

A New Optical Cell Switching Paradigm

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ABSTRACT

Most of the existing all-optical switching paradigms assume different wavelengths are switched independently, and hence require W switching planes at each core switch, where W is the number of wavelengths that an optical fiber can carry. As W is becoming as large as a few hundreds in the near future, the above requirement limits the scalability of core switches. In this paper, we present a novel all-optical switching paradigm, called optical cell switching (OCS), for the next-generation optical network. By time-division multiplexing (TDM), time in OCS is divided into time slots of fixed size, and every F consecutive time slots constitute a frame. Fine bandwidth granularity can be achieved by increasing F . The wavelengths in a time slot are all bundled, and each time slot is called an optical composite cell (OCC). The OCC is the switching unit in the OCS network. Therefore, each OCS core switch (OCX) requires only one switching plane and performs mere time-space switching, thus simplifying the management and reducing the implementation complexity of the OCX. Nevertheless, traffic can be aggregated at edge routers and groomed in the wavelength domain before entering the OCS core network. The OCS network can support both guaranteed and best-effort services. Optical time-slot interchangers (OTSI) can be employed to further improve the performance of OCS. We provide simulation results to show that the OCS network can achieve low call-blocking rate for guaranteed services, and low cell-loss rate for best-effort services.

1. INTRODUCTION

As more users gain access to the Internet, and as more applications emerge demanding increased transmission bandwidth, there arises an acute need for network technologies and facilities that can provide much higher transport and switching bandwidth than that of current high-speed networks. With the advent of wavelength-division-multiplexing (WDM) technologies, an optic fiber has been able to carry 300 channels of 11.6 Gb/s [1]. To accommodate traffic of such huge transmission bandwidth, the future core networks must be able to switch data streams quickly, efficiently, and reliably. Therefore, it has been widely recognized that all-optical switching is the key to the success of next-generation optical networks due to its transparency, high speed, and large capacity.

With reference to Figure 1, there are two types of network nodes, edge routers and core switches, in an all-optical network. The edge routers act as an interface between the electrical domain and the optical domain. They are capable of buffering data streams with electrical components, and converting electrical signals to optical signals and the reverse. On the other hand, the core switches perform mere optical switching without opto-electro-optical (OEO) conversion. To flexibly use the potential huge capacity of optical fiber, several all-optical switching paradigms, such as optical packet switching (OPS), optical burst switching (OBS), optical wavelength switching (OWS), have been proposed and under intensive study.

OPS performs packet switching in an all-optical manner [3-5]. In OPS, packets arrive at the switching node in an uncoordinated fashion, and their headers are examined in a packet-by-packet basis. Optical buffering is necessary because packets may contend for common resources at the same time. The implementation of sophisticated optical buffering is nevertheless a major problem of OPS. Moreover, under current technologies, optical switching devices are unable to be reconfigured within a time comparable to the packet transmission time (e.g., several nanoseconds). Therefore, OPS is still in an experimental stage and has yet to be implemented.

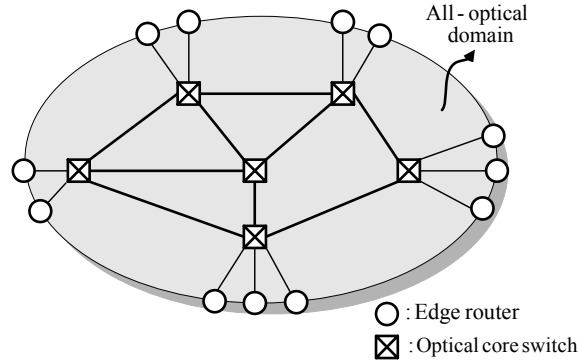


Figure 1. An all-optical network

To get rid of optical buffering and compensate for the low configuration speed of optical switching devices, OBS takes advantage of a one-way hop-by-hop reservation protocol such as just-enough-time (JET) or just-in-time (JIT) [6-11]. However, OBS suffers from a certain rate of burst loss. In general, if traffic is heavy in the network, the burst loss rate of OBS could be so high that the network resources are ineffectively reserved. To resolve part of the burst-loss issues, OBS switches can employ wavelength converters. The problem is then the high cost of wavelength converters because the related technology is not mature yet.

One way of dealing with the data loss problem without optical buffering is to employ static circuit switching in the all-optical network [12-15]. This approach is also called the OWS. In OWS, the connectivity must be provided for lightpaths (WDM channels) in an end-to-end basis. Hence, each lightpath must occupy the full bandwidth of the same wavelength (denoted as λ -bandwidth) along all links it traverses. The main drawback of OWS is the inefficient use of network resources, which is a direct consequence of the coarse granularity of bandwidth.

There is another common issue of the above all-optical switching paradigms. That is, they all assume different wavelengths are switched independently, and hence require W switching planes at each core switch, where W is the number of wavelengths that an optical fiber can carry. As W is becoming as large as a few hundreds in the near future, the above requirement limits the scalability of core switches.

