EFFECT OF BURST LENGTH ON LOSS PROBABILITY IN OBS NETWORKS WITH VOID-FILLING SCHEDULING

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By
Ahmet Kerim Kamçı
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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Ezhan Karaşan(Supervisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Nail Akar

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. İbrahim Körpeoğlu

Approved for the Institute of Engineering and Science:

Prof. Dr. Mehmet B. Baray
Director of the Institute Engineering and Science

ABSTRACT

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Ahmet Kerim Kamçı
M.S. in Electrical and Electronics Engineering
Supervisor: Assoc. Prof. Dr. Ezhan Karaşan
September, 2006

Optical burst switching (OBS) is a new transport architecture for the next generation optical internet infrastructure which is necessary for the increasing demand of high speed data traffic. Optical burst switching stands between optical packet switching, which is technologically difficult, and optical circuit switching, which is not capable of efficiently transporting bursty internet traffic. Apart from its promising features, optical burst switching suffers from high traffic blocking probabilities. Wavelength conversion coupled with fiber delay lines (FDL) provide one of the best means of contention resolution in optical burst switching networks. In this thesis, we examine the relation between burst loss probability and burst sizes for void filling scheduling algorithms. Simulations are performed for various values of the processing and switching times and for different values of wavelengths per fiber and FDL granularity. The main contribution of this thesis is the analysis of the relationship between burst sizes and processing time and FDL induced voids. This in turn creates a better understanding of the burstification and contention resolution mechanisms in OBS networks. We show that voids generated during scheduling are governed by the FDL granularity and the product of the per-hop processing delay and residual number of hops until the destination. We also show that differentiation between bursts with different sizes is achieved for different network parameters and a differentiation mechanism based on burst lengths is proposed for OBS networks.

Keywords: Optical burst switching, fiber delay line, wavelength conversion, Quality of service.

ÖZET

BOŞLUK-DOLDURMA ÇİZELGELEMESİ KULLANAN OBS AĞLARINDA ÇOĞUŞMA UZUNLUĞUNUN KAYIP OLASILIĞINA ETKİSİ

Ahmet Kerim Kamçı
Elektrik ve Elektronik Mühendisliği, Yüksek Lisans
Tez Yöneticisi: Doç. Dr. Ezhan Karaşan
Eylül, 2006

Optik çoğuşma anahtarlaması, artan yüksek hızlı bilgi trafiği talebi için gerekli olan yeni jenerasyon optik internet altyapısı için olan bir taşıma mimarisidir. Optik çoğuşma anahtarlaması teknolojik olarak zor olan optik paket anahtarlaması ile günümüzün düzensiz internet trafiğini verimli olarak taşıyamayan optik devre anahtarlaması arasında yer alır. Umut verici özelliklerinin aksine, optik çoğuşma anahtarlamasının karşılaştığı en büyük güçlük, yüksek trafik tıkanıklığı olasılığıdır. Boşluk kullanımından faydalanan dalga boyu dönüşümü ile optik lif gecikme hatlarının birlikte kullanımı optik çoğuşma anahtarlaması ağlarındaki en iyi çekişme çözümleme mekanizmalarından birini sağlar. Bu tezde göze çarpan çekişme çözümleme mekanizmaları ile optik çoğuşma boyutları arasındaki bağıntılar incelenmiştir. Deneyler farklı, işleme gecikmesi, anahtarlama gecikmesi, dalga boyu sayısı, optik lif gecikme hatları sayısı ve öğe boyutu için yapılmıştır. Bu tezin en büyük katkısı çoğuşma boyutları ile işleme gecikmesi ve optik lif gecikme hatları nedenli boşlukların arasında bağlantının inceleniyor oluşudur. Bu şekilde çoğuşma oluşturma ve çekişme çözümleme mekanizmaları hakkında daha iyi bir anlayış yakaladık ve çizelgeme sırasında oluşan boşlukların optik lif gecikme hatları ve işleme gecikmesi-hedef boğum noktası uzaklığı çarpımı ile idare edildiğini gösterdik. Ayrıca değişik ağ parametreleri için değişik boyuttaki çoğuşmalar arasında ayırım yapılabileceğini göstererek, çoğuşmalar arasında öncelik farklılığı sınıflandırması oluşturulabileceğini sergiledik.

Anahtar sözcükler: Optik çoğuşma anahtarlama, optik lif gecikme hattı, dalgaboyu değişimi, hizmet niteliği.

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Chapter 1

Introduction

The demand for higher bandwidth on the Internet has been rising over the past decade. With the emergence of HDTV video conferencing, 3G networks and decrease in subscriber service prices, the demand for broadband services will even be higher in the upcoming years. Fiber optic cables which can transfer the data faster to longer distances with greater reliability then copper wires are the current solution for the high traffic demand. The usage of Wavelength Division Multiplexing (WDM) [1] in optical networks, substantially increases the transmission rates over the fiber optic cables. In WDM, several data sources are multiplexed into the same fiber using different frequencies (wavelengths). With WDM technology, data speeds up to 1.6 Tbits/s per fiber has been demonstrated [2]. Unfortunately, the electronics based equipment used in the Internet infrastructure (optical-electrical-optical converters, electrical processing modules) may not be able to cope with this huge bandwidth and the electro-optic equipment are also costly. In order to fully utilize the accessible bandwidth, the necessity for electrical equipment must be minimized, paving the way for all-optical networks.

Several optical realizations are proposed for WDM based optical networks. Among these paradigms, Optical Circuit Switching (OCS) can provide a steady bandwidth between two nodes with a high predetermined QoS, but lacks the ability to adapt to different traffic conditions and has low channel utilization. In OCS, an end-to-end all optical lightpath is set between two nodes creating a seamless passage for data packets. But the two way reservation scheme over long distances in wide-area-networks, e.g., thousands of kilometers, introduces major delays and lower utilizations.

On the other hand, Optical Packet Switching (OPS) [3] provides a transparent transfer for optical packets and work with the same principles as an electrical network. In OPS, packet header is processed optically or electronically at each intermediate node while the optical payload is delayed and then forwarded after the switch is configured. At present, fiber delay lines (FDL) are the practical solution to optical buffering, but they can only provide granular delays and FDLs are scarce and expensive resources. OPS seems to be the ideal method for bandwidth efficient optical switching, but lack of viable optical processing and storage technologies makes this paradigm infeasible as of today.

Finally, Optical Burst Switching (OBS) [4, 5] has the best of packet switching and circuit switching in order to integrate bursty Internet traffic to optical networks. In OBS, the data coming from various applications that are destined for the same egress node are aggregated at each ingress node into optical packets, called bursts. Before the optical burst is transmitted, an out of band control packet containing the header information is sent into the network in order to make the necessary reservations. The control packet undergoes O/E/O conversions at each intermediate node and is processed electronically to configure the switch for the incoming burst. This reservation method is one way only so that the source node does not have to wait for a reply from the destination before transmitting a new burst and thus the bandwidth is used more efficiently. The offset-time between the transmission of the control packet and the optical burst, ensures that the switching configurations are completed at intermediate nodes before the arrival of the burst.

There are various protocols used for burst reservation in OBS networks. Amongst these mechanisms, in Tell-And-Go (TAG) [6, 7] the control packet reserves the bandwidth along the path from source to destination while being tightly coupled with the data burst. In Just-In-Time (JIT) [8] the reservation is done as soon as the control packet is received at the intermediate node and stays reserved until another explicit release packet is received. This process results in unused but otherwise available bandwidth throughout the network and causes lower utilization. Finally in Just-Enough-Time (JET) [9, 10] protocol the intermediate node's resources are only reserved for the transfer duration of the data packet. The control packet includes the necessary information such as the offset-time and incoming burst's length.

Amongst the proposed switching paradigms, OBS has the best of the two worlds with the ability to efficiently transfer especially bursty Internet traffic. Comparing with OCS, one way reservation protocols ensures that the data transfer can start without waiting for an acknowledgment from the destination node, thus harness the otherwise lost bandwidth resources. Using different channels for the control domain avoids the synchronization and buffering problems involved in OPS. However due to the one way reservation protocol and lack of optical memory, OBS suffers from high loss probabilities. Large loss probabilities can be reduced by using clever mechanisms so as to provide means for efficiently using the enormous bandwidth associated with optical transport. Contention in OBS occurs whenever two or more optical bursts try to leave the node at the same moment, from the same output port, using the same wavelength. For contention resolution, any of these variables may be altered. In wavelength domain, any of the contenting bursts may be sent to the next node over a different available wavelength by means of wavelength conversion. In the time domain, the burst can be delayed until the contending resources are once again available by means of fiber delay lines. Finally, using deflection routing, any of the contending bursts may be guided to another outgoing port to a different node, to be finally routed towards the destination node over a different path.

In this thesis, we focus on the contention resolution with wavelength conversion and fiber delay lines [5] in conjunction with the most widely used scheduling algorithm in OBS, namely Latest Available Unused Channel with Void Filling (Lauc-VF) [11] scheduling algorithm. The main advantage of Lauc-VF over other algorithms is it's ability to utilize the otherwise lost bandwidth space called voids.

Voids are unoccupied positions in the scheduling plane of a core node. Each

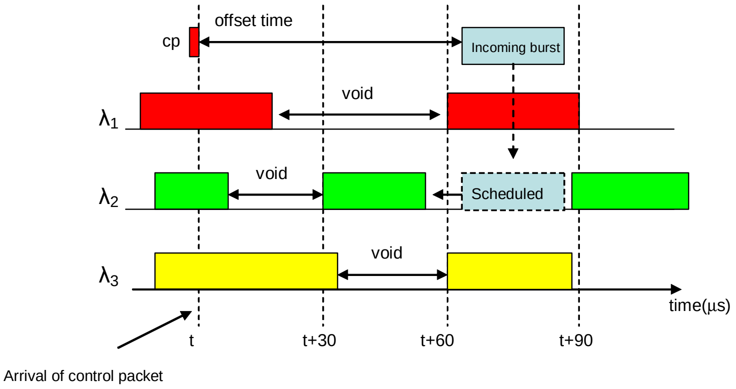
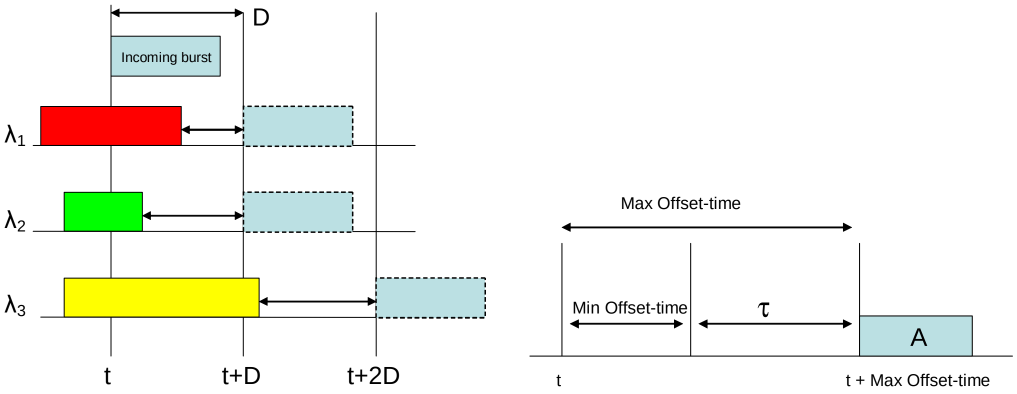


Figure 1.1: Voids in the scheduling plane of a core node

node in OBS has a table of currently scheduled bursts. This table is updated dynamically as the time passes. An example table can be seen in Figure 1.1. In the example, a control packet has just arrived at time t and is trying to schedule it's associated burst after an offset time, at $t+offsettime$. Suppose at that time, a vacant spot is available at wavelength λ_2 and the burst is scheduled without resorting to any contention resolution mechanism. In the scheduling plane, the time after no scheduling exists, is called the horizon of that channel. For instance in Figure 1.1, the horizon time for wavelength λ_1 and λ_3 are both just before $t + 90$. Horizon based algorithms such as LAUC [12], only keep track of these horizon times for each wavelength and try to assign an incoming burst to the latest available horizon (as long as the horizon is earlier than the start time of the burst), so that the generated void size can be minimized. Horizon based algorithms are relatively simple and easy to implement. However these algorithms suffer from low utilization and high blocking probabilities, as they tend to discard all the generated voids.

