A Bandwidth Allocation Scheme in Optical TDM Network

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Abstract

Wavelength Routing (WR) and Optical Burst Switching (OBS) are two optical network techniques that have received enormous attention over the last decade. However, the two techniques are plagued with many problems. The main concern with WR is the inefficient bandwidth utilization. On the other hand, the problem with OBS is resource contention and burst dropping. In this paper, we propose a new scheme to share network resources using Time Division Multiplexing (TDM) instead of the statistical multiplexing employed in optical burst switching. To avoid contention and improve bandwidth utilization, we resort to a simple reservation scheme that guarantees timeslot deliveries. In addition, we propose the deployment of a new device that we call Sequencer, a simplified form of Optical Time Slot Interchangers (OTSIs), to assist in mapping incoming timeslots to some available outgoing ones. Our goal is to achieve a contention free network, and improve performance. Many classes of traffic can coexist in our network by adjusting the bandwidth allocation parameters.

1. Introduction

The rapid growth of the Internet and the advent of WDM in the second generation of optical network systems [1,2,3] have led to the extensive use of optical resources available for switching and routing [4,5]. Such growth has boosted the research activities that focus on the most efficient techniques to make better use of the enormous speed and bandwidth of all-optical networks. Hence, the question for an optical carrier that adopts efficient techniques to share resources and maintain the essential quality of service became the focus. Following the trend of carrying IP traffic over WDM [6,7,8], many research initiatives started under two major strategies: Wavelength Routing and Optical Burst Switching.

Wavelength Routing [9,10,11] is a technique that allows the establishment of a direct end-to-end light channel between two nodes, known as a light path. The path carries traffic from a source to a destination, on a specific wavelength, without electronic switching at intermediate nodes. It is seen as a virtual link in a network of light paths leading to a virtual topology that emerges on the substrate of the physical structure, and provides a new topology for the higher layers. The wavelength routing scheme is more appropriate for networks where wavelength channels are required, and quality of service is essential. It is not suitable for all classes of traffic, where the quality of service requirements vary based on the application types. Wavelength routed networks have known some improvement especially with wavelength assignment algorithms. Unfortunately, this technique is still facing many problems, namely:

- The complexity of a wavelength assignment algorithm increases with the network size and the number of wavelengths per fiber link, which may hinder the future expansion of the network.
- Due to resource limitations, it is sometimes impossible to establish a direct light path between a source-destination pair of nodes. Therefore, intermediate nodes must be used as a tandem, which can lead to additional delay and routing complexity.
- Even when a light path is established between two edges, it is not necessarily the shortest one.
- Edges may not have enough loads to fill all the capacity of the established path; hence, a part of the bandwidth may be wasted.
- To establish a new light path, the manager may require a relatively long time to analyze and reserve the available resources.
- Some fractions of the available optical wavelengths remain unused on some fiber link.

Optical Burst Switching [12,13,14] is a forwarding technique employed with a transparent optical backbone aiming to keep a big part of the information in the optical domain, and reduce the opto-electronic conversion overhead. In addition, with OBS, there is no need to reserve a wavelength for each end-to-end connection. Rather, a wavelength is used based on its availability. The communication between two edge nodes is done by aggregating electronic traffic at the source node to form a burst, before sending the burst on a wavelength through the network to the destination. Prior to transmitting a burst, the source sends a control packet on a separate control wavelength to reserve resources at intermediate switches. At an intermediate switch, if the necessary resources can be reserved, the burst would go through; otherwise, it gets dropped. Due to the lack of intelligence inside the network, the optical burst switching technique suffers from a high contention ratio causing burst losses. Indeed, whenever two or more bursts arriving simultaneously at a given node compete for the same output, only the first one is sent and the others are dropped. Optical burst switching is suitable for networks where the traffic is uniformly distributed, and has no delivery guarantee.

Similar to wavelength-routed optical network, OBS cannot serve all classes of traffic. Each method has its own limitations and suffers from many drawbacks. With OBS, the burst contention ratio, which is inherent to this technique, decreases the performance in terms of throughput and delivery delay, especially with high traffic load. Several methods have been proposed in the literature to decrease the contention ratio (or burst loss rate). Some of these techniques are purely software, such as deflection routing [15,16] and burst segmentation [17,18]; while other approaches, such as burst buffering [19,20] and wavelength conversion [21,22,23], require specific hardware. These methods may reduce the contention, but they all remain sensitive to the traffic load. Indeed according to [12] it is clear that even in an ideal network, where the switches use a specified number of buffers and perform wavelength conversion, contention still occurs when the load gets heavier. Thus, the minimal delay and the delivery are not guaranteed making the network useless for many applications.

