Proceedings of the 2023 Winter Simulation Conference
C. G. Corlu, S. R. Hunter, H. Lam, B. S. Onggo, J. Shortle, and B. Biller, eds.

THE HOLISTIC PRIORITIZED SATCOM THROUGHPUT REQUIREMENTS (HPSTR) STOCHASTIC MODEL

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ABSTRACT

The U.S. Army's command and control modernization efforts rely upon an expeditionary, mobile, hardened, and resilient network. Dispersed network access and data availability are central to increasing the operational speed required for effective command and control. The Army must define its satellite communication (SATCOM) requirements to support network modernization. This paper proposes the Holistic Prioritized SATCOM Throughput Requirements (HPSTR) simulation that prioritizes and adjudicates SATCOM throughput requirements for operational military units. Additionally, the simulation evaluates the impact of a contested, degraded, and operationally limited (CDO) communication environment on force effectiveness. HPSTR addresses knowledge gaps concerning U.S. Army SATCOM activities in a large-scale combat operation (LSCO) to inform modernization decisions.

1 INTRODUCTION

In 1958 the United States Airforce launched the Signal Communications by Orbiting Relay Equipment (SCORE) satellite, the first step in deploying a military satellite communication (SATCOM) capability (Ilcev 2019). The U.S. Army's SATCOM utilization has steadily grown since then to provide a global information advantage (Rayermann 2003; Barone 2019). Establishing a SATCOM network is a time-consuming and expensive endeavor, costing billions of dollars (Air University 2017; Jones 2018). Developing the Army's future SATCOM capabilities requires substantial organizational personnel and budgetary resources, driving the need for in-depth analysis.

U.S. Army warfighting concepts continue to evolve in stride with its modernization efforts. First, information warfare and information-driven overmatch are central warfighting concepts (TRADOC PAM 525-3-1 2018). Second, increased exploiting advantages and maintaining the initiative require increased operational tempo. Third, for the U.S. to maintain an information advantage, the SATCOM enterprise must withstand jamming and other contested, degraded, and operationally limited (CDO) conditions. Finally, in future wars, there is a greater likelihood that the U.S. Army will execute communication contingency plans, the series of actions required to maintain communication after losing a communication node. These changes will increase the demand for timely SATCOM with ramifications on throughput capacity.

The U.S. Army recognized the need to update the SATCOM requirement analysis to enable the development of future SATCOM architecture (GAO-20-80 2019). The U.S. Army tasked TRAC to initiate the SATCOM Throughput Requirements Study (STRS), directing that STRS build on and refine previous analyses in the context of large-scale combat operation (LSCO) in two geographically independent future combat scenarios. These scenarios provide divergent operational conditions to identify and evaluate the Army's SATCOM requirements throughout the planning and execution of warfare. The study team designed and built HPSTR to address the Army's SATCOM-related information requirements. This paper will focus on the methodology and modeling process, organized into five sections: literature review, methodology, implementation, output and application, and conclusion.

2 LITERATURE REVIEW

The U.S. Army directed the study team to build upon the Follow-on SATCOM Bandwidth (FSB) study completed by TRAC in May 2017. The FSB codified a list of traffic types (e.g., email without attachment, full motion video, video teleconference) and identified triangular distributions for the required amount of throughput, measured in kilobits per second (Kbps), to send communication of the given type (GAO-20-80 2019). The FSB used network traffic information and exchange requirements to establish the number and size of communications sent during the execution of specific military tasks. Given this data, the FSB built a stochastic Throughput Generation Algorithm (TGA) to estimate the total throughput requirement and the uncertainty surrounding that requirement.

The follow-on SATCOM Bandwidth study's TGA is no longer sufficient to estimate Army requirements. First, the FSB assumed data would be sufficient for military decision-making if the sending unit communicated the message within fifteen minutes. The increased operational tempo of the future battlefield violates this assumption (TRADOC Pamphlet 525-3-8 2018). Second, TGA estimates total SATCOM capacity requirements without regard to the supply of SATCOM capacity, which means that TGA cannot implicitly simulate the impacts of the CDO environment. TRAC identified a requirement to build a more holistic model considering the demand for SATCOM and the network's ability to meet that demand.

