

# TECHNICAL RESEARCH REPORT

## Tactical and Strategic Communication Network Simulation and Performance Analysis

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# Tactical and Strategic Communication Network Simulation and Performance Analysis\*

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## ABSTRACT

*We describe a framework for the efficient modeling and performance evaluation of large networks consisting of a mixture of strategic and tactical components. The method emphasizes hierarchical, layered techniques that are fed parametric models at the lower level. In addition to the algorithmic structure, and some initial algorithms we describe an object oriented software architecture that is under development to support these algorithmic methods in a distributed environment.*

## 1 INTRODUCTION

Tactical and strategic modeling of communication networks is a daunting challenge given the complex nature and large scope of today's and tomorrow's communication systems. The approach being pursued within ATIRP Task 2.1 is top-down in design, but bottom-up in function-relying on low-level, discrete event simulation of tactical communication networks to generate statistical parameters for higher-level, hierarchical, analytical models to permit fast approximate performance evaluation of strategic communication networks.

The distinction between tactical and strategic network simulation is primarily one of the number of nodes to be modeled in the simulation. Tactical networks are classified as those small enough to be simulated in reasonable time with a discrete event simulation package. All other networks too large for this are designated as strategic, and must be evaluated using

approximation methods.

The discrete event simulation package of choice for the consortium is OPNET. OPNET will be used to accurately model small tactical communication networks. What signifies a tactical network will depend on the scenario. One may consist of a collection of mobile SINGARS-equipped units, or perhaps a cluster of mobile users surrounding rapidly deployable cellular base stations. The purpose of simulating networks at the tactical level is two-fold: (i) to accurately verify the functionality of network protocols and quantify their operation in terms of desired performance metrics and (ii) to provide appropriate statistical parameters to feed into the lowest level of a hierarchical analytic model. In the context of a strategic simulation, each tactical network becomes a node at the lowest level of the mathematical hierarchy. These nodes are referred to as "level 1" nodes.

The strategic network performance evaluation tool is currently under development at the University of Maryland. The tool consists of an algorithmic structure and a software architecture. The algorithm is hierarchical in form, deriving its structure from that of the network which follows the network's routing hierarchy. The mathematical basis for the model is a hierarchical modeling of traffic flows based on Markov modulated Poisson and Bernoulli processes. These models have been known in practice to model accurately a variety of multimedia traffic over a variety of channels and communication media. At each level, a node represents a set of nodes at a lower level. The boundary of a node is characterized by a set of statistical models. The statistics, and their parametric representations for the models of the level 1 nodes are obtained from the OPNET simulations which are run

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offline .

At each level, topology is represented by logical nodes and logical links. At the lowest (which is the highest resolution) level, each node and link represents a real switching system and a physical link. At higher layers, each node may represent either a real system, or a subnetwork, or a group of switching systems. At higher layers links may correspond to either a real physical link or a virtual link. Nodes are collected into peer groups (clusters). Peer groups are organized into a hierarchy where one or more peer groups are associated with a parent peer group (cluster) and so on. The states of the Hidden Markov Models that we have developed correspond to the link states as they are used in hierarchical state dependent routing, to node (switch) states as they are used in dynamic adaptive routing, and to other parameters of the multimedia flow including Quality of Service (QoS) parameters.

The model defines procedures that convey modeling, simulation and performance data up and down the hierarchy of models. There may be different hierarchies and the most typical one is based on the resolution and accuracy (fine or coarse) of performance and traffic data. The methodology allows user-definable hierarchy levels. It defines how each level of the hierarchy works and how multiple nodes at one level can be summarized in the higher layer. It also defines how state information among nodes within the same level and between different levels are exchanged.

The models in this approach form a hierarchical, progressive chain (from coarse to fine). We will then develop techniques from multi-level optimization, multi-grid numerical methods for progressive computation of performance metrics or trade-off curves. Progressive here means that the computations of the previous layer are used and are improved upon

$$\phi(J_n, K_n) = \phi(J_{n+1}, K_{n+1}) + \Delta_n^{n+1}(d_n, \lambda_{n+1})$$

$n = 1, \dots, N, 1 = \text{fine}, N = \text{coarse}$ . Here  $J$  and  $K$  are two performance metrics. The subindex indicates the layer or accuracy of the computation. The second term in the right hand side indicates the correction term that utilizes the data at the new layer and some aggregate variables propagated from the previous layer. In this paper we describe the algorithms developed to date for such networks. We consider the following performance metrics only: end-to-end delay,

throughout blocking probabilities, cell or packet loss rate.

