

An Interactive Design, Visualization, and Analysis Tool for Information Flow over a Tactical Data Network

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ABSTRACT: The United States Army is embracing the use of new information technologies to achieve tactical advantage over potential adversaries. Existing and future information systems place a significant load on the tactical data network, resulting in a bandwidth management crisis, yet there is no prioritization, allocation, planning, or management tool available to simulate information flows over time for different communications configurations under different operational conditions. The development of such a tool requires the implementation of a communication network model and the supporting discrete-event simulation system. Models for the information systems that induce flows, the command posts using the information systems, and the influence of operational conditions on the information flows are also required, as is a graphical user interface that allows the tactical planner to configure the system and set up data capture. The visual development techniques used in this tool make it easy for the planner to design and build communication networks to support operations, then interactively reconfigure the network, run "what-if" scenarios, and visualize the effects. The system can be used for training, design of experimental networks, and to support rapid decision-making.

KEYWORDS

Tactical Communications, Visualization, Decision Aids, Information Flow, Discrete Event Simulation

1. INTRODUCTION

The United States Army wants to improve the use of information systems to achieve tactical advantage over its adversaries. Various systems are already deployed, and as the Army modernizes its forces and updates its doctrine, new uses for these existing systems are developed. Simultaneously, the Army is investigating applications of new information technologies in the tactical arena. These new capabilities and new systems place increasing and uncoordinated demands on the tactical data network, resulting in a bandwidth management crisis. Unfortunately, there is no mechanism for prioritizing the information flows or for determining the best allocation of available communication system resources to support particular operational conditions. There is also no ability to examine the impact of new capabilities or new information systems on the information flows.

The Information Flow Design and Evaluation Tool was developed to support communication planners in an Army division and to enable experimentation. During tactical operations the communication network and the information flows traveling over it change significantly. The planners need a tool that allows them to consider different scenarios and develop the most effective configurations, improving communications capabilities and increasing combat effectiveness. They also need a tool to examine the potential effects of current and future battlefield information systems. This tool must be able to simulate the flows on the data network over time for different communications configurations under different operational conditions. The major design components of the tool are the supporting discrete event simulation mechanism, the communications network, the Army Battle Command Systems, the Command Posts, and the conditions they operate under.

Two major goals for the system are to provide a visual development environment and to display the results in an easy to understand visualization. Drag and drop methodologies and

other visual techniques such as right-click functionality and pop-up menus are used for placement of tactical entities and establishment of radio links. The loads placed on the system and the bandwidth utilization are visually represented for easy interpretation by the user. The system enables planners to rapidly determine viable configurations based on actual mission requirements and current systems availability that make more effective utilization of the available bandwidth.

2. THE TACTICAL INFORMATION ENVIRONMENT

When an Army Division deploys in the field it builds a complex information infrastructure. The specific composition of that infrastructure depends on several factors. Different types of operations, their subordinate phases, and the specific missions of the Command Posts create different information processing and generation demands on the Army Battle Command System and the supporting communications network.

The type of operation has a major impact. An Army division can conduct a wide variety of operations, each of which places different information requirements on the communications infrastructure. Typically, operations are divided into phases. Changing from one phase to another often result in new unit positions, activities, and information flows, necessitating a complete reconfiguration of the communications network.

The subordinate units have assigned missions and perform tactical tasks, and they both consume and produce information that must pass through their Command Posts (CPs). CPs are the nerve center for units, ranging from small battalion CPs to the very large division CPs. Every CP has different responsibilities and information processing requirements. Additionally, when the CPs have to move as part of their mission, or are attached to a different higher headquarters, reconfiguration of the ABCS systems and the communications network are required.

Within the CPs, the demands for tactical bandwidth come from the information systems that form the Army Battle Command System (ABCS) [1]. ABCS is a family of several distributed computing systems, seven of which are identified in Table 1. Each Command Post has a different configuration of ABCS systems, and may have multiple systems of any given type.

Table 1: Components of the Army Battle Command System

ABCS Systems
Global Command and Control System-Army (GCCS-A)
Maneuver Control System (MCS)
Advanced Field Artillery Tactical Data System (AFATDS)
Air and Missile Defense Planning and Control System (AMDPCS)
All Source Analysis System (ASAS)
Combat Service Support Control System (CSSCS)
Force XXI Battle Command Brigade and Below (FBCB2).