The team looked at commercial network bandwidth studies to determine what models already existed. In these studies, researchers used bandwidth allocation models addressing network demand given existing allocation data. These models often looked specifically at IP/MPLS/DS-TE and optical domains (Reale et al. 2017; Rafael et al. 2016). The study team could not utilize Bandwidth Allocation Models (BAMs) as they limited the model's scope. The team needed a model that did more than allocate existing bandwidth, and they also needed to predict bandwidth allocation in a contested environment based on priority.

Next, the team explored explicit network simulations. This research found that including every node and each data packet passed between those nodes would provide the best information to inform the study. However, a typical U.S. Army Corps has tens of thousands of soldiers, most of whom will have some form of network connection. Even if the team simplified the problem to SATCOM terminals, a fully fielded and supported U.S. Army Corps has over a thousand terminals. To further complicate matters, the U.S. Army does not field the communications equipment simultaneously, resulting in different versions of the same system in different years (GAO-20-80 2019).

Additionally, each unit deploys a unique communication architecture that supports its unique combination of communication and communication-enabled equipment (GAO-20-80 2019). Every time a unit deploys, they choose the best equipment combinations to best enable its specific mission. As a result, the simulation of military network capacity supply became overly complex, precluding its use due to study timeline constraints.

Network flows provide a powerful tool for exploring network requirements. These models can optimize the movement of data through a network and help identify potential bottlenecks and congestion points which can estimate the capacity requirements of the network and the necessary infrastructure to support the desired network performance. Network flows rely on the optimal routing of information through the network and assumes perfect network knowledge (Bazaraa et al. 2009). Military networks prioritize survivability over optimality. As a result, intentionally separating different parts of the network prevents attacks from destroying the entire network (Sangita et al. 2023). Moving between network sections represents a penalty in time rather than capacity. This time penalty determines the network routing of the communication method chosen by a soldier whose choice is often made without a complete understanding of the current state of the network. Thus, the U.S. Army's requirement to simulate CDO invalidated the use of network flows for the study.

Sufficiency analysis is a method used to simulate and analyze resourcing decisions over time. The U.S. Army frequently uses sufficiency analysis to determine the number and types of units sufficient to support different military operations. Sufficiency analysis requires three types of data: 1) a demand signal denoting the demand for resources over time; 2) a supply signal defining the resources available over time; and 3) a set of business rules explaining the logic behind apportioning supply to demand. Sufficiency analysis uses a simulation that walks through timesteps and uses the business rules to assign supply to demand. Such models simulate decisions made by individual soldiers with imperfect knowledge and adjudicate which communications are received. Using the design of experiments focused on the supply signal may identify which resourcing decisions drive communication success or failure, indirectly informing risk. Given its simplicity and computational efficiency, the study team used sufficiency analysis to inform Army SATCOM requirements (Gargin 2023). The following sections describe how the team utilized sufficiency analysis to develop SATCOM requirements using HPSTR.

3 METHODOLOGY

3.1 Simulation Overview

Figure 1 provides an overview of the HPSTR simulation. HPSTR is a stochastic discrete event simulation that models communication attempts made by a U.S. Army Corps during a LSCO. The model considers the architectural limitations, threat effects, and beyond-line-of-sight (BLOS) transport requirements. U.S. Army modernization efforts have refined the expected communication demands for tactical formations up to a U.S. Army Corps, as described in the next section. In a specific sending unit and tactical task combination, participants identified a specific need to communicate with an associated communication primary, alternate, contingency, and emergency (PACE) plan. Apportioning throughput is based on the unit's terminal capacity while accounting for threat effects. For example, jamming success depends on the jammer's proximity and effectiveness against a particular terminal type to assess the time required to overcome or mitigate the adversarial jamming threat. Failed communications will continue through the PACE plan until the identification of a feasible and acceptable transport method and the execution of the communication.

