Performance of a Robust WDM Network with Token Based Reservations and a Limited Number of Lasers at a Station[1]

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Abstract

The performance of a symmetric Robust WDM network that uses token-passing on the signaling channel and has a limited number of lasers per station is modeled and analyzed for circuit-switched connections. Robust WDM networks use a reservation interval during which all stations cease their WDM transmissions so that the station holding the token may establish a connection with its intended destination. The network performance is analyzed for different network parameters. Simulation results are used to evaluate the accuracy of the model.

1. Introduction

In recent years, wavelength division multiplexing (WDM) has emerged as the most promising solution to satisfy the increasing need for larger bandwidth [9]. WDM exploits the enormous capacity of the single mode fiber by dividing the available wavelength into smaller, more manageable, multiple wavelengths to carry out more than one transmissions at a time; thereby offering a potential aggregate throughput in Terabits per second range. It has intrigued a large number of researchers in the industry and academia resulting in prototypes such as Rainbow-I & II [10], STARNET [4], and LIGHTNING [5].

WDM architectures are based on transmitters and receivers that can be precisely tuned to predetermined, fixed wavelengths. wavelength of a laser shifts with temperature and the output power of the laser can also change even though a constant input current is applied. Wavelength and power stabilization of laser transmitters is a very critical and expensive task. For this reason the commercial exploitation of WDM systems has not made great progress. This is especially true for short-haul (SH) local area network (LAN) environment where the cost of the fiber and its installation would be considerably less in comparison to the cost of suitable transmitter sources.

Robust WDM network, a network being implemented at Colorado State University and University of Colorado, is an approach that allows relaxed manufacturing and operating wavelength tolerances [1]. Robust WDM networks can be implemented based on several different medium access protocols [7]. This paper evaluates a reservation type, token based medium access protocol for a Robust WDM network with circuit-switched connections.

In [2], we modeled and analyzed a symmetric Robust WDM circuit-switched network where each station can access all the c channels of the network. In this paper, we investigate a more realistic case where each station has only a limited number of lasers (c_s) and hence can access only c_s channels that are randomly spread over the total network channels (c).

Section 2 provides a description of Robust WDM network and the token based MAC protocol, Section 3 details the performance model, Section 4 discusses the test results and its comparison with the simulation results, and Section 5 concludes the paper.

2. Robust WDM Network

The network architecture, as it is illustrated in Figure 1, is based on a passive star, where each node has an array of lasers, one of which is dynamically selected at the transmission time [7,11,12,13].

The time is divided into slots, each of which consists of two subslots, namely the transmission interval (T_t) and the reservation interval (T_R). The WDM transmissions and the reservation intervals are interlaced, as shown in Figure 2. High-speed WDM transmissions are allowed only during the transmission intervals. Several stations, up to the total number of channels (c), may transmit simultaneously

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during a transmission interval, as long as they are on different channels (wavelengths). During a reservation interval, all stations stop their high-speed WDM transmissions and one station is allowed to establish a connection with its intended destination. Although the use of the reservation interval, during which no WDM transmissions take place, decreases the performance of the network, this protocol and the implementation have many advantages over the traditional WDM techniques in the areas of robustness and cost effectiveness. The reasoning for using reservation intervals is described in [7,11,12].

A station is considered 'full' if it has an incomplete, pending or being served, connection request; otherwise, it is 'empty'. In addition, a station is 'active' if its WDM transmission starts or continues in the current slot; otherwise, it is 'idle'. The reservation interval may also be used to acknowledge the ability of the receiver to lock on to the signal and to setup a reverse link if required.

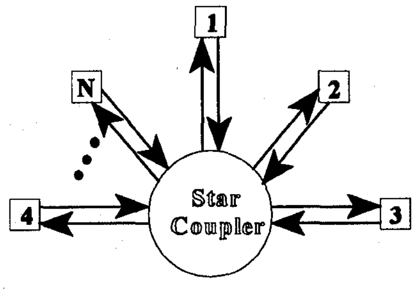

Figure 1: A generic WDM Star network.

A token-passing scheme is used to assign one of the waiting stations to the next reservation interval. The token travels on a separate low-speed control channel, visiting the stations in sequence. A station holds the token only if it is idle and has a request for a connection. Once an available channel is found, the station starts its WDM transmission at the beginning of the next transmission interval, and passes the token to the next station. The time to pass the token, the changeover time, is e. If the new station is active, or idle and empty, it does not hold the token but sends it to the next station. Each reservation interval is followed by a transmission interval in which all the WDM links resume their operation.

