Tunable Laser-based Design and Analysis for Fractional Lambda Switches

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***Abstract*— Fractional Lambda Switching (FλS) is a novel approach for traffic management over all-optical networks with sub-wavelength provisioning capability. The unique characteristic of FλS is the utilization of UTC (Coordinated Universal Time) for switching with minimum or no buffers. Several central research issues are still open in FλS and need to be formally defined and analyzed. In this paper, we introduce three novel switch designs that are based on the use of tunable lasers (which can be replaced in the future with wavelength converters). First, the paper presents analytical results of *scheduling feasibility*, which measures the total number of possible different schedules for each switch design. Then it is shown that the architecture with the *highest scheduling feasibility* is *strictly non blocking* in the space domain. Next, the paper provides a closed form analysis of the blocking probability in the time domain, which is applicable for any strictly non-space blocking switch, using combinatorics. In addition, the paper provides measures of the switching hardware complexity, which, for the strictly non-blocking architecture, has the same switching complexity as Clos interconnection network, i.e., $O(N'\sqrt{N'})$ where N' is the number of optical channels.**

***Index Terms*— optical networks; sub-lambda switching; time-driven switching; tunable laser; scheduling; switch architectures; blocking probability; strictly-non blocking.**

I. Introduction

Multi-wavelength optical networks [1] have been the subject of research for many years. However, the typical optical switching bandwidth granularity has been the entire optical channel – i.e., the whole lambda (λ). Consequently, with such design it is only possible to allocate the whole optical channel (λ) capacity or nothing. Switching a whole optical channel is often (very) inefficient, since each optical channel has a capacity ranging from 2.5 Gbit/s to 40 Gbit/s and can accommodate a very large number of conventional IP sessions/connections. Thus, it is more bandwidth efficient if an optical channel can be partitioned into a number of sub-lambda or fractional lambda channels [2]–[5].

Fractional lambda switching (FλS) capability is important at the backbone (core) of the network, as well as in local and metropolitan area networks (LAN/MAN), since the access traffic is dynamic and requires only a fraction of the optical channel. Grooming (multiplexing) the traffic from multiple access points is essential in order to improve the throughput and reduce the operational cost of optical networks. The obvious solution is the implementation of asynchronous IP packet switching. However, asynchronous IP packet switching is not suitable for all-optical networking, it is not scalable and not efficient supporting streaming media and large file transfer applications. FλS, on the other hand, will efficiently support streaming media applications all the way to the end-user. It is envisioned that streaming media and large file transfers (for example, in grid computing) will constitute most of the Internet traffic and revenue growth.

The contribution of this paper in the field of communications goes in several directions. We define three technically feasible FλS switch architectures of increasing complexity, cost, and performances; we analyze the performance of all three architectures in terms of traffic schedulability, which measures the capability of an architecture to support high traffic loads; we show that the most powerful architecture is strictly non-blocking in the space domain (internal blocking), also showing that it has a switching complexity that is equivalent to the known Clos switching network; and finally, for this architecture, we provide a combinatorial analysis of the static (i.e., with given traffic pattern) blocking probability in the time domain.

The paper is organized as follows. In Section II, the basic principles of FλS are introduced, and specifically in Section II-C the concept of tunable laser based FλS is explained. In Section III, three novel tunable laser based FλS architectures are described and analyzed. The analysis focuses on scheduling feasibility as a measure of the system's capability of exploiting resources. In Section IV, we show that the design with the highest scheduling feasibility is a strictly non-blocking architecture in the space domain with complexity equivalent to a Clos network. In Section V, we present a combinatorial analysis of the blocking probability in the time domain. Section VI closes this work with discussions.

II. FλS - Basic Principles

A. FλS Timing Principle

Sub-lambda or fractional lambda switching (FλS) is an effort to realize highly scalable networks [2]–[5] requiring minimum buffers. FλS has similar general objectives as OBS and OPS: gaining higher wavelength utilization, and realizing all-optical networks. In FλS, a novel concept of *common time*

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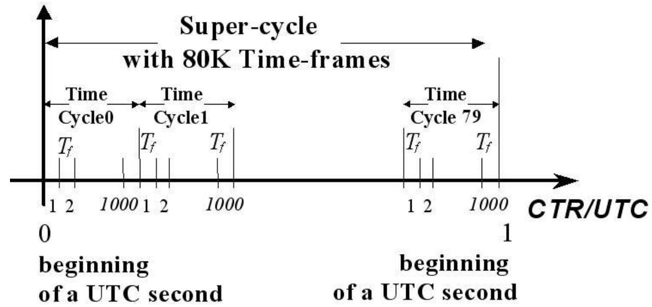
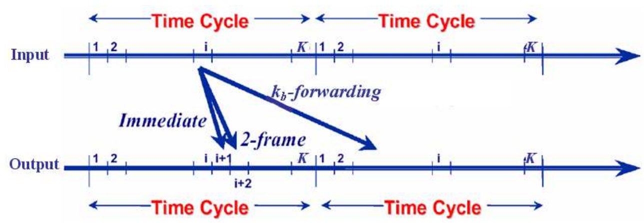


(a) A division of an UTC second in FλS



(b) Illustrations of IF and NIF in time domain

Fig. 1. FλS Principles.

reference using UTC is introduced. FλS utilizes a UTC second that is partitioned into a predefined number of time-frames (TFs). TFs can be viewed as virtual containers for multiple IP packets that are switched at every FλS node, based on and coordinated by the UTC. A group of K TFs forms a time-cycle; L contiguous time-cycles are grouped into a *super cycle*, as illustrated in Fig. 1(a). To enable FλS, TFs are aligned at the input ports of every FλS node before being switched. After alignment[1], the delay between inputs of any pair of nodes is an integer number of TFs, which is the necessary condition for pipeline forwarding. Pipeline forwarding is a known optimal method widely used in manufacturing and computing for latency and jitter minimization.

In a FλS network, a *fractional lambda pipe* (FλP) p is defined as a predefined allocation of resources (a schedule) for switching and forwarding TFs along a path of FλS nodes. The FλP capacity is determined by the number of TFs allocated in every time-cycle (or super cycle) for the FλP p. For example, for a 10 Gbit/s optical channel and K=1000, L=80 if one TF is allocated in every time-cycle or super cycle, the FλP capacity is 10 Mbit/s or 125 kbit/s, respectively.

