Distributed Holistic Bounding: Structuring Testbeds for Emerging Virtual Environments

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Adequately testing, evaluating and analyzing large, scale-free information systems is very difficult due to the nebulous nature of the systems boundaries and ever-changing number of links and nodes that comprise the overall system. This paper proposed that it is possible to conduct such studies through distributed holistic bounding and employment of disciplined experiment campaigning. Beginning with identification of the overarching purpose of the entire system and identifying the boundaries of the sub-systems that contribute to the overall system's functionality we can develop effective experiments that will identify critical environmental variables that affect system performance. By adhering to an experiment campaign strategy we can discover those variables, develop hypotheses that help determine optimal system configurations and ultimately build and demonstrate that optimal system.

Introduction

The United States Department of Defense (DoD) is a global organization that relies heavily on robust, reliable information systems to communicate around the world. Without adequate communication systems the DoD might not be able to meet its national security obligations and the security of the United States could be placed in jeopardy. "Information Superiority" is the term DoD uses to refer to maintaining communication paths and providing its forces with complete and accurate data, above and beyond that of any enemy. To meet the extensive communication and data intensive requirements needed to achieve Information Superiority the DoD has developed the Global Information Grid (GIG). (US Department of Defense 2002). The GIG is a combination of systems including artifact systems, human systems (organizational and psychological), and hybrid systems dealing with human-machine interfaces that provide information services to globally deployed military decision-makers. The ubiquitous nature of the GIG means the overall network will consist of constantly changing numbers of nodes and links. This type of network is considered to be a scale-free system (Baribasi 2003). The ever-changing boundaries of a scale-free system make it difficult to test and evaluate overall system performance, but it is not only the scale-free nature of the GIG that makes testing and evaluation of the complete system difficult, the complexity associated the nebulous and complex nature of its purpose (i.e., achieving Information Superiority) also contribute to difficulties in bounding any experiments associated with the GIG.

Information Superiority, by definition, is a measure of one force's information capabilities relative to those of an opponent. It would be impractical, however, to evaluate systems within the GIG against every possible opponent. Therefore metrics associated with GIG systems must be identified that can be measured exclusive of a specific opponent yet still produce results that indicate probabilities of reaching Information Superiority (the ultimate purpose of GIG systems.) Although there are no established (i.e., universally accepted) criteria for measuring the effectiveness of large information systems, there are three data metrics that can be used to evaluate the quality of information associated with achieving Information Superiority: *completeness*, *correctness* and *currency* (Perry, Signori, Boon 2004).

Simply measuring the completeness, correctness or currency of information within elements of the GIG is not enough to aid in achieving Information Superiority. If any examination should show a deficiency in one of these areas there must be a feedback mechanism in place that will help identify and correct the discrepancy. The scale-free nature of the GIG and its large footprint (i.e., global deployment) make development and measuring of specific feedback mechanisms a daunting task indeed. In this paper we will demonstrate that this can be accomplished through careful bounding of individual GIG systems within the context of the overall objective. We will explore the significance of identifying system boundaries and parameters associated with specific sub-systems within the larger network. We will also provide suggested methods for locating these system boundaries and developing a listing of parameters necessary to adequately assess specific performance characteristics of the system. Through this examination of GIG feedback mechanisms we will provide a methodology for developing experiment designs that can be applied to any large, scale-free network.

The role of feedback in information systems

Generally, machines and electronic systems, if left unattended or not maintained will strive to achieve their lowest energy state (i.e., they will stop functioning.) This is an example of open loop control. Open loop control systems use no measurement of outputs and no compensation for deviations from desired outcomes **(**Franklin 1994**).** Therefore, keeping a system operating effectively (i.e., in a manner that allows the system to achieve its objectives) requires some intervention. This is found in closed loop systems and is identified by the existence of a feedback loop. This intervention (feedback) can be accomplished manually by humans or automated within the system or a combination of the two. Regardless of the method, feedback is its own process within the system itself and must be accounted for in system design and implementation.

To better understand the feedback process (as we will apply it to the GIG) there are some definitional conventions that need to be established. *Feedback* is a method of controlling a system. *Control* is the process of causing a chosen system variable to conform to a desired value. Feedback is the process of measuring the controlled variable and using that information to influence the value of the controlled variable (Franklin 1994**).** The significant aspect of feedback within a system is that it should be integral to the system's design (i.e., it should not be an ad-hoc application of actions based on random measurements after the system has been fielded.) Feedback mechanisms that may be used to control large, scale-free systems may become quite complex; regardless of the complexity of feedback systems they all contain the same basic elements:

- A reference (desired outcome)
- Output sensors (to measure actual outcome)
- A comparator (which compares output data with input data)
- A process (for doing useful work with the compared data), and
- An actuator (which influences the input variable.)

