Wavelength Swapping using Tunable Lasers for Fractional λ Switching

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***Abstract*—Fractional Lambda Switching (FλS) is a novel proposal for the management of all-optical networks with sub-wavelength provisioning capability. The unique characteristic of FλS is the utilization of the UTC (coordinated universal time) for alignment and switching. Several central research issues are still open in FλS and need to be formally defined and analyzed. Within the scope of this paper, we introduce three novel switch architecture designs that are based on the use of tunable lasers. As an important goal, we introduce the notion "scheduling feasibility" that measure the number of possible different scheduling between an input and output time-frames.**

***Index Terms*—optical networks, sub-lambda switching, time-driven switching, tunable laser, scheduling.**

I. Introduction

Multi-wavelength optical networks [1] have been the subject of research for many years. The bandwidth granularity in optical channel routed networks is the bandwidth of the whole optical channel or lambda (λ), i.e., it is only possible to allocate the whole optical channel capacity or nothing. Switching a whole optical channel is not convenient, since each optical channel has a capacity ranging from 2.5 Gb/s to 40 Gb/s and can accommodate a very large number of conventional IP-traffic users. Thus, it is more bandwidth efficient if an optical channel can be partitioned into a number of sub-lambda or fractional lambda channels.

FλS capability is especially important in local and metropolitan area networks (LAN/MAN), since the end-users' traffic is very dynamic and requires only a fraction of the optical channel. FλS solves the problem of sub-wavelength traffic tricklets; however, to account for the highly dynamic nature of Internet traffic, it has to be coupled with grooming capabilities that dynamically multiplex IP level traffic into the appropriate sub-wavelength "virtual container" for transmission. Grooming (multiplexing) the traffic from multiple end-users is required in order to improve the throughput and reduce the operation cost of optical networks. The obvious solution is the implementation of asynchronous IP-packet switching, but looking for all-optical networking, asynchronous IP-packet switching is not suitable. Moreover, future traffic will include a large portion of multimedia distribution that is inherently synchronous. Consequently, fractional lambda switching combined with grooming has the potential to bring the benefits of optical networking in terms of reliability and capacity to the end-users.

Recently, Optical Burst Switching (OBS) [2] was proposed as a middle stage toward the realization of optical packet switching. A burst accommodates a possibly large number of packets. In OBS, control packets are forwarded in a control channel to configure switching nodes before the arrival of corresponding bursts, reducing the requirement of optical buffers. Though OBS is interesting and some protocols were defined for it [3][4], the behavior of burst switching as an asynchronous switching system makes it hard to implement and control the optical switching fabric even when the traffic load is moderate. Besides, grooming traffic into bursts at ingress nodes of OBS networks is another difficult issue. An Optical Packet Switching (OPS) network [5] may be the ultimate goal for all-optical networking. Unfortunately, the technology to manufacture optical random access memory and optical processing are not yet mature enough to realize OPS.

The contribution of this paper is the discussion of different possible architectures for the realization of FλS nodes, their complexity and their performance in terms of flexibility and redundancy for scheduling and switching time-frames from an input to an output port.

II. FλS - Basic Principles

A. *FλS Timing Principle*

Sub-lambda of fractional lambda switching was proposed as an effort to realize highly scalable dynamic optical networking [6][7][8], which requires minimum optical buffers. FλS has the same general objectives as in OBS and OPS: obtaining higher wavelength utilization, and realizing all-optical networks. In FλS, a concept of *common time reference* using UTC (Coordinated Universal Time) is introduced. A UTC second is partitioned into a predefined number of time-frames (see details in [6][7]). Time-frames can be viewed as virtual containers for multiple IP packets that are switched, at every FλS node, based on and coordinated by the UTC signal. As shown in Fig.1, a group of k time-frames forms a time-cycle; l contiguous time-cycles are grouped into a *super cycle* (in Fig.1, k =1000, l=80).

