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MEASURING THE OPERATIONAL IMPACT OF MILITARY SATCOM DEGRADATION

Paul J. Nicholas
Jeffrey C. Tkacheff
Chana M. Kuhns

Operations Analysis Directorate
Combat Development & Integration Department
Headquarters Marine Corps
3300 Russell Road
Quantico, VA, 22134, USA

ABSTRACT

Military forces are becoming increasingly reliant on the use of satellite communications (SATCOM) to provide critical command-and-control services. These forces face a variety of threats that may degrade or deny use of these communications systems, including jammers, cyberspace attack, and kinetic attack. The vast majority of research to examine the effects of SATCOM degradation focuses on physical phenomena, signal modulation, and communications networks behavior, but not on higher-level operational impact. We describe a new simulation methodology for examining and measuring the operational impact of degraded SATCOM capabilities on military forces. This methodology comprises high-fidelity simulation, network optimization, and queuing techniques, and enables us to examine the ability to execute fire support missions and fulfill logistics requests in U.S. Marine Air-Ground Task Forces. To our knowledge, we are the first to build a method for explicitly simulating and quantifying the operational impact of SATCOM degradation upon tactical U.S. Marine Corps forces.

1 INTRODUCTION

Military forces are becoming increasingly reliant on the use of satellite communications (SATCOM) to provide critical command-and-control (C2) services (Joe and Porche 2004, Fritz et al. 2006, Garcia 2015). These forces face a variety of threats that may degrade or deny use of these communications systems, including ground-, air-, and space-borne satellite jammers, cyberspace attack, and kinetic attack (Rausch 2006, Garino and Gibson 2008, Garcia 2015, Koch and Golling 2015). The U.S. Marine Corps Capstone Operating Concept *Expeditionary Force 21* (*EF-21*) (U.S. Marine Corps 2014) encourages overcoming these challenges by “Providing landing forces and support craft with beyond-line-of-sight, over-the-horizon, and on-the-move C2 systems capable of operating in a satellite-degraded communications environment.”

However, one should be able to gauge the operational impact of SATCOM degradation before comparing different methods and technical solutions to overcome or lessen its impact. The vast majority of analytic research to examine the effects of SATCOM degradation focuses on simulating physical phenomena (such as radio propagation), signal modulation, and communications networks behavior (see, e.g., Spink et al. 1998 and Koch and Golling 2015). Combat simulation models, including the Combined Arms Analysis Tool for the 21st Century (COMBAT XXI) and the Synthetic Theater Operations Research Model (STORM), do not explicitly simulate SATCOM degradation. Other than expensive (and unrepeatable) large-scale field exercises, there is little research considering the higher-level impact that SATCOM degradation will have upon the ability of a tactical military force to conduct combat operations. We feel this type of analysis is relevant to commanders in the field, who must make decisions on how to best mitigate SATCOM degradation given their available options. This insight is also beneficial to engineering and acquisitions professionals working to develop and field improved mitigation techniques.

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We develop and describe a simulation methodology for examining and measuring the operational impact of degraded SATCOM capabilities on military forces. This methodology incorporates high-fidelity signal simulation, network optimization, and queuing techniques. We use simulation to examine the impact of electromagnetic (EM) interference and jamming, cyber attack, and physical destruction of ground-based satellite terminals and space-based satellite systems, and the use of terrestrial wideband transmission systems that can be used as alternatives for SATCOM connectivity. We use network optimization techniques to examine communications network flow in a SATCOM-degraded environment. We then incorporate our simulation and optimization outputs into a queuing model to examine the operational impact of SATCOM degradation on the ability to execute two critical warfighting functions: conducting fire support missions and fulfilling logistics requirements. We present notional results of the types of outputs of our method.