Due to the nature of Horizon based algorithms, there is no distinction between bursts with different sizes in terms of the loss probability, as all the bursts have to be traversed up to the horizon time of the output channel and only the burst starting time is important at that point. On the other hand, for void filling scheduling algorithms, both the starting time and the length of the burst determine the successful transmission or loss of a given burst.



(a) FDL induced voids (b) Processing time induced voids

Figure 1.2: Generation of voids in OBS

In order to fully appreciate the void filling mechanisms during scheduling, one must have the necessary information of void generation, when and how the voids are generated. We have two situations that generate voids during the scheduling phase in OBS. The first one is due to the usage of FDLs. This part can be best described with an example. In Figure 1.2(a), a burst arrives at time t. At the moment of its arrival, all the wavelengths are occupied. To prevent contention, depending on the scheduling algorithm in use, the node uses FDLs and might also use wavelength conversion. In the example, a trip in an FDL loop will induce a delay of $D\mu$s. If a delay of D will not be enough to prevent contention, the burst can enter the FDL loop multiple times, to obtain a delay of Bx$D\mu$s (where B varies from 1 to maximum number of FDLs available). The arriving burst can be delayed for $D\mu$s, so that it can be scheduled to λ_1 or λ_2. A delay of 2x$D\mu$s is required if the scheduling is to be done to λ_3. In all three cases the voids generated by the use of FDLs and wavelength conversion will be varying such that 0μs $<$ void size $<$ $D\mu$s. We call these voids FDL induced voids.

The second source for void generation in OBS is attributable to the offset-time differences between bursts in JET reservation mechanism. The one way reservation methodology in OBS, implies that all the reservations in a core node will have to be made for future times. Unless the node is the destination of that specific burst, there will always be an offset time difference between the data burst and its control packet. This behavior inevitably generates voids. Lets see this in an example. In Figure 1.2(b) the offset-time induced void can be as long as the difference between the maximum offset time and the minimum offset time. Maximum offset time is calculated by the multiplication of maximum hops a burst must make in order to reach its destination by the processing time at each node. While the minimum offset time is used when the destination node is just one hop away and is equal to unit processing time. Lets say we are at time t and burst A's control packet has just arrived and managed to get burst A to be scheduled at $(t - maxoffset)$. If a new control packet with minimum available offset-time arrives just after t, it will have to face a void with size τ. τ denotes the maximum attainable void for the network and bursts bigger than τ will not be able to utilize voids. Depending on the offset-time differences of two consecutive control packets, the generated void's size varies such as 0μs $<$ void size $< maxoffset - minoffset$. We call voids generated in such manner, offset time induced voids.

The average size of void size and also their size distribution is of great importance for scheduling algorithms that utilize void filling, such as Lauc-VF. For instance if the average void size is smaller than most of the bursts in transit, the network will not be able to utilize those voids and the voids will most probably be wasted.

One trivial inference of void size and distribution knowledge is that, we can arrange the burst sizes in such a manner that, only some of the bursts will be able to utilize the existing voids. Void generation mechanisms indicate that created voids are not affected by burst size choices unless a void is utilized during scheduling. This ensures that changing the burst size distribution will not greatly interfere with the generated void sizes and distribution. In the case of void utilization during scheduling, the burst is scheduled right into the void and will create two new voids, whose sizes depend on the burst size and the scheduling algorithm in use. For instance basic version of Lauc-VF, uses min-sv [13] approach where the scheduler tries to minimize the starting void, which stands for the void generated between the starting time of the newly arriving void and the ending time of the previous burst in scheduling table.

Using the void size distributions, we can decide which bursts will be favored by void filling most (since they can fit into more voids) and which sizes will be handicapped as they will not be able to utilize voids. Simulation results indicate that, both the FDL induced and offset-time induced voids are able to create a class differentiation with different properties. FDL induced voids tend to create a more steep differentiation where only bursts smaller than FDL granularity is favored, while all other burst sizes have the same blocking probabilities. We managed to obtain burst loss probability ratios of up to more than 13 between burst sizes with the highest loss probability and with the lowest loss probability. On the other hand, offset time induced voids, tend to create a linear class differentiation between bursts of different sizes. Bursts larger than the maximum attainable void size will not be able to utilize voids at all and will all have same blocking probabilities. Using the offset induced voids, burst loss probability ratios exceeding 44 are obtained between the loss probabilities of the largest and smallest bursts.

The rest of the thesis is organized as follows: Literature search concerning Optical burst switching and related mechanisms such as reservation schemes and contention resolution mechanisms and quality of service are investigated in Chapter 2. Chapter 3 describes the simulation environment, the algorithms used and the parameters involved and presents the results obtained from simulations. Concluding remarks are presented in Chapter 4.

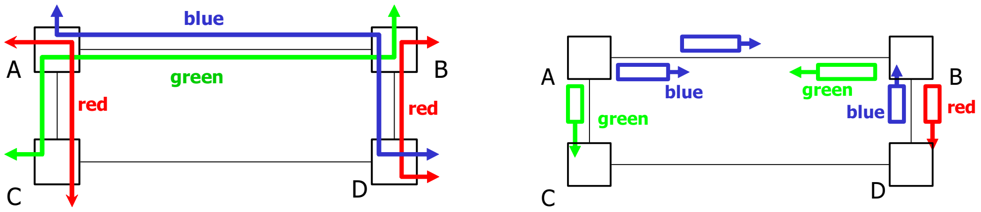
Chapter 2

Optical Burst Switching Networks

In this chapter, some of the topics in optical burst switching networks pertaining to the thesis are presented. The chapter starts with a comparison of optical switching paradigms, continues with mechanisms and protocols governing OBS, such as burst assembly, reservation and scheduling protocols. The contention resolution mechanisms in OBS are then described and the chapter finally ends with currently proposed QoS mechanisms in OBS.

2.1 An Overview of OBS

Wavelength-division multiplexing (WDM) was first introduced in 1970 [1] and WDM systems were realized in laboratory in 1978 [14]. A WDM system uses a *multiplexer* at the transmitter end to combine several optical signals at different wavelengths and a *demultiplexer* at the receiving end to split the signals. Systems today can combine up to 160 10Gbit/s wavelengths together to achieve transmission of 1.6 Tbit/s over a single fiber. Currently WDM networks are used as major backbone links for long distance carriers who use synchronous optical network (SONET) as the standard interface. WDM is also quite popular for



(a) Optical circuit switching

(b) Optical packet switching

Figure 2.1: Optical switching paradigms

telecommunications companies, as WDM allows the expansion of the network capacity without the need of altering the physical layer, namely the optical fibers. The *multiplexers* and *demultiplexers* constituting the network can be upgraded seamlessly to increase the capacity.

One of the major problems with WDM is the necessity of very high speed electro-optical converters which alters optical data to electrical domain and vice versa to handle the large capacities of bandwidth provided. Even with the increasing electronic computing capabilities, electrical/optical and optical/electrical converters are having problem with coping up with the ever increasing optical transmission speeds. To utilize the tremendous raw bandwidth available at the physical layer, clever switching technologies which minimizes the electrical part must be utilized.

Current solutions include optical circuit switching (OCS) which acts as a solid link between two nodes for long durations. In Figure 2.1(a) an example OCS network is given. There are four source/destination pairs in the topology (A-D,B-D,A-C and B-C) and three different wavelengths are necessary to transfer the associated traffic. Circuit switching first involves a two way reservation process which is called the link set-up phase. The source node sends a request to the network towards the destination node and waits for an acknowledgment. After the optical link is created the data gets transmitted and finally when there is no more data to send, the link is teared down (release phase). OCS is suitable for highly loaded, steady traffic and guaranties QoS due to the fixed bandwidth reservation. However high bandwidth optical links and large distances between nodes make the two way reservation protocol extremely inefficient for short duration sessions. Optical circuit switching cannot be easily used for transporting bursty Internet traffic since the bandwidth is lost during low or off traffic periods and since OCS introduces too much delay due to frequent set-up/release phases. Another aspect of OCS is its fully transparent switching nature. What this means is that once a link is setup between two nodes, there is no way of interfering with the on going data traffic. The data simply enters the network through an ingress node, traverses through the network without any processing and then finally emerges through the egress node. While the transparency is suitable for steady traffic, it strips OCS from valuable network management features, which are important to handle dynamic traffic.

Another proposed alternative is optical packet switching (OPS). In OPS, an optical packet contains both the header and the data payload, which can be fixed or variable. Unlike OCS, there is no network setup phase, as soon as the data packet is ready, it is sent to the network. In OPS, optical packets are stored and forwarded at each interconnecting node. The node receiving the packet, must first separate the payload and header and buffer the payload until the header is processed either optically or electronically (using O/E conversion). After the necessary processing is finished, the node combines the header and data and sends the packet to the next node, until the destination node is reached. This behavior is closely comparable to the traffic in a classical packet switching network, with the addition of optical processing and buffering. The per hop processing also assures that the available bandwidth can be shared statistically. OPS has some downsides mainly due to current technological limitations. First of all, optical buffer (memory) is not currently available. Instead optical data is sent through fiber delay lines (FDL), which can only induce deterministic and limited delays to the optical packet. The usage of FDLs at each node is necessary due to store-and-forward scheme in effect, which in turn leads to fixed packet length and synchronous switching. Secondly, all optical processing is still not available so the optical header should go through a O/E/O conversion at each node. As the

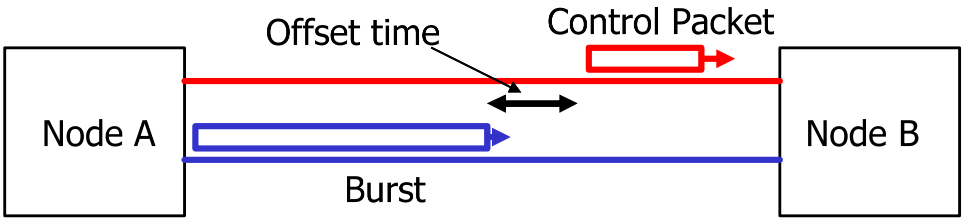


Figure 2.2: Optical burst switching

bandwidth in WDM networks increases this task becomes extremely difficult as the node should process all the headers coming through hundreds of wavelengths in each fiber. Finally, the tight coupling of header and data payload requires strict synchronization and fast processing/switching in the order of μs. An example OPS network can be seen in Figure 2.1(b). On the contrary to the OCS case, if the data is sporadic, only one wavelength is enough to carry the same traffic. Also a source node can send traffic to any destination without experiencing any delay, which is convenient for bursty traffic.

To summarize; OCS can provide steady, QoS guarantied traffic while inducing connection set-up delays and inability to handle bursty traffic. On the other hand, OPS provides mechanisms for efficient and manageable transport of traffic, but is not feasible with the current technology and it may not be realized in the near future since optical processing is far from reality.

