11TH ICCRTS
COALITION COMMAND AND CONTROL IN THE NETWORKED ERA

LIVE VIRTUAL CONSTRUCTIVE EXPERIMENTS FOR C2 EVALUATION

Topics: C2 Modeling and Simulation, Coalition Interoperability

Paper: I-090

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ABSTRACT

As Command and Control (C2) functionality expands in scope and complexity, the value of accurate, repeatable, and reproducible experimentation methodologies increases. Early recognition of this advantage led the US Army to sponsor and support a C4ISR Systems Engineering and Experimentation Laboratory (C4ISR SE2L). The C4ISR SE2L has been in operation for over a year and performs network analysis, including all aspects of the network - the sensors, communications, and C2 – in a live, virtual, and constructive (LVC) environment. The laboratory is an example of an environment for experimenting with C2 in realistic situations. Non-ideal conditions can be simulated in a controlled environment and effects on the applications measured. The laboratory environment can be extended to include interaction with systems in the field. The C4ISR SE2L has participated in two field experiments and is in the process of planning for a third. The architecture of the C4ISR SE2L allows, and in fact encourages, experimentation with multiple systems, Warfighter in the Loop components, and fielded components (i.e. vehicles, sensors) at actual test ranges. The results from these experiments are currently being folded back into the planning, requirements, and concept effort for future systems. This paper describes the philosophy and architecture of the C4ISR SE2L, experimental designs, results of recent experiments, and how these results can be used in the systems engineering process.

Introduction

It has long been held that knowledge is king. Information and intelligence feed and grow that knowledge. This allows leaders to make better decisions and achieve better results. This is true in any setting, whether it be a Fortune 500 company trying to capture market share or a US Army commander trying to capture insurgents in Baghdad. Command and Control (C2) relies on the commanders receiving comprehensive, timely, and accurate intelligence and information and then having the ability to relay direction to the forces they employ. Increasingly more sophisticated automated methods are being employed to gather, filter, fuse, store, distribute, and utilize battlespace data to increase situational awareness (SA). In the tactical environment, emphasis is being placed on equipping more soldiers and platforms at lower echelons with integrated network applications. These applications enable increased red and blue SA, collaboration tools, assisted and automated target-weapon pairing, logistics and maintenance support, and embedded training, to identify a few capabilities. For soldiers of the information age, this is a natural evolution of technologies. However, this evolution emphasizes the increased reliance on these applications, the system of systems architecture, and the importance of the infrastructure it rides upon - namely the network, made up of radios, computers, routers, sensors, applications, and the standards that define and allow integration and interoperability of the systems. In order for the commanders to exercise C2, data must move quickly and reliability through the evolving network.

The tactical environment relies on wireless communications. While this technology has seen great advancements and is virtually ubiquitous in today's society, it has not, will not, and cannot keep pace with software and hardware improvements that closely mirror Moore's Law of microprocessor innovation[1]. This is due largely to the limited resource of electromagnetic spectrum and the laws of physics. Therefore, network applications in the tactical, and in fact all environments must be optimized for network infrastructure, which is typically bandwidth constrained, dynamic, and sometimes unreliable. Traditional heavy armor and brute force are often being traded for information superiority and nimbleness. This is further evidence of the importance of the network and the associated applications. Additional emphasis in engineering the network - tailoring its configuration, providing early software evaluation, and measuring its performance in a variety of scenarios – is crucial in achieving success, with less direct contact between friendly and opposition forces (and thus less risk of casualties) through the synergy of superior information and weaponry versus weaponry alone.

[1] Gordon Moore projected the doubling of microchip complexity every twenty-four months in 1975. Carver Mead, a Caltech professor later coined the prediction "Moore's Law".

Concept

A live, virtual, constructive (LVC) environment provides a systems engineering tool to analyze the performance of the network applications and eventual force effectiveness of the future force. The LVC environment provides a simulated constructive environment made up of many entities, whether they be vehicles, radios, sensors, etc., that can then be interfaced with both live and virtual systems. This is particularly useful and necessary when systems engineering involves the development and integration of many systems, also known as a System of Systems (SoS). The constructive elements can represent systems still in development or be used to provide large quantities of systems that would be impractical to procure. Live systems are placed in the environment and can exchange messages, transported by the constructive simulation network. Likewise, sensors, whether represented by live components (e.g. prototypes, emulations or surrogates), virtual, or constructive simulations can be integrated into the environment to provide SA stimulation over the network and to the live systems. A variety of virtual environments can be examined, looking at different missions, terrain features, and weather conditions, to analyze the performance under different scenarios.

To illustrate an example implementation of this concept, one such modeling and simulation (M&S) environment will be examined. To take full advantage of the LVC environment, the US Army sponsors a Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Systems Engineering and Experimentation Laboratory (C4ISR SE2L) to support the development of the Future Combat System (FCS). The FCS concept is that of a total force transformation based on a networked SoS including vehicles, communications, sensors, sensor data fusion, C2 entities, C4ISR functionality, weapons, manpower, the Warfighter, and training. The C4ISR SE2L provides an architecture, development environment, and experimental test bed to examine and prove out concepts and refine requirements to drive the design and implementation of hardware and software before they are committed.

The overall architecture of the C4ISR SE2L as utilized for FCS is illustrated in Figure 1. As with the FCS program in general, this architecture is being instantiated in phases, based on the priority of experimentation activities and analyses related to the introduction of C4ISR systems and subsystems into the FCS Family of Systems (FoS), as well as external, complementary programs interoperating with FCS as part of the overall SoS. Although some architecture components have been identified and implemented quite easily (because of their uniqueness and long history of usage throughout the M&S community), others may require significant evaluation against other candidate components with similar functionality, but quite different ultimate purposes. Such evaluations could be in the form of trade studies, benchmarking individual models under normal and stressing operating conditions, performing analytical extrapolations to better identify and understand inherent model limitations, etc. Naturally,

implementing this architecture is best facilitated by collaboration with C4ISR partners throughout the US Army and Department of Defense (DoD), whose M&S activities could be directly leveraged by the FCS program. These activities, many of which predate the FCS program, are often accompanied by a strong pedigree of M&S tools, techniques, and architectures which have been subjected to significant (if not substantial) verification and validation (V&V) efforts. Such efforts provide confidence not only in results generated with these components, but also in results generated with M&S components derived from them. This approach is being employed throughout the population of the illustrated architecture.

