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MODELING AND SIMULATION OF LARGE HYBRID NETWORKS *

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ABSTRACT

This paper describes a modeling and simulation framework for large hybrid networks that include satellites, terrestrial wireless and mobile ad hoc networks. The purpose of the simulation framework is to parallel the actual implementation of a testbed network currently being constructed at ARL. The modeling framework uses the performance measures generated by the simulation to analytically study larger scaled versions of the testbed networks. The combination of the two methodologies allows the feasibility of the testbed architecture's widespread implementation to be studied without the associated costs of performing such experiments with actual equipment. Additionally, technological tradeoffs and interoperability issues can be studied so that informed decisions can be made about the implementation of future military communication networks.

1. INTRODUCTION

Modern military networks tend to be both hybrid and hierarchical. Such networks are constructed by integrating satellite, wireless, internet and ad hoc technologies. Under such a scenario, it has become important to study hybrid and heterogeneous networks from both a high level architectural point of view and a low level technological point of view. These studies will enable decision makers to choose the "right" technologies for this architecture, by providing a clear understanding of the tradeoffs and interoperability issues between differing technologies.

Previously, simulations have been used as a tool to verify protocol designs and to study network behavior. However, most of the previous work has been focused on validating a particular scheme, on testing parameter tuning, on studying specific elements of networks, or on studying highly abstracted views of networks. Very few simulations have studied a fully hybrid, heterogeneous network architecture with a high level of granularity. With improved simulation tools and increases in computing power, modeling of such large, complex networks becomes more feasible. Modeling large networks with a higher level of granularity (e.g. complete protocol stacks in every node) allows interoperability issues of different technologies and their effects on network performance to be accurately studied.

However, the sole use of simulations in the study of network scalablity to thousands of nodes is limited due to the huge amount of required simulation time. Therefore, an analytical approach is necessary to study highly-detailed, large size networks. Unfortunately, obtaining valid and verifiable analytical models or approximation schemes for such hybrid, technologically disperse networks is generally difficult due to mathematical complexities. The proposed modeling and simulation framework uses simulations to study detailed network behavior and uses analytical models to study the scalability issues associated with increased network size. These two frameworks are coupled in that performance measures obtained from the simulation are to be used within the analytical models to study large scale networks on a conceptual or abstract level. Such a methodology enables the design concept of the network to be verified prior to the large capital expenditures required for significant scale physical implementation.

The remainder of this paper is organized as follows: Section 2 summarizes the network architecture under consideration; Section 3 describes the simulation framework; Section 4 provides a description of the modeling framework and Section 5 concludes the paper.

2. NETWORK ARCHITECTURE OVERVIEW

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A typical military hybrid network is shown in Figure 1.

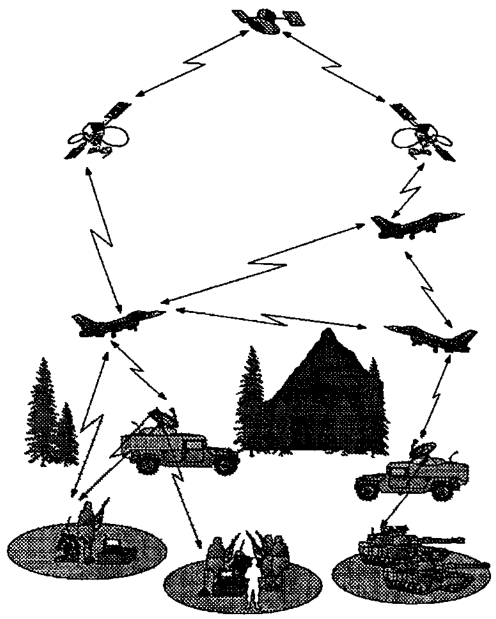

Figure 1: Hybrid, hierarchical military network

HUMVEEs form mobile "base stations" on the ground. HUMVEE-to-HUMVEE communication occurs either over terrestrial wireless media or over satellite links. A mobile ad hoc network can potentially attach to each HUMVEE and use the communication capabilities of the vehicle to gain access to valuable combat information from the "tactical internet." With respect to network topology, the HUMVEEs are considered to be relatively stable when compared with the ad hoc networks attached to them. From the ad hoc nodes' point of view, the HUMVEE serves as the the point of attachment to the tactical internet.

