Modeling and Performance Analysis of a Symmetric Fast-Circuit Switched Robust-WDM LAN with the AR/LTP Protocol

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Abstract—Robust wavelength division multiplexing (WDM) is a technique to implement WDM local area networks (LAN’s) in the presence of laser wavelength drifts. A medium access control (MAC) protocol is used in conjunction with a wavelength-tracking receiver to tolerate the variations of transmission wavelengths. Among the proposed medium access schemes, the aperiodic reservation (AR) scheme with token-passing based control channel gives the best performance. An AR protocol with a lenient token-passing policy (AR/LTP) is thus presented. An analytical model is developed to design Robust-WDM AR/LTP LAN’s and predict their performance characteristics. The model can be used to evaluate the variation of waiting time and throughput for load and network parameters such as the arrival rate, number of nodes, number of channels and timing parameters. It also addresses the issues related to traffic loss, channel blocking, token rotation time, network span and the effect of device parameters.

Index Terms—Access protocols, communication system performance, computer network performance, demand assigned multimedia, local area networks (LAN’s), laser stability, optical communication, optical fiber LAN, wavelength division multiplexing (WDM).

I. BACKGROUND

Despite the presence of its principles for a number of years, wavelength division multiplexing (WDM) has not been exploited in the local area [1], [2]. A major problem facing the proposed WDM local-area network architectures is the fact that most of them are based on transmitter and receiver systems that require extreme stability in terms of laser wavelength [3]–[5]. Fast channel tuning over large bandwidths is taken for granted as well. These overall requirements are difficult to meet in practice. In particular, fabrication of laser arrays with repeatable wavelength distributions is not simple. Maintenance of such fixed wavelength channels when transmitters and receivers are separated geographically under diverse ambient conditions is also difficult, and imposes a heavy burden on network hardware and cost. There is thus a technology gap between the wavelength stability expected by WDM access protocols and that provided by the available WDM components.

Practical constraints on WDM, particularly the variation of wavelength with device temperature, have been known since the late 1970’s [6], [7]. The channel capacities of WDM systems are limited due to instabilities of sources, filters, and gratings [8]–[12]. Meanwhile, filter characteristics are a function of the material from which filters are made and their temperature coefficients [13]. The variation of the channel wavelengths causes major difficulties in implementing WDM networks irrespective of the topology and architecture involved [10], [11], [14]. A sampling of techniques developed to stabilize WDM components is provided below. A method to suppress laser frequency drifts through the use of a passive equalization circuit is described in [12]. Reference [15] shows that the thermal drift in the passband of a liquid crystal Fabry–Perot tunable filter can be controlled by electronic feedback. It proposes a system that can lock onto the wavelength of the incoming signal and adjust the drive voltage that is applied to the liquid crystal to compensate for any wavelength drifts. Other wavelength stabilization schemes for WDM networks are described in [16]–[19]. The stabilization of the wavelengths of WDM arrays requires complex and expensive hardware. An experimental, four-channel dense WDM transmission system that uses a computer to stabilize frequency space of lasers is reported in [20]. An optical WDM demultiplexer developed at NTT Transmission Systems Laboratory [21] consists of a detector array and an electrical neural network. This demultiplexer regenerates the original signals by recognizing the different speckle patterns of each channel with the pattern-recognition function of the neural network.

Stabilizing WDM components to provide fixed wavelength operation still remains a complex and a costly task. This is the major reason for the limited inroads made by WDM into LAN arena, where the cost of transmitter/receiver devices cannot be too high in comparison to the fiber cost as well as the end system cost. While many research efforts have taken place to tackle this problem, the solutions proposed so far have not been cost-effective for the local area, and none has been adopted by the networking community in a noticeable way. It has been reported recently that a 16-wavelength dense WDM system costs just under $1 million for each network node [2]. Only public network carriers may find such a figure acceptable and would deploy WDM to alleviate bottlenecks on long-distance backbones. As far as the local area is concerned however, it...
Fig. 1. Schematic diagram of the Robust-WDM receiver.

is fair to say that a decisive WDM solution has not yet been found.

A technology gap can still be recognized between the WDM protocol requirements and the capabilities of the devices available. The Robust-WDM project is an ongoing research project at Colorado State University and the University of Colorado, that attempts to close this gap by focusing on receiver and MAC protocols to overcome device limitations [1], [3]–[5]. The overall goal of this project is to develop the technology needed to realize a robust, cost effective, wide-band optical local-area network based on broadcast-and-select WDM with passive star couplers. The robustness, i.e., adaptation of the network to wavelength drifts, is the distinct feature of this network. The central approach thereto is the design of suitable medium access control (MAC) protocols that are capable of exploiting a new WDM receiver technology [22], [23] which, in turn, does not rely on fixed wavelength channels. The design of advanced MAC protocols for practical Robust-WDM LAN's, as well as analyzing the performance of these protocols, is an important goal of the project [24]–[32].

