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

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Abstract

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 - MODEL BASED NETWORK MANAGEMENT

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) requirements various traffic control mechanisms have been suggested for Frame Relay [1, 2] and ATM networks [3, 4, 5, 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.

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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, 95^{th} 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 [20] has been implemented for Frame Relay networks. The 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.

To create a network model one can generally use analytic approximation techniques [7, 8, 9], or discrete-event simulation models [10, 11, 12]. 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 set-up 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 [13].

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 [13, 14, 15]. 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 [8], 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 95^{th} 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 numerical 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 Figure 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 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.

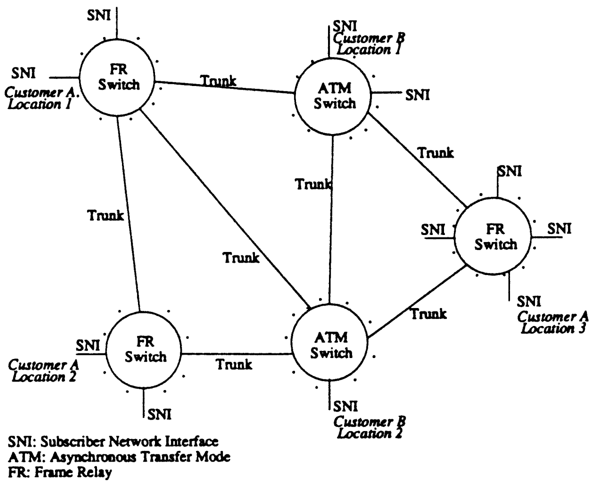

Figure 1: Generic Packet Switched Network Model

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 Figure 2, DATANMOT's 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 below), 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 Figures 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.

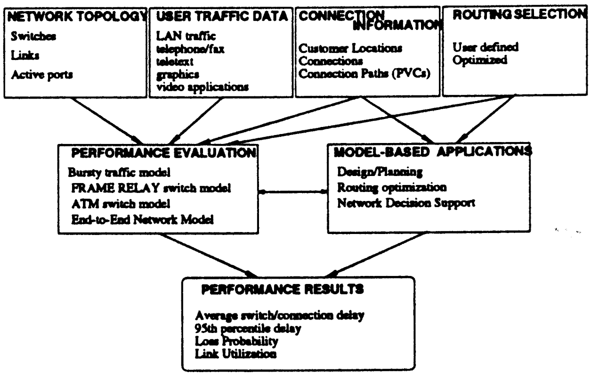

Figure 2: DATANMOT's functional block diagram

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 [10, 22, 23, 24]. 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 [24]. Secondly, results in [25], and more recently in [15, 16], 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 [26, 27, 28] 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 [7], enhanced by us to model a shared bus switch [21], 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 [29, 30, 25]. 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 [25]. 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

$$N_1(t) = \sum_i \mathrm{E}[N_{(i)}(t)] = \mathrm{E}[N(t)] = \mathrm{E}[\sum_i N_{(i)}(t)], \tag{1}$$

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

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

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:

$$p_e = \frac{R_{1,e}}{R_{p,e}}, \quad n_e = \lfloor \frac{R_{1,e}(R_{p,e} - R_{1,e})}{R_{2,e}} + \frac{1}{2} \rfloor, \quad r_e = \frac{R_{p,e}}{n_e}. \tag{4}$$

Here $\lfloor . \rfloor$ 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,

$$\varepsilon = \frac{\sum_{k=1}^{K}[I_1(t_k) - I_{1,e}(t_k)]^2}{\sum_{k=1}^{K}[I_{1,e}(t_k)]^2} + \frac{\sum_{k=1}^{K}[I_2(t_k) - I_{2,e}(t_k)]^2}{\sum_{k=1}^{K}[I_{2,e}(t_k)]^2}, \tag{5}$$

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,

$$I_1(t) \triangleq \frac{N_2(t)}{N_1(t)}, \quad I_2(t) \triangleq \frac{N_3(t)}{N_2(t)}, \quad I_{1,e}(t) \triangleq \frac{N_{2,e}(t)}{N_{1,e}(t)}, \quad I_{2,e}(t) \triangleq \frac{N_{3,e}(t)}{N_{2,e}(t)}. \tag{6}$$

The sampling points t_k are such that,

$$t_k = k\frac{T_K}{K}, \qquad k = 1, 2, ..., K, \tag{7}$$

where T_K is chosen such that,

$$| I_{1,T}(T_K) - I_{1,T}(\infty) | \leq \delta. \tag{8}$$

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 in [7] 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 in [7] to the Northern Telecom Frame Relay switch are described in [21]. 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.

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 Figure 3 the equivalent queueing model for this 128x128 multi-stage self-routing switch is shown. It consists of two stages of multiplexers (MUX1 and MUX2), one 4x4 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 4x4 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 [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 95^{th} percentile delay of each PVC's bursty traffic.