To avoid the contention resulting from optical burst switching and increase the network throughput at the same time, we propose in this paper a new bandwidth allocation scheme and switch architecture that uses slotted switching with flow reservation, which is a form of TDM. Slotted switching techniques were reported in [24, 25]. In [24], they talk about slot mapping and assignment schemes without using optical buffering in a TDM network. In [25], they present a switch architecture using Optical Time-Slot Interchangers (OTSI) to perform timeslot switching, and study the effect of alternative OTSI designs on the cost and performance. The OTSI is made of a set of optical crossbars and a number of variable size delay lines, needed to induce factors of timeslot delay. The three basic characteristics that would affect the cost and performance of an OTSI are the size of its internal crossbar, the amount of fibers needed for delay lines to reorder the timeslots, and the number of switching operations needed to be performed on a timeslot within the OTSI. The result of the study reported in [25] shows that an OTSI, with 4 delay lines of total delays equal to 15 µs, would provide excellent performance under heavy traffic load in a time slotted architecture, where the frame is made of 64 timeslots of 1 µs each. In addition, the average number of switching operations per hop is 3. In our scheme, we propose a similar slot delaying technique, but with different characteristics. We called the employed device Optical Time Slot Sequencer, or simply Sequencer.

In our study, we rely on the Labeled Switch Path (LSP) concept to route traffic from source to destination. An LSP corresponds to the reservation of one timeslot per TDM frame. We allow an edge node to reserve a flow of LSP groups to accommodate the transmitted traffic that might need more than one timeslots per frame, and sometimes more than one designated path. An LSP is identified by the path, wavelength on which data travels, and the slot position on each link. Note that, along the path, the timeslot position, assigned at the source, might change due to propagation and switching delays. An LSP group consists of one or more LSPs sharing the same path and wavelength between a particular source destination pair. A Flow is a set of LSP groups riding on different wavelengths and/or different paths. Routing at intermediate nodes is carried out on a time slot basis. Thus, switching from slot to slot must be fast enough to fit the narrow guard time that separates slot boundaries [24]. A further challenge for slotted traffic is the global synchronization. We aim to handle the challenge by assuming the length of fibers corresponds to propagation delays that are multiples of the slot size [24]; and, the clocks should be synchronized to tick in timeslot units. In addition, to account for the variable delay induced by the change in temperature, we need to dynamically align the incoming slot boundaries to the local clock. This can be achieved using a set of variable size delay lines with an optical switching component to form a Synchronizer [25].

Beside its capability of avoiding contention and improving bandwidth utilization in Slotted OBS, the proposed scheme and architecture can carry TDM traffic that aggregates at the edge nodes. With OBS, the burst is segmented to form multiple data packets, each having the size of a timeslot; while, with TDM, multiple low speed TDM packets are aggregated to fill one timeslot. Furthermore, the proposed techniques can serve WDM traffic when all the timeslots in a frame are exclusively used for an end-to-end connection between a source-destination pair.

The rest of this paper is organized as follows; Section 2 presents a slotted optical burst switching architecture, Section 3 presents the simulation results and analysis, Section 4 is the conclusion of this work.

2. Resource Allocation and Switch Architecture

In the proposed scheme, the source node decides on the number of timeslots that need to be periodically transmitted to a certain destination. The number of requested timeslots over a given wavelength must be less or equal to N, the number of slots per frame. Afterwards, it engages in a reservation scheme to allocate the network resources that are essential to transport the periodic traffic. The resources are reserved to serve the LSPs originating at the source, based on the requested bandwidth and its availability in various paths. The LSPs are organized in groups to form a flow as defined earlier. If the LSP group riding on a wavelength along the shortest path covers only part of the needed bandwidth, alternative LSP groups are checked to accommodate the remaining bandwidth. We propose a simple reservation method that relies solely on the lowest amount of available bandwidth in the physical links of a given path. The link that has the lowest bandwidth among the rest dictates the amount of traffic that can ride on the path, i.e. the size of the LSP group. The reservation method is not concerned with the timeslot positions since the time slotted traffic will be re-sequenced at intermediate nodes to fill up the empty slots. Thus, the source node is free to choose the slot positions for a reserved LSP group, knowing that the selected position may change along the route based on the various delays and the availability of a corresponding slot. After the reservation phase, presumably quick enough, the transmitted time slotted traffic on the reserved LSPs follows a schedule along the intermediate nodes. If an incoming timeslot reaches an intermediate node when another slot is using the outgoing link, then the timeslot has to be delayed an adequate amount of time to be mapped to an available slot position. For this purpose, a scheduling algorithm runs once per LSP to decide the amount of delays needed at every hop. Once the mapping table is defined by the scheduler, it will be used during the lifetime of the LSP to direct the incoming timeslot to the appropriate entry in the Sequencer, and hence produce the needed delay.