The mobile ad hoc network is composed of soldiers with portable receivers/transmitters enabling communication with both the HUMVEE and other ad hoc nodes. If the soldier is within the HUMVEE's range, then the soldier can directly communicate with the HUMVEE using existing wireless LAN technology. However, if the soldier is outside the range, then communication takes place over multi-hop links within the ad hoc network. In the most flexible network scenarios, one ad hoc network can attach to more than one HUMVEEs or multiple ad hoc networks can attach to a single HUMVEE.

3. SIMULATION METHODOLOGY AND FRAMEWORK

In this section we outline the simulation methodology and give detailed descriptions of individual components of the simulation model. The components were chosen to closely mirror the actual technologies used in the ARL testbed network. The model is currently being implemented in OPNET.

Methodology

The complex heterogeneous network will be divided into various components. Each of the components will be modeled in precise detail as separate sub-models in OPNET. At the sub-model level, various experiments and performance evaluation studies can be performed independently of other sub-models. Once the detailed sub-models have been completely developed and simulated, they will be integrated to form a model of the entire network.

HUMVEE Model

Our current configuration of a HUMVEE includes four workstations and a router. Each workstation has a complete TCP/IP protocol stack and is connected to the router via an Ethernet link. The current router model has an IP layer and multiple interfaces including Ethernet and ATM. For our purposes, the router needs to be modified to include the following:

- a satellite link interface, and
- a wireless interface.

The satellite link is needed so that the HUMVEE can receive satellite traffic throughout the simulation. The wireless interface is needed so that mobile ad hoc networks can connect with the HUMVEE. It is also needed to faciliate HUMVEE-to-HUMVEE communication during the simulation.

In the above configuration, the workstations communicate with nodes external to the HUMVEE through the router. Additionally, the traffic generated by the mobile ad hoc network is sent via the appropriate interface by the router. In order to correctly simulate sending traffic over the satellite link, an "SDH" module may need to be added below the IP layer within the router to create SDH frames.

Satellite Link Model

There are several options in implementing the satellite link model as the actual ARL testbed has multiple satellite technologies. The testbed network consists of the following satellite technologies:

- INMARSAT link (bi-directional) 64 kbps,
- DirecPC link (downlink only) 400 kbps, and

- Satellite cellular telephone 4.8 kbps.

With these technologies, the following satellite communication scenarios may be simulated:

- use INMARSAT link for all satellite communications,
- use the DirecPC link as the downlink and the INMARSAT as the back channel, and
- use the DirecPC link as the downlink and the Satellite cellular telephone as the back channel.

Mobile Ad Hoc Network Model

In the mobile ad hoc network model, an ad hoc routing protocol is needed so that packets may be correctly delivered over the multihop links within this network. The TORA algorithm [1] will be used as the ad hoc unicast routing protocol with CSMA as the MAC layer protocol. The use of multicasting in the ad hoc network model and the integration of unicast and multicast routing protocols is being investigated. In this model, OPNET's mobility functionality will be used to define a trajectory for each mobile node.

Channel Models

OPNET uses a "pipeline" for communication between nodes. This pipeline differs depending upon the type of communication link being modeled (e.g. broadcast radio versus point-to-point). The default radio pipeline stages will be modified so that the following effects will be taken into account:

- Terrain effect. This model involves processing terrain data and calculating line-of-sight. This effect is especially important for the ad hoc network part. Once terrain is incorporated with the ad hoc model, a mobile network with nodes moving over hills can be fully simulated with changes in transmission and reception quality.
- Error pattern. This model generates errors according to a specified pattern (Markovian, Self-similar, etc.) in addition to the BER parameter. This will be used in simulating both the satellite and wireless channels.
- Coding scheme. This model simulates the effect of different coding/decoding schemes, which can be used in conjunction with the error pattern model and BER.

Performance Enhancement Models

Protocol enhancement is mainly designed for the TCP layer, thus it is meant to improve performance between HUMVEEs either via satellite or wireless link. The TCP enhancements we have already implemented in OPNET include TCP SACK/FACK [2] [3], Fast Retransmit and Fast Recovery [4], large window option and time stamp option [5]. We also have RED [6] implemented at the IP layer. These will be incorporated into the architecture.