Finally, we have optical burst switching (OBS), which is a recently proposed switching paradigm as described in [12]. OBS lies between optical circuit switching and optical packet switching. OBS has the best of the two worlds: can provide necessary flexibility and efficiency for bursty traffic and is practicable with current technology. In OBS, the data and control plane are separated, with this hybrid approach control packets are sent over another wavelength and processed electronically at each node. The data burst and it's related control packet can be seen in Figure 2.2. During transmission the data stays in the optical domain throughout the network topology, so that the network acts as a transparent layer for the transmitted data similar to OCS. But unlike OCS, the core network can

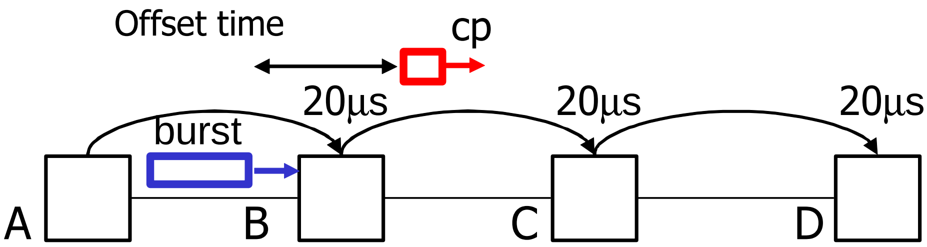


Figure 2.3: Optical burst switching, cp: control packet

still react dynamically to load and topology changes with the usage of out of band control packets. This is an advantage of OBS over OCS. The transparent nature of OBS also redeems the transport layer from the usage of optical buffers, which is the most challenging part of optical data transmission.

In OBS, data from several sources destined to same node are gathered into buffers and are held there until the necessary time or size constraint is reached. In order to overcome the header processing and O/E/O conversion overhead at each node, data packets are aggregated into super packets. If the burst size is chosen to be very small, in the order of several packets, the OBS network will act like an OPS network and the header overhead will be an issue. For instance, if the average burst size is chosen such that each burst consists of 100 data packets, the associated header overhead will be 100 times lesser in OBS compared to OPS. On the other hand, if the burst size is chosen to be very big, more than thousands of packet, the network will act like an OCS network and will not be able to cope with bursty traffic efficiently. After the data payload is aggregated into a data burst, the associated out of band header packet is sent to the network ahead of the burst.

The control packet makes the necessary reservations through the network before the data burst reaches that node so that the burst can pass through without any need for optical buffering. Of course, processing the header at each node will take time, but it must be ensured that the control packet will always stay ahead of the data burst. For example, let's assume an average header processing time of $20\mu s$ at each node and a destination 3 hops away as in Figure 2.3. The control packet must at least be sent $60\mu s$ ahead of the data burst, so that the control packet always stays ahead of the data burst until the destination is reached. This time difference is called the offset-time. After sending the control packet, the source node will wait for an amount of time equaling the calculated offset time and will then send the data burst. This one-way reservation protocol ensures that the data can be transferred between nodes that are far apart without the need to wait for acknowledgements which in turn increases the network utilization greatly.

Finally, the egress node receives the data burst, disseminates the packets and then send them to their appropriate electrical destinations.

2.1.1 Burst Assembly Mechanism

An OBS network consists of ingress nodes, where electronic packets are aggregated into optical bursts, core nodes, which act as a transparent transport medium for optical bursts and finally egress nodes, where optical bursts are disseminated to electronic packets. A simple OBS network topology can be observed in Figure 2.4 where red denotes the electrical access links and blue is for optical links.

Incoming electronic packets are first aggregated into bursts at ingress nodes. This process is called the burst assembly. There are several methods proposed for this process [15, 16, 17].

In general each node maintains multiple buffers for incoming electronic links from the local network according to their destinations and in some cases for their quality of service requirements as shown in Figure 2.5. Packets from different electronic sources are first stored electronically at the packet queues. Then the burst assembler, arranges the packets according to their destination appropriate burst queues. If QoS is required number of destination queues can be increased to accommodate priority classes. Finally the burst scheduler assigns the burst to their suitable outgoing port and wavelength.

Assembly algorithms, after a preset criterion is met, choose sufficient number

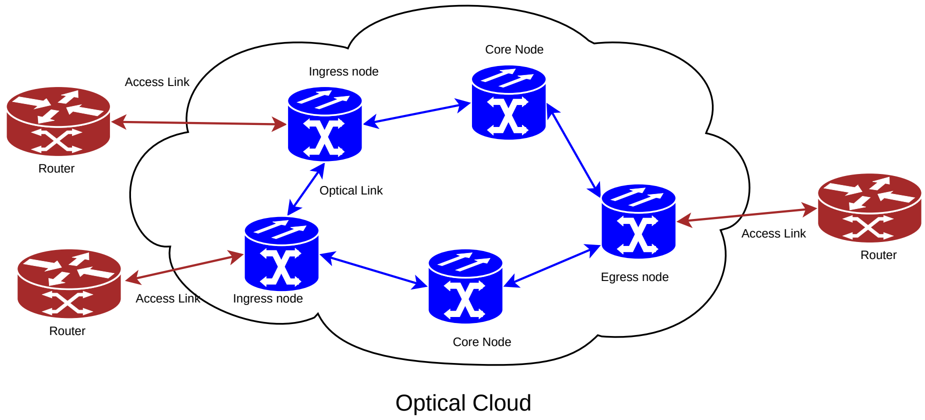


Figure 2.4: Optical burst switching network

of packets from the buffers, combine them and send the packets as an optical burst into the core network.

Assembly algorithms use either the assembly time limit or a fixed burst length or both as the decisive factors for burst creation. Parameters involved in the process are: T the time threshold, B the max burst length and b_{min} [18], which stands for the minimum allowable burst size for the particular optical network.

In **Fixed-time Min-Length** algorithm [15], only b_{min} and time threshold is used. Usually b_{min} is chosen such that $b_{min} < T * \lambda$, where λ is the average incoming traffic rate. The timer starts when a new packet is received at the empty burst assembly queue. When the pre-set time threshold is reached, the burst is created with the packets waiting at the burst assembly queue. If the burst length is smaller than the b_{min} value, packets are padded to satisfy the minimum length criterion. Fixed-time Min-length algorithm will not act effectively when λ is high, burst will still be influenced by high delay times.

Extending the above algorithm; B, max burst length is introduced according to the $b_{min} < T * \lambda < B$ equation. T gains importance when the network load

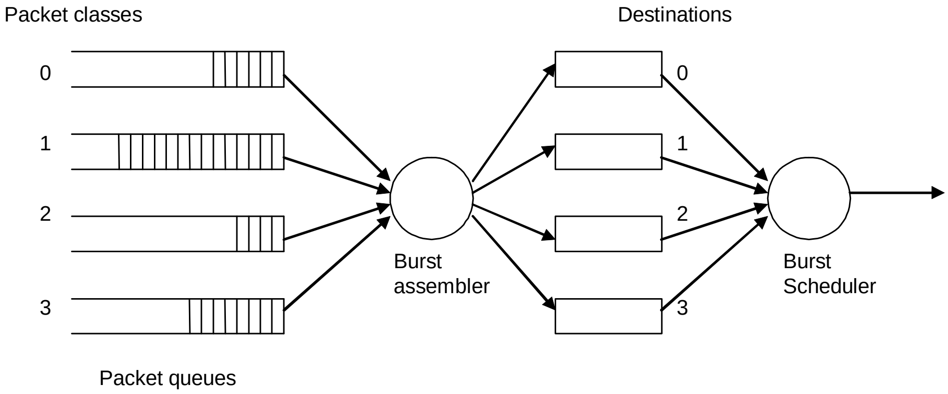


Figure 2.5: Burst assembly architecture

is low and creates an upper bound for the time necessary to create the burst. B is important especially in high load cases, where B successfully decreases the unnecessary delays.

The algorithm starts with examination of the incoming burst buffer, if there are more than B packets available a burst is created and sent. If not, the assembler starts the timer and waits for incoming bursts. Whenever the time threshold or the maximum burst length threshold is reached a new burst is created and sent. Padding will also be done when there are less packets then b_{min} available at the time of the burst creation.

After the burst is created an out of band control packet is sent ahead of the burst to setup the path and make the necessary reservations for the incoming burst. The control packet (depending on the architecture used) includes information about the burst size and the time difference between itself and the data burst, which is called the offset time.

There are several schemes involving the timing and methodology to send and receive the control packet, which will be discussed in the reservation schemes and protocols section.

After the predetermined offset-time passes, the data burst is received. If the burst was scheduled, the node is pre-set and the burst passes through the node transparently using FDL, wavelength conversion, both or none. After the burst passes through, the node will need some time to reconfigure itself for another burst. The time required is called the **switching delay**. Switching delay can act as the guard time [11], which can be at the beginning and end of the bursts (usually both) and helps to overcome the uncertainties involved in data burst arrival and data burst lengths due to clock drifts between nodes. The guard time is also responsible in correcting the delay variations in different wavelengths and optical matrix configuration times. Finally performance monitoring and optical error correction may need the use of additional delays. So the node is essentially busy for burst length in time + switching delay to effectively transfer a data burst.

2.1.2 Reservation Schemes and Protocols

There are several mechanisms proposed for reservation in optical burst switching [6, 7, 8, 9]. Prominent architectures involve a one-way reservation design thus lessen the long delays induced by round trip times. If instead a two way reservation scheme was used, in a usual scenario in OBS of long routes and high link bandwidths; incredible amounts of optical bandwidth would be wasted.

In Tell-And-Wait (TAW), a control packet from the source node travels and reserves bandwidth through the network. If the reservation is successful the destination sends a go-ahead packet to the source so that the transmission can start. Conversely, a negative acknowledgement is sent back, if the scheduling fails.

In Tell-And-Go [6, 7] data packets and control packets traverse the network simultaneously and are tightly coupled in time. At each node the data packet must be delayed until the control packet is processed and the resulting switching is completed, therefore usage of store and forward units for optical data at each node is necessary.

In Just-In-Time (JIT) [8], there are two control packets involved in reservation.

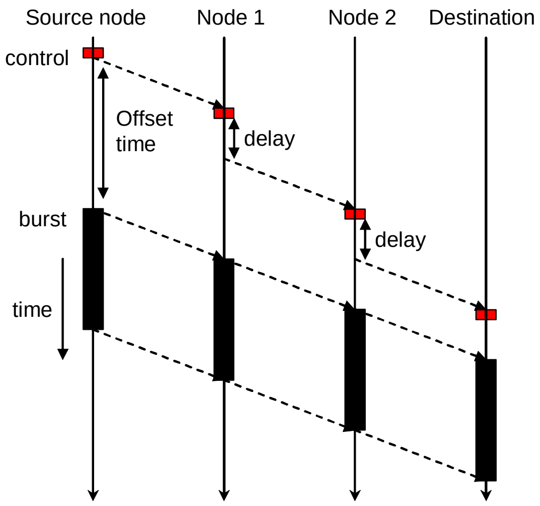


Figure 2.6: JET protocol

A setup packet is used for reserving the bandwidth for incoming burst, the node makes the reservation as soon as the control packet is received. This reservation is valid until a release packet is received.

Finally in Just-Enough-Time (JET) [9, 10] reservation protocol, the control packet reserves the core nodes for a period of time equal to the burst size, starting from the beginning of the burst. Throughout this thesis, JET based reservation scheme will be used. An illustration of JET based scheduling is shown in Figure 2.6. The source nodes which will be sending the data burst, after completing the burst to be sent, creates the control packet and sends it towards the destination node, using a dedicated channel.

Once the control packet is received at the intermediate node, it is transformed into electrical domain and is processed and transformed back into optical domain. This processing is called the optical-electrical-optical (OEO) conversion and the time required for the transformation constitutes the main part of the **processing delay**. Processing delay also includes the time required to receive and send the control packet. In order to compensate for each delay at each intermediate node, there is a time difference between the control packet and it's corresponding burst. This number must be large enough so that the control packet always arrives at a node before the corresponding burst. Time difference is selected to be the product of processing delay at each node by the number of hops the burst will traverse throughout the network and is simply called the **offset-time**. The offset time may also be deliberately chosen to be bigger than the necessary time. This difference effectively creates a quality of service differentiation amongst different bursts as described in [19, 20, 21].