To avoid the abovementioned problems, we believe that the future all-optical core-network switching scheme should possess the following properties. (i) Most network intelligence and functions are in the edge routers. (ii) Core switches are able to provide high-capacity switching with little processing to the high-speed data streams. (iii) No such expensive devices as OEO converters and wavelength converters are needed. (iv) Only limited, unsophisticated buffers are in core switches. (v) Fine bandwidth granularity. (vi) Traffic can be groomed at the edge of the core network. (vii) The data loss rate of priority service categories is bounded, if not completely eliminated. (viii) The core network is able to support best effort traffic.

To meet these goals, we propose a novel all-optical paradigm, called optical cell switching (OCS). With reference to Figure 2, by using time-division multiplexing (TDM), time in OCS is divided into time slots of fixed size, and every F consecutive time slots constitute a frame. The switching configuration of each core switch is changeable from slot to slot, and is repeated from frame to frame. The frame routing schedule can be updated whenever there are new connections admitted or old connections released. Fine bandwidth granularity can be achieved by increasing F . The use of TDM in all-optical networks is not new [16-18], but the existing optical timeslot-wavelength switching (OTWS) schemes have the same drawback as in OPS, OBS, and OWS – wavelengths need to be switched independently.

In the OCS network, wavelengths in each time slot are switched as a bundle. Thus, a time slot is also referred to as an optical composite cell (OCC). Because the core switches in OCS perform cell switching, they are referred to as optical cell switches (OCXs), while the edge routers in OCS are referred to as cell edge routers (CERs). With reference to Figure 3, to better utilize the network resources, OCCs between CERs and OCXs are allowed carry the full or partial set of

wavelengths. Nevertheless, the ingress OCX can groom different OCCs destined for the same egress OCX into a W -wavelength OCC. The W -wavelength OCC is the switching unit in OCXs. Therefore, only one switching plane is needed in each OCX.

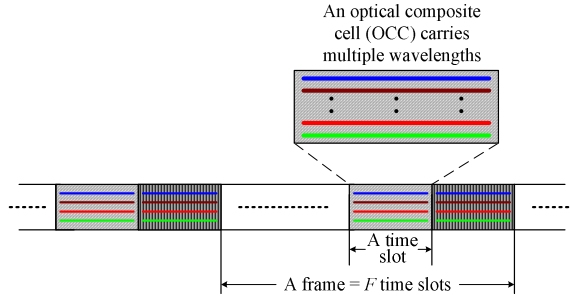


Figure 2. Time slot and frame in OCS

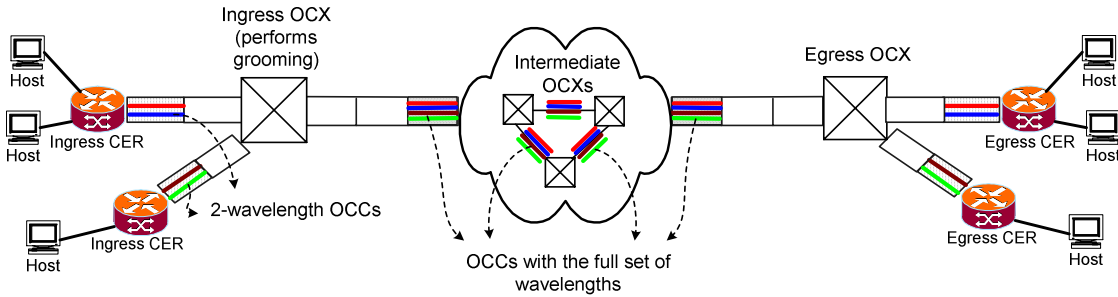


Figure 3. Ingress OCX can perform wavelength grooming

The bandwidth granularity between edge routers and the core network is $1/F \times \lambda$ -bandwidth, while the bandwidth granularity in the core network is $1/F \times \text{fiber-bandwidth} = W/F \times \lambda$ -bandwidth. For instance, suppose that $F=1000$, $W=100$, and λ -bandwidth = 10Gb/s, then the edge bandwidth granularity is 10Mb/s and the core bandwidth granularity is 1G/s. Ingress OCX aggregates multiple tiny flows in the same timeslot to achieve a high network utilization. Table 1 gives a comparison of the all-optical switching paradigms.

The remainder of this paper is organized as follows. Section 2 presents general concepts of OCS, such as service categories and routing protocols. In Section 3, we focus on the design issues of CERs and OCXs, and propose a new scheduling algorithm for shared-fiber-delay-line OCXs. Section 4 provides simulation results that justifies the performance of OCS. Section 5 presents the conclusions.

Table 1: A comparison between four optical switching paradigms

Optical Switching (paradigm)	Bandwidth reservation	Loss rate	Optical Buffer	Wavelength conversion	Add/Drop + Mux/Demux	Challenging issue
OPS	Nil	Moderate	Required	Necessary	Necessary	Large optical memory
OBS	Link-by-link	High	Not required	Necessary	Necessary	High loss rate
OWS	End-to-end	Nil	Not required	Not necessary	Necessary	Coarse bandwidth
OCS	End-to-end	Nil	Not required	Not necessary	Not necessary	Slot alignment

2. SERVICE CATEGORIES AND ROUTING PROTOCOLS

The OCS network service starts when IP network packets enter the OCS network via CERs located at the edge of the OCS network. A CER maps IP packets into OCS connections via a routing and resource allocation function at the CER. If a connection for the desired end-point already exists, binding the IP packets to the connection is straightforward. When a connection for the desired destination is not available, the CER initiates a connection set-up procedure to create a new connection. Once established, the connection generally holds the resources for a certain period. Nevertheless, the OCS network can also support connectionless traffic.

