Performance of a Packet Switched WDM Network with Dynamic Wavelength Selection*

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Abstract

WDM networks in general depend on transmitters and receivers that are precisely tuned to predetermined fixed wavelengths. Robust WDM is an approach aimed at relaxing manufacturing and operating wavelength tolerance requirements, which will lead to cost effective implementations. In this approach, connections are based on dynamically selected wavelengths as opposed to using fixed wavelength channels. A station that needs a connection selects a wavelength during a reservation interval. The performance of a simplified WDM protocol with dynamic wavelength selection is modeled and analyzed for packet traffic. In this version, the reservation intervals are assigned to stations randomly. The performance of the protocol is analyzed for different network parameters.

I. Introduction :

The research on fiber optic networks is driven by new emerging applications and services [5] such as networking full-motion color-graphics workstations and applications involving medical imaging. There is also a need for high-speed interconnection of supercomputers, LANs and MANs with those applications. The fiber optic technology provides the necessary high bandwidth medium for such applications. The single-mode optical fiber has presented the exciting dilemma of a transmission medium which has a bandwidth of several THz, that exceeds both the speeds at which it can be accessed by conventional means and the aggregate information rates for which it is likely to be used [3].

Since the maximum rate at which each user can access the network is limited by the electronic speed (to few gigabits per second), the key in designing lightwave networks in order to exploit the huge bandwidth is to introduce concurrency among multiple-user transmissions into the network architectures and protocols. In all-optical networks, concurrency may be provided by either wavelength or frequency (wavelength division multiple access - WDMA) [4,6,14], time slots (time division multiple access - TDMA) [8], or wave shape (code division multiple access - CDMA) [16]. The basic need of all-optical TDMA and CDMA to have nodes synchronized to within one time slot (for TDMA) and one chip time (for CDMA) make them less attractive than WDMA. On the other hand, WDMA employs mostly existing technologies associated with intensity-modulation direct-detection systems. Also, WDMA is the current favorite since all of the end-user equipments need operate only at the bit rate of a wavelength division multiplex (WDM) channel.

In WDM, the vast bandwidth of the fiber medium is divided into many different channels, each of which corresponds to a different wavelength (or frequency), wherein the bandwidth of each channel is limited by the operating capacities of the end resources [4]. Multiple connections can be present at the same time, as long as they are on different wavelengths. The minimum channel spacing is limited by crosstalk. The spacing between channels can be reduced if the end-user transmitters (lasers) are of good quality, i.e., they are stable and do not drift too far from their nominal operating wavelength range. WDM requires narrow spectral-width lasers and optical filters to distinguish between the different wavelengths. With the use of narrow-band lasers such as distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers, a channel spacing of 1 nm or less has been demonstrated [3,14].

Depending on the network architecture, the receivers are used differently. In broadcast-and-select networks [15], each station is provided with a small number (e.g.,

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two) of fixed-tuned optical transmitters and a small number of fixed-tuned receivers. The transmitters / receivers are tuned to certain wavelengths such that a "stable" logical configuration is maintained for a "reasonable" length of time. Stations can transmit data directly only to those stations that have a receiver tuned to one of their transmit wavelengths. Packets intended for other stations will then have to be routed through intermediate stations. In contrast, in single-hop networks, if the node is a packet switched one, then either the transmitters or the receivers need to be tuned to the appropriate wavelength for every slot, i.e., before the transmission of every packet. Transmitters and receivers must thus be able to tune to different channels quickly and precisely, a major challenge facing the single-hop networks [14].

Rapid tunability is not the only problem to be solved before packet-switched single-hop broadcast-and-select networks can be realized. An efficient media-access (MAC) protocol is essential to coordinate transmission between various stations [17]. Recent major contributions toward the realization of WDM networks include Rainbow [7] and Starnet [12]. The Robust WDM architecture, on which this paper is based, is aimed at relaxing manufacturing and operating wavelength tolerances, leading to a cost effective network implementation [9,10,18].