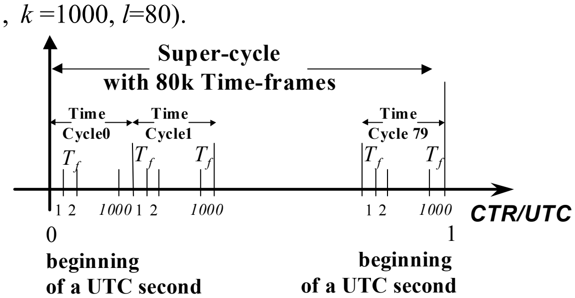

Fig. 1. Division of an UTC second in FλS [6].

To enable FλS, time-frames are aligned at the inputs of every FλS node before being switched. After alignment, the delay between any pair of adjacent switch nodes is an integer number of time-frames.

Another key element of FλS is the method of *pipeline forwarding*. In FλS, a *fractional lambda pipe* (FλP) p is defined as a predefined schedule for switching and forwarding time-frames along a path of subsequent FλS-enabled nodes. The FλP capacity is determined by the number time-frames allocated in every time cycle (or super cycle) for the FλP p. For example, for 10 Gb/s optical channel and k=1000, l=80 if one time-frame is allocated in every time cycle or super cycle the FλP capacity is 10 Mb/s or 125 kb/s, respectively.

B. FλS Forwarding Principle

FλS defines two possible types of forwarding, as shown in Fig.2. The first is *immediate forwarding* (IF), upon the arrival of each time-frame to an FλS node, the content of the time-frame are scheduled to be "immediately" switched and forwarded to the next node during the next time-frame. Hence, the buffer that is required is bounded to one time-frame and the end-to-end transmission delay is minimized.

The other type of packet forwarding is called *non-immediate forwarding* (NIF). NIF requires buffers at FλS nodes. Let us assume that, at each node, there is a buffer of b time-frames at each input channel. The content of each time-frame arriving to the FλS node can be buffered for k_b time-frames, $1 \le k_b \le b$, before being forwarded to the next node. NIF offers greater scheduling feasibility than IF. This increasing flexibility that makes schedules feasible is one of the main issues we discuss in this paper.

In FλS networks, a FλP is setup prior to the actual data transmission. With an already-established FλP, the end-to-end average delay is constant (i.e., accumulated buffer delay and transmission delay) and no data is lost due to packet dropping.

C. Tunable Laser Principle – Wavelength Swapping

This work focuses on FλS with tunable lasers, since they are available with high performances, e.g. a 16-channel 100-GHz-spacing digitally tunable laser with 0.8 ns switching time between channels has been experimented [9]. In general, the way tunable lasers are used in this work is to change the wavelength (color) of time-frames that contains IP packets every FλS node. When wavelength converters will be available they may replace the tunable lasers.

This operation can be viewed as wavelength swapping of packets. Namely, packets are transmitted with λ_1 over the first optical link, then with λ_2 over the second optical link and so on. The operation of swapping wavelength is equivalent to label swapping. Obviously, as in label swapping, packets of different connections (FλPs) should not have the same color (label) when being transmitted over the same optical link and having the same time index.

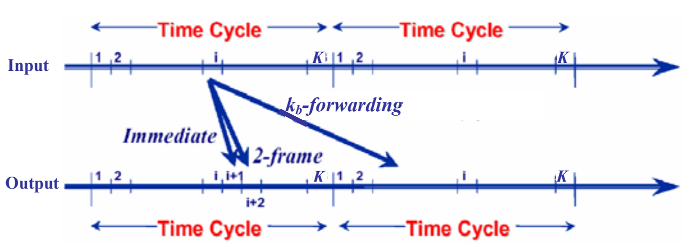

Fig. 2. Illustration of IF and NIF in time domain.