In the next section, we briefly review the principles of robust WDM and present the protocol with aperiodic reservations and lenient token-passing control channel, i.e., the AR/LTP protocol. In Sections III and IV, we develop an analytical model to design AR/LTP Robust-WDM LAN's and to predict and understand their performance characteristics. The results of the model are discussed in Section V and conclusions are presented in Section VI.

II. THE AR/LTP ROBUST-WDM NETWORK

The principles of Robust-WDM networking and the AR/LTP MAC protocol are discussed in detail in [4], [5]. Hence, we review only the aspects of Robust WDM which are necessary for subsequent modeling and performance evaluation.

A. The Robust-WDM Receiver

Fig. 1 is a schematic diagram of the Robust-WDM receiver. The incoming WDM signal is spectrally decomposed by a dispersion system and imaged onto an oversampled array of photodetectors which converts the photonic data into electronic form. Electronic signals are passed from the detector array to a preamplifier stage and subsequently to a winner-take-all (WTA) decoder, a special high-speed neural processing unit. This unit converts the position of the incoming electrical signals into amplitude values and very rapidly finds the detector element(s) at the brightest wavelength [22]–[25].

Robust-WDM relies on a reservation mechanism to setup connections among the nodes. During reservation periods, all transmissions on data channels are suspended and a network controller places all receivers in the WTA mode. Thus, if two nodes are to establish a connection, the spatial position of the detector element(s) corresponding to the transmission wavelength of one node can be found at the receiver of the other node by the WTA action. In this mode of operation, the analog voltages from the preamplifier stage are directly routed to the WTA decoder by using FET transistor switches. The WTA decoder figures out the local PIN position corresponding to the transmitting laser and sends this information to a translation table in the selector/router circuitry. The latter is basically a programmable crossbar-switching network that gets its routing information from this wavelength translation table. Each node in the network creates and stores its own translation table for the wavelength-PIN conversion. The principal function of the WTA mode thus is wavelength synchronization and connection setup. During the multiwavelength data transmission mode,
only the currents from a single detector element or from a few neighboring PIN's corresponding to a narrow wavelength band, identified during connection setup, is decoded and quantized at the receiving node. During the normal operation, entire network will continuously switch between the reservation and the transmission modes and thus the data-transmission times are interlaced with very short reservation periods. The frequency of this process and its periodicity or aperiodicity differ from one protocol to another. As a result of deploying this type of receiver technology, the expensive and difficult requirements of tight wavelength tolerances in WDM networks can be traded off for receiver complexity. However, the Robust-WDM receiver increases the architectural flexibility of the network, and also lowers the overall system cost.

B. The Network and the Protocol

Fig. 2 depicts the Robust-WDM network topology, a broadcast-and-select star using a passive star coupler. Each node is equipped with a transmitter and an array of lasers, one of which is dynamically selected at connection setup. Each node is equipped with the Robust-WDM receiver. Thus the transmission wavelengths may drift slowly with time. Two logical networks exist on the same physical star topology, the high-speed all-optical multwavelength data network and a relatively low speed signaling (control) network, the S-channel. S-channel is continuously monitored by all the nodes, and is realized by reserving a part of the optical spectrum for signaling purposes. The outputs of a subset of detectors of the wavelength-tracking receiver may be combined to implement the S-channel. The number of detectors is sufficiently large to ensure that the wavelength of the S-channel transmitter at each node does not drift beyond the range covered by these detectors. Several alternative S-channel implementations are also possible [1]. Access to S-channel is via an appropriate MAC protocol such as TDM [1] and the lenient token-passing protocol considered in this paper.

While the robust WDM approach relies on the wavelength-tracking receiver described in Section II-A, there are different medium access strategies that can be deployed [26]–[31]. A common connection setup mechanism is used however in all these strategies despite their differences. This is due to the

unified reservation-period scenario in all protocols. Details of the reservation period are addressed in [4], [5]. Fig. 3 depicts the reservation period in the case of a simplex connection request between, say, nodes A and B. A symmetric star is assumed with one-way node to node propagation delay of \( \tau \). \( T_{tx} \) denotes the transmitter select time, during which the node selects one of its lasers that does not overlap in wavelength with the current WDM transmissions. Absence of such a laser indicates that a channel is not available for the station to initiate a connection. If the PIN detector position corresponding to the particular laser overlaps with the detector positions corresponding to the active WDM data transmissions, the laser cannot be used. Let \( T_{rx} \) denote the receiver response time. The reservation period \( (T_{res}) \) in this case is bound by

\[
T_{res} \geq 2 \tau + T_{tx} + T_{rx}.
\]

(1)

In this paper, we consider Robust-WDM with aperiodic reservations (AR's) as opposed to the case with Periodic Reservations (PR) [27]–[32]. In the latter approach, reservations are invoked periodically by a network controller. Reservations thus occur on a regular basis and transmissions are suspended thereby even if no new connection is pending. This mechanism limits the network performance especially at low to medium network loads. Fig. 4 outlines the aperiodic reservation with lenient token-passing (AR/LTP) MAC protocol and the procedure to establish a connection between

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Fig. 2. The Robust-WDM LAN.