B. FλS Forwarding Principle

FλS defines two possible types of forwarding. The first one is immediate forwarding (IF): upon the arrival of each TF to a FλS node, the content of the TF is scheduled to be "immediately" switched and forwarded to the next node. Hence, the buffer that is required is bounded to one TF 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 an optical buffer of B TFs at each input channel. The content of each TF arriving to the FλS node can be buffered for an arbitrary number k_b of TFs ($1 \leq k_b \leq B$) before being forwarded to the next node. Fig. 1(b) illustrates the IF and NIF schemes. NIF offers greater *scheduling feasibility* (see Section III for a definition) than IF. Increasing the feasibility and flexibility of scheduling is one of the main issues we discuss in this paper.

For example, assume that TF 5 within the TC is available at the inlet and TF 7 within the TC is available at the outlet, then with two optical buffers (or scheduling delay of two TFs) it is possible to forward the IP packets within TF 5 to the outlet at TF 7. The optical buffers operation is predictable and repeated in every time cycle, and therefore, such buffers can be easily implemented with optical fiber delay lines.

C. Tunable Laser Principle – Wavelength Swapping

We focus on FλS with tunable lasers [18] [19], since they are available with high performances. For instance, a 16-channel 100-GHz-spacing digitally tunable laser with 0.8 ns switching time between channels has been experimented [19]. In general, the way tunable lasers are used in this work is to change the wavelength (color) of TFs that contain IP packets at every FλS node. When wavelength converters will be available they may replace the tunable lasers, further simplifying the switches' architecture.

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 (color) 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 within the time-cycle.

D. Related Works

Recently, optical burst switching (OBS) [6] was proposed as a middle stage toward the realization of optical packet switching (OPS). A burst accommodates a large number of packets. In OBS networks, control packets are forwarded in a control channel to configure switching nodes before the arrival of the corresponding bursts, hence reducing the requirement of optical buffers. Though OBS is interesting and some protocols were defined for it [7] [8], 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 or even low. In general, an asynchronous optical packet switching network may be the ultimate goal for all-optical networking. However, two key technological hurdles should be overcome: (i) realizing large asynchronous optical random access memory and asynchronous optical packet header processing, and (ii) ensuring adequate optical power budget and signal to noise ratio.

[1]Alignment issues are not addressed in this work. Several open questions, such as the impact of varying temperature on the refractive index of the fiber link and the propagation delay, can be solved by a dynamic alignment subsystem. An introduction to the alignment subsystem can be found in [2].

FλS utilizes a Common Time Reference (CTR), which can be realized with UTC (Coordinated Universal Time). UTC provides phase synchronization and time-of-day with identical frequencies everywhere. In contrast, traditional TDM (time division multiplexing) systems, such as SONET/SDH, have neither phase synchronization nor identical frequencies. Thus, unlike UTC-based systems, traditional TDM systems are using only frequency (or clock) synchronization with known bounds on frequency drifts. There are major challenges for implementing SONET/SDH TDM in the optical domain. Nevertheless, in the past ten years there were a number of works on combining WDM with TDM [12]–[15]. None of these works used UTC with pipeline forwarding, as discussed in Section II, and they neither provided the necessary detailed analysis of critical timing issues. Specifically, the accumulation of delay uncertainties, jitter, and clock drifts is a major source of impairments, which is solved by using UTC with pipeline forwarding, as discussed in Section II-B.

In [12], an optical time slot interchange (TSI) utilizing sophisticated optical delay lines is described with no detailed timing analysis. In [13] and [14] two experimental optical systems with in-band master clock distribution and optical delay lines are described, with only limited discussion about timing issues. In [15] a system with constant delays and clocks is described, which can be viewed as a close model of what we define immediate forwarding, however, no timing analysis and no consideration of non-immediate forwarding are presented. Early results on how UTC is used in packet switching were published in [9]–[11].

More recently, the idea of utilizing UTC in order to forward bursts of data in optical networks was proposed in the TWIN architecture [16] [17]. TWIN proposes to use fast tunable lasers at the network edge nodes while the core switching nodes are selective wavelength routers. Each edge node is equipped with a unique wavelength receiver. When one edge node transmits to another edge node it tunes its tunable laser to the unique wavelength receiver of that node. The TWIN architecture requires network-wide scheduling algorithms in order to ensure that each unique tunable receiver receives only one transmission at a time. Consequently, TWIN has limited wavelength reuse, but can efficiently accommodate bursts that are larger than the end-to-end propagation delay. Thus, TWIN may be suitable for local area networks. It is also worthy to note that if the TWIN architecture operates with near zero propagation delay and source-destination route length is two (i.e., only one core node), it will be equivalent to the FλS tunable laser switch design (called WR-FλS) presented in Section III-B.

Albeit FλS is a *switching* architecture, it is also related to grooming and dynamic multiplexing. Comparing it to a traditional Optical Add/Drop Multiplexing (OADM) scheme, the main difference is that FλS does not interrupt the optical path, and does not introduce any un-necessary buffering delay, while OADM schemes imply interrupting the optical path and moving traffic back and forth in the IP domain.

III. Architecture and Scheduling Feasibility of FλS with Tunable Lasers

The goal of a switching architecture is keeping complexity and cost at a minimum level while providing high performance and low blocking probability for incoming new flows. We introduce three tunable laser based FλS switches and discuss their hardware cost and complexity, as well as their suitability for deploying flexible routing strategies.

The performance of flow-based switching is measured by blocking, which is due to two different phenomena in time driven switching. External- or time-blockingis the impossibility of finding a TF on a suitable optical channel (see Section V for a formal definition of time-blocking) on the proper output port to set up a FλP across the switch. Internal- or space-blockingis instead the impossibility of setting up the FλP due to internal constraints of the switch, although resources are available at the output port.

In this Section, the different tunable laser switch architectures are compared using: i) the hardware complexity, and ii) the performance in terms of scheduling feasibility as defined below. The scheduling feasibility directly influences space-blocking, although there is no explicit mathematical relationship between the two; in Section IV we demonstrate that the architecture with the highest scheduling feasibility is strictly non-space-blocking.