For example, an oven may be designed to provide constant heat in its chamber. To do this it must 1) "know" the desired temperature (reference) 2) "know" its current temperature (through an output sensor), 3) have a means of determining the difference between (1) and (2) (comparator) 4) have a means of transmitting that data to the system so it can make adjustments to eliminate the difference between (1) and (2) (a process) and 5) a means of adjusting the heating element to reach the reference temperature (actuator.) The feedback system is using data from the environment (temperature) to control the output of the heating mechanism (actuator) to meet its objective (proper temperature in the oven's chamber.)

This is an example of a very simple automated control process using a feedback system. As mentioned, the GIG is considerably more complex and provides some interesting challenges in ensuring effective system performance but by focusing on the fundamental elements of a basic feedback mechanism we can more adequately evaluate the effectiveness of the mechanism within the system under study.

As we can see from the definition of feedback it is essential to identify the variables that most affect system output and that may be controlled or overcome by the system. In this study there are many environmental and physical system variables that may contribute to data loss. A system designed to achieve one objective (e.g., temperature control in a single chamber) may require only one sensor and one process to control the outcome. A more complex system, such as the GIG, may require more control and feedback processes to reach a desired outcome; more complexity will occur if these controlled variables are inputs, outputs or somehow affect other processes in the system.

The relationship between adaptability and feedback

As we will explore later, establishing the boundaries of a system is essential to studying and understanding the functions of that system. This section will explore the areas of most concern to the system under study and will help identify specific criteria for measurement. Identifying these criteria will be essential to the experiment we will outline at the end of this paper.

Adaptation is the first system characteristic we will explore in relation to system viability, survivability and utility. Adaptation occurs when an entity undergoes some change to fit a new or special situation. In our case, these new or special situations are the changing environment in which the system is operating. There are two forms of adaptation that should be considered when looking at a system. One is the long-term adaptation where the system changes over an extended period of time in reaction to technological changes, or political and legal changes. This form of adaptation may be seen as following evolutionary theories where individual organisms do not specifically adapt to an environmental change but rather slow changes over time ensure the survival of the species (i.e., system) (Platt 1970). The second form is short-term adaptation where the system (i.e., individual organism) reacts to immediate changes in the environment to ensure its own survival (Chakravarthy 1982). Our focus will be on the latter form of adaptation.

In testing the ability of an information system to adapt to changing conditions we must identify the environmental factors that may change in such a way that the system may not meet its operational objective. We must then determine if these apply to our metrics of completeness, correctness or currency. For the preliminary experiment we will look at the major contributors to potential data loss during transmission or reception (i.e., completeness.) At this point we will control the initial data (i.e., correctness) to ensure there is a good signal at the input to better measure the adaptability of the system to a changing physical environment[1].

The experimental campaign for this system should take into account all aspects of the system and the environment that might contribute to data losses between the source and the receiver.

[1]Since our experiment will focus on the physical characteristics of the information system we will not address human elements of adaptability that may affect the system (e.g., user expertise and knowledge, etc.)

The following six sources of signal loss/degradation that exist in this system's environment[2] (Sklar1988)

- Pointing loss
- Atmospheric loss and noise
- Space loss
- Adjacent channel interference
- Co-channel interference
- Galactic or cosmic, star, and terrestrial noise

The parameters for evaluating this system should be based on these elements and their expected prevalence and influence in the expected operating environment. The system under study will be operating in dynamic meteorological and geographic conditions and must demonstrate an ability to overcome any adverse environmental affects to be reach its objects. In this study it will be the human receiver that will determine if there is significant data loss. This information must be fed back to the source to allow retransmission or system alteration to compensate (i.e., adapt) to the changed environment. Currency, in the form of information timeliness, will also be investigated during the course of the experiment.

Bounding the Problem: Parsing the GIG

The United States military operates around the world and must therefore have efficient and reliable global communications capability. Although the US Government had been experimenting with global satellite communication through the Advanced Research Projects

[2] Sklar provides a more comprehensive listing of factors affecting signal loss, the items listed here are considered to be those that will be most prevalent in the system's operating environment.

