Contention avoidance in optical burst switching

Abdelilah Maach, Gregor.v.Bochmann, Hussein Mouftah

University of Ottawa, School of Information Technology & Engineering,
161 Louis Pasteur(CBY A617), PO. Box 450,Stn A,Ottawa,Ont,K1N 6N5 - Canada
Tel : 1 613 261 5800 Fax : 1 613 562 5664
Email amaach@site.uottawa.ca

Abstract : Optical burst switching (OBS) is a proposed new communications technology that seeks to expand the use of optical technology in switching systems. However, many challenging issues have to be solved in order to pave the way for an effective implementation of OBS. Contention, which may occur when two or more bursts compete for the same wavelength on the same link is a critical issue. Many contention resolution methods have been proposed in the literature but many of them are very vulnerable to network load and may suffer severe loss in case of heavy traffic. Basically, this problem is due to the lack of information at the edges and the absence of global coordination between the edge routers. This may result in increased network load and hence increased burst contention. In this work we propose another approach to avoid contention and decrease the loss. In this scheme the intermediate nodes report the loss observed to the edges so that they can adjust the traffic at the sources to meet an optimal network load. Furthermore, this new approach achieves fairness among all the edge nodes and enhances the robustness of the network. We also show through simulation that the proposed protocol is a viable solution for effectively reducing the conflict and increasing the bandwidth utilization for optical burst switching.

Keywords: Optical network, Optical burst switching, contention avoidance, load balancing.

1. Introduction

Dense Wavelength Division Multiplexing (DWDM) is a fiber-optic transmission technique [1,2]. It is a multiplexing of many different wavelength signals onto a single fiber to obtain a set of parallel optical channels. Each channel uses a specific wavelength or color. This allows efficient use of the fiber bandwidth and hence, limits the use of additional fibers.

Optical technology has been used for a long time to carry information in fibers; however, the rapid growth of the Internet and the progress being made in DWDM creates an opportunity for more extensive use of optical resources in switching and routing [3] in the second generation of optical network systems [4,5].

The novel idea of this kind of networks is to keep the information in the optical domain as long as possible. This allows the system to overcome the limitations imposed by the electronic processing and opto-electronic conversion, leading to high-speed data forwarding and high transparency. In this architecture, electronic switches are replaced by optical switches that can handle the optical information. In this paper we will be interested in optical burst switching (OBS) [1,6,7] as a forwarding technique. A burst switching network carries data over DWDM links with several channels per link [8,9]. At the same time, at least one channel per link is reserved to carry control information, which is processed in the electrical domain. In OBS, data packets are collected into bursts according to their destination and class of service. Then, a control packet is sent over the specific optical wavelength channel to announce an upcoming burst. The control packet, called also optical burst header (OBH), is then followed by a burst of data without waiting for any confirmation. The OBH is converted to the electrical domain at each node to be interpreted and transformed according to the routing decision taken at the nodes, and pertinent information is extracted such as the wavelength used by the following data burst, the time it is expected to arrive, the length of the burst and the label, which determines the destination. This information is used by the switch to schedule and set-up the transition circuit for the coming data burst. However, the main concern is burst blocking, which may occur when one or more bursts arrive at the same time and try to leave through the same output, using the same wavelength. This problem, also known as contention [1,10], is inherent to the OBS technique, due to absence of buffers and storage in the intermediate nodes.

The basic differences between an optical network and a conventional packet switching network are the techniques used to forward information at the network nodes as well as the layers involved in the routing process. Indeed, in the packet-switching network, the switches have the capacity to store and process information. In addition, an intermediate node can participate in managing and monitoring the network. Therefore, with this distributed architecture, the network can face difficult situations (in terms of load and congestion) and regulate the network load by using explicit methods to control the flux and regulate the load. However, in optical burst switching all intelligence resides in the edge nodes, which are at the same time the buffer and the processor of the network, whereas the intermediate nodes are used to forward messages according to their destination with no global coordination. Burst paths are determined at the edges according only to static information such as physical topology and the physical features of switches. This lack of information at the edge nodes (the global state of a network is unknown) may drift the network to an overloaded state where the intermediate nodes are experiencing more contentions. And hence leading to a large waste of bandwidth due to an excessive drop of bursts [11,12]. Even worse, unfairness could rise among edges since dropped bursts could belong to an edge node with low traffic.