Our approach applies to any military force utilizing SATCOM architectures, but we focus on U.S. Marine Corps Marine Air-Ground Task Forces (MAGTFs). In our classified technical report (Nicholas et al. 2015), we examine in detail the impacts of real-world threat systems in three defense planning scenarios. In the first, we consider a Marine Expeditionary Unit (MEU) company landing team conducting a raid, based on Integrated Security Construct B (ISC-B), Scenario 1. In the second, we consider a Marine Expeditionary Brigade (MEB) conducting counterinsurgency and security force assistance operations, based on Multi-Service Force Deployment (MSFD) scenario 6. In the third, we consider a Marine Expeditionary Force (MEF) conducting a major amphibious assault, based on ISC-B, scenario 3. Our technique can be seen as complementary to combat simulation analysis (such as COMBAT XXI or STORM), as we explicitly simulate SATCOM degradation while implicitly simulating some aspects of combat operations. To our knowledge, we are the first to build a method for simulating and quantifying the operational impact of SATCOM degradation upon tactical Marine Corps forces.

This paper is organized as follows. In the next section, we provide an overview of our approach. In Section 3, we describe our techniques for simulating SATCOM degradation. In Section 4, we detail our method for measuring the operational impact of SATCOM degradation by feeding the results of our simulations into a queuing model. We also provide notional results of the outputs. In Section 5, we provide our conclusions and suggestions for future research.

2 MODELING APPROACH

We focus on modeling the SATCOM network connections and the line-of-site (LOS) and troposcatter systems that provide wireless data connectivity down to the battalion level within U.S. Marine Corps MAGTFs, though our approach is applicable to any military force utilizing SATCOM. In practice data connectivity is often extended below the battalion level, but such networks are often “spurs” and do not provide redundant communications connectivity to other units. Push-to-talk single-channel radio systems can be used for data communications, but these systems typically have very low throughput rates and are not often connected into the larger *wide area network* (*WAN*). We consider the following wideband data transmission systems: the Very Small Aperture Terminal (VSAT), the Secure Mobile Anti-jam Reliable Tactical Terminal (SMART-T), the Point-of-Presence Vehicle (POP-V), the MRC-142 Line-of-Sight Radio System, the Wireless Point-to-Point Link D (WPPL-D), and the TRC-170 Troposcatter Microwave Radio Terminal. In our classified technical report (Nicholas et al. 2015), we consider the anti-satellite capabilities of several countries.

Our overall modeling approach is illustrated in Figure 1 and explained in greater detail in the following sections. We use Microsoft Visual Basic for Applications (VBA) to create a simple user interface and to serve as the “glue” language to interconnect several different software tools. First, VBA processes the specifications of the radios (including satellite transponders and ground radio stations) and threat systems (including jammers) into a format suitable for computation. We connect VBA to Systems Toolkit (STK) (Analytical Graphics, Inc. 2016) to simulate and calculate radio propagation between all applicable devices at each time step within a given scenario. We then use these radio propagation values to simulate communications traffic using an optimization model in the General Algebraic Modeling System (GAMS)

(GAMS Development Corporation 2016), which we solve using the Couenne nonlinear optimization solver (Computational Infrastructure for Operations Research 2016). We then visualize this information using Gephi (Gephi Consortium 2016), and simulate logistics and fire support operations using a queuing model in Arena (Rockwell Automation 2016).