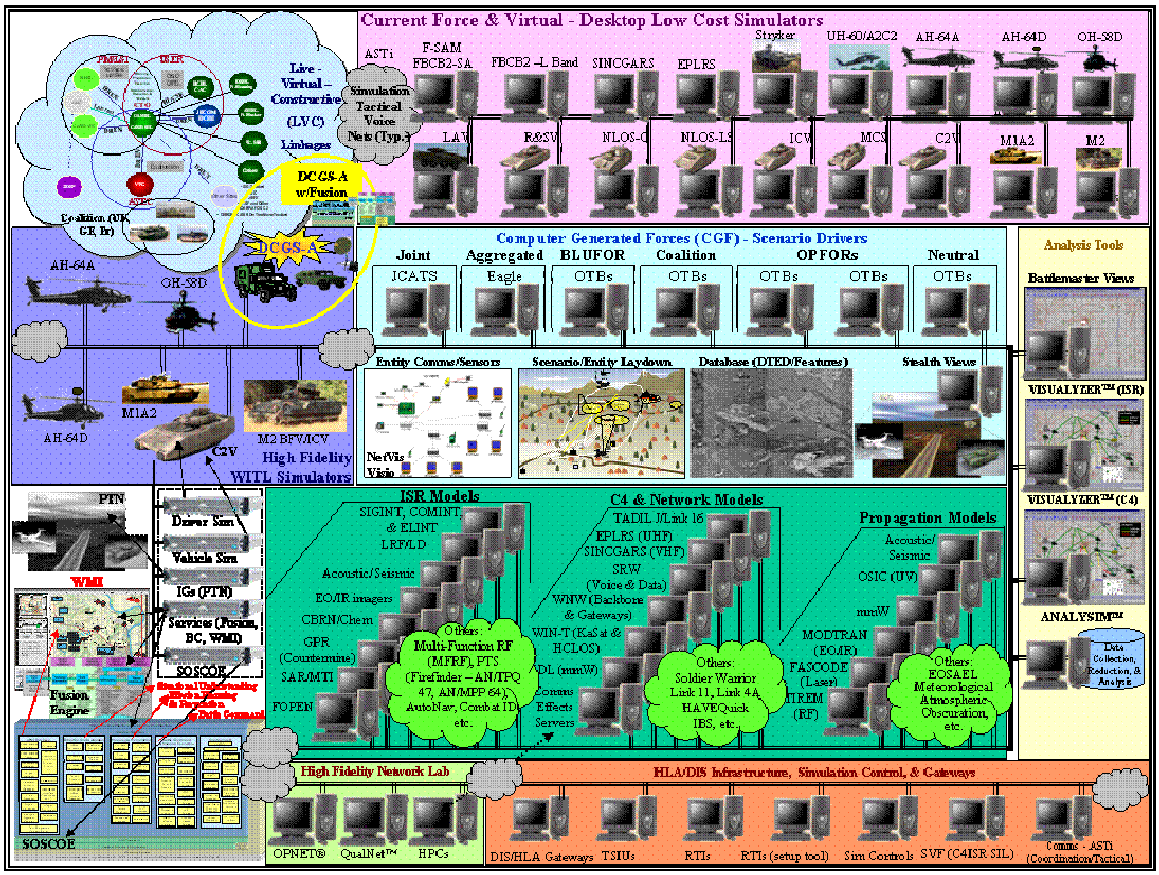

Figure 1 - C4ISR SE2L Architecture

The C4ISR SE2L consists of several components, each contributing models, tools, interfaces and functionality to the total environment. Within the C4ISR SE2L, the effort is directed to M&S that is utilized as a tool to conserve resources, provide pertinent analysis and answers to trade questions, provide easily changeable metric calculations, and provide hard statistical data that allow decision makers to exercise their decisions. M&S, appropriately utilized, will provide accurate and possibly mission critical data if the models or simulations correctly reflect real world systems. Therefore, all simulation and experimentation conducted in this environment is based on models that can be traced back to the

underlying physics, operational doctrines, and communication protocols between each component and the rest of the architecture. The models used in the M&S activity within the C4ISR SE2L range from high fidelity first principle approaches, to moderate and even extremely abstracted models wherein the real-time input/output performance correlates adequately (within the limitations of the overall LVC environment) with the high fidelity models and (when available) experimental data.

It has been recognized that no one model or simulation will be able to achieve the varying levels of fidelity needed for different trade studies and questions to be answered. To that end, the C4ISR SE2L has the capability to adapt to the needs of the particular problem under study, and optimize the associated simulation needed to provide the analysis data and tools. The approach to trading fidelity, complexity, and maturity of the M&S tools used for experimentation can be described by the following process: (1) initial component concepts are proposed; (2) candidate architecture products are developed to best illustrate the utility of the system components; (3) requirements for the initial concepts and architectures are developed; (4) the preliminary component designs are modeled and evaluated against the requirements; (5) the various components are assembled in the proposed architecture using M&S in a virtual and constructive environment, to evaluate the performance of the individual subsystems, system, family of systems, and SoS; (6) live elements, using either prototypes or surrogates, can be introduced to the virtual and constructive environment. The results of each step are fed back into the previous steps. This allows refinement of the requirements, concepts, designs, and modeling representations. The cycle is repeated until the system performance matches system requirements and the simulated and surrogate elements can eventually be replaced with fieldable software and hardware. With constant feedback, as M&S matures, the program benefits; consequently, as the program matures, the level of M&S sophistication increases. Command and Control (C2) is highly dependent upon information collection, fusion, and analysis to make informed decisions, information management to coordinate decisions, and timely dissemination to act upon those decisions. These processes occur in parallel, and the C4ISR SE2L allows for experimentation of concepts, scenarios, and tactics before committing to implementation.

The simulation architecture is divided into two distinct environments: High Fidelity Modeling and LVC. High fidelity modeling allows a very detailed degree of analysis at the component level. In the case of communications, this may entail protocol analysis of a small number of radios. This supports the design of components, but is usually limited in the scalability of the analysis and is performed in isolation of the other systems of the network. Once the performance of the individual components is characterized, it can be appropriately abstracted to analyze system interactions and performance in the LVC environment.

High Fidelity Modeling Environment

Within the high fidelity laboratory, detailed engineering models are used to study the performance of a low number of nodes, such as a small subnet of network nodes or single sensor fields. The expected sensor performance is determined through the exercise of the models under conditions that reflect the planned experimental environment. The fidelity of any model depends on the accuracy of the physical representation and the input data that drive it. For example, the acoustic/seismic model includes a detailed model of the atmosphere that is both altitude and range dependent (i.e. temperature, wind, humidity, turbulent modules, etc), and contains a detailed surface model that includes structures in the acoustical wavefront propagation path. The seismic model includes representation of the soil layers and underlying geological structure. A sample output indicating acoustic wavefront propagation losses over digital representations of actual terrain is shown in Figure 2. These propagation losses are then fed into algorithms which characterize the acoustic sensor's detection performance across the entire terrain grid, accounting for both deterministic and stochastic (statistical) effects, as well as acoustic signatures of both candidate targets and background noise sources. The C4ISR SE2L also contains a similar capability for seismic wavefront propagation and sensing. General trends regarding probabilities of target visionics detection, recognition, and identification are illustrated in Figure 3 for a notional ground based infrared (IR) sensor. These data, which represent the probabilities of achieving the noted targeting functions with a Warfighter-in-the-loop viewing sensor imagery, are being modeled using input parameter settings which vary based on sensor type, target type, target velocity, and desired level of successful targeting function. These parameter settings are also distributed throughout the program to organizations responsible for FCS analysis activities, thereby ensuring that a common methodology is being used across the program.