All of the information flow travels over the tactical data network, known collectively as the Mobile Subscriber Equipment (MSE) system. MSE "provides both voice and data communications on an automatic, discrete addressed, fixed-directory basis using flood search routing [2]." The MSE system uses routers called Node Centers (NCs) to form the backbone of the communications network. Small Extension Node (SEN) and Large Extension Nodes (LEN) routers are associated with CPs and connect to the NC backbone with either a wire or radio link. There are significant restrictions on how many SENs can be connected to a single NC and on the total bandwidth. Consequently, tactical bandwidth is a crucial and very limited resource that must be carefully managed to support tactical operations.

3. THE INFORMATION FLOW CHALLENGE

The challenge for division communication planners lies in designing and setting up the communications infrastructure to support information flows for current and future operations. It is prohibitively expensive to deploy the Division communications structure, Command Posts,

and information systems to the field every time an experiment is desired. Even if it wasn't, it is very difficult to stimulate the actual systems without conducting full-blown division operations, including the participation of an adversary force.

The planners need an automated tool for designing the tactical data network to meet the expected data bandwidth requirements of the battlefield information systems. This tool must be able to simulate the flows on the data network over time for different communications configurations and different operational conditions. The tool must have a good model of the information flows to be able to predict network performance. Ultimately, the tool will allow the planner to define “what if” scenarios, such as the loss of a major communications node or significant change in operational conditions.

4. RELATED WORK

Previous research related to this work has focused on the lower level communications architecture, including protocols, switching, and devices. The MSE System Control Center Version 2 (SCC-2) has a Network Planning Tool (NPT) built into it [2]. The NPT operates at the level of asset placement, terrain analysis profiling, frequency assignment management, and radio/antenna system engineering. The Tactical Internet Modeling and Simulations (TIMS) system focuses at the level of switching, protocols, and routing algorithms [3]. The Operational Planning and Simulation (OPSIM) system allows planners to build large-scale military networks while still being able to modify and observe the effects at the device level [4]. The Interim Division Design Tool allows for new equipment and protocols to be modeled and tested [5]. None of these systems consider the information flows driven at the highest level by tactical entities under specified operational conditions.

5. A DESIGN AND EVALUATION TOOL

The Design and Evaluation Tool must provide the planners with several capabilities. Breslau, et al., identify several requirements for network simulations, among which are scenario generation, visualization, and extensibility [6]. They also state the requirements for network simulation scenarios as "network topologies that define links and their characteristics, traffic models that specify sender and receiver locations and demands, and network dynamics that include node and link failures." An additional requirement, of course, is the ability to capture relevant data for analysis.

The division Information Flow Design and Evaluation Tool was developed with the idea of getting the maximum benefit from visual development and visualization of the results. With that in mind, the specific requirements for the tool are stated below.

- ?? **Scenario Generation:** The communication planners should be able to interactively place and configure the Command Posts (and their associated ABCS information systems), the communications network components, and the links between them. The tool should provide a drag-and-drop mechanism that makes building the scenario a simple, rapid process.
- ?? **Defined Links and Characteristics:** The constraints of the components must be built into the visual objects that represent them. For instance, the number of connections between nodes and their bandwidth allocations should be automatically set up when the user makes the connection with the visual drag-and-drop mechanism.
- ?? **Traffic Models:** This tool must be able to simulate the flows on the data network over time for different communications configurations and different operational

conditions. This requires the system to generate realistic information flows from each information system under particular operational conditions.

?? **Data Capture:** The system must be able to capture data about saturation and identify offending information systems or bottlenecks in the communications network.

?? **Visualization:** The system should visually display bandwidth saturation on links and bottlenecks at MSE Nodes in a manner that makes it easy for the planner to understand, at the aggregate level, what is going on in the communications network. The planners can then “drill-down” to the specific statistical data they are interested in.

?? **Network Dynamics:** The planners must have the ability to apply abrupt modifications to the communications network, such as the loss of a node or the elimination of a CP along with its ABCS information systems. These dynamic changes must be handled by the simulation system in the same manner as the real communications network. The changes must also be apparent in the visualization presented to the planners.

?? **Extensibility:** If new components, protocols, or information systems are produced, or new information about information flows under particular operational conditions is available, incorporation into the system should be as simple as 'plug and play.'

6. VISUAL DEVELOPMENT AND VISUALIZATION

The graphical user interface (GUI) enables interactive design of the MSE communications network, placement of the CPs and their associated ABCS boxes, configuration of the operational conditions, execution of the simulation, and visualization of the results. The planner can use the GUI to change the communication system setup, the operational conditions,

and the CP locations interactively. This is also the visualization mechanism for observing the effects of the traffic-flow over the communication architecture from messages generated by the ABCS boxes under given operational conditions.