There are two types of logical connections in the OCS network, namely OCX-OCX paths and CER-CER connections as shown in Figure 4. An OCX-OCX path starts from an ingress OCX, ends at an egress OCX, and conveys OCCs of W wavelengths. The path can carry several CER-CER connections that have the same core routing path.

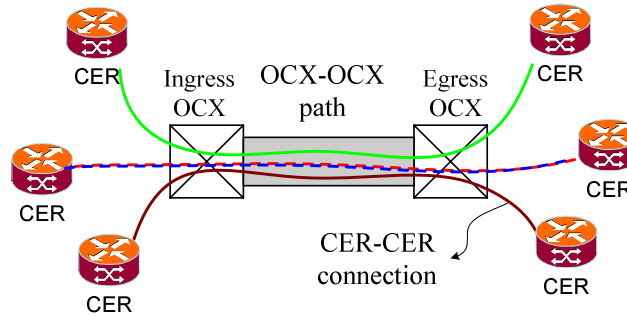


Figure 4. Two types of logical connections

2.1. Service categories

Table 2. Service categories of OCS

Properties	Circuit	VC	Best-effort
Slot reservation	Dedicated	Soft allocated.	No reservation
Loss	Lossless	Lossless	Lossy
Routing type	Pre-established routing	On-off source routing	JET or JIT source routing
Connection	Connection-oriented	Connection-oriented	Connectionless

In general, the OCS network can support three service categories, namely circuit, virtual circuit (VC), and best effort. They are described as follows.

2.1.1. Circuit

A circuit is a connection that requires one or multiple dedicated slots per frame along the path it traverses. Once a slot is assigned to the circuit, it cannot be used by any other connections. Therefore, cells of a circuit can be sent from ingress CER to egress CER without further request signals once it is set up because the routing path and slots for the circuit are fixed and always reserved.

2.1.2. VC

Like a circuit, a VC is a connection that requires one or multiple slots per frame along the path it traverses, but the slots are rather “soft-allocated” to the VC than dedicated. The VC transmits cells in an on-off manner, thus, it sends busy-period signals and idle-period signals alternately to the OCS network. In other words, the reserved slots for the VC can

be used by best-effort cells when it is idle. However, when the corresponding OCXs receive the busy-period signal from the VC, they withhold the reserved slots for it immediately. These slots can be released for best-effort cells after the busy period nevertheless.

2.1.3. Best-effort

The best-effort is the lowest-priority service category. Best-effort cells are sent without end-to-end connection-setup and slot-reservation procedures. The ingress CER determines a routing path for each best-effort cell, and sends a request signal with an amount of offset period (like JET or JIT in OBS) in order to set up a connection in a hop-by-hop manner along the path for the cell. The cell can use only free or unused soft-allocated slots for routing. Table 2 summarizes service categories of OCS.

2.2. Connection setup and routing protocols

For circuits and VCs, the connection-setup procedure is necessary for admission control and resource reservation. The procedure consists of two phases: (i) resource assignment and (ii) resource reservation.

Each CER locally maintains a resource-status table which indicates the reservation status of resources in the entire core network. In the resource-assignment phase, the ingress CER checks the local table to find an existing OCX-OCX path that can support the connection. If such a path exists, and there are sufficient unused wavelengths to carry the new connection, the ingress CER assigns several of these unused wavelengths to the new connection in accordance with the request. If insufficient wavelengths are available, the ingress CER activates the routing and slot assignment (RSA) algorithm and tries to find another set of resources for the connection. If no resources can be assigned to the new connection, it is blocked. The selection criteria of the RSA algorithm determine the overall call blocking probability of the network.

Once the resources have been locally determined for the connection, in the resource-reservation phase, the ingress CER sends a connection-request signal to the core network to grab resources and update the switching schedules of the OCXs involved. This reservation procedure is necessary not only for updating the switching schedule, but also as a contention resolution protocol. If contention occurs, the request may fail and the connection need to be re-assigned another set of resources (i.e., another path and/or slots) again at its ingress CER. Alternatively, if optical time-slot interchangers (OTSI) are available, the request may be reassigned empty slots immediately at the OCX in which contention occurs, and passed to the next OCX along the path.

Once the ingress CER receives the confirmation acknowledgments from all involved OXCs, the path establishment is done and the connection can start sending OCCs along this path. Moreover, the ingress CER should inform all other CERs about the corresponding slot(s) that have been occupied along the optical links so they can update their resource-status tables.

