Function	Definition
$F1$	$\langle l,n,d\rangle$
$F2$	$P_{max}-1\langle n\rangle$
$F3$	$\langle n\rangle$
$F4$	$\langle K_0,n,Token\rangle$
$F5$	$\langle K_0,n,NoToken\rangle$
$F6$	$[l=0\wedge d=0]\langle l,n,d\rangle+[d\neq 0\wedge l\neq 0]\langle\ominus l,n,\ominus d\rangle+$ $+[d=0\wedge l\neq 0]\langle\ominus l,n,d\rangle+[l=0\wedge d\neq 0]\langle l,n\ominus d\rangle$
$F7$	$[t=NoToken]\langle l,\oplus n,d\rangle$
$F8$	$[t=Token]\langle l,\oplus n,d\rangle$
$F9$	$\langle l,n,t\rangle$
$F10$	$\langle n,S\rangle$
$F11$	$\langle n,d\rangle$
$F12$	$\langle l,n,t,d\rangle$
$F13$	$\langle l,n,t,0\rangle$
$F15$	$\langle l,n,0\rangle$
$F16$	$\langle l,n,NoToken,d\rangle$
$F17$	$\langle l,n,NoToken,0\rangle$
$F20$	$[d=0]\langle\ominus l,n,d\rangle+[d\neq 0]\langle\ominus l,n,\ominus d\rangle$

Place color domain	Definition	Place	Initial marking
$D1$	In	M(SLOTS)	SLAT
$D2$	In,Co	M(TKN_ID)	$\langle n_1\rangle$
$D3$	Co,In,Tk	M(SCR)	$(P_{max}-1)\langle n_1\rangle$
$D4$	Co,In,Tk,Co	M(THINK)	S
$D5$	Co,In,Co		

FIGURE 2.2: Definitions of the functions, of the place color domanis and of the initial marking for the SWN model of Figure 1.

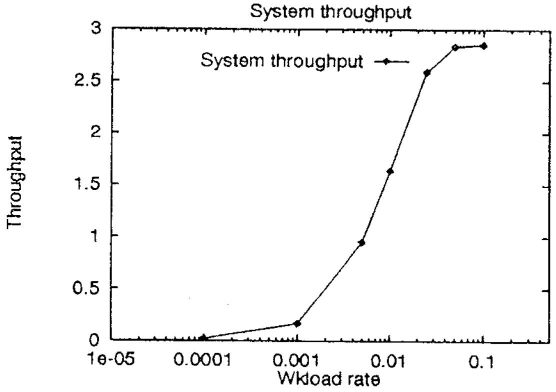

FIGURE 2.3: System throughput vs. rate of transition wkload.

CHAPTER 3

MODELING AND ANALYSIS OF MULTIACCESS MECHANISMS IN SUPERLAN

Adrian Popescu and Rassul Ayani

3.1 INTRODUCTION

Today, new multi-Gbps Local Area Networks (LANs) are designed to support a wide range of applications generating different isochronous and nonisochronous traffic at arbitrary bit rates. The growing demand for high bandwidth networking, under increasing performance constraints, has posed fundamental challenges to LAN design and implementation. In particular, due to the introduction of fiber optic technology, the performance bottleneck is no longer the transmission channel, but rather the network nodes. Three fundamental bottlenecks exist in a multi-Gbbps LAN environment that must be handled in order to achieve optimal performance. These are: the opto-electronic bottleneck, service bottleneck, and processing bottleneck.

The opto-electronic bottleneck results from the fact that networks are inherently limited by the use of electronic components at stations, resulting in performance limitations and inefficient resource utilization. The service bottleneck occurs between the Media Access Control (MAC) layer and the higher layers, and relates to the difficulties in providing the requested

Quality of Service (QoS) for all traffic classes which compete for common transport resources. Finally, the processing bottleneck is caused by the slow (software) processing versus high-speed transmissions.

A novel architectural solution, called SUPERLAN, has been proposed by Popescu[4] to open up all bottlenecks mentioned previously. SUPERLAN is an integrated multi-Gbps LAN where data rates up to 9.6 Gbps are provided in every data channel (isochronous or nonisochronous) for a variable number of stations (up to 60). Total network throughput of about 20 Gbps is achievable. Electronic logic speeds of 100 Mbps and processing speeds up to 20 - 30 MIPS are considered in the design. The total user traffic on the network is separated into two classes, isochronous and nonisochronous, each of which is allocated two or more wavelengths.

A Wavelength Division Multiplexing (WDM) network architecture is considered that is based on the Wavelength-Dedicated-to-Application (WDA) concept. Circuit switching services are considered for isochronous traffic, whereas packet switching services are considered for nonisochronous traffic, which are based on different delay-throughput trade-offs. Switched services at different rates, up to 1.2 Gslot/s, are assumed for each traffic class, for 8 bits/slot or more. Communicative and distributive multi-media services are also taken into account. These may include voice, audio, images, video and data traffic, and may require point-to-point and/or multi-point communications among a variable number of stations with a variable number of substations (at least 10 for every traffic class) connected to each station.

The network model has a physical ring configuration with $(n+1)$ stations. The network has a Master station (S_0) and n Ordinary stations, so-called SUPERLAN stations, denoted by $(S_1 - S_n)$. m substations $\{SS_{i1}, SS_{i2},..., SS_{ij},..., SS_{im}\}$ can be connected to each SUPERLAN station, where SS_{ij} represents the substation j connected to SUPERLAN station i. Each substation generates different types of traffic. Thus, every SUPERLAN station provides a flexible interconnection to different devices, such as multi-media workstations, high-performance computers, high-capacity storage systems, PBXs, diverse audio, image and video devices, with throughputs independent of the network data rates.