In this work we propose a protocol that can provide the edge nodes with statistical information on the burst loss rate, in order to adjust the traffic at the edges. This approach aims to control the traffic and keep the network out of congestion. In this scheme the edge nodes could have an important role in this protocol since they can store a burst or postpone its sending whereas intermediate nodes are only reporting losses. This way one can combine the intelligence of edge nodes with the high switching capacity of intermediate node to efficiently use OBS as a reliable carrier with low loss. Furthermore, using this protocol, the sources that suffer loss will be notified so that they can schedule the retransmission of the dropped bursts.

This helps to keep the performance in an optimum state and balance the load over all the available resources such as the fiber wavelengths and intermediate nodes. Therefore this protocol aims at reducing the burst loss rate as a first line of defense (by controlling the load and avoiding congestion at the optical level). For farther loss reduction, one could combine this approach with other techniques.

The rest of this paper is organized as follows. Section 2 presents the optical burst switching technique and contention problem. Section 3 presents a congestion avoidance and contention reduction technique. Section 4 presents simulation results and analysis that prove the efficiency of our proposed scheme. Section 5 concludes this work

2. Contention in optical burst switching

Optical burst switching is a technique for transmitting information across the network by setting up the switch and reserving resources only during the time the burst is crossing. In OBS, the data enters the optical cloud via an edge router where it is aggregated and converted to an optical burst to be sent through the core network. The principle is similar to the one used in conventional packet switching network, however the information is separated into two parts; a header and a payload. The main goal of this separation is to minimize the opto-electrical conversion and avoid the limitation incurred by the electronic technologies such as the processing time and conversion. The header is converted to the electrical domain at the receiving node, where it is processed and converted back to the optical domain. The payload is simply switched in the optical domain according to the information transported by the header. In this technique, the concept of the packet is replaced by a burst; this constitutes an interesting step towards an all-optical network where the largest part of the information remains in the optical domain.

In an optical network using optical burst switching technique, the edge nodes are able to store and process IP packet whereas the intermediate nodes will perform forwarding according to the egress destination. Data is collected at the edge nodes and aggregated into bursts to be sent through network core. Nevertheless prior to burst departure, the edge node sends an optical header, which informs each intermediate node of the upcoming data burst so that it can configure its switch fabric in order to switch the burst to the appropriate output port. The control packet (also called Optical burst header OBH) carries pertinent information and is converted to the electrical domain to be processed at each node.

The OBS technique may use an offset between the OBH and its corresponding burst. This offset is calculated by the edge to cover all the processing time through all the switches crossed by the burst. This assumes that the source knows the number of hops needed to reach the destination and the processing time at each node. Another alternative [6] consists of the use of delayed fiber lines to delay the data burst while the OBH is being processed at an intermediate node.

The routing principle of OBS is similar to the one used by Multi Protocol Label Switching [13,14] (MPLS) in the sense that both OBS and MPLS use a label to forward the data. The MPLS label edge routers (LERs) are substituted by the edge electronic routers and label switching routers (LSRs) are replaced by optical cross-connects (OXCs). An OXC is a path switching element that establishes routed paths for optical channels by locally connecting an optical channel from an input port fiber to an output port on the switch element. This device can move optical signals between different optical fibers, without the need for conversion to the electrical domain.

OBS can take advantage of this similarity and exploits recent advances in the MPLS control plane in terms of routing protocols, traffic management and quality of services. Nevertheless there are structural differences between LSRs and OXCs. Indeed with the former, the forwarding information is carried explicitly as part of the labels inserted at the beginning of data packets while with the latter the switching information is sent separately within another wavelength. Besides, OXCs do not perform packet level processing in the data plane while the LSRs are datagram devices, which may perform certain packet level operations in the data plane such as buffering, error correction and queuing with different level of priorities. These differences may incur some enhancement to adapt MPLS to the new environment especially to deal with the problems of quality of services and traffic engineering.

Basically OBS is designed to avoid the long end-to-end setup times of conventional virtual circuit configuration with no need for memory at intermediate nodes. However the major problem is the contention, which may occur when one or more bursts arrive at the same time (at an OXC) and try to leave through the same output port, using the same wavelength. Contention is inherent to the OBS technique, which basically assumes that the network is bufferless. This feature makes it quite different from the packet switching networks. Indeed, with the electronic switches, the contention is resolved by the store and forward mechanism, which simply keeps the messages in the memory of the switch and postpones their forwarding until the contended output gets free. The contention could affect tremendously the network performance in terms of loss ratio and delivery rate.

