

it of a high-speed
the development
based broadband
works. He is cur-
adband Network
om the 40th and
ations Advance-
1995 and 1996,
ics, Information,

A Model-Based Performance Management Tool for ATM and Frame Relay Networks¹

D. Tsaih,² G. Lapiotis,² S. Panwar,² and L. Tassiulas³

In this paper we describe a network modeling approach intended to assist in the performance management, design, and optimization of broadband traffic networks. Switch and source models, as well as routing optimization and decision support algorithms have been integrated in a prototype software tool, called DATANMOT (Data Network Modeling and Optimization Tool). The switch models developed are based on standard Frame Relay and ATM switch implementations. Specifically, an analytical model of the Fujitsu FETEX 150 ATM switch is described here in detail. Fluid-flow approximation methods were used for performance evaluation, with computational complexity low enough for near-real time applications. As a result, given the network configuration and input traffic, an evaluation of the quality of service can be derived and used in optimal routing, admission control and network planning. These techniques have been incorporated in our modeling tool to demonstrate the model-based approach to network management. In addition, all configuration, modeling, and management functions of the software tool are supported by a graphical user interface, and a database system.

KEY WORDS: Network design; performance management; broadband networks; ATM.

1. INTRODUCTION

With the introduction of high-speed packet-switched networks, such as Frame Relay and ATM networks, congestion control mechanisms have been pushed out to the endpoints of connections. To guarantee diverse Quality of Service (QoS)

¹This research was supported by NYNEX Science and Technology, Inc., the New York State Center for Advanced Technology in Telecommunications, Polytechnic University, and the NSF under Grant NCR-9115864.

²Polytechnic University, Center for Advanced Technology in Telecommunications (CATT), 6 Metrotech Center, Brooklyn, New York 11201. E-mail: {dtsaih,glapiot,panwar}@kanchi.poly.edu.

³Department of Electrical Engineering, University of Maryland, College Park, Maryland 20742.

requirements various traffic control mechanisms have been suggested for Frame Relay [1, 2] and ATM networks [3–6]. In general, these mechanisms can be classified as those that achieve either congestion avoidance (open-loop controls) or congestion recovery (closed-loop controls). In this paper we describe a tool that aims to assist in network congestion avoidance and performance management, by using analytical models of the traffic and components of high-speed networks.

Network modeling has been traditionally used for network dimensioning at the early stages of network design and planning. It is a critical part of performance management that provides for preventive control at the initiation of a network's design, as well as when either the system load is expected to increase or a design change is being planned. As technology advances and business networks constantly upgrade and expand, the need for future system performance evaluation for optimal design has dramatically increased. This proactive performance evaluation can then be combined with the actual values obtained by performance monitoring to perform any complementary functions (e.g., fine-tune input traffic parameters of users or services).

The Data Network Modeling and Optimization Tool (DATANMOT) is a prototype network performance management and design tool, which was developed in a joint effort by Polytechnic University and NYNEX Science and Technology, Inc. It can assist network operators to design and optimize the performance of permanent virtual circuit (PVC) networks. For a given ATM network configuration and routing, DATANMOT can evaluate the end-to-end QoS performance characteristics, e.g., average delay, 95th percentile delay, loss probability and link utilization. By changing the traffic, the topology, or the connectivity, the network manager can perform sensitivity analysis for any of those parameters, and quickly compare alternate network configurations. Furthermore, the model-based routing optimization technique from Flikop [7] has been implemented for Frame Relay networks. DATANMOT consists of the following modules:

- A powerful interactive graphical interface, through which the user can enter complete network information, and view the performance results for end-to-end connections or individual network elements.
- The system database, in which complete information about network configurations, connectivity, traffic, and quality of service status is maintained.
- Performance evaluation software that includes analytical models for the network traffic, and the Frame Relay/ATM switches used in the network. There are also algorithms for routing optimization and for an expert system decision support submodule, which can assist in network planning and fault analysis. These algorithms use the performance results of the modeling [8–10].

To create a network model one can generally use analytic approximation techniques, [8–10] or discrete event simulation models [11–13]. Simulations provide more accurate results and can be used either for long-term planning or for validation of analytic models. However, they take many hours to run even for small network models. By using analytic models, network design/planning can be accelerated, especially for large networks; it is easier to compare alternative topologies and configurations. Moreover, network performance results can be obtained for performance management applications, which need fast computation at a reasonable accuracy; such examples in DATANMOT are permanent virtual circuit setup and routing optimization. The analytic model-based approach allows for resource management on a preventive basis. This is important in a high-speed network context since the time-bandwidth product of high speed networks does not always allow for effective reactive control [14].

The ATM part of our generic network model was developed on the basis of stochastic fluid-flow analysis. This framework has been proven appropriate in the high-speed and especially in the ATM environment [14–16]. Bursty traffic is modeled by Markov Modulated Fluid Sources; each source generates traffic at a rate controlled by the states of a continuous time Markov chain. In order to model a multistage ATM switch, it is decomposed into its functional components, e.g., multiplexers, and the components are represented by appropriate server models. Performance results are obtained for individual switch components, for switches and for end-to-end connections. A few network modeling tools for ATM networks have been presented by Hwang and Li [9], who use an analytical approach in the frequency domain, and by Elwalid and Widjaja [17], who also introduced fluid-flow analysis for networks with buffered multi-stage topologies (Banyan, Benes, Clos, etc.), and simple output queueing switches. Recently, Mitra, Morrison and Ramacrishnan presented the TALISMAN [18] design and optimization tool based on effective bandwidths for traffic requirements and incorporates methods for multirate circuit-switched networks. The contribution of our work is that (i) DATANMOT supports arbitrary configurations for Frame Relay [19] and ATM networks, with accurate modeling of existing switch architectures, and (ii) extends performance analysis to network management applications.

The following section contains a presentation of the DATANMOT architecture. Section 3 describes the bursty traffic characterization and modeling used in the Fujitsu FETEX 150 ATM switch analysis. In Section 4, we summarize the general fluid-flow analysis and then present the techniques developed to appropriately model the stages of the ATM switch. Analytical results are derived for loss probability, average delay and 95th percentile delay. Section 5 outlines the model-based applications supported by the DATANMOT, i.e., network design, routing and decision support. These management applications take advantage of the fast modeling computations. Finally, Section 6 presents comparative numeri-

cal results of the approximate ATM switch model and simulations for several traffic scenarios.

2. DESCRIPTION OF THE DATA NETWORK MODELING AND OPTIMIZATION TOOL

In general a packet switched network can be represented as a set of nodes interconnected by a set of links. This gives a topological characterization of the network. Customers can send traffic over the network by connecting to one of the nodes via an input interface, and by sending messages to an output interface at the same or some other node. This is illustrated in Fig. 1. The nodes are the network switches, the links are the trunks connecting them, and switch ports are used either as trunk-to-switch connection interfaces or as Subscriber Network Interfaces (SNIs).

The DATANMOT network view can be described by the entities that are involved in the network modeling, and can be categorized as either network topology entities or network input entities. The first class consists of all the types of switches, trunks and internetwork interfaces that are used to model networks. Network input entities are the customers, their locations (SNIs) and connections, and the corresponding input traffic tables.

The software design architecture of DATANMOT permits modular expansion of the types of different networks that can be interconnected. At this

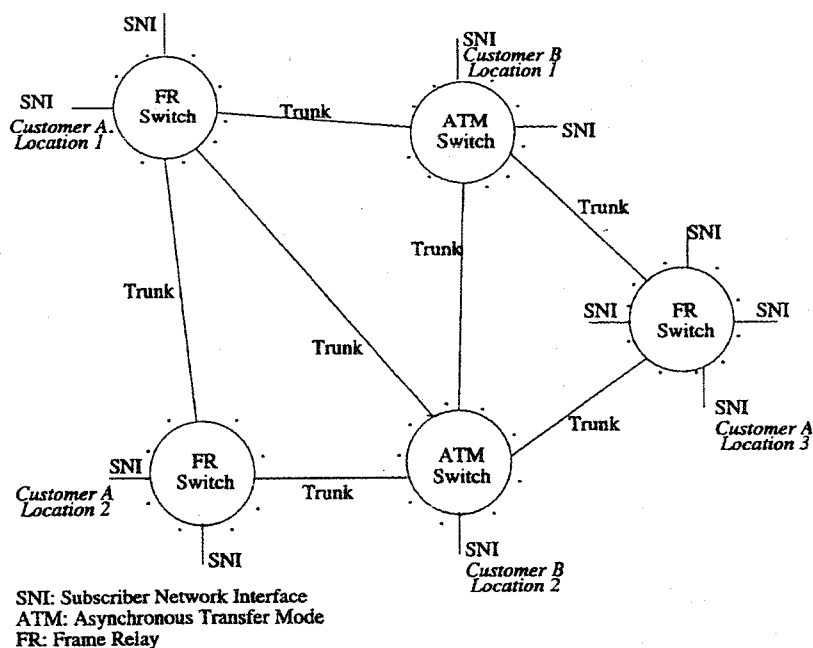


Fig. 1. Generic packet switched network model.

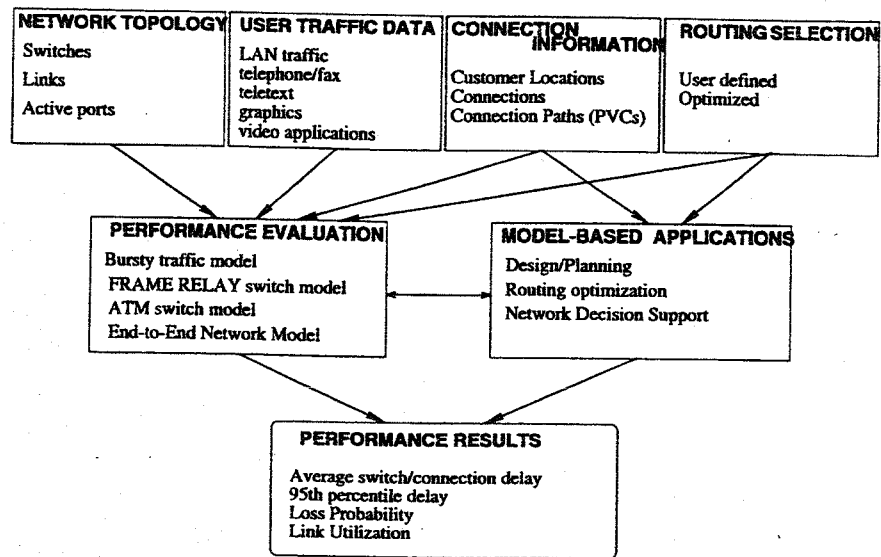


Fig. 2. DATANMOTs functional block diagram.

moment, DATANMOT can model Frame Relay and ATM networks, with specific telecommunication equipment from Northern Telecom for the Frame Relay subnetwork and the Fujitsu FETEX-150 for the ATM subnetwork. Modeling specific switch types is a complex problem, but given detailed information about the operation of the switches it was possible to create and analyze approximately the corresponding queueing models. The tradeoff we had to consider in developing these models was the processing time to obtain performance results versus the accuracy of the results.