Agency (ARPA) in the late 1950s, it was not until 1961 that the US Joint Chiefs of Staff validated a requirement to incorporate satellite communications capability into its Defense Communications System (DCS**)** (Pachall 1984). The DCS was a communication system with a global reach. The Defense Communications Agency (DCA) was established to oversee and manage the DCS in 1960 and later became the Defense Information Systems Agency (DISA); the DCS was then renamed the Defense Information Infrastructure (DII) through Defense Management Report Decision (DMRD) 918. The DII is now known as the Global Information Grid (GIG). (U.S. Defense Information Systems Agency 2005)

The GIG qualifies as a scale-free network in that it is considered to be *the globally interconnected, end-to-end set of information capabilities, associated processes, and personnel for collecting, processing, storing, disseminating and managing information on demand to warfighters, policy makers, and support personnel. The GIG includes all owned and leased communications and computing services, software (including applications), data, security services, and other associated services necessary to achieve Information Superiority* (U.S. Department of Defense 2002).

The strengths of this description are that it identifies the components of the GIG and provides a means of determining what organizations and personnel are associated with the system. It also identifies an objective for the system: achieving Information Superiority. The weaknesses of this description are that very few organizations and personnel fall outside of the system and the objective is immeasurable[3].

As discussed earlier, Information Superiority is a relative measure; it is the measure of one's own capabilities against those of a specific opponent. By definition it is *the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same*. Unfortunately this definition does not address the quality of information, it merely acknowledges information flows. Rephrasing the definition of the GIG to incorporate the definition of Information Superiority (the objective of the GIG) gives us: *The GIG is the globally interconnected set of all machines and all humans associated with any information associated with military operations the purpose of which is to ensure that there is always a flow of information.*

The existence of many types of systems and personnel within the GIG render it nearly (if not completely) impossible to identify and account for all the variables that could affect overall system performance. One approach to developing effective feedback mechanisms that will ensure reliability of the GIG may be to distribute the functionality across systems.

This approach would view the GIG as a single open-system operating in the global battlespace. The output sensors (the operational commander responsible for military activities within the battlespace) would monitor the GIG performance to determine if it

[3] Although there are proposed methods for measuring information utility and value (Perry, Signori and Boon 2004) DoD has established no specific metrics to measure Information Superiority itself.

helped achieve Information Superiority. If the commander were to be satisfied with the performance of the GIG there would be no specific direction for alteration of inputs (positive feedback). If, however, the commander determined that the Information Superiority being delivered by the GIG, he/she would be able to activate a sequence of events within the GIG that would correct inputs or processes to bring the output (Information Superiority) in line with expected/desired outcomes (negative feedback). The feedback process that would ensue from this point will be elaborate and complex but can still be effective and controllable if the systems and processes that comprise the GIG are understood holistically in their own right.

One possible means of accomplishing this is to adapt a combined methodology of stakeholder influences (Rowley 1997) and network cliques (Provan and Sebastian 1998). Rowley explored the significant impact that can be made on network performance by constituents using the network at various levels within the organization; Provan and Sebastian explored the issues of attempting to integrate full networks across independent organizations involved in the same functional area (i.e., multi-firm networks.) By combining these two areas we may be able to more effectively isolate the logical boundaries that identify influences across 'nodes' in the GIG thereby allowing the feedback process to correctly adjust the appropriate input to effect necessary corrections in the GIG process.

The initial purpose of this paper was to identify appropriate methods for developing useful feedback processes for the GIG. Through holistic treatment of the GIG we can identify shortcomings in its outputs that will trigger the negative feedback process. This process would involve a holistic view of the 'cliques' that make up the GIG and identify anomalous outputs that would, in turn, activate negative feedback processes within those cliques to adjust system functions to regain Information Superiority. Further exploration of this concept will be necessary to develop methods of identifying cliques within the GIG and the applicability of stakeholder theory to this process.

Rather than attempt to examine the entire GIG and identify feedback mechanisms that might control its outputs, we will explore one subsystem that interacts with, or is a part of, the GIG. This exploration should help identify the means through which future evaluations of feedback within the GIG can be made.

Selecting a subsystem (clique) for study involved identification of a significant information system within the GIG that performed a specific function (i.e., produced a measurable outcome.) The sub-system chosen for this study was the Lawrence Livermore National Laboratory/Tactical Satellite (LLNL/TacSAT) sub-system of the Tactical Network Topology (TNT).

The first step in adequately bounding the system for study is to identify the specific objective or outcome and its associated stakeholders. Building on concepts of clique identification (Poran and Sabastien 1998) and stakeholder influences (Rowley 1997) we will be able to identify the systems and stakeholders pertinent to our study. This is accomplished by examining the elements that affect the desired outcome and their relationships to each other.