We first consider a queueing system with N identical sources, where each source is modeled by a binary ON-OFF process. The transition rate for each binary source from OFF state to ON state is α, from ON state to OFF state is β and the peak arrival rate is l. These binary sources arrive to a buffer with size B and constant service rate c. Let x and i denote the number of cells in the system and the state of the phase process (i.e. the number of ON sources), respectively, and define $F_i(x)$ as the cumulative distribution function of x at state i, so,

$$F(x) = [F_0(x), F_1(x), ..., F_N(x)]^T . \tag{9}$$

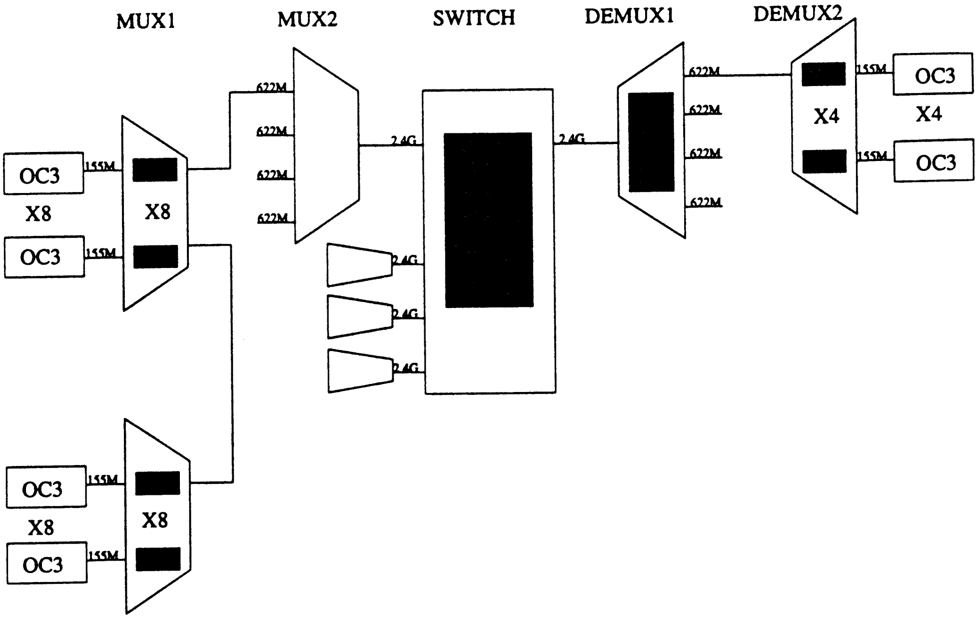

Figure 3: ATM Switch Equivalent Model.

After extensive analysis, a system of differential equations is solved, which is of the form,

$$D\frac{dF(x)}{dx} = MF(x), \tag{10}$$

where D=diag$\{-c, l-c, 2l-c, \ldots., Nl-c\}$, $x \geq 0$, and

$$M = \begin{bmatrix} -N\alpha & \beta & & & & \\ N\alpha & -\{(N-1)\alpha+\beta\} & 2\beta & & & \\ & (N-1)\alpha & -\{(N-2)\alpha+2\beta\} & 3\beta & & \\ & & & \vdots & & \\ & & & & -\{\alpha+(N-1)\beta\} & N\beta \\ & & & & \alpha & -N\beta \end{bmatrix}. \tag{11}$$

The solution of (10) is given by,

$$F(x) = \pi + \sum_{i=1}^{S} k_i \phi_i e^{z_i x}, \tag{12}$$

where π is the stationary aggregate-source distribution vector (i.e., π_i is the probability that i out of N sources are on simultaneously), k_i is the coefficient corresponding to the i-th eigenvalue z_i and eigenvector ϕ_i, and S is the number of eigenvalues that give bounded solutions. Explicit formulas are available for these quantities. The first three moments of buffer occupancy are,

$$\mathrm{E}(x) = \sum_{i=1}^{S} k_i (\sum_{j=0}^{N} \phi_{i,j})/z_i = \sum_{i=1}^{S} k_i \Phi_i(1)/z_i, \quad \mathrm{E}(x^2) = \sum_{i=1}^{S} \frac{-2k_i\Phi_i(1)}{z_i^2}, \quad \text{and } \mathrm{E}(x^3) = \sum_{i=1}^{S} \frac{6k_i\Phi_i(1)}{z_i^3}, \tag{13}$$

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:

$$\mathrm{E}(W) = \sum_{i=1}^{S} \frac{k_i \Phi_i'(1)}{z_i \mathcal{Y}} = \mathrm{E}(x)/(\frac{N\alpha}{\alpha+\beta}), \text{ and } \mathrm{E}(W^2) = \sum_{i=1}^{S} -\frac{2k_i\Phi_i'(1)}{z_i^2 \mathcal{Y}}, \tag{14}$$

where, $\mathcal{Y} = \sum_{\mathrm{i}=0}^{\mathrm{N}} \mathrm{i}\pi_{\mathrm{i}}$.