III. Scheduling Feasibility of FλS with Tunable Laser

We discuss and evaluate several optical switch architectures, which combine FλS with tunable lasers. The goal of each architecture is having the lowest possible complexity and cost, while maintaining the performance in terms of end-to-end blocking probability as low as possible. The computation of the blocking probability is a hard task, but we argue that it is a function of the scheduling feasibility as defined below. Hence in this paper we use the later to quantify the performance. Thus, the different switch architectures are compared using: (1) the hardware complexity, (2) the scheduling feasibility. The performance study of the blocking probability and the relationship with the scheduling feasibility is left for future study.

In order to give consistent and convenient descriptions of the different switch architectures, the following notations are used:

- C is the link capacity in terms of the number of wavelength (colors) per optical link.
- $N_{in} = N_{out} = N$ is the number of input/output ports per switch.
- $r = C/N$ is the connection ratio. For simplicity it is assumed that r is integer.
- $X(i, j)$ denotes device j of type X (e.g., tunable laser TL or star coupler SC) of the in-port i.
- R_T denotes the tuning range of a tunable laser.
- k denotes the size of time cycle in number of time-frames.
- h denotes the route length in number of hops.

Scheduling feasibility definition:* *for a generic FλP the scheduling feasibility is the number of distinct schedules that are available using time and wavelength swapping. The scheduling feasibility is function of: the forwarding method (IF or NIF), k, h, C and N.*

A schedule is a possible (not necessarily feasible) assignment of resources (time-frames, optical channels…) to build a FλP. A feasible schedule is not guaranteed to be available at the time of FλS setup due to blocking (e.g. switching fabric limitation, contention between multiple FλS setups).

The switch architectures studied in this work have four components:

1. WDM demultiplexers on the input side;
2. WDM multiplexers on the output side;
3. Tunable lasers that are connected to the WDM demultiplexers;

* In this paper, we consider the schedule feasibility for scheduling 1 time-frame FλPs. For the case of multiple time-frames scheduling, the IF scheme is tractable using combinatorial mathematic. On the other hand, considering the arbitrary NIF scheme, we have still not proven if it if it is tractable or not.

4. A connection network that connects the tunable lasers with the WDM multiplexers at the outputs, which is in essence what distinguish the various switch architectures that are discussed in this paper.

In this work we study the following switch architectures:

- *Tunable laser with fixed connection network (FC-FλS)*. The fixed connection network consists of point-to-point links from tunable lasers to output MUXs.
- *Tunable laser with static wavelength router (WR-FλS)*. The static wavelength router does not change its configuration over time.
- *Tunable laser with broadcast and select (BS-FλS)*. The broadcast and select operation is time dependent and the connection configuration can change every time-frame.

For the sake of simplicity, we do not show in figures how to implement buffering (NIF). In principle, a tunable laser behaves as an optical-electronic-optical conversion device, since the incoming optical signal is converted to electronic signal in order to modulate the tunable laser in a defined wavelength. Thus, buffering can be embedded at the electronic stage of tunable laser as it is done in any electronic buffering implementation. With FλS switches using all-optical wavelength converters rather than tunable lasers, all-optical buffering can be implemented by parallel fiber-delay-line approach.

A. Tunable laser with fixed connection network (FC-FλS)

1) Design and operation

Fig.3 shows the simple design of the FC-FλS for $C = 4, N = 2$, which uses tunable lasers with a fixed point-to-point connection network. DMUX separates WDM signals into C different wavelengths. Each incoming wavelength is fed to a tunable laser that transmits at any wavelength within its tuning range R_T. The output of each tunable laser is connected to a predefined output port. The number of fixed connection between a pair of in-port and out-port depends on the ratio between C and N, which defines the internal connection ratio $r = C/N$. A switch with $N = 8$ and $C = 16$ has $r = 2$ fixed connections between in-port/out-port pair.