Providing input to the sensor performance models are the detailed physical models of items such as atmospheric transmission in the visible and IR spectral regions for electro-optical (EO)/IR systems as illustrated in Figure 4. For communications models, radio frequency (RF) and/or millimeter wave (mmW) path loss (due to free space propagation and/or terrain effects), link quality, and expected transmission rates are computed for the experimental environment, as seen in Figure 5. These calculations are performed using models which are recognized standards throughout the US Government, industry, and/or academia, such as MODTRAN (wide-band moderate spectral resolution atmospheric transmission for visible/EO and IR sensors), Terrain Integrated Rough Earth Model (TIREM, for RF propagation), and FASCODE (deterministic transmission at a single spectral line for laser propagation). For example, MODTRAN can be executed at different meteorological visibility ranges to generate different transmission versus range curves. These curves are then fed into the target acquisition models to generate the multiple performance curves (as a function of visibility) illustrated throughout Figure 3. Additional tools are

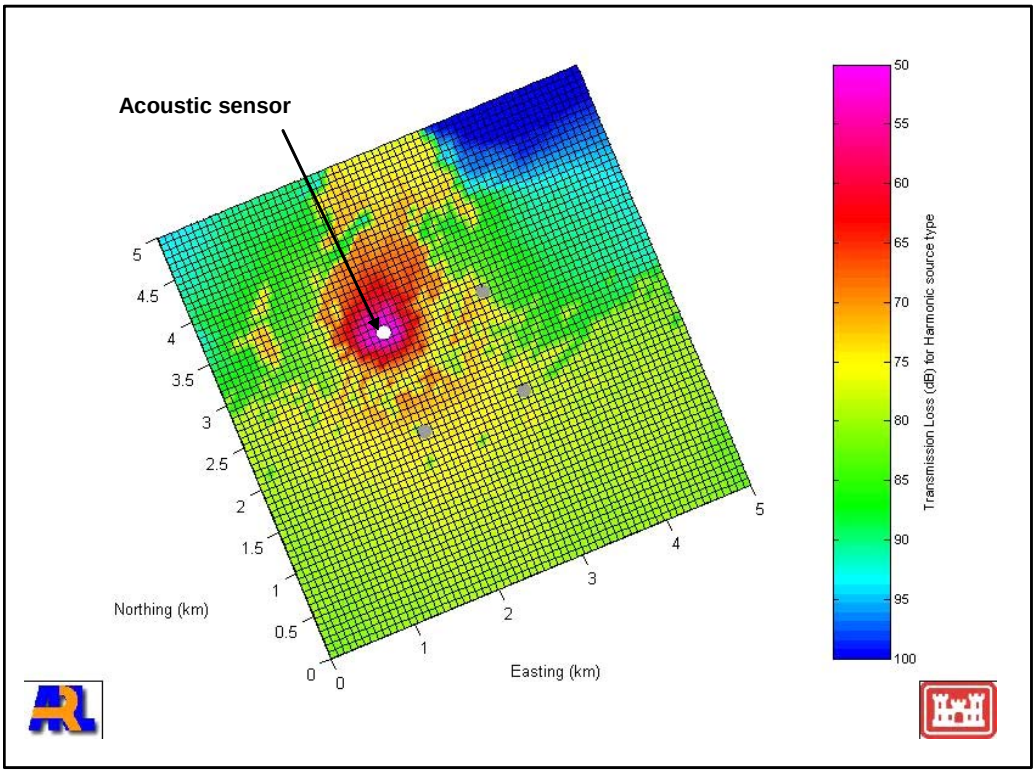

Figure 2 – Sample Acoustic Propagation Losses

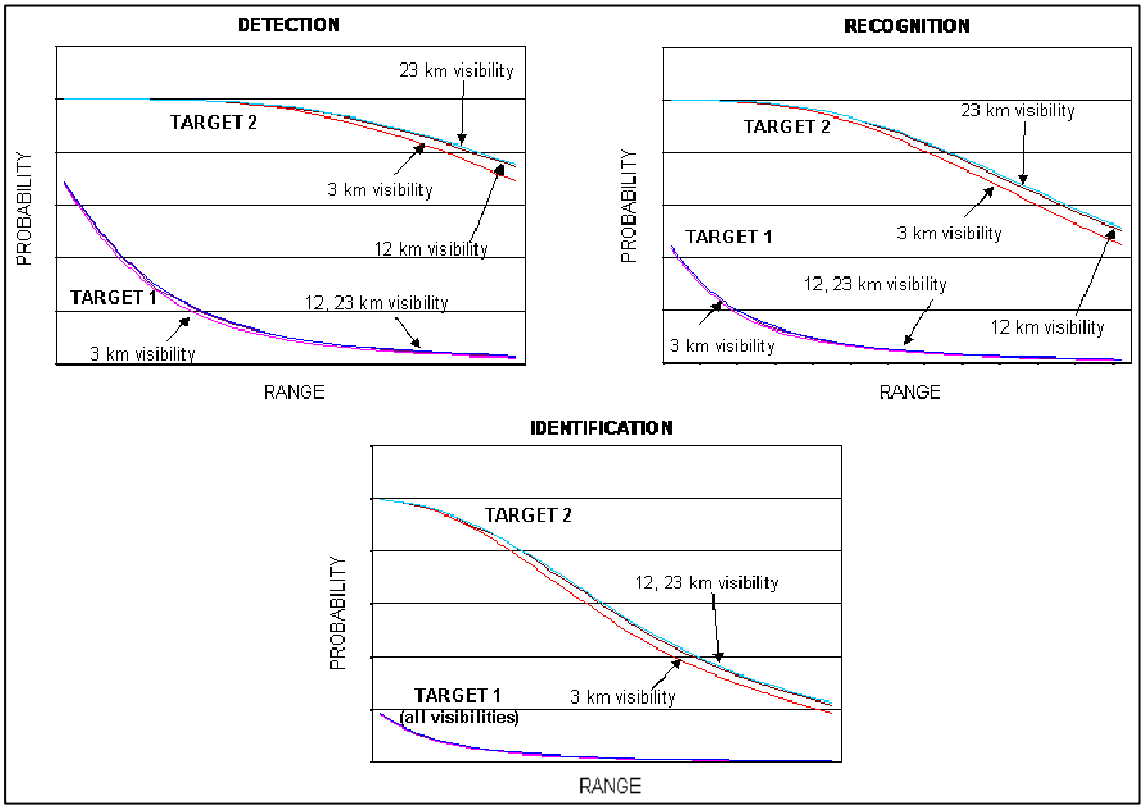

Figure 3 - Notional IR Sensor/Warfighter Visionics Detection, Recognition, and Identification Trends

available for calculating the stochastic effects of atmospheric turbulence on laser propagation. Both types of effects must be accounted for when modeling systems such as laser rangefinders and laser designators. Acoustic and seismic propagation effects are also modeled leveraging specialized tools developed by subject matter experts in these disciplines. Where possible, more than one analysis tool is utilized to compare the expected results. The comparison is important as each model contains assumptions that may be different from the other models and, in order to effectively plan and utilize the LVC experiment, the effects of each of these assumptions must be understood.