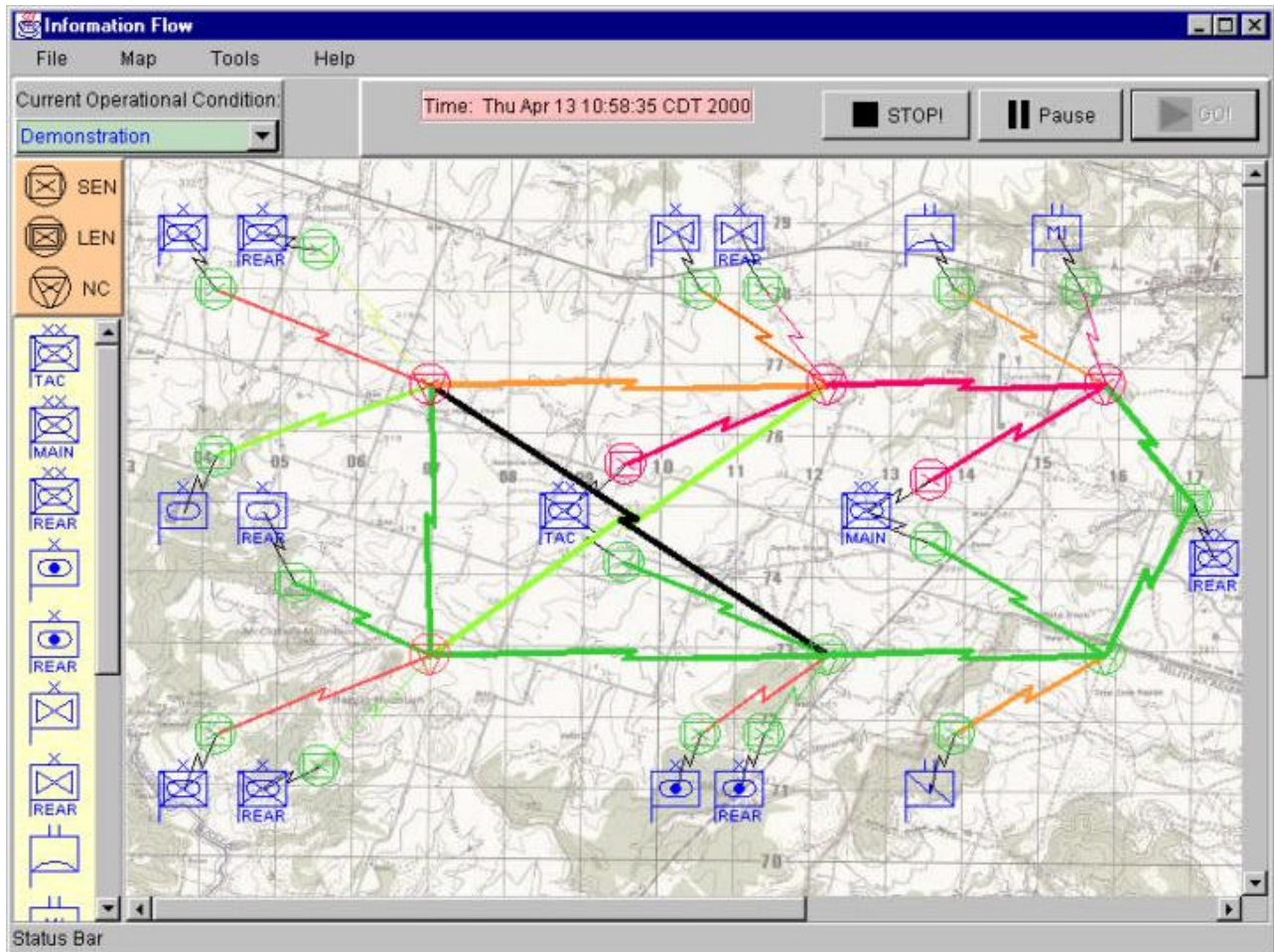


Figure 1: Prototype System

The system is designed to be as visually interactive as possible, providing for visual placement of entities through drag and drop, visual connection of radio links by dragging, and visual representation of loads and band width utilization. The screen capture in Figure 1 shows a demonstration setup on a piece of Fort Hood, Texas, terrain. Although the CPs and MSE nodes are placed artificially close for clarity, the image depicts the interaction mechanism and the visualization of the results.