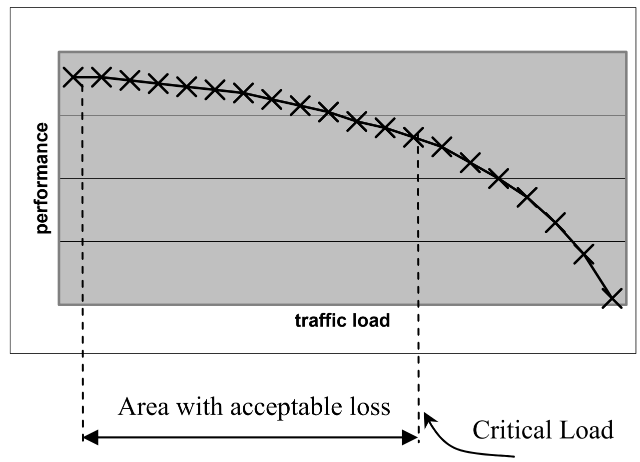
To meet QoS requirements such as bounded delay or guaranteed delivery, contention is a key. Several methods have been proposed in the literature to decrease the loss rate. Some of these techniques could be implemented in software, such as deflection [15] routing and segmented bursts [1], while the others require specific hardware, such as burst buffering [16,7] and wavelength converters [17,7]. These techniques may reduce the contention, but they all remain sensitive to the traffic load. Indeed according to [7] it is clear that even in ideal networks, where the switches use a number of buffers and can perform wavelength conversion, contention still occurs when the load gets higher. This means that the best way to deal with the contention problem is to control the traffic and keep the load in an optimal range as long as possible. Furthermore, in OBS, the load control could be done only by the edge nodes since they have more intelligence and they have physical resources such as buffers and can handle both electronic and optical information. Unfortunately, they do not have enough information to adjust their throughput accordingly. No global state is available and the edge nodes are sending data bursts without any coordination.

In the following section we will focus on an algorithm that controls the load and achieves fairness among all the network edges. They will be able to share the available network capacity while keeping the dropping probability at a low level. In the same time, whenever a burst is dropped the source node will be notified in order to retransmit the lost burst and hence guarantee delivery, thus avoiding the long retransmission delay of TCP.

3. Congestion avoidance and traffic shaping in optical burst switching

Regardless of the routing technique used with OBS, to reduce contention, the load is a determinant element, since a heavy traffic affects the performance and increases the burst loss-rate. The contention directly affects the network performance. Indeed each burst dropped means a wasted bandwidth, increased delivery delay and decreased throughput. This means that the global efficiency and performance of the global network depends on the loss rate, and hence the performance falls as the load gets higher.

Graph 1 shows a performance (in terms of delivery rate) as a function of traffic load. The graph represents only the performance pattern; the curve shape may depend on the network connectivity and the physical resources such as the number of channels by fiber and switches capacity. Each network has its own curve and it is completely characterized by this performance graph.



Graph 1. Performance as function of traffic load

According to this graph the delivery rate keeps decreasing with the load, until it becomes excessively low. One can divide the traffic load into two ranges:

- The area where the loss is acceptable. The critical load (CL) is the upper limit of this area. The CL itself depends on the maximum acceptable loss rate and the physical topology of the network.
- Contention area where the loss is too high.

In this work we propose an approach to keep the load in the acceptable area and make sure that all the edge nodes contribute fairly to this load. The basic idea of this technique is that the edges receive statistical reports (concerning the loss inside the network) that help to calculate the network performance, and hence determine from the loss-load relationship the current traffic load. Therefore by learning from this statistical data, each node increases or reduces its throughput. These statistical reports could be used by the edge nodes to monitor and control the whole network. A statistics distributor protocol could be implemented, as an extension in a control plan, using the same wavelength used to carry the burst headers.