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,

$$\Psi(x) = 1 - \sum_{i=1}^{S} \frac{k_i \Phi_i'(1)}{\mathcal{Y}} e^{z_i x}, \text{ where, } \Psi(x) = \mathcal{R}^T \boldsymbol{F}(x), \text{ and } \mathcal{R} = [0, \frac{1}{\mathcal{Y}}, \frac{2}{\mathcal{Y}}, \ldots, \frac{\mathrm{N}}{\mathcal{Y}}]. \tag{15}$$

The 95^{th} 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 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.

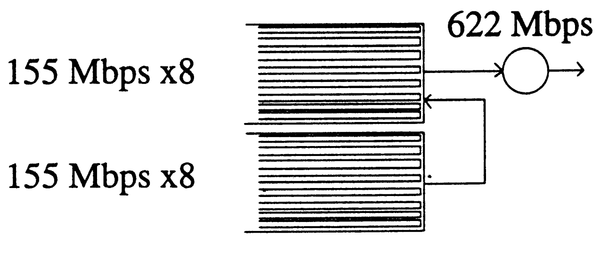

Figure 4: MUX1

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, $0 \le i \le N$. 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 lth buffer, $0 \le l \le N$. Let the transition rate in the server for the lth 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 :

$$(kr_l - c_0)\frac{dF_{0,k}(x)}{dx} = -[a + (n_l - k)\alpha_l + k\beta_l]F_{0,k}(x) + bF_{1,k}(x) + (k+1)\beta_l F_{0,k+1}(x) + (n_l - k + 1)\alpha_l F_{0,k-1}(x), \quad (16)$$

and

$$(kr_l - c_1)\frac{dF_{1,k}(x)}{dx} = -[b + (n_l - k)\alpha_l + k\beta_l]F_{1,k}(x) + aF_{0,k}(x) + (k+1)\beta_l F_{1,k+1}(x) + (n_l - k + 1)\alpha_l F_{1,k-1}(x). \quad (17)$$

Let $\boldsymbol{F}(x) = [(F_{0,0}(x), F_{1,0}(x)), (F_{0,1}(x), F_{1,1}(x)), (F_{0,2}(x), F_{1,2}(x)), \ldots (F_{0,n_l}(x), F_{1,n_l}(x))]^T$.
By rewriting the differential system of (16),(17) in matrix form, and by solving the corresponding eigenvalue problem (see [35] and references therein), the solution has the spectral representation,

$$\boldsymbol{F}(x) = \hat{\pi} + \sum_{i=1}^{\mathcal{S}} a_i \hat{\phi}_i e^{\hat{z}_i x}, \quad (18)$$

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

$$\overline{x} = \sum_{i=1}^{\mathcal{S}} \frac{a_i \mathbf{1}' \hat{\phi}_i}{\hat{z}_i}. \quad (19)$$

By Little's Law the average queuing delay for our system will be $\overline{x}/\rho$, where ρ is the average load of the sources. From the cumulative delay distribution function, we get, as in (15), the 95^{th} percentile delay.

4.4 4X2 Switch Structure and Modeling

We now consider the 4X4 switch module which consists of two identical 4X2 elements (switching submodules). Each input line is of OC-48 rate (2.4 Gbps). The cells that come to the 4X4 switch module will enter one of the two 4x2 submodules, depending on which pair of the four output lines they are destined to. Since the two 4X2 submodules are identical, we actually need to create identical models for both and then model them independently. In each 4x2 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

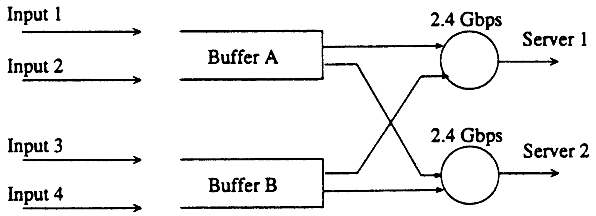

Figure 5: 4X2 Model Structure

enter the second buffer, as in Figure 5). All the cells are served by two OC-48 output lines (depending on destination) using a FIFO policy.

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 in [35] for the overflow probability in buffer A is,

$$Loss_A = \begin{cases} \sum_{i=0}^{B_u} \frac{(\lambda_{A,1}+\lambda_{B,1})}{\lambda_{A,1}} f(\frac{[\lambda_{A,1}+\lambda_{B,1}]i}{\lambda_{A,1}})(1 - G(\frac{[\lambda_{A,2}+\lambda_{B,2}][B_u-i]}{\lambda_{A,2}})), \\ \quad \text{for } f(\frac{[\lambda_{A,1}+\lambda_{B,1}]B_u}{\lambda_{A,1}}) < g(\frac{[\lambda_{A,2}+\lambda_{B,2}]B_u}{\lambda_{A,2}}) \\ \sum_{i=0}^{B_u} \frac{(\lambda_{A,1}+\lambda_{B,1})}{\lambda_{A,2}} g(\frac{[\lambda_{A,2}+\lambda_{B,2}]i}{\lambda_{A,2}})(1 - F(\frac{[\lambda_{A,1}+\lambda_{B,1}][B_u-i]}{\lambda_{A,1}})), \\ \quad \text{for } f(\frac{[\lambda_{A,1}+\lambda_{B,1}]B_u}{\lambda_{A,1}}) > g(\frac{[\lambda_{A,2}+\lambda_{B,2}]B_u}{\lambda_{A,2}}), \end{cases} \tag{20}$$

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 Figure 6, as four independent queueing systems, consisting of the homogeneous equivalent binary sources and a 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:

$$Loss = \sum_{i=0}^{B_d} \sum_{j=0}^{B_d-i} \sum_{k=0}^{B_d-i-j} f_1(i)f_2(j)f_3(k)(1 - F_4(B_d - i - j - k)), \tag{21}$$

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 functions. 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.