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 optical channels (colors) per optical fiber, which is associated with each input/output port;
- N is the number of input/output ports (or in-ports/out-ports for short) per switch;
- $r = C/N$ is the internal connection ratio; for simplicity it is assumed that r is integer;
- R_T is the tuning range of a tunable laser;
- K is the size of time-cycle in number of TFs;
- h is the route length of a FλP in number of hops.

Additionally we use the following acronyms to identify the building blocks of the architectures:

- MUX and DEMUX are wavelength multiplexers and demultiplexers; they operates between optical fibers with WDM channels and the in-/out-ports;
- TL is the tunable laser device with tuning range R_T that operates the λ swapping; TL(n, c) means the tunable laser connected to the c-th optical channel of in-port n;
- WR is a static wavelength router with fixed permutation pattern;
- SC is a star coupler, i.e., one-to-n broadcast device; SC(n, c) is the star coupled connected to the c-th tunable laser of in-port n;
- OO is an ON/OFF switching element; OO(n, c, n') is the ON/OFF switching element connecting in-port n with out-port n' using the tunable laser c;
- TuF is a tunable filter; TuF(c, n') filters the output of a star coupler c toward the out-port n'.

Definition: Scheduling Feasibility — For a generic FλS the scheduling feasibility is the number of *distinct schedules* that are available using time and wavelength swapping. The scheduling feasibility is a function of the forwarding method (IF or NIF), K, C and N, on a given route with h hops (where h is not a variable for feasibility measure).

A *schedule* is defined as a possible allocation of TFs and wavelength swapping along a given route so that a FλP can be setup. In fact, the scheduling feasibility is a relative (not absolute) measure of how resilient each tunable laser switch architecture is in face of different scheduling requests.

A feasible schedule is not guaranteed to be available at the time of FλP setup due to the space- or time-blocking (e.g., switching fabric limitation, contention between multiple setups); however, it is clear that the more the available schedules are, the less is the chance that it is not possible to find a non-blocked schedule. The switch architectures studied in this work have four key common parts:

1) WDM de-multiplexers on the in-port side;
2) WDM multiplexers on the out-port side;
3) Tunable lasers at the output of the WDM de-multiplexers;
4) A connection network between the tunable lasers and the WDM multiplexers at the out-ports, which is in essence what distinguishes the switch architectures discussed in this paper.

We define the following three switch architectures:

- *Tunable laser with fixed connection network* (FC-FλS): The fixed connection network consists of point-to-point links from tunable lasers to out-port 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 TF.

For the sake of simplicity, we do not show in figures how to implement buffering. In principle, a tunable laser behaves as an optical-electronic-optical conversion device. Specifically, the incoming optical serial-bit-stream is converted to an electronic signal that is used directly to modulate the tunable laser, and thereby, converted back to optical signal without "stopping" the serial-bit-stream. Thus, buffering can be done optically with programmable fiber-delay-lines. Note that this is only one possible tunable laser design.

A. Tunable Lasers with Fixed Connection Network (FC-FλS)

1) Design and operation: Fig. 2 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. DEMUX 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 out-port. The number of fixed connections between an in-port/out-port pair is equal to r, i.e., a switch with N=8 and C=16 has 2 fixed connections between any in-port/out-port pair.

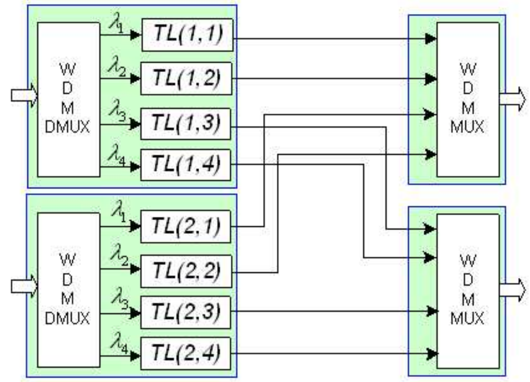


Fig. 2. An illustration of a 2 × 2 FC-FλS switch with C=4 (TLs are coordinated by UTC time signal, which is not shown).

Tunable lasers are tuned every TF, where TFs are derived from UTC, such that TFs are switched from in-ports to out-ports without conflicts at any out-port. Due to the nature of the fixed connection system, the color of a TF after switching defines the out-port, and hence, it defines the route it takes.

2) Hardware complexity and scheduling feasibility: The hardware complexity of this design is CN tunable lasers. Each in-port requires C tunable lasers, corresponding to C channels. The in-port DEMUX and out-port MUX devices are not counted in the hardware complexity since they are identical for all the designs described in this paper.

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

$$S_{FC}^{(IF)} = Kr^h = K\left(\frac{C}{N}\right)^h \tag{1}$$

$$S_{FC}^{(NIF)} = Kr^h B^{h-1} = K\left(\frac{C}{N}\right)^h B^{h-1} \tag{2}$$

Proof of (1): At the 1^{st} hop, to forward a TF to the 2^{nd} hop of the defined route, a TF must be carried on 1 of r wavelengths; each channel has K different TFs. Hence, there are Kr scheduling choices for the 1^{st} 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 the product $(Kr)_{1^{st}} \times (r)_{2^{nd}} \times ... \times (r)_{h^{th}}$ of all the possible single hop schedules. $(*)_{h^{th}}$ is the contribution of h^{th} hop to the combinatorial result.

Proof of (2): The 1^{st} hop contribution is equal to that of (1). For the other contributions, there are more options to forward a TF thanks to NIF. A TF can be switched immediately or buffered for up to B TFs, before being switched. Thus, for all hops except the 1^{st} one, there are rB options to schedule a

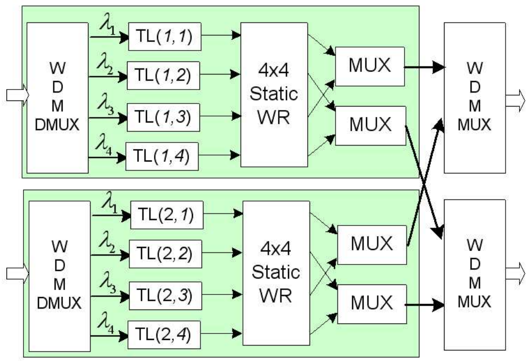


Fig. 3. An example of 2×2 WR-FλS switch where UTC time signal is not shown.