Tunable lasers are tuned every time-frame, where time-frames are derived from UTC, such that time-frames are

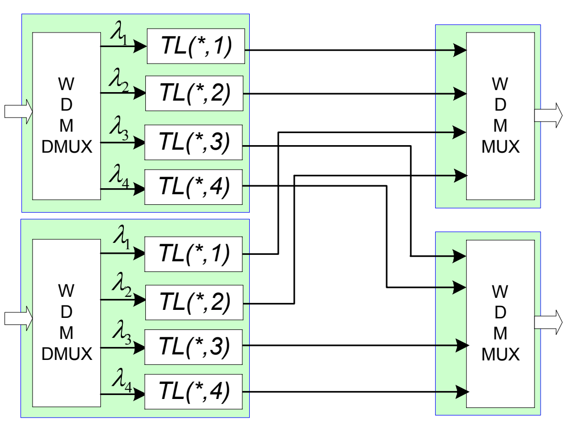

Fig. 3. Illustration of a 2×2 FC-FλS switch (tunable lasers are coordinated by UTC signal, which is not shown in the figure).

switched from in-ports to out-ports without conflicts at any out-port. Due to the nature of fixed connection system, the color of a time-frame after being switched defines the out-port, and hence, it defines the route it must go on.

2) Hardware complexity and scheduling feasibility

The hardware complexity of this design is CN tunable lasers. Each input requires C tunable lasers, corresponding to C channels. The DMUX and MUX devices are not counted in the hardware complexity since they are identical for all the designs described in this paper.

Scheduling time-frames using FC-FλS is rigid due to the nature of fixed point-to-point internal connection network. To route a time-frame along a predefined route path between source and destination (s,d), a tunable laser that receives a signal must tune the output to one wavelength among r. For simplicity, it is assumed that lasers have full tunable range, that is $R_T = C$. With this assumption, the scheduling flexibilities of this design are given in (1) for IF, and (2) for NIF.

$$S_{FC}^{(IF)} = kr^h = k\left(\frac{C}{N}\right)^h \qquad (1)$$

$$S_{FC}^{(NIF)} = kr^h b^{h-1} = k\left(\frac{C}{N}\right)^h b^{h-1} \qquad (2)$$

Proof sketch of (1): At the 1st hop, to forward a time-frame to the 2nd hop of that predefined route, a time-frame must be carried on 1 of r wavelengths or channels in which each channel has k different time-frames. Hence, there are kr scheduling choices for the 1st hop†. The following $(h-1)$ hops are all identical and there are only r possible schedules at each hop. Scheduling at all hops is independent. Therefore, the number of possible schedules is given by product of all the $(kr)_{1^{st}} \times (r)_{2^{nd}} \times \ldots \times (r)_{h^{th}}$ possible single hop schedules. $(.)_{h^{th}}$ is the contribution of h^{th} hop to the combinatorial result.

Proof sketch of (2): 1st hop-based component is equal to that of (1). For 2nd hop-based component, there are more options to forward a TF thanks to NIF. A TF can be switched immediately or buffered for k_b TF durations ($1 \le k_b \le b$), before being switched. Thus, for all hops except 1st one, there are rb options to schedule a TF. The final result is given by the product $(kr)_{1^{st}} \times (rb)_{2^{nd}} \times \ldots \times (rb)_{h^{th}}$.

3) Robustness and practical issues

Though FC-FλS has a simple design with low cost and low control overhead, a network deployed with FC-FλSs is subject to some disadvantages. First, it is hard to deploy different routing protocols since routing is rigid due to the nature of fixed internal connection network. In other words, it is impossible to separately account for the routing and

† Note that the definition of IF is actually meaningful from the second FλS-enabled switch only. We are analyzing FλP *setup*, so that the time-frame in the first hop can be chosen freely and will represent the IF constraint for subsequent hops.

wavelength assignment problem if FC-FλSs are deployed, since the wavelength assignment in one switch will determine the route in the next. Second, for IF scheme shown in (1), the scheduling flexibility of this design strongly depends on the connection ratio r.

B. Tunable laser with static wavelength router (WR-FλS)

1) Design and operation

A design using tunable lasers and wavelength router (WR) is depicted in Fig.4. The idea for this design builds on an OBS switch design in [10]. The key characteristic of this design is that different in-ports use different sets of channels, whose size is r and depends on the permutation pattern, to reach the same out-port. More specifically, in order to switch a time-frame received by $TL(i,j)$ to out-port m, $TL(i,j)$ must tune to one channel among r channels defined by the designed permutation pattern so that the transmitted time-frame can reach $MUX(i,m)$. Two common types for the selection of fixed permutation pattern are *contiguous wavelength selection* and *randomized wavelength selection* [10].