Thus, the sequence of events that take place at a station is as follows. First, the station receives a request for a connection. The node waits until it is visited by the token. The station holds the token for a random time h, with mean H=E[h], until it gets an available channel (free wavelength) to setup a circuit-switched connection. Only then, does it transmit the token, on the signaling channel, to the downstream station as well as start the WDM transmission corresponding to the request. When the connection ends, the station awaits the next arrival, and the pattern repeats.

By an available channel we mean an unused wavelength, e.g., λ_1 in Figure 2, that is accessible to the station, rather than a predefined wavelength [1]. Thus, the spacing between adjacent channels may change and need not be constant. In this protocol, a node can be forced to re-select another laser after transmitting for a certain maximum time; hence, the protocol is able to tolerate slow variation of the laser wavelength. However, in our model, the variation of laser wavelengths with time is not considered

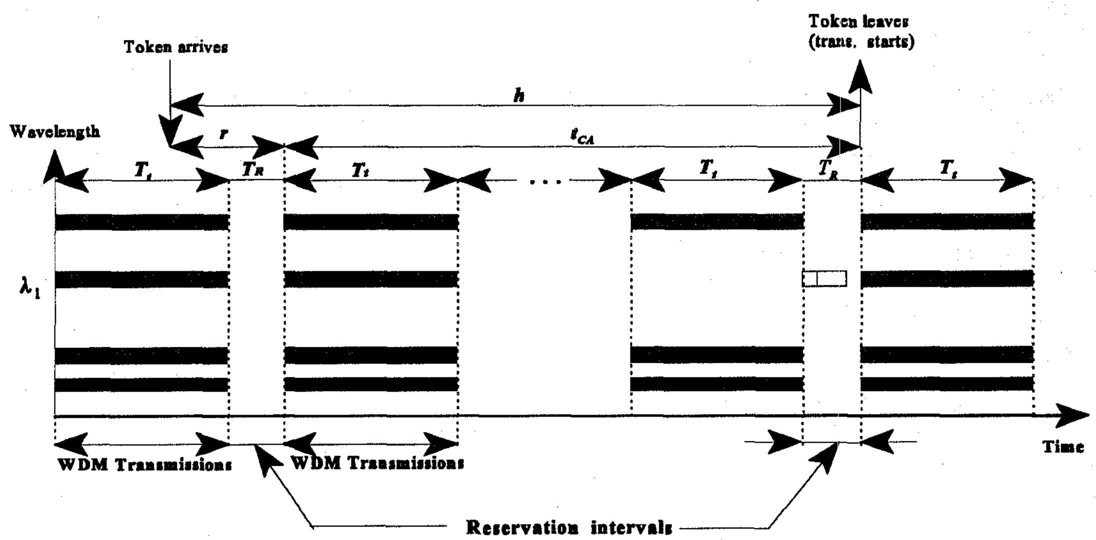

Figure 2: Interlaced WDM transmissions and reservation intervals.

3. The performance model

Assumptions

* The network consists of (N) stations and (c) transmission channels.
* Each station has c_s lasers ($c_s \leq c$), the wavelengths of which are non-overlapping and randomly distributed among the c-channels.
* A symmetric network is considered where arrival rate, service time distribution as well as the node characteristics are the same for all the stations.
* Requests for connections arrive at stations according to independent Poisson processes (mean λ_s arrivals per sec per station).
* A station can handle only one connection request at a time. New requests arriving before the station completes a prior request are lost.
* The service times of connections are independent, independent of the arrival process and is geometrically distributed, with parameter p; i.e., the transmission continues in the next slot with probability p.
* The token changeover time (e), from a station to another, is constant.
* Only simplex WDM transmissions are considered.

Analysis

Consider the token as a server that serves a station for a time h as shown in Figure 2. h is the time from the arrival of the token at a station till the connection is established. Since the token serves a station for only one request at a time, the serve-at-most-one discipline can be considered. In [6], the cyclic queueing model was analyzed by defining the server vacation model, where the server periodically leaves the queue, taking a vacation. This is similar to the model of N queues served in a cyclic order when the vacation is interpreted as the time interval from when the server leaves a queue until it returns to that queue after visiting the other (N-1) queues. In [8], it was viewed that a vacation occurs every time the server executes a changeover between queues.