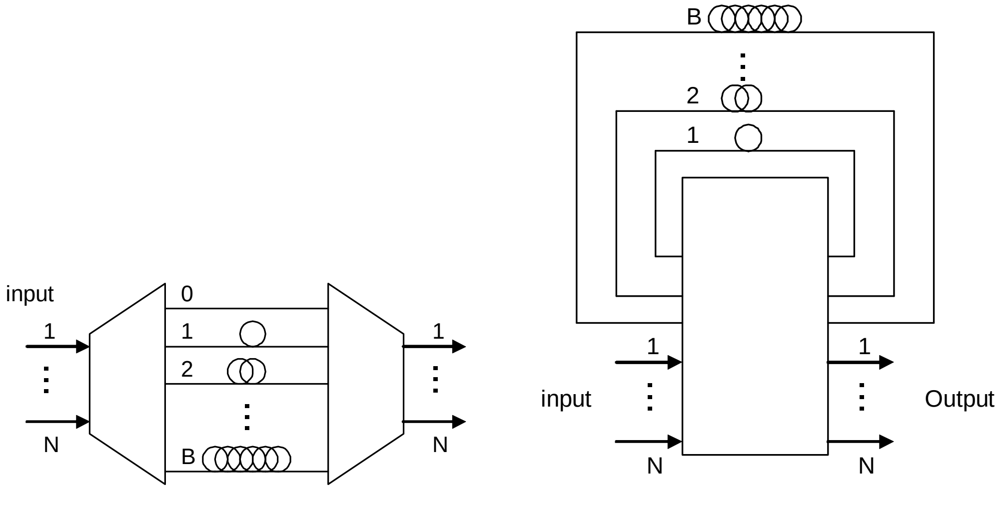
The offset-time is an important factor in networks using FDLs, as this product, combined with the information of average burst length constitutes the average horizon time [12] of the scheduler. Horizon is the time on the output channel of a core node, after which no scheduled burst exists.

2.2 Contention Resolution in Optical Burst Switching

In an OBS network, upon receiving the control packet, a node must decide how and when to schedule the incoming data burst and must configure itself accordingly. Lack of ability to store the optical data optically (lack of optical memory) and one-way reservation protocols used, makes the task harder. Due to this bufferless property, when multiple bursts content for the same output port, at the same time, for the same wavelength, only one burst can be scheduled and the rest should be dropped. This causes the main disadvantage of optical burst switching, high loss probability. Fortunately any of the parameters that cause contention can be altered so that the overall blocking probabilities may be lower.

For contention resolution in wavelength domain, any of the contending bursts can be sent using a different wavelength by means of wavelength converters. The wavelength converters in the network may be sparse and may not always be able to provide full conversion from one frequency to any other frequency.

For time ambiguities, burst can be delayed, not as flexible as an optical memory would have been, but for limited and granular amounts of time. For time



(a) Feed through (b) Feed-back

Figure 2.7: An example of FDL modules, Feed through buffering does not support priority routing and feed-back suffers from signal attenuation

delays, bursts are sent into fiber delay loops which are called **fiber delay lines** (FDLs) [10, 22, 23].

An FDL is simply a fixed length fiber. Once the optical packet enters a fiber, the packet will emerge from the other side after a fixed time delay. The burst can be traversed through several of these long cables, or multiple times from a given fiber cable, providing granular delays from 1 to B times the delay of a single fiber line.

Finally, bursts can be sent to another output port destined to another node, which may or may not be in the initial source-destination route of the incoming burst. This method is called deflection routing and provides limited improvements heavily dependent on the network topology and traffic density as examined in [24]. Deflection routing is not investigated in this thesis.

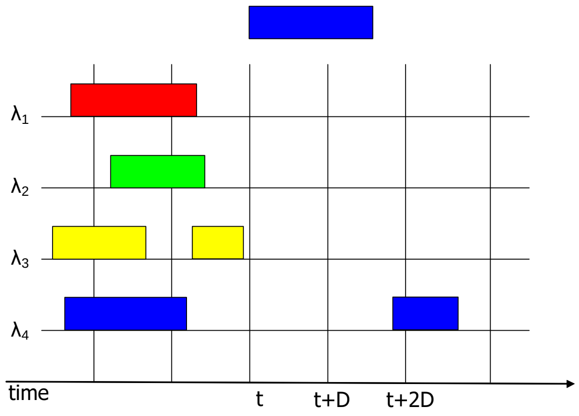


Figure 2.8: First fit algorithm example

2.2.1 Contention Resolution Algorithms

In an OBS environment bursts are usually not received one after another with no interval in between. There are usually certain gaps between the bursts, which are called voids. These voids can be generated during the assembly or scheduling processing also the use of fiber delay lines and different offset-times may cause void generation in between burst. Voids can get wasted as unused channel capacity if an ineffective scheduling algorithm is used. Not all of the contention resolution algorithms in OBS make use of voids and they will be discussed next, starting from simpler ones to more complex ones.

First fit algorithms, in which the incoming burst is just attempted to be scheduled to an outgoing wavelength. This search may be done in a round robin fashion or randomly. In this algorithm, generated voids are totally disregarded, resulting in high drop rates. In the example shown in Figure 2.8; the received burst can be scheduled to λ_1, λ_2 or λ_3.

Horizon Scheduling (LAUC) was first proposed by Turner [12]. In this algorithm the scheduler holds track of only the horizon times for each wavelength, where horizon stands for the time of the scheduler after which no reservation exists. The scheduler has access to a FDL buffer which can delay a burst by

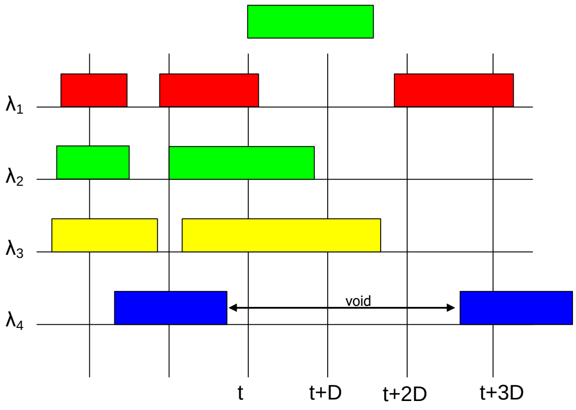


Figure 2.9: Lauc algorithm example

multiples of FDL granularity D from 1 to B.

When a newly incoming burst arrives at the node the scheduler assigns the burst to the latest horizon as long as the burst's arrival time is larger than the horizon time. If no channel is available, then the received burst is delayed by a multiple of FDL units until a suitable unscheduled channel is found. If even after maximum number of FDL units is used and no channel is found, the burst is simply dropped.

Trying to find the latest available data channel decreases the lengths of voids generated by the scheduling process. However discounting the voids, causes low utilization and high drop rates.

Figure 2.9 shows an example of LAUC algorithm. The incoming burst arrives at time t. Unable to find an immediate suitable wavelength, the scheduler makes use of FDLs one by one until a suitable unscheduled channel is found. In the first incrementation, λ_2 is found to be accessible and the burst is scheduled.

LAUC-VF [11] is an improved version of LAUC. Unlike LAUC, which only stores the information of horizon time, after which no scheduled burst exist, LAUC-VF also keeps tracks of all available voids in the output port beyond the current time, as well as the information of horizon time. The scheduler has access to an FDL buffer with same properties as the LAUC algorithm.

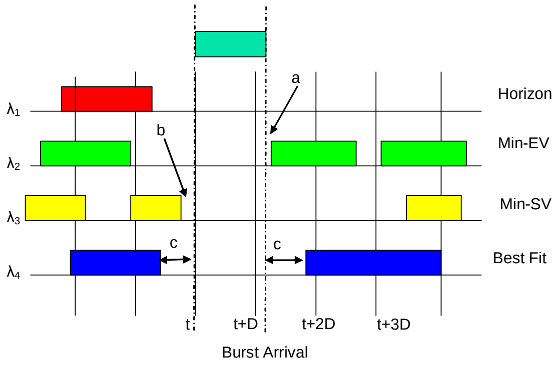


Figure 2.10: Lauc-VF algorithm example

When a control packet arrives at an intermediate node at time t with size L, the scheduler at that node tries to find an output port available for the duration (t to $t+L$) of the burst. If more than one available channel is found the scheduler selects the latest available data channel, to minimize the size of the void generated. If none is found, the burst is delayed by D and the scheduler looks for an available port for ($t + D$ to $t + D + L$) time interval. This process goes until an available spot is found are all the FDLs up to B is sought.

There are several criterions in effect depending on the variations of LAUC-VF in use. The first criterion is to find a void interval which minimizes the time difference between the start of the incoming burst and the ending time of the latest scheduled burst and is called the minimum starting void fit (Min-SV). This is also the behavior of the original LAUC-VF [25]. Similarly we can try to minimize the time difference between the end of the incoming burst and the start time of the first scheduled burst, as well as the opposites, namely Max-EV and Max-SV [13]. Finally the burst can be scheduled to the smallest overall void duration, this conduct is called the Best-Fit.

All the variations described above can be observed in Figure 2.10. The newly arriving burst is scheduled to a different wavelength for each condition.

The formal description of the LAUC-VF algorithm is presented below. $Ch\_Search(x)$ is the function which searches for a appropriate latest available channel at time x and returns that value. If a suitable channel is not found, returns -1. t is the time of the data burst arrival and j is the outgoing data channel selected to carry the burst. Finally Q_i is the delay induced by the i^{th} FDL.

```
Begin {LAUC-VF algorithm}
    Step 1: $i = 0; x=t;
    Step 2: j = Ch_Search(x);
        if (j != -1)
        {report the selected data channel j and the selected FDL i;
            stop; }
        else
        {
            i = i + 1;
            if (i > B)
                {report failure in finding an outgoing data
                channel and stop;}
            else
            {x = t + Qi, goto Step 2;}
        }
End {LAUC-VF algorithm}
```

2.3 Quality of Service in OBS

The increased amount of available bandwidth by means of WDM networks, gave rise to various applications over the Internet demanding quality of service differentiations. There are four major categories in which quality of service under OBS can be investigated, based on the stage at which the differentiation is performed. These are: during assembly-time, reservation, scheduling and finally during contention resolution.

2.3.1 Service Differentiation during Assembly-Time

In this class of QoS schemes, service differentiation requirements are tried to be handled, before the bursts are sent into the network.

The intentional dropping scheme proposed in [26] aims to achieve a proportional differentiation between classes. In order to achieve the initially determined burst blocking probabilities, packets from lower priority classes are intentionally dropped such that the percentage of bursts transferred for that specific service class are proportional to the number of bursts transferred from other classes. This scheme does not add any additional delays or does not discriminate between bursts of different sizes. However when the network load is relatively low and the network capacity is enough to handle all of the classes' QoS requirements, unnecessary droppings will still be done, leading to performance drops in low priority classes.

2.3.2 Service Differentiation during Reservation

Schemes categorized under this group, create the necessary separation using different reservation protocols for different classes.

In offset-time based schemes, bursts with higher priorities are given extra offset-times [27], so that the reservation of higher priority bursts are done before bursts from other priority classes, over the intermediate nodes. Total class isolation can be achieved if the offset-time of higher priority class i is chosen to be greater than (maximum burst length + offset time) of a lower priority class j, so that the blocking probability of class i is completely independent of traffic properties of class j [28]. On the other hand, offset-time based schemes add increased end-to-end delays to higher priority classes. Also the excessive creation of voids during reservation disfavors lower priority class bursts with larger sizes.

In the Forward Resource Reservation(FRR) [29], the control packets of bursts with lower priorities are created and sent only after the burst is assembled, however control packets of bursts with higher priorities are sent before burst is completely assembled. This in turn creates the class differentiation without inducing additional delay to higher priority bursts. The required information of burst size is filled in using linear predictive filters. If assembled burst's size is larger then as predicted, a new control packet with the new size information must be sent. The efficiency of this scheme depends on the accuracy of burst size predictions and may not be appropriate for bursty traffic.

The wavelength grouping scheme proposed in [30] restricts the lower priority bursts to certain set of wavelengths while letting higher priority bursts use a larger set or even the complete set of available wavelengths. The difficulty of this scheme rises in the identification of the degree of differentiation between classes of different service requirements.

2.3.3 Service Differentiation during Scheduling

The classes in this section create the differentiation at intermediate nodes using the burst scheduling mechanisms.