6.1. Placement of Entities

The first step in designing the communications system is to load a map as a visual reference in placing the CPs and MSE nodes. The map is contained in a scrollable view port, allowing the planner to pan across the entire area of operations. The system interface includes two palettes. The first palette contains icons representing the three types of MSE Node – SEN, LEN, and NC. The second palette contains icons for each type of CP normally found in the division area of operations. Since there are many different types of CPs, this palette is scrollable, allowing the planner to rapidly find the desired icon. The planner typically begins by placing the CPs on the map in accordance with the operational plan by using a 'drag and drop' gesture with the mouse that places a new instantiation of the icon on the map display. The same technique is used to place MSE Nodes. Once on the map display, both MSE Nodes and CPs can be freely repositioned with a drag gesture. All entities retain their position on the map when it is scrolled.

6.2. Establishment of Links

The system uses a 'rubber-band line' mechanism for establishing the radio links between entities. That is, the user clicks on an entity and drags the mouse to another entity while a visual link is constantly maintained between the source entity and the point of the mouse. When the mouse is over the target entity, the planner releases the mouse and the system attempts to establish the link. To distinguish this drag gesture from an entity movement gesture, the right mouse button is used. It is at this point that the rules for making links are enforced. If there is not an available radio port of the correct type on both ends the link is denied, otherwise it is established. If it is a high-speed link, a thicker line is used to represent the higher bandwidth. If it is the second or third low-speed link between a Small Extension Node (SEN) and a Node Center (NC) then the width of the line is increased. The visual representation of the links retain their 'rubber-band' properties so that if an entity at one end is moved by the planner, all of the

visual links follow the entity. Each visual link has a line-proximity method for determining how close a mouse-click is to the link. If the planner right-clicks within three pixels (configurable) of the line, a popup-menu appears offering options for that link, such as deletion.

6.3. Execution Under Particular Operational Conditions

Once the CP and MSE Nodes have been placed and the links established, the planner sets the Operational Condition (OC). The system uses a much finer granularity in describing the OC than the operations and phases normally associated with plans. For example, the operation could be an Area Defense, the phase could be counter-attack, and the operational condition would be specific to the artillery fires and helicopter strikes that are part of that phase. The OCs are mark a clear distinction in the types of information flows between particular ABCS systems.

Now that everything is in place and the OC has been specified, the planner starts and controls the simulation with the Simulation Toolbar (in Figure 1, the panel that contains the time display and the Stop, Pause, and Go buttons). VCR-like controls are used since they are more familiar to most people than simulation instructions. In fact, the planners don't even have to be aware that there is a simulation running in the background.

6.4. Load and Bandwidth Visualization

As the simulation runs the planner can observe the effect of the information flows on bandwidth utilization. The color of the MSE Nodes represents the load, or backlog, of information flows trying to pass through the node. The color of the links represents the bandwidth utilization over a (configurable) time window. The color-coding itself is configurable, but generally follows the convention shown in Table 2 (for clarity in grayscale, the name of each color is also provided).

Table 2: Color Representation of Loads and Bandwidth Utilization

Load / Bandwidth Utilization Colors		
Black		0%
Dark Green		0-10%
Green		10-20%
Green-Yellow		20-30%
Yellow-Green		30-40%
Yellow		40-50%
Yellow-Orange		50-60%
Orange-Yellow		60-70%
Orange		70-80%
Orange-Red		80-90%
Red		90-100%

The screenshot in Figure 1 provides several interesting examples. The bandwidth utilization is very high on the links between the TAC CP and the MAIN CP on the northern links. An alternate route exists through the NCs to the south, but the green coloring indicates they are underutilized. Within the NC backbone there is a completely unutilized (black) high-speed link from the upper-left NC to the lower-middle NC. The planner could consider moving this link between the two center NCs to help relieve the flows between the TAC CP and the MAIN CP. The low-speed link from the SEN for the Brigade CP in the southwest corner is saturated (red) to the southwest NC, but the high-speed link carrying the traffic northeast to the north-center NC is only lightly saturated. The planner could consider adding additional low-speed links out of the SEN to increase the flow.

6.5. Interaction

The planner can interact with the system while it is running to observe the effects of changes in the system. For instance, the planner can remove a component by right-clicking it and selecting "Delete" from the drop-down menu. When an MSE Node is removed, all links to it are automatically dropped also. The system detects the loss and reroutes the information flow. The same is true if a planner removes a link. MSE Nodes can be dragged back into the display

and have new links established. When information flows are congested (information is being dropped) the system will look for better routes and find the newly installed links. The planner also has the ability to freeze the action to capture visualization and data at a specific point, or stop the simulation and start over.