Assuming that the token changeover times (e) is constant; $e^{(2)} = e^2$, the waiting time (W_Q) can be stated using the results given in [6,8] as follows:

$$W_Q = [\frac{1-\rho}{1-\rho-\lambda e}]\,[\frac{(N-1)e}{2(1-\rho)} + \frac{\lambda H^{(2)}}{2(1-\rho)} + \frac{e}{2} + H] \quad (1)$$

where,

W_Q .... mean of the total waiting time, measured from the instant of a connection request arrival to the time when the connection is established.

N .... number of stations in the network.

$H, H^{(2)}$ first and second moments of the service time (visit period of the token).

e .... mean token changeover time.

λ .... total effective arrival rate to the network [arrivals / sec].

ρ .... total token (server) utilization.

λ_s .... rate of connection request arrivals to a node.

Let P_{ES} = Prob {the station under consideration is empty}, then:

$$\lambda = N\lambda_s P_{ES} \quad (2)$$

$$\rho = \lambda H \quad (3)$$

H and $H^{(2)}$

From Figure 2, assuming that r and t_{CA} are independent, H and $H^{(2)}$ can be obtained as follows:

$$H = E[r + t_{CA}] = R + T_{CA} \quad (4)$$

$$H^{(2)} = E[(r + t_{CA})^2] = R^{(2)} + 2RT_{CA} + (T_{CA})^{(2)} \quad (5)$$

$$T_{CA} = \sum_{i=0}^{\infty} i.S.P_{CA}(i) \quad (6)$$

$$(T_{CA})^{(2)} = \sum_{i=0}^{\infty} (i.S)^2 P_{CA}(i) \quad (7)$$

$R, R^{(2)}$ .... first and second moments of the residual time (r), where r is measured from the instant of the token arrival to a station till the beginning of the next transmission interval. Expressions for R and $R^{(2)}$ can be found in [3].

T_{CA}, $(T_{CA})^{(2)}$... first and second moments of the time t_{CA}, measured from the beginning of the transmission interval next to the token arrival to the moment when the token leaves the station.

S $= (T_t + T_R)$ .... slot time.

Assuming that the time for which a station may use a channel, i.e., the duration of a connection, is geometrically distributed with a mean value L slots/connection,

q = Prob {at the beginning of a slot, the station under consideration gives up the channel, i.e., the station becomes 'idle'} $= 1/L$

p = Prob {at the beginning of a slot, the station under consideration keeps the channel for another slot} $= 1 - q$

Let (t=0) correspond to the beginning instant of the transmission interval next to the token arrival, where (t) is a time expressed in slots; and consider only the simplex WDM transmissions.

Let C_t be the set of c_s channels accessible by the station that is holding the token and C_o be the set of c_s channels accessible by the station under consideration.

$N > c_s$:

For i>0:

$P_{CA}(i)$ = Prob {there is a channel available, exactly at $t=i$ **and** not before that}

$P_{CA}(i) = P(E \cap F) = P(E/F).P(F)$

$P(E/F)$ = Prob {there is a channel available, exactly at $t=i$ | no channel is available before that}

= Prob {exactly at $t=i$, a channel or more of the c_s busy channels become(s) free | all the c_s channels were busy for i-successive slots from t=0}

$$= 1 - p^{c_s}$$

This follows from the geometric distribution assumption for connection duration.

$P(F)$ = Prob {no channel is available before $t=i$}

c_s busy channels at $t=0$, may include a new one that became busy right at that moment. This condition needs to be excluded, i.e., we are interested only in the case where all the c_s channels are busy at $t=-1$ and have continued for another slot. Hence,

$P(F)$ = Prob {all the c_s channels in C_o are busy at $t=-1$ **and** all of them continue for $(i+1)$ successive slots}

= Prob {all the c_s busy channels keep busy for $(i+1)$ successive slots | all of them were at $t=-1$}

. Prob {all the c_s channels are busy at $t=-1$}

$$P(F) = p^{c_s(i+1)} P_{CSB}$$

P_{CSB} = Prob {all the c_s channels, accessible by the station, are busy at the beginning of a transmission interval}

Hence, for $N > c_s$ and $i > 0$:

$$P_{CA}(i) = (1 - p^{c_s})\, p^{c_s(i+1)} P_{CSB} \qquad (8)$$

Substituting from equation (8) into equations (6) and (7), we get T_{CA} and $(T_{CA})^{(2)}$, respectively, as follows:

$$T_{CA} = \frac{(p^{c_s})^2}{1 - p^{c_s}}\, S\, P_{CSB} \qquad (9)$$

$$(T_{CA})^{(2)} = \frac{(p^{c_s})^2 (1 + p^{c_s})}{(1 - p^{c_s})^2}\, S^2 P_{CSB} \qquad (10)$$