By adopting the proposed scheme, we achieve higher bandwidth utilization and avoid contention. The reservation and scheduling methods are simple and straightforward making the set-up time minimal. Compared with OBS, we discard the need for a data header and rely on the slot position to identify an LSP. In our scheme, a switch forwards the timeslot of an LSP based on its position in the frame. Based on this architecture, multiple classes of services become possible by selecting the number of timeslots to be transmitted from a source to a destination. For instance, high priority traffic can be transmitted in a flow of many LSP groups; and low priority data can travel on a group of a few LSPs. Stating the merits leaves us with one major drawback that need to be resolved, which is the problem of out-of-order delivery. Since the traffic is slotted and can be sent through multiple LSPs, some slots might reach the destination faster than the others due to the varying delivery delays based on the different propagation and switching delays occurring on different LSPs. Hence, the destination node has to cope with reordering the traffic to match its original pattern. A possible solution is to add a sequence number to the header of every traffic segment, corresponding to a timeslot, at the source node before sending it through the optical domain.

2.1 Switch Architecture

The architecture of an intermediate switch is shown in Figure 1. The figure shows only one wavelength per fiber link. In addition, each link carries a dedicated control wavelength that goes to the switch controller, where the control data gets converted to the electrical domain. As shown, every output port is coupled with a Sequencer used to align the slotted data in order to prevent link contention. Each sequencer is connected to the output side of the optical cross-connect via N input lines. The admission control module is responsible for the signaling to decide the amount of bandwidth available on a given path in order to assist the source node to decide on the size and number of LSP groups needed to transport certain traffic. Its main responsibility is to define the lowest amount of available bandwidth on the set of links making a path, and propagate the information back to the source. It can also handle other functions such as forecasting the average delivery delay. The admission control module is used during the reservation phase. On the other hand, the scheduler module is responsible for setting the amount of delays needed per timeslot to map it to an available position in an outgoing frame. Once the amount of delay is defined for an LSP, the scheduler reserves the appropriate resources in the corresponding Sequencer, and updates the next intermediate node about the new slot position. This exercise is performed when the resource reservation for a new flow is made and the corresponding LSPs are established. During the transmission process, the scheduler periodically instructs the switching element to direct outgoing timeslot to the appropriate FDL entry in order to produce the needed delay.

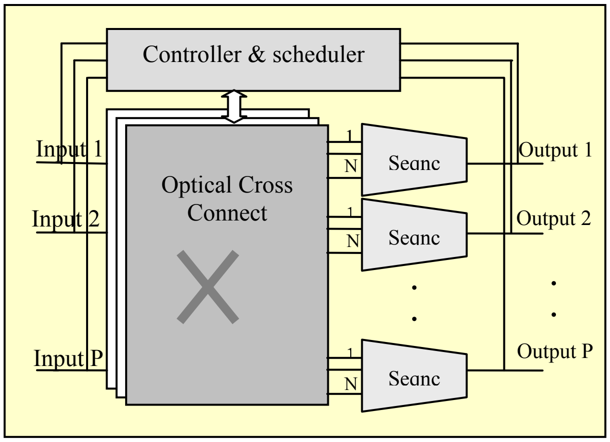


Figure 1 – Switch Architecture

The proposed Sequencer is a multi-input queue of N sequentially connected fiber delay lines (FDLs), each matching a timeslot size; see Figure 2. The delay imposed by every FDL is exactly equal to the time slot period. A Sequencer of size N has N inputs connected to a switching component and 1 output. Every input leads to the beginning of one of the sequentially connected FDLs. After a slot enters a designated FDL at the queue position j, it moves across all the subsequent FDLs in the queue until it reaches the shared output link. In this case, the slot experiences a delay in the sequencer equal to j multiplied by the time slot period T. Note that the first sequencer entry at position 0 goes directly to the output without being delayed. Generally, an FDL position in the sequencer is selected based on the incoming traffic that shares the output link. It is determined by considering all the timeslots that share the same output resource (i.e. link and wavelength). For instance, if K slots are in line to be sent to the output link, the new slot is assigned to the Kth FDL position in the sequencer.

The unique characteristic of the Sequencer is that the number of switching required for a timeslot per hop is always 1. On the other hand, with the optimized Optical Time-Slot Interchanger proposed in [25], the average number of switching per hop is equal to 3. An OTSI having the same characteristic of the Sequencer is possible. However, the total length of the needed delay lines is equal to N2/2, arranged in N lines of length 1, 2, … N. Meanwhile, the total length of the single delay line employed in the Sequencer is equal to N.