2.1. The DATANMOT Database Structural Entities

The network parameters, which are the topology, connections, and traffic input at customer access points, are entered by the user through the graphical user interface in the system database. Then, by selecting the network analysis menu options, the modeling routines of DATANMOT are invoked. The analytic models retrieve the DATANMOT entity attributes from the database tables. There are also menu options for selecting the routing optimization and decision support functions of the tool. In Fig. 2, DATANMOTs functional block diagram is given. In the following, we present the database entities in the order that a user would insert them in the DATANMOT graphical user interface.

2.1.1. Topology Entities

Networks: This is obviously the largest superset of network topology entities and is simply any network configuration DATANMOT can support. This can be an ATM network, a Frame Relay network, or interconnected networks

of both types. The topological creation of a network is an interactive process in which the user chooses network elements from menus and places their icons in a drawing window of the screen. Whenever additional information is needed for new entities (as described later), data entry from the keyboard is requested from the user. The networks created by the user are stored in the system database tables and may be retrieved whenever the corresponding icons are clicked with a mouse. Two example networks, as seen on the DATANMOT screen, are shown in Figs. 7 and 8.

Telecommunication Switches: As mentioned before, two types of switches are currently supported by DATANMOT. These are the Northern Telecom Frame Relay Switch and the Fujitsu FETEX-150 ATM switch. The open architecture of DATANMOT allows incorporation of new switch models and the existing modeling techniques can be extended to model other switch types. In general, a telecommunications switch consists of input-output ports, that receive and transmit packets of information, and of the internal packet handling mechanisms. To store a switch entity in the DATANMOT database the attributes involved are the specific network the switch belongs to, a switch ID number, an indication of whether the switch is active or not, and several constants that are characteristic for each switch type (e.g., fixed internal delays). The switch "active" indication is user-defined (default is active) and serves in switch fault analysis, when scenarios of damaged switches must be studied for network restoration, planning and provisioning.

Switch Ports: The number of ports a switch supports is determined by its type, but because a port may or may not be active, it is considered as a stand-alone entity. Attributes of ports are stored in special tables. These attributes are the port ID number, port usage (trunk or customer access), delay performance results, and other functional constants (e.g., port transmission delay).

Links: This entity includes trunks and internetwork interfaces. The generic trunk notion in DATANMOT is a representation of telecommunication cables, namely T1 lines for Frame Relay networks and OC3 (initially) lines, for ATM networks. The link attributes in the system database include topological data (nodes and the ports each link connects), the link type, the actual cost and a link "active" indication. The link type determines whether it is a T1 or an OC3 trunk. In case a link connects different network types, it includes protocol conversion equipment, which is incorporated as an interworking unit model. The link "active" indication serves again as a link fault analysis parameter, and is used in connection rerouting studies in case of damaged trunks or interfacing equipment.

2.1.2. Network Input Entities

Customers, Customer Access: The DATANMOT is a virtual private network oriented tool and supports communication services between a number of

customer sites. The first step to define connections is to determine the customer access points on the network, which are essentially interfaces on switch ports, and the requested connections between different sites, as described next.

Connections, Connection Paths: After the insertion of customers and their access ports, connections can be defined between two sites. A connection, as defined in the DATANMOT, is an association between a pair of customer locations with manually, i.e., through the graphical interface, or automatically defined routes and traffic. A connection path is a route that connects two sites in the network topology. A multi-path connection is one that uses more than one connection path. Each of the connection paths in the database corresponds to a Permanent Virtual Circuit (PVC) of the same connection, defined by the user. A connection's traffic may therefore be split among the PVCs. This property of connections can be employed by routing optimization algorithms, which control the traffic assignment from a single connection to multiple PVCs. DATANMOT supports a single-path and a multi-path mode for routing connection traffic. In the first mode it is assumed that the routing algorithm does not split a single connection's traffic to several PVCs, and only one path is finally chosen to carry the entire connection traffic. This method applies to networks that do not support multi-path connections. In the second mode, it is assumed that the routing algorithm optimally allocates each connection's traffic to several PVCs. The two modes allow for flexibility in the routing optimization algorithms that can be incorporated in DATANMOT.

Connection Traffic Tables: A major part of DATANMOT modeling concerns traffic sources. Source modeling techniques are transparent to end-users, who only have to define the telecommunications services carried over the connection, by choosing from among a list of standard services. The list includes LAN interconnection, facsimile, teletext, high resolution graphics—electronic imaging, and video applications, and is amenable to extension. Additionally, usage characteristics of each service are entered, such as the number of devices (telephones, workstations, etc.), as well as the expected frequency of their use. In a second step, DATANMOT routines convert the user traffic description to source model parameters (traffic descriptors). There are also menu selections that allow the user to directly enter the values of the traffic parameters.

3. CHARACTERIZATION AND MODELING OF TRAFFIC SOURCES

As contemporary packet switched networks tend to accommodate an increasing number of different services, a major task involved in network control is characterizing the input packet flow and its statistical transformations through network nodes. A first step is determining those traffic descriptors, or traffic parameters, that can best quantify the effects of merging and splitting of traffic units through network components, mainly multiplexers, demultiplexers,

and switches. The validity of traffic descriptors will affect the accuracy of the queueing model. It is therefore important to obtain source models, that efficiently characterize all of the diverse service traffic types, and yet can be represented by a unique set of traffic parameters amenable to modeling analysis. The most important properties of network traffic are described by the statistics of the input arrival rate, including burstiness, and the size of packets for variable packet-size networks (e.g., Frame Relay).

In recent years, there has been considerable work in modeling traffic sources [11, 20–22]. It has been shown that many traffic types cannot be accurately modeled over a wide range of time scales by traditional queueing models. These source models are valuable as inputs to simulation models. However, we believe that the traditional Markovian models for bursty sources, which we have used in DATANMOT, continue to be valid for engineering networks, for the following reasons. The first reason is that traditional source models are accurate representations of traffic over small time scales [22]. Secondly, results by Sen et al. [23], and more recently by Elwalid et al. [15] and Heyman and Lakshman [24], show that even for long-range dependent sources, Markov models are sufficient for engineering purposes. Thirdly, both Frame Relay and ATM leaky bucket mechanisms are used to control the traffic at the user-network interface. Violating traffic is either discarded or marked low priority. Thus, over time periods for which the leaky bucket parameters do not change, the traffic parameters are bounded and can be modeled using the source models we use. Finally, it should be emphasized that our approach cannot be used to model the impact of dynamic feedback congestion control techniques on the network, but only for a small interval of time when traffic is essentially stationary. An analytical network model that reflects source models over all time scales as well as network dynamics is an interesting open problem.

There are two traffic specification modes in DATANMOT. In the first, the user selects among a list of standard services. The list includes LAN traffic, facsimile, teletext, high-resolution graphics, video applications, and is amenable to extension. For each service certain customer-level parameters are required; for example, in the case of faxes the user inserts the number of fax machines in the premises, and the expected number of copies sent per hour. This information is combined with statistical data provided by historical network service traffic measurements [25–27] in a service-to-traffic descriptor conversion routine. The traffic descriptor values are stored in the system database and used for performance evaluation. In the second mode the user can insert the actual source model parameter values. For Frame Relay PVCs these are the mean arrival rate, the squared coefficient of variation of packet arrival time, the mean packet length, and the squared coefficient of variation of packet lengths. These parameters have been experimentally shown to be sufficient to characterize Frame Relay data network traffic [19]. The set is also convenient for the Queueing Network Analyzer

modeling technique [8], enhanced by us to model a shared bus switch [28], used for the Frame Relay portion of DATANMOT networks. However, for the integration of the ATM subnetwork portion more complex source modeling was necessary.

3.1. ATM Source Modeling and Approximation

In ATM networks, all types of sources need to be considered, including variable bit-rate (VBR) video, data and voice. In order to characterize the source traffic, many papers have suggested different source models. Burstiness due to correlated cell arrivals is a key element to capture in ATM traffic modeling. The Batch Poisson Process, Markov Modulated Poisson Process (MMPP) and Markov Modulated Fluid Process (MMFP) have been used in the literature [23, 29, 30]. Parameters associated with these models have been chosen to match the statistical characteristics of traffic in ATM networks with varying degrees of accuracy. Although burstiness is difficult to characterize, second order effects in MMPP have been used to capture it [31, 32]. However, such traffic characterization generates a large state space, which is intractable for real-time applications.

In order to capture the traffic burstiness, we model each source by a stochastic fluid-flow process (Markov Modulated Fluid Process), with two states, i.e., an ON-OFF or binary source. At any time the source is either in an active or silent state. In the silent state the source does not send any traffic and in the active state the source generates traffic at the peak source rate. In DATANMOT we used exponentially distributed source active and silent periods. However, the source model parameters can originate from general distributions that may prove more effective in capturing the nature of particular sources. More complex sources, such as VBR video, can be modeled as aggregations of MMFP sources [23]. This source model results in a reduced state space and computation time. Its traffic parameters are (i) the transition rate a from OFF to ON state, (ii) the transition rate b from ON to OFF state, and (iii) the peak access rate r when the source is in the ON state, given as a fraction of the total input line rate. If we replace one of the transition rates a , b , with the source activity factor $p = a/(a + b)$, then an equivalent traffic parameter set results. The traffic of each individual PVC is modeled as a binary MMFP source with parameters obtained from traffic conversion routines. However, the short computation time requirement still does not allow for a very large number of heterogeneous sources, and for this reason further approximation was needed.