For $N \le c_s$:

$P_{CA}(i) = 1$; for i=0

$= 0$; otherwise

From equations (6) and (7), for $N \le c_s$:

$$T_{CA} = (T_{CA})^{(2)} = 0 \qquad (11)$$

Evaluation of P_{CSB}

To find P_{CSB}, the discrete-time Markov chain, shown in Figure 3, is used. Each state represents the number of busy channels (n) in C_o at the beginning of a transmission interval. The state $n=c_s$ represents the case where all the c_s channels of the station are busy due to other active stations,

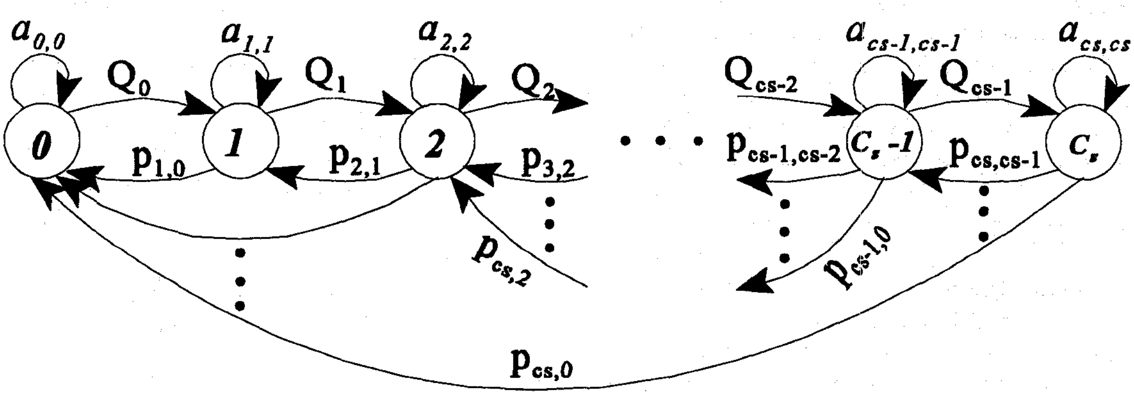

Figure 3: Markov chain for the number of j-busy channels.

i.e., no channel is available to the station under consideration. In the token-passing scheme only the station that is holding the token can start its transmission when there is a channel available. Thus, the number of the active stations and accordingly the number of busy channels can increase by at most one. On the other hand an arbitrary number of active stations may quit at the same time and hence the number of the busy channels can decrease by any number.

The steady-state probabilities can be obtained by solving (12) and (13). Thus, P_{CSB} (p_{cs}) which corresponds to being in state c_s in the Markov chain, can be obtained.

$$\pi = \pi P \qquad (12)$$

$$\sum_{i=0}^{c_s} p_j = 1 \qquad (13)$$

where, $\pi = [p_0 \; p_1 \; p_2 \; \dots \; p_{cs}]$

p_j = Prob {j channels, in C_o, are busy at the beginning of a transmission interval}

$P = [p_{i,j}]$ the matrix of the transition probabilities (i, j = 0, 1, 2, ..., c_s).

$p_{n,n+1} = Q_n$ ($n<c_s$) ;

Q_n = Prob {($n+1$) channels, in C_o, are busy in current slot | n channels in C_o were busy in previous slot}

= Prob {all the n-busy channels from previous slot continue to be busy in current slot}

. Prob {one of the stations from the other (N-n) stations is holding the token, has access to one or more of the (c_s-n) free channels **and** selects one of these channels}

$$Q_n = p^n . P_{HT}(n) . P_{as}(n) \qquad for \quad n \geq 0 ;$$

where,

$P_{HT}(n_1)$ = Prob {a station is holding the token | n_1 channels, in C_o, were busy in **previous** slot}

$P_{as}(n_2)$ = Prob {the station that is holding the token has access to one or more of the (c_s-n_2) free channels of the station under consideration in **current** slot **and** selects one of them}

$a_{n,n} = p_{n,n}$ = Prob {n channels in C_o are busy in current slot | n channels in C_o are busy in previous slot}