Fig. 3. Reservation period for a simplex connection. Shading indicates transmissions over data channels and dashed lines designate signaling.
any two nodes A and B. The central principle in the AR approach is restricting the occurrence of reservations to the instances where it is absolutely necessary, thereby increasing the efficiency of the MAC protocol.

Two important timing parameters characterize the AR/LTP protocol. The first is $T_{c_{\text{max}}}$ which is the maximum lifetime the network permits for a connection. Any laser drift during this time can be tolerated at the receiver. Shoulde the lifetime of a connection exceed the threshold $T_{c_{\text{max}}}$, the protocol terminates the connection as indicated in Fig. 4, and a new connection is initiated. Thus, introducing this parameter allows the network nodes to recover from laser drifts. The model neglects the need to reestablish a connection when the message length exceeds $T_{c_{\text{max}}}$, thus effectively using a truncated exponential distribution. However the simulation results used for verification of the model are based on exponentially distributed message lengths. The second parameter $T_{s_{\text{min}}}$ is the minimum time the network permits between two successive reservation periods. It is aimed at avoiding the performance degradation due to frequent reservation intervals especially at high network loads.

In an AR network, the S-channel is used to pass a token among the nodes in a certain logical order. Upon receiving the token, a node that does not have a connection request passes the token immediately to the following node. A node will hold the token only when it has a connection request, and the possession of the token will be the permit to access the S-Channel. Having captured the token, the node will launch a
stop-transmission signal ST(s) in this channel. Upon reception of this signal, all ongoing data transmissions in the network are suspended and the medium will become idle. The connection establishment scenario shown in Figs. 3 and 4 now takes place. Node A checks the availability of a laser that does not overlap in wavelength with the WDM channels in use. If such a channel is not available, A transmits a Resume Transmission, (RT(s)), signal thus terminating the reservation period. If a channel is available, A sends a request for establishing a connection, Conn req, on the selected WDM channel. This signal, carrying the address of destination, is detected by B, which responds by sending an Acknowledge and Resume Transmission (ART(s)) frame on the S-channel. This terminates the reservation period. When the connection between A and B is no longer needed, the first of the participating nodes to get the token will broadcast a connection-completion (CC) signal, whereby all other nodes are notified about the release of channel(s). In this protocol, we presume a lenient token-holding policy (LTP). If a node encounters channel and/or receiver blocking it does not hold the token. Instead, it passes it to the following node and waits for its turn in the following token cycle.

III. THE AR/LTP MODEL

Let N denote the number of nodes and C the number of channels in the network. We shall assume C to be constant. N >> C is generally the case in a practical WDM LAN. In fact, we are interested in local-area networks in which N >> C, rather than backbone networks where this may not be the case. A typical figure for C would be 4–8 channels, in a network with over 32 nodes. The case N <= C will be considered as a special case. We consider a data network for medium and large buildings, enterprise network in a small number of buildings or a campus-type network, and therefore focus on a star diameter (D) in 1–5 km range.

The token is captured by a node when it has a connection request and the connection establishment scenario takes place. Fig. 5 shows how the reservation periods are randomly scattered among token switchover times which, in turn, equal the node to node propagation delay τ [1], [5]. The token rotation time, denoted by the random variable T r, is defined as the time elapsed between two successive token arrivals at a node. We postulate that T r has an average value T r. The reservation-based approach of Robust-WDM is a circuit switched approach as opposed to a packet switching one. The type of circuits hypothesized so far, however, assume a time duration in the range from 0.1 to 10 ms. This assumption suggests the specification of fast circuit switching (FCS) [33], [34], rather than traditional circuit switching, in which the circuit is held for the entire duration of a call.

A general and exact solution of the problem to be analyzed is not possible. It is therefore necessary to introduce pertinent assumptions about network and traffic details. We assume every network node to be equipped with C Robust-WDM receivers and one transmitter with an array of C lasers. Each node is thus capable of transmitting to only one other node at a given time, but can receive from up to C nodes. This assumption eliminates the need to consider receiver blocking, something that can happen when two nodes try to communicate with the same destination at the same time irrespective of the MAC protocol being used. When N >> C, channel blocking would dominate over receiver blocking, and the performance of a network with C receivers per node is fairly close to that of a network with one receiver per node [31]. Each node is assumed to have buffer space sufficient for one connection request. Connection requests to a node that is busy with an ongoing call will be thus blocked and lost. We consider the network load to be uniformly distributed among the nodes. This assumption allows us to use results from models on symmetric token passing networks [35], [36]. A Poisson arrival process is assumed with an average arrival rate of λ connection requests per second per node. We also consider the effective arrival process, i.e., the rate at which requests are admitted to network and result in reservations, to be approximately poissonian. Connection duration is assumed to be exponentially distributed with mean T c. Only simplex connections are considered and all reservation periods are given by the lower bound of (1). Any variation from this value can easily be incorporated to the model by appropriately modifying τ, T e, or T r.