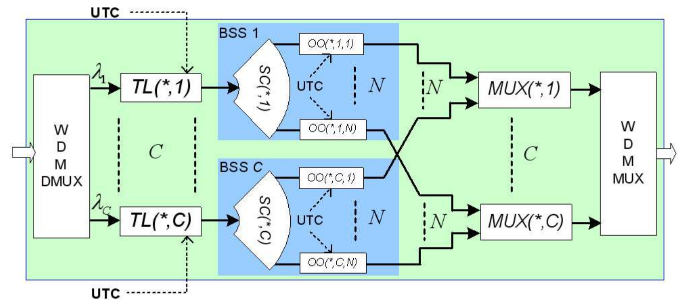


Fig. 4. BS-FλS, a strictly non-space-blocking architecture.

TF. The final result is given by the product

$$(Kr)_{1^{st}} \times (rB)_{2^{nd}} \times ... \times (rB)_{h^{th}}$$

3) Robustness and practical issues: Though FC-FλS has a simple design with low cost and low control overhead, a network implemented 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. Second, for the IF scheme the scheduling flexibility of this design strongly depends on the internal connection ratio r, as shown in (1), requiring many wavelength channels for good performance.

Finally, since the next hop output port is selected by choosing one of the proper wavelengths, the architecture is meaningful only for $R_T > N$, so that using limited tuning ranges ($R_T < C$) is hardly conceivable.

B. Tunable Lasers with Static Wavelength Router (WR-FλS)

1) Design and operation: An example of the design using tunable lasers and wavelength router (WR) is depicted in Fig. 3. The idea for this design is built on an OBS switch design described in [20]. 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 TF received by TL(n, c) to out-port n', TL(n, c) must tune to one among r channels defined by the designed permutation pattern so that the transmitted TF can reach MUX(n, n'). Two common types for the selection of fixed permutation pattern are *contiguous wavelength selection* and *randomized wavelength selection* [20].

Note that if the WR-FλS switch architecture is distributed, namely, if the TLs are connected to the WRs by long optical links, those TLs can be seen as edge nodes. Such TL edge nodes are similar to edge nodes in TWIN [16] [17]. Moreover, if out-ports of WR-FλS are also connected to a central WR by long optical links, a node that is similar to a core TWIN node is formed. Thus, we can infer that TWIN and a modified version of WR-FλS are similar.

2) Hardware complexity and scheduling feasibility: WR-FλS requires CN tunable lasers, N modules of $C \times C$ static WRs, and N^2 multiplexers at the output of the WRs. The scheduling feasibility of WR-FλS for both IF and NIF schemes are given in (3) and (4):

$$S_{WR}^{(IF)} = KCr^{h-1} = K\left(\frac{C}{N}\right)^h N \quad (3)$$

$$S_{WR}^{(NIF)} = KC(rB)^{h-1} = K\left(\frac{C}{N}\right)^h B^{h-1}N \quad (4)$$

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

3) Robustness and practical issues: Networks using WR-FλS have no constraints on routing, since TFs coming to an in-port can reach any out-port. The scheduling feasibility is still limited by r, which is a strong constraint to the scalability. Although routing is not limited, space-blocking is possible in this architecture.

A limited conversion range R_T can be taken into account using $r' = R_T/N$ instead of $r = C/N$ in all non first hop components, but for the formula to be exact r' must be integer.

C. Tunable Lasers with Broadcast and Select (BS-FλS)

1) Design and operation: The illustration of BS-FλS design is shown in Fig. 4. This design uses one tunable laser and one broadcast-and-select switching (BSS) component per channel. A BSS is composed by the combination of a single 1-to-N star-coupler (SC) and N simple ON/OFF switching elements.

TL(n, c) receives the signal of λ_c and then transmits using any channel in its tunable range. The transmitted signal from a laser is broadcast to all out-ports using the star-coupler SC(n, c) and it is allowed to reach a single out-port enabling the corresponding ON/OFF switching element to that port. The BSS design also enables multicasting. All tunable lasers and ON/OFF switching elements are controlled and coordinated using the UTC signal.

The BS-FλS design allows a tunable laser to transmit TFs to all out-ports. Moreover, BS-FλS has the advantage over

WR-FλS that a tunable laser can transmit TFs to any out-port using the full channel range C, assuming $R_T = C$, while WR-FλS only allows using the small fixed set of channels r. Thus, compared to WR-FλS, BS-FλS has a much 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 switching elements. The scheduling feasibility of BS-FλS design for both IF and NIF schemes are given in (5) and (6):

$$S_{BS}^{(IF)} = KC^h = K\left(\frac{C}{N}\right)^h N^h \tag{5}$$

$$S_{BS}^{(NIF)} = KC\,(CB)^{h-1} = K\left(\frac{C}{N}\right)^h B^{h-1}N^h \tag{6}$$

Proof of (5) *and* (6): For the 1^{st} hop, there are KC options to schedule one TF, since every channel can be routed following any predefined route. For the 2^{nd} 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 $(C)_{1^{st}} \times (C)_{2^{nd}} \times ... \times (C)_{h^{th}}$, and for NIF scheme it is $(C)_{1^{st}} \times (CB)_{2^{nd}} \times ... \times (CB)_{h^{th}}$. Note that $S_{BS}^{(IF)}$ and $S_{BS}^{(NIF)}$ are independent from r. The right most expressions in (5) and (6) are only for comparison purposes with the other architectures. As in the WR-FλS architecture, limited tunability can be accounted for using R_T in the derivation.

In terms of scheduling feasibility, the BS-FλS design gains N^h times compared to the WR-FλS design in both IF and NIF schemes. It is also worthy to highlight the following observations on this design.

Observation 1: Using a single SC per in-port, then the scheduling feasibility of the BS-FλS design reduces C times.