3.2. The Homogeneous Sources Approximation

The aggregated heterogeneous sources can be approximated by one statistically equivalent set of homogeneous sources, which significantly reduces the

computation time. The homogeneous set of binary sources are chosen to have similar transient characteristics and long-term behavior as the original aggregated heterogeneous sources set, by using a matching procedure of the moments and time correlations of the original aggregate sources' arrival rate [33, 34]. The set of homogeneous sources is characterized by the following parameters: (i) the number of binary sources n_e , (ii) the transition rate from the OFF state to the ON state a_e , (iii) the transition rate from the ON state to the OFF state b_e , and (iv) the peak rate of the source r_e in the ON state. An equivalent characterization can be derived by using the activity factor p_e , as defined in the previous section, of the homogeneous sources. The approximation method makes use of $R_{(i)}(t)$, the i th PVC cell generation rate at time t ; $R(t) = \sum_i R_{(i)}(t)$ is the aggregate heterogeneous sources' cell generation rate at time t . Also, R_p is the peak rate of the aggregate heterogeneous sources, R_1 is the average source arrival rate, R_2 is the variance of source arrival rate, and R_3 is the third central moment of source arrival rate. These four parameters are derived from the steady state distribution of the heterogeneous binary source aggregate process. In addition to the steady state distribution, we need to consider rate correlations in time. Define $N_{(i)}(t) = \int_0^t R_{(i)}(\tau) d\tau$. Define also, $N(t) = \sum_i N_{(i)}(t)$, and

$$N_1(t) = \sum_i E[N_{(i)}(t)] = E[N(t)] = E \left[\sum_i N_{(i)}(t) \right] \quad (3.1)$$

$$N_2(t) = E[(N(t) - N_1(t))^2] = \sum_i E[(N_{(i)}(t) - E[N_{(i)}(t)])^2] \quad (3.2)$$

$$N_3(t) = E[(N(t) - N_1(t))^3] = \sum_i E[(N_{(i)}(t) - E[N_{(i)}(t)])^3] \quad (3.3)$$

where $N_1(t)$, $N_2(t)$, and $N_3(t)$ are the mean, variance and third central moment of the number of cell arrivals respectively, from time 0 to time t . Applying the previous definitions for the homogeneous set of binary sources, we find its peak rate and moments of arrival rate $R_{p,e}$, $R_{1,e}$, $R_{2,e}$, and $R_{3,e}$. There are also explicit expressions available for the rate correlations $N_{1,e}(t)$, $N_{2,e}(t)$, and $N_{3,e}(t)$ of the homogeneous binary source model [35].

In order to implement the modeling approximation, a model matching parameter procedure is used in which R_p , R_1 , R_2 , and R_3 of the heterogeneous sources that feed a common multiplexer are matched to $R_{p,e}$, $R_{1,e}$, $R_{2,e}$, and $R_{3,e}$ of the homogeneous set. The homogeneous set parameters p_e , n_e , and r_e are obtained after some algebraic manipulations as follows:

$$p_e = \frac{R_{1,e}}{R_{p,e}}, \quad n_e = \left\lfloor \frac{R_{1,e}(R_{p,e} - R_{1,e})}{R_{2,e}} + \frac{1}{2} \right\rfloor, \quad r_e = \frac{R_{p,e}}{n_e} \quad (3.4)$$

Here $\lfloor \cdot \rfloor$ denotes the floor function. In order to derive a_e and b_e an optimization method is used from [33], where a normalized error ϵ is minimized and is given by,

$$\epsilon = \frac{\sum_{k=1}^K [I_1(t_k) - I_{1,e}(t_k)]^2}{\sum_{k=1}^K [I_{1,e}(t_k)]^2} + \frac{\sum_{k=1}^K [I_2(t_k) - I_{2,e}(t_k)]^2}{\sum_{k=1}^K [I_{2,e}(t_k)]^2} \quad (3.5)$$

under the constraint that $p_e = a_e/(a_e + b_e)$, where I_1 and I_2 are the indices of traffic dispersion defined as,

$$I_1(t) \triangleq \frac{N_2(t)}{N_1(t)}, \quad I_2(t) \triangleq \frac{N_3(t)}{N_2(t)}, \quad I_{1,e}(t) \triangleq \frac{N_{2,e}(t)}{N_{1,e}(t)}, \quad I_{2,e}(t) \triangleq \frac{N_{3,e}(t)}{N_{2,e}(t)} \quad (3.6)$$

The sampling points t_k are such that,

$$t_k = k \frac{T_K}{K}, \quad k = 1, 2, \dots, K \quad (3.7)$$

where T_K is chosen such that,

$$|I_{1,T}(T_K) - I_{1,T}(\infty)| \leq \delta \quad (3.8)$$

Different choices of t_k 's and δ will result in different sets of solutions for a_e and b_e . For the numerical results in Section 6 we used $\delta = 10^{-2}$ and $K = 40$.

By matching R_p, R_1, R_2 , and R_3 of the two source models and by minimizing the mean square error between $I_{1,e}(t), I_{2,e}(t)$ and $I_1(t), I_2(t)$, we then find the parameters of the equivalent set of homogeneous binary sources. Note that if $R_p, R_1, R_2, R_3, N_1(t), N_2(t)$, and $N_3(t)$, can be derived either analytically or by measurement for a set of sources with arbitrary ON and OFF period distributions; these can be matched using the same procedure.

3.3. Traffic Modeling in a Multi-Stage Network

In order to model a multi-stage network we need to model the output traffic of each stage, so that it can be used as input traffic to the next stage. We use nodal decomposition in the sense that under reasonable conditions [36] the statistics of the input traffic of a stage are not significantly distorted at the output of that stage. However, the aggregate peak rate of the sources traversing a stage is constrained by the service rate of its output line (or lines). Therefore, the set of heterogeneous binary sources on a line connecting two successive stages is approximated by a homogeneous set of binary sources with the same moments and dispersion indices, but constrained aggregate peak rate. This procedure is necessary only if the aggregate peak rate of the input traffic of the stage exceeds its service rate. To summarize, the steps required to model traffic in a multi-stage network in DATANMOT are the following:

- A homogeneous set of sources approximates the traffic at each input line of a stage with a separate buffer, using the statistical matching method of Section 3.2. The additional peak line rate constraint is applied, if necessary.
- At the input of a stage with a shared buffer for all lines, the first step is used for each input line, for which the peak line rate constraint applies. Then, the heterogeneous mix of sources on all of the input lines is approximated by an overall set of homogeneous sources.

4. ATM SWITCH MODELING AND PERFORMANCE ANALYSIS

The source modeling techniques described in the previous section were intended to be compatible with the multiplexer modeling frameworks by Whitt [8] for the Frame Relay switch and [37] for the ATM switch. These models have been appropriately adapted and extended to analyze the performance of the two types of switches. As a first step, an equivalent representation of the internal switch architecture is created using queue modeling. This is a server model that captures the specific packet-handling mechanisms implemented in the switch, i.e., service policy, buffer management, etc. Next, we analyze the individual switch component models. To obtain end-to-end results for the ATM switch the nodal decomposition method described in Section 3.3 is applied. The details of applying the techniques by Whitt [8] to the Northern Telecom Frame Relay switch are described by Sarachik *et al.* [28]. This model was validated by experimental tests conducted by NYNEX. Next, we present the equivalent model of the Fujitsu FETEX 150 ATM switch and the approximate models for each of its component stages.

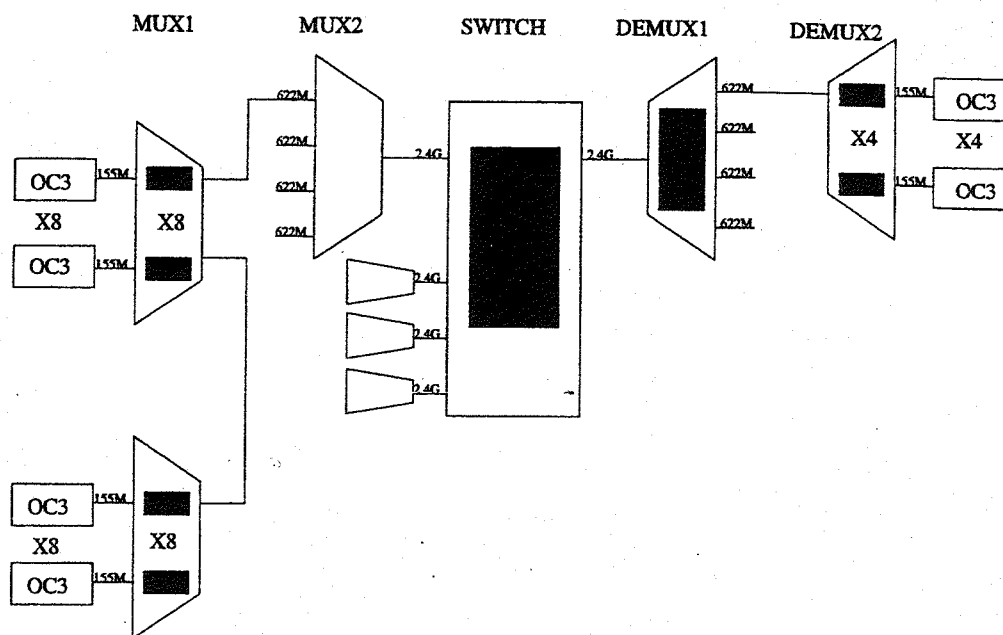


Fig. 3. ATM switch equivalent model.