We will be focusing on two types of protocol boosters [7], namely the FEC booster and the ACK compression booster. FEC booster is designed to reduce error over wireless links and will be implemented at the channel level. ACK compression booster is designed to enhance the asymmetric satellite link and will be implemented at the IP layer.

Traffic Models

Valid traffic models are key to obtaining realistic simulation results. Poisson and Normal distributions are typically used within OPNET to model traffic sources. However, research experiments have shown that the bursty nature of aggregated traffic makes the Poisson distribution a very poor approximation of actual Internet traffic. A more accurate approach would be to use self-similar traffic models. We have built one type of self-similar traffic model into the existing OPNET client-server application module.

4. ANALYTICAL MODEL DEVELOPMENT

Our methodology for modeling and performance evaluation of large hybrid networks employs hierarchical algorithms to obtain fast performance estimates with reasonable approximations. We have developed fast algorithms [8] to estimate end-to-end blocking probabilities, in multirate multihop loss networks, using fixed point approximations. In our earlier work [9] we presented these algorithms and their extensions to cover min-max routing schemes, where one selects the route that maximizes the free bandwidth on the link which has the minimum free bandwidth on the route.

The fixed point is achieved by mappings between the following four sets of unknown variables:

ν_{js}: the reduced load/arrival rate of class-s calls on link j;

a_{js}: the probability that link j is in a state of admitting class-s cal ls;

$p_j(n)$: the steady state occupancy probability distribution of link j, i.e., the probability that exactly n units of circuits are being used on link j. n takes any integer value between 0 and C_j, the capacity of link j;

q_{rms}: the probability that a call request (r,s) is attempted on route (r,m).

First, we fix a_{js} and q_{rms} to get ν_{js}. Then we fix ν_{js} to get $p_j(n)$ and a_{js}. Finally we fix $p_j(n)$ to get q_{rms}. The mappings are illustrated in the figure bellow:

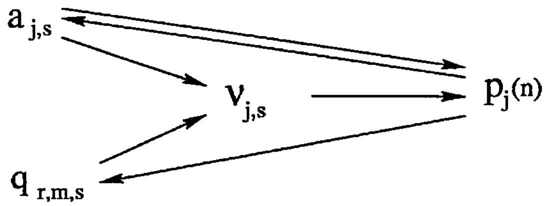

Figure 2: Relationship between variables

The details of the analytical expressions describing the mappings

$$a_{js}, q_{rms} \longrightarrow \nu_{js} \tag{1}$$

$$\nu_{js} \longrightarrow a_{js}, p_j(n) \tag{2}$$

$$p_j(n) \longrightarrow q_{rms} \tag{3}$$

were presented in [9]. The fixed point is obtained via repeated substitution from these maps.

The qualitative properties of the analytical expressions of these maps (equations (1-3)) are such that have allowed us to show that there exists a fixed point under the fixed point approximation we use. The proof essentially employs the Brower fixed point theorem.

We now sketch how we establish asymptotic correctness of the fixed-point approximation we have employed.

Under steady state, for traffic stream (r,s), the probability of attempting the call on the m^{th} route is q_{rms}. Since the fixed point exists, it's natural to take q_{rms} as fixed and constant in our evaluation of the algorithm.

Here we would like to point out how the routing of the traffic is approximated in the model. In reality, when a call request comes, no matter what kind of routing scheme we have, in order to be adaptive and dynamic, the call is routed according to the traffic load in the network at that point in time. This type of traffic dispersement is called "metering" [10].

However, in our approximation the routing is modeled as if for each traffic stream, it has fixed probabilities to be routed onto a set of routes, and those probabilities add up to 1. This method is called "randomization". Generally the metering method gives a better performance over randomization. Therefore, our approximation represents a conservative estimate, especially under heavy traffic, of the end-to-end call blocking probabilities.

Accepting this assumption, since randomly splitting a Poisson process according to a fixed probability distribution results in processes which are individually Poisson, we have $\nu_{rms} = \lambda_{rs} \cdot q_{rms}$, the equivalent offered load onto route (r,m) from traffic (r,s), which is still a Poisson process.