Let us assume that all channels of an in-port share a single SC. SC is a broadcast device, meaning that a signal at a given input is broadcasted to all outputs. At every TF 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 TF 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.

Observation 2: A tunable filter per out-port can be used in replacement of the CN ON/OFF switching elements. In this case the scheduling feasibility is bounded by:

$$KC\,(C')^{h-1} \le S_{Filter}^{(IF)} \le K\left(\frac{C}{N}\right)^h N^h$$

and

$$KC\,(C')^{h-1}B^{h-1} \le S_{Filter}^{(NIF)} \le K\left(\frac{C}{N}\right)^h B^{h-1}N^h$$

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

Assume that ON/OFF switching elements are removed and outputs of SC devices are connected to tunable filters (TuF), as shown in Fig. 5. At a given TF, TL(n,c) is scheduled to transmit to out-port n' and TL(m,c) is scheduled to transmit to out-port m', both using channel $\lambda_{c'}$. Consequently, there are conflicts at both inputs of TuF(n',c) and TuF(m',c). Therefore, a given tunable laser must coordinate with all the other $(N-1)$ tunable lasers that are connected to the TuF for transmitting to an out-port. 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 a lower bound of $(KC)_{1^{st}} \times (C')_{2^{nd}} \times ... \times (C')_{h^{th}}$ for IF scheme, and $(KC)_{1^{st}} \times (C'B)_{2^{nd}} \times ... \times (C'B)_{h^{th}}$ for the NIF scheme. The internal blocking due to conflicts in the TuF cannot be accounted for with combinatorial analysis, thus we can only give the upper and lower bounds of the scheduling feasibility.

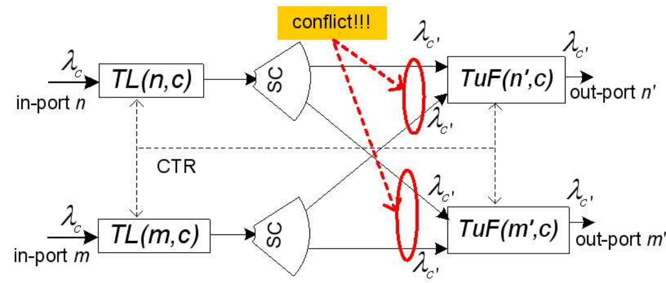


Fig. 5. One tunable filter replacing N ON/OFF switching elements produces internal conflicts.

3) Robustness and practical issues: BS-FλS is a *strictly non-blocking* design in the space domain (see the proof in Section IV). An incoming TF always finds the path to be forwarded to a desired out-port if a free corresponding TF is found at the outgoing channel. The BS-FλS design also allows deploying multicast and broadcast easily.

D. Comparison between Architectures

The comparison among the three switch designs is summarized in Table I. Parameters to be compared include hardware complexity, scheduling feasibility and optical routing adaptability. Optical routing adaptability indicates the freedom of changing the routing wavelength on the same optical fiber. For instance, the color of a TF coming to an in-port of a FC-FλS node will fit a unique next-hop of that TF no matter of how the corresponding TL is tuned. For a WR-FλS node, the next-hop of an incoming TF can be partially controlled depending on a fixed configuration of internal WRs. With a BS-FλS node, the next-hop for an incoming TF is fully controllable.

Design components that are the same in all switch designs, such as WDM-MUX and WDM-DEMUX 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.

Fig. 6 shows some plots of the scheduling feasibility $S^{(IF)}$ and $S^{(NIF)}$ of the architectures we presented, in order to graphically represent the performance behavior of the three architectures. The number of TFs per TC, K, as well as the optical buffer size B are kept small to avoid numerical problems, since both $S^{(IF)}$ and $S^{(NIF)}$ grows exponentially.

TABLE I

COMPARISONS BETWEEN TUNABLE LASER-BASED FλS SWITCH DESIGNS FOR A GIVEN h

Design	**Hardware Complexity**				**Scheduling Feasibility**		**Optical Routing Adaptability**
	N_{TL}	N_{WR}	N_{SC}	N_{OO}	IF scheme	NIF scheme	
FC-FλS	NC	- -	- -	- -	$K\left(\frac{C}{N}\right)^h$	$K\left(\frac{C}{N}\right)^h B^{h-1}$	None
WR-FλS	NC	N	- -	- -	$K\left(\frac{C}{N}\right)^h N$	$K\left(\frac{C}{N}\right)^h B^{h-1}N$	Partial
BS-FλS	NC	- -	NC	N^2C	$K\left(\frac{C}{N}\right)^h N^h$	$K\left(\frac{C}{N}\right)^h B^{h-1}N^h$	Full

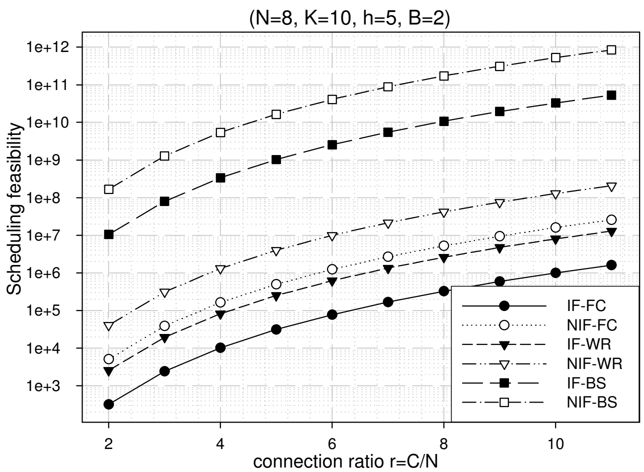


Fig. 6. Scheduling feasibility vs. connection ratio r.

As a first performance observation, notice that the number of possible FλP schedules is so large that proper signaling and heuristics must be found to exploit the resources of a FλS network. The second observation regards the relationship between available schedules and time-blocking. Although we are unable to provide a mathematical rule relating the scheduling feasibility with time-blocking, it is clear that for any given situation reducing the freedom in the schedule choice (i.e., reducing the number of available schedules) can only leave the situation unchanged or lead to block a pattern that would be otherwise unblocked. The inverse situation, where a blocked pattern is unblocked by removing available schedules, is absurd. The situation is well exemplified by (12) and (13) in Section V-A, where available schedules C_{avail} are reduced by load and not by the architecture. However, whatever the reason, reducing C_{avail} increases the time-blocking since the total number of schedules remains constant.