IV. PERFORMANCE ANALYSIS

Consider a connection request which arrives at node A. We define the time interval between the arrival of a connection request at “A” and the immediately following arrival of the token at this node as the residual token-rotation time, T r. T r is a random variable, the average of which is T r. Having captured the token, node A will launch a stop-
transmission signal ST(s), which will be heard by all nodes after \( \tau \) time units. Then, the reservation period takes place. Following reservation, the node will hold the token for the interreservation period \( T_{\text{min}} \). There are two possible scenarios for the reservation period: namely a successful scenario which ends with the establishment of a connection or a failure scenario due to channel blocking, i.e., the nonavailability of a channel. In the latter case, node A passes the token along and waits to receive it in the next cycle. As soon as “A” recaptures the token it retries to set up a connection. If blocking is encountered again, the token is released. This scenario would repeat until a free channel is found and a connection is set up. The number of times the token may be recaptured by “A” before the connection is established can thus vary, theoretically, from zero to infinity. Define this random number as the excess token rotation factor \( m_{\text{rt}} \), which has an average \( \bar{m}_{\text{rt}} \). Assuming \( m_{\text{rt}} \) and \( T_{\text{rt}} \) to be independent, the average waiting time \( \bar{W} \) encountered by a typical connection can be written as

\[
\bar{W} = \bar{T}_R + 2\tau + T_{\text{res}} + \bar{m}_{\text{rt}}\bar{T}_{\text{rt}}.
\]

A. Traffic Loss/Admittance Probability (\( P_L / P_{ad} \))

A connection request is lost if and only if it arrives at a node that is occupied by another request. We define the Loss Probability (\( P_L \)) as the long-run average transmitting node occupancy. \( P_L \) can thus be written as (see Appendix A):

\[
P_L \approx \frac{\lambda[W + \bar{T}_c + \bar{T}_{\text{ex}}]}{1 + \lambda[W + \bar{T}_c + \bar{T}_{\text{ex}}]} \quad (3)
\]

\( \bar{T}_{\text{ex}} \) is the average connection excess time, which represents the increase in the connection lifetime beyond its average \( \bar{T}_c \) due to reservations. Since each reservation interval suspends data transmissions for \( \tau + T_{\text{res}} \) time units, \( \bar{T}_{\text{ex}} \) can be estimated as (see Appendix A)

\[
\bar{T}_{\text{ex}} = \frac{(N-1)\lambda T_c [\tau + T_{\text{res}}] P_{ad}}{1 - (N-1)\lambda [\tau + T_{\text{res}}] P_{ad}} \quad (4)
\]

where \( P_{ad} \) is the probability of admission of connection requests to the network, i.e., \( P_{ad} \approx (1 - P_L) \).

B. Probability of Channel Blocking (\( P_B \))

If all the C channels are occupied, the station cannot setup a connection. The WDM channels are selected randomly by individual stations, and the connection durations are independent and exponentially distributed. Further, the nodes of the network are geographically distributed. Hence, assuming independence among the channels, corresponding Probability of Blocking (\( P_B \)) is

\[
P_B = \left( \bar{O}_{\text{ch}} \right)^C \quad (5)
\]

\( \bar{O}_{\text{ch}} \) is the average channel occupancy, i.e., the long-run fraction of time a typical channel is occupied in the steady state, and can be expressed as (Appendix A)

\[
\bar{O}_{\text{ch}} = \frac{N\lambda(\tau + T_{\text{res}}) \bar{m}_{\text{rt}} + N\lambda \bar{T}_c}{1 - N\lambda(\tau + T_{\text{res}}) P_{ad}}. \quad (6)
\]

C. The Average Excess-Token-Rotation Factor (\( \bar{m}_{\text{rt}} \))

Consider a connection request admitted to a node. Average time prior to attempting the connection is \( \bar{T}_R + 2\tau + T_{\text{res}} \). Note that the period during which the WDM transmissions are suspended \( \tau + T_{\text{res}} \) does not include the time required for the ST(s) signal. Let \( P_1 \) be the probability that the node will encounter channel blocking at this point in time and will therefore wait for an additional token rotation. We also define \( P_2 \) as the probability that the node will find a free channel, i.e., \( P_0 \triangleq 1 - P_1 \). We can also define \( P_2 \), corresponding to \( m_{\text{rt}} = 2 \), as the probability that the node will encounter channel blocking in some token cycle given that blocking occurred in the previous cycle. \( P_1(i \geq 2) \) is defined in a similar manner. Due to the memoryless property of the exponential distribution of the connection time \( T_c \), we can consider that

\[
P_2 = P_3 = P_4 = \cdots = P_{\infty}. \quad (7)
\]