= Prob {the number of continuing busy channels in $C_o = n$ | all of them were busy during previous slot}

. Prob {there is no station among the other (N-n) stations that is holding the token ***or*** (there is a station holding the token ***and*** it cannot access and select one of these channels)}

+ Prob {the number of continuing busy channels in C_o =(n-1) | n channels in C_o were busy during the previous slot}

. Prob {there is a station among the other (N-n) stations that is holding the token, has access to one or more of the other (c_s-n+1) free channels **and** selects one of them}

$$a_{n,n} = p^n . [(1 - P_{HT}(n)) + (1 - P_{as}(n))] + [np^{n-1}q] . [P_{HT}(n) P_{as}(n-1)] \qquad for \quad 0 \leq n \leq c_s ;$$

Similarly:

$P_{n,m}$ = Prob {m channels in C_o are busy in current slot | n channels in C_o were busy in previous slot}

$$P_{n,m} = [\binom{n}{m} p^m q^{n-m}][(1-P_{HT}(n)) + P_{HT}(n)\ (1-P_{as}(m))] + [\binom{n}{m-1} p^{m-1} q^{n-m+1}] . [P_{HT}(n) P_{as}(m-1)] \qquad for \quad m>0 ;$$

$$P_{n,0} = q^n\ [(1 - P_{HT}(n)) + P_{HT}(n)(1-P_{as}(0))]$$

Evaluation of $P_{as}(n_2)$ and $P_{HT}(n_1)$

$$P_{as}(n_2) = \sum_j \pi_1 P_{jBz} \qquad (14)$$

P_{jBz} = Prob {the station has j busy channels in C_t}

π_1 = Prob {the station that is holding the token has access to one or more of the free channels in C_o **and** selects one of them | it has j-busy channels}

$$\pi_1 = \sum_{k=y_1}^{y_2} \pi_2 . \pi_3$$

π_2 = Prob {the station that is holding the token selects one of the k free channels common with C_o | it has access to these k channels and it has j busy channels}

$$\pi_2 = \frac{k}{(c_s - j)}$$

π_3 = Prob {the station that is holding the token has access to k channels, from the (c_s-n) free channels in C_o | it has j-busy channels}

$$\pi_3 = \binom{c_s-n}{k}\binom{(c-j)-(c_s-n)}{(c_s-j)-k} / \binom{c-j}{c_s-j}$$

Since the number of busy channels in C_t (j) is limited between z_1 and z_2, P_{jBz} can be obtained from the Markov chain, Figure 3, as follows:

$$P_{jBz} = P_{jB} / \sum_{i=z_1}^{z_2} P_{iB}$$

P_{jB} = Prob {the station has j busy channels $|z_1=0$ and $z_2=c_s$}

Figure 4 illustrates different scenarios of selecting C_o and C_t from the total c channels to evaluate the limits of j and k which are needed in the above equations. Assume that the station under consideration has n busy channels in C_o, the set of c_s channels accessible to it The station that is holding the token has j busy channels in C_t, C_t being the set of c_s channels accessible to it. Let k be the number of free channels in $C_t \cap C_o$, i.e., accessible by both of the stations. Figure 4(a) shows the general relation between n, j, and k. To find the lower limit of j ($=z_1$), Figure 4(b) is used assuming that all the n busy channels are overlapping with the $(c-c_s)$ channels that are not in C_t . n may be less or greater than the $(c-c_s)$ channels that are not in C_t, thus:

$$z_1 = j_{min} = \max\{0, [n-(c-c_s)]\}$$

Similarly, Figure 4(c) is used to find the upper limit of j ($=z_2$), assuming that the (c_s-n) free channels in C_o, are the only free channels in c, thus the rest of min(N, c) stations are busy. n cannot exceed c_s, thus,

$$z_2 = j_{max} = \min\{c_s, \min[N, (c-(c_s-n))]\}$$

To find the lower limit of k ($=y_1$), Figure 4(d) is used, assuming that there is an overlap between C_o and C_t and that all the n busy channels are in that overlap, thus:

$$y_1 = \max\{0, [(2c_s-c)-n]\}$$

Figure 4(e) is used to find the upper limit of k ($= y_2$), assuming a complete coincidence between C_o and C_t, thus:

$$y_2 = \min\{(c_s-n), (c_s-j)\}$$

$P_{HT}(n_1)$ ≡ Prob {a station or more, from the other $(N-n_1)$ stations, is (are) idle and full | n_1 channels, out of C_o, were busy in the previous slot}