Identifying the elements begins with an assessment of the LLNL/TacSAT system and its contributions to Information Superiority. In identifying significant elements it is useful to use a variation on Granovetter's work on identifying strong and weak ties (Granovetter 1973)(Poran and Sabastien 1998). Using this framework will help determine the major contributors to the output of the system under study. The assignment of weak v. strong relationships between elements in a system such as TNT is important when establishing feedback loops. In applying Granovetter's methods to this application we are proposing that strongly tied elements rely on each other for information essential to mission success. Weakly tied elements either provide non-mission essential information to each other or have multiple weak ties to other elements that can provide the essential information (i.e., redundant links.)

System Environment

The purpose of the LLNL/TacSAT network is to assist the US Coast Guard in positively identifying contraband radiological material in ships and watercraft entering US waters. The expansiveness of US controlled waters and the jurisdiction of the US Coast Guard make it unfeasible for radiological technical experts to be on-scene for every inspection, therefore it is essential that the information be brought to the expert for evaluation. Networked systems allow data acquired by the boarding party to be delivered to a geographically dispersed set of experts to ensure the on-scene-commander has the right information to make the correct decision and minimize the possibility of a type II error[4]. Figure 1 depicts the basic architecture of the LLNL/TacSAT network that supports this scenario.

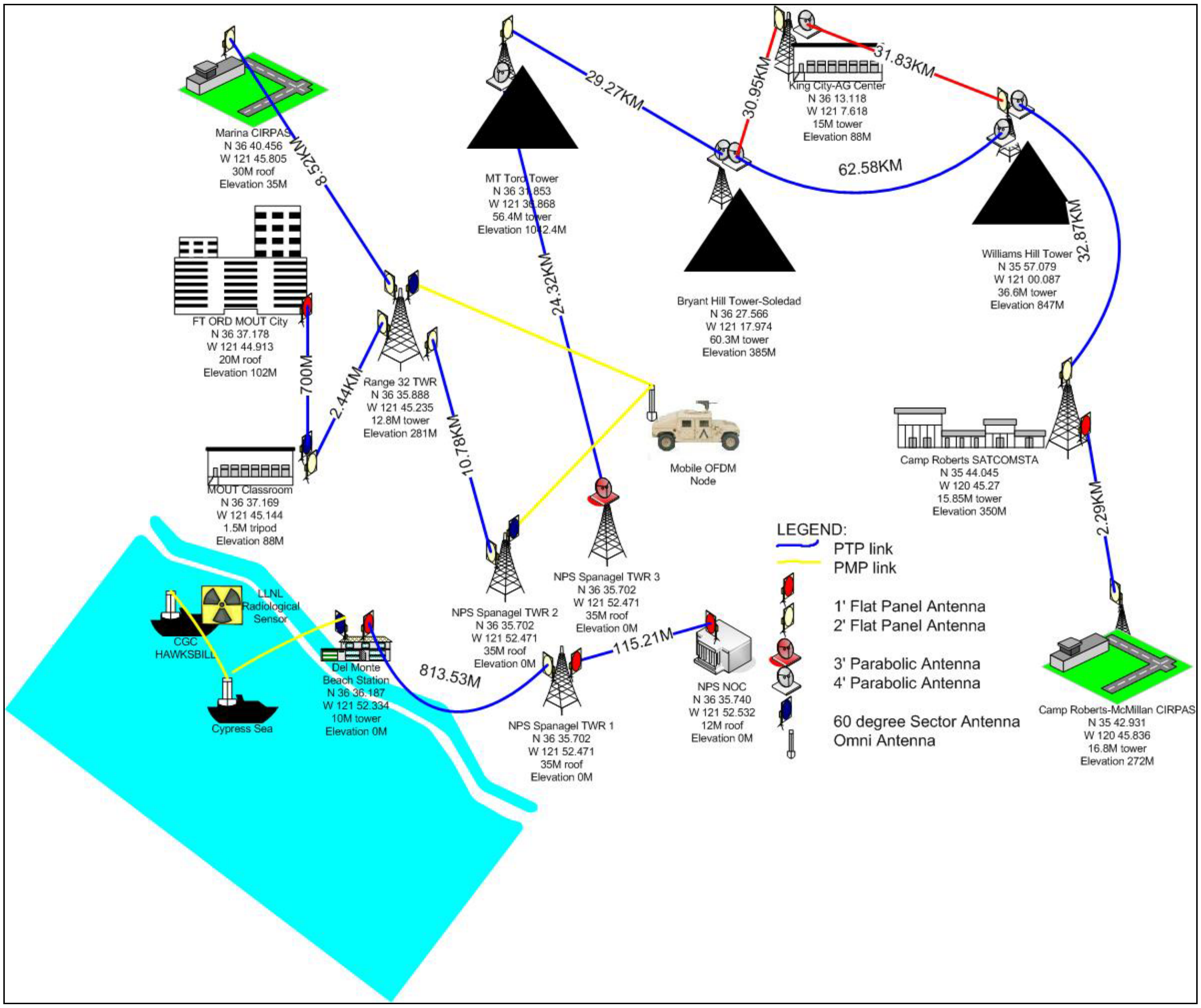

Figure 1: LLNL/TacSAT Topology

[4] In this case the alternate hypothesis for the boarding party is that the ship is carrying contraband radiological material, therefore the null hypothesis is that the ship is carrying no such material. The significant impact of unauthorized radiological material entering the US is such that the probability of a type II error (accepting a false null hypothesis as true) must be low (Kerlinger 2000).

The Tactical Network Topology

The TNT is an evolving network designed to increase the efficiency and effectiveness of US armed forces through exploitation of multi-path transmissions and mesh network operations. The TNT is not a single system but rather a concept of integrating many network technologies including desktop and laptop computers, handheld Personal Data Assistants (PDAs), and mobile relay devices (Bordetsky 2005). As previously discussed, the purpose of the GIG is to obtain and maintain information superiority over an adversary, the TNT, as a part of the GIG, must somehow contribute to this objective. Identification of the system's objective (or reason for being) is significant to identifying the appropriate feedback mechanisms necessary to help control the system in order to meet this objective. The TNT supports the GIG's overall objective by helping ensure that the right information can get to the right people at the right time.

For the TNT to meet its goal there must be a mechanism that can monitor the information processes and make alterations or allow alterations to be made should outputs fall outside of acceptable parameters (Franklin 1994) By measuring the actual output of the system against the intended output we can identify possible problems within the system and more adequately troubleshoot these issues before they result in catastrophic failure of the system. The intent of the TNT and its multi-path, multi-platform architecture is to allow information to flow despite individual system failures. The task now is to identify and describe the elements that comprise the feedback process and develop measures and means to help control the system based on the feedback comparisons (Johnson 1962). Identifying system elements begins with locating the boundaries of the system under study.