Since \( P_1 \) equals \( P_B \) by definition, the derivation of an exact expression for \( \bar{m}_{\text{rt}} \) would require the determination of \( P_2 \). Queuing theory is the traditional tool used to tackle this type of problems [37]. The AR/LTP Robust-WDM network, however, is very difficult to model using queuing theory [1], [26]. In Robust-WDM, the WDM connections are initiated by means of a token passed in the control channel, but the WDM transmissions continue in parallel with the token transmissions. We therefore introduce an approximate method, which will be proven efficient and will result in satisfactory outcomes in the ranges of parameters that are of interest to us. Let us assume that

\[
P_2 \approx P_1 \triangleq P_B. \quad (8)
\]

Intuitively, the above approximation is valid for the case when the average connection duration is much less than the average token rotation time. This is a very practical case to consider given the foundation of our model \((N \geq 32 \text{ and } D \geq 1 \text{ km})\). Results will show that this approximation, in fact, leads to good results in many cases where \( \bar{T}_c \leq \bar{T}_{\text{rt}} \), in general. We now have

\[
\bar{m}_{\text{rt}} = \frac{P_B}{1 - P_B}. \quad (9)
\]

D. Average Token-Rotation Time (\( \bar{T}_{\text{rt}} \))

Given (8), we may write \( T_{\text{rt}} \) as follows (see Appendix A):

\[
\bar{T}_{\text{rt}} = \frac{N\tau}{1 - N\lambda T_c \left( \frac{P_{ad}}{1 - P_B} \right)} \quad (10)
\]

where \( T_s \) is the token service time, i.e., \( T_s \triangleq 2\tau + T_{\text{res}} + T_{\text{min}} \), (see Fig. 5).

E. Average Residual-Token-Rotation Time (\( \bar{T}_R \))

The concept of residual time in queueing systems is described by Kleinrock [37]. Kleinrock’s result was used by Sethi and
Saydam [35] to determine residual token-rotation time in
token-ring LAN’s. We thus have

$$T_R = \overline{T^2_{tr}}$$

(11)

where $\overline{T^2_{tr}}$ is the second moment of $T_{tr}$.

We adopt an approach that is similar to that described
in [35]. A crucial step in this adoption is the definition of
the effective service time of a connection request and
subsequently the effective traffic intensity of a node. Some
different views are discussed thereto in [1], [26]. Since $\overline{m}_{tr}$
is usually much less than 1 [1], we adopt an approach that
involves an approximation. We assume an effective Poissonian
arrival process with an average rate of $\lambda[P_{ad}/(1 - P_B)]$ and
an average service time of $(1 + \overline{m}_{tr})T_{tr}$. The arrival rate here
refers to that seen by a token. The rate of arrivals admitted
to the nodes due to unity buffer assumption is $\lambda P_{ad}$. When a
token arrives at a node holding a connection request, it
services the node by attempting to setup a connection. If
channel blocking results in an unsuccessful attempt, the next
token visit will repeat this procedure. Thus the effective arrival
rate seen by the token is $\lambda[P_{ad}/(1 - P_B)]$.

Hence, the effective traffic intensity of the node would be

$$\rho = \lambda[P_{ad}/(1 - P_B)](1 + \overline{m}_{tr})$$

(12)

Using (10)–(12), we obtain

$$\overline{T_R} = \frac{N(N - 1)\lambda^2}{2} \left[ \frac{P_{ad}}{1 - P_B} \right]^2 (1 + \overline{m}_{tr})^2 \overline{T_{tr}}$$

$$+ N\lambda T_s(2N\tau + T_s) \left[ \frac{P_{ad}}{1 - P_B} \right] (1 + \overline{m}_{tr}) + \frac{N^2\tau^2}{2} \overline{T_{tr}}$$

(13)

F. Waiting Time ($W$)

Combining (2), (9), (10), and (13) we get

$$\overline{W} = \frac{N^2(N - 1)\lambda^2}{2} \left[ \frac{P_{ad}}{1 - P_B} \right]^2 (1 + \overline{m}_{tr})^2 + N\tau \overline{m}_{tr}$$

$$- N\lambda T_s \left[ \frac{P_{ad}}{1 - P_B} \right]$$

$$+ \left\{ \frac{N\tau T_s(2N\tau + T_s)}{2} (1 + \overline{m}_{tr}) - \frac{N^2\tau^2}{2} \right\}$$

$$\cdot \left[ \frac{P_{ad}}{1 - P_B} \right] + \left[ \frac{N}{2} + 1 \right] \tau + T_{res}$$

(14)