2) Hardware complexity and scheduling feasibility

WR-FλS requires CN tunable lasers, N modules of $C \times C$ static WRs. The scheduling feasibility of WR-FλS for both IF and NIF schemes are given in (3) and (4).

$$S_{WR}^{(IF)} = kCr^{h-1} = k\frac{C^h}{N^{h-1}} = k\left(\frac{C}{N}\right)^h N \tag{3}$$

$$S_{WR}^{(NIF)} = kC(rb)^{h-1} = kr^h b^{h-1} N = k\left(\frac{C}{N}\right)^h b^{h-1} N \tag{4}$$

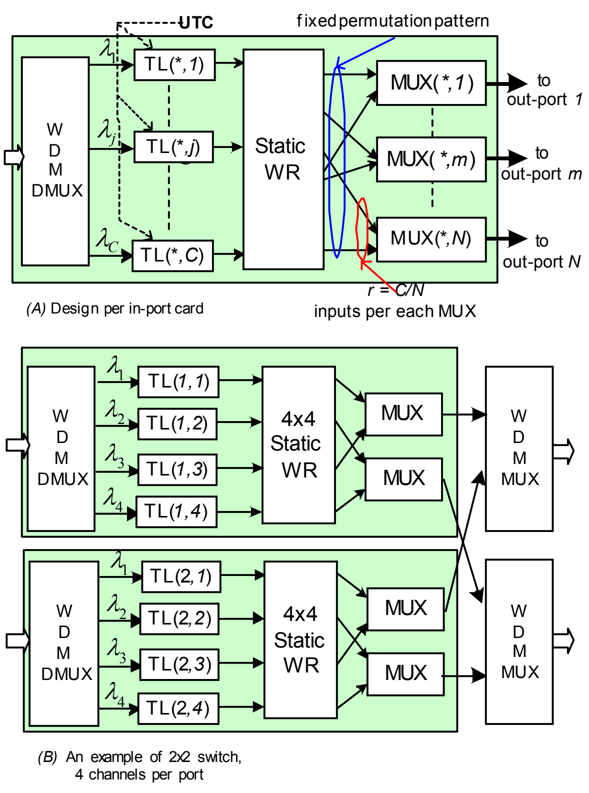

Fig. 4. (A) A design of WR-FλS, (B) a 2x2 switch (UTC signal is not shown).

Proof sketch of (3) and (4): The proof can be done following the same scheme used to prove (1) and (2) with the following modification made for the 1st hop. Using WR-FλS, there are always kC options to select a TF for the 1st hop, since no constraint on routing exists. For the 2nd to h^{th} hops, an incoming TF has only r options to reach a desired out-port, again assuming $R_T = C$. Therefore, the products of all hop-based components are given as $(kC)_{1^{st}} \times (r)_{2^{nd}} \times \ldots \times (r)_{h^{th}}$ and $(kC)_{1^{st}} \times (rb)_{2^{nd}} \times \ldots \times (rb)_{h^{th}}$ for IF and NIF, respectively.

3) Robustness and practical issues

WR-FλS is another simple design. Networks using WR-FλS has no constraint on routing since time-frame coming to an in-port can reach any out-port. WR-FλS has no internal conflict due to the switching nature of WR devices. However, the scheduling feasibility is still limited by the factor r.

C. Tunable laser with broadcast and select (BS-FλS)

1) Design and operation

The illustration for per-in-port and per-out-port card design of BS-FλS is shown in Fig.5. This design uses one tunable laser and one broadcast-and-select switching (BSS) component per channel. A BSS is fabricated by the combination of 1-to-N star-coupler (SC) and N simple ON/OFF switching elements.