The above connection-setup protocol can guarantee that cells of the connections with reservation never incur any loss in the core network. In some cases, however, the request-acknowledgment round-trip delay can be undesirably large. An option to exclude such a delay is to let the new connection send cells without waiting for acknowledgments. When contentions occur, the new connection may lose in the contention and may lose its first few cells as well. Nevertheless, if OTSI is available, an OTSI-path can be assigned immediately and thus reduces the cell-loss rate.

3. DESIGNS OF CER'S AND OCX'S

3.1. Design of CERs

The slots that depart from an ingress CER are actually the logical outputs of that CER. Figure 5 depicts the CER architecture that we propose. In this CER architecture, each input line card packs incoming traffic streams into cells and maintains F (for example, 1000) virtual slot queues (VSQs), each of which is dedicated to a particular slot queue (output queue). The switch fabric in the middle is responsible for transferring cells from inputs to outputs. In the output side there are F slot queues. The outgoing optical fiber reads cells from these slot queues in a round-robin manner. To reduce

the size of the switch fabric, a number (for example, 10) of logical slot queues can be grouped into a physical output queue. These cells will then be delivered on the fiber with multiple wavelengths at the different time slots.

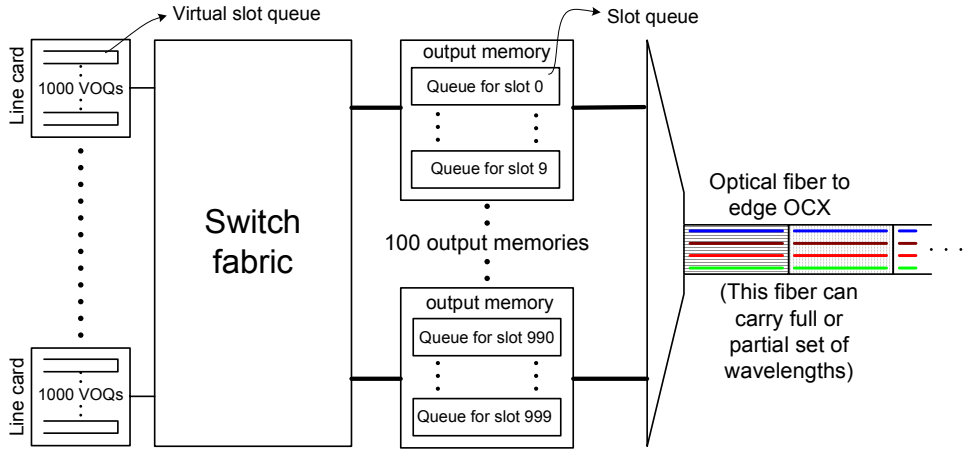


Figure 5. The switch architecture of CER (F=1000)

3.2. Design of OCXs

Each OCX consists of the following devices: optical synchronizers (OSYNs), OTSIs, and a single-plane optical switch fabric (OSF).

3.2.1. OSYN and guard-time overhead:

At each OCX, arriving slots must be in alignment so that cells can be routed simultaneously. A flexible way of aligning slots is to adopt optical synchronizers (OSYNs) [2] at input ports of each OCX. Figure 6 depicts a possible solution for implementing the OSYN, assuming the tolerable slot misalignment is $2^{-K} T_{cell}$.

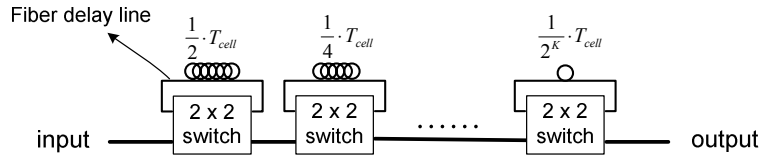


Figure 6. An OSYN

The tolerable slot misalignment described above can be offset by the offset period associated with each time slot. In addition to the offset period, a reconfiguration time is also needed for optical switching devices to reconfigure the switching state to accommodate cells from slot to slot. The offset period and the reconfiguration time constitute the guard time in a time slot as shown in Figure 7. For instance, suppose that $T_{cell}=1\mu s$, reconfiguration time = 15ns (e.g., semiconductor-optical-amplifier (SOA) switching devices), and offset period = 35ns (which requires $2^{-K} T_{cell} < 31.25ns$, $K=5$). Then, the guard time is 50ns, and the overhead is 5% of T_{cell} .

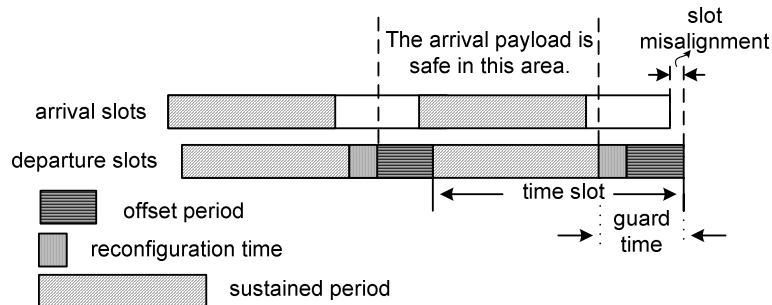


Figure 7. Guard time and sustained period.