4.1. Equivalent End-to-End ATM Switch Model

The diversity of broadband traffic sources, high line speed, and switching capacity requirements have led to more complex source and server modeling for the ATM switch. In Fig. 3 the equivalent queueing model for this 128×128 multi-stage self-routing switch is shown. It consists of two stages of multiplexers (MUX1 and MUX2), one 4×4 switching element (SWITCH) and two stages of demultiplexers (DEMUX1, DEMUX2). Each of these components needs special modeling and performance analysis. Each PVC is modeled as a binary source entering from an OC3 input line in MUX1. PVCs coming out of MUX1 go through a time division multiplexer (MUX2) and merge through a 2.4 Gbps line into a 4×4 switching element (SWITCH). After this, they are demultiplexed through a shared buffer demultiplexer (DEMUX1) with output lines of 622 Mbps. Finally, traffic passes through DEMUX2, a demultiplexer with dedicated buffers at each output line.

4.2. A General Multiplexing System

In Anick *et al.* [37] cells are considered to be an information flow that can be stored in a buffer and then flow out of the buffer at a constant rate. The method for the shared multiplexer has been adapted and extended to be used for the different switch components. We evaluate the mean and moments of delay, the overflow probability and the 95th percentile delay of each PVCs bursty traffic.

$$E(x) = \sum_{i=1}^S k_i \left(\sum_{j=0}^N \phi_{i,j} \right) / z_i = \sum_{i=1}^S k_i \Phi_i(1) / z_i,$$

$$E(x^2) = \sum_{i=1}^S \frac{-2k_i \Phi_i(1)}{z_i^2}, \quad \text{and}$$

$$E(x^3) = \sum_{i=1}^S \frac{6k_i \Phi_i(1)}{z_i^3} \tag{4.5}$$

where $\mathbf{1}'$ is the row vector with all its $N + 1$ elements equal to 1 and $\Phi_i(x)$ denotes the generating function of ϕ_i , i.e., $\Phi_i(x) \triangleq \sum_{j=0}^N \phi_{i,j} x^j$. The first and second moments of waiting time W in the multiplexer are:

$$E(W) = \sum_{i=1}^S \frac{k_i \Phi_i'(1)}{z_i \gamma} = E(x) / \left(\frac{N\alpha}{\alpha + \beta} \right) \quad \text{and} \quad E(W^2) = \sum_{i=1}^S \frac{2k_i \Phi_i'(1)}{z_i^2 \gamma} \tag{4.6}$$

where, $\gamma = \sum_{i=0}^N i\pi_i$.

Define $\Psi(x)$ as the cumulative distribution function of the normalized cell delay x , seen by arriving cells. By considering the buffer content distribution seen by cells at arrival instants we obtain,

$$\Psi(x) = 1 + \sum_{i=1}^S \frac{k_i \Phi_i'(1)}{\gamma} e^{z_i x}, \quad \text{where,}$$

$$\Psi(x) = \mathcal{R} F(x), \quad \text{and}$$

$$\mathcal{R} = \left[0, \frac{1}{\gamma}, \frac{2}{\gamma}, \dots, \frac{N}{\gamma} \right] \tag{4.7}$$

The 95th percentile delay is calculated by solving for x the equation $\Psi(x) = 0.95$.

4.3. MUX1 Structure and Modeling

MUX1 is a multiplexer with 8 OC-3 input lines (expandable to 16 input lines with a daisy chain mechanism). Each input line has a dedicated buffer (Fig. 4). However, cells arriving from all the input lines join a global logical FIFO (First In First Out) queue with a service rate of 622 Mbps. The difficulty of solving this queueing system is due to the large size of the state space. In

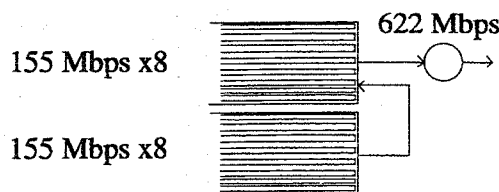


Fig. 4. MUX1.

order to reduce the state space, we assume independence among the buffers of MUX1 and decompose the queueing model for MUX1 into several simpler independent queueing systems, one for each line. Each subsystem is a single queue with equivalent homogeneous binary source inputs and a variable service rate. We model this variable service by a two state (On-Off) server, each state corresponding to a different service rate.

Let us assume that the queueing system we are modeling has $N + 1$ buffers (8 or 16 for MUX1). Each buffer i has n_i identical binary sources, each with α_i as the transition rate from OFF to ON, β_i as the transition rate from ON to OFF, and r_i as its peak rate, $0 \leq i \leq N$. These $N + 1$ buffers are then served FIFO by the server with constant rate c , and each has the same buffer size B . Let the buffer we are modeling be the l th buffer, $0 \leq l \leq N$. Let the transition rate in the server for the l th buffer from state 0 to state 1 be a , the transition rate from state 1 to state 0 be b , and the service rate be c_0 in state 0, c_1 in state 1, with $0 < c_0 < c_1 < c$. To determine the values of a and b , we also model the output from all the other N buffers as a 2 state Markov Modulated Rate Process, with a transition rate of a from state 0 to state 1, a transition rate b from state 1 to state 0, an output rate $c - c_0$ in state 0, and $c - c_1$ in state 1. Then, by matching the first three moments of the traffic input to the N remaining buffers to the first three moments of the output traffic from the same buffers, we can derive the values of a and b . The reason for using this matching method was the observation that traffic statistics do not change substantially from input to output for FIFO queues in the traffic region of interest. The moment matching procedure is similar to the one described in Section 3, and is not included here for brevity.

We then need to analyze a queueing system with n_l identical binary sources served by a two-state server of known parameters. Let $F_{i,k}(x)$ be the cumulative distribution function of the buffer content in the buffer for a server in state i with k active sources, $i = 0, 1$, and $0 \leq k \leq n_l$. Next, we set up the differential equations of the fluid-flow system, which are:

$$(kr_l - c_0) \frac{dF_{0,k}(x)}{dx} = -[a + (n_l - k)\alpha_l + k\beta_l]F_{0,k}(x) + bF_{1,k}(x) \\ + (k + 1)\beta_l F_{0,k+1}(x) + (n_l - k + 1)\alpha_l F_{0,k-1}(x) \quad (4.8)$$

and

$$(kr_l - c_l) \frac{dF_{1,k}(x)}{dx} = -[b + (n_l - k)\alpha_l + k\beta_l]F_{1,k}(x) + aF_{0,k}(x) + (k+1)\beta_l F_{1,k+1}(x) + (n_l - k + 1)\alpha_l F_{1,k-1}(x) \quad (4.9)$$

Let $F(x) = [(F_{0,0}(x), F_{1,0}(x)), (F_{0,1}(x), F_{1,1}(x)), (F_{0,2}(x), F_{1,2}(x)), \dots, (F_{0,n_l}(x), F_{1,n_l}(x))]^T$. By rewriting the differential system of (4.8) and (4.9) in matrix form, and by solving the corresponding eigenvalue problem (see [35] and references therein), the solution has the spectral representation,

$$F(x) = \hat{\pi} + \sum_{i=1}^S a_i \hat{\phi}_i e^{\hat{z}_i x} \quad (4.10)$$

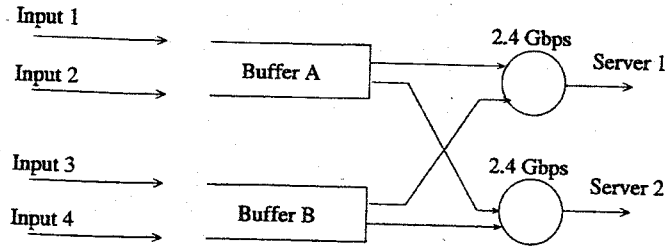
where $\hat{\pi}$ is the stationary source probability, S is the number of negative real eigenvalues, \hat{z}_i are the eigenvalues, and $\hat{\phi}_i$ their corresponding column eigenvectors, $1 \leq i \leq S$, and a_i are the coefficients which satisfy the conditions at the boundaries. So $1 - 1'F(B)$ will be the approximate probability of system overflow. The average buffer occupancy is given by

$$\bar{x} = \sum_{i=1}^S \frac{a_i 1' \hat{\phi}_i}{\hat{z}_i} \quad (4.11)$$

By Little's Law the average queuing delay for our system will be \bar{x}/ρ , where ρ is the average load of the sources. From the cumulative delay distribution function, we get, as in (4.7), the 95th percentile delay.

4.4. 4×2 Switch Structure and Modeling

We now consider the 4×4 switch module which consists of two identical 4×2 elements (switching submodules). Each input line is of OC-48 rate (2.4 Gbps). The cells that come to the 4×4 switch module will enter one of the two 4×2 submodules, depending on which pair of the four output lines they are destined to. Since the two 4×2 submodules are identical, we actually need to create identical models for both and then model them independently. In each 4×2 switch module, all the cells that come from the 4 input lines will enter two buffers (input line 1 and input line 2 enter the first buffer, input line 3 and input line 4 enter the second buffer, as in Fig. 5). All the cells are served by two OC-48 output lines (depending on destination) using a FIFO policy.

Fig. 5. 4×2 model structure.

Let B_u be the size of each of the buffers A and B , $f(x)$ be the density function of the total number of cells in buffers A and B destined to server 1, and $g(x)$ be the density function of the total number of cells coming from in buffers A and B destined to server 2.

We first obtain $f(x)$ and $g(x)$ by using fluid flow modeling on each of the logical queues of cells from both buffers that are destined to server 1 and server 2, by assuming independence between cells which go to different destinations. An approximate expression derived by Tsaih *et al.* [35] for the overflow probability in buffer A is,

$$Loss_A = \begin{cases} \sum_{i=0}^{B_u} \frac{(\lambda_{A,1} + \lambda_{B,1})}{\lambda_{A,1}} f\left(\frac{[\lambda_{A,1} + \lambda_{B,1}]i}{\lambda_{A,1}}\right) \left(1 - G\left(\frac{[\lambda_{A,2} + \lambda_{B,2}][B_u - i]}{\lambda_{A,2}}\right)\right), \\ \text{for } f\left(\frac{[\lambda_{A,1} + \lambda_{B,1}]B_u}{\lambda_{A,1}}\right) < g\left(\frac{[\lambda_{A,2} + \lambda_{B,2}]B_u}{\lambda_{A,2}}\right) \\ \sum_{i=0}^{B_u} \frac{(\lambda_{A,1} + \lambda_{B,1})}{\lambda_{A,2}} g\left(\frac{[\lambda_{A,2} + \lambda_{B,2}]i}{\lambda_{A,2}}\right) \left(1 - F\left(\frac{[\lambda_{A,1} + \lambda_{B,1}][B_u - i]}{\lambda_{A,1}}\right)\right), \\ \text{for } f\left(\frac{[\lambda_{A,1} + \lambda_{B,1}]B_u}{\lambda_{A,1}}\right) > g\left(\frac{[\lambda_{A,2} + \lambda_{B,2}]B_u}{\lambda_{A,2}}\right) \end{cases} \quad (4.12)$$

where $\lambda_{A,1}$ is the average cell arrival rate from buffer A to server 1, $\lambda_{B,1}$ is the average cell arrival rate from buffer B to server 1, and $F(x) = \int_0^x f(\tau)d\tau$, $G(x) = \int_0^x g(\tau)d\tau$. This approximation essentially distributes the cells with common destination to the two buffers according to the fraction of the traffic load that each receives. The loss probability in buffer B can be similarly approximated.