$TL(i,j)$ of the in-port i receives the signal of λ_j and then can transmit using any channel in its tunable range. The transmitted signal from a laser is broadcasted to all out-ports using the star-coupler $SC(i,j)$ and it is allowed to reach a single out-port if and only if a corresponding ON/OFF element to that port is ON. The BSS design also enables

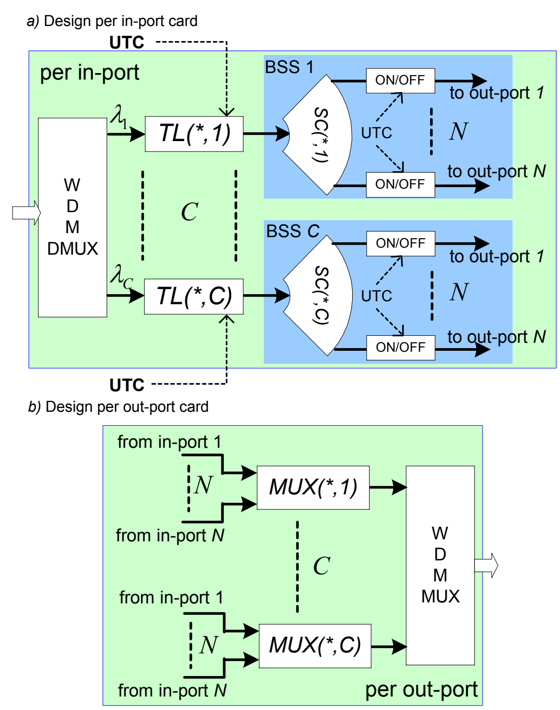

Fig. 5. BS-FλS architecture.

multicasting. All tunable lasers and ON/OFF elements are controlled and coordinated using the UTC signal. Each time-frame, a WDM-MUX allows a maximum C different channels to be multiplexed to the fiber.

A BS-FλS design allows a tunable laser to transmit time-frames to all out-ports. Moreover, BS-FλS has the advantage over WR-FλS that a tunable laser can transmit time-frames to any out-port using the full channel ranges C, while WR-FλS only allows to use the small fixed set of channels r. Thus, compared to WR-FλS, BS-FλS has a larger scheduling feasibility.

2) Hardware complexity and scheduling feasibility

The hardware requirements for BS-FλS design are: CN tunable lasers, CN star-coupler modules, CN^2 programmable ON/OFF devices.

The scheduling feasibility of BS-FλS design for both IF and NIF schemes are given in (5) and (6):

$$S_{BS}^{(IF)} = kC^h = k\left(\frac{C}{N}\right)^h N^h \quad (5)$$

$$S_{BS}^{(NIF)} = kC\left(Cb\right)^{h-1} = k\left(\frac{C}{N}\right)^h b^{h-1}N^h \quad (6)$$

Proof sketch of (5) *and* (6): For the 1st hop, there are kC options to schedule one TF, since every channel can later be routed following a predefined route. For the 2nd to h^{th} hops, a tunable laser can exploit all the C channels to transmit the signal. In fact, if available TFs are found at both incoming and outgoing channels, there is a path to schedule the transmission. Therefore, the product of all hop-based components for IF scheme is $(kC)_{1^{st}} \times (C)_{2^{nd}} \times ... \times (C)_{h^{th}}$, and for NIF schemes is $(kC)_{1^{st}} \times (Cb)_{2^{nd}} \times ... \times (Cb)_{h^{th}}$. Note that $S_{BS}^{(IF)}$ and $S_{BS}^{(NIF)}$ are independent from r. The right most expression is included only for comparison purposes with the other architectures.

In term of scheduling feasibility, the BS-FλS design gains N^h times compared to the WR-FλS design in both IF and NIF schemes.

Lemma 1: If using a single SC per in-port, then the utilization of the BS-FλS design reduces C times.