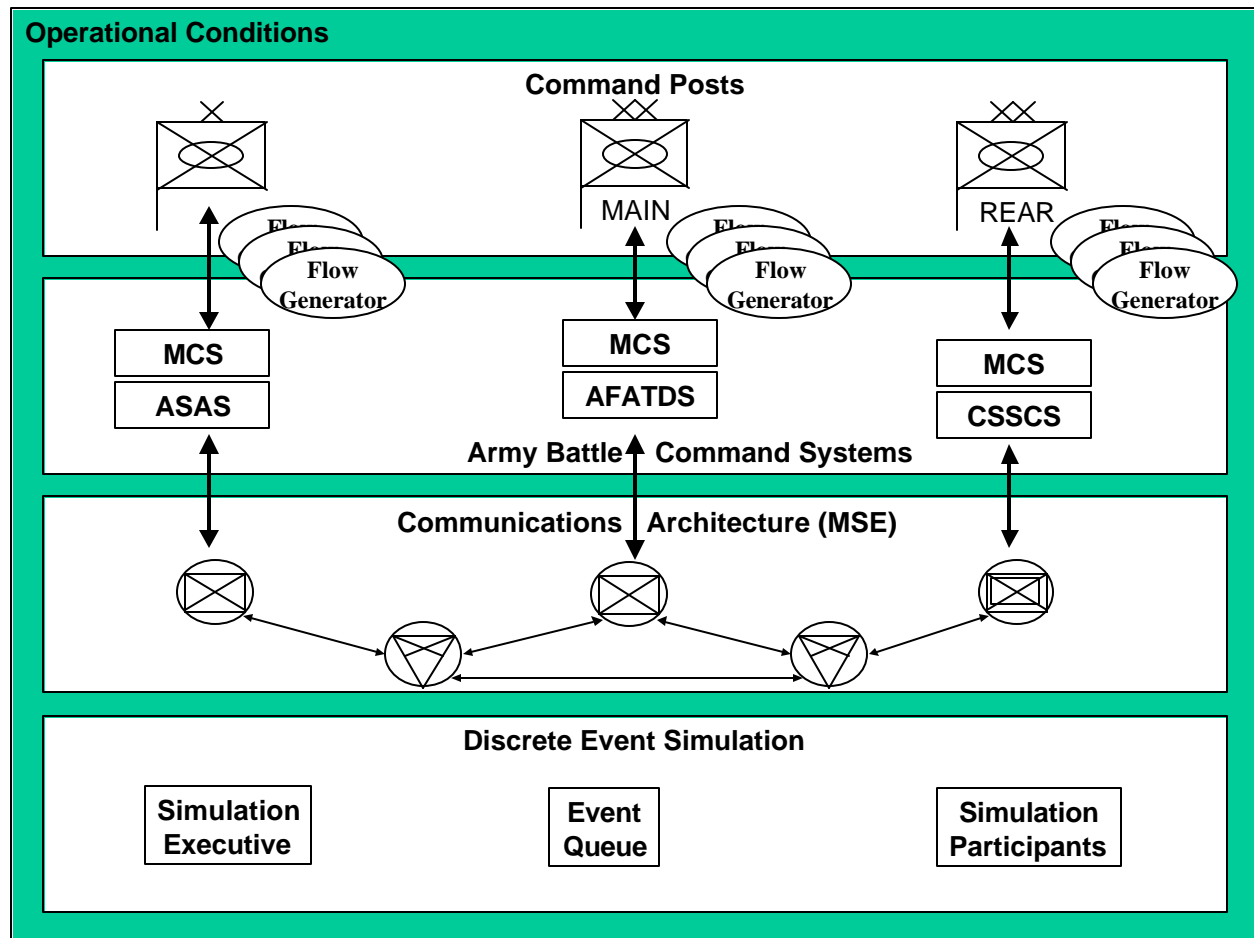


Figure 2: Layers of the System Design

7. DESIGN AND IMPLEMENTATION

One of the most important parts of the design of this tool is the separation of functionality that provides for flexibility and ease of analysis. This section expands on the discussion of the methodology presented by Hill, et al. [7]. The key to the model is the relationship between operational conditions, the tactical entities, and the information flows over the communication network. In this design, Operational Conditions are separated as a factor that affects all other

components and distinct layers are used for the tactical entities, the ABCS boxes, the MSE communications network, and the discrete event simulation mechanism. See Figure 2 for a depiction of the layers. This layered design allows for flexibility in construction and analysis, and makes the addition of new components or protocols very simple.