3.2.2. OTSI and shared-FDL modules:

OTSIs are used to interchange the positions of time slots. Figure 8 depicts a nonblocking OTSI with single input and single output. The implementation complexity of the nonblocking OTSI is very high [18]. Thus in practice, the blocking OTSI is a more attractive solution for performing time-slot interchange in OCXs. A switch module associated with fiber delay lines (FDLs) that are shared among all inputs and outputs is referred to as the shared-FDL switch module. An example is given in Figure 9. Note that a shared-FDL switch module can be blocking or nonblocking, depending on the FDLs employed.

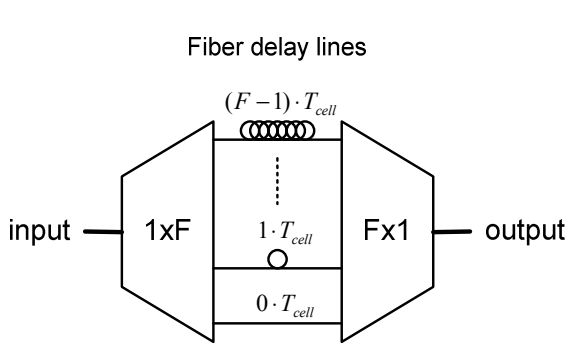


Figure 8. Nonblocking OTSI

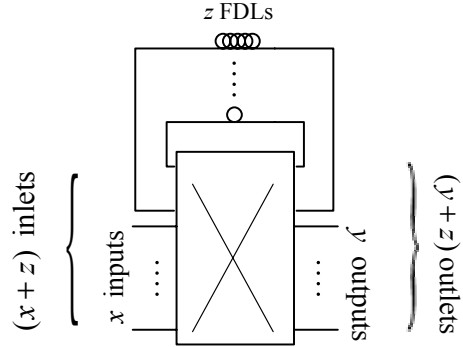


Figure 9. A shared-FDL module

3.2.3. OCX switch fabric:

The switching elements based on semiconductor-optical-amplifier (SOA) [19-21] and electro-absorption (EA) technologies can be best adopted to construct the OCX because they are able to switch wavelengths in bundles. The SOA should be able to cover broad wavelength range, e.g., 1.3 – 1.6 μm , and exhibit low crosstalk [20]. Figure 10(a) depicts a 1x8 SOA/EA, in which SOAs amplify the optical signals; the star coupler (SC) broadcasts the signals; and EAs perform the on-off function. Note that such a switch module can perform multicasting easily by turning on the corresponding set of output EAs. An 8x8 SOA switch module is shown in Figure 10(b). Using the 8x8 as building blocks, a larger switch can be implemented with the Clos-network structure.

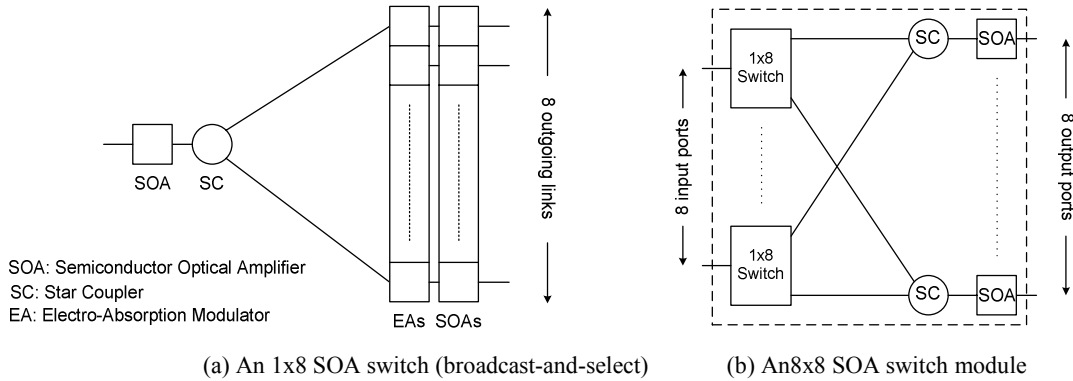


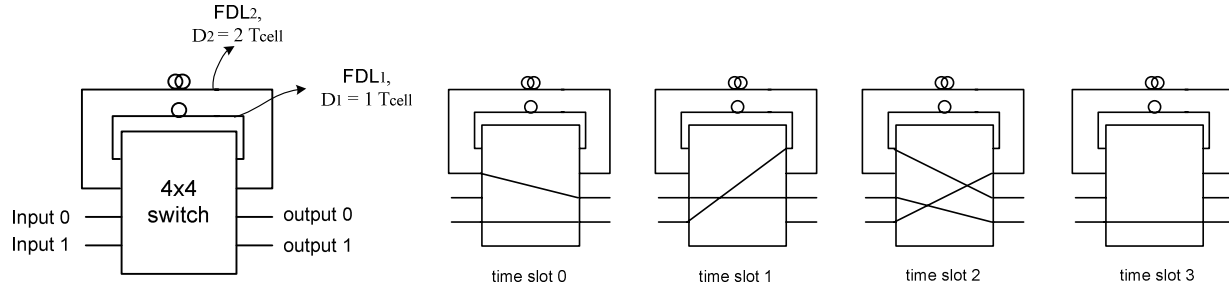
Figure 10 SOA switching element and module