In this paper, an analytical model is developed for evaluating the performance of a Robust WDM network protocol. The paper is arranged as follows. In the following section, the robust WDM network's characteristics and architecture is explained. Section III, deals with the performance evaluation. The assumptions are outlined and the network's performance is analyzed . In section IV, the test results of the performance model are discussed. Conclusions are given in section V.

II. Robust WDM Networks :

The overall goal of the Robust WDM Networks project, being carried out jointly by Colorado State University and the University of Colorado, is to realize a robust, cost effective, scalable, wide-band optical network based on WDM. The WDM architectures being implemented at present rely on extremely precise and stable laser transmitters or transmitter arrays. Obtaining the required wavelength stability requires the temperature of the components to be tightly stabilized, which would impose a heavy burden on the cost and the hardware especially in distributed environments. There is a technology gap between the stability expected by the WDM access protocols and that provided by the available components. The approach of the Robust WDM network is to use an access protocol that can tolerate a large variations of wavelengths of transmitters over both limited and extended periods of time. The medium access protocol does not depend on fixed wavelength channels, but dynamically adapts to the variations of the signal wavelengths. Thus, the Robust WDM network does not depend on extremely stable laser or tunable filters and can be implemented with low cost optical components [9,10,18].

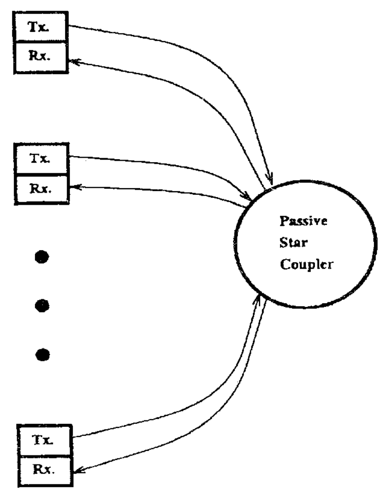

Figure 1: Generic WDM network using tunable receivers.

The Robust WDM architecture is based on a passive star, where each node transmitter is equipped with an array of lasers, one of which is dynamically selected at the transmission time, as shown in Figure 1 . This network differs from other networks in that the wavelength at a node may drift slowly with time, and even overlap with those of another station at a given time. In addition it uses reservation periods during which a waiting stations compete for getting an available channel. The network will see the WDM transmissions interlaced with the reservation periods as shown in Figure 2.

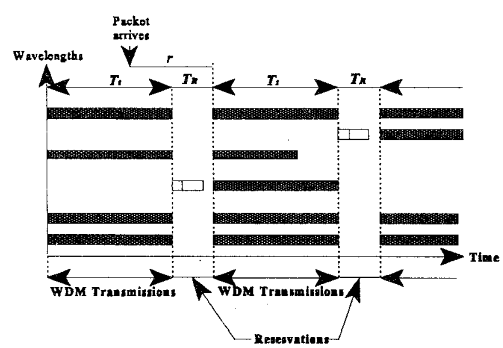

Figure 2: Timing diagram illustrating interlaced WDM transmission and reservation periods.

Assuming simplex transmissions, high-speed WDM transmissions are allowed only during the transmission periods. During the reservation period, all stations have to cease high-speed WDM transmissions. Among the functions to be done during the reservation period is that one of the waiting stations gets an available channel, if one exists, corresponding to a wavelength that is not used by any other station. Only one of the waiting stations can get an available channel during the reservation period, even if there is more than one channel available and more than one station requiring a channel at that moment. Once an unused wavelength is found, the station establishes a link with the intended destination. The reasoning for having a reservation period and how it enhances robustness are addressed elsewhere [9,10,18]. Note that in this context, the term available channel refers to a wavelength that is not used by any other station, rather than a predefined wavelength. As a result, the spacing between adjacent channels will vary with time.

In this paper, we analyze a network where a selected station out of all those waiting for a channel is granted the reservation interval. The allocation of the reservation interval among stations may be done using a control channel. The protocol analyzed here is one of the many that can be used in a wavelength tolerant LAN [10]. The reservation interval may also be used to acknowledge whether or not the receiver was able to lock-on to the signal. After the reservation period, all WDM links resume their operation.