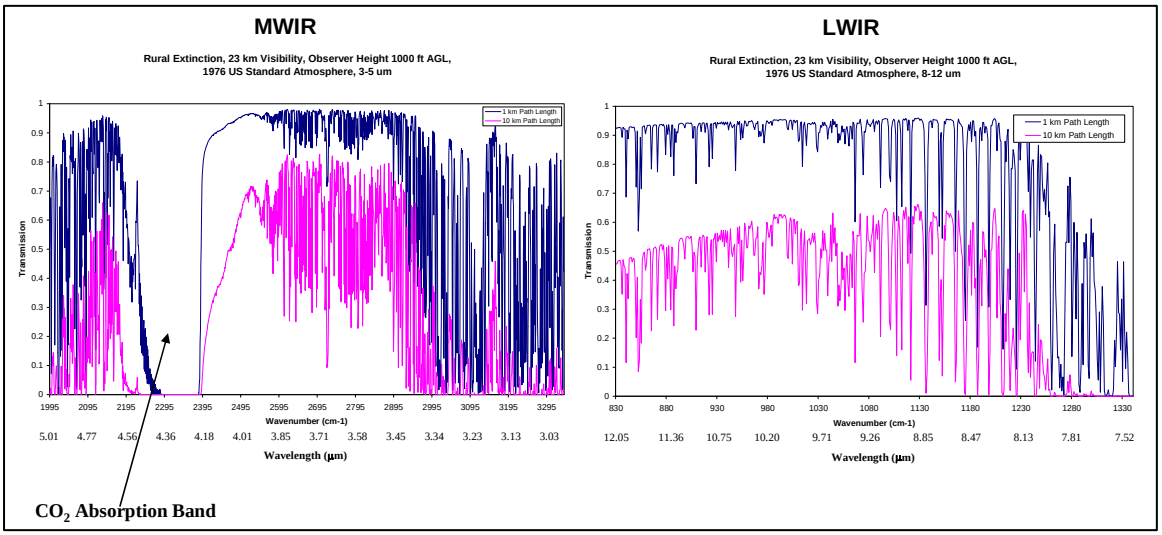

Figure 4 – Sample EO/IR Atmospheric Transmission Plots

In addition to the sensor and wavefront/radiation propagation models, the high fidelity portion of the laboratory also includes models of the network and communications. These are discrete event simulations (DES) that are used for detailed simulations of the proposed network. Some typical model outputs that are collected and analyzed include Message Completion Rate (MCR) and Latency (or Delay) as functions of the number of simulated nodes, network loading, message size distribution, and the distribution of differing message priorities. Figure 6 displays notional MCRs for differing numbers of nodes at a nominal network loading of one megabit per second (Mbps). One can note the differing latencies as a function of both scenario time (x-axis) and notional message priorities.