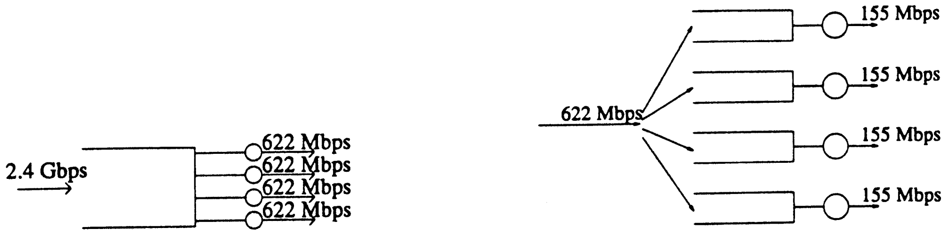

Figure 6: DEMUX1 and DEMUX2 Model Structure

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 95^{th} 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 THE DATANMOT

In this section we describe the model-based performance management methods, 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 [20] is incorporated in DATANMOT. By clicking the corresponding option in the graphical user interface menus (see Figure 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 direction, 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 Figures 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 [21]. The performance measures evaluated were cell loss probability, average cell delay, and the 95^{th} 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 Figures 9 through 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 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 Figure 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 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 Figure 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.

In Figures 15 and 16, a comparison of the model's prediction for average end-to-end delay and 95^{th} 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 prediction 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 95^{th} 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 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.