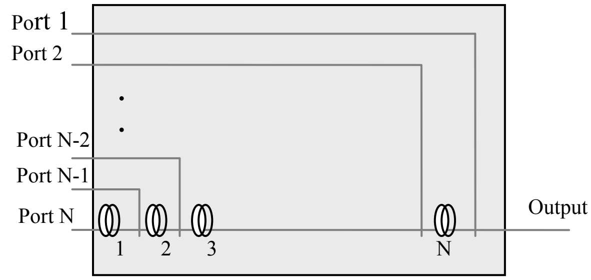


Figure 2 - Sequencer

To reduce the switch complexity, where an optical cross-connect of $m \times N$ outputs is required (N = number of timeslots per frame, and m = number of output fibers), we propose an alternative approach. We place the Sequencer at the input side of the switch, and connect it to the input fiber by a small $1 \times N$ optical cross-connect, whose role is to direct incoming timeslots to the appropriate entry in the sequencer. See Figure 3. In this case, the main cross-connect of the switch remains simple. The price of this approach is the introduction of some blocking, and the complexity of dealing with it. For instance, blocking can occur when 2 consecutive timeslots are to be switched to the same timeslot position, but in two different outgoing links. Although both timeslots get assigned to 2 consecutive FDL positions, the second slot cannot go through its assigned FDL since this position would be used by the first after moving one position forward.

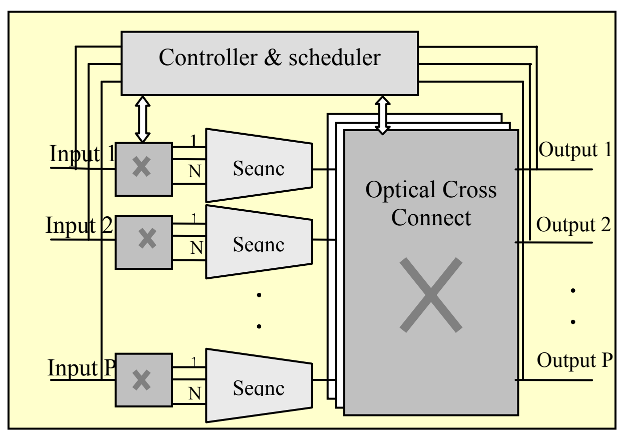


Figure 3 – Alternative Switch Architecture

2.2 Flow Reservation

In this simple reservation scheme, a flow of LSP groups (LSPGs) is established from source to destination before traffic transmission. The size *Z* of an

LSPG, representing the number of its LSPs, is an integer number bounded by the lowest available bandwidth on the set of links forming the path. We use the term “available bandwidth” to describe the number of available timeslots per frame on a given link. A path P, made of a sequence of links $l_1 l_2 \ldots l_p$, provides a maximum bandwidth B_{max} (in terms of timeslots), where $B_{\max} = Min(B_1, B_2, ..., B_p)$ and B_j is the available bandwidth on link l_j. The size of a possible LSPG running on P can be between 1 and B_{max} ($1 \leq Z \leq B_{max}$). A source node S willing to periodically transmit n timeslots of data to a destination D would require n LSPs ($n \leq N$), organized in a flow of k LSPGs such that $n = \sum_{i=1}^{k} Z_i$ where Z_i is the size of the i^{th} LSPG.

To reserve a bandwidth capacity equal to B_{req} (slots) in the network, a source node starts with the shortest path P_1 first, which has a maximum number of available slots equal to B_1. If $B_{req} \leq B_1$, then the source node reserves a single $LSPG_1$ consisting of a number of LSPs equal to B_{req}. In addition, the bandwidth B_j on every link l_j, forming the path, becomes equal to $B_j - B_{req}$ (or $B_j = B_j - B_{req}$). If $B_{req} > B_1$, then the source node reserves an LSPG of size B_1, and proceeds with considering the second shortest path P_2. If $B_{req} - B_1 \leq B_2$, then an $LSPG_2$ is reserved with a size equal to $B_{req} - B_1$. Otherwise, the same procedure is repeated for k alternative paths $P_1, P_2, \ldots, P_k$, where $k \leq B_{req}$, until $B_{\mathrm{Re}q} - \sum_{j=1}^{k-1} B_j \leq B_k$. If $k = B_{\mathrm{Re}q}$ *and* $B_{\mathrm{Re}q} - \sum_{j=1}^{k-1} B_j > B_k$, then the request can be partially granted to accommodate a number of slots equal to $\sum_{j=1}^{k} B_j$; while the remainder of the requested bandwidth, derived by $B_{\mathrm{Re}q} - \sum_{j=1}^{k} B_j$, gets blocked.