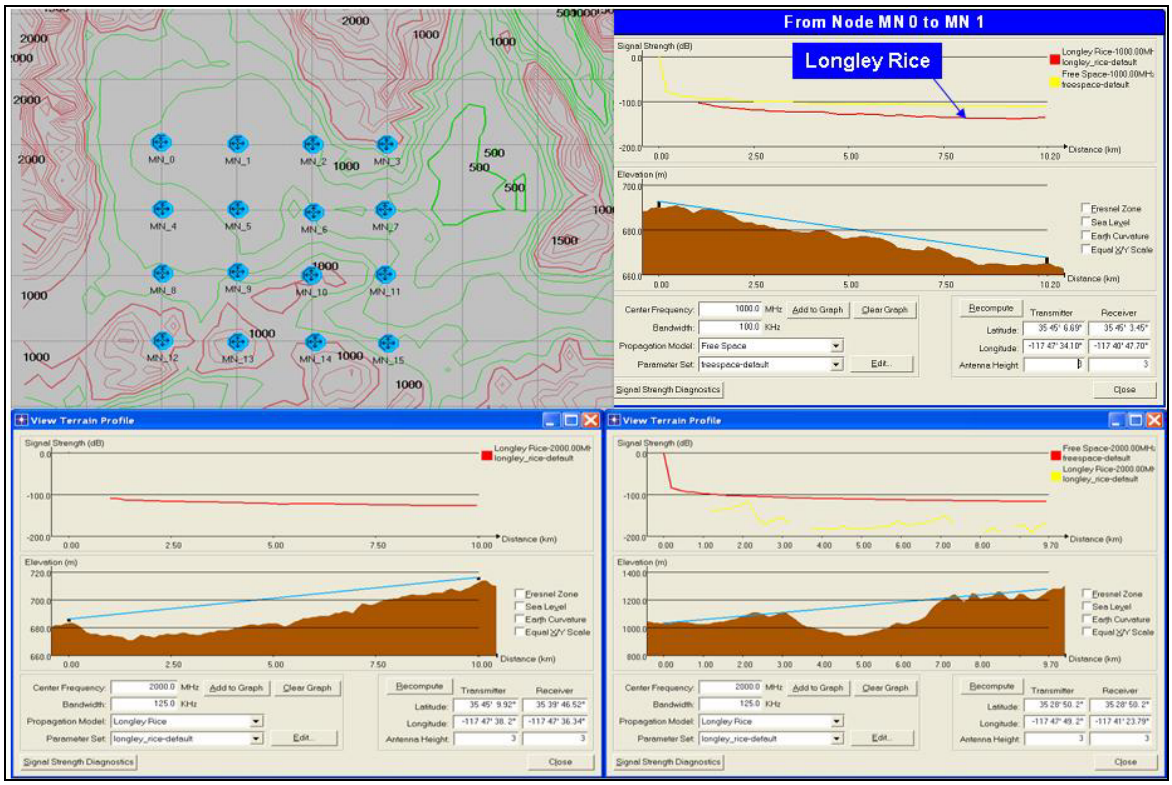

Figure 5 - Communication Terrain Effects

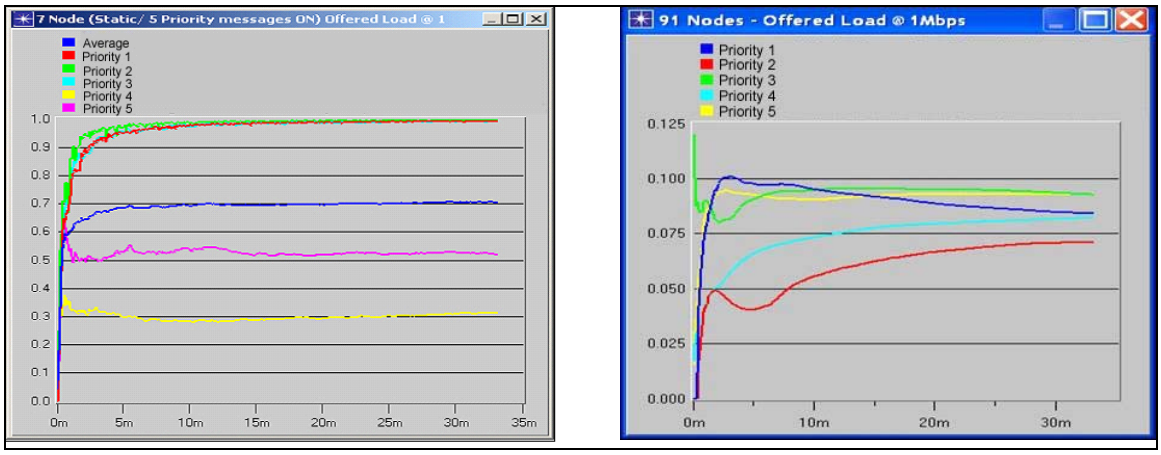

Figure 6 – Notional Message Completion Rates versus Message Priority and Number of Communications Nodes

LVC Environment

Information collection is a combination of real-time sensor data, fusion processors to reduce data collected by multiple sensors into individual, deconflicted objects, soldier reports, and other source intelligence. Each of these can be modeled and simulated within the C4ISR SE2L; or, for the case of a cooperative live exercise, actual sensor feeds and field reports can be integrated into the simulation. The sensor and communication models in the C4ISR SE2L's high fidelity environment illustrated in Figure 7 are used, in real time where possible, or in the form of abstracted models, probability curves, lookup tables, and sensitivity analyses to simulate the sensor and network performance under the variety of experimental conditions. These models can also be used (at the appropriate level of abstraction) in large scale experiments, made up of hundreds or thousands of nodes, in a real-time environment.

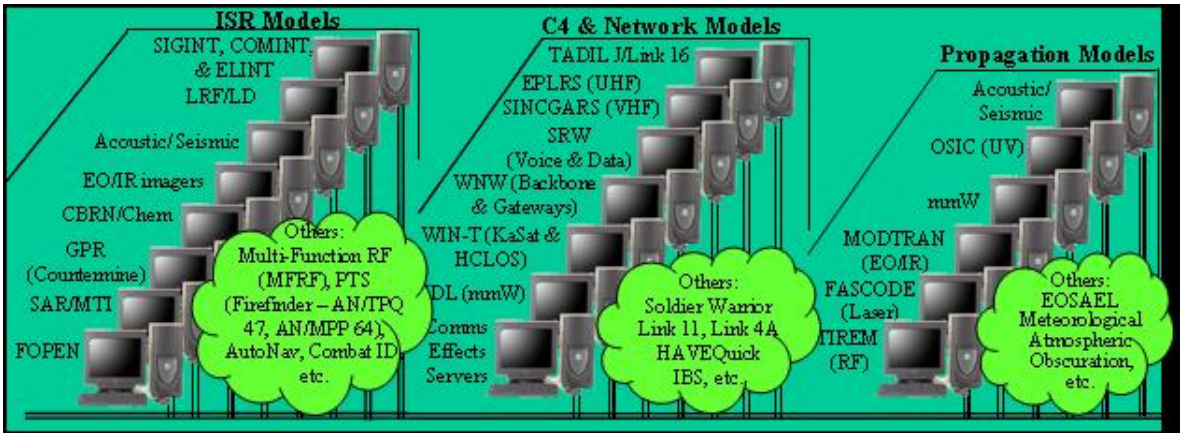

Figure 7 – Representative High Fidelity Models and LVC Models and Simulation Tools

When experimenting with larger scenarios that include tens, or even several hundreds of entities, use of live forces becomes prohibitive in terms of cost, time and space. Within the C4ISR SE2L, Computer Generated Forces (CGFs) make up the constructive entities and stimulate the simulation tools as shown in Figure 8. This includes blue and red entities, the entity missions and routes, and terrain. In force effectiveness analyses, the CGFs may also provide the final analysis results by recording loss exchange ratios, lethality data, and hit/miss ratio. Depending on the objective of the experiments/analyses, a number of different CGFs can be used to stimulate the LVC environment. Different levels of abstraction are available that aggregate brigade or battalion elements or explicitly represent individual elements down to the vehicles and soldiers. Likewise, the CGF behavior representation can vary from being completely scripted, scripted with the aid of artificial intelligence, or be assisted by trained scenario developers who control the entities. Often a combination of these behavior representations is needed in an experiment or analysis. Human controlled entities provide the most accurate representation, but also consume the most resources in terms of time and money. No matter what CGF is used for a particular analysis, the output is

recorded so that it may be played back. This allows re-creating the analysis or experiment, keeping the scenario constant while varying other parameters such as radio configuration, or correlating analysis results with specific maneuvers or decisions during the scenario. Figure 8 illustrates the CGF capability available to the C4ISR SE2L. For a given real-time simulation, the number of CGF entities is limited only by the number of CGF platforms/workstations available, and the bandwidth of the simulation network. As an example, a full Brigade Combat Team (BCT) was recently simulated for communications capabilities analysis.