III. The performance model:

A performance model for the WDM network allow us to quantify the effects of different parameters on the overall performance. The effect on the network throughput and blocking probability due to factors such as the number of stations, number of channels, the arrival rates, the propagation delay, and the receiver tuning time are of interest. In this paper, we consider a version of a Robust WDM architecture, where nodes are selected randomly for using a reservation period. We also do not take into account the variation of laser wavelengths or their initial wavelength distributions. Therefore the results presented here indicate how the protocol performs with stabilized lasers. We also assume the availability of a fixed number of channels, and that each station has a large enough number of lasers that allows a node to use any unused channel. We analyze the performance for packets, although the Robust WDM network is more suitable for circuit switched applications.

Assume a (WDM) network which consists of (N) stations and has (c) transmission channels. The packet arrivals is a Poisson process, and the packet service time is constant. Each station has a queue that can hold one packet.

The network uses a scheme in which the time is divided into slots. Each slot consists of two sub-slots namely the reservation (T_R) and the transmission (T) sub-slots as it is illustrated in Figure 2. High-speed WDM transmissions are allowed only during the transmission sub-slots for a station that holds a channel and has a full queue.

Assume that the length of the transmission sub-slot is equal to one packet transmission time. During a transmission sub-slot, more than one station, up to the number of the channels (c), may transmit simultaneously on different channels. A station that is holding a channel is allowed to continue its transmission on the same channel if during the transmission of a packet its packet queue becomes full with another packet. Assume that the

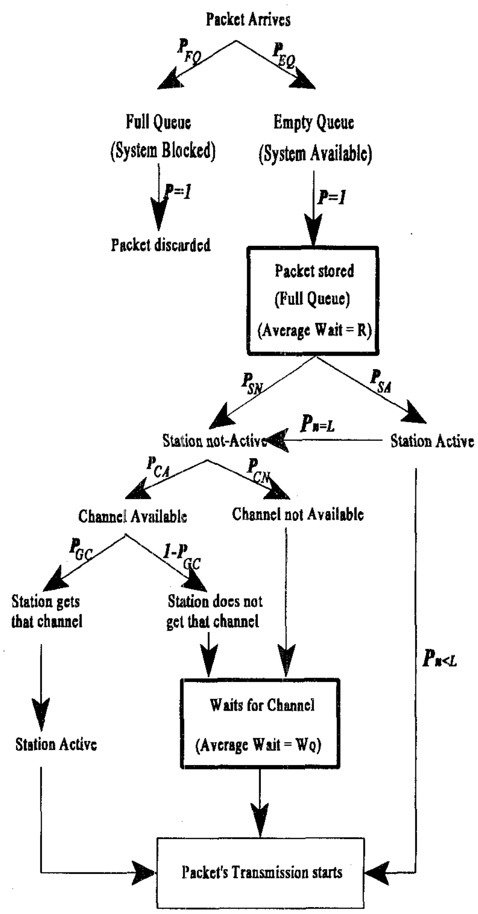

Figure 3: The flow diagram of the transition probabilities for all the possible situations that a packet may encounter.

maximum number of sucessive slots a station is allowed to use for transmission is (L) slots, after which the station has to cease transmission on that channel even if its packet queue is full. If a station that is holding a channel does not receive a packet during the last packet's transmission, that station has to give up the channel even if it does not reach the maximum number of slots which it is allowed to use.

A station that has its first arrival during any time of a slot has to wait, for an random residual time with mean (R), until the end of reservation sub-slot, during which the station may or may not get an available channel. If that station doesn't get a channel, it has to wait for an average time W_Q until the station gets an available channel with mean W_Q and before starting its packet's transmion.

All the possible situationthat a packet may encounter from the moment of its arrival until its transmission starts are illustrated in Figure 3. Whenever a packet arrives the packet queue may be either full or empty. If it is full, the system is considered blocked and the packet is discarded. If the packet queue is empty, the system is considered available and the new packet is stored in that queue; and hence the queue becomes full. The packet's arrival may occur at any time during a slot and its station has to wait for the residual time (r), measured from the instant of arrival to the end of the next reservation sub-slot. The average value of the residual time is (R).