Solving for $\overline{m}_{tr}$, we finally get

$$H'(W)G'(W) - F'(W) = 0$$

(15)

where $g' = (\overline{m}_{tr} + 1)/\overline{m}_{tr}$ and $H(W), F(W), and G(W)$
are polynomial functions in $y$. The roots of (15) can be obtained
using numerical methods, i.e., Matlab, and the corre-
responding set of roots of $\overline{m}_{tr}$ can be calculated. These
possible values of $\overline{m}_{tr}$ are initially screened by exclusion of
all negative and/or complex roots. Then all possible values of
$\overline{W}, P_L, P_{ad}, P_B, T_{tr}, and \overline{T_R}$ corresponding to the
screened roots of $\overline{m}_{tr}$ can be obtained. The corresponding
values of the throughput ($S$) are calculated also. Then, all
values are screened, once again, for the final choice of the
correct root(s) of $\overline{W}$. This second screening excludes any root
that does not satisfy three conditions:

1. $\overline{W} = \overline{T_R} + 2\tau + T_{res}.$

2. $0 \leq (P_L + P_B) \leq 1.$

3. $0 \leq S \leq 1.$

G. Waiting Time in the Special Case $N \leq C$

In the special case where $N \leq C$, no channel blocking is
possible, and therefore $P_B = 0$ and $m_{tr} = 0$. This would
make possible in a backbone interconnecting a small number of
servers. In this case, (2) reduces to

$$\overline{W} = \overline{T_R} + 2\tau + T_{res}.$$  \hspace{1cm} (16)

An approach similar to that adopted above may then be
followed to obtain $W$. However, in this special case we choose
to consider the approximation introduced in [36] ($\overline{T_R} = T_{tr}/2$). Hence, (10) reduces to:

$$\overline{T_{tr}} = \frac{N\tau}{1 - N\lambda T_s P_{ad}}$$

(17)

and we can easily get

$$H'(W)G''(W) - F'(W) = 0$$

(18)

where $F'(W), G'(W),$ and $H'(W)$ are simple polynomial
functions in $W$. The choice of the suitable root is accomplished
using the same criteria employed above in Section IV-F for
the general case.

H. Throughput ($S$)

By definition, the throughput per wavelength channel ($S$) is
given by

$$S = G(1 - P_L)$$

(19)

where $G$ denotes the network load ($G = N\lambda T_s/C$).

V. RESULTS AND DISCUSSION

In this section, we evaluate the model by comparing its results
with those generated by a simulator. The comprehensive
event-driven simulator has been written in C, and is
capable of generating performance results for several different
Robust-WDM MAC protocols [31]. The simulator covers
packet-switched and circuit-switched Robust-WDM networks
with TDM, token passing and random access in S-channel. It
supports a variety of traffic sources and provides support for
including models for laser drift.

In Figs. 6–16, the results from the analytical model are
represented by solid lines whereas results from the simulator are
indicated by small stars and circles. In cases where the
simulator is not capable of producing a performance parameter,
only the analytical results are provided. Assuming the speed
of light in fiber to be $2.6 \times 10^9$ m/s, we estimate $\tau, T_{res}, and
T_{min}$ to be $3.5, 8,$ and $16\mu s$, respectively, in the case of a
1-km star and 19.23, 39.5, and 79 $\mu s$, respectively, in the case of a 5-km star.

Fig. 6(a) depicts the variation in waiting time as the network load is increased from 10 to 150%. The general trend is obvious as the delay increases with increase of both the arrival rate $\lambda$, and the number of nodes at a given load (due to larger token cycles). Three important observations can be made. First, at low loads analytical results clearly agree with simulation. As the load is gradually increased, for some “intermediate” loading region, analysis tends to give slightly different values for $W$ as compared with simulation points. Finally, as the load is increased beyond this region, the results of the model resume being very close to the values from simulation. Second, as the number of nodes is increased, for a given set of the parameters, compliance between the model and simulation is improved. The third observation concerning Fig. 6 is that agreement between analysis and simulation is fairly good around 100% loads. This observation is particularly important since this is the range of loads that is of utmost concern to network designers.

Fig. 6(b) examines the corresponding behavior of the traffic-loss and the channel-blocking probabilities. At low loads, blocking probability $P_B$ (or equivalently $P_1$) is virtually zero. In this case, neither $P_1$ nor $P_2$ affects the outcome of the
analysis in any significant way. With sufficiently accurate loss estimation and in the absence of noticeable blocking, it is obvious that analytical results agree with simulation at low loads. Now, let us look at the region where $P_D$ increases rapidly and starts to be significant, e.g., when $\lambda$ approaches 750 arrivals/second per node at the case $N = 32$. At this point, blocking probability is about 0.12. In fact one would expect both $P_1$ and $P_2$ to increased with $\lambda$, but their rates of increase would differ and it would take $P_2$ higher loads than $P_1$ to reach the same numerical value. Thus, a relatively large difference in magnitude between $P_1$ and $P_2$ would exist for a certain range of medium loads. In this range, the model outcome would be affected by the approximation of (8). As the load is increased further, both probabilities continue to increase. An accurate account of the difference in their rates of increase however is impossible to obtain since $P_2$ cannot be estimated. Nevertheless, as Fig. 6 indicates, $P_1$ saturates around some upper limit and the gap between both probabilities tends to narrow again. Several tests were carried out similarly in order to investigate the delay-versus-load characteristics using many different network configurations and loads, of which Fig. 7 is an example. The results depicted in this figure, and all others, are strikingly similar to those of Fig. 6.