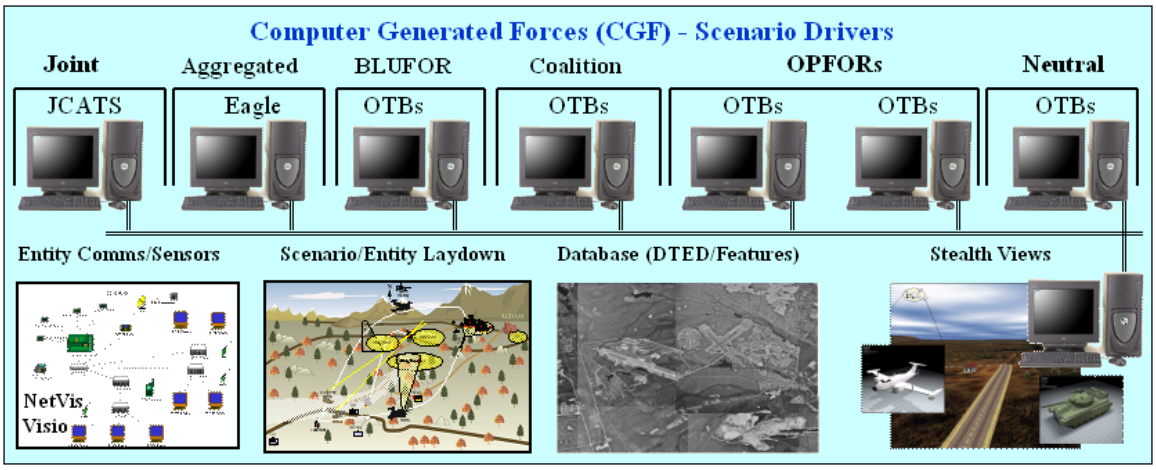

Figure 8 - Computer Generated Forces

The C4ISR SE2L architecture supports Warfighter in the Loop (WITL) experiments by interfacing hardware such as actual HMMWVs, M1A2 tank simulators, and helicopter cockpit simulators (with examples shown in Figure 9) into the distributed environment. The soldier can experiment and train with the networked systems in a realistic, immersive environment, over a variety of scenarios. In addition, results from WITL experiments can be used to further refine the CGF behaviors for future experiments, thus increasing the degree of reality in the simulations.

In instances where real vehicles or motion-based simulators are not available, are cost-prohibitive, or where more WITL nodes are needed, another capability of the C4ISR SE2L is the use of Reconfigurable Desktop Simulators (RDS). These inexpensive PC based simulators can put a soldier in the real-time experiment by providing a display and functional control in a fixed base simulation that represents the vehicle and the soldier's function within that vehicle (i.e. driver, commander, and gunner). RDSs provide a moderate level of vehicle fidelity, as opposed to the cockpit simulators, which provide higher level of fidelity as necessary. Clearly, as was noted above, higher fidelity may require additional resources to implement; nonetheless, the C4ISR SE2L architecture supports various levels. Figure 10 depicts the MIRAGE-RDS™ and some of the vehicle types which can be represented using the RDS systems.

Figure 9 – Cockpit Simulators

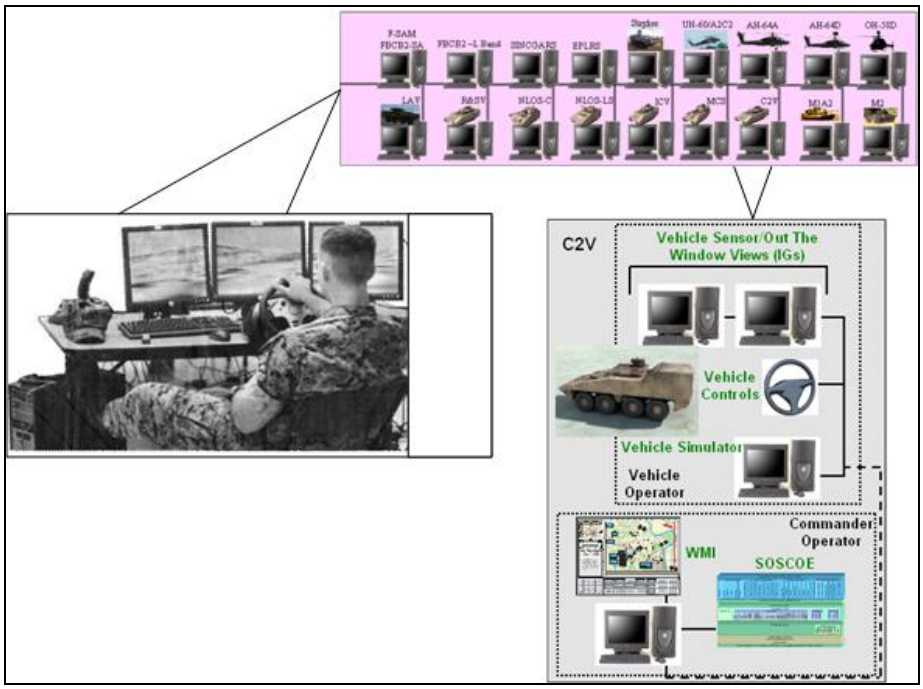

Figure 10 – MIRAGE-RDS^{TM} Reconfigurable Desktop Simulators

The collection and analysis of data is key to understanding the complex interactions of an LVC experiment. Several tools are available to collect, analyze and where desired, display the data in real-time. Examples of these tools are shown in Figure 11. These tools allow real time visualizations of the simulation results, data logging, and rapid analysis that can be fed back into the experiment, or used in reporting the results.

In order to support the live parts of LVC experimentation, as well as to interface with other laboratories, the C4ISR SE2L has a set of gateways depicted in Figure 12 that link to the other entities within external LVC architectures. The gateways provide protocol translation (i.e. DIS <-> HLA/SVF, DIS<->Tactical Radio Packets, etc.) among architecture components, and synchronization and control of the interacting environments. A capability is being implemented to establish these interfaces/gateways using communications links between the C4ISR SE2L and the other experiment participants through short- and long-haul network connections. These connections have been exercised in both laboratory and field experiments distributed throughout the Continental United States, and involving Joint and Multinational/coalition partners. Future C4ISR SE2L activities will involve extensive coordination with (and ultimately reachback to) multiple coalition partners, thereby demonstrating a greater degree of interoperability beyond American forces.