7.1. Operational Conditions.

In the context of the design of this system, Operational Conditions (OCs) are distinct from operations and from phases, as they were previously defined, but are related to both. An OC is any distinguishable portion of a phase that causes a significant alteration in the behavior of the tactical entities, the configuration of the communications network, or the distribution or utilization of the ABCS information systems. OCs can be chained in order to produce a phase or an entire operation.

7.2. Command Posts.

Command Posts, which contain the ABCS boxes, can be placed in different locations, removed from play (taking their ABCS boxes with them), or be given a different mission (affecting the nature of their information flow patterns). In this case the effect on information flows and on the communications network can be observed. The CPs are modeled so that they can generate varying flows through the information systems onto the communication system. CPs contains some number of each type of ABCS system, and each system produces messages according to a user-configurable distribution (for each particular OC). Currently, information flows generated by multiple ABCS boxes of the same type (MCS boxes, for example) within a tactical entity are aggregated. Future iterations of the tool may decompose the elements within the tactical entity and address management of internal communications.

7.3. Army Battle Command System (ABCS).

The ABCS systems are modeled and considered as components within the appropriate CP. The OCs cause the ABCS systems to generate different types of information flows. ABCS systems are in a separate layer so that generation of information flows is a distinct element that causes traffic (message / packet level) over the MSE communications network. In this way message patterns between individual ABCS boxes can be altered and the effect on the communications network components and on the CPs can be observed.

Because the purpose of this simulation was to measure the network traffic between, not within, headquarters, each ABCS system type (e.g., MCS, ASAS, AFATDS, etc.) within a CP is represented as a single entity. In addition, communications between ABCS boxes in the same CP are not modeled, and competition for access to the associated MSE Node is incorporated into the aggregation of ABCS systems within the tactical entities.

In order to measure the load on the various links and node centers, the simulation needed a method of generating loads (in the form of messages). For purposes of this model, messages are not broken into the various protocol packets; rather, they are treated as single messages. It is not important for this simulation to know that a message has been broken down into four TCP/IP packets of 1500 bytes each. It *is* important, however, to know that the message is 6000 bytes long. Length of packet headers and time to disassemble and reassemble messages is ignored. Messages are generated from distributions defined by the user to replicate actual message generation under particular operational conditions.

Each ABCS entity within a CP has a certain number of Flow Generators attached to it, based on its headquarters type, the particular operational conditions being simulated, and the messages that doctrinally between the CPs [1]. Messages have two dimensions, frequency and length. Frequency indicates how often the message is generated, and length indicates the number

of bytes in the message. Both dimensions of the messages can be represented as either table lookups or probability distributions. During research and development of this system, it became clear that some messages might be best represented by probability distributions and others might be best represented as a table lookup.

Since the Exponential Distribution is often used to represent inter-arrival times of customers and messages, this distribution is supported in the prototype system [8]. In addition, the Normal distribution is supported. The current implementation only supports these two distributions, but a wide variety of distributions can be allowed with minimal effort, including Weibull, Gamma, Uniform, Lognormal, various Pearson distributions, and Triangular.

Operational Condition	0	Planning Phase
Sending Device		
Echelon	6	Division
Type	0	TAC
ABCS System	4	AFATDS
Message Type	FA_geometry	
Receiving Device		
Echelon	5	Brigade
Type	1	Main
ABCS System	4	AFATDS
Frequency		
Distribution Type	1	Exponential
Parameter 1	4000	seconds
Parameter 2	0	unused for Exponential
Length		
Distribution Type	0	Normal
Parameter 1	20000	mean in seconds
Parameter 2	500	standard deviation in seconds

Figure 3: Extract from a Flow Generator Configuration File

When CPs are instantiated, so are their associated ABCS systems. Each ABCS system instantiates a Flow Generator, which builds the initial set of Message Creators (MCs), then monitors the current OC so that it can delete and add appropriate Message Creators. When a Flow Generator for an ABCS system is created, it reads a configuration file that indicates which MCs are needed based on the ABCS system's headquarters type, echelon, and the indicated

operational condition. An extract of the information contained in this configuration file is shown in Figure 3.

When an MC is instantiated it is given the message frequency and message length information by its owning Flow Generator, as specified in the table lookup or probability distribution. When the simulation is initialized, each MC determines the time of its first message and schedules a message arrival event in the simulation event queue. It also determines when its next message should be created and schedules a future message creation event. As the simulation progresses and a message creation event is removed from the event queue, the associated MC executes the event, creating a new message and scheduling a message arrival event at its associated ABCS system.