At the end of a reservation sub-slot, the state of the station determines whether the packet is immediately transmitted or not. The station is said to be active if it was transmitting during the last transmission sub-slot, otherwise it is not-active. If a station is active and it doesn't reach the maximum number of slots (L) that it is allowed to use for successive transmissions, the packet's transmission starts at the beginning of the transmission sub-slot next to the packet's arrival. But, if the station is active and has reached the maximum number of slots (L), it will be considered as not-active during the current slot. If the station is not-active, it will compete with other stations for a new channel. If there is no channel available, the station has to wait for a random time, with mean W_Q, until it gets an available channel and only then will it start its packet's transmission. But, if there is a channel available, the station may or may not get that channel as there may be other stations competing for the reservation sub-slot and the channel. If the station gets an available channel it has to start the transmission of its packet right at the beginning of the transmission sub-slot which is next to the arrival of its packet. On the other hand, if the station cannot get the available channel, it competes with other stations during the next reservation sub-slot. In a practical implementation however, we need to consider a scheme such as TDM or alike for allocating the reservation sub-slot [11]. In this analysis, we consider a simplified protocol where a station is selected randomly, from the waiting stations, to use the reservation interval, and therefore get an available channel. We neglect the overhead associated with selecting the random station. There are many possibilities here, including the use of a signaling channel that would make this overhead negligible.

The probabilities used for the analysis are defined as follows:

P_{FQ} = Prob {the packet queue at a station is full}
P_{EQ} = Prob {the packet queue at a station is empty}
$= 1 - P_{FQ}$
P_{SA} = Prob {the station of interest is active}
P_{SN} = Prob {the station of interest is not-active}
$= 1 - P_{SA}$
$P_{n=L}$ = Prob {the number of successive transmissions (n) completed by an active station under consideration is equal to the maximum allowed number (L)}
$P_{n<L}$ = Prob {the number of successive transmissions (n) completed by an active station under consideration is less than the maximum allowed number (L)}
$= 1 - P_{n=L}$
P_{CA} = Prob {a channel(s) is available}
P_{CN} = Prob { no channel is available}
$= 1 - P_{CA}$
P_{GC} = Prob {the station under consideration gets the available channel}
$P_{a=0}$ = Prob {no packet's arrive at the station of interest during a slot}
$P_{a\geq 1}$ = Prob {arrival of one or more packets at the station of interest during a slot}
$= 1 - P_{a=0}$

The average waiting time (T) :

The average total waiting time (T) that a stored packet has to wait can be calculated from Figure 3 as follows :

$$T = R + (P_{SN} + P_{SA}P_{n=L})[P_{CN} + P_{CA}(1 - P_{GC})]W_Q \quad (1)$$

Where :

R ... is the mean residual time. Residual time is the average time between the instance of the packet's arrival and the beginning of the next transmission sub-slot.

$$R = (T_R + T_t)/2 \quad (2)$$

T_R ... is the duration of the reservation sub-slot.

T_t ... is the duration of the transmission sub-slot.

W_Q ... is the mean waiting time of a station with a full packet queue, from the end of the reservation sub-slot until it gets an available channel and then starts transmission.

Note that W_Q does not include the residual time.

The queuing time (W_Q) :

To calculate the average waiting time (W_Q) of a station waiting to get an available channel, assume that the average number of the waiting stations at any time is (N_Q) and the number of waiting stations change with a rate (λ_Q) where a station waits for a time (W). Then, applying Little's Theorem [2,13]:

$$N_Q = \lambda_Q \, W_Q$$

and hence,

$$W_Q = N_Q / \lambda_Q \qquad (3)$$

The rate (λ_Q) can be considered as the mean number of the accepted packets per second arriving at stations that are not able to transmit during the first transmission sub-slot following the arrival.

From Figure 3, it is seen that :

$$\lambda_Q = N\lambda P_{EQ}[P_{CN} + P_{CA}(1 - P_{GC})](P_{SN} + P_{SA}P_{n=L}) \qquad (4)$$

$$N_Q = NP_{SN}P_{FQ} \qquad (5)$$

λ ... is the mean packet arrival rate per station [packets/second].