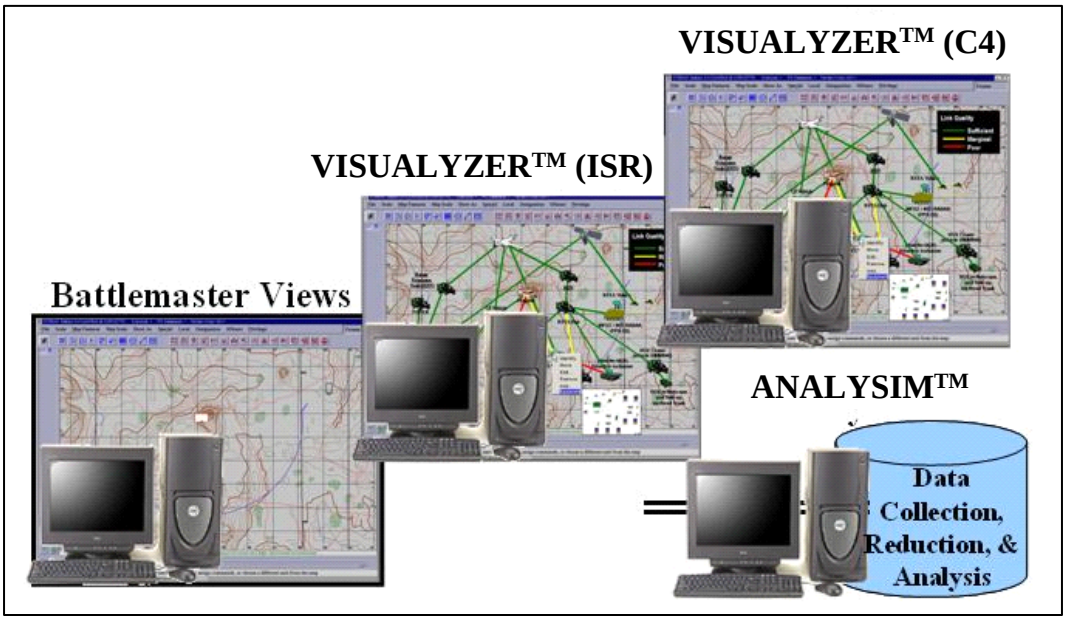

Figure 11 - Visualization Tools

Figure 12 – Gateways and Protocol Translators

To demonstrate the capabilities of the C4ISR SE2L, representative results from recent experiments are presented in the following section. The experiments were designed to (a) examine the adequacy of a proposed communications architecture supporting a brigade sized scenario, and (b) examine the sensor reporting performance during the scenario. The network traffic was modeled using a traffic database correlated to the scenario describing the messages in terms of message type, size, source, destination, priority, and time of transmission that fed traffic generators. The database used was the standard database used throughout the program, thereby ensuring the proper data pedigree among participating organizations. The traffic generators converted each message into the simulation format and loaded it onto the simulated network at the appropriate time. The locations of various Brigade Combat Team elements at one time slice of the scenario are shown in Figure 13.

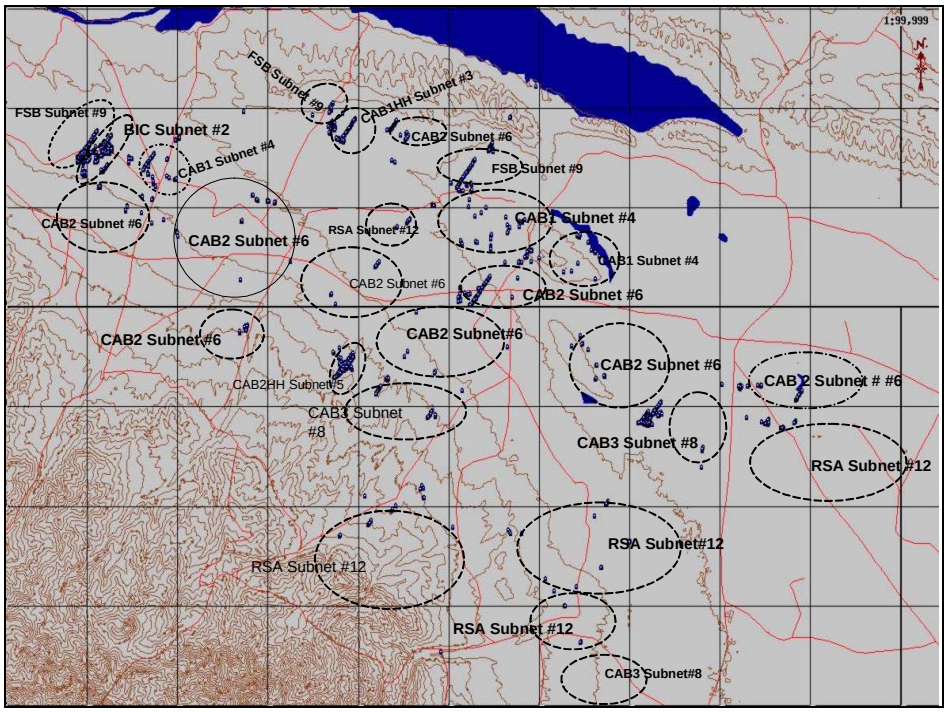

Figure 13 - Force Structure Laydown

The sensors were a combination of airborne and ground based sensors to detect, classify and potentially identify enemy targets. As part of the LVC architecture, live applications were integrated into the experiment to provide blue and red SA, map information, and sensor imagery. The applications represented a combination of mature, fielded battle command systems and prototyped software (added to display the sensor imagery), shown in Figure 14. This software allows a soldier in the loop to review the sensor output, perform visionics targeting functions (up to and including possible target identification), and respond by initiating a message (i.e. a spot report). Although automated sensor fusion has not been modeled to date, the capability has been recently added for future evaluation. Since the sensor traffic, as well as the spot reports, travel on the network, it adds to the network loading and, as such, is accounted for when calculating the overall network performance. The specific thread can be traced through the live and simulated network from the sensor to messages eventually arriving at Brigade Headquarters.

Figure 15 illustrates an additional capability within the C4ISR SE2L which displays, in real time, the quality of each communications link. In this display, the color of the link indicates the probability of completing the message. For example, the green links have very good quality (i.e. greater than 90% anticipated chance of the message being transmitted successfully), yellow have marginal quality, and red poor link quality (i.e. less than 50% anticipated MCR). This display is updated at each simulation step with the message source, destination and instantaneous link quality. This visual display can give the experimenter a quick look and qualitative analysis of where potential choke points are developing, where the advantaged and disadvantaged nodes are located, and the overall connectivity versus time. The data that drive the display are also logged for later playback and analysis.

In addition to the results illustrated above, the Information Assurance (IA) systems are also active in these experiments. IA is dedicated to maintaining the security of the network by separating security enclaves, employing encryption techniques; validating messages through mechanisms such as Public Key Infrastructure (PKI); and monitoring for unusual network activity, as in the case of Intrusion Detection Systems (IDS). While these IA mechanisms make the network more secure, they also affect system performance in terms of latency, added network load, and filtering of information. The IA effects on network and system performance are logged, measured, and analyzed for optimal implementations within the C4ISR SE2L (and subsequently FCS) architecture.