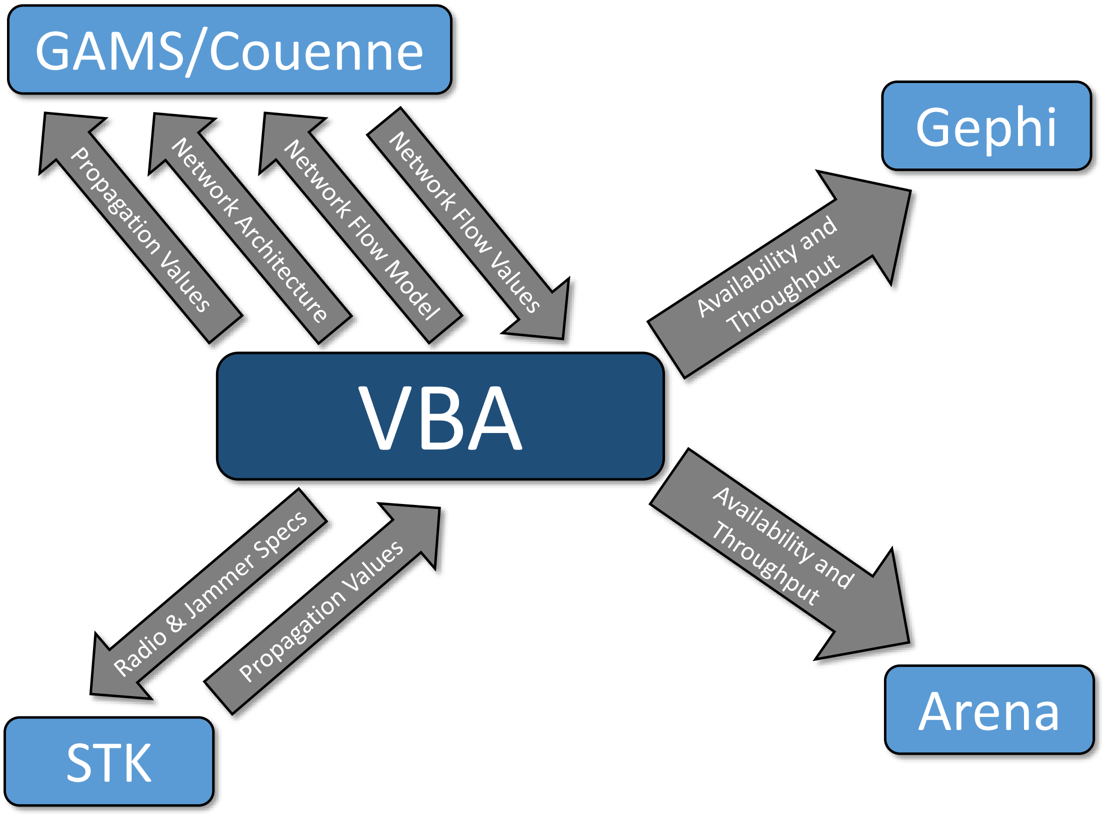

Figure 1: Our overall modeling framework. VBA serves as the glue language between Systems Toolkit (STK) (for radio propagation simulation), GAMS/Couenne (for communications network simulation), Gephi (for network visualization), and Arena (for logistics and fire support modeling).

3 SIMULATING SATCOM DEGRADATION

In order to quantify the operational impact of SATCOM degradation, we first develop a method of simulating these types of communications. We simulate radio propagation (including SATCOM, terrestrial radio, and jammer transmissions), and then simulate communications network performance using the radio propagation information.

3.1 Radio Propagation Simulation

We model each radio in a particular scenario (including satellite transponders, ground satellite terminals, threat systems, and LOS and troposcatter transceivers) in STK at successive time steps. STK provides a high-fidelity four-dimensional (i.e., including time) environment that models the spatial-temporal relationships between objects such as ground, sea, and air vehicles and satellites. STK allows us to simulate the movement and operation of these radios in a realistic fashion, including actual satellite orbits, signal modulation, Doppler shift, satellite footprints and antenna patterns, signal propagation, absorption, etc.

We use VBA to launch STK and calculate radio propagation between each radio that must communicate at each time step (between a few minutes and one hour). STK uses the Terrain Integrated Rough Earth Model (TIREM) (Alion Science and Technology Corporation 2016) to calculate radio propagation. This is the de facto standard government model for radio propagation analysis, and considers such propagation effects as atmospheric absorption, tropospheric scatter, Fresnel zone obstructions, and knife-edge diffraction. Radio and antenna characteristics are based on specifications provided by subject matter experts and equipment manufacturers. The radio propagation values are pulled from STK directly into VBA using STK Connect commands. A wireless connection between two radios is considered operational if the received signal strength (calculated in decibel watts) from the transmitting node to the receiving node is above the receiver's minimal operating threshold, considering background noise and any interference received from threat systems (if present). Radio propagation is calculated in both directions, due to the possibility of differing transmission strengths, antenna patterns, operating thresholds, objects in the Fresnel zone, and other asymmetric factors.