4.5. DEMUX1 Structure and Modeling

We model DEMUX1, which is shown in Fig. 6, as four independent queueing systems, consisting of the homogeneous equivalent binary sources and a

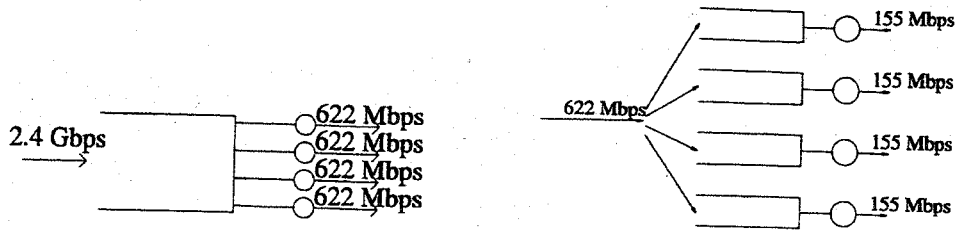


Fig. 6. DEMUX1 and DEMUX2 model structure.

fixed rate server, which share the same buffer with buffer size B_d . By using the results of Section 4.2 we approximate the loss probability $Loss$ by convolving the distributions of the four queues as follows:

$$Loss = \sum_{i=0}^{B_d} \sum_{j=0}^{B_d-i} \sum_{k=0}^{B_d-i-j} f_1(i)f_2(j)f_3(k)(1 - F_4(B_d - i - j - k)) \quad (4.13)$$

where $f_i(x)$ is the density function for the number of cells in the buffer which are destined to server i , $1 \leq i \leq 4$ and $f_1(B_d) \leq f_2(B_d) \leq f_3(B_d) \leq f_4(B_d)$. $F_1(x)F_2(x)$, $F_3(x)$ and $F_4(x)$ are the corresponding cumulative distribution function. Note that due to the exponential nature of the distributions, convolution can be computed easily using transforms. Also, by using the previous results from the fluid flow model analysis, we can derive an expression for the delay distribution.

4.6. DEMUX2 Structure and Modeling

We used the fluid flow model with homogeneous sources and fixed service rate to model each individual buffer in DEMUX2 (Fig. 6). First, by using the equivalent binary source approximation, we find one set of identical binary sources and then limit its peak arrival rate to be less than or equal to 622 Mbps. We then derive the loss probability and delay statistics for this component of the switch by using the analysis of Section 4.2.

With the modeling of all the individual components of the entire ATM switch we conclude this section. The end-to-end switch mean delay and loss probability is the sum of the single stage results of mean delays and loss probabilities, respectively. By convolving the single stage delay distribution functions, we also calculate end-to-end switch 95th percentile delays. The last section contains modeling and simulation results showing that the switch model is a reasonable approximation for our purposes. We note that while simulations take hours, the DATANMOT gives results, from minutes for a network of several nodes, to seconds for a single switch. This model was also independently validated by Fujitsu, Inc. using internally developed models [38]. The switch modeling code

is now integrated as the ATM switch entity model in DATANMOT. All results of interest can be accessed using the graphical user interface of the tool.

5. PERFORMANCE MANAGEMENT APPLICATIONS IN DATANMOT

In this section we describe the model-based performance management method, namely permanent virtual circuit (PVC) admission, routing, and decision support for network design, planning and provisioning. The objective of these methods is meeting the required QoS across each PVC. Traditional network optimization methods use models that approximate delay by solely using mean arrival rates for traffic characterization. This is not a viable approach in broadband traffic networks, mainly because of the traffic burstiness, which has a serious impact on network performance. Moreover, nodes are often modeled as statistical multiplexers, ignoring buffer management and the internal switch design, which requires more elaborate modeling. The traffic and node analysis techniques in DATANMOT provide a higher level of accuracy in this regard. At the same time, their short computation time allows running the performance management applications in a time range of seconds to minutes. In addition, the flexible configuration interface allows the user to experiment with arbitrary topology scenarios. This capability of the tool can assist the network manager in the network design, planning, and provisioning.

As a first approach to performance management, DATANMOT can be used as a PVC admission controller for a broadband network. In case of a traffic increase in a pre-established PVC, the specific new service or services are entered through the graphical user interface in the PVC traffic tables. Then the operator can decide whether to admit the new request or not, based on the performance results that take the new connection's PVCs into account. For example, there are menu options that notify the operator if some PVC's delay exceeds the predefined threshold. The same procedure applies to new PVC connection requests.

As a further step to efficiently allocate network resources and to control congestion in Frame Relay networks, a routing optimization algorithm [7] is incorporated in DATANMOT. By clicking the corresponding option in the graphical user interface menus (see Fig. 8), this multi-path routing method is invoked, which uses a cost optimization function based on the model performance analysis results. The traffic of a single connection is re-assigned to all feasible routes of the connection. The routing results can be seen by checking either the new link utilizations, or the updated PVC traffic tables.

In addition, the flexible configuration interface allows the user to experiment with arbitrary topology and traffic scenarios. This capability of the tool can assist the network manager to design and plan the network. Towards this direc-

DT. All results
he tool.

management
ing, and deci-
e objective of
raditional net-
y solely using
e approach in
ss, which has
often modeled
internal switch
node analysis
n this regard.
: performance
. In addition,
with arbitrary
work manager

T can be used
use of a traf-
r services are
les. Then the
on the perfor-
For example,
elay exceeds
C connection

control con-
[7] is incor-
the graphical
l is invoked,
mance analy-
asible routes
ther the new

er to experi-
f the tool can
ds this direc-

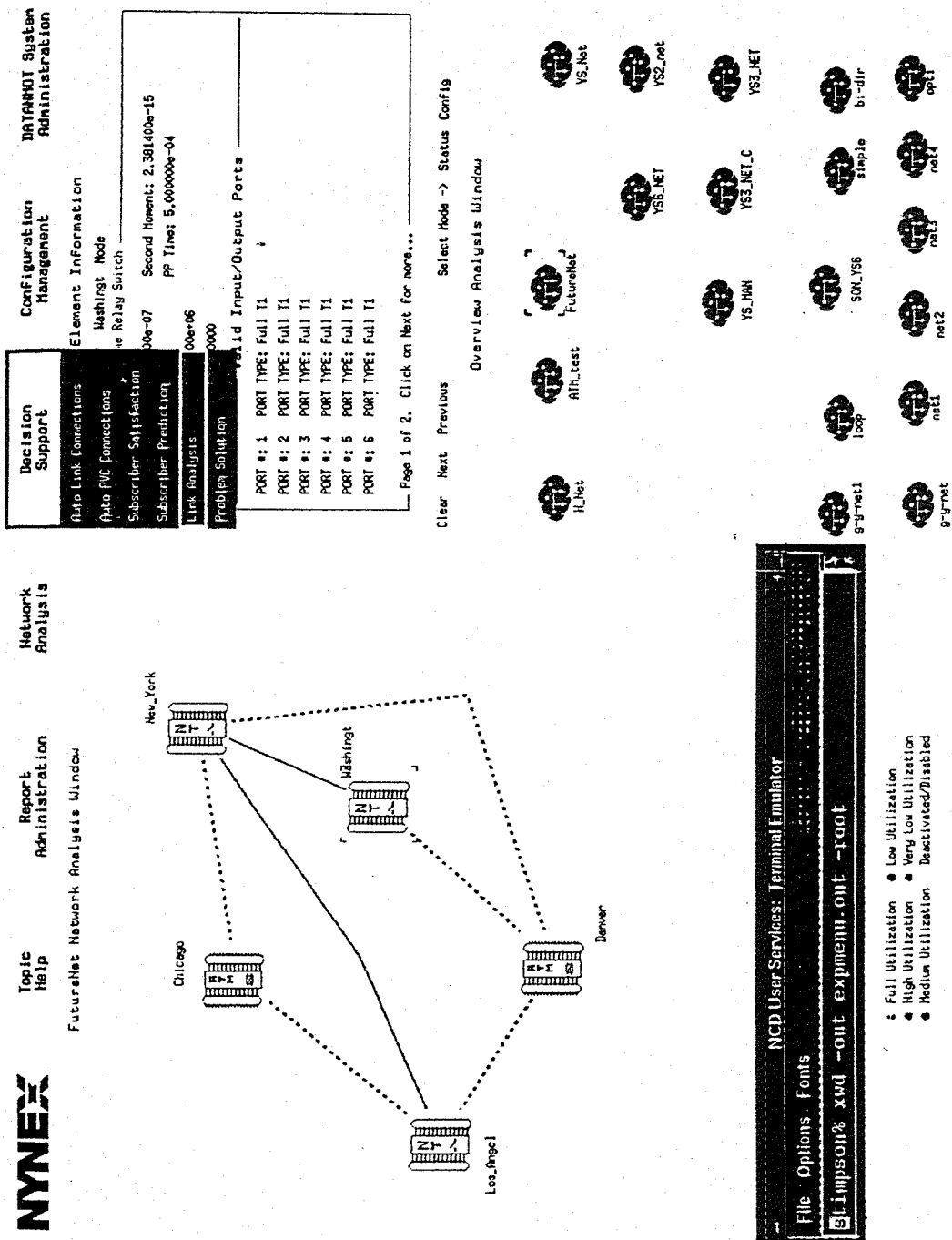


Fig. 7. The DATANMOT expert system functions.