The experiments from which the previous samples were derived were carefully planned and executed to characterize the performance of the maturing network and its effect on the applications using the network. The simulation architecture being implemented within the C4ISR SE2L allows comparisons to be made relatively easily when varying the network parameters, scenarios, sensors, and

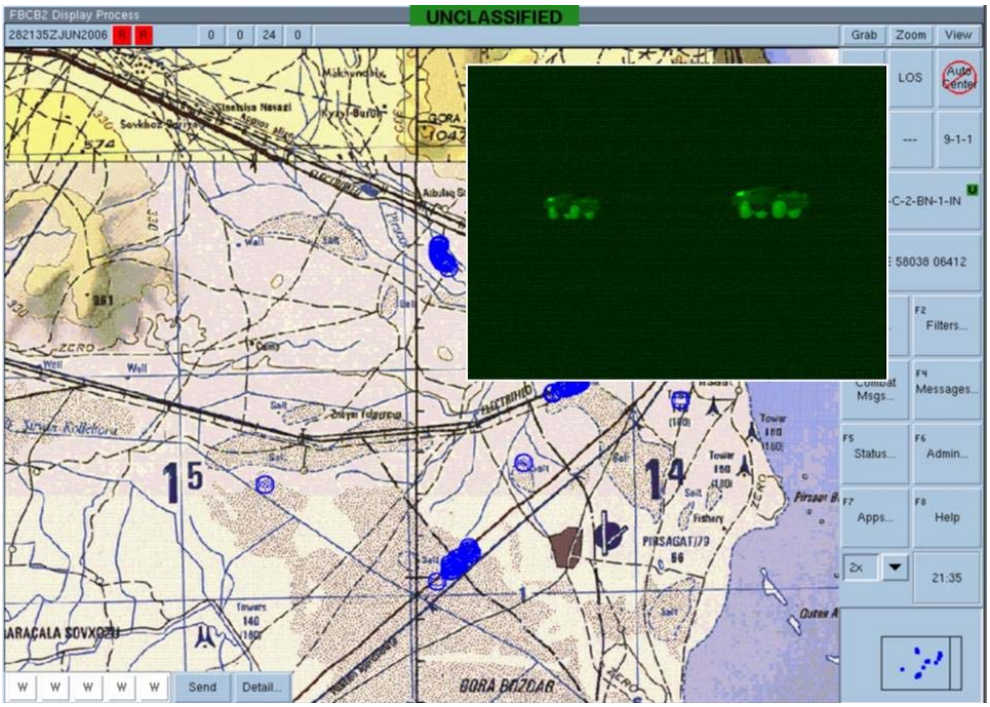

Figure 14 – Sample Fielded Battle Command System Display with Added Sensor Imagery

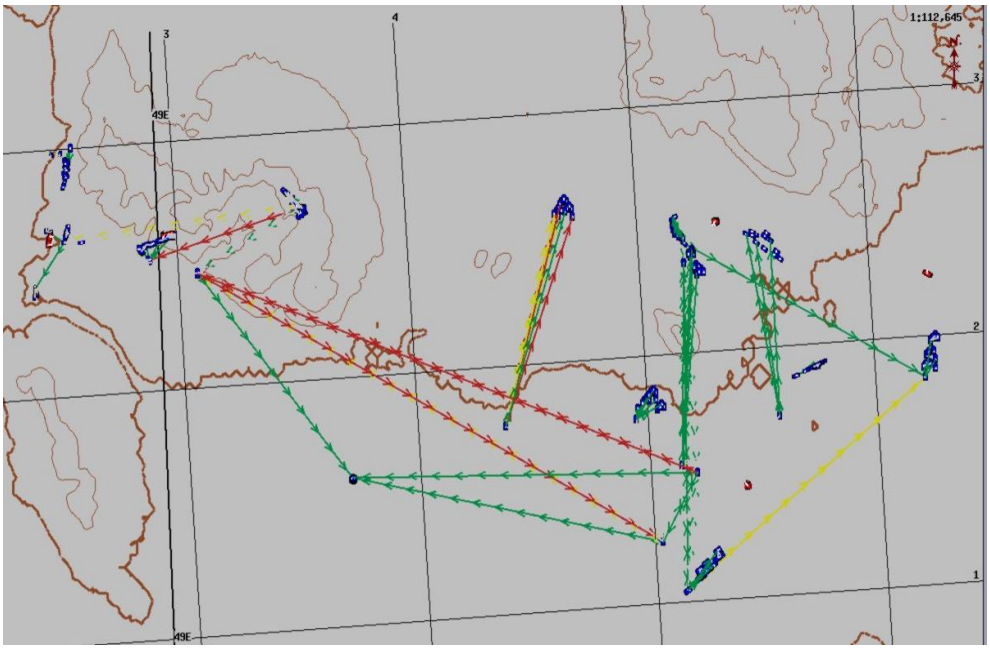

Figure 15 - Link Quality Visualization

radio configurations. It provides quantitative and qualitative feedback on the performance of key components of the FCS FoS (based on the phased development and integration of systems and subsystems), and is constructed such that it will ultimately be capable of evaluating a significant subset of the C4ISR components within the FCS SoS.

Conclusions

The C4ISR SE2L provides the FCS program with a sound capability, architecture, and LVC environment for performing C4ISR M&S activities for the purposes of engineering analyses, assessments, and experimentation – all in direct support of FCS C4ISR risk mitigation. Such mitigation activities are critical throughout the life cycle of US Army and DoD acquisition programs, which can easily experience tumultuous times when system development hands off to formal acceptance via independent test and verification. This is especially true when product maturity has not been properly ensured during system development. The activities performed within the C4ISR SE2L also encompass all facets of C4ISR. These include ISR sensor data collection, communication of these data to C2 applications, processing of and analyzing these data (via evolving battle command, with sensor data fusion), and timely data dissemination and display by C2 throughout the BCT (via robust communications networks and Warfighter-Machine Interfaces). These C2 applications have been (and will continue to be) exercised within the realm of experimentation involving Army, Joint, and Multinational/coalition forces. As such, the C4ISR SE2L is postured towards the enhancement of collaborative C2 across many echelons of global warfare.

Within the C4ISR SE2L, the activities and capabilities noted in the previous paragraph (and discussed throughout the paper) have been instantiated using an evolving LVC architecture which mirrors much of the FCS C4ISR functionality. This architecture supports both laboratory and field experimentation – all to demonstrate a similarly-evolving product maturity. The C4ISR SE2L described in this paper has provided and will continue to provide an environment for rigorous systems engineering experimentation. The architecture of the C4ISR SE2L encourages the blending of high fidelity physics based models, real-time abstractions, surrogates, simulators, emulators, other laboratories, test facilities, and personnel-in-the-loop to examine, evaluate and understand the performance of the FCS networked systems. Many of these M&S applications have been chosen because of their robustness, strong pedigree, and/or extensive history of use for similar applications by the US Government, industry, and/or academia. Others will be chosen based on sound engineering evaluations and characterizations to determine their adequacy within the C4ISR SE2L architecture. Information and results generated by the C4ISR SE2L are fed back to decision makers within the FCS program, Army, Joint, Interagency, and Multinational/coalition C2 and C4ISR arenas, thereby influencing the evolving

SoS towards its threshold requirements of information superiority and force nimbleness. Ultimately, the C4ISR SE2L, its architecture, and its many LVC components will play a critical role in the success of the FCS program, and subsequently the capabilities and effectiveness of the future force in an ever-changing battlespace.

References

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