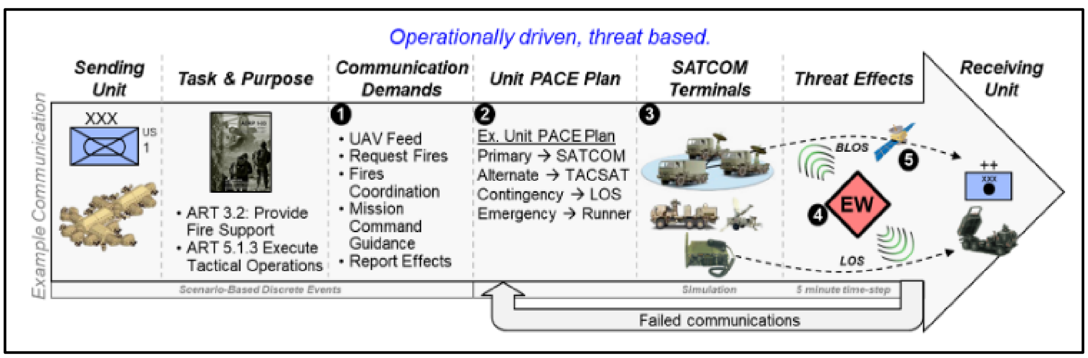

Figure 1: HPSTR simulation.

U.S. Army requirements developers refined communication demands from the FSB study and updated traffic types and sizes to provide a stochastic communication demand signal. Capability managers maintain data concerning the current capacities of Army SATCOM equipment, particularly Army SATCOM terminals. Jamming success depends on the jammer's proximity and effectiveness, and Army engineers maintain a running understanding of how susceptible U.S. Army equipment is to threat actions. Combining capacity information with threat effects enables the construction of a stochastic supply signal for the scenario's duration. Technology and doctrinal updates provided the options and logic for communication contingency (i.e., PACE) planning in this study. As a result, these PACE plans to provide the basis for the business rules used to apportion supply to demand within each timestep.

HPSTR tracks two types of throughput supply. The first is associated with the deployed SATCOM terminal capacity. This portion of supply scales with the number of terminals deployed and thus is roughly proportional to the deployed force size. The second supply type is network throughput capacity, constrained by satellites, regional hub nodes, gateways, and undersea cables. This supply type does not scale with the number of units deployed to a theater. In HPSTR, communication can only succeed if there is sufficient capacity at the sending unit, the network, and the receiving unit. HPSTR can simulate the impacts of threat effects on these supplies by reducing or eliminating the supply according to a jamming plan defined by threat analysts.

3.2 Simulation Inputs and Operational Context

This section discusses the input data required to run the HPSTR simulation, including the operational context, task organization, communication demands, the associated file sizes (in Mbps), and the terminal capacities. The study team used realistic future combat scenarios addressing the terrain, unit locations, equipment, and threat. The team identified two 48-hour vignettes each from both scenarios.

3.2.1 Communication Demands

The simulation demand signal is the aggregation of millions of communication demands. The components of communication demands are 1) unit and scenario attributes, 2) communication attributes, and 3) timeliness attributes. The first category, unit and scenario attribute, comprises the tactical tasks, warfighting functions, vignette phases, and the sending and receiving units. These attributes clarify the task completion, the time step, and units, which feeds into the warfighting function, a metadata component of the input file to provide contextual information for analysis of throughput drivers. The second category, communication attributes, comprises the communication purpose, line of sight indicator, message priority, and communication PACE plan. The PACE plan designates the order in which the sending unit will move through available communications systems until they have contacted the receiving unit. The PACE plan also specifies which traffic types and transport methods the sending unit will attempt to use as communication begins to break down. The final attribute category, timeliness, comprises transmittal requirements, frequency, and schedule. This category describes when, how fast, and how often sending specific messages in the scenario occurs. HPSTR can schedule or randomize different communication demands to simulate scheduled meetings and event-driven reporting.