We are developing fast algorithms to compute trade-off curves, and to perform interactive trade-off analysis, among these performance metrics by linking the hierarchical modeling and simulation system to multi-objective optimization packages. In this way we can compute performance metric sensitivities with respect to network parameters using the simulation model; a particular instance of this idea is what is called simulation differentiation.

## 2 ALGORITHMS BASED ON FIXED-POINT METHODS

The first analytical method that we have investigated, is that of *fixed point* methods for estimating blocking in multihop, multirate integrated service networks with state dependent admission control and routing. This analytical technique is at the connection level, and applies to synchronous transfer mode (circuit-switched) services, and to asynchronous transfer mode (ATM) services. These methods have been shown to be efficient and accurate in previous work [3-5].

Recently, fixed point methods or reduced load approximations for network analysis have attracted substantial interest [2-5]. They provide an appealing alternative and complement to discrete event simulations, especially in network design and in performance evaluation of large networks. They also can be used for worse-case analysis since they are quite accurate under overload conditions.

In our work, we have concentrated on integrated services networks, *vs* voice where past work focused, and on hierarchical solutions and formulations of the fixed point equations. One of the difficulties of moving these effective methods into multirate methods has been the fact that in multirate networks the computational complexity of these algorithms is infeasible. Here we use some methods first introduced in [3] to circumvent this computational complexity obstacle.

The network model that we assumed is as follows.

We consider general networks of  $N$  nodes, indexed  $1, 2, \dots, N$ . A link  $(i, j)$  between nodes  $i$  and  $j$  has capacity  $C_{i,j}$ , counted in bandwidth units termed *trunks*. Links are undirected;  $(i, j)$  and  $(j, i)$  denote the same link. Calls offered to the network fall into  $S$  classes, differentiated by bandwidth and possibly by priority via trunk reservation, as described below. A call of class  $s$  has bandwidth  $b_s$ , meaning that if the

call is admitted to the network then it is allocated  $b_s$  trunks on each link of a path from its source to its destination. A link's state is characterized by the number of calls in progress  $n_s$ , of each call class.

A call is admissible on a given path if it is admissible on every link of that path. Consider a call of class  $s$  offered to node pair  $(i, j)$ . Link admissibility may be decided with or without control. In the absence of control, the call is admissible on a link if the call's bandwidth  $b_s$  is less than or equal to the idle bandwidth  $C - \sum_t b_t n_t$ . Admission controls considered here are of trunk reservation type. Specifically, the call is admissible on link  $(i, j)$  if the call's bandwidth  $b_s$  is less than or equal to the idle bandwidth  $C - \sum_t b_t n_t$  plus  $r$ , where  $r$  is a static parameter, which may depend on  $s, i, j$ , and other factors, such as the length of the route associated with the call. Thus, choosing parameter  $r$  to be small allows the call type greater access to scarce capacity. If admitted on a path in the network the call simultaneously seizes for its exclusive use  $b_s$  trunks on every link of the path. Similarly, the call simultaneously releases  $b_s$  trunks on every link of the path when it completes.

We consider routing policies where each node pair  $(i, j)$  is assigned an ordered list  $P_{i,j}$  of paths between nodes  $i$  and  $j$ :  $P_{i,j}^{(1)}, P_{i,j}^{(2)}, \dots$ . The call is admitted on the first path in the list where it is admissible. If the call is not admissible on any path then it is blocked; that is, rejected and lost.

Traffic is modeled as follows. Calls of class  $s$  are assumed to arrive to node pair  $(i, j)$  according to a Poisson process with rate  $\lambda_{i,j}(s)$ . If admitted to the network, the call holds for an exponential period of time with mean  $\mu_{i,j}(s)$ . Thus, these calls constitute a load of  $\rho_{i,j}(s) = \lambda_{i,j}(s)/\mu_{i,j}(s)$ .

The key performance metrics are the node pair by node pair, class by class call blocking probabilities,

$$Pr\{\text{blocking a call of class } s \text{ arriving to node pair } (i, j)\},$$

or (equivalently) the availability probabilities, defined as corresponding probabilities of admitting the call.

The fixed point method that we use is based on the following two approximations (assumptions):

(A1) (Link Independence): The probability that a cell is admissible on a given path in the network is the product of the probabilities that the call is admissible on each link of that path.

(A2) (Poisson Rates): Arrivals of calls of a given class to a given link are described by a Poisson process. The rate of the process may depend on the state of the link.

It is important to note that although arrival rates to node pairs are given and are assumed to be Poisson, admission control and routing depends on link-states and thus perturbs the Poisson character of the link arrivals. These two assumptions, lead to a system of equations, whose unknowns are, for each link  $(i, j)$  and call class  $s$ :

- (i) arrival rates  $\nu_{i,j}(s)$  of calls of class  $s$  from any node pair that includes link  $(i, j)$  on some route, given that link  $(i, j)$  is in a state that admit calls of class  $s$ , and
- (ii) probabilities  $a_{i,j}(s)$  that link  $(i, j)$  is in a state that admits calls of class  $s$ .