In the slot-based prioritized scheduling proposed in [31], data bursts are sent in units of slots (fixed intervals of time), while the control packets are sent in groups which are carried in one slot. The schedulers chooses the higher priority control packets in a group first, allowing them to have a better chance of finding a free channel. In this scheme, the choice of slot size is of importance for success. A small slot size choice may reduce the scheme to that of a classless system, while a larger selection may create unfair discrimination of lower priority bursts.

2.3.4 Service Differentiation during Contention Resolution

During contention between two bursts, any of the contending bursts may be segmented and the segmented part can be dropped or deflected to another outgoing port. The method proposed in [32] segments only the tail (ending) of bursts, in order to minimize out of sequence packets received at the destination. Having known that packets situated at the tail of a burst will have a greater probability of delay or blocking, packets from classes with different priorities are arranged in a burst with a decreasing order of priority, starting from the highest priority packet situated at the beginning of the burst, up until the lowest priority burst at the ending of the burst. However this method does not provide a fully controllable service differentiation mechanism.

Chapter 3

Loss Analysis in OBS Networks Utilizing Voids

In this chapter, we first introduce the main problem addressed in the thesis, followed by the description of the simulated topology. We then give details about the simulation parameters. The chapter ends with the explanation of the results and relevant discussions.

3.1 Void Characterization in OBS

OBS as stated earlier, stands between optical circuit switching and optical packet switching. OBS has the best of the two worlds; low overheads and less burden on the switching nodes like circuit switching and high utilization and traffic adaptation like packet switching. Nevertheless OBS has its own incapabilities.

The main problem in OBS is the high burst loss probability, which is mainly due to the one-way reservation protocol. In order to decrease the contention between bursts and to increase the utilization; contending or newly received bursts must be scheduled as efficiently as possible so that the intervals between bursts would be as small as possible. Lesser idle times (voids) between bursts, successfully increase the channel utilization.

Due to the working principles of optical burst switching networks; generation of voids between bursts is inevitable. Firstly, the granular structure of optical buffers prevents precise accommodation of newly arriving bursts to the appropriate output port and wavelength. If use of FDLs is necessary because of a contention in progress, in most of the cases a void equal to or less than FDL granularity will be generated.

Secondly bursts, due to the nature of reservation schemes in use, e.g. JET protocol, will have an offset difference associated with their control packet in transit. A burst may be scheduled to a much further destination on the optical network. When the control packet of the burst in consideration arrives at the first node on its way to the destination node, the control packet will try to schedule the node and inform that a burst will arrive after the offset-time difference. As there are many hops left after the first node, the offset time difference will be large, thus the burst will be scheduled to future time. As we know from [19, 20, 21] this burst will a have high probability of getting scheduled and will be easier to employ. There will also be a void induced between the current time and the start time off the burst as great as $(totalhopcount - 1)$ times processing time.

Most promising contention resolution algorithms exploiting the voids have lower blocking probabilities. In order to fully use the voids generated during scheduling, one must truly understand how and when voids are generated. As stated earlier, there are two possible means of void generation, one is due to the use of FDLs, called FDL induced voids, and the other is due to processing and offset-time differences, called the processing time induced voids.

This thesis focuses on the understanding of void generation mechanisms during scheduling of optical bursts. We present the relationship of burst size choices with generated void sizes and density in other to exploit the generated voids to full extent and decrease the blocking probability for bursts of different sizes. Using the void size distribution of an OBS network with given parameters, we can decide which bursts will be favored by void filling scheduling algorithms and which bursts will not be able to utilize voids, by simply altering the bursts sizes according to the investigated network's void size distributions. This decision can easily be used to create a class differentiation between bursts of different sizes and will let us create a simple burst size dependent QoS mechanism.

3.2 OBS Simulator

Optical burst switching due to the inherent behavior does not have many simulation environments readily available for use. One solution could be the commercially available OPNET software, one can also use the *ns*2 simulation environment.

*ns*2 proves to be a powerful tool for network simulations. Most of the protocols necessary for both wired and wireless networks are readily available; unfortunately optical burst switching is not one of the offered.

There are four main parts of an optical burst switching simulator.

- Burst aggregation and dissemination, also the creation and management of the control layer.
- Multiple packets progressing through one link, as optical burst switching makes use of multiple wavelengths
- The scheduling and reservation protocols
- Implementation of wavelength converters, fiber delay lines and deflection routing if used.

For this thesis work, we needed a simple yet powerful tool to fully understand the problem in consideration and to devise a solution without dealing with the induced problems due to other parameters. Hence a simulator was written in Dev-C++ 4.9.9.2 available under the GNU General Public License. The simulator is programmed in such a way that;

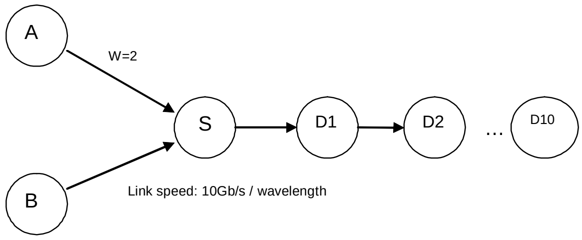


Figure 3.1: Burst arrivals, Basic outline of the simulated architecture

- Both LAUC and LAUC-VF are implemented.
- Tell-And-Go and JET Reordering schemes are available.
- Processing time and switching delay are adjustable in automated steps.
- Both the number of FDLs and their granularities are adjustable, scheduling without FDLs is also possible.
- Number of wavelengths is adjustable.
- The simulator is capable of processing between $4 * 10^7 - 8 * 10^7$ bursts/min depending on the parameters used.

3.2.1 Network Topology and Simulation Parameters

In order to investigate the properties of void generation and the correlation between processing time and FDL structure, a simple node architecture is used. The topology used in the simulations is depicted in Figure 3.1. There are 2 sources, namely A and B, contending for the output port at S. Each source creates bursts, destined to $D1$ to $D10$. Burst size varies between 10 packets and 190 packets, which in turn means an average length of 100 packets. Each packet consists of 1500bytes of data, thus the average burst length is $100 * 1500 * 8/10Gbit/s = 120$ μs. Burst destined to S are not considered in the simulations as only the output port of S is investigated. Each optical link has a bandwidth of 10Gbit/s and has 2 different wavelengths.

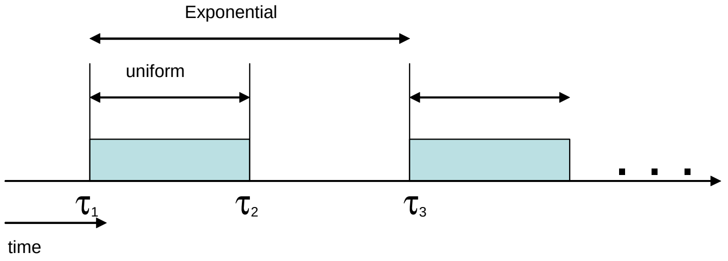


Figure 3.2: Burst generation process

Burst inter-arrival times are generated using a poisson process (see Figure 3.2). The burst size is randomly chosen according to a uniform distribution (τ_2 - τ_1, t_{burst}). From the start time of the burst, exponentially distributed idle time (t_{idle}) is added (τ_3 - τ_1). The ratio of the idle times are adjusted in accordance the desired arrival rates such that $t_{idle} = \rho \ . \ t_{burst}$, where ρ is the arrival rate. The rates used throughout the numerical results section, will be the rate of only one optical channel (for example from A to S), thus total rate of traffic going out of node S will always be two times the given rate in the results.

The exponential time difference between the starting times of two subsequent bursts in some cases may be chosen to be smaller than the size of the first burst. So to say τ_3 may be smaller than τ_2. In this case the bursts will already be contending when they arrive at the source node S. This effectively increases the dropping probability of the pure Poisson burst generation process.

Burst traversing through node S can be destined to $D1$ through $D10$. At each jump the control packet for a burst will be delayed by a process time. For the simulations various processing times are used, from 10μs to 100μs. So the offset-time for each burst varies from unit processing time to 10 times the processing time, hence with a processing time chosen to be 20μs, average offset-time will be 110μ.

These numbers -summed and individually- play an important role on burst drop rates. If the channel is empty before the burst arrival, a new scheduled burst on the average will create a horizon of 230μs, which consists of the addition of

110μs (mean of process time) and 120μs (mean of burst length).

When the total FDL delay is greater then the number calculated above, the effect of FDL granularity is much more observable. In these scenarios voids generated are mainly due to FDL delay differences between bursts. Thus we see a decrease in drop rates for bursts smaller than the FDL granularity. We call this steep decrease in drop rates for bursts smaller than burst FDL granularity D, the **knee-effect**. Result concerning this behavior will be presented in the numerical results section.

The simulator is capable of processing the contenting burst according to LAUC and LAUC-VF. LAUC-VF was proved to be a better performing algorithm so is chosen as the main interest.

3.3 Numerical Results and Discussions

3.3.1 Effects of FDL Parameters and Number of Wavelengths

In order to fully understand the results in the following sections, we must have an understanding of the underlying properties of optical burst switching networks. The effects of number of wavelengths used in scheduling, FDL granularity and number, on burst loss probabilities are investigated.

Throughout the thesis the following terms will be used:

N_{FDL} Number of FDL buffers

D Delay of each FDL unit in terms of μs, also called the FDL granularity

T_p Processing delay per node

T_s Switching delay per node

ρ Average utilization per incoming channel

W Number of wavelengths per link

The simulations only use 2 wavelengths per channel, since the incoming burst process is a true Poisson one, increasing the number of wavelengths will give similar results only with much lesser loss probabilities.

In Figure 3.3, the loss probability is plotted as a function of the burst size for different values of W. In the graph the y axis represent the loss probability of bursts with the indicated size in x axis. Increasing the number of available wavelengths from 2 to 4 decreases the average loss probability 5.85 times. Similarly an increase from 4 to 8 wavelengths will decrease the average loss probability 54.32 times. The decrease in loss probability is due to the fact that when many wavelengths are used the scheduler has more choices for assignment for an incoming burst.

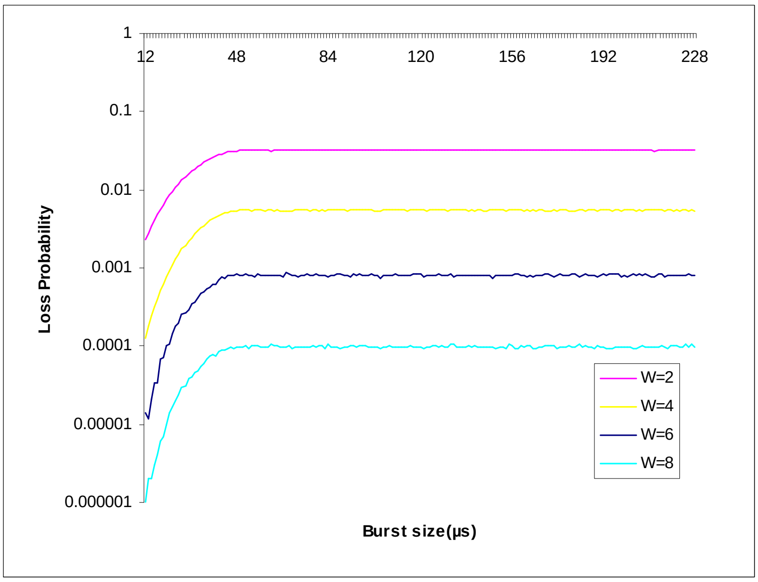


Figure 3.3: Number of wavelengths vs average loss probability, ρ=40%, N_{FDL}=16, D=50μs, T_p=50μs, T_s=0μs

Similarly in Figure 3.4 the effect of increased FDL number is graphed. As expected, burst drop rate decreases with increasing number of FDL units. The scheduler has a better range to delay the contending burst in order to find a suitable outgoing wavelength. As observed, for 8 * 50μs FDL case, there is a steep decrease in drop rates before the 50μs burst size limit. The effect diminishes as the number of FDL units decrease. The motivation behind this behavior will be discussed in the next chapter. Figure 3.4 only gives a brief look at the major effect of increased number of FDL units on loss probabilities.