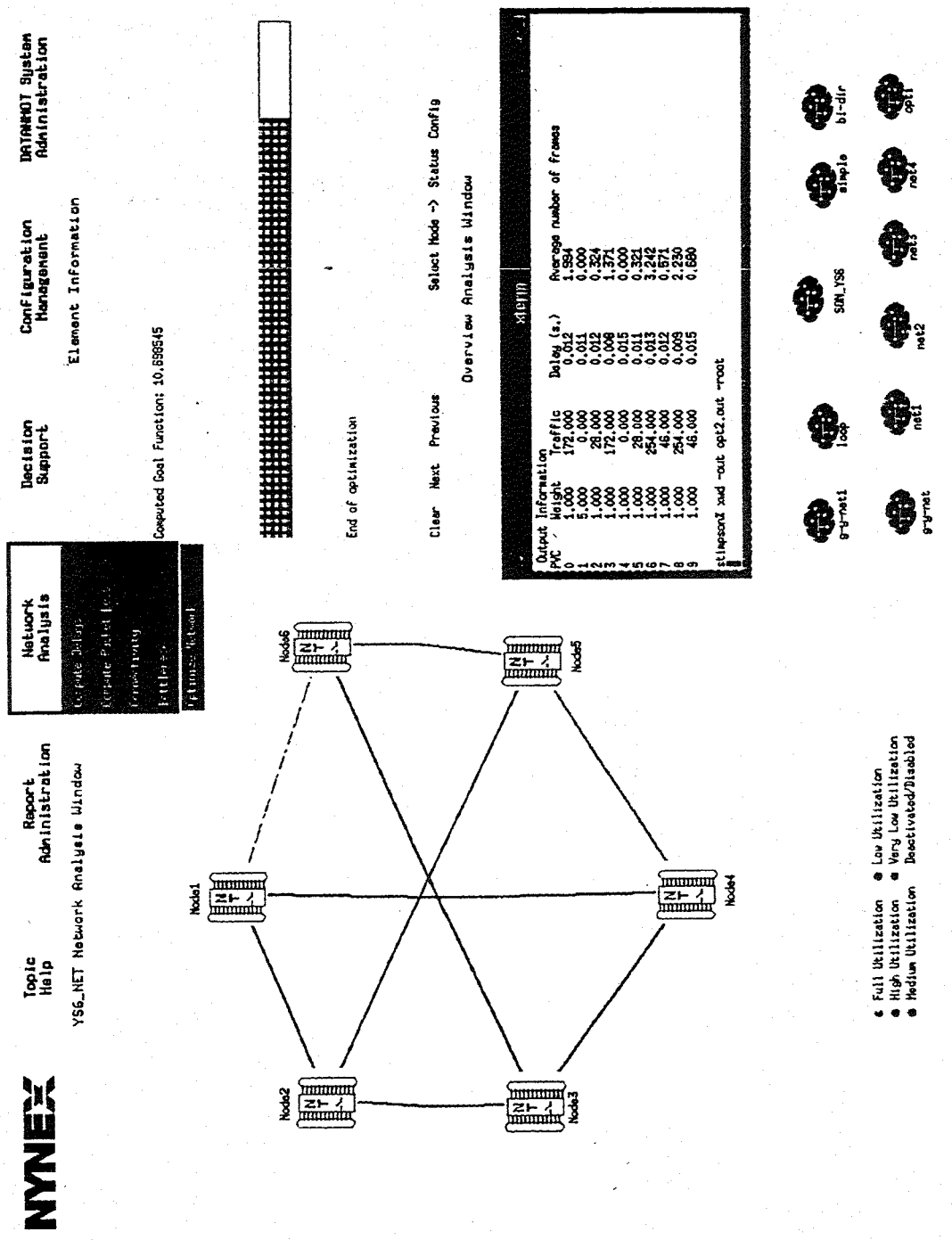


Fig. 8. Routing optimization execution.

tion, a decision support expert system shell has been integrated in the DATANMOT environment. The expert system is based on the modeling performance results, and can (i) set-up multi-PVC connections with optimal routing by reading the customer information, (ii) indicate the overutilized links and suggest a local link capacity increase to alleviate traffic bottlenecks, and (iii) support long-term rule development for network troubleshooting, with extensive experimentation on various configurations.

As an illustration of the DATANMOT graphical user interface and incorporated functions, we include Figs. 7 and 8.

6. NUMERICAL RESULTS

In this section several sets of results are presented, which compare the accuracy of the approximate model of the ATM switch to simulations. Results for the Frame Relay switch are included in Ref. 28. The performance measures evaluated were cell loss probability, average cell delay, and the 95th percentile cell delay, which is derived from the cumulative probability distribution of delay. Modeling and simulation results were obtained both for each component of the switch individually and for the end-to-end case. The component buffer sizes were set to obtain loss probabilities in the region of interest. Simulation run lengths were adjusted such that in the worst case, which corresponded to runs to estimate the smallest expected loss probability, the 95% confidence interval is within 20% of the estimated value.

In Figs. 9-12, the cell loss probability of each component is plotted versus the average burst length (active source period) counted in cell slot periods. The traffic used as input is a homogeneous set of sources, each applied to one of the

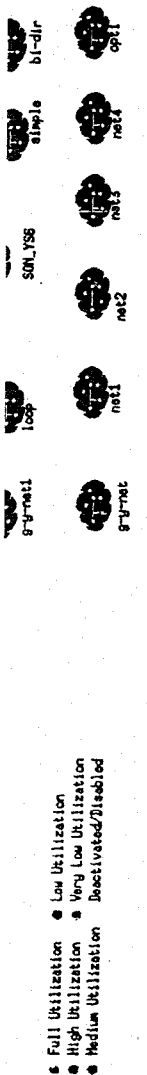


Fig. 8. Routing optimization execution.

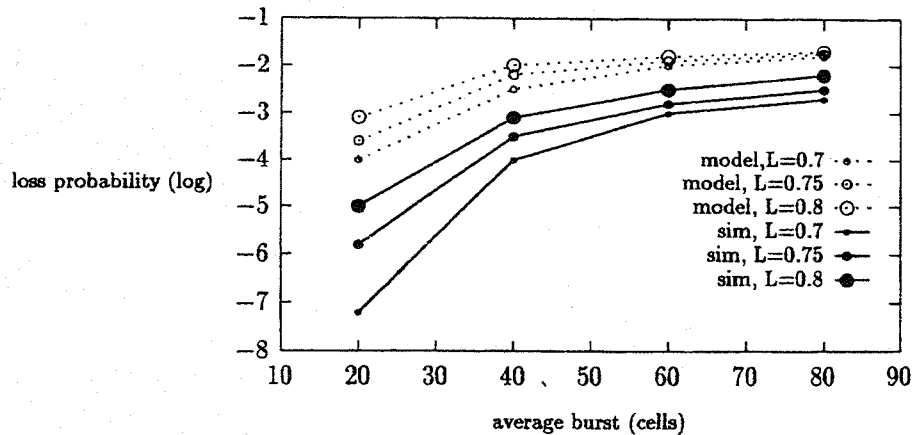


Fig. 9. Model and simulation for MUX1 (homogeneous traffic sources).

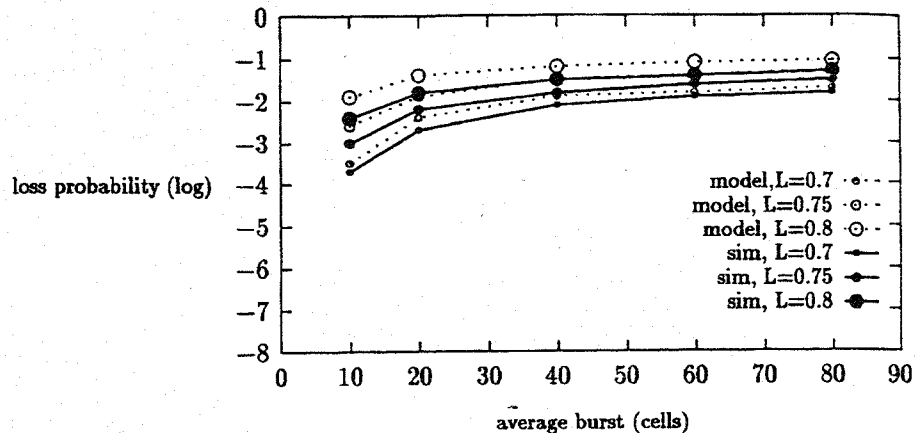


Fig. 10. Model and simulation for DEMUX1 (homogeneous traffic sources).

input lines of the multiplexers (MUX1's) of the switch fabric. Each source is characterized by a peak rate of 155 Mbps, by its load L (channel utilization), and average burst length, which are used as variable parameters. Both approximate model and simulation results are plotted for comparison. It can be seen that in most cases for all components we obtain a conservative estimate of the loss probability.

In Fig. 13, 8 heterogeneous sources are applied to the input lines of MUX1. All sources have a fixed load value of 0.85. Their burst period duration takes values beginning from 40 cell slots and increases at every successive input line by a constant step. The graphs correspond to model and simulation results with steps of 0 (homogeneous case), 5 and 10 cell slot periods. It can be seen that the gradual increase in the ON duration at every successive input line corresponds

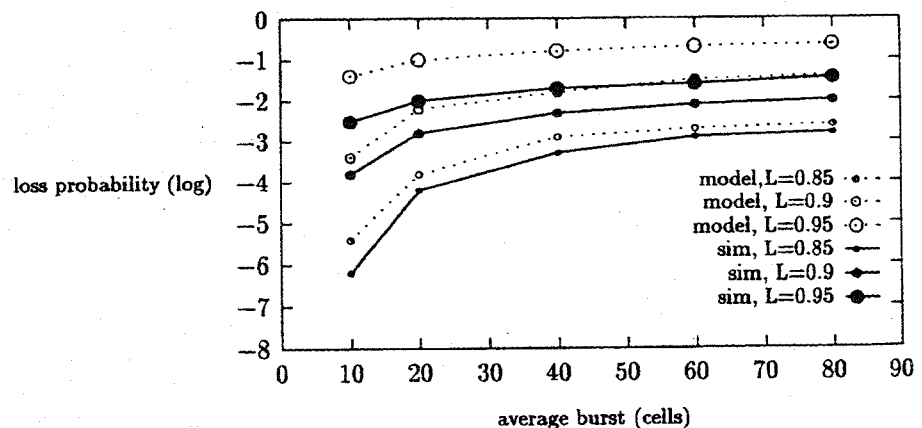


Fig. 11. Model and simulation for SWITCH (homogeneous traffic sources).

