LIGHTRING: A DISTRIBUTED AND CONTENTION-FREE BANDWIDTH ON-DEMAND ARCHITECTURE

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Abstract: As opposed to current SONET/SDH solutions that provide static tributary signals, modern access and metro networks require bandwidth-dynamic architectures that can efficiently handle the transmission of users' data bursts. This paper presents the LightRing, a bandwidth-efficient multi-wavelength ring architecture that allows user to set up and tear down optical circuits on-demand. A unique distributed multi-token reservation mechanism is used in the LightRing to set up optical circuits in a contention-free manner. i.e., once initiated the reservation is always completed successfully. A tell-and-go approach is therefore possible whereby data transmission is initiated while the circuit is being set up. The LightRing's distributed control yields fast set-up times that are below the ring round trip propagation time, fair blocking probability and high bandwidth utilization even in presence of relatively short optical bursts of data.

Key words: LightRing, WDMring, bandwidth on-demand, distributed control, multi-token reservation mechanism, Routing and Wavelength Assignment (R-WA), optical burst switching

1. INTRODUCTION

The increasing demand for Internet connectivity and network applications drives the current explosion of network traffic volume worldwide.

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35491-0_28

A. Jukan (ed.), *Towards an Optical Internet*

It is expected that this exponential growth of traffic volume will continue in the foreseeable future. Optical fiber communication technology based on Wavelength Division Multiplexing (WDM) has been successfully employed as the major means to cope with the traffic volume growth. While WDM technology has already revolutionized the backbone network by enabling unprecedented increases in the leveraged capacity of a single fiber, a parallel revolution is now taking place in the access and metro networks.

One of the most critical challenges in designing today's access and metro networks is the fact that bandwidth demands have been consistently exceeding the most aggressive network planning prediction. In addition, the individual user's traffic burstiness makes static bandwidth reservation (e.g., SONET/SDH like) neither bandwidth efficient nor adequate to delay-sensitive traffic. This situation has generated an increasing interest towards all-optical networks that are capable of allocating network resources, i.e., bandwidth, in a dynamic way. Such networks must be able to reserve the necessary bandwidth on-demand, just prior to the transmission of the user's data burst. Once the transmission of the burst is completed, the reserved bandwidth is promptly released and made available to other burst transmissions.

In order to be of practical use, the bandwidth on-demand concept requires few but fundamental features. Three of the features are:

- fast set-up time of the optical circuit (or lightpath)
- fair blocking probability irrespective of the lightpath span (i.e., the number of fiber lines the lightpath is routed through)
- high bandwidth efficiency, i.e., the fraction of reserved bandwidth actually used to transmit data.

To understand how challenging it is to achieve these three features in the same architecture at once, one must observe that users' requests for lightpath are unpredictable and may occur simultaneously at distinct and geographically separated source nodes. As a result, concurrent lightpath requests may compete with one another for the same common resources, i.e., the available wavelengths in the network, and originate a number of unsuccessful attempts as some requests may be blocked by others that booked the resources first. In this scenario, it is thus possible to experience long set-up times, unfair blocking probabilities — lightpaths with longer span are more likely to be blocked as they require successful wavelength reservation on each and every fiber line they are routed through — and bandwidth waste due to the unsuccessful attempts to establish lightpaths.

Approaches so far proposed to solve the Routing and Wavelength Assignment (RWA) problem in dynamic WDM ring — access and metro rings are of particular interest due to the already existing fiber layouts — can be classified as either centralized [1, 4] or distributed [3, 5].

With a centralized approach, the source node sends the request for a lightpath to a special node called *controller.* The controller keeps track of the available network wavelengths and serves the nodes' requests on a First-Come First-Serve (FCFS) basis, by assigning one of the available wavelengths to the incoming request. The resource contention is thus resolved at the controller. In a unidirectional ring, latency of the signaling required between the source and the controller to set up and eventually tear down the lightpath is proportional to the ring latency, i.e., ring round trip propagation time. This latency may considerably delay the set-up time and reduce the bandwidth efficiency in metro applications.