In Figure 3.5, overall loss probabilities for different processing time and FDL unit sizes are presented. Overall loss probability is the ratio of dropped bursts of all sizes over total number of bursts processed. The loss probability for no FDL case is fairly high, 0.290 and 0.251 for processing times of 100μs and 10μs respectively.

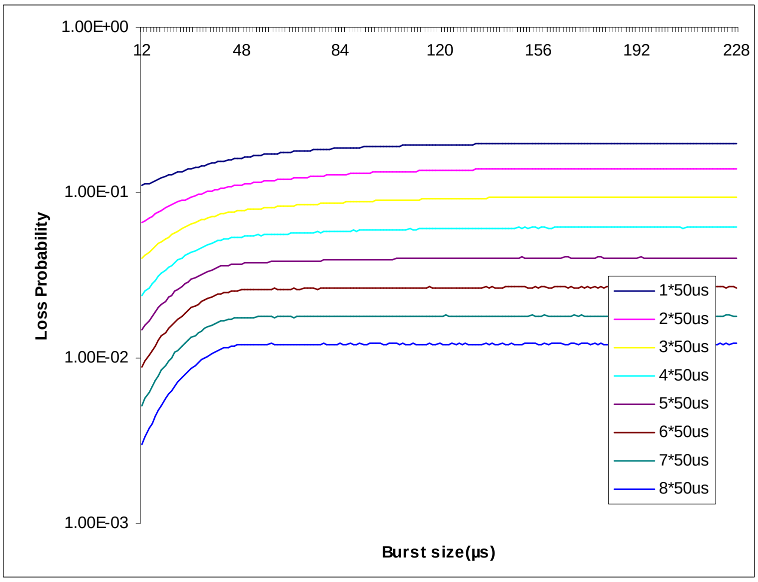


Figure 3.4: Total FDL delay vs burst length histogram, ρ=30%, T_p=20μs, T_s=0μs

3.3.2 Effects of Voids on loss Probabilities

This section focuses on the FDL and processing time induced void generation mechanisms and presents an understanding of the effects caused by several parameters. In order to characterize the duration of voids, the histogram of void durations is generated. The void histograms in this section are created as follows: when a new control packet is received at the source node, all the available void sizes at that moment are counted and corresponding numbers in histogram buckets are incremented by 1. The buckets in the histogram is separated by 1μs.

Figure 3.6 shows different scenarios with FDL granularity varying from 10μs to 100μs. Number of FDLs used is altered accordingly such that the total FDL delay is maintained at 400μs. Burst loss probabilities seem to stabilize after burst sizes get larger than the fdl granularity; actually this is not the case. In the scenario above, voids generated due to FDL granularity (because of their huge numbers) suppress the effect of offset-time difference induced voids. Void histograms for D=25μs,N_{FDL}=16 case shown in Figure 3.8 clearly identify the tendency of smaller void sizes.

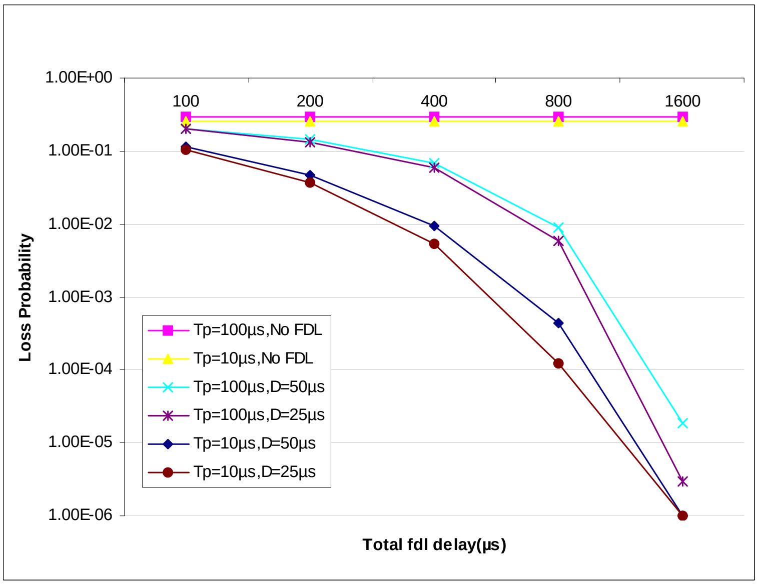


Figure 3.5: Total Fdl delay vs Overall Loss Probability, ρ=30%, T_s=0μs

Average loss probability decreases, when a smaller FDL granularity is chosen. Smaller FDL sizes, enable the scheduler to move the burst with greater precision along the output port. This in turn increases the void filling utilization thus decreases drop rates.

In the condition where the total FDL delay is smaller than the mean horizon time, the number of voids generated with offset-time differences are much more obvious. Also there is an increase in average loss probability in contrast to the case with total FDL delay of 400μs. This behavior is shown in Figure 3.7.

In Figure 3.7, total FDL delay of 100μs is selected with varying FDL granularities of 10μ, 25μ, 50μ and 100μ. Void sizes are mainly governed by the process delay which can be observed in Figure 3.8. In comparison, when the total FDL delay is smaller, number of voids generated due to FDL granularity is also smaller, which sequentially increases the effect of processing delay.

Finally, the void generation effect of offset-time differences alone is depicted in Figure 3.9. Unlike the FDL granularity induced voids, there is no linear correlation between void sizes and drop rates. This exponential behavior may be used

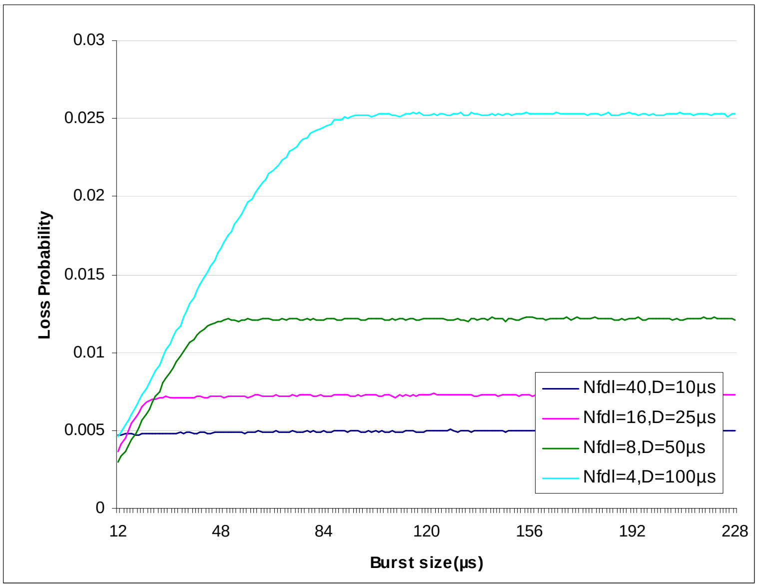


Figure 3.6: Loss Probability vs Burst Size for total FDL delay of 400μs, ρ=30%, T_p=20μs, T_s=0μs

to create high QoS differentiation between various burst sizes. Without the use of FDLs, the effect of processing time is much more obvious. Ideally a burst which is destined to the nearest node, arriving just after the scheduling of a burst destined to the farthest node creates the situation of the highest schedulable void filling. This number is calculated by *max_hop* (10) minus *min_hop* (1) multiplied by the processing delay. Bursts bigger than the “process time, hop multiplication” will not see the benefits of void filling, thus bursts bigger than this threshold will all have the same drop rates. Figure 3.10 depicts the loss probability flattening points after which loss probabilities converge to the same value. They are all in concurrence with the multiplication of hop difference with processing time.

In Figure 3.10, we also observe that as T_p increases the overall loss probability increases. A higher value of T_p increases the mean horizon time and decreases the ability of the FDLs to traverse the contenting burst up until the horizon time of the scheduler. Number of voids generated also increases as T_p increases, but is not enough to compensate for the losses associated with FDLs incapability. On the other hand, blockage of bigger bursts will affect the scheduling of smaller

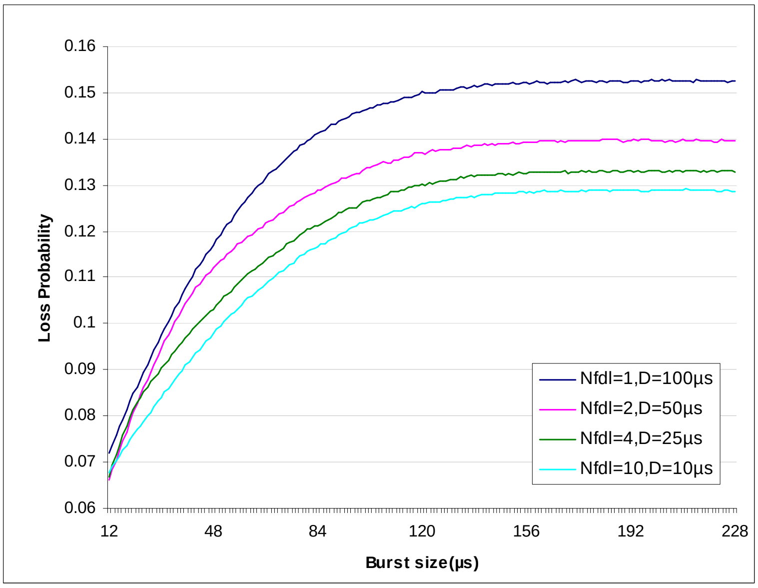


Figure 3.7: Loss Probability vs Burst Size for total FDL delay of 100μs, ρ=30%, T_p=20μs, T_s=0μs

bursts, because the outgoing channel will be less crowded with scheduled bursts and smaller bursts have a better chance of finding a void and be scheduled up until the horizon time of the scheduler. Thus we see that the behavior of the burst loss probability histogram in Figure 3.10 reverses for bursts smaller than a certain size. In the example in consideration, loss probability relation of bursts smaller than 45μs is inverted for bursts bigger than that value. Above 45μs, bigger T_p means higher blocking probabilities, while below 45μs, smaller T_p induces higher blocking probabilities. Higher loss probability of bigger bursts will give more room to smaller bursts and results in lower loss probability for smaller bursts.

Finally burst histograms for each destination for the T_p=20μs in Figure 3.10 are tabulated in Figure 3.11. The flattening points shift, depending on the outgoing destination, according to the same formula, *max_hop* (10) minus *hop_count*. For instance burst destined to for the fifth destination node will encounter voids with at most the size of 100μ (calculated from *max_hop* (10) minus *hop_count* (5) times T_p (20μ)) . So bursts longer than 100μ will not be able to see the benefits of void filling and will all have the same loss probability. This behavior can be

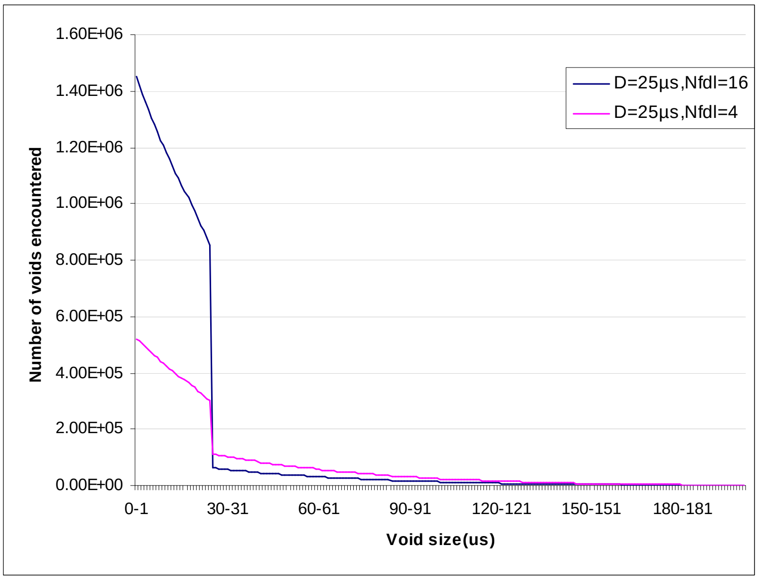


Figure 3.8: Voids histogram for ρ=30%, T_p=20μs, T_s=0μs

observed in Figure 3.11(b). We also observe a decrease in burst loss probabilities as the destination number increases. This outcome is in par with the previous works [19, 20, 21] as the offset-time increases the bursts gain priority over other bursts and have a lower blocking probability.