Fig. 8 studies the behavior of $\overline{T_{tr}}, \overline{T_R}$, and $\overline{m_{tr}}$ as the external arrival rate ($\lambda$) is increased. We consider a network configuration and loads that are similar to those of Fig. 7 ($N = 64$ case). The upper part of Fig. 8 scrutinizes the three critical variables individually. Two main phenomena can be observed. We first notice that in the case of the parameters of Fig. 8 $\overline{m_{tr}}$ does not get higher than 0.4, even at 150% load. The second observation is that the proportion of $\overline{T_{tr}}$ that $\overline{T_R}$ represents increases, almost linearly, as the load is increased [1]. Although one may expect the contributions of both $\overline{T_{tr}}$ and $\overline{T_R}$ to the waiting time $\overline{W}$ to increase similarly, it is indeed the average residual token rotation time ($\overline{T_R}$) that matters most. This important fact is highlighted in the lower part of the figure and by recalling (2). While $\overline{T_R}$ adds to the waiting time directly, $T_{tr}$ affects this time through the product $\overline{m_{tr}}T_{tr}$. Since the term $2\tau + T_{res}$ in (2) is in the range of $\mu$, it is clear that $\overline{W}$ is quite dominated by $\overline{T_R}$ at low loads. At high loads, the term $\overline{m_{tr}}T_{tr}$ starts to contribute to waiting time. Nevertheless, the contribution due to residual time remains clearly larger.

The capability of the model to provide sufficiently accurate delay results as the average connection length ($\overline{T_c}$) varies from 0.1 to 50 ms can be seen from Fig. 9. This is another sensitive issue as it relates to the limits, if any, that would be imposed on the connection length according to the approximation of (8). Clearly, the model is highly tolerant to the variation in the value of $\overline{T_c}$ as it can be increased by more than two orders of magnitude while the accuracy of results is unaffected.

Fig. 10 depicts the variation in waiting time as the number of network nodes is increased from 4 to 64 in a four-channel network for load values of 50 and 150%. There is close agreement between analysis and simulation. The region of $N < 32$ is shown to give an indication of the outcome of the model outside its main scope of application. The points at $N = 4$ were calculated using the special case of Section IV-G. Accurate results are obtained in the range $4 < N < 32$ despite the fact that we have not targeted this range in our modeling. At 150% load, however, the results are less accurate. The reason for this situation is the fact that the token cycle $T_{tr}$ becomes relatively shorter. This situation weakens the basis of the approximation used to derive (8), $P_1 \approx P_2$. However, at low loads the network suffers negligible blocking probability, and $P_1$, $P_2$ and $m_{tr}$ tend to be very small. Thus, the accuracy of the analysis would not be seriously affected. On the other hand, at high loads the blocking probability and $m_{tr}$ are not
Fig. 8. Variation of $T_{tt}$, $T_{R}$, and $m_{tt}$ versus the arrival rate per node ($\lambda$).

Fig. 11 shows the variation in waiting time as the number of channels is increased.

The effect of increasing the receiver response time ($T_{rx}$) on the average delay is shown in Fig. 12. We assume the transmitter select time ($T_{tx}$) to be in the range of 0.5 $\mu$s. The figure reveals a linear increase in waiting time as $T_{rx}$ is increased. However, as $T_{rx}$ is increased from 0.5–100 $\mu$s, a factor of 200, the waiting time increases by a factor of about 2.5. The slope clearly suggests that $W$ is not particularly sensitive to the magnitude of $T_{rx}$. Thus, large tolerances may be allowed in manufacturing the Robust-WDM receiver without compromising the network performance. On the other hand, Fig. 13 depicts the effect of changing the star diameter on waiting time. In this case, where we get a very good match between simulation and analysis, one can observe the strong influence of the network physical span on the delay characteristics of the AR/LTP Robust-WDM network. The increase in the star diameter ($D$) is seen by the protocol in terms of a corresponding increase in the propagation delay $\tau$. This latter delay, in turn, affects $T_{res}$, $T_{tx}$, and $T_{R}$. Therefore, $T_{res}$ has to be increased to fulfill its role at high loads.