This approach aims to control the traffic and keeps it out of congestion area. Similar approaches to congestion avoidance [18,19,20], have been considered in the literature for TCP/IP packet switched networks and asynchronous transfer mode (ATM). Congestion control is a recovery mechanism that helps a network to get out of a congestion state, whereas congestion avoidance scheme allows a network to operate in a safe area. Many solutions have been proposed in the literature to practically control congestion, the most popular are window flow-control and rate flow control. In the windows flow-control scheme [21] (used by TCP), the destination specifies a limit on the number of packet that could be sent by the source. This limit is increased and decreased by the destination dynamically during the whole session to regulate a data flow. In rate flow-control scheme [22,23,24] (used by ATM) the destination or the network may ask a source to decrease its rate. Besides that, ATM uses other sophisticated mechanisms to control congestion including traffic shaping and admission control as well as resource reservation. Regardless of the efficiency of these mechanisms, all of them perform congestion control in the electrical level where some resources are available especially buffers and storage spaces that contribute actively in the control process. The idea of optical congestion control is to push some of these functions to the optical domain where a new constraints (buffer-less network) and new challenges rise. Performing congestion avoidance and congestion control in the optical domain increases the performance (in terms of loss rate) of optical burst switching and improves resource utilization.

Another concern is related to fairness. It may occur that some edge nodes flood the network which results in increased burst blocking, also for nodes with low traffic. Fair congestion control is therefore necessary.

Fairness, among all edge nodes, is considered to be achieved if:

- Each edge node is guaranteed the amount of bandwidth proportional to the whole capacity of the network. This is the quota of the edge node.
- Dropping probability of the burst belonging to edges with traffic below their quota should reflect this traffic load. This means that they do not have to pay for the excessive load generated by other edge nodes.
- Each edge gets a fair share of the excess capacity. In case that some edge nodes do not use their full quota, the bandwidth left should be shared equally among those who need more bandwidth.

To avoid congestion and achieve fairness all the edge nodes should adjust their sending traffic continually according to the feedback received from the intermediate nodes.

If we assume that Li is the traffic load of edge node Ei, then to keep the loss in the acceptable area, the load Li is constrained by the following formula: Σ Li < CL. CL is the critical load and is calculated empirically to meet the network requirements in terms of loss.

According to this formula, a global coordination is needed to meet the optimal conditions. Unfairness may occur with heavy traffic (Σli > CL) when some edge nodes send more traffic and overload the network.

The critical load (CLi) of node Ei is defined as the maximum of traffic the node can send through the network in case of heavy traffic. Cli is the quota assigned to node Ei. The critical load of all the nodes should not exceed the critical load of the network that is Σ CLi < CL.

This traffic control scheme could be performed by the edge nodes by the following algorithm:

Let LR be the loss rate, this value is calculated by the edge using the information received from the intermediate nodes. Indeed the intermediate nodes report the loss observed and the number of bursts delivered correctly. Let CLR be the critical loss rate, this is the loss observed when the network load is in the critical load CL.

The critical load for each edge node is CLi

An edge node Ei will behave as follow:

If the load Li is less than CLi then Ei will not be involved in the adjustment process. And it can increase its load up to CLi. But if the load Li is more than CLi, the edge Ei must do the following:

- Decreases its load if LR > CLR
- Increases its load if LR < CLR (if needed of course)
- Keeps the same load if LR = CLR

This algorithm guaranties a minimum bandwidth to each edge node. Nonetheless, when a spare of bandwidth is available, (if some edge nodes are not using their full quota) the other edge nodes can share it. They will be notified as the loss ratio is below the critical lost, thereby they can increase their load progressively until the loss ratio becomes equal to the critical loss. On the other hand if some of the edge nodes (with low traffic) increase their load, those with high traffic will give up their advance in terms of used bandwidth and if necessary they will return back to the critical load. The critical load is taken for granted for all the edge nodes.

This algorithm is a simple coordination between the different nodes of the network. Based on the report sent by the intermediate nodes, the edge nodes will measure the network efficiency. For a simple implementation, a single variable is enough to maintain the global stat, this variable is updated whenever the edge nodes receive a report, in general all the nodes receive the same information and hence they have the same value of loss rate. But for more details about the network status, the edge nodes could maintain the status of each node; in this case the edge nodes will calculate the traffic load at each node according to the report received from this node and adjust different flow separately

The information used by this algorithm is sent by the intermediate nodes using a statistic report distribution protocol. In this protocol, all the intermediate nodes will broadcast, to the edge nodes, the number of dropped bursts and some of them (those directly connected to the edge nodes) will broadcast the number of successful forwarded bursts. This accounting information will help the edge nodes to determine in which range the network is running, thereby they can redress and rectify the situation.