The Master station S_0 provides diverse auxiliary functions (clock and frame generation, total loop-length adjustments, resource allocation for isochronous traffic, network management, etc.), while the SUPERLAN stations S_1 - S_n provide communication channels for their (local) traffic. Any SUPERLAN station may transmit and receive simultaneously on both data and control channels.

A single optical fiber (unidirectional link) is used for station-to-station interconnection. A number of eight wavelength channels are used on the fiber.

The network is composed of eight logically separate subnetworks, but provides users with the functionality of a single, integrated multi-Gbps network. It makes use of eight parallel, wavelength-separated channels with time synchronization provided among subnetworks belonging to the same user-traffic class (see Popescu[4]).

A specific solution is proposed for the MAC protocols in SUPERLAN. In this solution, each traffic class/application is provided with its own simple, low-speed, application-oriented MAC protocol, with no interference from other applications. The MAC protocols are separated in the wavelength domain. Their main parameters are chosen based entirely on the application needs of interest. Two control channels, placed at two distinct wavelengths, are dedicated to multiaccess mechanisms for isochronous and nonisochronous control traffic, respectively. Furthermore, two additional channels, placed at two other wavelengths, are dedicated to isochronous and nonisochronous data traffic, respectively.

A Connection-Oriented (CO) procedure with a centralized MAC protocol is provided for the isochronous traffic. The three phases in a CO procedure are supported by different subnetworks in SUPERLAN, i.e., the connection and the termination phases by the control subnetwork, and the data transfer by the isochronous data subnetwork. In the first phase, unknown statistics are considered for isochronous traffic. An admission control mechanism operating at the call level and based on the peak rate for different isochronous traffic classes, both continuous bit-rate (CBR) and variable bit-rate (VBR), is used. The isochronous bandwidth resource available in the data subnetwork (up to 9.6 Gbps) is partitioned into separate bandwidth pools, dedicated to different isochronous traffic classes. This partitioning method is aimed at providing equalization of the blocking probabilities (i.e., fairness) among various traffic classes with different loads and bandwidth requirements. This is based on a multidimensional Erlang loss formula.

3.2 PERFORMANCE MODELING

The network model has a ring configuration (Fig. 3.1) consisting of a master station S_0, *n* ordinary stations that provide isochronous services $\{S_1, ..., S_i, ..., S_n\}$, and *m* (isochronous) substations connected to each ordinary station $\{SS_{i1}{}^2, SS_{i2}{}^1, ..., SS_{ij}{}^k, ..., SS_{im}{}^1\}$, where $SS_{ij}{}^k$ represents the substation *j* connected to station *i* that provides the subclass *k* of isochronous service. It is assumed that $SS_{ij}{}^k$ can provide only the isochronous traffic *k*, which is decided according to different performance experiments. In the case of multimedia substations/terminals, traffic differentiation is still considered according to this model.

In the model, *k* types of isochronous traffic subclasses, denoted by $\{t_1, ..., t_k\}$, are considered. The *k*-tuppel $\{b_1, b_2, ..., b_k\}$ denotes the number of temporal slots from the data channel *w_d* that are allocated (per call) to these subclasses in every 125 µs frame, i.e., b_k corresponds to peak traffic per call for subclass *k*. For instance, the (CBR) voice traffic needs, in this case, only one slot with a capacity of 64 kbps (i.e., 8 bits/slot), whereas a (VBR) video traffic of type high definition television (HDTV) needs 400 slots of 768 kbps (i.e., 96 bits/slot) every 125 µs frame. This results in a peak traffic of about 300 Mbps.

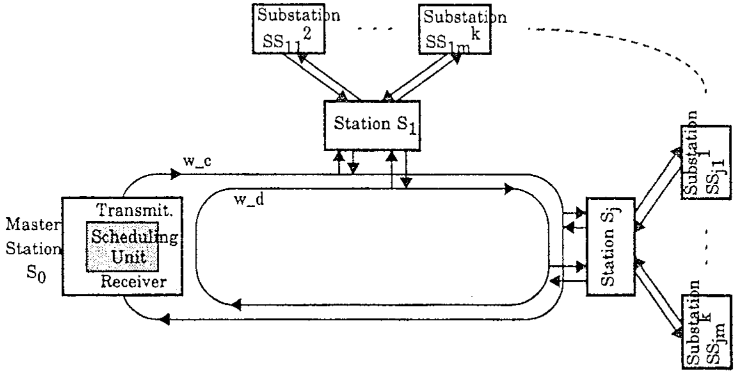

FIGURE 3.1. Network Model for Isochronous Traffic

A specific policy for resource partitioning is used in the master station for allocating bandwidth resource (i.e., temporal slots in *w_d*) to different classes of traffic and demanding stations. According to this, each traffic class has access to a maximum of $\{w_1, w_2, ..., w_k\}$ temporal slots (of 10 ns each) in every 125 µs frame (bandwidth pools).

The ordinary station S_i is modeled by a multiqueue system with a single cyclic server for the transmission side, and a buffer with two servers for the receive side (Fig. 3.2). A head-of-line (HOL) non-preemptive M/D/1 model with three queues is used to model the transmission side. These queues are dedicated to disengagement requests (priority 2), signaling messages (priority 3), and requests for call setup (priority 4). The highest priority in the transmit multiqueue (Fig 3.2) is given to the incoming upstream traffic, i.e., the incoming control cells from the control channel *w_c* that are not addressed to that station, and therefore continue further to the next station. Hence, this is a multi-user system with an intermittently available server. In addition, an exhaustive policy is used for serving the accumulated cells in the transmit multiqueue. According to this policy, all newly arrived control cells may be transmitted in the same 125 µs frame, under the condition that they do not exceed the number of cells allowed for that station to be transmitted in one frame.