3.3. FDL assignment algorithm

In the shared-FDL switch module shown in Figure 9, when two or more connections ask for the same output in the same time slot, only one of them can get access and the others may need to traverse one or more FDLs in order to be shifted to other slots for that output. Finding a nonblocking FDL route for a connection request is called the FDL assignment. Recently, a new FDL assignment algorithm has been proposed in [18] to assign FDL route in the single-input-single-output blocking OTSI. In this section, we extend the FDL assignment algorithm for the shared-FDL switch module. With reference to Figure 9, suppose that the switch module

contains z feedback FDLs, each can delay cells by a fixed amount of time. Note that any two FDLs may have the same or different delay values. The number of inputs to the module is x ; the number of outputs from the module is y . The outputs (inputs) of FDLs and the inputs (outputs) of the module are collectively called the inlets (outlets) of the switch. Thus, there are $x+z$ inlets and $y+z$ outlets, and the switch size is $(x+z) \times (y+z)$.

The shared-FDL switch module maintains a configuration table (switching schedule) for forwarding cells. In the following, we use an example to illustrate the configuration table, slot transition diagram, and FDL assignment algorithm. Consider a shared-FDL switch module with two inputs, two outputs and two FDLs as shown in Figure 11(a). Suppose that $F=4$ and the existing connections in each time slot are given in Figure 11(b). These connections are recorded in a configuration table as in Figure 12(a). For $s \in \{\text{outlets}\}$, $0 \leq t \leq F-1$, the entry of row s and column t in this table consists of two variables, $u(s,t)$ and $v(s,t)$, where $u(s,t) \in \{0,1\}$, and $v(s,t) \in \{\text{inlets}\}$. $u(s,t)$ is a Boolean variable that indicates whether outlet s is connected to any inlet in time slot t . That is, if $u(s,t)=0$, then outlet s is idle in time slot t ; if $u(s,t)=1$, then outlet s is connected to inlet $v(s,t)$ in time slot t . The size of this configuration table is $(y+z) \times F \times [1 + \log_2(x+z)]$.



(a) A 2x2 switch module, 2 FDLs.

(b) Existing connections in the switch module ($F=4$)

Figure 11. Switch module and existing connections

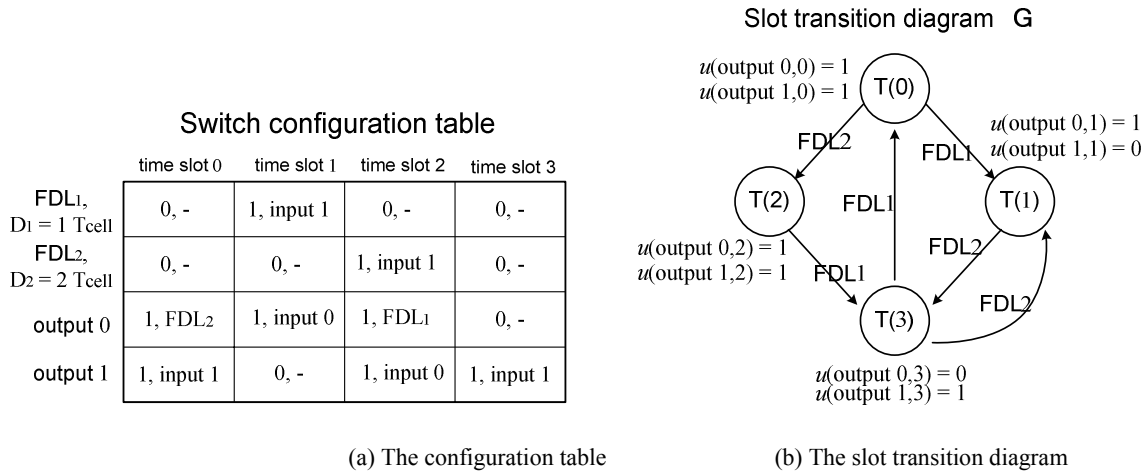


Figure 12 Setting up a connection that arrives in time slot 0 from input 0 to output 0

From the configuration table, a slot transition diagram, G , can be constructed for new connections as follows. With reference to Figure 12(b), time slot t is represented by a node with label $T(t)$ in G . For $q \in \{\text{FDLs}\}$, if FDL_q is available in time slot t (i.e., $u(q,t)=0$), it is represented by an arc from $T(t)$ to $T[(t+Dq) \bmod F]$, where Dq is the delay value of FDL_q . With such a representation, a nonblocking FDL route from time slot t to time slot τ is denoted by a path from $T(t)$ to $T(\tau)$ in G . Note that since different FDLs can have the same delay values, there can be multiple arcs directed from the same source node to the same destination node in G . In addition, $T(t)$ also keeps the availability status of all outputs in time slot t , i.e., $u(p,t)$, for $p \in \{\text{outputs}\}$. Therefore, finding a nonblocking FDL route starting from time slot t (in which

output p is not available) to a time slot in which output p is available, is equivalent to finding a path in G from $T(t)$ to any $T(\tau)$ in which $u(p, \tau)=0$. Note that if $u(p, t)=0$ in the beginning, the connection can be routed to output p immediately in time slot t without passing through any FDL.