The system needs to be able to capture the specific data about the impact of information flow at any particular point in the system. The planner is allowed to attach statistics modules to any desired MSE Node or Link to capture saturation or other data. This data can be as detailed as which ABCS box is sending the messages to which other ABCS box over which particular link. Although the planner will “attach” the modules to icons representing elements of the communications network, the actual statistics collection occurs within the Simulation Executive, since it is aware of every event and every entity. The statistics mechanism also serves as the repository for information required for “playback” visualizations of the loads on the communication network.

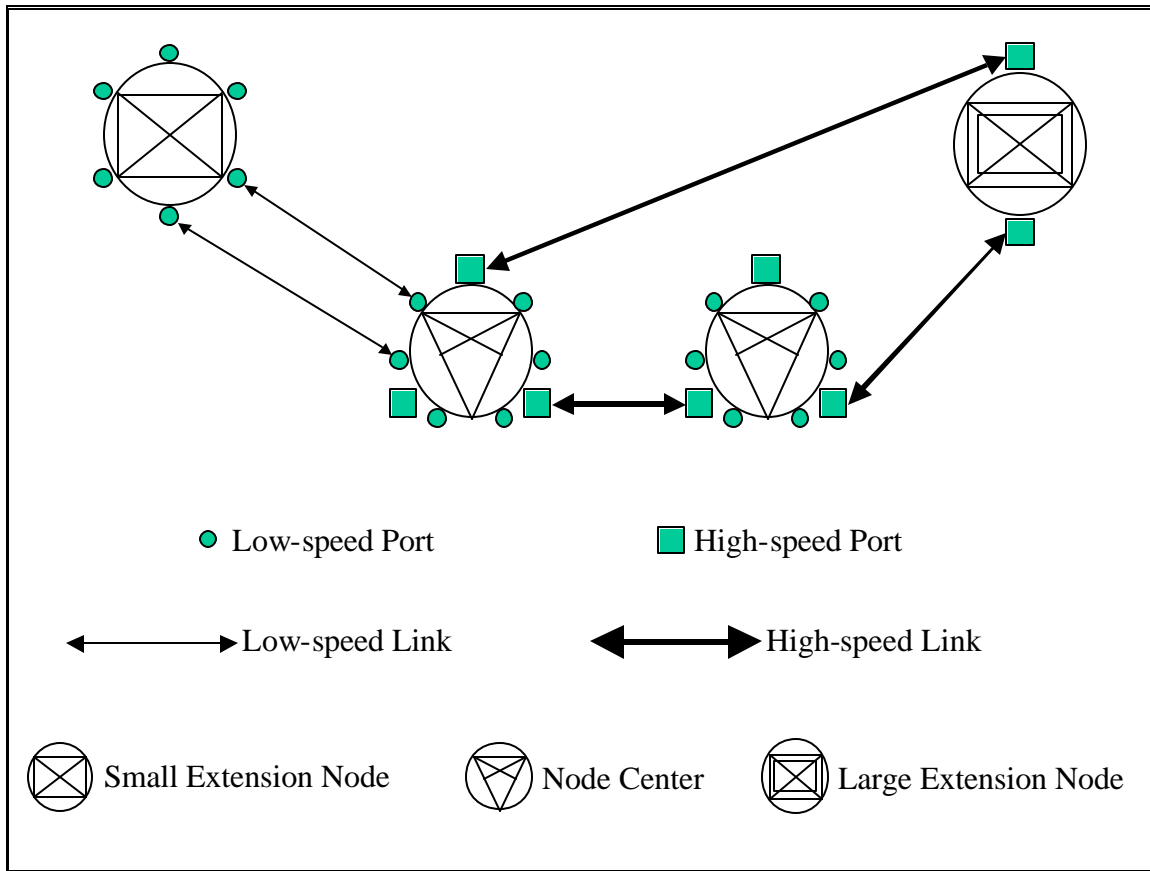


Figure 4: MSE Components

7.4. Communication Network.

The elements of the Mobile Subscriber Equipment (MSE) communication network architecture are modeled by the number, type, and bandwidth of their connections, as well as rules for how those connections are made. See Figure 4 for a depiction of the Link, Port, and MSE Node objects used in the model.

The Link object is a separate entity so that it can be tagged individually for statistics capture, analysis, and visualization. The link is able to execute a 'start message' event at the scheduled time. It responds to queries from the ports at either end of the link about the next available start time. It answers the query by determining how fast the sending port can send the message and how fast the receiving port can receive it, then determining the elapsed time for the size of the message. The elapsed time for the messages is what consumes time when the system

is run. Since multiple messages may pile up on either port, the Link has to keep a ‘request queue’ in order to remember what start time has been promised.