3.2.2 Traffic Types & File Sizes

HPSTR parses communications into discrete and continuous categories. Discrete communications include chat, text/email, picture/graphic, multiple graphics, Microsoft Office files, and video clips. Conversely, continuous communications link a sender to a receiver for a specified duration at a constant bit rate. This type of communication includes full motion video, voice, and video teleconference. Since these communications occur over time, drawing throughput and duration stems from triangular distributions.

3.2.3 SATCOM Terminal Capacities

Wideband SATCOM throughput is a function of the unit's SATCOM terminal quantities and projected terminal performance in a CDO environment. SATCOM terminal performance is a function of the operationally constrained Scenario context dictates network architecture, geographic location, and various satellite constellation implications. SATCOM network and terminal subject matter experts provided throughput estimates for each terminal with the most current data.

4 MODEL IMPLEMENTATION

Section 4 describes the software architecture and functions used to build HPSTR. HPSTR is composed of interdependent Python packages and applications developed at TRAC. Together, these applications automatically execute iterations across any specified set of runs.

4.1 Run-Handling

Due to the simulation's stochastic nature, TRAC designed an internal grid-computing framework capable of supporting studies requiring multiple iterations, each with a large number of runs. The framework scales across non-homogeneous sets of windows machines on an internal network. The model uses a distributed grid-computing architecture to increase scalability and reliability.

4.2 Build Demand Schedule

Before iterating through the time steps, the simulation stochastically assigns start times for each communication demand, which are assumed to be independent. Demands can occur simultaneously and not be sequenced. The primary data structure used throughout the simulation depicts tables where the columns are unique combinations of the filterable output metadata, and the rows are the individual time steps. The simulation consolidates the rows to the unique combinations of filterable output metadata to reduce the memory load on the machine. The tables show non-negative integers denoting the number of times in a time step communication demands occur. Communication demands are sequentially read from the input file and added to the table. The model follows a series of steps drawn out in Figure 2 to insert the data into the demand schedule.

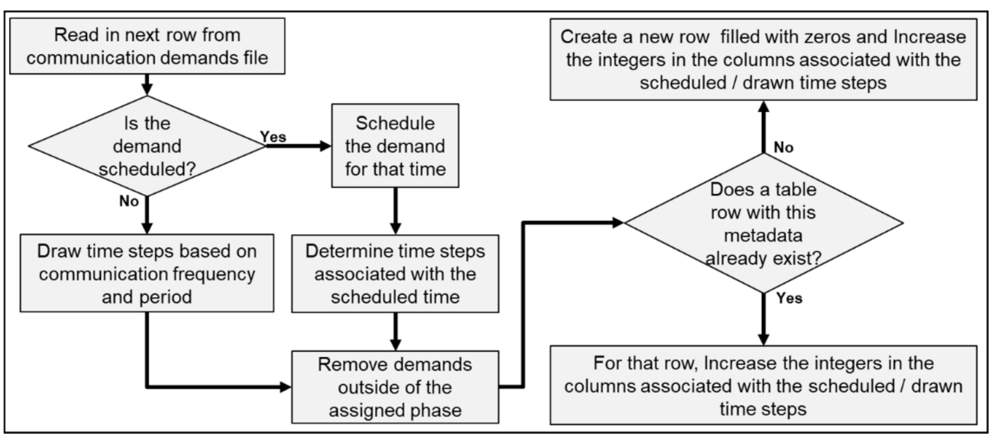

Figure 2: Demand schedule generation.

The simulation generates the demand schedule, which begins by reading the communication demand file described in section 3.2.1. Whether a demand is scheduled or random, the simulation lists time steps when the demand will occur. Figure 3 provides an illustrative example of a demand schedule.