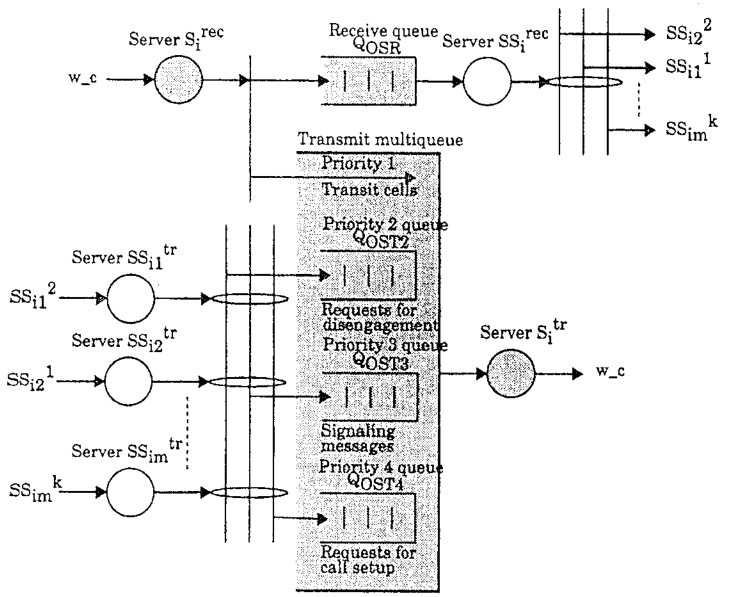

FIGURE 3.2. The Queueing Model for Ordinary Station S_i

The master station S_0 assumes a fork-join model, where the different incoming cells are differentiated, processed (or delayed), and joined for further transmission onto the *w_c* channel (Fig. 3.3). Four servers and four queues are used to model the master station. The join model has a HOL non-preemptive M/D/1 form, with two queues. These queues are dedicated to signaling messages (priority 1) and MAC messages (priority 2).

A destination removal scheme is used for removing transmitted cells from the *w_c* channel, i.e., the destination station is responsible for the removal of cells addressed to it.

There are two algorithms for iso MAC protocol, namely in the master station (**procedure** *mac_ms*) and in the ordinary station (**procedure** *mac_os*).

The *mac_ms* algorithm contains five distinct **procedures:** *mac_ms_in* (initialization), *mac_ms_tr* (transmission), *mac_ms_rc* (reception), *mac_ms_set* (service of requests for call setup), and *mac_ms_dis* (service of requests for disengagement). The last four procedures operate concurrently. The *mac_os* algorithm contains three distinct and specific **procedures** that operate concurrently: *mac_os_in* (initialization), *mac_os_tr* (transmission), and *mac_os_rc* (reception). The interested readers are referred to Popescu[4] for details of these algorithms.

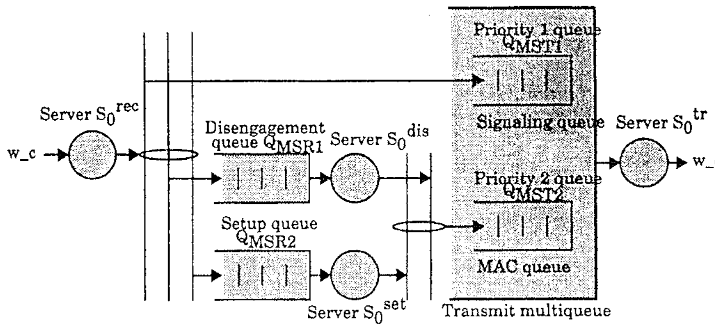

FIGURE 3.3. The Queueing Model for Master Station S_0

A simple complete partitioning policy is chosen for the resource allocation in the *w_d* channel. The fairness criterion used for the (preliminary) partitioning of resources to different traffic classes (with different bandwidth requirements on *w_d*) is based on the balancing/equalization of blocking probabilities for these traffic classes, i.e.,

$$\mathbf{P}_{B,1} \approx \mathbf{P}_{B,2} \approx \dots \approx \mathbf{P}_{B,j} \approx \dots \approx \mathbf{P}_{B,k} \tag{3.1}$$

where $\mathbf{P}_{B_j}$ is the probability of blocking for traffic class *j*.

A similar complete partitioning policy is used for resource allocation, in the *w_c* channel, among the demanding stations S_i. Accordingly,

$$\mathbf{C}^c = \sum_{i=1}^{n} \mathbf{C}_i^c \tag{3.2}$$

where $\mathbf{C}^c$ is the number of temporal slots in *w_c* allocated for MAC purposes, and $\mathbf{C}_i^c$ is number of cells allocated to station i ($1 \le i \le n$). Fairness is provided, in this case, by a specific partitioning of the *w_c* resource, where $\mathbf{C}_i^c$ reflects the percentage traffic intensity demands of station S_i. Accordingly,

$$\mathbf{C}_i^c = \zeta_i^c \cdot \Lambda \tag{3.3}$$

where Λ is the total (average) arrival rate at the master station for call setup requests, and

$$\sum_{i=1}^{n} \zeta_i^c = 1 \tag{3.4}$$

Also

$$\mathbf{C}_i^c \ge \lambda_i \tag{3.5}$$

3.3 PERFORMANCE METRICS

The performance metrics used are the *call setup delay*, the *blocking probability*, and the *expected number of blocked calls*. The assumptions made in this analysis are:

- Static resource allocation policies are used to assign the *w_d* and *w_c* channels to the k traffic classes (data channel allocation), and to the n stations (control channel allocation);
- Exhaustive policies are used for serving the requests for resource in *w_c* and *w_d* channels;
- No signaling procedures (and messages) are considered in this model;
- Similar procedures for call setup and disengagement are assumed for all k classes of traffic;
- All substations SS_{ij} are assumed to behave independently;
- The generation of requests for call setup at each substation SS_{ij}^l (providing class l traffic) follows a Poisson process with average arrival rate $\lambda_{ij}^l = \lambda^l$;
- An uniform distribution is assumed in choosing the destination address. According to this, a request for call generated at substation SS_{ij} (where $1 \le i \le n$; $1 \le j \le m$) is targeted to station S_x (where $1 \le x \le n$; and $i \ne x$) with probability 1/n, and to substation SS_{xy}^l (where $1 \le y \le m$; and $j \ne y$) with probability (1/n) (1/m^l). The parameter m^l represents the number of substations per station dedicated to class l traffic;
- The call holding times for all k traffic classes are assumed to have exponential distribution with average values $(\mu^l)^{-1}$ (where $1 \le l \le k$);
- Calls are considered to be aborted if the substation cannot access the *w_d* resource in a time period exceeding one second after sending the request for call setup;
- The (transmission and processing) delay between a station and its substations is ignored, since this is a minor part of the total call setup time; and
- All servers (Figures 3.2 and 3.3) have deterministic, constant processing times.

The performance metrics are evaluated as follows.

3.3.1 Setup Delay

The *call setup delay time*, denoted by T for an isochronous call, is the time taken from the instance a substation/user generates a request for call setup to when the substation receives the answer message from the master station. This delay includes:

- the queueing delay W_{QOS} in the queue Q_{OST4} at the ordinary station (Fig. 3.2);
- the access time W_{AOS} at the ordinary station, i.e., the time taken for the first element/cell in queue Q_{OST4} to get its first free (temporal) slot in *w_c*;
- the transmission times T_{TR} at the ordinary and master stations;
- the transmission delays T_D to and from the master station, including the propagation delay on optical fiber and cross-station delays through the intermediate stations;

- the queuing delay W_{QMSR} in the queue Q_{MSR2} in the master station (Fig. 3.3);
- the processing time T_{MS} at the server S_0^{set} in the master station (Fig. 3.3);
- the waiting time W_{QMST} in the queue Q_{MST2} in the master station (Fig. 3.3); and
- the synchronization latency W_{SYNC} between the data and control channel.

It is assumed that the processing time of server SS_i^{rec} is small enough to avoid queuing in the receive queue Q_{OSR} at the ordinary station (Fig. 3.2). The processing delay of server S_0^{rec} is included in T_D^{iso}. Also, the vacation periods due to the sync header SH, trailer T and gap G fields in the *w_c* temporal frame are ignored, since their contribution to the call setup delay is negligible. This means that an uniform distribution is assumed in accessing the temporal slots in the *w_c* channel.

Taking expectations of the above-mentioned times, we have:

$$E[T] = E[W_{QOS}] + E[W_{AOS}] + 2 \cdot T_{TR} + 2 \cdot E[T_D] + E[W_{QMSR}] +$$

$$+ T_{MS} + E[W_{QMSR}] + T_{MS} + E[W_{QMST}] + E[W_{SYNC}] \qquad (3.6)$$

where,

- the average waiting time in the queue Q_{OST4} at the ordinary station can be calculated with the formula for a low priority queue in a HOL non-preemptive M/D/1 model (see Bertsekas et al.[2])

$$E[W_{QOS}] = \frac{2\lambda_i (m_{ctr})^2}{2(1-\rho_i)(1-2\rho_i)} = \frac{\lambda_i (m_{ctr})^2}{(1-\lambda_i m_{ctr})(1-2\lambda_i m_{ctr})} \qquad (3.7)$$

where m_{ctr} is the (constant) length of the cell (temporal slot in *w_c*); ρ_i is the traffic intensity at the ordinary station i, which is given by

$$\rho_i = \frac{\lambda_i}{\mu_{ctr}} = \lambda_i m_{ctr} \qquad (3.8)$$

Furthermore, the parameter λ_i represents the average arrival rate for call setup (or disengagement) requests at station *i*. This is calculated with

$$\lambda_i = \sum_{j=1}^{m} \lambda_{ij} \qquad (3.9)$$

- the average access time $E[W_{AOS}]$ at the ordinary station has two components that are due to the limited capacity available during one temporal frame of 125 μs (fairness considerations) $E[W_{LM}]$, and to the periods of server inability $E[W_{BS}]$. These are busy time slots used by the upstream ordinary stations, to send request cells, and by the master station, to send response cells, with two response cells for each incoming request cell. An exhaustive policy is used in accessing temporal slots in the *w_c* channel, i.e., every station is allowed to transmit its cells in idle slots as long as the number of transmitted cells in one frame does not exceed a fixed, predetermined number. $E[W_{LM}]$ is calculated with the formula for a M/D/1 model with limited service (see Bertsekas et al.[2]), and $E[W_{BS}]$ is calculated with a formula similar to (3.7).

$$E[W_{AOS}] = E[W_{LM}] + E[W_{BS}] =$$

$$= \left[\frac{n^2\lambda_i}{2(1-n m_{ctr}\lambda_i)} + \frac{\frac{3}{2}\Lambda + \lambda_i}{2\left(1-\frac{3}{2}m_{ctr}\Lambda\right)\left(1-\frac{3}{2}m_{ctr}\Lambda - m_{ctr}\lambda_i\right)}\right](m_{ctr})^2 \qquad (3.10)$$

The parameter *n* is the number of stations in the network, and Λ is the average arrival rate at master station for call setup (or disengagement) requests, which is given by

$$\Lambda = \sum_{i=1}^{n} \lambda_i \qquad (3.11)$$

An average traffic $\Lambda/2$ from upstream ordinary stations is considered to pass through the ordinary station. Accordingly, the average traffic due to the master station is Λ.