The $(N-n_1)$ stations, in the above probability, can be divided into two groups, s_1 and s_2, where the s_1 stations are known to be idle while the s_2 stations may be either idle or active. From Figure 4(c):

$$s_1 = [(N-n_1) - (c-c_s)] \quad ; \text{if } (N-n_1) > (c-c_s)$$
$$= 0 \quad ; \text{if } (N-n_1) \leq (c-c_s)$$

Thus: $s_1 = \max\{0, [(N-n_1) - (c-c_s)]\}$

$$s_2 = (N-n_1) - s_1$$

$P_{HT}(n_1)$ = 1 - [Prob {none of the s_1 idle stations is full} . Prob {none of the s_2 (idle/active) stations is idle and full}]

$$P_{HT}(n_1) = 1 - (\pi_4)^{s_1} (\pi_5)^{s_2} \quad (15)$$

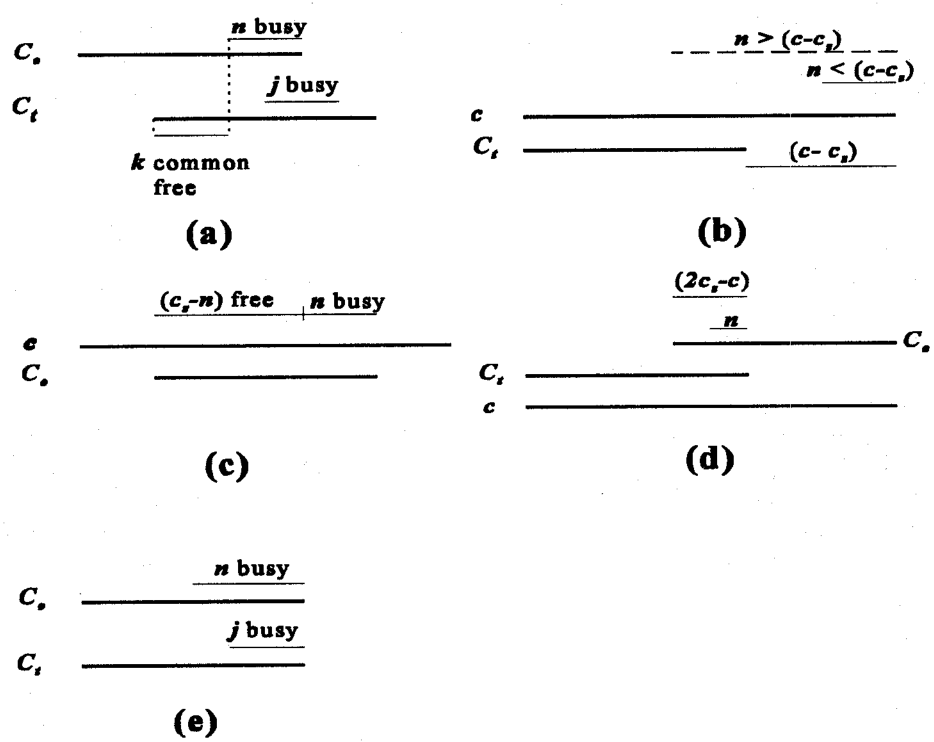

Figure 4: Relations between c, C_o, and C_t.

π_4 = Prob {the station was empty at the beginning of the previous slot (E) | it was idle (I)

. Prob {no arrival to the station during the previous slot}

$$\pi_4 = P_{E/I}\, e^{-\lambda_s S}$$

$$\pi_5 = 1 - P_{IF}$$

P_{IF} = Prob {a station is idle and full}

Evaluation of $P_{E/I}$, P_{IF}, λ and ρ

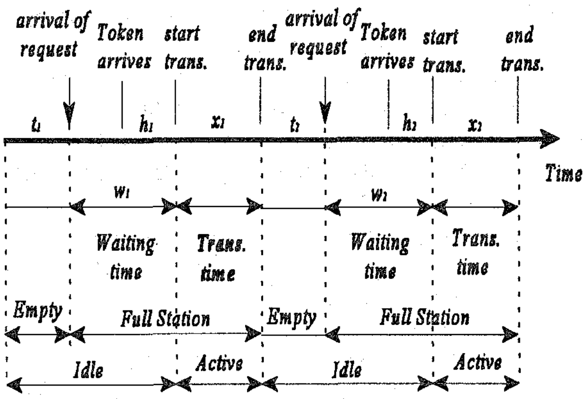

Figure 5: The different events that take place at a station.

t_i ... time between the end of transmission of request (i-1) and the instant of next connection request arrival i. $E[t_i] = 1/\lambda_s$, assuming Poisson arrival process.

h_i ... token holding time until the WDM transmission of the connection request i is started. $E[h_i] = H$.

x_i ... transmission time of request i ; $E[x_i] = X$.

w_i ...waiting time of connection request i ; $E[w_i] = W_Q$.