2.3 Basic Scheduling

Sophisticated scheduling algorithms can be designed to manage the timeslot switching and delaying in the network (i.e. Sequencer delays). In these algorithms, many parameters can be considered such as the number and size of Sequencers, and the maximum tolerated delivery delay. However, we rely on a basic scheduling algorithm after assuming that every output link is connected to a dedicated sequencer of size N. A logical vector V of size N (or bitmap) represents the states of all the timeslots in the outgoing link. If the ith position in V is set to 1, it means that the corresponding timeslots on the outgoing link is reserved for usage by a cross-connected incoming link. To know the availability of the i^{th} timeslot position in an outgoing link, we perform the logical OR operation on V and 2i. If the answer is 0, it indicates that the i^{th} timeslot position on the outgoing link is free. An LSP, riding on timeslot j, must be switched to another timeslot if the j^{th} position is not available on the outgoing link. In this case, once the scheduler identifies the first available position i, starting from the least significant bit in V, it sets the i^{th} position in the corresponding logical vector to 1. Based on this one time mapping procedure, it periodically assigns the traffic arriving on the j^{th} timeslot to the $(|i-j|+1)^{th}$ FDL in the Sequencer of the outgoing link. Hence, the j^{th} incoming timeslot is delayed by a period equal to ((i - j + N) mod N) x T, where T is the timeslot duration. Note that the position of the incoming timeslot is relative to the local clock at the intermediate switch. Although a node transmits a timeslot at position x, the adjacent node on the path might see the timeslot at position y due to the propagation delay t in the link, [y = (x + t) mod N]. This scheduling process is done only once after the reservation in order to define the mapping tables, which will be used by the controller to forward timeslots to the appropriate positions in the sequencer.

The delivery delay DL imposed by the proposed scheme is equal to the distance propagation delay PD added to the total delays incurred at the intermediate Sequencers. If M is the number of intermediate nodes that an LSP crosses, then the maximum delivery delay is $PD + (M \times (N-1) \times T)$. For instance, if the timeslot duration is 10 µs, the frame is composed of 100 slots, and the number of intermediate nodes is 10, the maximum delay will be 10 ms on top of the propagation delay (5ms/1000km).

As an example, consider an intermediate switch having 3 inputs, 2 outputs, and one wavelength λ available for service (figure 4). We need to setup a new LSPG on input In3, which passes through the output Out1 and consists of 4 LSPs. At each input link, we show a bitmap representing the timeslots states of the incoming frame. In addition, we use the logical vectors V1 and V2 to reflect the timeslots availability in Out1 and Out2 respectively. Initially, we have some traffic on the input links In1 and In2 that share the output links Out1, and Out2. At the input In1, the first 2 timeslots are mapped to the same timeslot positions in the output Out1, and the 6th in In1 is set for the 6th position in Out2. For this reason, the corresponding bits are set to 1 in V1 and V2. A similar representation is done for the traffic arriving at input In2, where the 5th timeslot is mapped to the same position in Out1, and the 6th is set for the 7th position in Out2. Note that the total number of reserved timeslots at Out1 is 3 as shown by V1. It indicates that the node can accommodate the 4 LSPs of the requested LSPG. This step is done at the reservation phase; however, we mention it for clarification purposes. The arriving frame on In3, carrying the LSPs of the resquested LSPG, is represented by the bitmap [10000111] assuming that In3 did not have any traffic previously. Considering the 1st timeslot, we notice that it can go through the 3rd timeslot in Out1. Therefore, the 3rd bit needs to be reserved in the logical vector V1. The amount of Sequencer delay in this case is 2 (i.e. 3-1). Thus, the 1st incoming timeslot will be switched to the 3rd FDL entry in the corresponding Sequencer. We do the same procedure with every LSP of the considered LSPG to book its corresponding output timeslot and define its Sequencer delay. To see the mapping of all LSPs from In3 to Out1, consult the table included at the bottom of the figure. In addition, you find the new bit values in the vector V1 included next to the table itself.

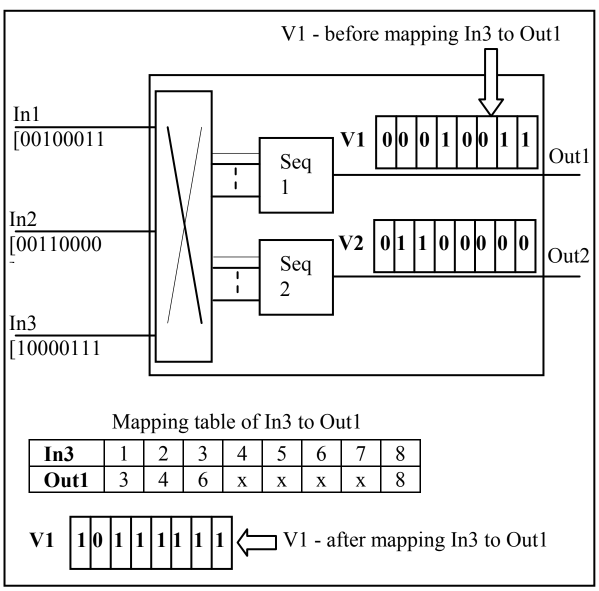


Figure 4 – Scheduling Example

3. Wavelength Conversion and Slot Delaying

We may think of the optical slot sequencer in the same sense we understand the optical wavelength converter. The slot sequencer delays traffic arriving on a certain time slot by a period of n time slots where $1 \leq n \leq d$; d is the number of fiber delay lines that exists in the slot sequencer. On the other hand, the optical wavelength converter shift traffic riding on a given wavelength λ to another wavelength λ' where λ' belongs to a spectrum of nearby wavelengths [26, 27]. The spectrum of nearby wavelengths is a range of r possible frequencies to which λ can be converted. If we consider a network of one wavelength only, where the bandwidth is shared by dividing it into N timeslots, a sequencer of d fiber delay lines can be described as a wavelength converter converting to a range of d nearby frequencies. Instead of converting between nearby channels, the device will be converting between nearby timeslots. Based on the similarity in the behavior of both devices, we expect that the performance analysis of wavelength converters, as reported in the literature [27, 28], holds true in the case of time slot delayers.