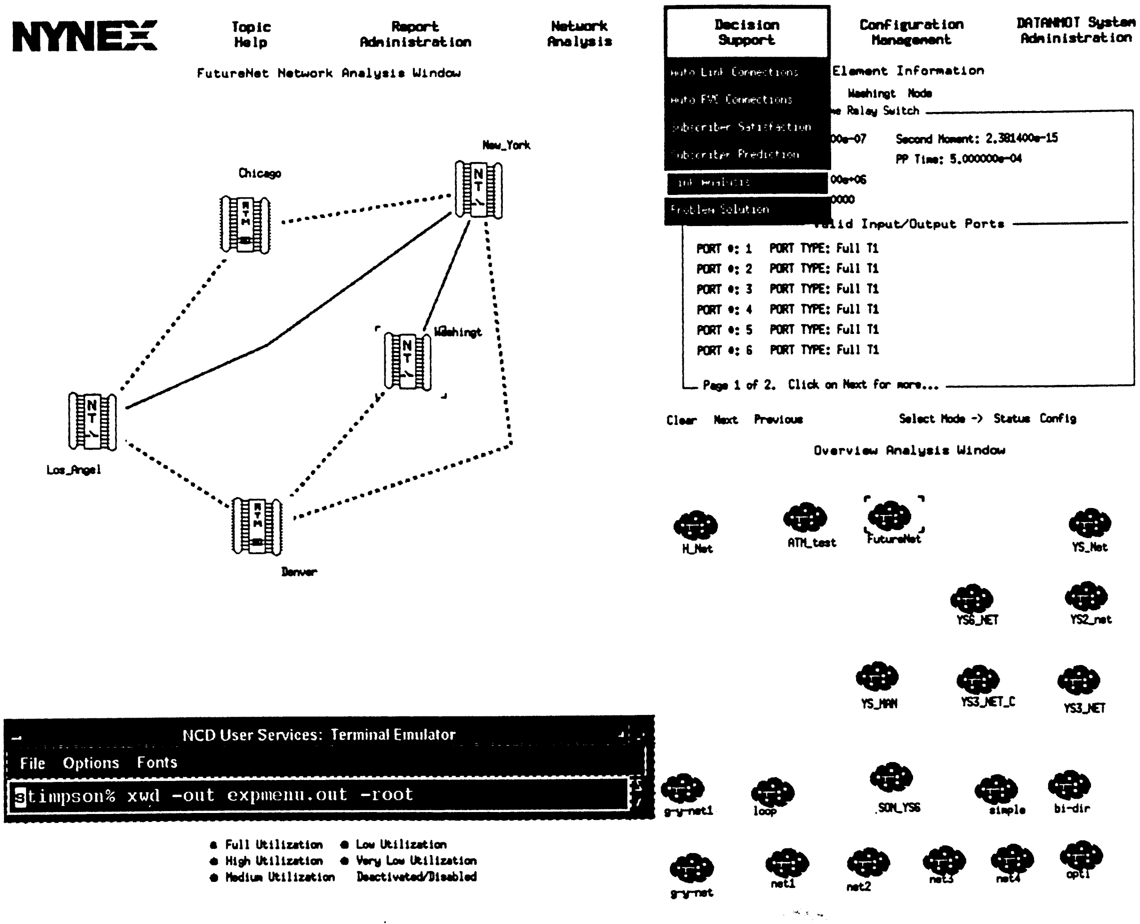

Figure 7: The DATANMOT Expert System Functions

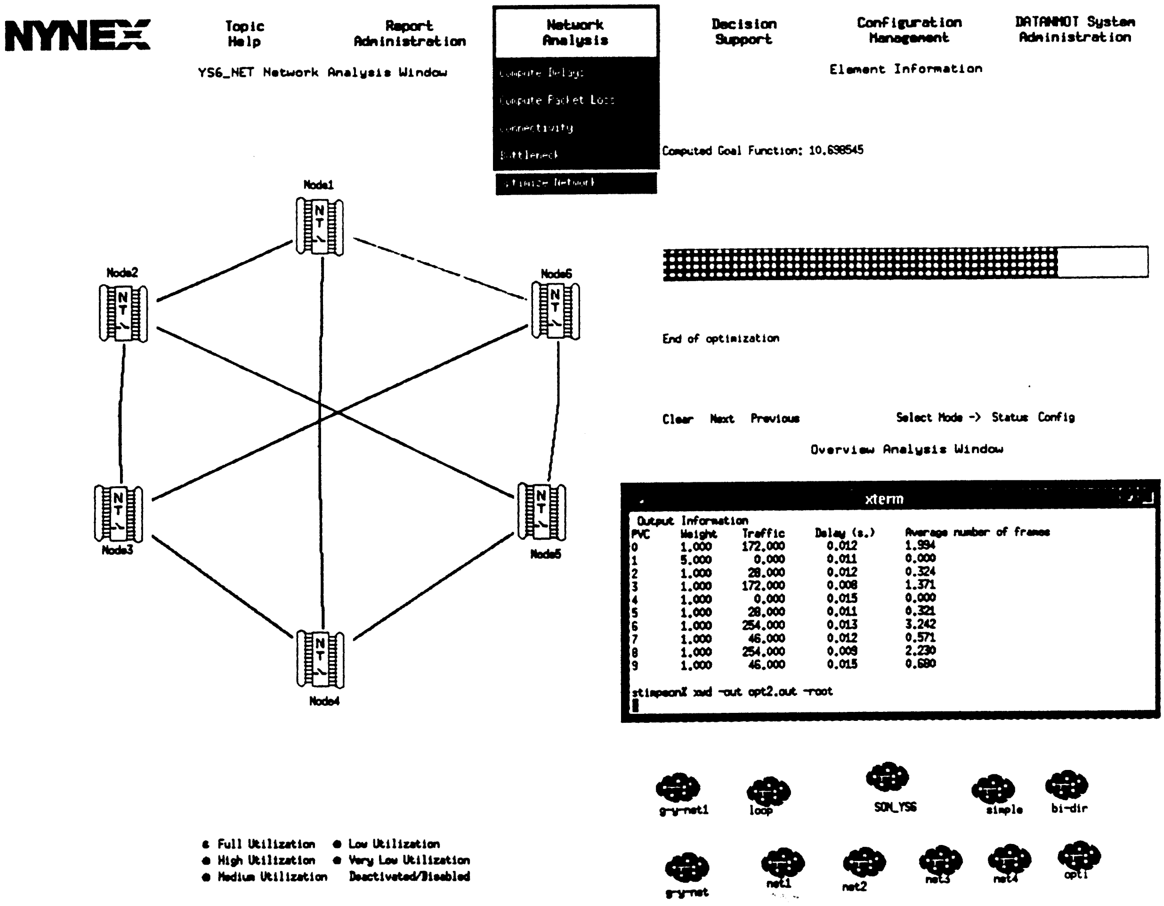

Figure 8: Routing Optimization Execution

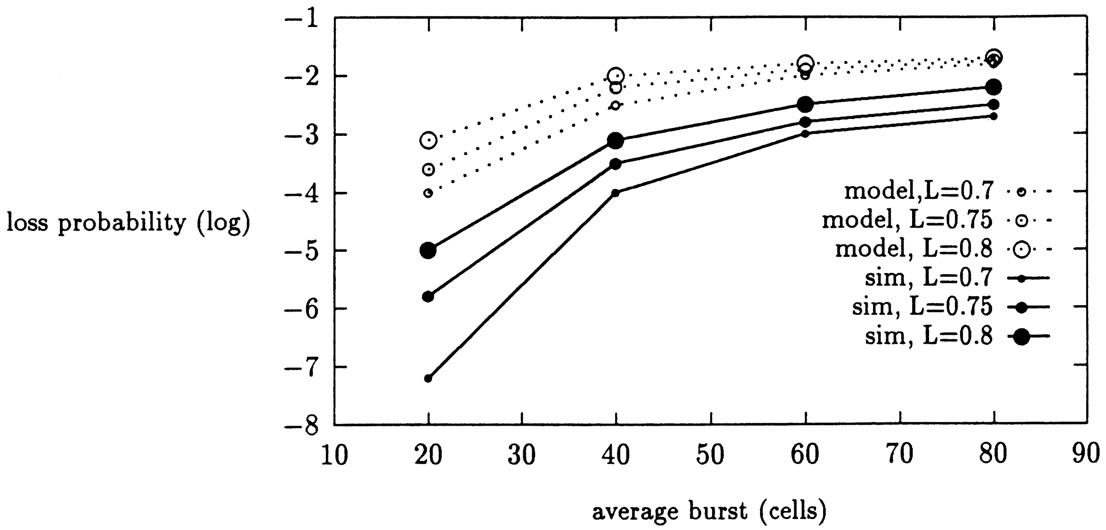

Figure 9: Model and simulation for MUX1 (homogeneous traffic sources)