- the transmission time for one cell (i.e., the service time for servers S_0^{tr} and S_i^{tr}) is fixed

$$T_{TR} = m_{ctr} \qquad (3.12)$$

- the average value of the transmission delay to/from the master station is modeled as

$$E[T_D] = \left(\left\lceil \frac{n+1}{2} \right\rceil\right)\left(\delta\, m_{ctr} + \frac{3}{2} m_{ctr}\right) = \left(\left\lceil \frac{n+1}{2} \right\rceil\right)\left(\delta + \frac{3}{2}\right) m_{ctr} \qquad (3.13)$$

where the parameter $\delta \cdot m_{ctr}$ captures the propagation delay between stations, and the parameter $(3/2) \cdot m_{ctr}$ is the service time of server S_0^{rec} or S_i^{rec}.

- the processing time in the master station is captured by

$$T_{MS} = \alpha\, m_{ctr} \qquad (3.14)$$

- the average waiting time in the queue Q_{MSR2} at the master station is calculated with the formula for M/D/1 model

$$E[W_{QMSR}] = \frac{\Lambda\, (\alpha)^2 (m_{ctr})^2}{2(1-\Lambda\, \alpha\, m_{ctr})} \qquad (3.15)$$

- the average waiting time in the queue Q_{MST2} at the master station approaches zero (i.e., $E[W_{QMST}] \approx 0$) under the assumption that the servers S_0^{set} and S_0^{dis} have equal service times.
- the synchronization delay is averaged over the station position in the ring, with reference to the master station

$$E[W_{SYNC}] = \frac{(\beta + 1) f}{2} \qquad (3.16)$$

where the parameter β depends on the number of stations in network and the cell size, and f is the frame size, i.e., $f = 125$ µs. For a number of stations less than 60, $\beta = 1$ (see Popescu[4]).

3.3.2 Blocking Probability

The network is modeled, with respects to the data channel *w_d* and for class *l* traffic, as a circuit-switched exchange, where the number of inputs is given by the total number of users of class *l*, and the number of outputs is given by the maximum number of calls of class *l* that can be simultaneously serviced. Accordingly, the blocking probability $\mathbf{P}_{B,l}^{tc}$ (time congestion) for class *l* traffic (where $1 \le l \le k$), in a generic loss system with X_l inputs (homogeneous sources) and Y_l outputs (where $X_l > Y_l$), can be calculated with the Erlang formula (see Schwartz[5])

$$\mathbf{P}_{B,l}^{tc} = \frac{\left(\frac{\lambda^l}{\mu^l}\right)^{Y_l} \binom{X_l}{Y_l}}{\sum_{n_l=0}^{Y_l} \left(\frac{\lambda^l}{\mu^l}\right)^{n_l} \binom{X_l}{n_l}} \qquad (3.17)$$

where every user is either idle (in the case of class *l* traffic) for an (exponential) period of average $(\lambda^l)^{-1}$, or (eventually) generates a call with (exponential) call/session time of average $(\mu^l)^{-1}$. Furthermore,

$$\binom{x}{y} = \frac{x!}{(x-y)!\,y!} \qquad (3.18)$$

is the usual notation for the number of combinations of x objects taken y at a time ($x > y$).

The parameter X_l is the total number of users in the network that provide class *l* traffic

$$X_l = \sum_{i=1}^{n} \sum_{j=1}^{m} ss_{ij}^{l} \qquad (3.19)$$

The parameter Y_l represents the maximum number of calls of class l traffic that can be simultaneously serviced by the network

$$Y_l = \left\lfloor \frac{w_l}{b_l} \right\rfloor \qquad (3.20)$$

The parameter b_l is the peak traffic allocated to call of type l and w_l is the total number of temporal slots in *w_d* dedicated to traffic class l in every 125 μs frame (bandwidth pool).

As mentioned in section 3.2, fairness is enforced by providing a specific preliminary percentage allotment of the total resource, available in the *w_d* channel, among the traffic classes. This resource partitioning is done according to the network configuration (i.e., the total number of substations dedicated to different traffic classes) to provide better balancing of blocking probabilities for these traffic classes.

3.3.3 Expected Number of Blocked Calls

The expected number of blocked calls per unit of time (1 hour) for class l traffic is calculated with:

$$\mathbf{N}_{B,l} = n_l^{ut} \cdot \mathbf{P}_{B,l}^{cc} \qquad (3.21)$$

where n_l^{ut} represents the expected number of calls per unit of time for class l traffic, and $\mathbf{P}_{B,l}^{cc}$ is the loss probability (call congestion) of class l traffic. To calculate the parameter n_l^{ut}, we use the formula of traffic intensity for a finite population system (see Körner[3])

$$n_l^{ut} = \rho_s^l \cdot \mu^l = \frac{X_l \cdot \rho_u^l}{1 + \rho_u^l (1 - \mathbf{P}_{B,l}^{cc})} \cdot \mu^l \qquad (3.22)$$

where ρ_s^l represents the traffic intensity per system for class l traffic, and ρ_u^l is the traffic intensity per user for class l traffic ($\rho_u^l = \lambda^l / \mu^l$).