Letting $\mathbf{n} = \{n_{rms}\}$, where n_{rms} is the number of calls in progress on route (r,m) from traffic (r,s), we obtain an analytic expression for the stationary distribution $\pi(\mathbf{n})$. We next let $\mathbf{b}$ be the vector $\{b_{jrms}\}$, where b_{jrms} is the bandwidth requirements of class s on link j, and route (r,m). Let $\mathbf{C}$ be the vector $\{C_j\}$, where C_j is the bandwidth of link j.

Following Kelly's method in [11], we consider the problem of maximizing $\pi(\mathbf{n})$ to find the most probable state $\mathbf{n}$:

$$\text{Maximize} \sum_{(r,m)} \sum_{s} (n_{rms} log\nu_{rms} - log\nu_{rms}!) \tag{4}$$

$$\text{subject to } n_{rms} \geq 0,\ b_{jrms} n_{rms} \leq C_j. \tag{5}$$

Using Sterling's formula log$n! \approx n$log$n - n$, and replacing $\mathbf{n}$ by a real vector x, the primal problem becomes:

$$\text{Maximize} \sum_{(r,m)} \sum_{s} (x_{rms} \text{log} \nu_{rms} - x_{rms} \text{log} x_{rms} + x_{rms}) \quad (6$$

$$\text{subject to } x_{rms} \geq 0,\ b_{jrms} x_{rms} \leq C_j. \tag{7}$$

Since the objective function of a good approximation to this optimization can be shown to be differentiable and strictly concave, and the feasible region is a closed convex set, there exists a unique maximum. Using Lagrangian multipliers $\mathbf{y}$, the maximum can be expressed as:

$$x_{rms} = \nu_{rms} \cdot \exp(-\sum_j y_j b_{jrms}). \tag{8}$$

Note now that x_{rms} is a representation of the traffic flow on route (r,m) from traffic stream (r,s). Rewriting the result, we have:

$$x_{rms} = \nu_{rms} \cdot \prod_{j \in (r,m)} (1 - d_j)^{b_{jrms}}, \tag{9}$$

and d_j is any solution to the following:

$$\sum_{(r,m)} \sum_{s} b_{jrms} \nu_{rms} \cdot \prod_{i} (1 - d_i)^{b_{irms}} \begin{cases} = C_j & \text{if } d_j > 0 \\ \leq C_j & \text{if } d_j = 0 \end{cases} \cdot (1$$

and $d_j \in [0,1)$.

Using the expression of the optimal solution and various analytical arguments we show that the estimates of blocking probabilities obtained by our method are asymptotically correct in the limiting regime proposed in [11]:

$$\frac{\lambda_{rs}(N)}{N} \longrightarrow \lambda_{rs}, \quad \frac{C_j(N)}{N} \longrightarrow C_j \quad \text{as } N \longrightarrow \infty \qquad (11)$$

with λ_{rs}/C_j fixed.

Let

$$k_{jrms} = \frac{\nu_{rms}}{C_j} = \frac{\lambda_{rs} q_{rms}}{C_j} \qquad (12)$$

also be fixed based on previous discussion. Following from [11], the blocking probability $B_{rms}(N)$, which is the stationary probability that a call from source (r,s) is rejected by route (r,m) is given by:

$$1 - B_{rms}(N) = q_{rms} \prod_j (1-d_j)^{b_{jrms}} + o(1) \qquad (13)$$

where d_j is the solution to (10).

After some work, the asymptotic form (13) can be written as

$$1 - B_{rms}(N) = q_{rms} \prod_j (1-d_j)^{b_{jrms}} + o(1) \qquad (14)$$

$$= q_{rms} \prod_j a_{js} + o(1) \qquad (15)$$

Therefore we get the approximation

$$B_{rs}(N) = 1 - \sum_m q_{rms} \prod_j a_{js}, \qquad (16)$$

which is exactly the form we presented in the algorithm. Similarly, from (9), load on route (r,m) from source (r,s) becomes

$$x_{rms} = \nu_{rms} \cdot \prod_{j \in (r,m)} a_{js} = q_{rms} \lambda_{rs} \prod_{j \in (r,m)} a_{js}. \qquad (17)$$

Therefore, as seen by any individual link i,

$$x_{irms} = q_{rms} \lambda_{rs} \prod_{j \in (r,m), j \neq i} a_{js}, \qquad (18)$$

which is our first mapping in the algorithm.