P_{SN}, P_{SA}, P_{FQ}, and P_{EQ}

To calculate these probabilities, consider the discrete time Markov chain which is illustrated in Figure 4. The state of a station is defined at the end of a reservation sub-slot. A station at that instant may be in one of three states. The first state, at which a station is not-active and has an empty packet queue has a probability ($P_{SN}P_{EQ}$). At the second state, a station is not-active and has a full packet queue. This state has a probability ($P_{SN}P_{FQ}$). While at the third state, a station is active with probability (P_{SA}). The probabilities can be expressed as products since P_{SA}, P_{SN} are independent of P_{EQ}, P_{FQ}.

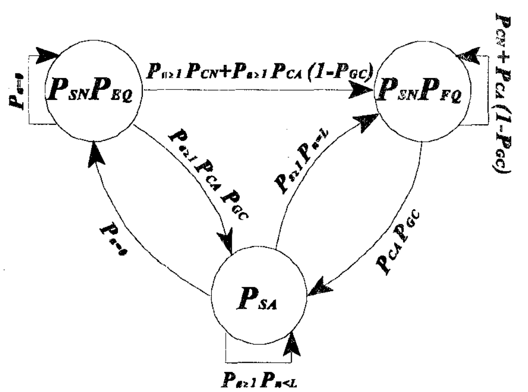

Figure 4: The Markov chain of all possible states of a station.

The transition from a state to another one may occur at the end of the reservation sub-slot with a probability which is indicated on the transition arrows of Figure 4. Only one transition per slot from a state to another can occur.

Analyzing the Markov chain in Figure 4, the different probabilities can be calculated as follows:

$$P_{SN} = (D + B)/(A + B) \qquad (6)$$

$$P_{SA} = 1 - P_{SN} \qquad (7)$$

$$P_{FQ} = B/(D + B) \qquad (8)$$

$$P_{EQ} = D/(D + B) \qquad (9)$$

where:

$$A = P_{CA}P_{GC} \qquad (10)$$

$$B = P_{a\geq 1}(P_{a=0} + P_{a\geq 1}P_{n=N} - P_{a=0}P_{CA}P_{GC}) \qquad (11)$$

$$D = P_{a=0}P_{CA}P_{GC} \qquad (12)$$

Now we derive expressions for P_{GC}, P_{CA}, P_{CN}, $P_{a\geq 1}$, $P_{a=0}$, $P_{n=L}$, and $P_{n<L}$.

P_{GC} :

P_{GC} = Prob { the station under consideration gets an available channel}

Assuming that each of the competing stations have an equal probability of getting an available channel,

$P_{GC/n}$ = Prob { a station gets the available channel | (n) other not-active stations have full queues}

$$= 1/(n + 1)$$

Denote :

P_{nF} = Prob {(n) other not-active stations have full queues}

Hence, See equation (13).

P_{CA} and P_{CN} :

P_{CA} = Prob {a channel(s) is available}

= Prob {(# of active stations "i" that have not completed L successive transmissions with packet arrivals during previous slot) < # of channels (c)}

See equation (14).

$$P_{CA} = 1 \quad ; \; for\; N \leq c \;\; \text{OR} \;\; L \leq c \qquad (15)$$

Equations (6), (8), (13), (14), and (15) are solved itratively to find P_{SN}, P_{FQ}, P_{GC}, and P_{CA}. Substituting in

$$P_{GC} = \sum_{n=0}^{N-1} P_{GC/n}\, P_{nF} = \sum_{n=0}^{N-1} \left(\frac{1}{n+1}\right) \binom{N-1}{n} (P_{SN}\, P_{FQ})^{n} \, (1-P_{SN}\, P_{FQ})^{N-n-1} \qquad (13)$$

$$P_{CA} = \sum_{i=0}^{c-1} \binom{L}{i} (P_{SA}\, P_{n<L}\, P_{a\geq 1})^{i}\, (1 - P_{SA}\, P_{n<L}\, P_{a\geq 1})^{N-i} \quad ; \; for \;\; N > c \;,\;\; L > c \qquad (14)$$

equations (7) and (9) to get P_{SA} and P_{EQ} respectively. Then, the values of P_{SN},P_{FQ}, P_{GC} ,and P_{CA} ,which depend on each others, are found.