We have discussed how both the FC-FλS and WR-FλS architectures have limitations in optical routing adaptability, while the BS-FλS can support any routing algorithm. Later in the paper, we will show that the BS-FλS is strictly non-space-blocking and provide a combinatorial analysis of the time-blocking. FC-FλS and WR-FλS, instead, have internal blocking and their time-blocking performance is expected to be poorer, although the correlation between space-blocking and time-blocking makes a combinatorial analysis of the latter alone for the simpler architectures not possible.

IV. BS-FλS - A STRICTLY NON BLOCKING DESIGN IN SPACE DOMAIN

In this section, we focus on the more general BS-FλS design, since it was proved to have the highest scheduling feasibility in Section III. We formally prove that this broadcast-and-select design is strictly non-blocking in space domain. The formal definition of a strictly non-blocking FλS design in space domain is given in *Def.* 2 below. Intuitively, if there is available capacity at both in-port and out-port (i.e. free TFs to satisfy the IF scheme), but the switch can not configure itself to form a forwarding path (i.e. no more available resource in the fabric), we see it as a blocking event in the space domain.

We assume that at anytime there is at most one setup request to forward one TF from a given inlet and to a given outlet[2]. For the sake of clarity, we introduce the following notations:

- $tf_{n,c,k}$ denotes a TF k belonging to inlet c of in-port n.
- $tf'_{n',c',k'}$ denotes a TF k' belonging to outlet c' of out-port n'.
- $\{tf'_{n',c',k+1}\}$ denotes the set of all immediate-forwarding positions (i.e., $k' = k+1$) of out-port n', with the assumption $R_T = C$.

We give the following definitions:

Def. 1: Schedulable TF — A TF $tf_{n,c,k}$ is said to be *schedulable* if and only if $tf_{n,c,k}$ is free and at least one TF in the set $\{tf'_{n',c',k+1}\}$ is free. A TF $tf_{n,c,k}$ is said to be *schedulable to* $tf'_{n',c',k+1}$ if and only if $tf_{n,c,k}$ is *schedulable* and $tf'_{n',c',k+1}$ is *free*. Note that the definition is valid only for the IF scheme.

Def. 2: Strictly non-space-blocking FλS switch — A FλS switching fabric is considered *strictly non-blocking* in space domain if and only if any connection between a given in-port and a given out-port can be established immediately to forward an arbitrary *schedulable* TF without interference with any arbitrary existing connection.

Theorem 1: If a TF $tf_{n,c,k}$ is *schedulable to* $tf'_{n',c',k+1}$, then the forwarding path

$$\begin{aligned} fp \quad \models \quad & tf_{n,c,k} \to \mathrm{TL}(n,c) \to \mathrm{SC}(n,c) \to \\ & \mathrm{OO}(n,c,n') \to tf'_{n',c',k+1} \end{aligned}$$

is always successfully setup during TF k, without any interference with existing forwarding paths.

Proof: The proof is obtained by showing that violating the setup postulate, implies that $tf_{n,c,k}$ is NOT *schedulable to* $tf'_{n',c',k+1}$. To setup fp, all devices

[2]It is important to distinguish between an "in-port" and an "inlet", and between an "out-port" and an "outlet". In/out-port indicates the fiber port, whereas inlet/outlet indicates a single wavelength or optical channel.

$\big(\text{TL}(n,c),\ \text{SC}(n,c),\ \text{OO}(n,c,n')\big)$ involved in fp must be available during TF k.

Let us denote S_X^k the status of device X during TF k, that is:

$$S_X^k = \begin{cases} \text{`0'} & \text{if item } X \text{ is } \textit{busy} \text{ during TF } k \\ \text{`1'} & \text{if item } X \text{ is } \textit{free} \text{ during TF } k \end{cases}$$

- Assume $S_{TL(n,c)}^k =$'0' $\Rightarrow$ $tf_{n,c,k}$ is busy, it is not *schedulable* (violate the setup postulate).
- Assume $S_{SC(n,c)}^k =$'0' $\Rightarrow$ $S_{TL(n,c)}^k =$'0' $\Rightarrow$ $tf_{n,c,k}$ is not *schedulable*.
- Assume that during TF k, another tunable laser of a certain in-port has been scheduled to forward TF on channel c' to out-port n', i.e. $tf'_{n',c',k+1}$ is busy $\Rightarrow$ $tf_{n,c,k}$ is *schedulable* but NOT *to* $tf'_{n',c',k+1}$ (violate the setup postulate).

Therefore, we have $S_{SC(n,c)}^k =$'1' and $S_{TL(n,c)}^k =$'1', implying that $S_{OO(n,c,n')}^k =$'1' (i.e, available during TF k). Thus all elements evolved in forwarding path fp are available during TF k. In addition since the default status of ON/OFF switching element is OFF and only the scheduled ON/OFF switching element is ON, setting up fp does not interfere with other existing FλPs. ■

A $tf_{n,c,k}$ is *schedulable* only if it is *schedulable to* at least one TF belonging to the set $\{tf'_{n',c',k+1}\}$, the above theorem implies that a BS-FλS is strictly non-space-blocking.

Corollary — Equivalency with Clos interconnection network complexity: If $N = C$ then it implies that the number of inlets/outlets of the switch is N'=NC=N^2. Therefore the hardware complexity in number of ON/OFF switching elements of the BS-FλS design is CN^2=$N'\sqrt{N'}$, which is the same as a Clos interconnection network [21] with N' inlets/outlets.

This result is significant since the Clos interconnection network is known to have the lowest switching complexity for strictly non-blocking switch matrices. Note that the equivalence is meant only for the number of active switching elements, since the passive optical broadcast cost cannot be quantified in the sense of switching complexity.