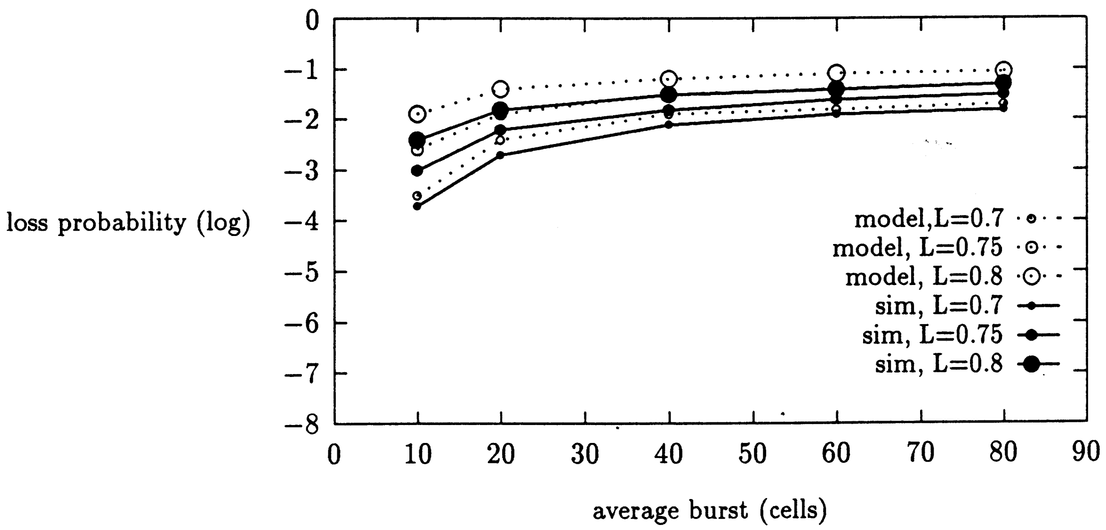

Figure 10: Model and simulation for DEMUX1 (homogeneous traffic sources)

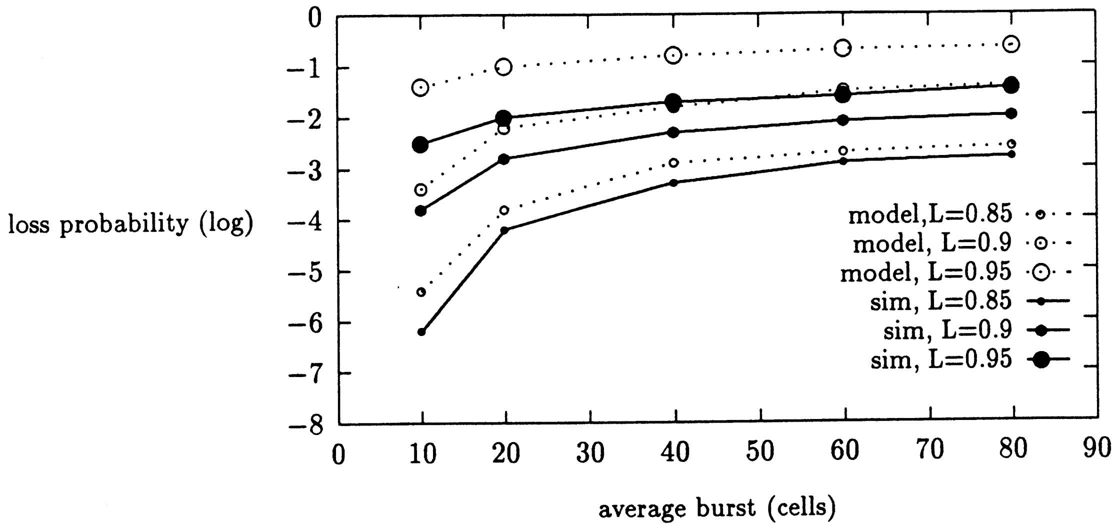

Figure 11: Model and simulation for SWITCH (homogeneous traffic sources)