The performance of all-optical networks with wavelength conversion has been studied since mid 90s. The main factors that hinder the deployment of such devices are their high cost and current immaturity. However, it has been proven in many experimental studies that employing these devices with the appropriate bandwidth allocation scheme can yield a substantial improvement in network performance. "The use of wavelength conversion can considerably reduce the blocking of the network, but there is minimal difference in the wavelength requirements" [26].

As we noted earlier, the results of many years of studies, investigating the effect of employing the optical conversion technology in all-optical networks, can be imported and adopted to describe the effect of using the Sequencer in slotted optical networks. Hence, the expected performance improvement induced by using the slot sequencers in TDM optical networks will be similar to the one resulting from employing the wavelength converters in WDM networks. In addition, it has been proven that the number of converters and the conversion range can be drastically reduced to a certain threshold without affecting the network performance [28]. Similarly, we expect a reduction in the number of Sequencers and the delay range that maintain the same network performance up to a certain threshold

4. Simulation result and analysis

We studied the performance of the proposed architecture by means of network simulations, considering the NSFNET topology with 14 nodes as shown in Figure 5. We assumed that each single fiber link is bi-directional, and has the same number of wavelengths operating at 50 Gbps. The distance of each fiber link is shown in the network graph of Figure 5. One of the available wavelengths is initially reserved for signaling and control traffic. Each wavelength is divided into 50 small timeslots (circuits) of 1 Gbps each. The propagation delay between two connected nodes ranges between 1.5 and 14 ms. In the network, a node can route, generate, and receive traffic. A source node is responsible for segmenting the bursts into timeslots for transmission, and re-assembling the slots upon reception. The traffic is uniformly distributed across the network. In the simulation, we used Dijkstra algorithm to establish a shortest light path between source and destination to carry a set of LSPs packed in one LSPG. Since one path might not provide all the required bandwidth, especially in the case of Slotted OBS, we may establish more than one alternative path to accommodate all timeslots in a flow of LSP groups. We employ a full sequencer (size 50) at each node, where a segment could be delayed for a period of time ranging between 1 and 49 slots of times. We do not employ conventional buffers or wavelength converters in the simulated switch architecture. The traffic is generated by different request rates. Each request carries a number of slots ranging from 1 up to the number of slot in the frame (50 in this case).

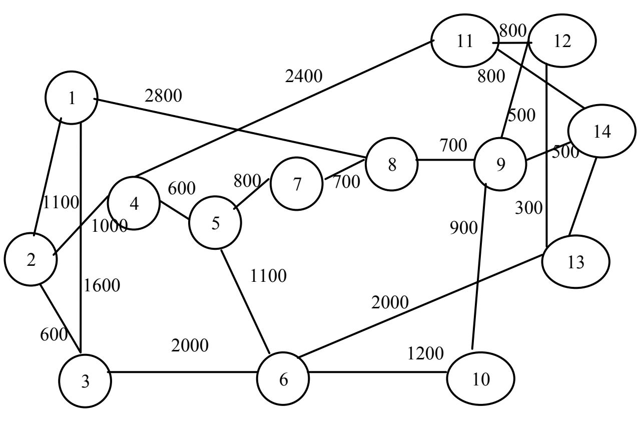
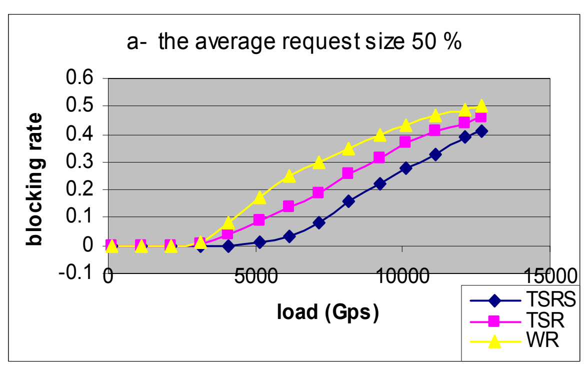


Figure 5 - NSFNET topology with 14 nodes

We run the same simulation under two different cases; first, we limit the request size to be on average equal to 50% of the frame size. In the second case, we decrease the average to 10%.

The goal of the experiment is to study the performance of our proposed scheme, time slot routing with Sequencer (TSRS), as compared to wavelength routed optical network (WR). In this study, we also investigate another variant of the bandwidth allocation scheme where we remove the Sequencers (TSR).