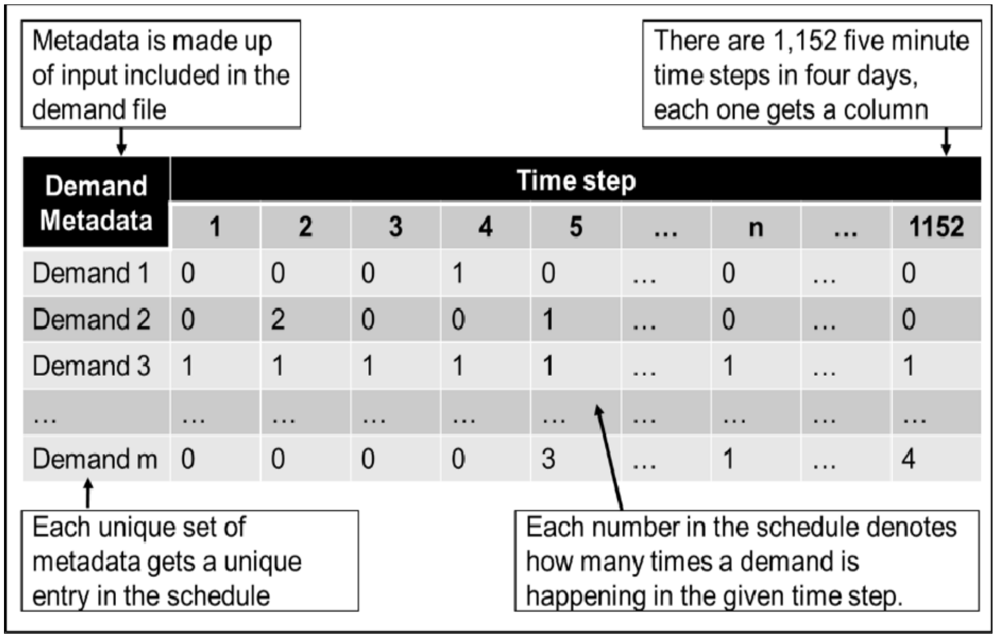

Figure 3: Example demand schedule.