Hence, all time parameters that contribute to waiting time are increased as a result of enlarging the network physical span. The effect of this process on the delay performance is quite
obvious. Fig. 14 puts the above two pieces (effects of $T_{rx}$ and $\tau$) together and demonstrates the variation in the waiting time as a function of the Robust-WDM reservation period ($T_{res}$) when $T_{tmin}$ is held equal to $2T_{res}$. Here, $\bar{W}$ increases linearly with increasing $T_{res}$. However, given the parameters of Fig. 14, it will take an increase in $T_{res}$ from 8 to 100 $\mu$s, for $\bar{W}$ to increase from about 70 to 180 $\mu$s. The dependence of $\bar{W}$ on $T_{res}$ is thus quite limited. Fig. 15 depicts the variation in the average waiting time as the interreservation threshold ($T_{tmin}$) is increased from the few $\mu$s range to 1 ms ($T_{res}$ kept constant). The important conclusion is that for a given set of network parameters and load, there would be some range of $T_{tmin}$ to which the waiting time is not very sensitive. As the interreservation threshold is increased beyond this range, delay would increase rapidly.

Finally, Fig. 16 depicts the change in throughput as the network load is increased. As the load is increased the traffic loss starts to be significant. This results in two effects. First,
throughput gets reduced proportionally. Second, the model tends to be less accurate, due to the fact that our estimation of the connection excess time \(T_{cex}\) was not exact. Our waiting time calculation is sensitive to the approximations used in the derivation, especially those related to the blocking probability. The throughput calculation, however, is mainly affected by our consideration of the mechanism of traffic loss.

Thus, the results of our study show that the realization of high-performance Robust-WDM LAN’s is a possibility. The expected average delay per connection request is mostly in the range of a few ms at high loads. High throughput is also possible. We have also demonstrated that the AR/LTP analytical model possesses many advantages as a tool that is suitable for the design of Robust-WDM LAN’s and pertinent for their performance study. The model can provide an understanding of the mechanism by which all network parameters work together. Several AR protocol aspects such as traffic loss, residual token-rotation time, connection excess time and the excess token rotation factor can be investigated carefully for the first time.
VI. CONCLUSION

Despite the efforts of many research groups in the area of WDM LAN’s, the practical realization of these networks remains a challenge. The communication protocols that rely on fixed wavelength channels demand more from system components than the latter can actually deliver with a reasonable cost. The Robust-WDM project addresses this problem. The present work has concerned itself with the study of Robust-WDM local area networks with aperiodic reservations.

An analytical tool has been developed, and proven able to successfully predict the performance characteristics of Robust-WDM LAN’s with the AR/LTP protocol. It is shown that this model can also serve as a design tool for Robust-WDM LAN’s. The manner in which the performance measures, such as delay and throughput, may vary versus the variations in loading, number of network nodes, number of channels, device parameters, and network parameters has been demonstrated. It is shown that the realization of high-performance Robust-
WDM LAN's is possible. This study therefore extends the ongoing efforts aimed at assessing the potential of Robust-WDM as a new networking technique and as an approach to gigabit networking in the local area.

APPENDIX A
DERIVATION OF $P_L$, $T_{ce}$, $O_{ch}$, AND $T_{ex}$

The period of time a typical connection request keeps a transmitter busy is $W + T_c + T_{ce}$. Since the total rate of connection requests admitted to the network is $N \lambda (1 - P_L)$ per second, invoking Little's Law

$$P_L = \lambda (1 - P_L) \left[ W + T_c + T_{ce} \right]$$

which results in (3). The increase in the connection lifetime beyond its net average $T_c$ due to reservations depends on the arrivals admitted to the other $(N - 1)$ network nodes, during the entire life time of a connection, given by $(T_c + T_{ce})$.
\[ T_{\text{core}} \text{ can therefore be stated as} \]
\[ T_{\text{core}} \simeq (N - 1)\lambda(1 - P_L)(T_c + T_{\text{core}})(\tau + T_{\text{res}}) \]
\[ (21) \]

which can be rearranged as (4). Token is sometimes released by a station without establishing a connection due to nonavailability of a channel. Thus, every admitted connection request may interrupt \( C \) ongoing connections on average \( m_{\text{tr}} \) times where each interruption period would last for \( \tau + T_{\text{res}} \) time units (recall Fig. 3). Then, an idle channel is found during the next reservation wherein data transmissions are suspended along the \( O_{\text{ch}}C \) active channels. Finally, every connection request consumes \( T_c \) time units in data transmissions along one channel. Thus, at steady state, \( O_{\text{ch}} \) can be expressed as
\[ \frac{N\lambda P_{\text{adv}}[m_{\text{tr}}C(\tau + T_{\text{res}}) + O_{ca}C(\tau + T_{\text{res}}) + T_c]}{C} \]
\[ (22) \]

Given (8), we may write \( T_{\text{tr}} \) as follows:
\[ T_{\text{tr}} \triangleq N\tau + N\lambda(1 - P_L)T_{\text{tr}} T_s \sum_{i=0}^{\infty} P_B^i \]
\[ (23) \]

where \( T_s \) is the token service time. Equations (6) and (10) follows directly from the above equations.

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REFERENCES


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