V. Blocking Probability in Time Domain - A Combinatorial Analysis

So far we have discussed the architecture and complexity of FλS switches, as well as their performances in terms of scheduling feasibility that describe their potentiality to achieve high throughput, demonstrating that the BS-FλS design is strictly non-blocking in space. The ultimate goal of connection-oriented switches is however the minimization of blocking probability as a function of the load, i.e., time-blocking in the notation of this work. We only tackle the problem for the BS-FλS design because of its intrinsic interest as non space-blocking architecture and because the intertwining of space-blocking and time-blocking in the other architectures makes the task forbidding. We also restrict the analysis to the IF scheme, in part because of complexity, and in part due to its technical feasibility. We are interested in blocking properties that do not require existing traffic reconfiguration.

Traditionally, the term 'call blocking' is used in many works on blocking analysis (e.g., [22]–[25]). 'Call rejection' is considered as an event when no more network resources (e.g., circuits in telephony or radio channels in wireless) can be allocated in order to successfully establish a new call. Thus, an analysis of 'call rejection' probability is called 'call blocking' probability analysis. When analyzing 'call blocking' probability, traffic patterns and stochastic distributions are taken into account.

However, in this work, we do not study the blocking probability at the call level. A blocking in the time-domain occurs even when there are available network resources (i.e., available TFs) at both inlet and outlet of a FλS switch. A time-blocking occurs not due to running out of transmission resources, but because no schedule can be found to properly allocate available resources (i.e., a sequence of free TFs), and this explains the relationship between available schedules an time-blocking.

We assume a switch in isolation, but consider its load as part of a FλP, so that we deal with both input and output resources and compute the time-blocking by counting the number of non feasible schedules versus the total number of schedules given an identical but uncorrelated load pattern in input and output. The following combinatorial analysis is valid not only for the BS-FλS design but also for any strictly non space-blocking FλS switch. First we compute the time-blocking in case of a single channel per port, then we extend it to C channels per port.

A. Single Switch Analysis

We assume the switch is part of a large network which enforce independence of each channel, thus we can examine a single channel of the switch. Assuming independence between nodes, we use the following model for the traffic load.

Load assumptions — The load is defined as the number of busy TFs per time-cycle per channel. The symbol b denotes the number of busy TFs per time-cycle. For all channels, the busy TFs within each time-cycle is assumed to be distributed uniformly. Thus, the probability that a TF is busy is b/K and the probability that a TF is available is $(K-b)/K$ (where K is the number of TFs in each time-cycle). The load of an inlet/outlet is identified as (K,b).

In the analysis it is further postulated that $i)$ the number of busy TFs b is identical for all inlets and outlets, and $ii)$ the distribution is independent, i.e., the TF distribution of the inlet is independent from the one of the outlet. This later assumption is rather restrictive for small switches, but can be reasonable for large ones.

Def. 3: Single channel time-blocking probability — For a given inlet/outlet pair of a generic strictly non-space-blocking FλS switch with identical and independent load distribution (K,b), the single channel time-blocking probability p_b is defined as the probability that no *schedulable* TFs is found between the inlet/outlet pair.

Def. 4: Scheduling availability — For a given load (K,b), the *scheduling availability* p_a is the probability that at least one *schedulable* TF is found; $p_a = 1 - p_b$.

Def. 5: Overlap TFs — TFs tf_k and tf'_{k+1} are said to overlap if they are busy in both the inlet and the outlet, i.e.,

tf_k and tf'_{k+1} are busy.[3]

Given (K, b), the total number of different combinations C_{total} is:

$$C_{total} = \binom{K}{b} = \frac{K!}{b!(K-b)!} \tag{7}$$

For an arbitrary combination of inlet and outlet, let us denote:

- o : the number of *overlap* TFs.
- s : the number of *schedulable* TFs.
- $a = K - b$: the number of available TFs per time-cycle.

(*Def.* 1) and (*Def.* 5) imply that the number of *busy but not overlap* TFs $(b - o)$ of the inlet/outlet must be equal to the number of *available but not schedulable* TFs $(a - s)$ of the outlet/inlet. Therefore, we have $b - o = a - s$, or:

$$o = b - a + s = 2b + s - a - b = 2b + s - K \tag{8}$$

Given (K, b), the maximum number of *schedulable* TFs is $s_{\max} = a = (K - b)$. We have $o_{\max} = (2b + K - b - K) = b$. In order to compute the scheduling availability we have to ensure that there are *schedulable* TFs, thus we set $s_{\min} = 1$. This implies $o_{\min} = (2b - K + 1)$. Therefore, we have:

$$o_{\min} = (2b - K + 1) \le o \le o_{\max} = b \tag{9}$$

Lemma 1: If $b \le \lfloor (K-1)/2 \rfloor$, then $s \ge 1$, i.e., there is always at least one available schedule for any available TF on the inlet.

Proof: We consider the worst case where $b = \lfloor (K-1)/2 \rfloor$. The worst combination happens when the positions of b busy TFs of the inlet superimpose the $a = (K - b) > b$ positions of the outlet. For this worst case, we still have $s = (a - b) \ge 1$ *schedulable* TFs. ■

Lemma 1 implies that it is meaningful to compute the time-blocking probability only for the range $\lfloor (K-1)/2 \rfloor < b < K$.

Next, we compute the number of different combinations $C(o)$ as a function of the *overlap* TFs, o:

$$C(o) = \binom{b}{o}\binom{K-b}{b-o} \tag{10}$$

From (9) and (10), we derive the number of different combinations that forms at least one *schedulable* TFs, C_{avail}:

$$C_{avail} = \sum_{o_{\min}}^{o_{\max}} C(o) = \sum_{o=2b-K+1}^{o=b} \binom{b}{o}\binom{K-b}{b-o} \tag{11}$$

where $b > \lfloor (K-1)/2 \rfloor$.

Thus, from (7) and (11), the probability that at least one *schedulable* TFs is found, or the *scheduling availability* p_a is given by:

$$p_a = \frac{C_{avail}}{C_{total}} = \sum_{o=2b-K+1}^{o=b} \binom{b}{o}\binom{K-b}{b-o} \Big/ \binom{K}{b} \tag{12}$$

[3]Since we analyze only one inlet and one outlet in isolation, we simplify the notation by removing n, c, n', c'

and the time-blocking probability for a single inlet/outlet, p_b, is given as:

$$p_b = 1 - p_a = 1 - \sum_{o=2b-K+1}^{o=b} \binom{b}{o}\binom{K-b}{b-o} \Big/ \binom{K}{b} \tag{13}$$

B. Multi-channel Analysis

Def. 6: Multi-channel time-blocking probability — For a given in-port/out-port pair of the switch, each one with C channels with identical and independent load distribution (K, b) on all channels, $P_b(C)$ is the probability that no *schedulable* TF is found between the port pair.