λ_s ... arrival rate to a station.

In Figure 5, consider the station is initially empty. Assuming Poisson arrivals, the mean time until the next connection request arrival is ($1/\lambda_s$); and only then does the station become full. After a random waiting time whose mean value is W_Q the corresponding transmission starts. The transmission time is an independent random variable and independent of the arrival process, with mean value X. Then, the next connection request arrival occurs after a time whose mean is ($1/\lambda_s$), and so fourth.

Considering a cycle of events in Figure 5, we get $P_{E/I}$, P_{IF} and P_{ES} as follows:

$$P_{E/I} = 1/(1+\lambda_s W_Q) \qquad (16)$$

$$P_{IF} = \lambda_s W_Q \,/\, [1+\lambda_s(W_Q+X)] \qquad (17)$$

$$P_{ES} = 1 \,/\, [1+\lambda_s(W_Q+X)] \qquad (18)$$

Using equations (2), (3), and (18):

$$\lambda = N\lambda_s \,/\, [1+\lambda_s(W_Q+X)] \qquad (19)$$

$$\rho = N\lambda_s H \,/\, [1+\lambda_s(W_Q+X)] \qquad (20)$$

Substituting for λ and ρ in equation (1) and rearranging, W_Q is given by:

$$AW_Q^2 + BW_Q + D = 0 \qquad (21)$$

where,

$A = 2\,\lambda_s$ (22)

$B = 2+[2X-2(N+1)H-3Ne]\lambda_s$ (23)

$D = -\{Ne+2H+[(X-H)Ne+NH^{(2)} +2H(X-NH)]\lambda_s\}$ (24)

Use equations (12) and (13) to get P_{CSB} and (9), (10), and (11) to get T_{CA} and $(T_{CA})^{(2)}$. Use (4) and (5) to obtain H and $H^{(2)}$. Now, it is possible to obtain B and D using equations (23) and (24). Hence, W_Q can be obtained from equation (21).

4. Results

In the following analysis, a network configuration, with fifty stations (N=50) and ten transmission channels (c=10) with each station having access to five channels (c_s=5) is considered. Considering the device tuning time and propagation delays, the reservation intervals (T_R) and the token changeover time (e) are chosen to be 1 μ sec and 0.1 μ sec, respectively. The duration of the transmission intervals (T_t=100 μ sec) and the mean connection duration (L=100 slots) are kept constant. In addition, the mean arrival rate to a station (λ_s) is selected to be either 10 or 100 arrivals/sec, to achieve reasonable values of the network load. These parameters are used in the analysis unless otherwise stated. The normalized network load (G) is given by $G=\lambda X/c$, where $X=L(T_t+T_R)$ is the mean transmission time,.

Solving equation (21), by iteration, we get two values for the mean waiting time (W_Q). In each experiment, we found only one viable value of W_Q. The remaining solution is either negative or results in nonfeasible values (negative or greater than one) for P_{ES} and ρ.

To illustrate the effect of the different parameters on the mean waiting time (W_Q), we change one parameter at a time, keeping the others constant. Results obtained by using the model described in this paper are compared with those generated by simulation. The detailed description of the simulator can be found in [14]. In all the following figures the analytic results are plotted with continuous lines; while the simulation values are represented by *'s.

Figure 6 illustrates the variation of the mean waiting time (W_Q) against the rate of request arrivals at a station (λ_s). At low arrival rates, increasing λ_s, decreases P_{ES} and increases W_Q. As λ_s is further increased, more stations become full thus blocking new arrivals and limiting W_Q to its maximum value.