The Port object is the mechanism for connecting Links to MSE Node objects (defined below). The Port maintains specifics about maximum bandwidth, current bandwidth capability, and an output queue to hold outgoing messages until the Link is ready for them in turn. This also helps track statistics, such as the length of the output queue, the delta between arrival and departure time, etc. The SmallExtensionNode, the LargeExtensionNode, and the NodeCenter objects are subclasses of the MSE Node object. Every instantiation of an MSE Node has some number of high-speed and low-speed ports depending on its type.

The MSE Node performs several steps when it executes a message arrival event. First, it checks to see if the destination ABCS system is attached to this MSE Node (SEN and LEN only). If so, the message is sent to the ABCS system. If not, it is processed for further delivery. Second, if the routing table contains an entry for the appropriate port for the destination ABCS box then it queries the Link on that Port about the next available start time. The MSE Node then schedules a start time for that message with the Link. Since an MSE Node can have more than one Port and the Links may be occupied, processed messages are effectively added to the tail of the appropriate Port output queue. For the purposes of the simulation, the movement of arrived messages to queues within a node is instantaneous.

It is important to note that the MSE Node also schedules a timeout event in case no acknowledgement is ultimately received for the sent message. This ensures that the message can be re-sent and, when appropriate, a search can be initiated to determine the new best path to the destination ABCS system. There may not be a new path, due to destruction of all nodes providing a path or the destruction of the CP containing the destination ABCS system.

The search to find a new path to a destination ABCS system is a standard flood search of existing Links, but any algorithm could be tried (and analyzed). The searching MSE Node inserts a flood search message into the appropriate Ports' message queues (schedules them with the simulation). It also schedules a timeout event for the flood search. The MSE Node maintains a status of the replies, and when they are all back (or the timeout has occurred), the MSE Node determines the correct path and then inserts the message(s) into the queue of the appropriate Port (reschedules them).

7.5. Discrete-Event Simulation Mechanism.

At the lowest level there is a discrete-event simulation (DES) mechanism that enables the representation and analysis of the communications system under particular operating conditions. Hill, et al., provide more detailed information about the methodology behind the simulation [9]. The supporting simulation is a Java implementation of common DES techniques, defining a simulation executive, simulation participants, and a simulation event queue.

A Simulation Executive (SimExec), implemented as the DESimExecutive object, manages the event queue and maintains the simulation time. It accepts requests from the simulation participants to schedule an event through a call to its Schedule() member function. As each event is pulled from the queue, the Execute() method for the appropriate participant is called. Every object that participates in the simulation must implement the appropriate member functions for the Java interface DESimParticipant, such as the Register() member function that establishes communications with the simulation executive.

The fundamental simulation event is the DESimEvent object. Instantiations of DESimEvents are constructed with a SimTime parameter and a parameter for the participant that will execute the event. As each event is removed from the event queue, the Execute() method of the associated participant is called. New types of simulation events are created by extending the

DESimEvent object to include any additional information or processing steps that are required. This is particularly useful for the creation of data capture events.

8. CONCLUSION

Future work on this project will include more realistic representation of operational conditions, particularly as more refined information flow data is captured and analyzed. The system will work at a higher fidelity, incorporating battalion and lower tactical entities, and perhaps interfacing the lower-level function to OpNet, NetCracker, or other device-level network simulators. It will also incorporate improvements to MSE devices, and new generations of equipment that the Army is considering. As the system becomes more sophisticated, it will eventually include Artificial Intelligence tools to identify problems and propose solutions.

The visual development techniques used to meet the requirements identified in section 5 for this tool make it easy for the planner to design and build communication networks to support operations. In less than ten minutes the planners can create and configure a virtual communications network that would take the division Signal Battalion an entire day to setup. Once the network and conditions have been setup, the planner can execute the simulation and visualize the information flows being carried by that network. Armed with this understanding, the planner can interactively reconfigure the network, run "what-if" scenarios, and observe the effects. Analysis of the results can form the basis for establishing the actual network to be used during the operation.

The system can be used in a variety of ways, including training of new planners, design of experimental networks or incorporation of experimental components, and support for rapid decision-making. The Design and Evaluation Tool enables planners to rapidly determine viable configurations based on actual mission requirements and current systems availability. This

results in more effective utilization of the available bandwidth and assists in determining prioritization of information flow in the future.

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