3.2 Communications Network Simulation

We use the outputs from the STK simulation as inputs into our communications network simulation. We use VBA to calculate two measures of network performance: *network availability* and *network throughput*, and then use the outputs of the model as inputs into our queuing model (Section 4). Note that most node pairs within a tactical communications network do not need to communicate. For example, infantry battalion headquarters do not need to communicate with aircraft group headquarters. Hence, each network is far from completely *connected*, i.e., containing a direct logical connection between every pair of nodes. For each scenario we consider, we work with subject matter experts to determine required network traffic flows and their relative importance.

3.2.1 Calculating Network Availability

Network availability is a count of the number of logical network *flows* that can be successfully transmitted, where a flow connects a source and destination node that must communicate. In other words, two nodes are *available* if they must and are able to communicate at that point in time using either direct wireless data connections or other routed data connections through the WAN. Overall network availability is derived by summing this over the entire network. Network availability can also be calculated among smaller subsets of nodes, e.g., between a command element and each of its major subordinate commands. In previous work, we demonstrate the utility of this metric in characterizing overall network performance (Nicholas et al. 2013).

We calculate network availability by running a *depth-first reaching algorithm* using VBA between each pair of nodes that must communicate. Starting at a given source node, the algorithm searches for wireless connections (either SATCOM, LOS, or troposcatter) to other nodes that may connect it (directly or via routing through other nodes) to the given destination node. If paths comprising connected nodes exist between the source and destination nodes in both directions, these two nodes may pass digital traffic and are counted as available.

In this way, network availability is calculated independently of actual network traffic load and demands. That is, if two nodes can form a routed path between them using wireless radio links, then they are considered connected and are thus available to each other. In reality, this connection will also depend on the amount of traffic on the network and other factors. However, to our knowledge, there is no definitive performance data describing the amount of network traffic to be expected in a "typical" MAGTF network, much less one specific to the selected scenarios at specific time steps (though we do have access to packet captures of portions of some networks). We use this lower-fidelity approach in order to provide insight with the available network performance information; with more detailed information our framework could include high-fidelity network simulation tools such as OPNET (Riverbed Technology 2016).

3.2.2 Calculating network throughput

Network throughput is a measure (in bits per second) of capacity between source and destination pairs. As with network availability, we calculate this metric across the entire network as "overall" network throughput, as well as among smaller subsets of nodes. We calculate network throughput by solving a *nonlinear network optimization problem* (see the Appendix for details). The mathematical model aims to maximize equitable throughput between each network flow pair, subject to constraints on the capacity of each wireless link. By valuing equitable flows, the model aims to prevent any two nodes from using large portions of network capacity while other nodes are allowed little or none. The network model does not consider return flows between nodes (i.e., handshakes or acknowledgements), and thus is similar to the *user datagram protocol* (*UDP*) (Postel 1980).

We formulate the model using GAMS (GAMS Development Corporation 2016), and solve it using the Couenne nonlinear optimizer (Computational Infrastructure for Operations Research 2016). We use VBA to automatically write the applicable GAMS file, run Couenne, and read in the results, for each time step in each scenario.

We then use VBA to post-process the results of the network availability and throughput simulations into a format suitable for analysis and visualization. We use Gephi (Gephi Consortium 2016) to create two-dimensional temporal representations of the network. Figure 2 is produced using Gephi, and is a depiction of throughput in a notional network at a moment in time; our actual, classified results are qualitatively similar. We simulate at multiple time steps within each scenario, and with different levels of degradation (based upon the specific threat systems being simulated).