With a distributed approach, every source must solve the RWA problem for its own newly requested lightpaths. One way to achieve this objective is to allow every node to keep track of the network-wide wavelength availability. The RWA problem is then solved based on shared global information [3]. In another approach, each node makes use of a local routing table for each wavelength which specifies the next hop and the cost associated with the shortest path to each destination on this wavelength [5]. Since multiple nodes may concurrently try to assign the same wavelength to distinct lightpath requests, resource contention may arise. Both distributed approaches need a positive acknowledgment to complete a reservation successfully. In case of reservation failure due to resource contention, multiple set-up attempts are required for the same lightpath. Therefore, at least one round trip time between source and destination, i.e., the ring latency in the case of unidirectional ring, is necessary to complete the lightpath set-up prior to beginning data transmission.

This paper presents the *LightRing* architecture whose objective is to overcome the drawbacks of the centralized and distributed reservation mechanisms so far proposed to handle on-demand bandwidth reservation in multi-wavelength ring. The LightRing architecture solves the RWA problem with a distributed approach and at the same time provides a contention-free reservation mechanism. It resorts to a unique distributed multi-token control according to which, access to each wavelength is controlled by a *wavelength specific signaling-token* that is circulated among the nodes connected to the ring in a round robin fashion. A lightpath is set up and torn down on a given wavelength only when the corresponding token is acquired by the source. While circulating along the ring, token broadcasts the lightpath status information to every node of the ring.

Contrary to all conventional wavelength assignment algorithms whereby an available (somehow optimal) wavelength is sought for each given lightpath request, the LightRing distributed control seeks the lightpath request — stored in the so called Best-Fit-Window (BFW) of the source's transmission queue — that optimally fits the resource availability on the wavelength identified by the arriving token. The bandwidth efficiency achieved by the proposed wavelength reservation mechanism is proportional to the number of requests that the reservation mechanism can choose from, thus it is proportional to the size of the BFW. Contrary to most of the existing reservation mechanisms whose complexity is proportional to the number of wavelengths, the complexity of the LightRing reservation mechanism is proportional only to the size of the BFW. The LightRing architecture thus scales well when the number of wavelengths increases.

The proposed LightRing reservation mechanism achieves better network performance than the exiting centralized and distributed reservation mechanisms by applying a tell-and-go reservation mechanism, that once initiated — i.e., acquiring of a token whose corresponding wavelength provides available resources from source to destination — is contention-free and always successful. Wavelength assignment is made locally by each source without requiring an hand-shake protocol with intermediate nodes, destination node or controller. With LightRing, the impact of ring latency on the network performance is mitigated because the set-up time of the lightpath may be significantly less than the ring latency. As a matter of fact, the larger the number of wavelengths, the shorter the expected set-up time becomes, since more tokens circulate in the ring and source is given more frequent opportunities to set up a lightpath.

In summary, as demonstrated in the following sections, due to its various unique features, the LightRing yields fast lightpath set-up times, fair blocking probability and efficient bandwidth utilization under a variety of data burst sizes.

2. SYSTEM DESCRIPTION

The network in question is a single fiber ring network that connects N nodes. The network makes use of W data channels and one control channel, for a total of $W + 1$ wavelengths. The optical signal on the control channel does not go through the node and it is separately handled by a control receiver and a control transmitter. For each data channel

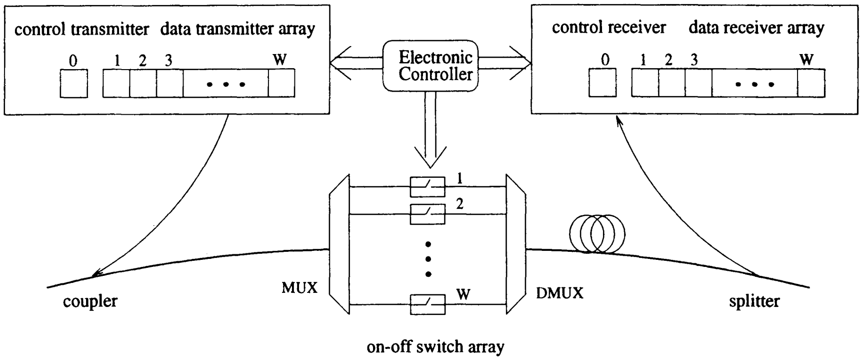

Figure 1 Node architecture.