With the above existing configuration, suppose that there arrives a new connection from input 0 in time slot 0, requesting to be connected to output 0. Since output 0 is busy in time slot 0 (i.e., $u(\text{output } 0, 0)=1$), we have to find an FDL assignment to route the new connection to any time slot, say τ , in which $u(\text{output } 0, \tau)=0$. With the slot transition diagram given in Figure 12(b), we can modify any search-based algorithms, such as the breadth-first search, shortest path algorithms, for this objective. In the above example, two nonblocking FDL routes, $T(0) \rightarrow \text{FDL}_1 \rightarrow T(1) \rightarrow \text{FDL}_2 \rightarrow T(3)$ and $T(0) \rightarrow \text{FDL}_2 \rightarrow T(2) \rightarrow \text{FDL}_1 \rightarrow T(3)$ can be found, and both route the connection to $T(3)$ — the only time slot in which output 0 is available. In practice, we may be able to find more than one $T(\tau)$ in which the desired output is available. However, we only need to assign any one of them to the new connection. On the contrary, if no such $T(\tau)$ can be found, the connection is blocked.

4. PERFORMANCE STUDY

In this section, we study the performance of OCS by two simulation models. In the first simulation, we study the call blocking rate in the OCS network for circuits and/or VCs. In the second simulation, we study the cell loss rate at a shared-FDL OCX for best-effort traffic.

4.1. Call blocking rate for circuits and/or VCs

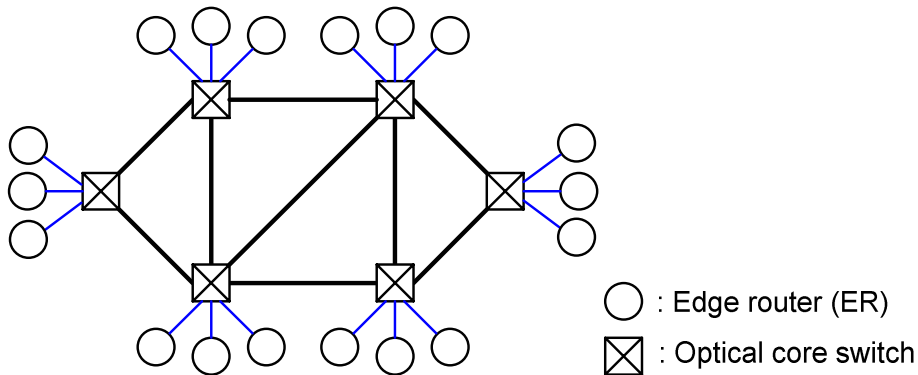


Figure 13. Network topology for simulation

The simulation is based on the mesh network topology shown in Figure 13. Calls arrive at each edge router as a Poisson process, and are equally likely to be destined for any other edge routers. After being admitted, a call stays in the network for a finite amount of time which is exponentially distributed. In addition, we employ fixed-alternate routing and the first-fit [29] wavelength-slot assignment algorithm in the simulation.

The input parameters to the simulation are: the network load, which is equal to *arrival rate* \times *mean holding time*; W , the number of wavelengths supported by a link; F , the number of calls that can be carried on a wavelength. Note that in OCS, F is also the number of time slots supported by a link.

Figure 14 compares the performance of OCS, OWS, and OTWS. The call blocking probability of OCS is much lower than that of OWS even if $W=F=16$. It is because the edge OCXs can groom multiple OCCs that share the same time slot on the same OCX-OCX path, thus improving the network utilization. However, the performance of OCS is not as good as, but very close to, that of OTWS. This makes sense because with wavelength-bundle switching, OCS is less flexible than OTWS.

To give a fair comparison between the performances of OCS under different selections of frame size (F), we define the normalized network load as the network load (*call arrival rate* \times *mean holding time*) multiplied by $1/F$ (bandwidth requirement of each call). The normalized network load represents the bandwidth load of the network. Figure 15 shows the performances of OCS under different selections of F versus the normalized network load. The performance of OCS

is improved as F is increasing because the larger F provides the finer bandwidth granularity, thus achieves the lower call-blocking probability.