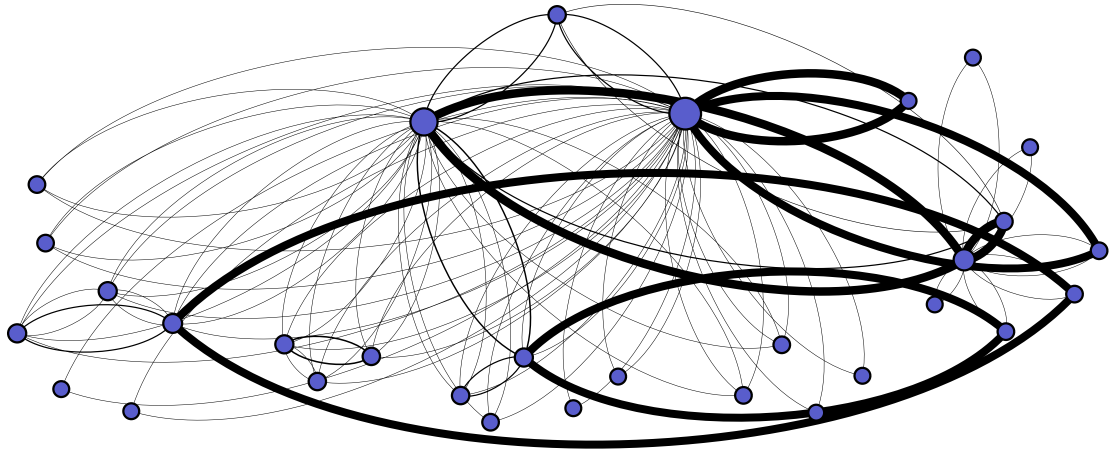

Figure 2: Example of a visualization from Gephi, using a notional network. Each circle represents a radio (either satellite transponder, ground station, or terrestrial system), where the width of each line is proportional to the relative throughput. The size of each circle is relative to the *degree* of that radio (i.e., number of connections). The large black lines represent terrestrial wideband radio systems, which generally have much greater throughput than SATCOM systems (i.e., the thinner lines).

Our simulation approach assumes that radio propagation effects from environmental background noise and vegetation are constant, i.e., they do not vary over time, nor do they vary by area. While in reality this will not be true, by holding this constant we are able to focus on the variables of interest, namely the level of SATCOM degradation. This analysis also assumes that electromagnetic spectrum is sufficiently available. More than likely, this will not be true (see, e.g., Nicholas et al. 2013). Future work may consider this potential shortage.

4 MEASURING OPERATIONAL IMPACT

Having developed methods for simulating signal propagation between satellite transponders, ground radios, and threat systems, and simulating the flow of communications traffic, we next describe our method of integrating this information with another model in order to quantify the operational impact of SATCOM degradation.

Based on the communications architectures we examine and input from subject matter experts, we find that there is generally much redundancy in the ability of a tactical military force to communicate. Even if all SATCOM capability is denied, there are likely other methods of communication available, including single- and multi-channel radio. In fact, Marine communications battalions still have motorcycles to enable Marines to serve as physical messengers in case of extreme communications difficulties. Due to this redundancy, we find that there are very few (if any) instances where a tactical mission is critically dependent on just one specific method of communication.

Due to this redundancy, and based on interviews with tactical communications experts, we find that the most likely operational effect of SATCOM degradation and denial is to delay certain events from occurring. Two areas that may be seriously affected are fire support coordination and logistics (specifically, resupply) operations. Both processes benefit greatly from digital communications architectures, which enable the rapid and reliable exchange of information between multiple users. The degradation of either process greatly hinders modern combined arms operations, which rely heavily on the use of supporting fires (including artillery, rockets, naval gunfire, and close air support) and robust logistics networks to provide vast quantities of goods (including water, food, fuel, ammunition, etc.) from supply points to the front lines. For these reasons, we focus our quantification of the operational impact of SATCOM degradation on these two types of operations.

We use *queuing models* to gauge the operational impact of SATCOM degradation on the ability to conduct logistics and fire support operations. *Queuing theory* models the arrival and processing of events over time (see, e.g., Gross et al. 2008). We use Rockwell Automation's Arena v14.0 software to model our queuing processes (Rockwell Automation 2016). Within the context of a given combat scenario, an event (either a logistics or fire support request) occurs with a given probability. The results of the communications network analysis are used to determine wireless connectivity. If the requisite units are able to communicate (via SATCOM or terrestrial radio systems), virtually no communications delay is incurred. If the units cannot communicate, a time delay is incurred as the request must be relayed via single-channel radio or other slower means of communications. With some probability, a request will take too long to process and will eventually be dropped from the system. For example, a fire support mission may no longer be needed if the delay is too long. Should digital communications not be restored quickly, an increasing queue may develop, and eventually the system may reach a state where it cannot recover, i.e., most requests are dropped.