The TNT exists to support armed forces personnel in myriad missions in the battlespace by providing robust communication links between dispersed elements. Although there are a considerable number of missions that might use the TNT all of them rely on the same fundamental command and control concepts to accomplish the objective. Command and Control is the phenomenon through which a commander with appropriate authority commands troops to accomplish a specific mission, this is done through personnel, equipment and procedures (U.S Department of the Navy 1995). This study focuses on the equipment portion of command and control. By limiting our investigation to one area of command and control we can explore a single mission associated with the TNT as a model for future assessment of other mission areas or uses of the TNT. This paper focuses on the desired outcome of identifying contraband radioactive material on board sea going vessels.

The process of identifying such material involves the US Coast Guard intercepting and boarding a vessel suspected of carrying such material (target ship) and dispatching a boarding party to inspect the vessel for contraband. Identification of radioactive material is outside of the expertise of US Coast Guard boarding parties so a means of remote rapid identification must be available for the Coast Guard to meet its objectives (Klopson 2005). The TNT architecture provides a possible solution to this problem.

Lawrence Livermore Laboratories has developed a portable radiation detection device that produces a digital output for computer analysis. Using elements of the GIG, the boarding party can gather data onboard the target ship and transmit these data (via TNT and the GIG) to radiation experts located at laboratories ashore for near-real time evaluation. These evaluations can then be transmitted back to the boarding party where appropriate action can be taken should the material indeed by contraband.

Without a proper feedback mechanism between the laboratory personnel and the boarding party there would be no assurance that the proper data were transmitted or received. This could lead the boarding party's not taking appropriate actions based on misinterpretation or incomplete transmission of information. (Klopson, 2005)

Determining Relationships Among System Elements

Examining the scenario with Coast Guard personnel revealed that there are five major elements that must be present in this scenario (Klopson 2005):

- Target Ship (a vessel suspected of carrying contraband material)
- Launch Ship (a vessel capable of intercepting the target ship)
- Boarding Party (a group of individuals from the Launch Ship capable of boarding and inspecting the target ship)
- Detection Equipment (equipment or personnel capable of determining the location and nature of contraband)
- Expert personnel (remotely located at various locations throughout the US)

Examining the relationships between these elements should reveal whether they are strongly or weakly tied. This definition of strong ties differs from Granovetter's in that he identifies strong ties with temporal and emotional commitments between elements (Granovetter 1973) and here we identify strong ties by assessing informational commitment between elements. Therefore, care should be taken to assess the number of unique information sources when determining the strength of ties, and not simply the number or proximity of links.