The loss probability $\mathbf{P}_{B,l}^{cc}$ (call congestion) for a number of X_l inputs can be calculated with the Engset formula (see Körner[3] and Schwartz[5])

$$\mathbf{P}_{B,l}^{cc}(X_l) = \mathbf{P}_{B,l}^{tc}(X_l - 1) \qquad (3.23)$$

where $\mathbf{P}_{B,l}^{tc}(X_l - 1)$ is the blocking probability (time congestion) for $(X_l - 1)$ inputs (eq. 3.17).

3.4 PERFORMANCE EVALUATION

The performance of a class of centralized MAC protocols for isochronous traffic is evaluated in terms of the main parameters of interest: the call setup delay, the blocking probability and the expected number of blocked calls.

3.4.1 Test Conditions

The following test conditions are considered for performance evaluation:

- A cell structure with 74 bits/cell is used in *w_c* (see Popescu[4]);
- Balanced configuration is assumed for traffic intensity demands from all stations;
- $m_{ctr} = 74 \cdot 10$ ns $= 740$ ns (cell length);
- $C^c = a = 166$ (number of slots in *w_c* allocated for MAC in one 125 μs frame - equation 3.2);
- $n = 64$ (maximum number of stations);
- $m = 16$ (number of substations per station);
- $C_i^c = 3$ slots/frame for $i = 1$ to 38; and $C_i^c = 2$ slots/frame for $i = 39$ to 64 (resource partitioning in *w_c*);
- $k = 3$ (number of application/traffic classes);
- $b_1 = 64$ kbps (peak rate for class 1 traffic - telephony

application);

- b_2 = 48 Mbps (peak rate for class 2 traffic - still picture/graphics application);
- b_3 = 307 Mbps (peak rate for class 3 traffic - application of type color full-screen, full-motion video);
- B_1 = 1 slot/frame with 8 bits/slot (resource allocated to class 1 call in *w_d*);
- B_2 = 125 slots/frame with 48 bits/slot (resource allocated to class 2 call in *w_d*);
- B_3 = 400 slots/frame with 96 bits/slot (resource allocated to class 3 call in *w_d*);
- w_1 = 320 slots/frame (bandwidth pool allocated for class 1 traffic in *w_d*);
- w_2 = 2900 slots/frame (bandwidth pool allocated for class 2 traffic in *w_d*);
- w_3 = 9200 slots/frame (bandwidth pool allocated for class 3 traffic in *w_d*);
- λ^1 = 5 requests/h (average number of requests for class 1 call);
- λ^2 = 3 requests/h (average number of requests for class 2 call);
- λ^3 = 2 requests/h (average number of requests for class 3 call);
- $(\mu^1)^{-1}$ = 3 min (average session time for class 1 call);
- $(\mu^2)^{-1}$ = 20 min (average session time for class 2 call);
- $(\mu^3)^{-1}$ = 30 min (average session time for class 3 call).

3.4.2 Setup Delay

Fig. 3.4 shows the variation of the expected call setup delay time E[T] with the processing time in master station T_{MS}, for different number of stations available on the ring and for a control cell size b = 74 bits/cell. A long distance of about 1.5 km is assumed between stations, which corresponds to $\delta = 10$ (equation 3.13). Also, the service partitioning per station is assumed to be $\{m^1, m^2, m^3\} = \{14, 1, 1\}$, where m^l represents the number of substations per station dedicated to class l traffic.

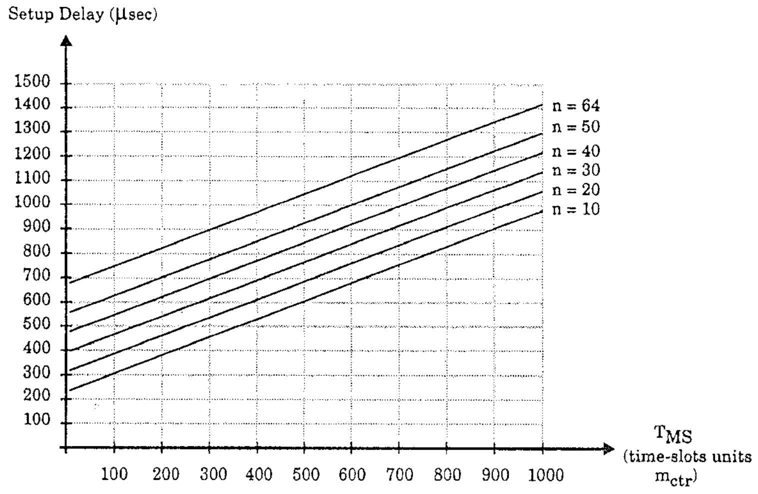

FIGURE 3.4. Call Setup Delay Time for Isochronous Traffic with n Stations

Good performance results are obtained for call setup delay times E[T] in that they do not exceed 1.5 ms for even extreme conditions such as assuming long distance between stations, maximum number of stations, high arrival rates for call setup requests, and large processing times in master station to serve the requests for call setup. Also, it is seen from this figure that there is no congestion in the *w_c* channel. There are therefore no aborted calls because of access delays exceeding 1 second.

These performance results are mainly due to the large capacity available in *w_c*, whereby the contention for this resource is practically eliminated. The disadvantage, however, is that resource is wasted in the *w_c* channel. To minimize this, powerful signaling mechanisms acting at a call level and/or during the call can be developed on *w_c* as well.