The fixed point formulation, essentially consists of two mappings. One such mapping is for every node pair  $(i, j)$  from probabilities  $a_{k,l}(s)$  (with  $k$  and  $l$  dependent on the routing structure) to rates  $\nu_{i,j}(s)$ . The other mapping is for each link  $(i, j)$  from rates  $\nu_{i,j}(s)$  to probabilities  $a_{i,j}(s)$ .

To estimate equilibrium network performance, we solve for the fixed point of the composition of these two mappings, simultaneously fixing the  $\nu_{i,j}(s)$  and  $a_{i,j}(s)$ . The algorithms as in [3] are inspired by the close mathematical similarity of these equations to certain problems in network reliability.

The mapping from admissibility probabilities to arrival rate is now described.

Let  $\nu_{i,j}^{(m)}(k, l, s) =$  rate that  $(k, l)$  admits class  $s$  calls on its  $m^{\text{th}}$  route, if that route contains link  $(i, j)$ ; otherwise  $\nu_{i,j}^{(m)}(k, l, s) = 0$ . Thus, link  $(i, j)$  receives calls of class  $s$  at aggregate rate

$$\nu_{i,j}(s) = \sum_m \sum_{k,l} \nu_{i,j}^{(m)}(k, l, s).$$

We now proceed to compute  $\nu_{i,j}^{(m)}(k, l, s)$ , assuming link  $(i, j)$  belongs to the  $m^{\text{th}}$  route, for node pair  $(k, l)$ .

For  $m = 1$

$$\nu_{i,j}^{(1)}(k, l, s) = \lambda_{k,l}(s) \prod_{(u,v) \in P_{k,l}^{(1)}, (u,v) \neq (i,j)} a_{u,v}(s)$$

where  $\lambda_{k,l}(s)$  denotes the original rate of arrivals for calls of class  $s$  for node pair  $(k, l)$  and  $a_{u,v}(s)$  is the admissibility probability for class  $s$  on link  $(u, v)$ .

For  $m > 1$ ,

$$\nu_{i,j}^{(m)}(k, l, s) = \lambda_{k,l}(s) \cdot R_{i,j}^{(m)}(k, l, s) \cdot \prod_{(u,v) \in P_{k,l}^{(m)}, (u,v) \neq (i,j)} a_{u,v}(s)$$

$$R_{i,j}^{(m)}(k, l, s) = Pr\{\text{none of the paths } P_{i,j}^{(1)} \dots P_{i,j}^{(m-1)} \text{ are admissible} \mid \text{path } P_{i,j}^{(m)} \text{ is admissible}\}.$$

Combining the formulas above completes the mapping from link admissibility probabilities to link arrival rates.

We next describe the mapping from arrival rates to admissibility probabilities when there is admission control in the network. It is well known that admission control destroys the product-form of the link occupancy probabilities  $P(n)$ , which in turn destroys the efficient and exact computation of those probabilities by a formula such as:

$$a(s) = 1 - \sum_{n=C-b_s+1}^C P(n)$$

where  $C$  is the link capacity,  $S$  the number of classes and  $b_s$  the bandwidth of each class  $s$  call. Instead, we now have to compute the equilibrium distribution of a Markov chain with a large state space; a prohibitive computational task. Instead we employ an approximation first introduced in [6,7]. This method transforms the problem into one-dimensional one essentially by:

- (a) assuming that while  $n_s$ , the number of calls in progress of a class  $s$  varies, the proportion of such calls in progress remains fixed (or varies slowly), and
- (b) obtaining that proportion by equating the admission rate of calls of class  $s$  to the corresponding departure rate.

The following method appears to be very effective. Letting  $\alpha(s)$  denote the average number of calls of type  $s$  in progress,

$$\alpha(s) = a(s)\lambda(s)/\mu(s).$$

since these calls enter into service at rate  $a(s)\lambda(s)$  and depart at rate  $\alpha(s)\mu(s)$ . Treat the  $\alpha(s)$  as given, and consider the one-dimensional Markov chain, which, for any state  $n$  and call classes  $s$ , jumps to:

- (c) state  $n+b_s$  with rate  $\lambda(s)I(C-n \geq r+b_s)$ , where  $r$  is the trunk reservation parameter, and to
- (d) state  $n-b_s$  with rate  $\mu(s)n\frac{\alpha(s)}{\sum_t \alpha(t)}I(n \geq b_s)$ . In the true system, this jump down depends on the number of calls in progress  $n_t$  for each class  $t$ , rather than the aggregate state  $n = \sum_t n_t$ , so this is an approximation, that follows from estimating  $n_s$  by  $n\alpha(s)/\sum_t \alpha(t)$ .