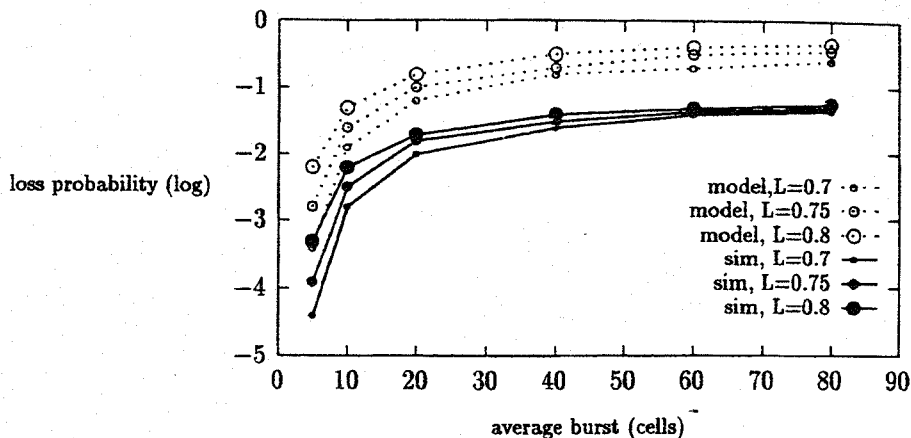
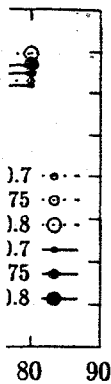


Fig. 12. Model and simulation for DEMUX2 (homogeneous traffic sources).

rces).

Each source is utilization), and h approximate e seen that in te of the loss

to an increase in loss probability, which varies from $10^{-4.5}$ to $10^{-1.8}$. Similar results for heterogeneous sources were obtained for all components [35].

In Fig. 14, the end-to-end switch cell loss probability is plotted, as evaluated from the approximate model and simulations. A set of 128 sources of 155 Mbps are inputs to the switch fabric and their average burst period and load are left as parameters. In the end-to-end traffic scenario for the traffic loads considered, the approximate model is more conservative than simulation results.

nes of MUX1. duration takes sive input line on results with e seen that the e corresponds

In Figs. 15 and 16, a comparison of the model's prediction for average end-to-end delay and 95th percentile delay are compared to simulation results. All traffic sources generate cells at 155 Mbps peak rate. In both figures the model results are reasonably close to the simulated cell delay.

From these various results it is apparent that the model's accuracy of pre-

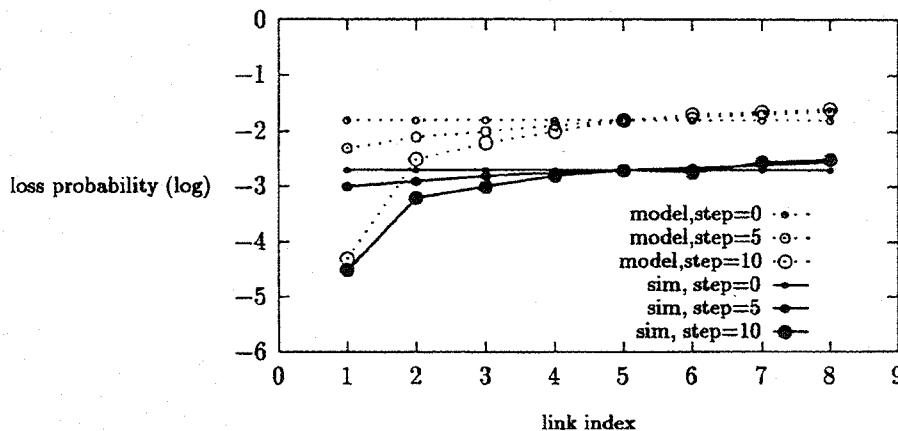
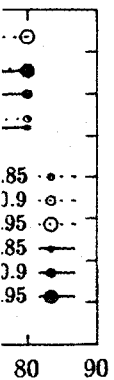


Fig. 13. Model and simulation for MUX1 (heterogeneous traffic sources).

rces).

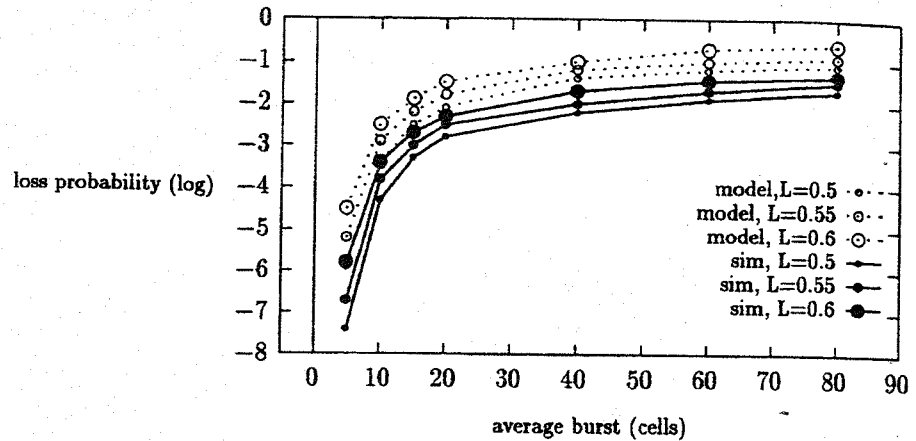


Fig. 14. Model and simulation loss probability results for the end-to-end multistage switch.

dition of loss probability increases as the average burst length or active period duration increases. This is an inherent characteristic of fluid-flow approximations, since the basic assumption is that the cell transmission time is very small compared to the length of an ON period. In our study, the approximate end-to-end fluid-flow model gives in most cases, a conservative estimate of the switch loss probability, average delay and 95th percentile delay, and can be used to evaluate switch performance for traffic management purposes.

7. CONCLUSIONS

We have described the implementation and modeling methodology of a permanent virtual circuit network management tool. The intention of developing approximate traffic source and switch models is the prediction of network performance in as short a time as possible. This allows for the network model to

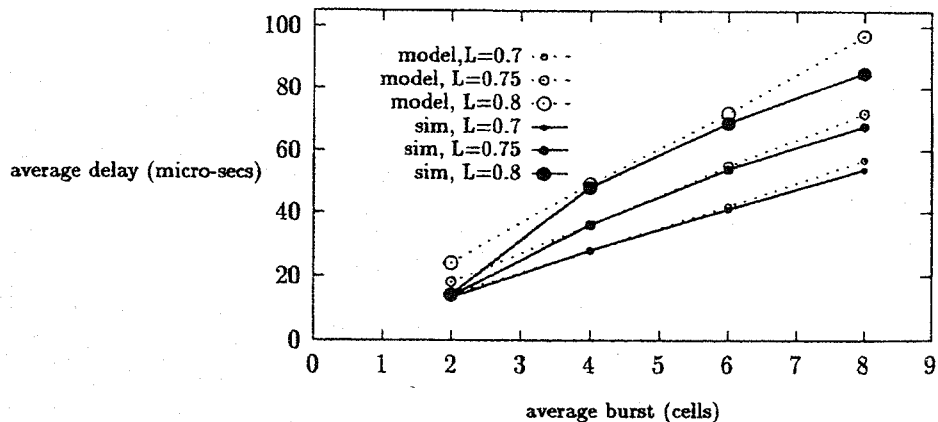
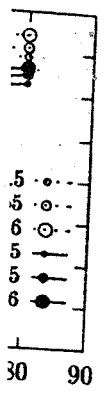


Fig. 15. Model and simulation average delay results for the end-to-end multistage switch.



stage switch.

active period
approxima-
s very small
nate end-to-
f the switch
be used to

gy of a per-
developing
network per-
k model to



switch.

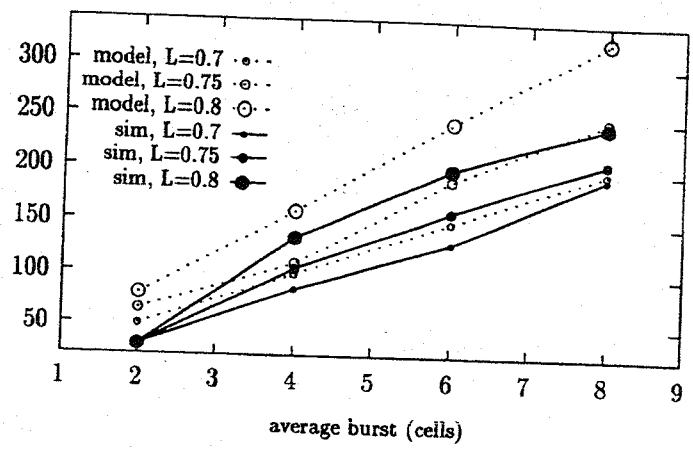


Fig. 16. Model and simulation 95th percentile results for the end-to-end multistage switch.

be used as part of a routing optimization and a network planning module for high-speed networks. The source models approximate broadband traffic, while the switch models correspond to existing architectures. The techniques described here can be applied to model other switches with similar architectures. The methods used in DATANMOT are examples of applying network modeling to supplement real-time network traffic monitoring and simulation models for network performance management. Further research on the tool is directed (i) to create a complete set of buffer management models using similar analytic techniques; (ii) to refine the modeling of output traffic from the components of a multi-stage network; and (iii) apply alternative routing algorithms for PVC routing.