a node has one fixed transmitter, one fixed receiver and one optical on-off switch connected as shown in Figure 1. This architecture allows the node to transmit and receive data independently (and simultaneously) on any data channel. The on-off switches are used to control the flow of optical signals through the node and prevent signal re-circulation in the ring. Once transmitted by the source node, the optical signal is removed from the ring by the destination node.

A transmission buffer is provided at each source to queue the outstanding lightpath requests. The nodes activities are regulated by an electronic control that determines the state for each on-off switch and the wavelength used to set-up any given lightpath request. The electronic elaboration of the control signal is done in parallel while the optical signal in the data channel propagates through the fiber delay line that connects the splitter to the demultiplexer.

The LightRing architecture does not require wavelength converters.

2.1. WAVELENGTH RESERVATION MECHANISM

To resolve resource contention arising between concurrent attempts to set up a lightpath originating at distinct sources, a wavelength reservation mechanism is required. In the LightRing architecture, this mechanism is based on a distributed multi-token control. Each data channel is assigned a token that is circulated among the nodes using the control channel, and regulates the access to the corresponding data channel. A total of W tokens are circulated and uniformly distributed along the ring perimeter. A lightpath may be set up and torn down only when a token is acquired by the lightpath source. Since only one node at a time is allowed to make a reservation on a given wavelength, LightRing is contention-free. While circulating along the ring, token broadcasts the source and destination of the lightpath being established to all nodes of the ring so that no other node will attempt to set up a lightpath on the same wavelength that overlaps in space with the one being established. As the token propagates towards the destination, each intermediate node sets one of the on-off switches to create the lightpath. The token is shortly followed by the data transmitted on the lightpath under construction, thus achieving the "tell-and-go" feature of the proposed reservation mechanism.

Upon reception of a token, source node first updates its local control table that keeps track of the available resource on the wavelength associated with the token, i.e., the fibers (or the ring segments) in which the wavelength is not assigned to any of the existing lightpaths in the network. Then it seeks a lightpath request that can be set up using the available resources on that wavelength. Since multiple requests may be awaiting transmission in the source transmission queue, an algorithm must be designed to determine which lightpath request (if any) shall be served first.

A Best-Fit-Window (BFW) algorithm is proposed to choose the lightpath request based on the following two observations.

Intuitively, a long-span lightpath request is more likely to be blocked than a short-span lightpath request, especially under medium and high workload. This is due to the well-know fragmentation problem in which short-span lightpaths already established on the wavelength in question block newly generated lightpath requests that span across multiple fibers. To counterbalance this effect the BFW algorithm selects the lightpath request with the longest span in the transmission queue that fits into the currently available fibers. If multiple requests exist with the same span, the oldest one is selected. An additional advantage of the BFW algorithm is to circumvent the head-of-the-line blocking that occurs when the oldest request in the queue, i.e., the first one in line, is blocked.

To limit the variance of the request waiting time in the queue, the BFW algorithm gives priority to those requests that due to blocking cannot be served within a chosen time interval. This objective is achieved by combining the best fit window scheme and the FCFS scheme as follows. Newly generated requests are first served using the BFW scheme. If the request cannot be served for a time interval longer than a threshold, it is then served using the FCFS scheme.

The BFW algorithm is formally described in the next two sections.

2.1.1 Definition of Parameters. The following parameters are defined to provide a formal description of the BFW algorithm.