$P_{a\geq 1}$ and $P_{a=0}$:

Assuming that the packet's arrival process to a station is Poisson with rate (**λ**) packets per second. The probability of (**k**) packets arrivals during an interval of time (t) is [13]:

$$P_k(t) = \frac{(\lambda t)^k}{k!}\, e^{-\lambda t}$$

As the duration of a time slot is $(T_R + T_t$

$$P_{a=0} = P_0\,(T_R + T_t) = e^{-\lambda\,(T_R + T_t)} \qquad (16)$$

$$P_{a\geq 1} = 1 - P_{a=0} = 1 - e^{-\lambda\,(T_R + T_t)} \qquad (17)$$

$P_{n=N}$ and $P_{n<N}$:

Assuming that the packet arrivals are statistically independent and the arrival process is Poisson which is memoryless, hence

$$P_{n=L} = P_{a\geq 1}^{L-1} = [1 - e^{-\lambda\,(T_R + T_t)}]^{L-1} \qquad (18)$$

$$P_{n<L} = 1 - P_{n=L} \qquad (19)$$

Note that for **L** sucessive transmissions, a station has to have an arrivalor more during each of the ***(L-1)*** subsequent slots. The first packet's arrival in a session may have to wait for several slots before its transmission starts.

After calculating the different probabilities equations (4), (5) and (3) can be used to get λ_Q , N_Q and W_Q respectively. Equation (1) can now be used to the mean waiting time **T**.

IV. Test results :

To analyze the performance of the network, we selected a network configuration with ***N=50*** stations and ***c=10*** transmission channels. The values of the reservation sub-slot (**T_R**) and the transmission sub-slot (T_t) are selected to be 10^{-7} seconds and 10^{-6} seconds respectively.

The network load (**G**) is given by **$G=N\lambda s/cb$**, where **G** is the network load, **s** is the packet length in bits, and **b** is the bit rate / channel in bits/sec.

In general, increasing the packet length (s), the number of stations (N), increases the average total waiting time (T). While increasing the number of slots (**L**) that a station is allowed to transmit continuously, or the number of transmission channels (**c**) in the network, decreases the average total waiting time (**T**) until it reaches a constant value, for each of these parameters, after which any increase in any of these parameters has no effect on **T**.

In all the figures, the solid line indicates the result from the analytical model.

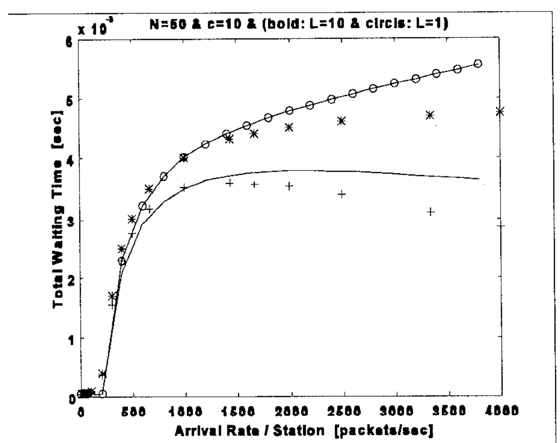

Figure 5: The variation of the total waiting time (*T*) vs the arrival rate / station (*λ*). Simulation (++:L=10 & **:L=1)

Figure 5 illustrates the variation of the total waiting time (**T**) with the packet's arrival rate (**λ**) for ***L=1*** and ***L=10***. In both curves, the values of **$b=10^7$** bits/channel and $s=1000$ bits/packet are kept constant. $\lambda=2000$ packets/second corresponds to 100% network load. For $L=1$, regardless to the number of transmission channels per network (c), the network uses only one channel. Hence, increasing λ,T increases accordingly. While for $L>1$, increasing λ increases T until certain value of λ at which the network is saturated in the sense that a station holding a channel will keep it for the maximum allowed number of slots (L) before giving it up and hence T is almost constant. In general, increasing L decreases T. Note that the rate of increase of the delay decreases with the increase of the arrival rate due to blocking at individual nodes.