The broadcasting may be performed either synchronously or asynchronously

- Synchronously: each station can periodically send its report to all the edge nodes.
- Asynchronously: at specific events (whenever a burst or a given number of bursts are dropped) the intermediate node will send its report to all the edges.

We think that the second technique is more suitable to measure the drop. First, there is no need for broadcasting information if there is no drop. Second, with no control information received the edge nodes assume that the network load is in the acceptable loss area.

Statistic reports will be sent by each intermediate node to all the network edges through predefined broadcasting trees established between each intermediate node and the edge nodes. As shown in figure 1, the broadcasting tree is 1 to n.

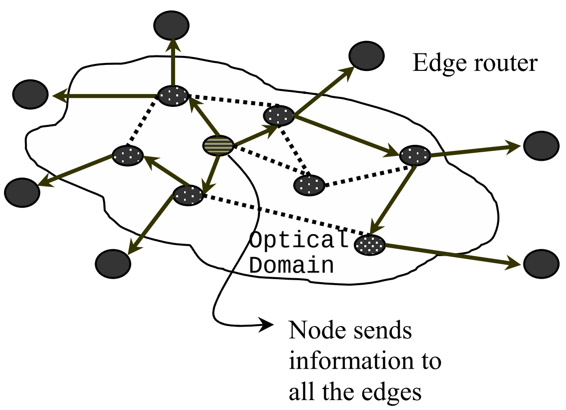


Figure 1. A broadcasting tree from a node to the edge node

4. Simulation results and analysis

In order to evaluate the performance of the proposed congestion avoidance scheme, we performed a number of simulations on a mesh network. In this simulation we consider a NSFNET topology with 14 nodes as shown in figure 2. In this model, it is assumed that each single fiber has the same number of wavelengths. All the links are bi-directional, wavelength channels are operating at 2.5 Gbps (one wavelength is used for the control channel). The fiber length is shown in figure 2, the propagation delay between two connected node range between 1.5 ms and 14 ms. Also each node of the network consists of an optical burst switch handling both bypassing and local traffic (locally generated or terminated). A static route was chosen between each pair of nodes using Dijkstra algorithm. The switching time and the processing time of a control packet in each node are set to 5 µs. Also it is assumed that no buffers and no wavelength conversion are used in the nodes.

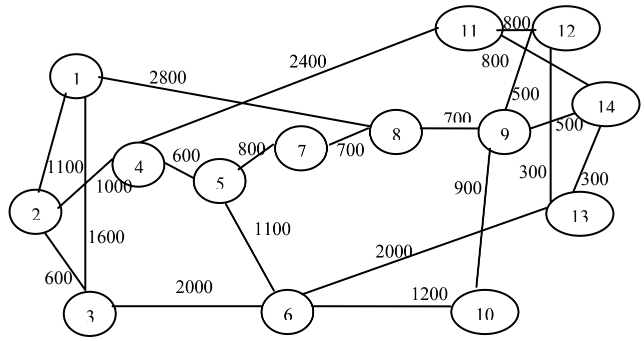
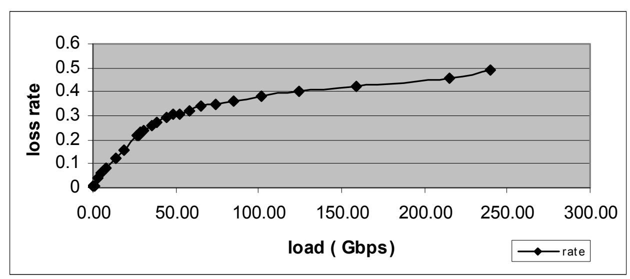


Figure 2. NSFNET topology with 14 nodes

First, in order to determine the critical load for this network, we consider a simulation where each node generates bursts according to a Poisson distribution (burst arrival) the burst length is exponentially distributed with an average of 40 µs (100Kb with 2.5 Gbps). Each node is equipped with a burst generator. The inter-arrival time is varied and the loss probability is analyzed for each load.