BFW : maximum number of lightpath requests in the transmission queue considered by the BFW algorithm;

r_i : ith lightpath request stored in the transmission queue, $i = 0$ being the oldest one, i.e., the head-of-the-line request;

s_i : span of request r_i;

R_{TxQ} : $\{r_i \mid r_i \text{ in transmission queue }\}$;

R_{BFW} : $\{r_i | r_i \in R_{TxQ}, 0 \leq i < BFW\}$;

t : current time;

$t_i^{(a)}$: arrival time of r_i in R_{TxQ} (time at which r_i is stored in the transmission queue);

$t_i^{(s)}$: beginning of the service time of r_i (time at which r_i is removed from the transmission queue);

$t_j^{(t)}$: arrival time for token j;

$t_i^{(q)}$: time spent by r_i in R_{TxQ};

$t_i^{(w)}$: time spent by r_i in R_{BFW};

$e^{(w)}(t)$: estimated expected time spent in R_{BFW} by requests (this quantity may vary with time, t);

$d^{(w)}(t)$: soft deadline for r_i leaving R_{BFW} (this value is compared with the time spent by the request in R_{BFW});

R_{LATE} : $\{r_i | r_i \in R_{BFW}, t_i^{(w)} > d^{(w)}(t)\}$ (set of requests whose time in R_{BFW} exceeds the soft deadline);

b_j : number of fibers between source and the first downstream node (including source) that is currently using wavelength j (if wavelength j is not used at all, $b_j = N$);

$l_j(i)$: $b_j - s_i$ (a negative number indicates that $r(i)$ overlaps with lightpath(s) already set up);

$Fit(R, \lambda_j)$: $\{r_i | r_i \in R, l_j(i) \geq 0\}$;

$BestFit(R, \lambda_j)$: $\{r_i | r_i \in R, l_j(k) \geq l_j(i), \forall r_k \in R\}$;

$FCFS(R)$: $\{r_i | r_i \in R, t_i^{(a)} < t_k^{(a)}, \forall r_k \in R\}$;

2.1.2 Best-Fit-Window Algorithm. It assumed that no information is available on the life time of each lightpath request. The lightpath will be torn down once the transmission of data has been completed, but the network is not aware of how long the transmission will last.

The BFW algorithm is defined as follows:

- only r_i in R_{BFW} can be served upon a token's arrival

- arriving requests are dropped when no space is available in the transmission buffer R_{TxQ}.

At source, the following BFW algorithm is used to determine the lightpath request to be served next:

1. Upon arrival of token j, $t = t_j^{(t)}$ —
   set up lightpath for request r_i
   If $(Fit(R_{LATE}, \lambda_j) \neq \Phi)$ {
   $r_i = FCFS(Fit(R_{LATE}, \lambda_j))$
   release token j with current lightpath info
   set up r_i and begin data transmission
   } else if $(Fit(R_{BFW}, \lambda_j) \neq \Phi)$ {
   $r_i = BestFit(R_{BFW}, \lambda_j)$
   release token j with current lightpath info
   set up r_i and begin data transmission
   } else
   pass token j onto next node;
2. Upon setting up r_i, $t = t_i^{(s)}$ —

i) remove r_i from R_{TxQ} and R_{BFW}; ii) set $e^{(w)}(t) = \beta e^{(w)} t_{i-1}^{(s)} + (1 - \beta) t_i^{(w)}$, where β is a value between 0 and 1, that is used to weight the previously measured waiting times. *beta* is chosen to be close to 1;

iii) set $d^{(w)}(t) = \alpha e^{(w)}(t)$, where $\alpha = \frac{d^{(w)}(t)}{e^{(w)}(t)}$ is a constant chosen by the designer to determine the soft deadline that triggers the FCFS scheme. α is chosen to be greater than 1 but close to 1.

3. ANALYTICAL MODELS

Two analytical models are presented that help better understand the fundamental difference between the proposed reservation mechanism and the existing ones. The models are derived to assess the achievable throughput as a function of the expected size of the data burst and provide a preliminary performance comparison. For the LightRing reservation mechanism it is assumed that the size of the best fit window is $BFW = 1$. Being this the worst possible scenario for the LightRing architecture, the result will be considered as a lower bound on the achievable throughput for the proposed architecture.