To demonstrate operational impact, we consider a very large Marine Corps amphibious assault against a near-peer enemy force, where MAGTF forces move from naval ships to the shore and assault inland. This type of operation produces many fire support and logistics requests. We build a logistics process model based on various military publications, including Marine Corps Warfighting Publication (MWCP) 4-11 *Tactical Level Logistics* (U.S. Marine Corps 2000), and MCWP 3-31.5 *Ship to Shore Movement* (U.S. Marine Corps 2007), and interviews with various logistics subject matter experts. The fire support process model is based on various military publications, including Joint Publication (JP) 3-09.3 *Close Air Support* (U.S. Department of Defense Joint Staff 2014), NAVMC 3500.120 *DASC Training and Readiness Manual* (Department of the Navy 2013), and MCWP 3-25.5 *Direct Air Support Center Handbook* (U.S. Marine Corps 2001), Badalis (2008), and interviews with various fire support subject matter experts.

Each queuing model, in its simplest form, has various battalions or squadrons producing requests for logistics or fire support. These requests flow through the communications architecture until they reach servicing units (either logistics hubs or fire support entities). Process modules and decision nodes (representing various military units) simulate some action taken on the request, affecting the time required to process the request. Data connectivity is determined via the radio propagation and network simulation methods described in the previous sections. If data communications are possible, then the delay is negligible (representing automated electronic processing). If communications are degraded or denied, communications delays begin to accumulate. We use VBA to capture the queuing model outputs and to conduct post-processing.

We describe overall system performance using metrics such as the average time to process a request and the number of dropped requests. Figure 3 depicts example results for notional communications architectures A, B, and C. The left side of Figure 3 shows the number of dropped requests as a function of time, and the right side shows a box-and-whisker plot indicating the inner quartile, median, maximum, and minimum values for average time to completion for each architecture. After an initial warm-up period, Architecture A quickly reaches a steady state and is unaffected by jamming events. Architecture B (perhaps subject to degradation or denial of a critical SATCOM system) experiences a spike in processing time from which it is unable to recover. Architecture C experiences a sharp spike – perhaps also due to a loss of a critical SATCOM system – but the service is eventually restored (or another, unaffected system is brought online) and the architecture is able to return to a steady state of processing requests. While our actual results (Nicholas et al. 2015) are classified, these depiction are qualitatively similar.