3.3.3 Switching Delay

Switching delay acts as a guard time [11] in order to overcome the uncertainties involved in burst scheduling and transferring. Guard time can be at the beginning or at the end of the burst. Switching delay is just added to the constructed burst and effectively increases the burst size without increasing the carried load.

In order to fully understand the effects of the switching delay on loss probabilities we conducted several simulations for varying processing delays and FDL parameters, for different switching delays as shown in Figure 3.13. The average utilization is set to 30%.

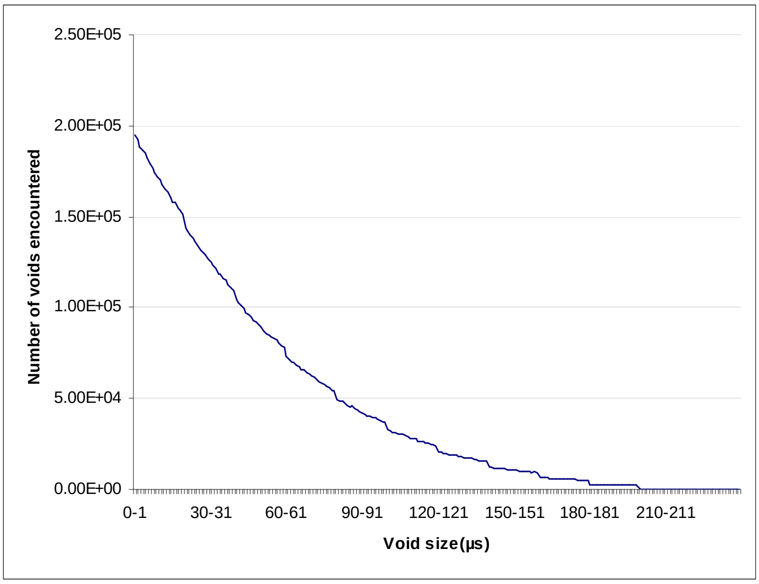


Figure 3.9: Void histogram with no FDL used, ρ=30%, T_p=20μs, T_s=0μs

Figure 3.12 illustrates the overall effect on loss probabilities. We see that increasing the switching delay increases the loss probabilities. Inducing larger switching delays effectively increases the burst sizes. A burst with 20 packets will initially last for 24μs, but with the addition of 10μs of switching delay the burst will be larger hence harder to fit in the available voids. Actually throughout the simulation FDL will greatly reduce the loss probability of bursts smaller than the FDL granularity of 25μs. Addition of 10μs of delay will increase the smallest bursts length to 24μs and hinder the effect of FDL granularity greatly. With the use of 100μs of delay the knee-effect is completely omitted. These features can be observed in Figure 3.13.

In Figure 3.13(a), the knee-effect is still visible and bursts smaller than $D(granularity) - switchingdelay$ equaling 24μs, have greatly reduced drop rates. But as we increase the switching delay to 10μs, the knee-effect starts to vanish, actually only the smallest bursts with size of 12μs can benefit from the knee-effect. Finally when the switching delay is set at 100μs, FDLs knee-effect is totally omitted. Bursts are now 100μs larger and even the processing delay induced voids are not totally utilized. As we recall from the previous section, processing time

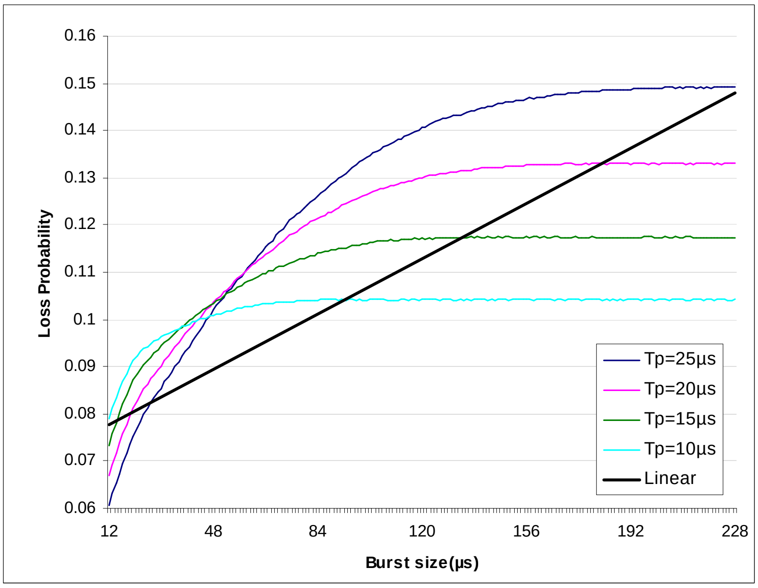


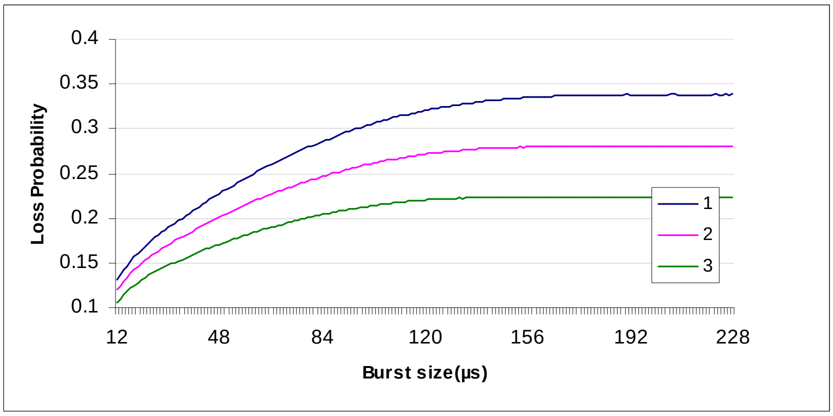
Figure 3.10: Flattening points of loss probability curves for various processing delays, ρ=30%, N_{FDL}=4, D=25μs, T_s=0μs

induced voids are 9 times the processing time; thus maximum void sizes are 90μs,180μs,270μs,360μs for processing times of 10μs,20μs,30μs,40μs respectively. For the processing time of 10μs with switching delay of 100μs (Figure 3.13(c)), effective burst sizes are 112μs to 328μs, bigger than any currently available void induced for that specific simulation conditions (biggest void size is 90μs), hence we observe a totally flat burst loss probability histogram.

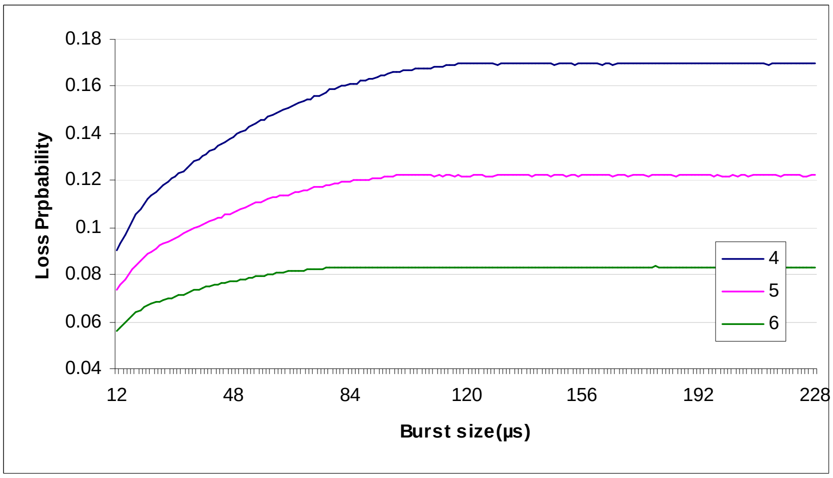
3.3.4 QoS in OBS

Using the information in the previous part of simulations, it is observed that for certain simulation variables, a differentiation is possible between bursts with different sizes. This property may be exploited as a future work in order to create a class structure for different length bursts.

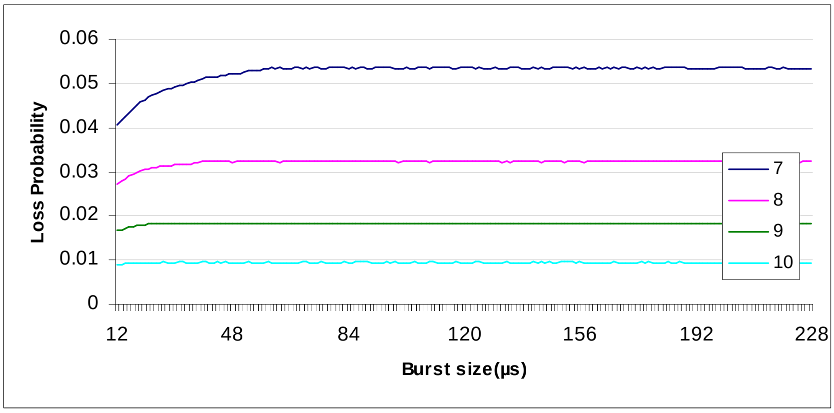
For varying simulation environments, proportion of the longest burst's loss probability over shortest burst's loss probability is plotted.



(a) Destinations 1-3



(b) Destinations 4-6



(c) Destinations 7-10

Figure 3.11: Burst loss probability for each destination, ρ= 30%, N_{FDL}=4 D=25μs, T_p=20μs, T_s=0μs

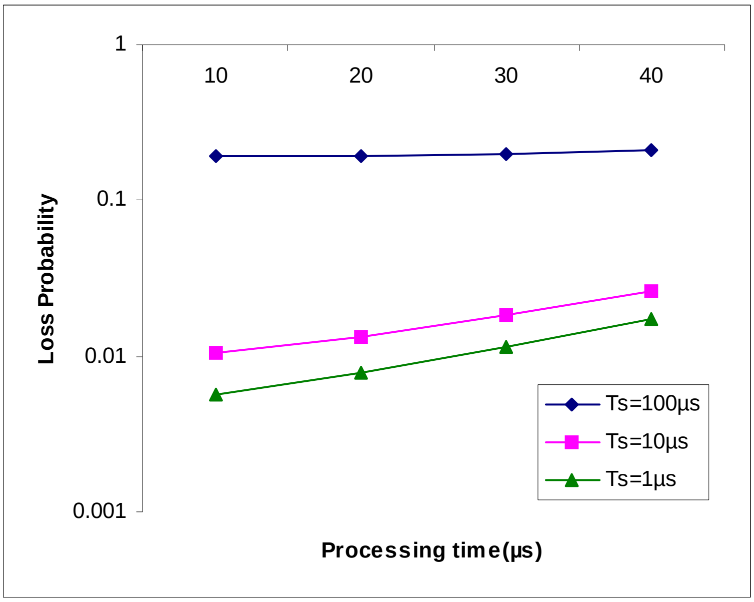
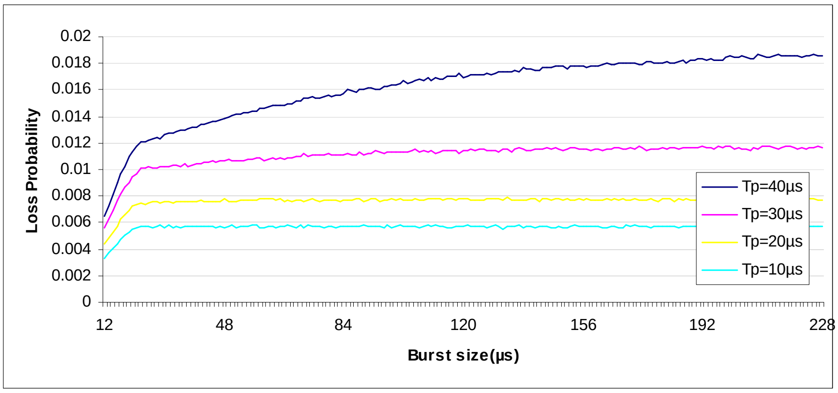