Proof sketch: Let us assume that all channels of an in-port share a single SC. Since SC is a broadcast device, meaning that a signal at a given input will broadcast to all outputs. At every time-frame, strictly one and only one signal can be fed to one of the inputs of SC, otherwise there is conflict. Hence, if all C tunable lasers of an in-port share the same SC, at every time-frame, only one of them is allowed to transmit, therefore, resulting in the reduction of the utilization of the design by C, compared to the design that deploys a single SC per tunable laser.

Lemma 2: If the ON/OFF element is not used, then a tunable filter can be used and scheduling feasibility is bounded:

$$kC\left(C'\right)^{h-1} \le S_{Filter}^{(IF)} \le k\left(\frac{C}{N}\right)^h N^h \quad \text{and}$$

$$kC\left(C'\right)^{h-1} b^{h-1} \le S_{Filter}^{(NIF)} \le k\left(\frac{C}{N}\right)^h b^{h-1}N^h$$

where $C' = (C - N - 1) \ge 0$.

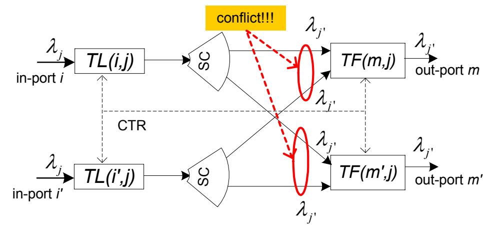

Fig. 6. One tunable filter replacing N ON/OFF switching elements.

Proof sketch: Assume that ON/OFF switches are removed and outputs of SC devices are connected to a tunable filter (TF), as shown in Fig.6, that is coordinately controlled by UTC signal. At a given time-frame t, $TL(i, j)$ is scheduled to transmit to out-port m and $TL(i', j)$ is scheduled to transmit to out-port m', both using $\lambda_{j'}$. Consequently, there are conflicts at both inputs of $TF(m, j)$ and $TF(m', j)$. Therefore, a given tunable laser can not freely selects channel to transmit to a given out-port, but has to watch out for the other tunable lasers that are connected to the same filter. There are N tunable lasers that share the same filter. Therefore, in the worst case, a given tunable laser has only $C' = (C - N - 1)$ channel options, since the other $(N-1)$ channels are used by the other tunable lasers. This yields $(kC)_{1^{st}} \times (C')_{2^{nd}} \times ... \times (C')_{h^{th}}$ for the IF scheme, $(kC)_{1^{st}} \times (C'b)_{2^{nd}} \times ... \times (C'b)_{h^{th}}$ for the NIF scheme.

3) Robustness and practical issues

BS-FλS is equivalent to a non-blocking crossbar switching fabric since it does not introduce internal blocking. A BS-FλS design also allows deploying multicast and broadcasting easily.

IV. DISCUSSION

Comparisons between designs are summarized in TABLE 1. Parameters to be compared include hardware complexity, scheduling feasibility and routing adaptability. Design components that are the same in all switch designs, such as WDM-MUX and WDM-DMUX are not shown in this comparison table. N_{TL}, N_{WR}, N_{SC}, N_{OO} stand for the number of TLs, $C \times C$ static WRs, 1-to-N SCs, ON/OFF switching elements, respectively.

To highlight the scheduling feasibility measure, we plot some graphs of $S^{(IF)}$ and $S^{(NIF)}$ versus the connection ratio $r = C/N$ (Fig.7), the hop number h (Fig.8) the buffer size b (Fig.9).