The result given in (13) is extended for a multi-channel non-blocking switch. A BS-FλS switch is characterized by N, C. Since the load distribution (K, b) is identical and independent for all inlets and outlets, we have:

$$P_b(C) = \prod_{i=1}^{C}\prod_{j=1}^{C} p_b(i,j) = (p_b)^{C^2} \tag{14}$$

where $p_b(i,j) = p_b$ for all $i, j = 1, .., C$.

Proof: The proof of (14) is straightforward. Observing that for C optical channels per port there are C^2 combinations to select inlet/outlet pair. Since the load distribution is identical and independent on all channels, any combination of inlet i and outlet j, where $i, j = 1, .., C$, has the same time-blocking probability. That is $p_b(i,j) = p_b$ where p_b is given in (13). ■

Notice that the product form of (14) is in principle valid also if the traffic loads are not identical, provided that they are independent; however, since we consider all possible inlet/outlet pairs, the only way to obtain i.i.d distribution is by assuming that the load is (K, b) on every inlet or outlet. The rational idea in considering all inlet/outlet pairs is that at connection setup there is freedom in the switch resource assignments, so that all possible combinations are valid and the resources occupied by the incoming traffic are not fixed *a priori*. This does not take into account the correlation between subsequent switches in the same FλP, which is outside the scope of this paper that deals with the switch architectures.

Some numerical results, for different values of K and C, of the analysis in (14), are illustrated in Figs. 7 and 7. It is clear that the time-blocking probability is reduced for higher K and C.

VI. Discussion

In this work we presented three switch architectures for fractional lambda switching paradigm. They use tunable lasers (and in the future wavelength converters). As it was shown, the use of tunable lasers has similar attributes, in the optical domain, to label swapping in the space domain. Three switch architectures were presented: (1) Fixed Connection (FC-FλS), (2) Wavelength Router (WR-FλS) and (3) Broadcast and Select (BS-FλS). While the second architecture can be seen as an equivalency to TWIN, the first and last architectures are entirely novel and most interesting due to their characteristics.

The first architecture, FC-FλS, is fabric-less, since it has no optical switching element. However, FC-FλS is limited as

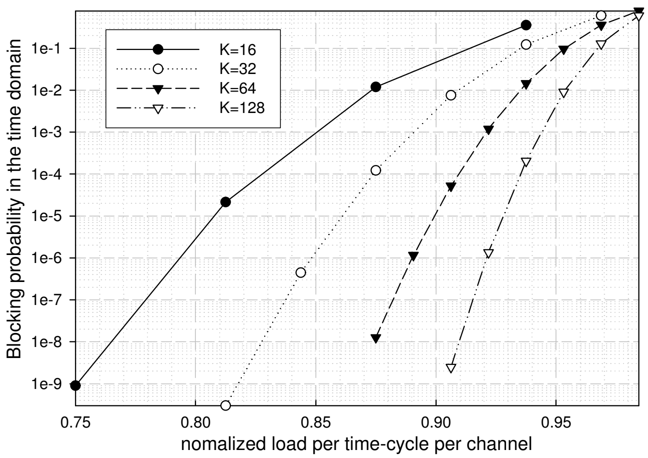


Fig. 7. Numerical results of the analysis for fixed C=4, while K varies.

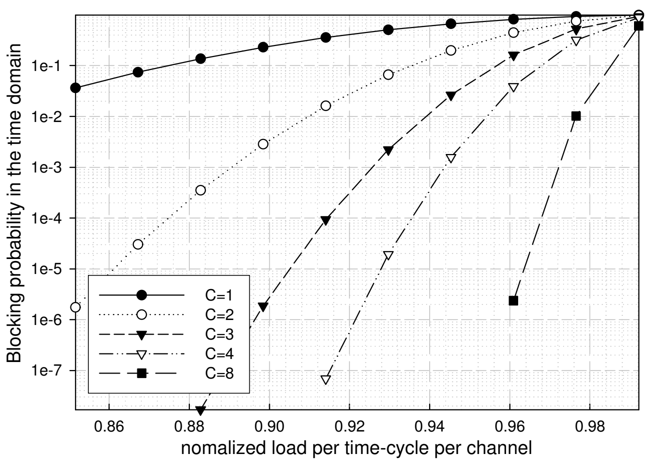


Fig. 8. Numerical results of the analysis for various fixed K=128, while C varies.

indicated by the scheduling feasibility measure and it does not allow for flexible routing. The last architecture, BS-FλS, has been shown to be strictly non-blocking with a hardware switching complexity that is equivalent to Clos interconnection network (when $C = N$), which is the minimal complexity for strictly non-blocking architectures. The BS-FλS architecture requires only simple 1-by-2 switching elements. Furthermore, regarding the optical power budget, the BS-FλS has two desirable attributes: (i) equal power distribution and (ii) low insertion loss, e.g. for $N = C = 32$ (an optical switch with 1024-by-1024 optical channels) the power loss is $3\log_2 32 = 15$dB. (This is the broadcast loss over the 32-by-32 passive optical star.)

Using combinatorial analysis, we provided a close form of time-blocking probability to measure the probability that time-frames are available at the in-port and at the out-port but not at the same position within the time-cycle.

There are several directions in which we intend to extend our research, some examples are:

- Finding blocking probability along a path of two or more nodes with (i) immediate forwarding and (ii) non-immediate forwarding.
- Finding blocking probability when the switching fabric is blocking, e.g. Banyan network. In this case the blocking probability can be due to blocking within the switching fabric.
- Finding efficient ways to select the schedule along a path of nodes with non-immediate forwarding. As was shown the number of possible schedules grows exponentially with the length of the path (number of hops).

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