REFERENCES

1. B. T. Doshi and H. Q. Nguyen, Congestion control in ISDN frame-relay networks, *AT&T Technical Journal*, November/December 1988.
2. K.-J. Chen, K. K. Y. Ho, and V. R. Saksena, Analysis and design of a highly reliable transport architecture for ISDN Frame-Relay networks, *IEEE Journal on Selected Areas in Communications*, Vol. 7, No. 8, pp. 1231-1242, October 1989.
3. Cui-Qing Yang and Alapati V. S. Reddy, A taxonomy for congestion control algorithms in packet switching networks, *IEEE Network Magazine*, Vol. 9, No. 5, July/August 1995.
4. The ATM Forum, *ATM User-Network Interface Specifications*, Version 3.0, Prentice Hall, New Jersey, 1993.
5. A. Gersht and K. J. Lee, A congestion control framework for ATM networks, *IEEE Journal on Selected Areas in Communications*, Vol. 9, No. 7, pp. 1119-1130, September 1991.
6. J. Y. Hui, Resource allocation for broadband networks, *IEEE Journal on Selected Areas in Communications*, Vol. 6, No. 9, pp. 1598-1608, 1988.
7. Z. Flikop, Routing optimization in packet switching communication networks, *European Journal of Operating Research*, Vol. 19, pp. 262-267, 1985.
8. W. Whitt, The queueing network analyzer, *Bell Systems Technical Journal*, Vol. 62, No. 9, November 1983.
9. C. L. Hwang and S. Q. Li, On the convergence of traffic measurement and queueing analysis: A Statistical-MATCH Queueing (SMAQ) tool, *Proc. IEEE Infocom'95*, Vol. 2, pp. 602-612, 1995.

10. D. W. Bachmann, M. E. Segal, M. M. Srinivasan, and T. J. Teorey, NetMod: A design tool for large-scale heterogeneous campus networks, *IEEE Journals on Selected Areas in Communications*, Vol. 9, No. 1, pp. 15–24, January 1991.
11. D. Geist and B. Melamed, TESTool: An environment for visual interactive modeling of auto-correlated traffic, *Proc. International Conference on Communications*, Chicago, Illinois, Vol. 3, pp. 1285–1289, 1992.
12. *OPNET Modeling Manual, Release 2.4*, MIL3, Inc., Washington D.C., 1993.
13. *Network II.5 User's Manual, Release 9.0*, CACI Products Company, La Jolla, California 1993.
14. R. S. Pazhyannur and R. Agrawal, Feedback-based flow control in B-ISDN/ATM networks, *IEEE Journal on Selected Areas in Communications*, Vol. 13, No. 7, pp. 1252–1266, September 1995.
15. A. I. Elwalid and D. Mitra, Effective bandwidth of general Markovian traffic sources and admission control of high speed networks, *IEEE/ACM Transactions on Networking*, Vol. 1, No. 3, pp. 329–343.
16. A. Elwalid, D. Heyman, T. V. Lakshman, D. Mitra, and A. Weiss, Fundamental bounds and approximations for ATM multiplexers with applications to video teleconferencing, *IEEE Journal on Selected Areas in Communications*, Vol. 13, No. 6, pp. 1004–1016, August 1995.
17. A. I. Elwalid and I. Widjaja, Efficient analysis of buffered multistage switching networks under bursty traffic, *Proc. IEEE Globecom'93*, Vol. 2, pp. 1072–1078, November 1993.
18. D. Mitra, J. A. Morrison, and K. G. Ramakrishnan, ATM network design and optimization: A multirate loss network framework, *IEEE/ACM Transactions on Networking*, Vol. 4, No. 4, August 1996.
19. P. Sarachik, S. Panwar, L. Po, S. Papavassiliou, and L. Tassiulas, The network modeling and management tool, *Technical Report for NYNEX Science and Technology*, CATT, Polytechnic University, December 1992.
20. V. Paxson and S. Floyd, Wide area traffic: The failure of Poisson modeling, *IEEE/ACM Transactions on Networking*, Vol. 3, pp. 226–244, June 1995.
21. V. Frost and B. Melamed, Traffic modeling for telecommunications networks, *IEEE Communication Magazine*, Vol. 33, pp. 70–80, March 1994.
22. W. Leland, M. Taqqu, W. Willinger, and D. Wilson, On the self-similar nature of Ethernet traffic (extended version), *IEEE/ACM Transactions on Networking*, Vol. 2, pp. 1–15, February 1994.
23. P. Sen, B. Maglaris, N-E. Rikli, and D. Anastassiou, Models for packet switching of variable-bit-rate video sources, *IEEE Journal on Selected Areas in Communications*, Vol. 7, pp. 865–869, 1989.
24. D. P. Heyman and T. V. Lakshman, What are the implications of long-range dependence for VBR-video traffic engineering?, *IEEE/ACM Transactions on Networking*, Vol. 4, No. 3, June 1996.
25. K. M. Khalil, K. Q. Luc, and D. V. Wilson, LAN traffic analysis and workload characterization, *Proc. 15th Conference on Location Computer Network*, pp. 112–122, October 1990.
26. H. J. Fowler and W. E. Leland, Local area traffic characteristics, with implications for broadband network congestion management, *IEEE Journal on Selected Areas in Communications*, Vol. 9, No. 7, pp. 1139–1149, September 1991.
27. W. E. Leland and D. V. Wilson, High time-resolution measurement and analysis of LAN traffic: Implications for LAN interconnection, *Proc. IEEE Infocom'91*, pp. 1360–1366, 1991.
28. P. Sarachik, S. Panwar, P. Liang, S. Papavassiliou, D. Tsaih, and L. Tassiulas, A modeling approach for the performance management of high speed networks, in I. T. Frisch, M. Malek, and S. S. Panwar (eds.), *Network Management and Control*, Vol. 2, Plenum Press, New York, pp. 149–163, 1994.
29. K. W. Fendick, V. R. Saksena, and W. Whitt, Dependence in packet queues, *IEEE Transactions on Communications*, Vol. 37, No. 11, pp. 1173–1183, November 1989.

30. H. Heffes and D. M. Lucantoni, A Markov modulated characterization of packetized voice and data traffic and related statistical multiplexer performance, *IEEE Journal on Selected Areas in Communications*, Vol. SAC-4, No. 6, pp. 856-868, Sept. 1986.
31. F. Yegenoglou and B. Jabbari, Modeling of aggregated bursty traffic sources in ATM multiplexers, *Proc. IEEE ICC '93*, Vol. 3, pp. 1703-1707, 1993.
32. H.-D. Sheng and S.-Q. Li, Second order effect of binary sources on characteristics of queue and loss rate, *Proc. IEEE Infocom'98*, Vol. 1, pp. 18-27, 1993.
33. H. W. Lee and J. W. Mark, ATM network traffic characterization using two types of ON-OFF sources, *Proc. IEEE Infocom'93*, Vol. 1, pp. 152-159, 1993.
34. S. Blaabjerg, H. Andersson, and H. Andersson, Approximating the heterogeneous fluid queue with a birth-death fluid queue, *IEEE Transactions on Communications*, Vol. 43, No. 5, pp. 1884-1887, May 1995.
35. D. Tsaih, G. Lapiotis, S. Panwar, and L. Tassiulas, Fujitsu FETEX 150 ATM Switch Model, Technical Report for NYNEX Science and Technology, CATT, Polytechnic University, December 1993.
36. W.-C. Lau and S.-Q. Li, Traffic analysis in large-scale high-speed integrated networks: Validation of nodal decomposition approach, *Proc. IEEE Infocom'93*, Vol. 3, pp. 1320-1329, 1993.
37. D. Anick and D. Mitra, and M. M. Sondhi, Stochastic theory of a data-handling system with multiple sources, *Bell Systems Technical Journal*, Vol. 61, pp. 1871-1894, 1982.
38. H. Paul Holzworth, Fujitsu Network Systems, private communication.
39. Z. Flikop, Traffic management in packet switched networks, *Proc. IEEE ICC '93*, Vol. 1, pp. 25-29, 1993.

Derchian Tsaih received his B.S. from the Chinese Culture University at Tapei in 1983, and M.S. from George Washington University at Washington D.C. in 1989. He received the Ph.D. degree in electrical engineering in 1995 from the Polytechnic University, Brooklyn, New York.

George D. Lapiotis was born in 1971 in Athens, Greece. He received the Diploma in electrical engineering from the National Technical University of Athens (NTUA), and the M.S. degree in electrical engineering from Polytechnic University, Brooklyn, New York, in 1993 and 1994, respectively. He is currently working toward the Ph.D. degree in electrical engineering at Polytechnic University in the area of communication and computer networks. He has been a graduate research assistant with the Center for Advanced Technology in Telecommunications (CATT) of Polytechnic University since August 1993. His research interests are in the field of stochastic network modeling with emphasis on broadband network performance analysis and management. He is a member of the IEEE Communications Society, and the Technical Chamber of Greece.

Shivendra S. Panwar received the B.Tech. degree in electrical engineering from the Indian Institute of Technology, Kanpur, in 1981, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Massachusetts, Amherst, in 1983 and 1986, respectively. He joined the Department of Electrical Engineering at the Polytechnic Institute of New York, Brooklyn (now Polytechnic University), where he is now an Associate Professor. He is currently the Director of the New York State Center for Advanced Technology in Telecommunications. During the summer of 1987, he was a visiting scientist at the IBM T.J. Watson Research Center, where he worked on flow control mechanisms for high-speed networks. He has been a consultant to several corporations in the area of networks. He has also performed research in high-speed networks sponsored by the National Science Foundation, and is the author of numerous journal and conference papers in this area.

Leandros Tassiulas was born in 1965, in Katerini, Greece. He obtained the Diploma in Electrical Engineering from the Aristotelian University of Thessaloniki, Thessaloniki, Greece in 1987, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Maryland, College Park in 1989 and 1991, respectively. From 1991 to 1995 he was an Assistant Professor in the Department of Electrical Engineering, Polytechnic University, Brooklyn, New York. Since July 1995 he has been an Assistant Professor in the Department of Electrical Engineering, University of Maryland, College Park. His research interests are in the field of computer and communication networks with emphasis on wireless communications and high-speed network architectures and management, in control and optimization of stochastic systems and in parallel and distributed processing. He received an NSF Research Initiation Award in 1992 and an NSF Faculty Early Career Development Award in 1995. He co-authored a paper that got the INFOCOM '94 best paper award.