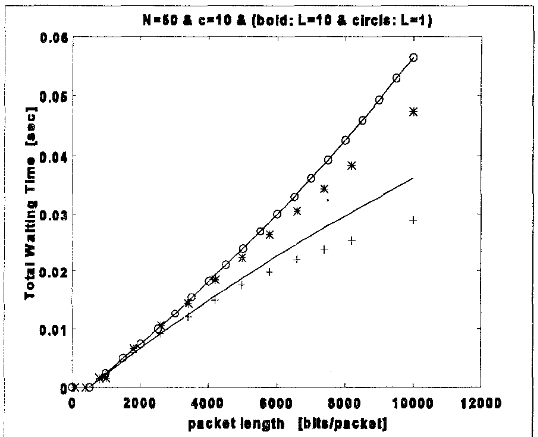

Figure 6: The variation of the total waiting time (T) vs the packet length(s). Simulation (++:L=10 & **:L=1).

Figure 6 shows the variation of T with the packet length (s) at $L=1$ and $L=10$, with $b=10^7$ bits/channel and $\lambda=400$ packets/second. Also, $s=5000$ bits/packet corresponds to a network load of 100. In general, increasing s increases T, for all values of L. Also, increasing L decreases T, for all values of λ.

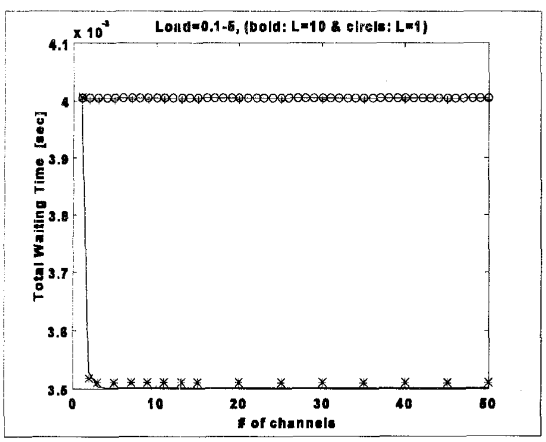

Figure 7: The variation of the total waiting time (T) vs the number of channels (c). Simulation (++:L=10 & **:L=1).

In Figure 7, the variation of T against the number of channels per network (c) is illustrated at $L=1$ and $L=10$, $s=1000$ bits/packet, $b=10^7$ bits/channel, and $\lambda=1000$ packets/second. As we keep the arrival rate constant, changing c inversely changes the percentage network load (d), where $c=5$ corresponds to network load of 100% and $c=50$ corresponds to 10% of network load. It is obvious that for $L=1$, changing c has no effect on T, since in this case the network uses only one channel regardless to the number of channels it has. While for $L>1$, for small values of c, increasing c sharply decreases T. The rate of changing T decreases with increasing c until it becomes almost zero.

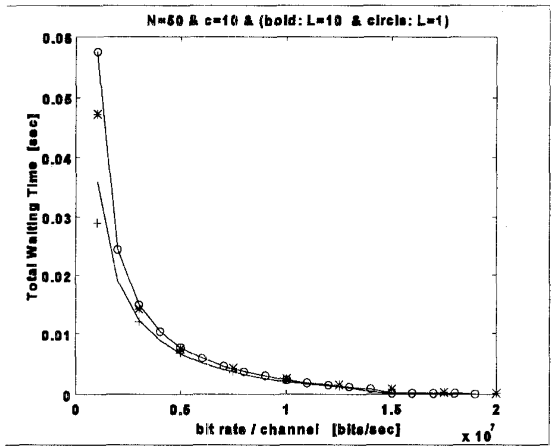

Figure 8: The variation of the total waiting time (T) vs the bit rate / channel(b). Simulation (++:L=10 & **:L=1).