Figure 3.12: Overall effect of switching delay

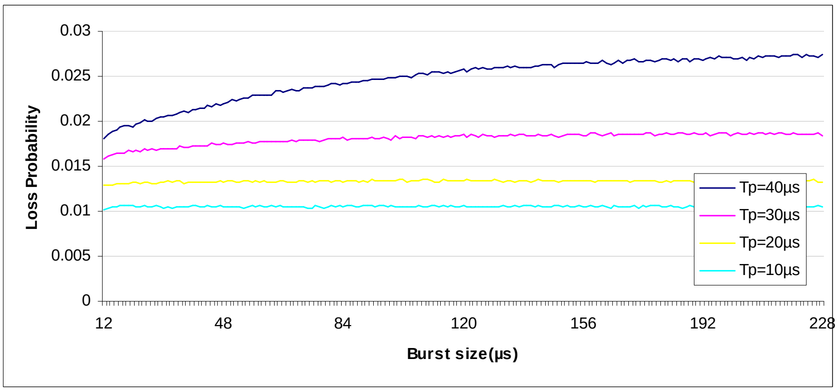
In Figure 3.14, the maximum ratio is for the case with total FDL delay of 800μs with FDL granularity of 50μs. Up to a total delay of 400μs, we see that same process times give nearly same drop rate ratios. Processing delay is the main cause of voids when the total delay is less than the mean horizon time. For a processing delay of 50μs, we have horizon time of 570μs (calculated as 9*50μs (mean offset-time) + 120μs (mean burst size)). Similarly for 100μs of processing delay the mean horizon time is 1020μs.

But when the total FDL delay is larger than the mean horizon time, granularity becomes the main reason of created voids and the ratios correlate depending on the granularity.

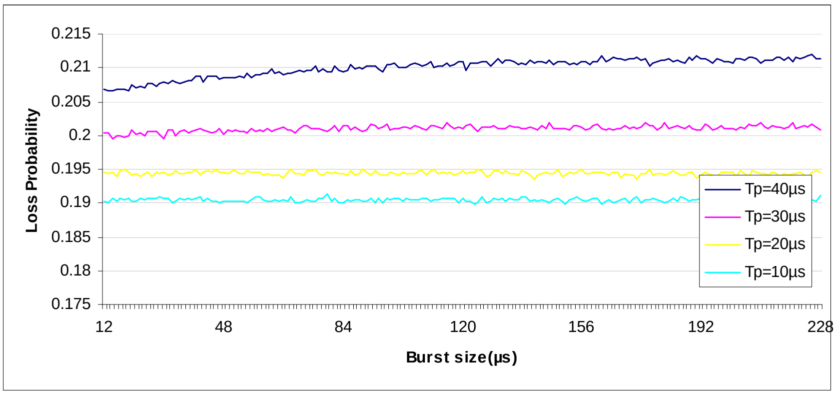
Two of the scenarios is investigated, one for processing delay of 50μs and one for 100μs. For the cases denoted above overall path loss probabilities are calculated using the formula:



(a) Switching Delay: 1μs, N_{FDL} 16 ,D=25μs, ρ=30%, T_p= 10μs-40μs



(b) Switching Delay: 10μs, N_{FDL} 16 ,D=25μs, ρ=30%, T_p= 10μs-40μs



(c) Switching Delay: 100μs, N_{FDL} 16 ,D=25μs, ρ=30%, T_p= 10μs-40μs

Figure 3.13: Effects of switching delay on loss probabilities for various burst sizes depending on the processing delay

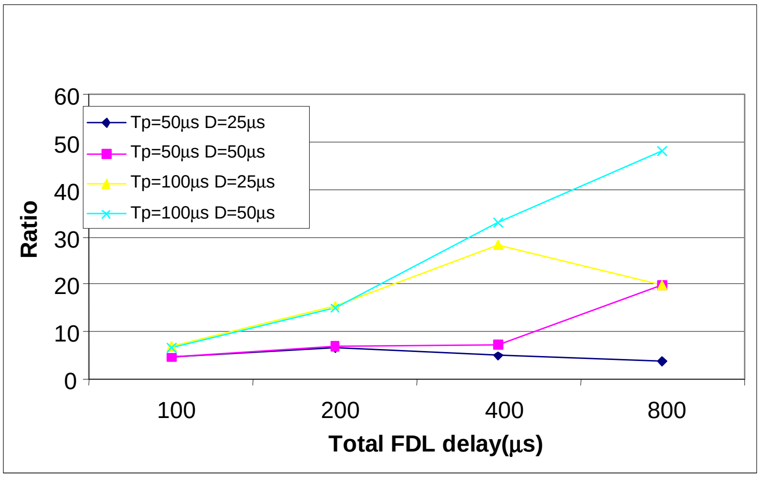
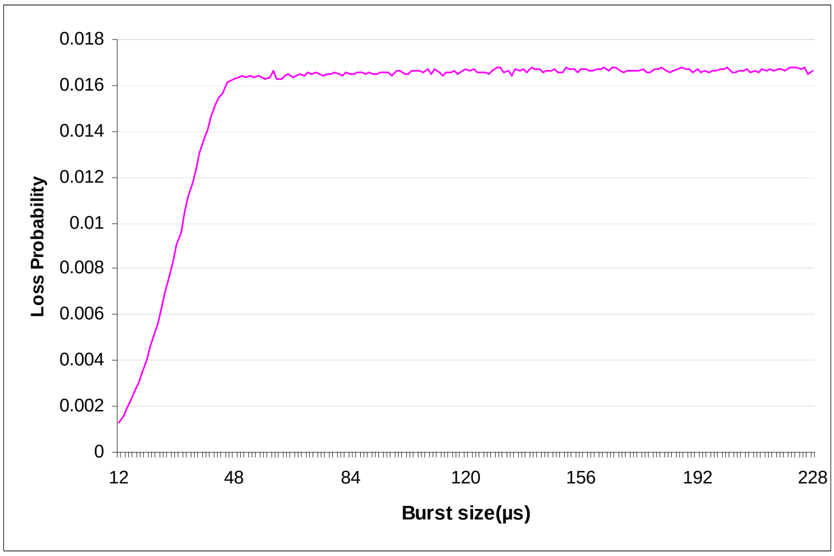


Figure 3.14: Ratio between the loss probability of the longest burst vs the smallest burst, ρ=30%, T_s=1μs

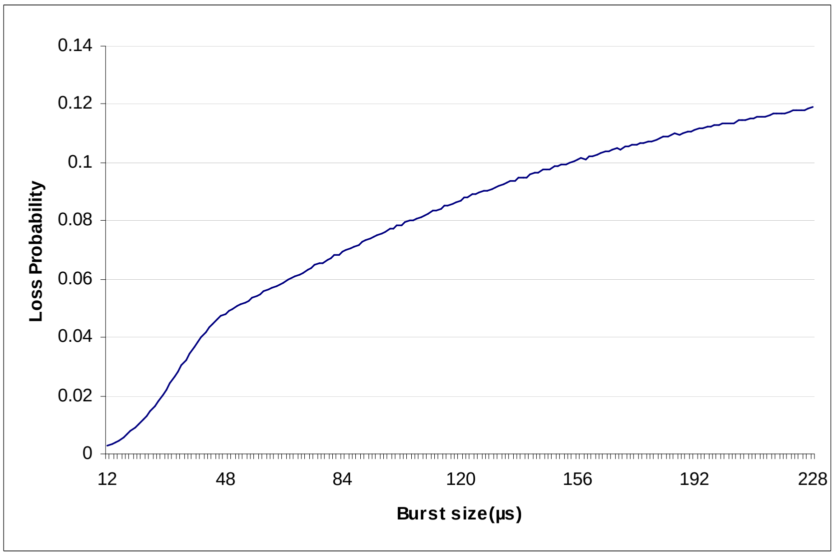
$$\frac{1 - \prod_{dest} (1 - \rho_l^{\max})}{1 - \prod_{dest} (1 - \rho_l^{\min})}$$

where $\rho_l^{\max}$ denotes the loss probability of the biggest burst and $\rho_l^{\min}$ denotes the loss probability of the smallest burst over each destination l. Using the formula the ratio for path loss ratio of 16 FDLs each with 50μs granularity is tabulated in Figure 3.15.

Knee-effect is clearly visible in Figure 3.15(a), where as the offset-time induced voids rule out in Figure 3.15(b). Path loss ratio for Figure 3.15(a) is found to be 13.317 and the ratio for Figure 3.15(b) is 44.301. Both of these cases are useful, if QoS differentiation is needed only for limited number of cases, total FDL delay can be chosen to be larger than mean horizon time, such as in Figure 3.15(a), and if a QoS differentiation over all available burst sizes is needed, total FDL delay can be chosen to be smaller than the mean horizon time so that the offset-time induced voids can rule out and similar result as Figure 3.15(b) can be achieved.



(a) Loss probability vs Burst size for T_p= 50μs, T_s=1μs, N_{FDL} 16 ,D=50μs, ρ=30%



(b) Loss probability vs Burst size for T_p= 100μs T_s=1μs, N_{FDL} 16 ,D=50μs, ρ=30%

Figure 3.15: Cases with maximum overall path loss probabilities

Chapter 4

Conclusions

The main contribution of this thesis is to investigate how the loss probability depends on the burst length in OBS networks which are using void filling burst scheduling algorithms. The void durations in OBS are also characterized. It is shown that voids are generated according to two main parameters in OBS networks: FDL granularity and processing delay induced offset-times. To the best of our knowledge no such investigation involving void generation and void utilization has been carried out in the literature.

As we have observed voids are unavoidably generated during the scheduling phase in OBS networks. To increase the utilization of channel capacity, number of voids and their sizes should be minimized. This way the outgoing packets can be packed tighter, so that the network will be able to send more packets in the same amount of time, effectively increasing the throughput. This can be done in two ways. Firstly the size of the generated voids can be reduced during the burst assembly. Actually the LAUC-VF algorithm makes the scheduling in this manner to minimize the generated void sizes. Secondly, burst sizes can be chosen in such a way that, they are suitable with the generated void sizes, so that the packets can be scheduled right into the voids.

There is also another implication of choosing burst sizes that coincide with the generated bursts sizes. Bursts smaller than the average void size will have a greater chance of being scheduled, so that their blocking probabilities will be smaller than bigger bursts. Likewise, bursts having sizes bigger than the theoretical maximum void size induced by the network parameters, will not be able to utilize the voids generated and will have higher loss probabilities.

One trivial implication of the void size knowledge is that we can understand which burst sizes will be favored by void filling and which burst sizes will not. The simulations showed that, this was indeed the case and we were able to create a quality of service differentiation between burst of different sizes. Using smaller burst sizes for high priority traffic can be used as a QoS mechanism for burst loss differentiation. Using smaller sized bursts for high priority traffic not only reduces the loss probability but also results in a smaller delay since burst aggregation times are smaller. This can be exploited as a future research problem.

We have also investigated the effects of two void generation mechanisms, i.e., the FDL and offset time induced voids. FDL induced voids tend to distinguish blocking probabilities of different burst sizes in a steeper manner. Burst smaller than the FDL granularity are affected greatly from void filling and tend to have smaller blocking probabilities, while burst greater than the granularity all have same loss probabilities. On the other hand, offset time induced voids, affect the blocking probabilities of burst with different sizes, in a linear manner. The loss probabilities increase as the burst sizes increase up to the maximum void size available. Beyond that point the loss probability is fixed. For the tested topology, loss probability ratio between the largest and smallest sized bursts exceeding 44 are obtained.

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