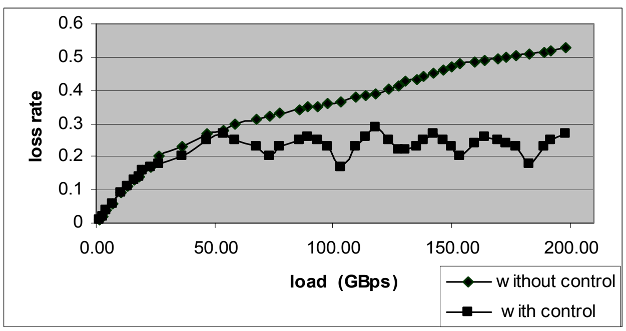
Graph 2 shows the loss rate versus the load. As we mentioned before the loss keeps increasing as the load gets higher. The critical load is a parameter design that determines the loss rate that the network designers are welling to accept. In this simulation the critical loss considered is 20%. It corresponds to a generation of burst in each node as Poisson arrival distribution with 100 ms inter arrival time and length of burst exponentially distributed with an average of 40 µs.



Graph 2. Loss rate as function of load

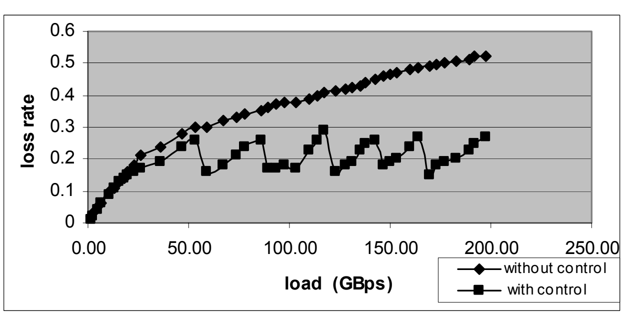
In the second simulation we test the performance of our proposed scheme against OBS without congestion control. The performance metric we use for this purpose is burst loss rate. In this model, the edge nodes are receiving traffic (they handle both electrical and optical information). The external traffic is feeding the nodes buffers. This in turn is aggregated into bursts to be sent to the core network. In the case of OBS without congestion control the burst are assembled using Poisson distribution the inter-arrival time average is increased or decreased to reduce the buffer length. Whereas, in case of OBS with congestion control the inter-arrival time is adjusted according to the statistics received from the network and the buffer size. The external traffic feeds all the nodes. However, in this simulation we divide the nodes into three categories; those who receive data with the same rate the whole session, those with increased rate and those with decreased rate. Initially, the burst generator at every node is operating with an inter-arrival time corresponding to the critical load (this is for OBS with congestion control). The destination of each burst is selected at random from a uniform distribution among all the other nodes.

The burst generation is Poisson distributed with exponential burst length. Initially the inter-arrival time, of all nodes, is 100 ms. when a node has more traffic and the critical loss is below the critical one, it could decrease the inter-arrival time of its burst generators by 5 ms to send more traffic. In this simulation we investigate two decreasing scheme. The first one consists of decreasing the inter-arrival time by 5 ms (to send more traffic) if the inter-arrival time is larger than 100 ms and the loss rate is higher than the critical one. The second one consists of returning back to the critical load (the node sets the inter-arrival time to 100 ms when the congestion is detected).



Graph 3. Loss rate as function of load wit and without congestion control

Graph 3 shows the loss rate with and without congestion control with progressive adjustment (when the loss rate is higher than the critical one all the nodes with sending traffic larger than the critical load decrease their load by increasing the inter-arrival time of their generator by 5 ms). The loss of optical burst switching with congestion control keeps the loss lower around the critical loss. The oscillation observed is due to the fact that the nodes sent their report only after a certain number of burst drop (in this simulation, a notification is sent by a node when a 3 bursts have been dropped)



Graph 4. Loss rate as function of load wit and without congestion control

Graph 4 shows the loss rate s observed in the network. In this simulation we investigate the scheme that consists of returning back to the critical load (when congestion is detected, all the nodes with traffic load beyond the critical load should return back to the critical load). We observe that the loss is dropped sharply to the critical loss when the congestion is detected and continues to oscillate around the critical loss. Nonetheless the result is very similar to the previous one where the loss is dropped progressively to the critical loss. And both of them prove that the congestion control technique effectively controls the loss and optimizes the resource utilization.