Figure 8 shows the variation of T for different values of the channel bit rate (b), at $L=1$ and $L=10$, with $s=100$ bits/packet and $\lambda=400$ packets/second. Increasing b, decreases d. Here, $b=2*10^6$ bits/second correspond to a network load of 100%. In general, increasing b decreases T. Also, increasing b after a certain value has no effect on T where T becomes constant and equals to the average residual time (R).

Figure 9 illustrates the changes that occur in the average total waiting time (T) with increasing the number of stations (N) in the network, at $L=1$ and $L=10$, with $s=1000$ bits/packet, $b=0.5*10^7$ bits/channel, and $\lambda=400$ packets/second. Increasing N, increases d accordingly, where $N=25$ and 50 stations correspond to network loads of 100% and 200% respectively. For small (N), T is constant and has a small value. After that, T increases as (N) increases. The number of stations for which T

remains constant, changes with the value of the number of slots (*L*) that a station is allowed to transmit

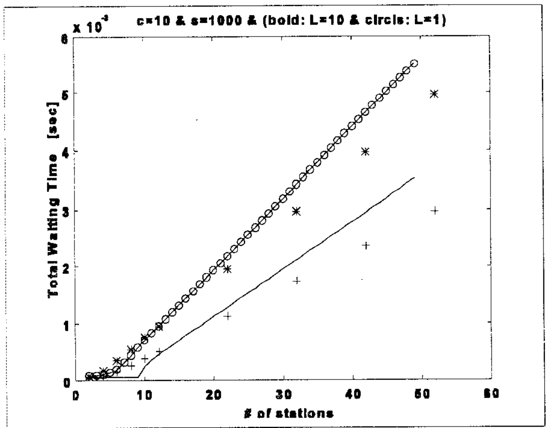

Figure 9: the variation of the total waiting time (*T*) vs the number of stations (N). Simulation (++:L=10 & **:L=1).

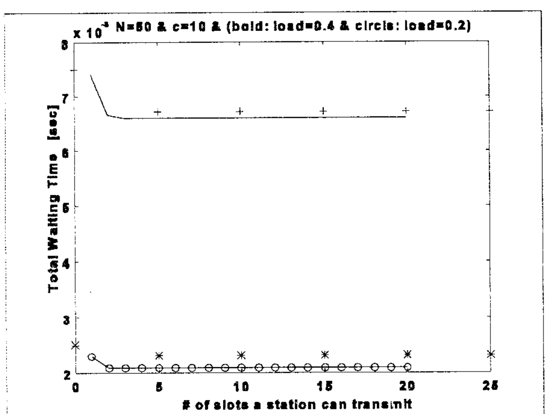

Figure 10: The variation of the total waiting time (*T*) vs the max. Number of slots (L). Simulation (++:load=0.4 & **:load=0.2).

continuously. The smaller the ***L***, the smaller is that number of stations. In general, decreasing ***L*** increases the average total waiting time (***T***).

Figure 10 illustrates the effect of changing the value of the maximum number of slots (***L***), that a station is allowed to transmit successively, with ***T***, at network loads ***d=0.2*** and ***d=0.4***. Here, ***s=1000*** bits/second, ***b=0.5*10⁷*** bits/channel, and ***λ=400*** packets/second are kept constant. ***T*** decreases with ***L*** until ***T*** reaches a fixed value. Increasing the load, increases ***T***, for all values of ***L***.

Further results based on this analysis can be found in [18]. We compare the model results with those obtained from simulations. Details of the simulator can be found in [19].

V. Conclusions :

In this paper, a performance model was proposed and analyzed for the Robust WDM network. All the test results indicated that the proposed model provides reasonable agreement with simulation results. The proposed model provides useful design information such as the number of stations, the number of channels, the arrival rate, the bit rate, and the packet length, to achieve a given grade of service.

The model is analyzed under the following assumptions: a fixed set of available channels, each station has a large number of lasers, a station is selected randomly to use the reservation interval, each station has a buffer for one packet, Poisson arrivals, constant packet time equal to transmission sub-slot, and simplex transmissions.

The future work include the extension of this model to cover more realistic assumptions and practical implementations [11], including the one being prototyped at the Colorado State University and the University of Colorado.

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