The only element that could create congestion in the *w_c* channel is the processor in the master station S_0^{set} in the case of large processing times and/or sophisticated algorithms for resource allocation (to improve the blocking probability). It is, however, not the case in this model. For instance, about 50 high-level instructions are required to implement the **procedure** *mac_ms_set* (see Popescu[4]). This corresponds to about 3 Millions of Instructions Per Second (MIPS) in the case $T_{MS} = 100\ m_{ctr}$, and less than 1 MIPS when T_{MS} is larger than 300 m_{ctr}. The first congestion limit (i.e., for $n = 64$) is met in the case of very slow processing in the master station, at $3 \cdot 10^{-4}$ MIPS, which corresponds to $T_{MS} \approx 10^6\ m_{ctr}$. An average number of four low-level instructions are considered in this case for one high-level instruction. A large reserve of processing capability is therefore available to implement better mechanisms for resource partitioning in *w_d* and to improve the blocking performance.

3.4.3 Blocking Probability

Fig. 3.5 shows a representative group of analytical curves for the blocking probability $\mathbf{P}_{B,3}{}^{tc}$ as a function of offered traffic $\rho^3 = \lambda^3/\mu^3$ for different numbers of class 3 users in the network. The total number of class 3 users in the network is given by $n{\cdot}m^3$, where n is the number of stations and m^3 is the number of substations per station dedicated to class 3 traffic.

The model is a birth-death process, with arrival rate $\lambda_x{}^l$ and departure rate $\mu_x{}^l$ when x calls are in progress:

$$\lambda_x^l = (X_l - x)\lambda^l \qquad for \quad 0 \le x \le Y_l \le X_l \qquad (3.24)$$

$$\mu_x^l = x \cdot \mu^l \qquad for \quad 1 \le x \le Y_l \qquad (3.25)$$

where X_l represents the total number of substations in the network that provide class l service, and Y_l represents the maximum number of simultaneous calls supported for class l traffic. When $X_l > Y_l$, the Engset distribution provides the best approximation for the model statistics. However, when $X_l >> Y_l$ and $\lambda^l \dashrightarrow 0$, the model is better captured with the Erlang distribution (see Schwartz[5]). For $X_l = Y_l$, a binomial distribution is obtained.

Fig. 3.6 shows an example of network dimensioning to obtain fair (i.e., balancing of) blocking probabilities among different traffic classes, in the case of three traffic classes and a fixed resource partitioning in *w_d*.

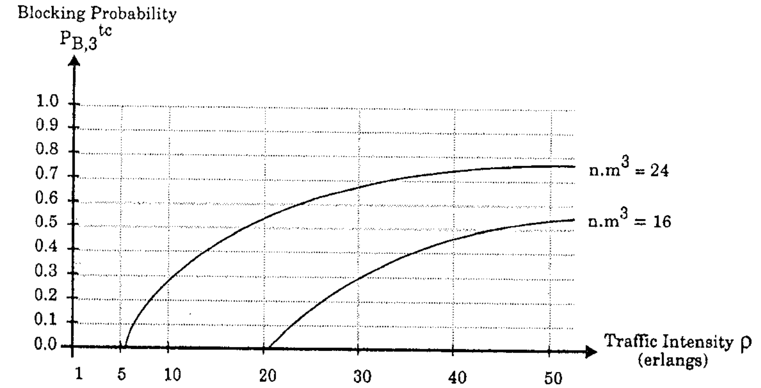

FIGURE 3.5. Blocking Probability for Class 3 Traffic

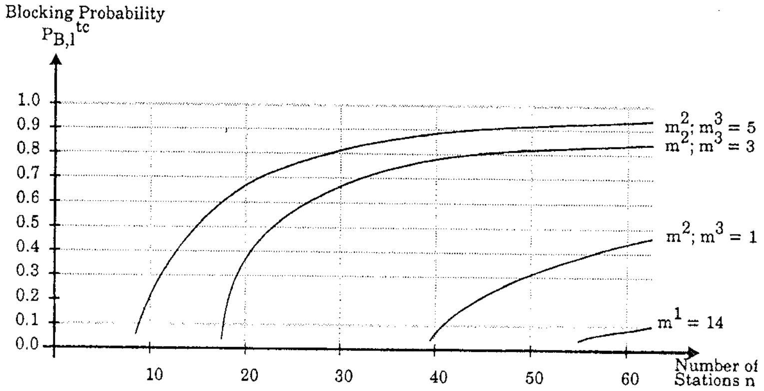

FIGURE 3.6. Blocking Probability versus Number of Stations

The best fairness performance is provided when

$$\{m^1,\ m^2,\ m^3\} = \{14,\ 1,\ 1\} \qquad (3.26)$$

where m^l represents the number of substations per station dedicated to class l traffic. Also,

$$m = m^1 + m^2 + m^3 = 16 \qquad (3.27)$$

As Fig. 3.6 indicates, the blocking probabilities for all traffic classes are, in this case, the same for a number of stations n up to about 40 and for $\{m^1, m^2, m^3\} = \{14, 1, 1\}$. Beyond this n, $\mathbf{P}_{B,2}{}^{tc}$ and $\mathbf{P}_{B,3}{}^{tc}$ increase more rapidly than $\mathbf{P}_{B,1}{}^{tc}$ because of higher traffic intensity ρ offered for classes 2 and 3.

The main limitation for blocking probability is given by the policy used in the master station for resource allocation that is of the fixed/static resource allocation type. Dynamic access policies, based on dynamic resource sharing mechanisms for resource allocation, must be used to improve the blocking performance. These models provide stations free access to a variable resource in w_d according to instantaneous needs for bandwidth, resource availability, fairness criteria, and access control mechanisms.

3.4.4 Expected Number of Blocked Calls

Fig. 3.7 shows the number of class 3 calls expected to be blocked in an one hour period for different (user) traffic intensities ρ_u and a variable number of users in the network.