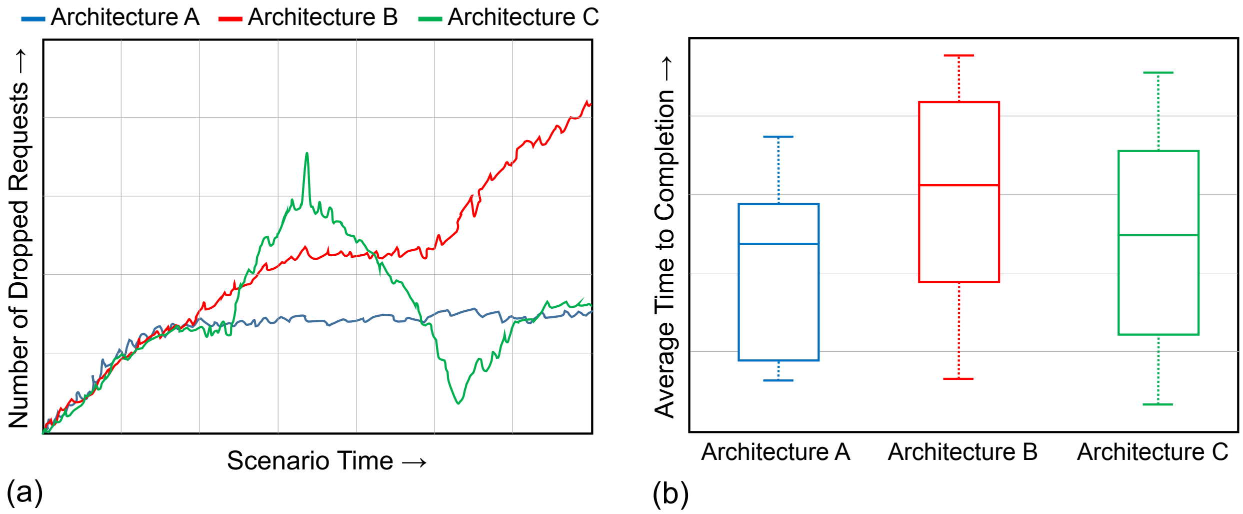

Figure 3: Example results from simulating logistics or fire support requests, for notional communications architectures A, B, and C. On the left is a depiction of the number of dropped requests for each architecture at each time step during the given scenario. On the right is a box-and-whisker plot of the average time to complete a request for each architecture. Architecture B experiences critical communications degradation (perhaps due to the loss of a SATCOM link), and its processing time and number of dropped requests increases thereafter. Architecture C also experiences an outage, but another system is brought online and it is able to recover.

These operational-level metrics are likely to be much more useful in determining the impact of SATCOM degradation than describing, for example, the decibel watt level of a satellite link or the throughput in megabits per second of a particular network segment. Our metrics speak directly to the ability to successfully conduct military operations. For example, if close air support is immediately required by a platoon commander, he/she may not be able to wait 30 minutes for a fire support request to be coordinated and executed. Our approach can quantify these impacts to support informed decision-making.

5 CONCLUSIONS AND FUTURE WORK

We present a methodology for quantifying the operational value of SATCOM and other types of communications, going beyond just stating “better” or “worse” or using stoplight comparison charts, or providing technical “bits-and-bytes” measures that do not directly translate into operational impact. Metrics such as logistics and fire support request processing times and the number of dropped requests can be useful in capturing and quantifying the operational impact of SATCOM degradation. This information may assist commanders in planning for and mitigating this impact, and it may aid acquisition decision-making in identifying and evaluating the value of new technical solutions, including controlled-reception pattern antennae (CRPA) and terrestrial- and aerial-layer networks.

We do not explicitly consider human factors, such as the ability to quickly change between digital and analog communications methods, or proficiency with backup systems. These factors are important but are difficult to quantify; applicable human performance data should be collected and incorporated into this model. In future work, we would like to determine which links or nodes are most vulnerable to attack and have the greatest impact on network performance (and thus should be considered for protective hardening or redundancy) (see, e.g., Alderson et al. 2014). We would also like to examine methods of allocating electromagnetic spectrum under degraded conditions.

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A APPENDIX

This appendix provides details on the network optimization model we use to simulate communications traffic (based largely on Nicholas et al. 2015). A *maximum flow problem* maximizes delivered flow between a given *source* and *destination* node, subject to constraints on arc capacity (Ahuja et al. 1993). The *multi-commodity maximum flow problem* (*MCMFP*) considers multiple flows of commodities, often distinguished based on source and destination (Schrijver 2003). This multi-source, multi-destination approach is often used to roughly approximate digital communications traffic (Pióro and Medhi 2004, Ahuja et al. 1993, Koster and Muñoz 2009).

Using communications architectures and traffic flow models derived from subject matter expertise and available network traffic captures, we formulate and solve a MCMFP to simulate network performance. We model the wireless *wide area network* (*WAN*) as a *directed graph* G of nodes $i \in N$ (alias j) and arcs $(i,j) \in A$. Nodes may represent any type of radio used for WAN data communications, including satellite transponders, ground-based SATCOM radios, and terrestrial wideband radios. Each node may serve as a source, destination, and/or relay for communications traffic. Though this formulation allows directed arcs between every pair of nodes (i.e., a *complete* graph), in practice the networks we simulate in our scenarios are quite *sparse*.