The portion of TNT under study exhibits an overall strong tie between the detection equipment and the expert personnel because each is solely dependent on the other for the information necessary to complete their mission. This occurs because the information necessary to make the assessment (of whether specific material is contraband) is resident on the target ship and gathered by the boarding party. There are also strong ties between the boarding party-launch ship and the launch ship-expert personnel because the boarding party represents the only source for the vital data. Should the technology exist that would allow the boarding party to communicate directly with the expert personnel the launch would become a weak tie in this scenario.

Identifying the Feedback Loop

The existence of strong ties indicates a tenuous relationship between elements; relationships that must be monitored and controlled to ensure the links are maintained. This control is accomplished through a feedback loop. Earlier we established that a feedback loop must consist of the following elements (Franklin and Lee 1994):

- Reference (desired outcome)
- Output sensors (to measure actual outcome)
- Comparator (which compares output data with input data)

- Process (for doing useful work with the compared data)
- Actuator (which influences the input variable)

Therefore, we must identify the elements of the TNT system that perform these functions.

- Reference: positive identification of suspect material
- Output sensors: detection equipment
- Comparator: expert personnel
- Process: maneuvering detection equipment into position to acquire data
- Actuator: Coast Guard personnel operating the detection equipment

The feedback loop in this case would function to help the expert personnel positively identify whether the material in question is or is not contraband by allowing them to receive data on the material and direct the boarding party to gather more or different data to ensure accurate assessment of the material. Now we can evaluate this cycle to determine what parameters and criteria can be measured to assess the effectiveness of the feedback process.

Feedback Parameters and Criteria

The objective of the system is to provide adequate data to the expert personnel for assessment of suspect material. As identified earlier, there are three parameters that can be used to assess the effectiveness of system achieving Information Superiority: completeness, correctness and currency. The data not only have to be adequately collected, they must be transmitted to experts for analysis ant the experts must be able to communicate with the boarding party about the quality of the data and also their findings (e.g., if the data are incomplete or insufficient for analysis the boarding party may have to acquire more data, or if contraband the Coast Guard must take appropriate action, etc.) This requires identification of the design variables within the criteria of interest (denoted as $\alpha_1, ..., \alpha_N$) and associated performance criteria constraints (denoted as phi (ϕ)):

- α_1 = Completeness/Data Integrity
    - ϕ_{11} = Percentage of target ship accessible by the sensor
    - ϕ_{12} = Percentage of the accessible area actually scanned by the sensor
    - ϕ_{13} = Aggregate packet loss between sensor and laboratory expert
    - ϕ_{14} = Error rate
- α_2 = Correctness. In this case correctness is the degree to which the recorded data (at the sensor) approximates the actual "ground truth" of the contraband material (Perry, Signori, Boon 2004). For the purposes of these experiments this is held constant (i.e., $\alpha_2 = 1$)
- α_3 = Currency/Time
    - ϕ_{31} =Time from acquisition of data (via the detector) to time of receipt by expert personnel
    - ϕ_{32} =Total time for evaluation by expert personnel
    - ϕ_{33} =Time from determining findings by experts to time of receipt by boarding party
    - ϕ_{34} = Data transfer rate between detection equipment and boarding party laptop computer
    - ϕ_{35} = Data transfer rate between the laptop computer and the launch ship relay/bridge (R_{c-s})

- ϕ_{36} = Data transfer rate between the ship and the expert analyst

Each of these criteria can be applied to each node/link in the system, however, a feedback loop is designed to adjust a process based on deviation of an output from the desired outcome. Therefore, the parameters associated with these criteria should be measured between the input (detection equipment) and the output (completion of expert analysis on received data) and then between the expert analysts's response to the boarding party and the boarding party's actions based on that response. The objective of this system is to provide maximum confidence in data analysis while minimizing the time it takes to properly identify the suspect material to the boarding party, therefore we can develop functions associated with measuring system effectiveness; the objective function would be one that will maximize α_1 with the minimum α_3. The Pareto set for inclusion in a Parameter Space Investigation (PSI) model becomes (Statnikov 2005):

- Data Completeness (α_1) is a function of packet loss (ϕ_{13}) and error rate (E);

  α_1=f(ϕ_{13}, ϕ_{14})

- Time between data acquisition (ϕ_{31}) and the conclusion of expert analysis (ϕ_{32}) is

  α_3 = f($\phi_{31,}$ $\phi_{32,}$ $K_{eq,}$ $\phi_{34,}$ $\phi_{35,}$ ϕ_{36})

Although further study and development are needed to develop the associated equations and the means to measure α_2, the existence of numerous measurable design variables within these two criteria (data completeness and currency) indicate that this feedback system can be quantitatively evaluated to develop an optimal design. The multi-variable nature of this problem indicate that the Dr. Roman Statnikov's Parameter Space Investigation (PSI) method of multi-criteria optimization may be the best approach to identifying optimal conditions for controlling systems within the TNT.