The studied performance is measured based on various metrics. The first metric is the blocking ratio, which reflects the percentage of traffic that must be discarded due to shortage in resources. The generated charts (see Figure 6) show the blocking ratio versus the traffic load in 3 cases: WR, TSR, TSRS. As the traffic load increases, the charts show that TSRS accommodates more traffic than the other methods. In addition, TSR performs better than WR. With a traffic load ranging between 4000 and 6000 Gbs, TSRS maintains a zero blocking ratio; while TSR and WR blocked around 10 and 20% of the traffic respectively. When the load per request gets lighter (graph 5-b), the wavelength routing technique turns down more traffic. This is resulting from the excessive use of resources and inefficient bandwidth allocation with respect to the requested load. However, TSRS and TSR are more stable and their performance is not affected by the granularity of the requested bandwidth. The difference in performance between TSR and WR stems from the efficiency of bandwidth utilization. While WR exclusively utilizes a full channel to transport a load equal to a fraction of its bandwidth, TSR makes better use of the channel by sharing it among multiple low load connections. In addition, when WR cannot accommodate a request, all the requested bandwidth is blocked. However, TSR in this case can accept part of the requested bandwidth that can be accommodated, and block the rest.



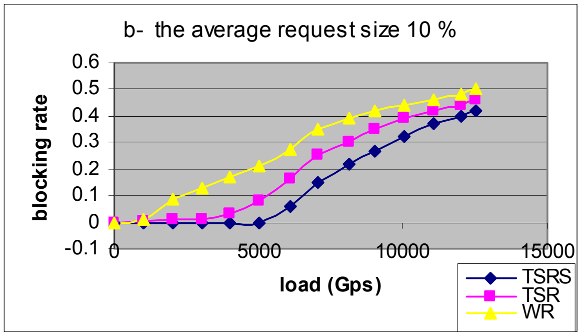


Figure 6 - blocking rate of TSRS, TSR and WR

The generated charts, described in Figure 7, show the number of established paths verses the traffic load in the case of TSRS, TSR and WR. It is clear that the TSR uses more paths than WR. In fact, while WR uses only one path to ship traffic from a source to a destination, TSR may use more than one LSPG. However, as the traffic load increases, the number of LSPGs slightly decreases since a single LSPG tends to carry more timeslots.

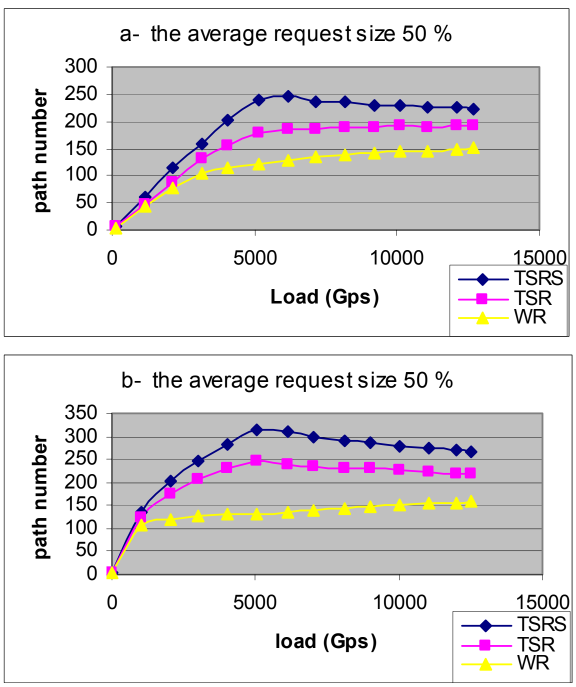


Figure 7 - average number of paths for TSRS, TSR and WR

The third metric is the average number of hops crossed by the LSPGs. It reflects the average cost of establishing and tearing down a light path (or LSPG) between a source-destination pair. The generated charts, described in Figure 8, show the average number of hops per path verses the traffic load. As expected, the average number of hops required for TSR is slightly higher than what is required for WR. In fact, while WR uses shortest possible path between a source-destination pair, TSR and TSRS may send traffic through multiple paths. The number of possible paths per a source-destination pair in TSR can be from 1 to 50, with a slightly higher average number of hops than the shortest path. The difference is negligible as shown in the graphs.