Application of the algorithm to a medium size commercial network (borrowed from [12] with minor changes) shows that we obtain accurate estimates in times 1000 faster than OPNET discrete event simulations. The network is shown in Figure 3, and part of the performance results are shown in the tables below: (FPA stands for fixed-point algorithm and DES stands for discrete event simulation)

Hierarchical algorithms [8] employing such a scheme in each layer can provide speed ups of 10^6 or higher times, as compared with discrete event simulation.

5. CONCLUSION[1]

In this paper we have provided a modeling and simulation framework for large hybrid military networks consisting of satellites, wireless, terrestrial and ad hoc technologies. We first described the simulation architecture of a specific hybrid military network. Then, we discussed the modeling methodology and some developments in this area. The convergence and asymptotic correctness results of our fixed-point based algorithms were presented. We also demonstrated the validity of the obtained performance estimates on a commercial sized network. The results demonstrate the potential of these algorithms to provide good performance estimates within times several orders magnitude faster than discrete event simulations. The next immediate objective in this area is to develop and evaluate similar algorithms for large-scale military networks.

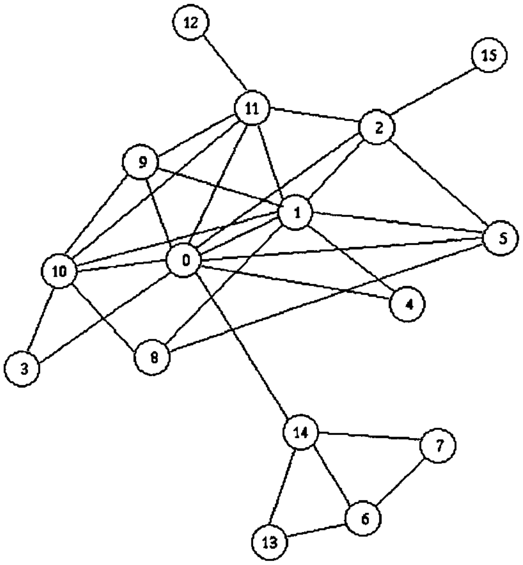

Figure 3: Topology of Example Network

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[1] The views and the conclusions expressed in this paper are those of the authors and should not be interpreted as representing the official policies, either expressed or implied of the Army Research Laboratory or the U.S. Government.

Node Pair	Class	FPA	DES
$(0,4)$	4	0.000178	(0.0, 0.0)
$(0,13)$	1	0.006341	(0.0021, 0.0034)
$(1,6)$	1	0.006473	(0.0030, 0.0034)
$(5,6)$	3	0.020463	(0.0189, 0.0201)
$(6,10)$	2	0.013222	(0.0109, 0.0138)
$(9,13)$	4	0.028468	(0.0185, 0.0245)
Number of Iterations		18	
CPU Time(seconds)		94.1	3.7×10^4

Table 1: Nominal Traffic.

Node Pair	Class	FPA	DES
$(0,4)$	4	0.018213	(0.0122, 0.0179)
$(0,13)$	1	0.074434	(0.0729, 0.0766)
$(1,6)$	1	0.077371	(0.0697, 0.0701)
$(5,6)$	3	0.229528	(0.2262, 0.2278)
$(6,10)$	2	0.147436	(0.1420, 0.1483)
$(9,13)$	4	0.307191	(0.2794, 0.2848)
Number of Iterations		28	
CPU Time(seconds)		145.43	4.3×10^4

Table 2: 1.4 Times The Nominal Traffic.

Node Pair	Class	FPA	DES
$(0,4)$	4	0.112658	(0.0025, 0.0026)
$(0,13)$	1	0.135564	(0.1492, 0.1500)
$(1,6)$	1	0.156322	(0.1445, 0.1466)
$(5,6)$	3	0.419781	(0.3922, 0.3940)
$(6,10)$	2	0.269145	(0.2572, 0.2583)
$(9,13)$	4	0.519083	(0.4791, 0.4793)
Number of Iterations		24	
CPU Time(seconds)		125.11	2.3×10^6

Table 3: 1.8 Times The Nominal Traffic.

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