System Summary

This paper identified a means of evaluating a feedback mechanism within one element of the GIG. It demonstrated that the criteria by which the effectiveness of that mechanism can be identified and measured through analysis and evaluation of the ties between major elements of the system. The parameters associated with these criteria were also identified and objective functions were outlined as a launch point of further investigation through the PSI method of multi-criteria optimization. Application of this model should provide system users with near-real time assessments of the effectiveness of the feedback loop within this particular TNT functional area. By understanding the relationship between data completeness and timeliness the system users can assess whether adjustments must be made to the network in order to meet mission objectives. This foundation will allow development of experiments that can explore the viability of the LLNL/TacSAT and TNT networks in various environmental conditions.

Experiment Design

We have explored the purpose and basic functionality of the LLNL/TacSAT network and determined that the system must be capable of gathering and delivering data in a manner that will allow US Coast Guard boarding parties to make accurate assessments of the existence or non-existence of contraband radiological material on board specific vessels. At issue now is how to gather information that will help us construct a system that will accomplish this objective. We must design an adequate experiment campaign strategy that will provide verifiable evidence that the LLNL/TacSAT system can meet its design objectives in anticipated operational environments. Observation of the system's performance within a controlled environment is essential to this type of scientific exploration (Cohen and Nagel 1934).

As discussed, the GIG and the LLNL/TacSAT networks are large information systems spanning several topologies and geographic regions. As such there will be a considerably large number of variables that will/could affect the system and hence any experiments attempting to 'grab' all of these variables in one experiment. Therefore it is necessary to conduct a series of experiments that systematically considers sets of these variables until the most favorable system can be developed. This systematic approach can be considered an experiment campaign (Alberts and Hayes n.d.)

The experiment campaign begins with the recognition of a problem and developing expressions that put this problem into a manageable form (Kerlinger and Lee 2000). This may be the most critical part of the campaign, and perhaps the most difficult. Without adequately identifying the problem or the question to be answered, experiments cannot be designed that will reveal useful information (Kerlinger and Lee 2000.) Although a viable system may result, there is no means of determining if the system is optimal or that is can be expected to properly function in various environments. This first step of the experiment campaign can be accomplished through discovery experiments (Alberts and Hayes n.d.).

Following the formulation of an acceptable problem statement the campaign will progress to hypothesis development and testing. A hypothesis is a conjectural statement about the relationship between two or more phenomena or variables (Kerlinger and Lee 2000: 15). Once a hypothesis has been put forth concerning the problem identified in the discovery experiments the campaign can proceed to test these hypotheses. Alberts and Hayes divide hypothesis testing into two phases: preliminary and refined hypothesis testing (Alberts and Hayes n.d.). The goal of preliminary hypothesis testing is to develop a basic evidence base concerning the problem and related hypotheses. The refined tests hope to develop predictive knowledge about the problem. The experiment campaign concludes with a demonstration of what was learned. Alberts and Hayes dubbed these demonstration experiments. This experiment campaign methodology can be applied to our investigations of the LLNL/TacSAT system and should provide a bounded means of developing an optimal system within the GIG to help achieve Information Superiority.

The LLNL/TacSAT Experiment Campaign

The first step of the experiment campaign was described earlier in this paper where we identified a problem: that of providing correct, complete, and current expert assessment of potentially contraband material to a remotely located US Coast Guard boarding team. At issue is how to best accomplish this. Although the LLNL/TacSAT network, as designed, consists of proven technology (see figure 1) and there have been some preliminary technology demonstrations (Klopson 2005) there has been little experimentation designed to discover the environmental variables that could affect system performance. Rather that leave it to chance that the system, as designed, will work in varying operational environments an experiment campaign beginning with extensive discovery experimentation is proposed.

