technology is primed for field testing in a LVC training
environment.

The research reported in this dissertation has the potential to significantly
influence training methods employed at training sites distributed throughout the world.
In this regard, this body of research could realistically assert a global impact.