5. Conclusion

OBS is one of the proposed solutions to be used with DWDM to route information in switched network. Indeed OBS has a big potential to exploit the bandwidth provided by DWDM. OBS remains viable switching technology, however to keep the performance in acceptable range, the traffic load must be controlled, and for each topology there is an optimal range of traffic where OBS could give good performance. In this work we proposed an method to supervise the state of network and provide the edges with more information in order to adapt the traffic and balance the load. The algorithm we proposed in this work uses the information sent by the intermediate nodes to control the load. We proposed also a protocol used to send the accounting information, this protocol uses an overlapping architecture to take advantage of DWDM technology. The algorithm we proposed can be easily extended to control the traffic at each node and over each wavelength separately.

6. References

[1]: A.Maach, G.V.Bochmann "Segmented Burst Switching: Enhancement of Optical Burst Switching to decrease loss rate and support quality of service", Next generation optical network design and modeling, pp 69-84, February 2002.

[2]: Shaowen Song "Switching issues in the all optical DWDM network", Electrical and Computer Engineering, 2000 Canadian Conference, vol. 2, pp. 998 -1002, March 2000.

[3]: M. Listanti, V.Eramo, R. Sabella, "Architectural and Technological Issues for Future Optical Internet Networks", IEEE Communications Vol 38, no 9, pp. 82-92, September 2000

[4]: Alferness, R.C, "The all-optical networks", Communication Technology Proceedings, 2000. WCC - ICCT 2000. International Conference, vol. 1, pp. 14 -15, August 2000.

[5]: D. K. Hunter, I. Andonovic "Approaches to Optical Internet Packet Switching", IEEE Communications Magazine, vol. 19, no.. 9, pp. 116-122, September 2000

[6]: M.Yoo, C.Qio, “Optical Burst Switching [OBS]- A New Paradigm for an Optical Internet,” J.High Speed Networks, vol. 8, no. 1, pp. 68-84, 1999.
[7]: Jonathan Turner, “Terabit Burst Switching,”, Journal of High Speed Networks, vol. 8, no.1, pp. 3-16, 1999.
[8]: S.Verma, H.Chaskar and R.Ravikanth, “Optical Burst Switching: a viable solution for terabit IP backbone”, IEEE Network, vol 14, no. 6, pp. 48-53, December 2000.
[9]: M.Yoo and C.Qiao “A New Optical Burst Switching Protocol for Supporting Quality of Service”, SPIE Proceedings, All-Optical Networking: Architecture, Control and Management Issues, vol. 3531,pp. 396--405, November. 1998
[10]: S.Yao, B.Mukherjee, S.Dixit, “Asynchronous Optical Packet-Switched Networks: a preliminary study of contention –resolution schemes” Proceedings of Optical Network Workshop, February 2000
[11]: M. Yoo, C. Qiao, S. Dixit, "QoS Performance in IP over WDM Networks," IEEE Journal on Selected Areas in Communications, vol. 18, no. 10, pp. 2062-2071, October 2000
[12]: K. R. Venugopal, E. Ezhil Rajan and P. S Kumar “Performance Analysis of Wavelength Converters in WDM Wavelength Routed Optical Networks”, Proceedings of 5th IEEE International Conference on High Performance Computing, pp. 239-246, December. 1998
[13]: R. Doverspike, J. Yates, "Challenges For MPLS in Optical Network Restoration", IEEE Communications Magazine, vol 39, no. 2, pp. 89-96, February 2001.
[14]: C. Qiao, S.Buffalo “Labeled optical burst switching for IP-over-WDM integration”, IEEE Communications Magazine, vol. 38, no. 9, pp. 104-114, September 2000.
[15]: M Jeong, Y Xiong, H C Cankaya, M Vandenhoute and C Qiao, "Efficient Multicast Schemes for Optical Burst-Switched WDM Networks", IEEE ICC'00, pp. 1289-1294, New Orleans, LA, June 2000.
[16]: X. Wang, H. Morikawa, T. Aoyama “Burst optical deflection routing protocol for wavelength routing WDM networks”, SPIE Optical Networks Magazine, vol. 3, no. 6, pp. 12-19, December 2002
[17]: I. Chlamtac, A. Fumagalli, and C.J.Suh, "Multi-Buffer Delay Line Architectures for Efficient Contention Resolution in Optical Switching Nodes", IEEE Transactions on Communications, vol. 48, no. 12, pp. 2089-2098, December 2000.
[18]: K.-C. Lee and V. O. K. Li, "A wavelength-convertible optical network," Journal of Lightwave Technol., vol. 11, pp. 962-970, May/June 1993.