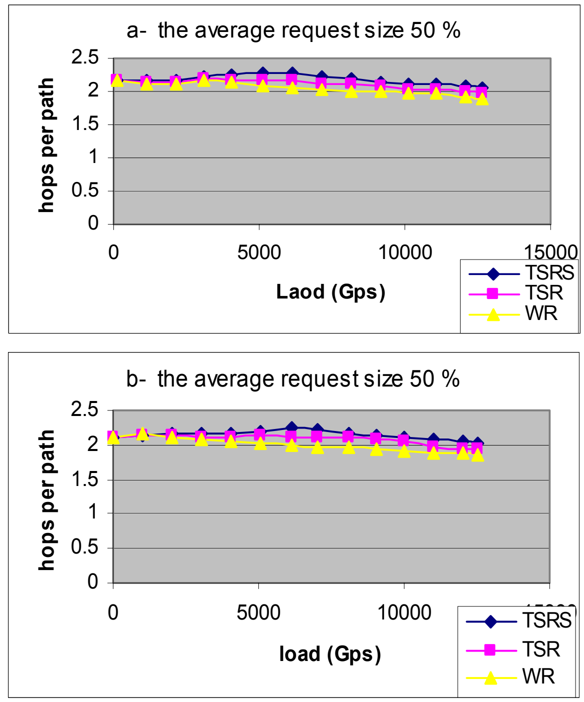
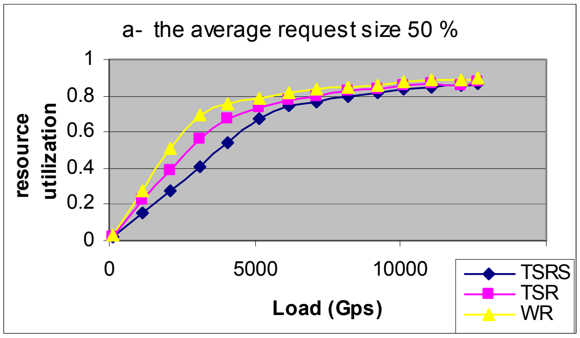


Figure 8 - average number of hop versus the load for TSRS, TSR and WR

The last metric is the resource utilization ratio, which reflects the percentage of network resources used to accommodate the traffic load. The most effective network architecture has the lowest possible resource utilization ratio. The charts, described in Figure 9, show the ratio of used resources verses the traffic load in the case of TSRS, TSR and WR. It shows that TSRS and TSR require fewer resources to accommodate the generated traffic load, especially between a range of 2000 and 6000 Gps. The usage of Sequencers yields a slight improvement in the resource utilization ratio as the traffic load increases. The spared resources, resulting from using the Sequencers in TSRS, can be used in balancing the traffic load across the network to accommodate more traffic.



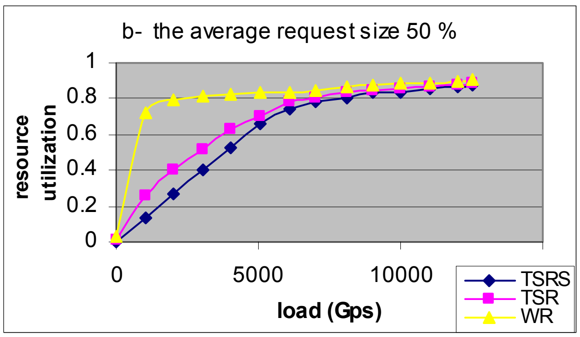


Figure 9 resource used by TSRS, TSR and WR

The graph in Figure 9-b shows the resource utilization of all the techniques with a relatively small load per request. As stated earlier, WR allocates the resources for a full channel even if it is partially used. Thus, the bandwidth utilization is severely affected by the average amount of traffic per connection (or request size). However, the resource utilization of TSR and TSRS does not depend on the request size. Rather, it grows linearly with the global traffic load. This result is due to sharing channels and resources which maximize their utilizations.

5. Conclusion

In this paper, we proposed a new bandwidth allocation scheme and switch architecture to share network resources, avoid contention, reduce blocking ratio, and improve bandwidth utilization. The improvement in bandwidth utilization and reduction in blocking ratio were achieved by employing Sequencers, a form of Optical Time-Slot Interchangers, to delay an incoming timeslot for an adequate period of time in order to match a free outgoing timeslot. The proposed Sequencer is a passive array of FDLs, one feeding into the other, and connected to a switching component. The blocking ratio is improved further by a simple reservation scheme that uses multiple paths to transmit traffic. Every path corresponds to an LSP group consisting of many LSPs; each LSP is labeled by its timeslot position. The contention is avoided by employing a basic scheduling algorithm to derive the amount of delay needed at intermediate sequencers, after constructing the mapping tables. In the TSR with Sequencer approach (TSRS), some QoS parameters can be easily managed and guaranteed such as the delivery delay. The delay can be sized by increasing or decreasing the number of LSPGs, modifying the number of timeslots per LSPG, and using sophisticated scheduling. The results of our study show that adopting the TSRS yields to an improved blocking probability over TSR and WR. In addition, it improves bandwidth utilization when the traffic load increases.

Further work is needed to account for the traffic engineering parameters. For instance, one can study the usage of better reservation and scheduling schemes that give the sender a variety of class of services. It would be interesting to measure the delay with respect to the traffic rate. In addition, some work can be done in optimizing the switch architecture to minimize the number of needed Sequencers and their size. During this optimization work, a comprehensive comparison between the optimizations of the Sequencers and Optical Converters would become possible.

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