The models are derived from the analysis of blocking probability developed by Barry and Humblet in [2] for a WDM network in which lightpaths are set up one at a time. In Barry's model the signaling latency is ignored. Barry's model allows to compute an approximate value for the blocking probability of any given lightpath request under a given network throughput. It must be noted that Barry's model does not cover the case in which lightpaths with relatively short life time are dynamically established and torn down.

The key variables in Barry's model are P_l — the probability that a lightpath ends and drops at any given node, and P_n — the probability that a lightpath starts at any given node on any given wavelength. The two variables have the following relationship

$$P_n = \frac{\rho P_l}{1 - \rho(1 - P_l)} \tag{1}$$

where ρ is the wavelength utilization factor. In absence of wavelength conversion the blocking probability is

$$P_b = [1 - (1 - P_n)^H]^W \tag{2}$$

where H is the number of hops of the lightpath, or span, and W is the number wavelengths in every fiber.

The above model is used to derive the blocking probability for the WDM ring architecture of interest. In the case of unidirectional WDM ring, $P_l = 2/N$. An iterative technique is used to derive the blocking probability for a randomly chosen lightpath request. Let $y = P'_b - P_b$ be the gap between the computed blocking probability at two consecutive iterations — P'_b is the result of the next iteration using P_b. Under saturation load, the following steps are used to derive the blocking probability:

the plane y versus P_b is used –

1. set network load $d = 1$, $P_{b0} = 0$ and $P_{b1} = 1$;
2. $\rho 0 = d(1 - P_{b0})$; $\rho 1 = d(1 - Pb1)$;
3. compute P'_{b0} and P'_{b1} from Eq. 1 and Eq. 2;
4. $y0 = P'_{b0} - P_{b0}$ and $y1 = P'_{b1} - P_{b1}$;
5. connect point $(P_{b0}, y0)$ and point $(P_{b1}, y1)$ with a straight line, and let P_b be the intersection of this line with axis $y = 0$;
6. compute $y = P'_b - P_b$, where P'_b is derived from Eq. 1 and 2 using $\rho = d(1 - P_b)$; if y has the same sign as y0, $P_{b0} = P_b$, otherwise $P_{b1} = P_b$;
7. go back to step 2 until $|y|$ is less than the desired resolution.

The achievable throughput is then derived taking into consideration the blocking probability, P_b, and the lightpath utilization, $E[\eta_a]$, that is the fraction of time during the lightpath life time that is actually used to transmit data

$$thr = E[\eta_a](1 - P_b) \tag{3}$$

The value of $E[\eta_a]$ is a function of the chosen reservation mechanism and the probability density function of the burst transmission time, $g_a(t)$. In the next two sections $E[\eta_a]$ is derived for both the LightRing reservation mechanism and the other existing mechanisms under the assumption that the burst transmission time is exponentially distributed with average a. In the derivation, the switching latency of the on-off switches is assumed to be negligible when compared to the ring latency, D.

3.1. LIGHTRING RESERVATION MECHANISM

In the LightRing architecture, data transmission begins at the same time instant when the lightpath is established. Once data transmission is completed, the lightpath is torn down as soon as the token that corresponds to the wavelength assigned to the lightpath reaches the source again, thus

$$E[\eta(a)] = \sum_{n=0}^{\infty} \int_{nD}^{(n+D)} \frac{t}{(n+1)D} g_a(t)dt. \tag{4}$$

If the burst transmission time is exponentially distributed with average a, then

$$\begin{aligned} E[\eta(a)] &= \sum_{n=0}^{\infty} \int_{nD}^{(n+D)} \frac{t}{(n+1)D} \frac{1}{a} e^{-t/a} dt \\ &= \sum_{n=0}^{\infty} \frac{a}{D(n+1)} (e^{-nD/a} - e^{-(n+1)D/a}) \\ &+ \sum_{n=0}^{\infty} \frac{1}{n+1} (ne^{-nD/a} - (n+1)e^{-(n+1)D/a}) \\ &= 1 + (e^{D/a} + \frac{a(1-e^{D/a})}{D}) \ln(1-e^{-D/a}) \end{aligned} \tag{5}$$

3.2. OTHER RESERVATION MECHANISMS

As already discussed in the Introduction, the other exiting reservation mechanisms require at least one round trip time within the ring to complete the reservation. In the case of centralized reservation mechanism, it is exactly one round trip time. In the case of distributed reservation mechanism, one round trip time is the lower bound on the time required to successfully set up a lightpath. Only the centralized reservation mechanism is therefore considered here as it represents the most efficient solution among the exiting ones excluding the LightRing.