As identified earlier, we have three areas of interest for measuring information related to obtaining Information Superiority: completeness, correctness and currency. By conducting discovery experiments associated with each of these areas and determining the variables or phenomena associated with each we will be better poised to develop (and test) hypotheses focused on creating an optimal system. This group of discovery experiments can be considered a campaign in and of itself within the framework of the overall experiment campaign. Each individual discovery experiment will consist of several 'engagement' experiments. An engagement experiment is one which focuses on providing evidence associated with a single phenomenon within its overarching experiment campaign (i.e., an experiment campaign would consist of discovery, preliminary and refined hypothesis, and demonstration campaigns (Alberts and Hayes n.d.) and each of these would consist of discovery engagements, preliminary hypothesis engagements, etc.)) Here we will develop the framework for a discovery experiment focused on the completeness of measured data.

In our case the discovery experiment campaign is designed to identify the most significant variables (environmental, organizational, etc.) that might affect system performance (as related to mission objectives.) As in any experiment the most important factors are identifying and bounding the problem (and adequately articulating the problem.) This applies to engagement experiments as well. The remainder of this paper will outline the process for developing an initial 'discovery engagement' focused on identifying variables affecting completeness of information within the system.

As shown in figure 1 there are several links between the initial data acquisition point (the LLNL radiological sensor) and the expert analysts ashore (in this case they are assumed to be located at the NPS NOC.) Identifying variables that could affect signal completeness along this path can be done through brainstorming sessions with information systems experts. This method will help develop an initial list of factors that have been known to cause signal disruption, interference, or any adverse affects for each of the transmission methods and media (e.g., 802.11, 802.16, UHF, copper, etc.) in various environmental or physical conditions (e.g., rain rate, sunspots, sea state, ship material, foliage, etc.) After developing a baseline listing of possible variables further experiment design can proceed.

The next step is to develop a list of engagement experiments that will adequately explore the possible relationships of these variables to the different links of the system. This will help identify what variables have debilitating affects on system performance (associated with the criterion of interest: completeness) and provide evidence for future study on mitigating the effects of these variables. By developing experiments and models that account for the variables associated with one link of the system, other experiments within the overall campaign can draw on these existing models and perhaps treat each engagement scenario as a single variable within this new engagement scenario.[5]

When assessing the flow of data from the LLNL sensor to the expert in the NPS NOC it is useful to use basic electronic troubleshooting techniques (Buban and Schmitt 1972). Troubleshooting involves the location of correction of any condition adversely affecting a systems performance. This requires knowledge of the input data, knowledge of the expected output data and knowledge of the components and process that act on the data between the input and output. This is why the assessments and system bounding discussed at the beginning of this paper are so important. By understanding the system boundaries and the expected functionality within these boundaries we can better understanding the effects each variable will have on completeness of our data.

This method of bounding the experiment helps control the independent variables in the experiment and account for any extraneous variables that may affect the outcome but not be a part of the study. The fidelity of the experiment (i.e., the assurance that the results will translate to 'real-world' systems) is maintained in this instance because the experiment is conducted with actual operational systems. There are aspects of this experiment, however, that can be replicated in a laboratory or incorporated from previous research (e.g., the propagation characteristics of wireless transmissions through various materials, etc.) Care must be taken, however, to account for actual conditions that may exist in the expected

[5] This method of treating a single engagement experiment as a single variable (or object) within another engagement experiment is not fully developed, however, I will identify this method of experimentation as Object Oriented Experimentation (OOE).

operating environment (e.g., salinity, corrosion, paint, etc.) Again, expert brainstorming sessions prior to model development will increase the fidelity of such methods.

Upon completion of this engagement experiment the investigator should have a comprehensive (and well documented) understanding of the variables within the operational environment that will impact data completeness. From these results the overall campaign can progress into the preliminary hypothesis development and testing phase. Development of this phase lies outside the scope of this paper, however, it is in this phase where ideas can be developed and explored on means to mitigate the possible adverse affects identified in the discovery campaign. Each of these hypotheses can be explored in individual engagement experiments utilizing the Object Experiments developed in previous engagement experiments. Alberts and Hayes provide a comprehensive checklist of items for developing an experiment campaign and individual experiments (Alberts and Hayes n.d.).

Summation

Testing, evaluating and analyzing large, scale-free information systems are possible through distributed holistic bounding and employment of disciplined experiment campaigning. Beginning with identification of the overarching purpose of the entire system and identifying the boundaries of the sub-systems that contribute to the overall system's functionality we can develop effective experiments that will identify critical environmental variables that affect system performance. By adhering to an experiment campaign strategy we can discover those variables, develop hypotheses that help determine optimal system configurations and ultimately build and demonstrate that optimal system.

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