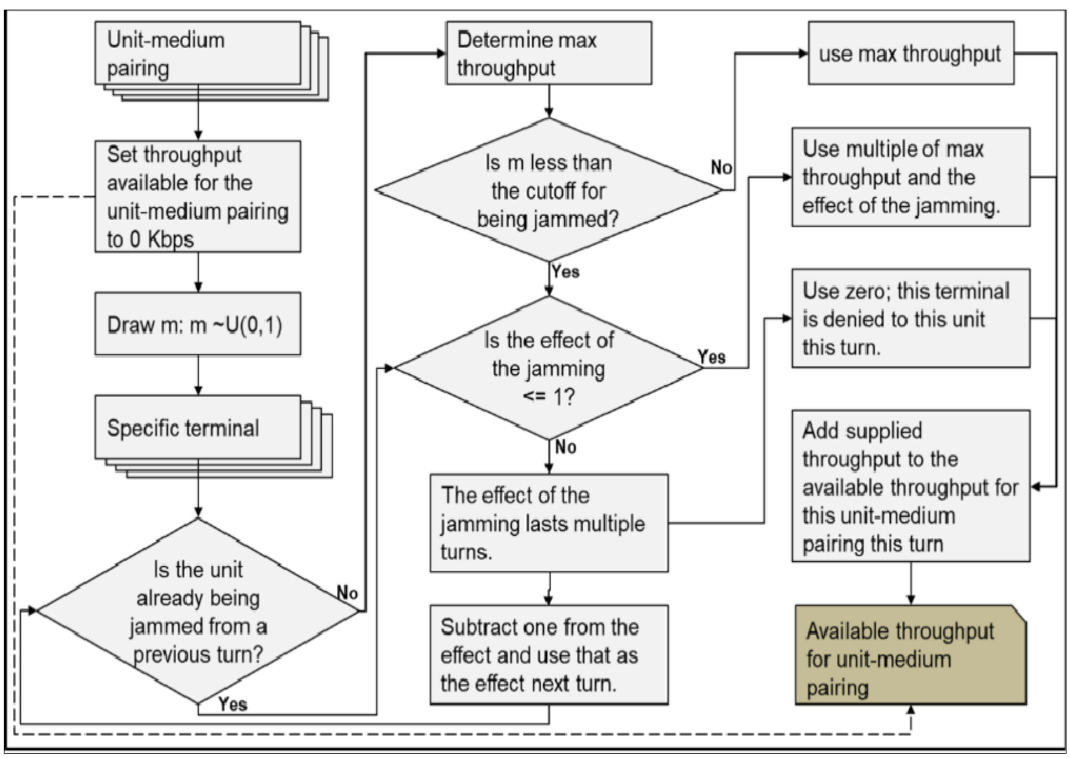

Figure 4: Determination of throughput available by unit-medium pairing.

The simulation iterates through each tactical formation to determine the available throughput by transport type. The simulation starts by setting the available throughput to zero. It then draws the parameter used to determine the jamming of a unit-transport pairing during the time step seen in Table 1. The simulation determines if the terminal is experiencing active jamming and subsequently determines the effects of the jamming parameter.

Table 1: Effects of jamming.

Jamming Parameter	Jamming Effect
> 1	Terminal is jammed for multiple time steps.
≤ 1	Terminal is jammed for a one-time step.

Once the unit has iterated over all terminals in a unit-medium pairing, the simulation sums the operationally constrained throughput available for each assigned unit lessening the effects of jamming. It then begins the final step of demand adjudication. As with any supply and demand analysis, the demand adjudication order dictates the simulation results. When throughput resources are scarce, communication demands adjudicated late within a time step are much less likely to succeed than those adjudicated when resources are less constrained. The communication demand priority, described in section 3.2.1, prioritizes the adjudication order. Figure 5 depicts the adjudication of demands, and the following paragraphs describe the adjudication in additional detail.

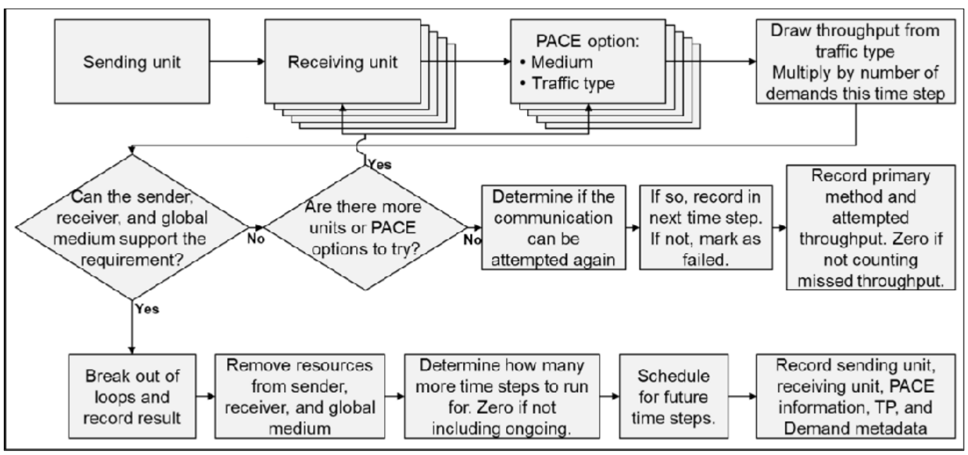

Figure 5: Communication demand adjudication.