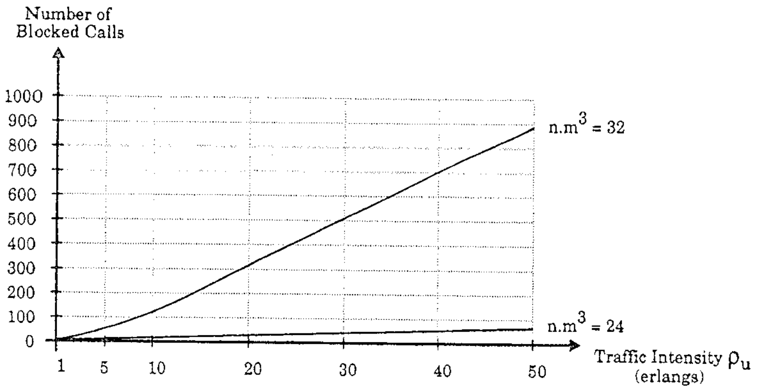

FIGURE 3.7. Expected Number of Blocked Calls for Class 3 Traffic

The parameter $n{\cdot}m^3$ represents the number of class 3 users in the network, where n is the number of stations and m^3 is the number of substations per station dedicated to class 3 traffic.

3.4.5 Simulation Experiments

A satisfactory performance evaluation of the protocol requires observation of SUPERLAN for at least one hour. Considering the slotted ring structure of SUPERLAN (for instance, with a frame size of 125 µs and slots of 740 ns), a detailed simulation of the protocol would require several weeks of computer time. As an alternative solution, we developed a parallel discrete-event simulator and conducted several simulation experiments. The parallel simulator used both a Conservative Time Window based and an optimistic Time Warp based scheme. Description of the parallel simulator and its performance is beyond the scope of this paper. The interested readers are referred to Ayani et al.[1]

3.5 CONCLUSIONS AND FURTHER RESEARCH

Performance modeling, analysis, and evaluation of a class of MAC protocols for isochronous traffic has been presented. The protocol performance was evaluated in terms of delay for call setup, blocking probability, and expected number of blocked calls.

The performance results show that there is no congestion in the control channel to serve the requests for call setup, and delay requirements are well fulfilled. A large reserve of processing capability is available in the master station to develop specific (and more sophisticated) mechanisms for resource partitioning.

The blocking probability for a simple model, based on static resource partitioning in the master station, has been analyzed and evaluated. The main performance limitation in this case is caused by the policy used for resource allocation, which is a static algorithm and cannot use the resources efficiently. However, we believe that dynamic resource sharing mechanisms can reduce the blocking probability. These mechanisms can provide stations free access to a variable resource, according to their needs for bandwidth, resource availability, fairness criteria, and access control mechanisms. These are topics for further research.

Signaling mechanisms, to complement the MAC protocol, and procedures for multipoint communication, must also be studied and developed. Given the large resource available in the control channel, powerful signaling protocols can be developed to improve system performance.

Finally, another area of interest is to study the separation of the Continuous Bit-Rate (CBR) traffic from the Variable Bit-Rate (VBR) traffic, together with specific media access mechanisms acting at the call and/or burst level. This separation can be done either in the time or in wavelength domain. Similarly, the control channels for these two classes of traffic can be separated in the time or wavelength domain.

REFERENCES

1. AYANI, A., ISMAILOV, Y., LILJENSTAM, M., POPESCU, A., RAJAEI, H. and RÖNNGREN, R.,"Modeling and Simulation of a High Speed LAN," Simulation (Journal of the Society for Computer Simulation), **64(1)**, pp 7 - 14, (January 1995).
2. BERTSEKAS, D. and GALLAGER, R., Data Networks, (Prentice Hall, Englewood Cliffs, NJ 07632, USA, 1987).
3. KÖRNER, U., Tillförlitlighetsteori och Köteori Applicerat på Telekommunikations- och Datorsystem, (Studentlitteratur, Lund, Sweden, 1987).
4. POPESCU, A., A Parallel Approach to Integrated Multi-Gbit/s Communication over Multiwavelength Optical Networks, Ph.D. Dissertation, (TRITA - IT - 9306, Stockholm, Sweden, 1994).
5. SCHWARTZ, M., Telecommunication Networks: Protocols, Modeling and Analysis, (Addison-Wesley Publishing Company, USA, 1987).

CHAPTER 4

MODELING AND MANAGEMENT OF SELF-SIMILAR TRAFFIC FLOWS IN HIGH-SPEED NETWORKS

Ashok Erramilli, Walter Willinger
and Jonathan L. Wang

4.1. INTRODUCTION

In common with findings in many other branches of science and engineering, measurement studies involving working packet networks[1,2,3,4,5] have convincingly demonstrated that the bursty nature of actual network traffic is associated with fluctuations or variations on many time scales; this property is referred to as the *fractal* or *self-similar* nature of traffic[1]. Loosely speaking, the term "fractals" refers to phenomena that vary over many length or time scales. In stark contrast, traditional traffic theory and practice make the implicit assumptions that the fluctuations or variations occur over one, or a limited range of time scales. An example is the Poisson arrival process, in which most of the variation can be said to occur over a single time scale, corresponding to the average inter-arrival time. While the probability of large excursions from the average value is non-zero, the tail of the distribution decays so rapidly that the occurrence of large excursions is highly unusual and does not significantly impact the phenomenon under study. With "heavy-tailed" distributions that underly fractal phenomena, there can be appreciable probability mass many orders of magnitude removed from the average value, and these extreme excursions can dominate system performance even when they occur infrequently.