Then the probability of admitting a call of class  $s$  is approximately  $a(s) = 1 - \sum_{n=C-b_s+1}^C P(n)$ . Taking  $P(n)$  to be the equilibrium distribution for this one-dimensional chain, we arrive at a small system of fixed point equations. In [6,7] it is shown that this approximation becomes asymptotically exact in overload conditions, for large  $C$  and  $b_s \ll C$ . More refined approximations are also discussed in [6,7].

In our work to date we have developed hierarchical versions of these algorithms that are based on hierarchical routing in the network being analyzed. We are currently working on versions of these hierarchical algorithms that are progressive.

### 3 SOFTWARE ARCHITECTURE

The software implementation of the performance evaluation tool is written in Java. Consortium users will access the tool via any World Wide Web browser that supports Java from any hardware platform. The software architecture is fundamentally client/server-based. Users access the simulation kernel-hosted on a server at the University—via a browser-based, graphical user interface (GUI) which forms the client. Thus, while simulations are constructed within the client, they are executed within a high-speed, multi-processor server.

The software architecture is CORBA-compliant, with all Java objects being specified first in CORBA's Interface Definition Language (IDL). The Object Request Broker of choice is Iona's OrbixWeb. Simulation objects may be made persistent via an object adapter to ObjectStore.

Nodes and channels form the basis of the network model's object structure. Nodes form an object hierarchy of their own, and have a different representation on both the client and server. Server node objects contain all data that must be persistent from run to run, and client node objects are decorated versions of the server objects containing additional GUI functionality. Channel objects also have differing representations on both client and server. Client channel

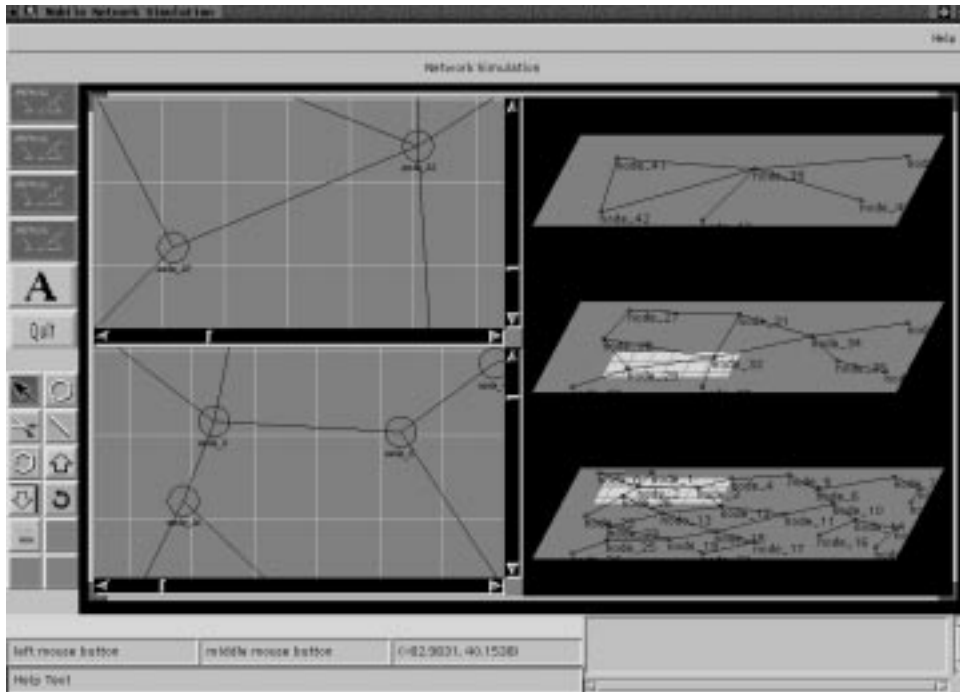


Figure 1: The GUI to the hierarchical performance evaluation tool.

objects primarily capture the spatial, topological and qualitative characteristics of the channel whereas, on the server, channel objects are translated into mathematical quantities imbedded in the model.

Figure 1, depicts the current GUI to the hierarchical performance evaluation tool.

The near-term goals of our work are to develop a Java-based GUI prototype, and to have a preliminary alpha version incorporating a single “level 1” node type for mathematical analysis by August 1997. Thus, the initial version will be capable of approximate performance analysis over a large homogeneous network. Introducing heterogeneity into the system will be the subject of future work.

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