Based on the sending unit's PACE plan, the simulation first identifies which potential receiving units can support a communication demand. Each PACE plan option comprises the medium and the traffic type, described in section 3.2.2. The stochastic throughput requirement encodes the traffic type as a triangular distribution. The simulation draws a requirement from the triangular distribution and multiplies by the number of communications attempted during the time step to determine the total throughput required. The simulation compares the required throughput to the sending unit's available capacities on the transport method and the receiving unit. Suppose the throughput requirement is smaller than the throughput available. In that case, the simulation checks to see if the units are within line-of-sight (LOS) and if the preferred transport method requires LOS for transmission. The demands successfully transmit if every terminal has the capacity and no LOS discrepancies. Suppose one of the three resource pools needs to be more significant. The simulation will loop through the remaining PACE plan options until the communication can successfully transmit.

The communication remains unmet if no combination of receiving units and PACE plan options is successful. Table 2 defines the potential transmission options cataloged for each time step. Following each run, the simulation prepares and publishes the data. The following section will describe the output data types available with the HPSTR simulation.

Table 2: Transmission status definitions.

Communication Status	Definition
Delayed	Demand is unmet for at least one-time step before being met.
Failed	Demand is unmet for the entirety of its timeliness requirement.
Completed	Demand successfully transmits for every required time step.
Primary	Completed demand using the Primary PACE option.

5 MODEL OUTPUT AND APPLICATION

The three primary output files generated by the HPSTR simulation include a demand schedule, adjudicated demands, and each unit's throughput available by a medium. These output files examine throughput drivers for BLOS communication requirements, operational implications, and terminal shortcomings. This model can prioritize and adjudicate SATCOM throughput requirements for commercial use as the network demand grows.

6 RESULTS

All existing HPSTR results are controlled and not publicly releasable. However, the graph below provides a notional example of the kind of analysis HPSTR can enable. Along the x-axis is resource availability (e.g., terminal capacity, satellite capacity). The y-axis is the simulation-generated rate of communication failure. The y-axis subdivides by color, denoting subjective risk levels provided by subject matter experts. The function plotted on the graph estimates the resource requirements necessary to reduce risk between subdivisions. The function also estimates the amount of investment, beyond which no further investment will change the risk. Graphs like this provide customers with a range of possible decisions and associated consequences.

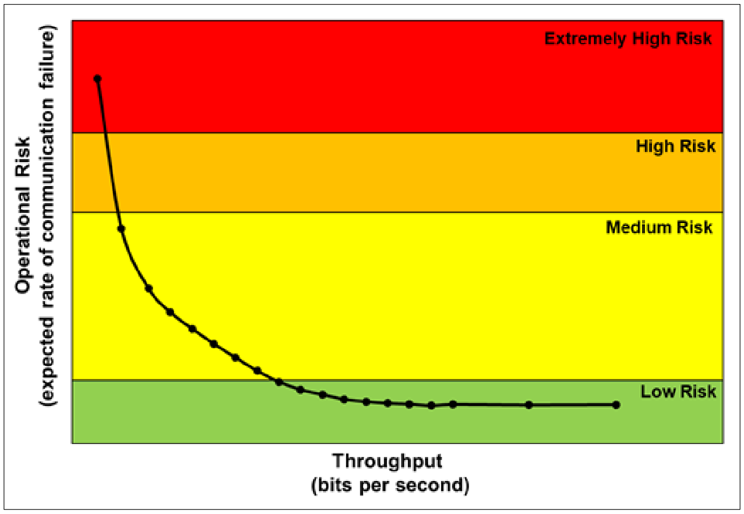

Figure 6: Notional resource requirements to reduce risk.

7 CONCLUSION

In this paper, we concentrate our efforts on the proposed model, the Holistic Prioritized SATCOM Throughput Requirements (HPSTR) simulation. The proposed HPSTR simulation prioritizes and adjudicates SATCOM throughput requirements for Army forces conducting operations while also evaluating the impact of a CDO communication environment. Additionally, we demonstrated overcoming knowledge gaps regarding the Army's communication over SATCOM in LSCO. The results obtained in this paper are vital in examining how to inform decision-making to improve the Army's communication. Future directions include using HPSTR to prioritize and adjudicate SATCOM throughput requirements for commercial use and investigating throughput requirements for other transport LOS and NLOS methods.

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