Observing that the lightpath is considered to be set up as soon as the controller assigns a wavelength to it, and it is torn down by the controller as soon as a disconnect signal is received from the source, the life time of the lightpath equals the burst transmission time plus the ring latency.

Thus, in general

$$E[\eta(a)] = \int_0^\infty \frac{t}{D+t} g_a(t)dt. \tag{6}$$

and for the exponentially distributed transmission time

$$E[\eta(a)] = \int_0^\infty \frac{t}{D+t} \frac{1}{a} e^{-t/a} dt. \tag{7}$$

4. PERFORMANCE RESULTS

The performance results presented in this section are obtained either from simulation or from the analytical models derived in Section 3. The simulation time is chosen to achieve a confidence interval of 5% or less at 98% confidence level. Unless otherwise stated, the network under consideration is a WDM ring with 32 wavelengths and 16 nodes evenly distributed over 80 km of fiber. Each wavelength supports fixed transmission rate of 10 Gbps. For demonstration purpose, the data bursts are assumed to be generated according to a Poisson arrival process and have size that is exponentially distributed. Traffic is uniformly distributed, implying that the source and the destination nodes of a newly generated data burst are randomly chosen.

Results obtained on the blocking probability confirm the fair behavior of the LightRing architecture with respect to all possible lightpath spans. This is due to the fact that newly generated data bursts are dropped only when they cannot be stored in the already full transmission queue. Consequently, data bursts are dropped irrespective of their source-destination pair.

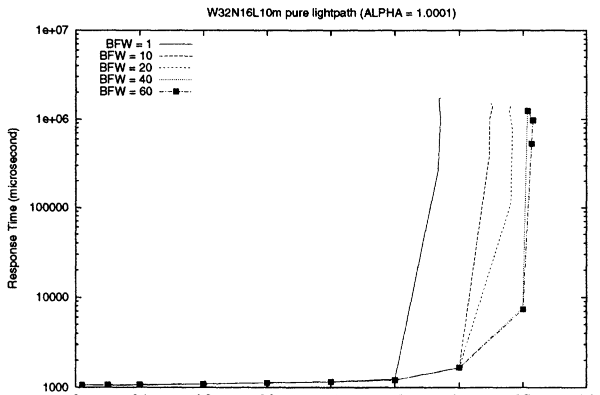

Figure 2 LightRing: expected response time versus throughput

Simulation results in Figure 2 plot the expected response time versus throughput obtained for various sizes of the BFW. Response time is defined as the sum of the waiting time in the transmission queue and the transmission time of the burst. Throughput is normalized to be equal to one when all wavelengths in all fibers are always used to transmit actual data. The expected burst length is chosen to be 10 Mbit, thus requiring an expected transmission time of 1 ms. The figure shows that response time and control complexity can be traded for throughput by varying the BFW size. The achievable throughput increases around 30% as the size of the BFW grows from 1 to 40. However, further increase of the BFW size does not yield any significant throughput gain, but it increases the complexity of the BFW algorithm. At low and medium workload the expected response time is less than the response time of the centralized reservation mechanism that is bounded from below by the sum of the ring latency and the expected burst transmission time, i.e, 1.4 ms. This fact indicates that the expected time required to establish a lightpath in the LightRing architecture can be well bellow the ring latency.