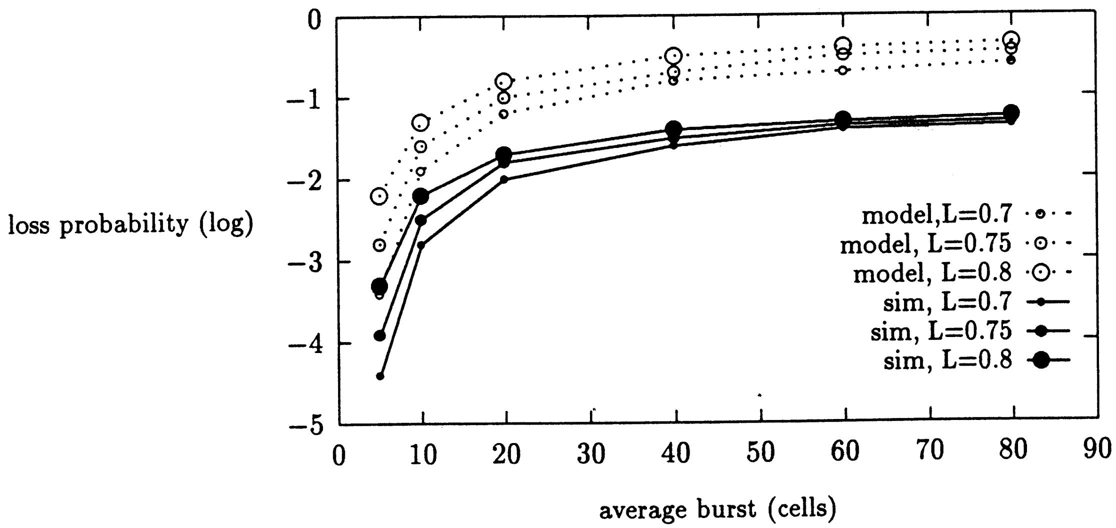

Figure 12: Model and simulation for DEMUX2 (homogeneous traffic sources)

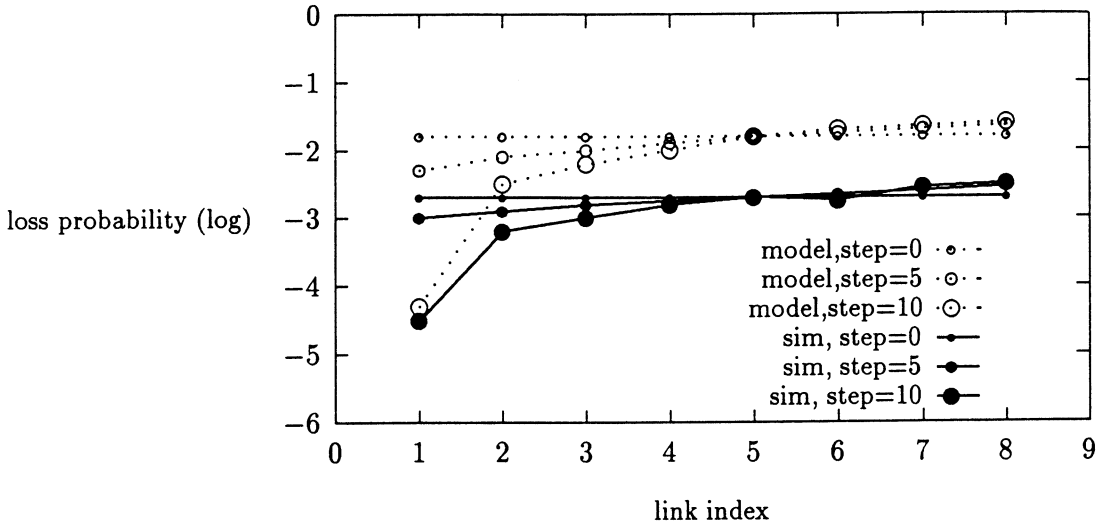

Figure 13: Model and simulation for MUX1 (heterogeneous traffic sources)