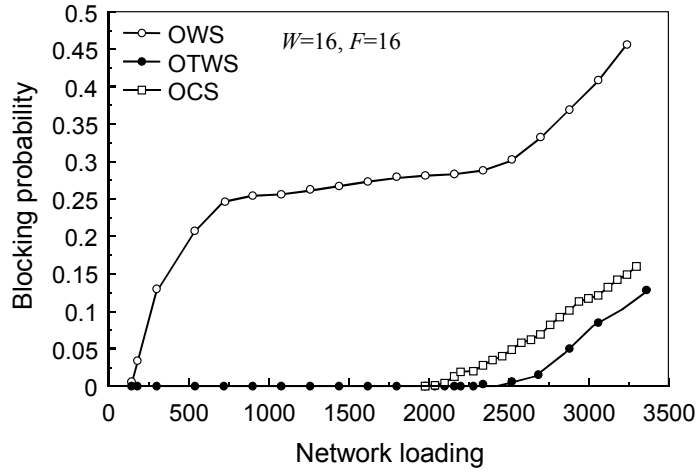


Figure 14. Call blocking rate vs. Network load

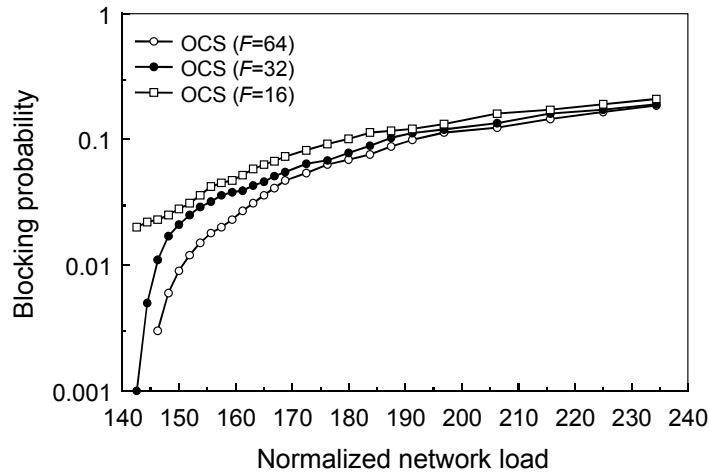


Figure 15. Call blocking rate vs. Normalized network load

4.2. Cell loss rate for best-effort cells

In the second simulation model, we study the performance of the shared-FDL switch module. With reference to Figure 9, consider a shared-FDL switch module with 32 inputs, 32 outputs, and 32 FDLs. We assume that this shared-FDL switch module is used to perform switching for best-effort cells. A best-effort cell arriving at an input port is equally likely to be destined for any one of the output ports, and it is discarded immediately if neither direct connection nor FDL route can be set up for it. We modify the FDL assignment algorithm developed in Section 3.3 to find FDL routes for cells when necessary.

With a given frame size F , a cell can be delayed at most $F \cdot T_{\text{cell}}$, and the delay values of the 32 delay lines are distributed as evenly as possible between T_{cell} , $2 \cdot T_{\text{cell}}$, $4 \cdot T_{\text{cell}}$, ..., $F/2 \cdot T_{\text{cell}}$. Figure 16 shows the cell discarding probability in the above switch model with different frame sizes. Under the uniform Bernoulli traffic assumption, the switch model can achieve a close-to-zero cell discarding probability even if the traffic load is as high as 0.9. The cell discarding probability can be further improved as the frame size increases because cells that have lost contention can have more alternative delay values for them to search for the slots in which the desired output ports are available. Note that when a cell

traverses an FDL once, an additional switching operation is needed for accommodating that cell. Our simulation also shows that most of the cells can be assigned routes that involve less than three switching operations for their output ports. Overall, the simulation result implies that we can use shared-FDL switch modules to perform time-slot interchanging yet can achieve a performance very close to that of nonblocking OTSIs in OCX.

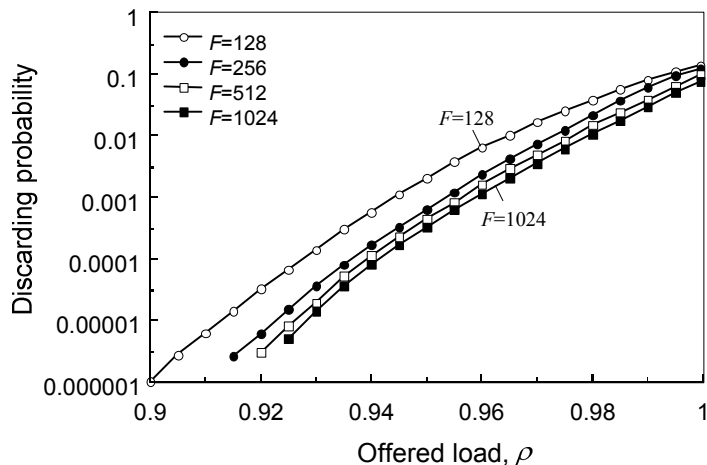


Figure 16. Cell discarding probability vs. offered load for best-effort cells

5. CONCLUSIONS

In this paper, we have presented a new all-optical switching paradigm – optical cell switching (OCS). The OCS network preserves the full advantages of network transparency, provides lossless core-network routing for priority service categories, achieves fine granularity of bandwidth, and switches wavelengths in bundles (thus requiring only one switching plane per core switch) in the core network. It can also perform traffic grooming, and support both guaranteed and best-effort services. Through simulation, we have given a comparison between the call-blocking rates of OCS, OWS, and OWTS. Our simulation shows that the OCS scheme is comparable with OTWS scheme, but much better than OWS. With the FDL assignment algorithm that we have proposed, the optical core switches can achieve low cell-loss rate for the best-effort cells, as shown in our second simulation model.

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