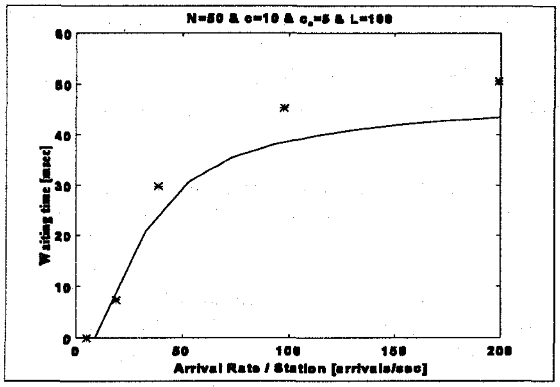

Figure 6: Mean waiting time (W_Q) vs arrival rate per station (λ_s).

The mean waiting time (W_Q) with the number of stations in the network (N) is illustrated in Figure 7. As long as $N \leq c$, the network behaves, on average, as always having a channel available for each station, and hence a request arrival does not wait for more than the residual time (r). Increasing N beyond that, increases the number of full stations that can hold the token and hence increases the token rotation time and hence accordingly W_Q. Then, the token serves all the stations in sequence and hence W_Q increases almost linearly with N.

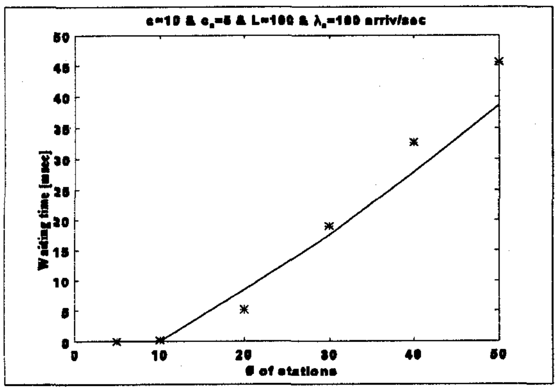

Figure 7: Mean waiting time (W_Q) vs number of stations in the network (N).

Figure 8 shows the effect of changing the transmission interval (T_t) on the mean waiting time (W_Q). Increasing T_t, increases the slot duration ($S=T_t+T_R$) and hence increases the mean connection duration ($X=LS$) which increases the channel holding time by a transmitting station. Thus, a station holds the token for longer time (h) until it gets an available channel and as a result W_Q increases.

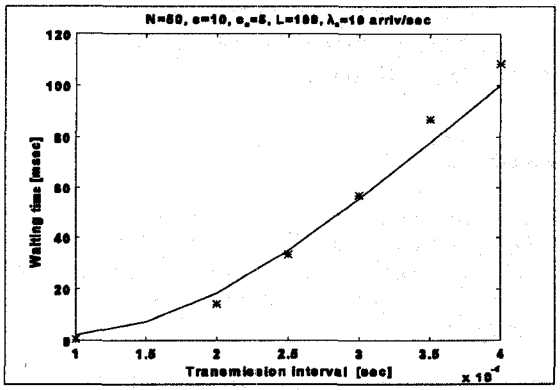

Figure 8: Mean waiting time (W_Q) vs transmission interval (T_t).

The relation between the mean waiting time (W_Q) and the reservation interval (T_R) is illustrated in Figure 9. As mentioned above, increasing T_R, increases S which increases X. Accordingly, h increases which increases W_Q. Since T_R is small, compared with T_t, its effect on W_Q is smaller; and within this small range of variation, W_Q changes almost linearly with T_R.

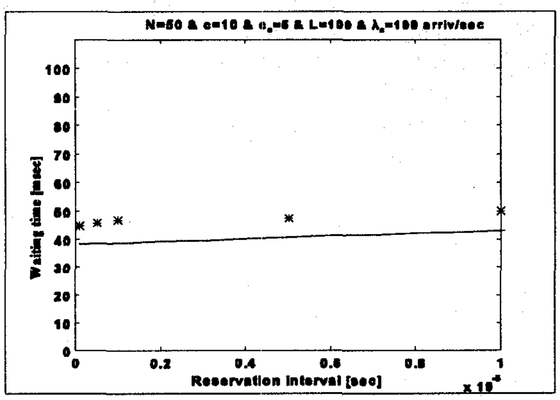

Figure 9: Mean waiting time (W_Q) vs reservation interval (T_R).

5. Conclusion

This paper considers a network with a given number of lasers per station and as a result presents a more realistic scenario compared to the prior model [2] that assumes each station to have a laser corresponds to each possible channel wavelength.

The mean request waiting time (W_Q) was evaluated for the different network parameters. Comparing the results with the simulation's ones indicates that the model can accurately predict the network performance. The model is to be extended to analyze a more realistic network, closely to the one being prototyped at Colorado State University and University of Colorado.

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