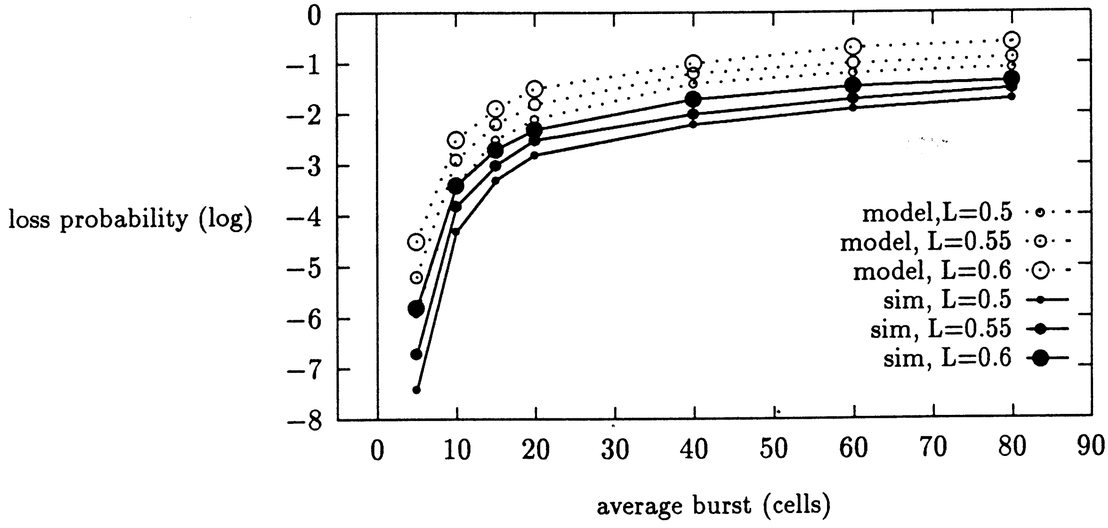

Figure 14: Model and simulation loss probability results for the end-to-end multistage switch

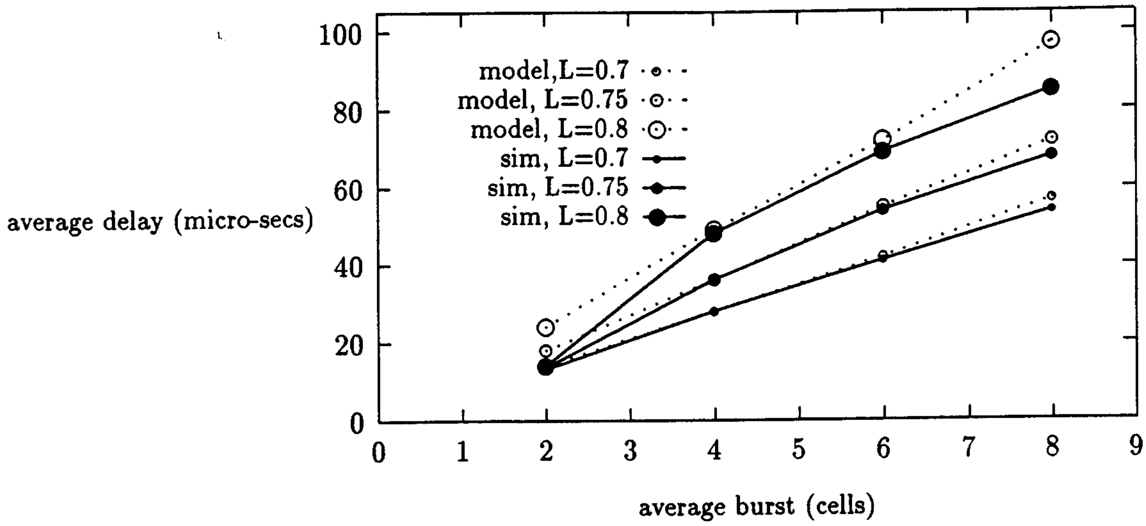

Figure 15: Model and simulation average delay results for the end-to-end multistage switch

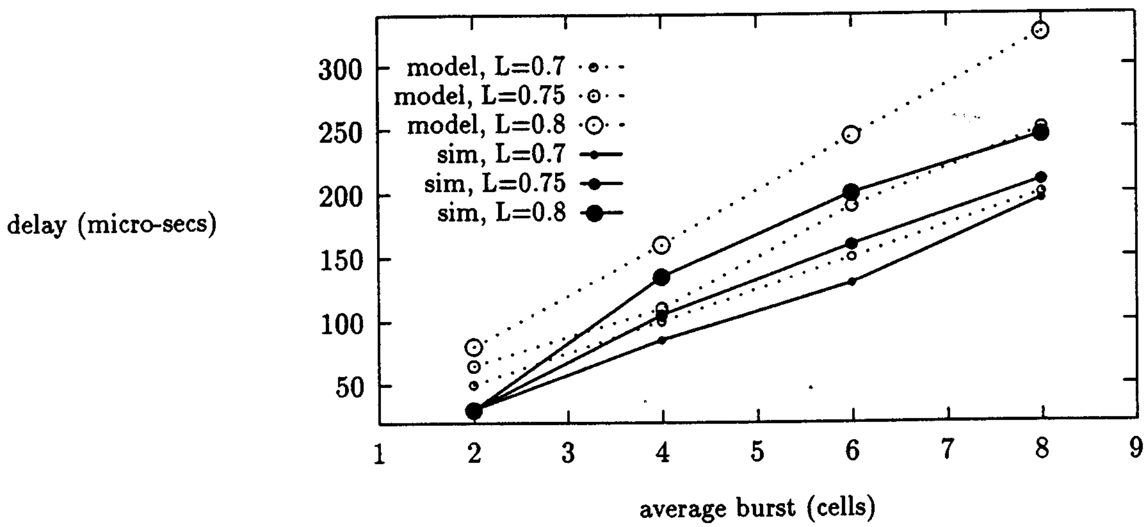

Figure 16: Model and simulation 95^{th} percentile results for the end-to-end multistage switch

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