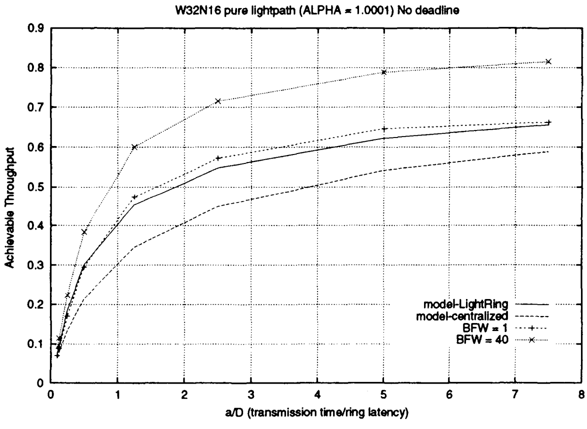

Figure 3 Achievable throughput, *thr*, versus expected burst transmission time normalized to the ring latency, a/D

Figure 3 depicts the achievable throughput versus the expected burst transmission time normalized to the ring latency, a/D. (For example, $a/D = 1$ indicates an expected burst transmission time of 400 μs in a 80 km ring.) Two curves are derived from simulation, respectively, for the case of LightRing with $BFW = 1$ and $BFW = 40$. The other two curves, respectively, for the LightRing architecture with $BFW = 1$ and the centralized reservation mechanism, are obtained using the models described in Section 3. The analytical results of the LightRing closely match the simulation results for $BFW = 1$, thus cross-validating the analytical model approximations and the simulation results. As expected, the LightRing architecture outperforms the centralized reservation mechanism for a variety of burst sizes. Theoretically, the two analytical curves converge when the burst length approaches infinity. In the LightRing architecture with $BFW = 40$, bandwidth efficiency is further improved for most of the burst lengths shown in the figure.

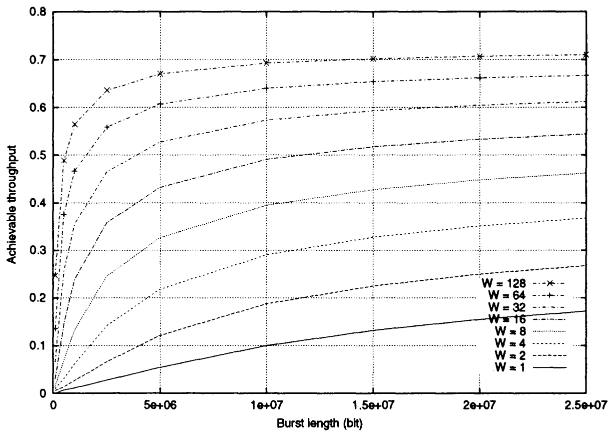

Figure 4 Achievable throughput, *thr*, versus expected burst length for various numbers of wavelengths but fixed total fiber bandwidth of 80 Gbps

Figure 4 shows the achievable throughput of the LightRing architecture as a function of the expected burst length for a variety of numbers of wavelengths. Results are derived from the analytical model. The total bandwidth is fixed at 80 Gbps, thus any increase in the number of wavelengths, proportionally reduces the transmission rate on each individual channel. Figure 4 indicates higher bandwidth efficiency when the number of channels increases. This is due to two factors, namely 1) with a larger number of wavelengths (and tokens) the source acquires tokens more frequently and 2) with a lower channel transmission rate, short data bursts can still be efficiently transmitted in relatively large rings.

5. SUMMARY

The LightRing architecture was presented in which a distributed and contention-free multi-token reservation mechanism is used to set up optical circuits on-demand. By performing a tell-and-go reservation of wavelengths, the LightRing architecture yields fast set-up time and efficient bandwidth utilization even in presence of relatively short bursts of data, e.g., bursts whose expected transmission time is 1 ms in a 80 km ring.

Among other interesting features, the LightRing architecture is compatible with optical packet switching [6] and its performance improves with the growing number of wavelengths, consistently with the current technological trend. Complexity of the reservation mechanism is not a function of the number of wavelengths, and can be varied to trade response time for bandwidth efficiency. Finally, the LightRing architecture is compatible with emerging protocols devised to provide bandwidth reservation in the optical layer, e.g., MPλS, and yields fair blocking probability irrespective of the circuit span in presence of uniform traffic.

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