A *commodity* in this network flow model represents a network traffic flow between a given source and destination over a period of time, a practice consistent with the Internet Engineering Task Force (Amante et al. 2011) and network optimization literature (Ahuja et al. 1993). Let $D \subseteq N$ be the set of all destination nodes, indexed by $d = 1, 2, \ldots, |D|$, and let $(i,d) \in P$ be all source-destination pairs that must communicate (as dictated by a given network traffic model). Let the decision variable $F_{ij}^{d} \geq 0$ indicate the amount of flow from i to j destined for d. A flow need not be symmetric or have an associated return flow; in this way we assume *user datagram protocol* (*UDP*)-like traffic transmission without handshake dialogues (Postel 1980). Based on subject matter expertise and packet captures from Marine Corps field exercises, we assign each source-destination pair a $weight_{i}^{d}$ to indicate the relative importance of the associated flow. Let the decision variable $S_i^d \geq 0$ indicate the total amount of flow sent from i to d via any path(s) through the network.

Our formulation values only flows between source-destination pairs, as we are not concerned about flows between other pairs of nodes. Following Xiao et al. (2004) and Li et al. (2004), we use an objective function that maximizes overall delivered flow. Our *log-utility* objective function:

$$\max_{F,S} \sum_{(i,d)\in P} \log_2 \left(weight_i^d S_i^d \right) \tag{1}$$

provides decreasing benefit for increasing flow, thus incentivizing equitable distribution of flow among source-destination pairs. Further, flows less than one receive a penalty, so there is strong stimulus to provide at least unit flow between each pair.

We use the following sets of constraints to ensure *balance of flow* at each node:

$$\sum_{i:(j,i)\in A} F_{ji}^d - \sum_{i:(i,j)\in A} F_{ij}^d = \left\{ \begin{array}{ll} S_j^d, & j \neq d \\ -\sum\limits_{i,i\neq d} S_i^d, & j = d \end{array} \right\} \quad \forall j \in N, d \in D. \tag{2}$$

These constraints ensure that the total amount of flow delivered to a destination node d is equal to the difference between incoming and outgoing flows sent to that node.

Maximum network throughput is limited by the capacities of the individual wireless connections. Following Xiao et al. (2004), we assume nodes themselves do not have limits on capacity. We constrain the aggregate throughput on each arc (regardless of traffic source or destination) using $capacity_{ij}$, which are derived from the STK simulations and network throughput calculations. Each arc is thus constrained:

$$\sum_{d\in D} F_{ij}^d \leq capacity_{ij} \quad \forall (i,j) \in A. \tag{3}$$

Threat systems (such as jammers) will reduce or eliminate $capacity_{ij}$ values, as calculated in our simulations.

Our MCMFP comprises equations (1-3). The nonlinear objective function (1) is concave and strictly increasing and all constraints are linear, so this is a concave nonlinear maximization problem. Note this formulation does not consider network queuing delays, collisions, or wireless transmission losses. These simplifications allow us to bound the maximum throughput capacity of a given WAN, and can aid in validating the results using other, higher-fidelity models such as OPNET (Riverbed Technology 2016).

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AUTHOR BIOGRAPHIES

PAUL J. NICHOLAS is an operations research analyst at the U.S. Marine Corps Operations Analysis Directorate, and an adjunct faculty member in the Systems Engineering and Operations Research Department at George Mason University. He holds an M.S. in operations research from the Naval Postgraduate School. His research interests include optimization and simulation, focusing on applications in cyberspace and electronic warfare. His email address is paul.nicholas@usmc.mil.

JEFFREY C. TKACHEFF has worked for the military as a computer scientist, mathematician and operations research analyst since 1982. Currently, he works at the U.S. Marine Corps Operations Analysis Directorate, Capabilities Analysis Branch. He holds degrees in mathematics and computer science from the State University of New York (SUNY). His email address is jeffrey.tkacheff@usmc.mil.

CHANA M. KUHNS has worked for the military as an operations research analyst since 2006. Currently, she works at the U.S. Marine Corps Operations Analysis Directorate, Capabilities Analysis Branch as a member of the COMBAT XXI team. She holds an M.S. in applied and computational mathematics from Johns Hopkins University. Her email address is chana.kuhns@usmc.mil.