TABLE 1: Comparison between tunable laser - based FλS designs

	Hardware complexity				**Scheduling feasibility**		**Routing adaptability**
	N_{TL}	N_{WR}	N_{SC}	$N_{ON/OFF}$	IF scheme	NIF scheme	
FC- FλS	NC	--	--	--	$k\left(C/N\right)^{h}$	$k\left(C/N\right)^{h} b^{h-1}$	No
WR- FλS	NC	N	--	--	$k\left(C/N\right)^{h} N$	$k\left(C/N\right)^{h} b^{h-1}N$	Yes
BS- FλS	NC	--	NC	N^2C	$k\left(C/N\right)^{h} N^{h}$	$k\left(C/N\right)^{h} b^{h-1}N^{h}$	Yes

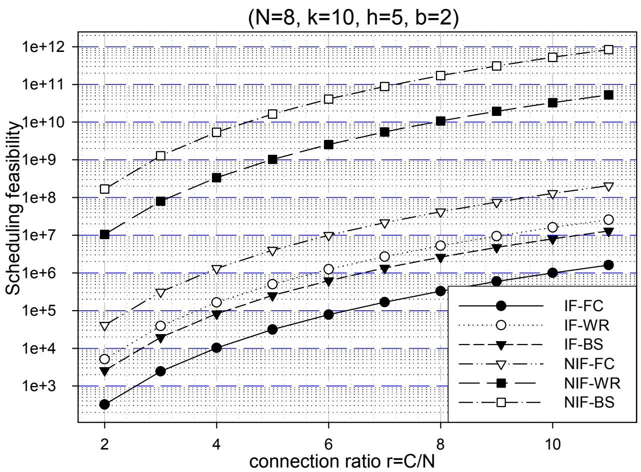

Fig. 7. Scheduling feasibility versus connection ratio.

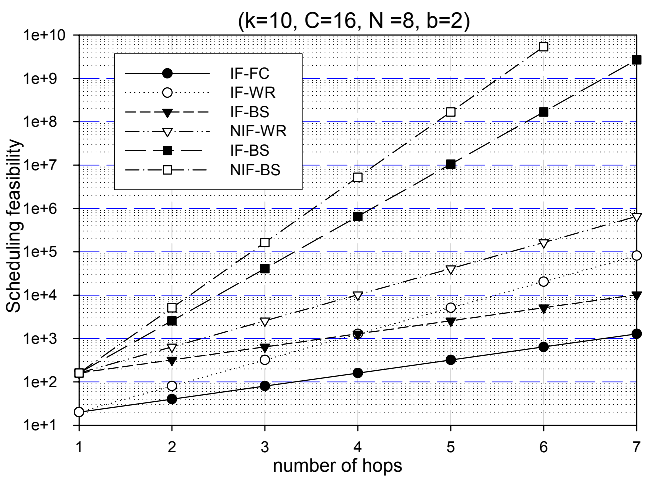

Fig. 8. Scheduling feasibility versus hop numbers.

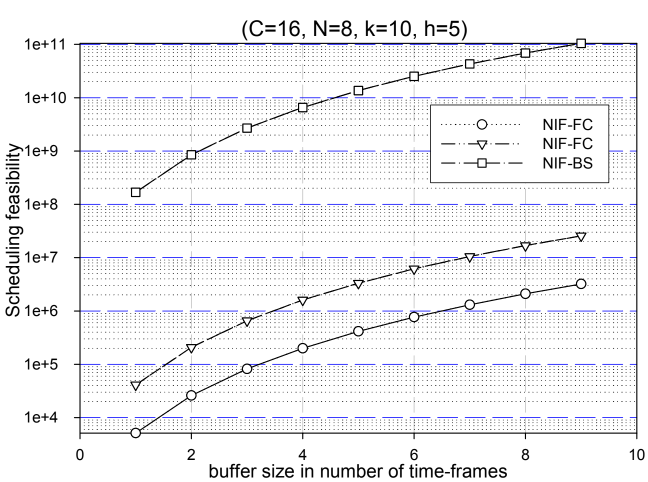

Fig. 9. Scheduling feasibility versus arbitrary NIF.

It is an easy conjecture that the higher the scheduling feasibility is, the less probable is that a time-frame is blocked at scheduling time. The mathematic relation between scheduling feasibility and blocking performance is one of the next steps of this work.

Moreover, the exponential growth of scheduling feasibility implies that optimum scheduling to fulfill the long-route FλP setup is not trivial. This is another research direction: proposing some heuristic algorithms with performance as close as possible to the optimum scheduling.

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