Ultra Scalable Optoelectronic Switching Fabric for Streaming Media over IP

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Abstract

As data traffic on the Internet continues to grow exponentially, there is a real need to solve the switch bottleneck by developing ultra-scalable switching fabrics. Although in recent years there have been a lot of efforts to solve the switching fabric scalability problem, in the optical domain, the proposed solutions have been (very) expensive, (very) complex and (much) larger than electronic switching fabric alternatives. Unfortunately, electrical interconnection of existing (off-the-shelf) electronic switching devices is very difficult due to wave reflections on transmission lines, impedance mismatching, crosstalk and noise. Consequently, electronic switching with electrical interconnections has major scalability limitations. Thus, the question is whether and how optical interconnects can be used to link off-the-shelf electronic switching devices in order to develop optoelectronic switching fabrics that can scale up to 10-100 terabit per second (Tb/s) capacity in a single chassis. In order to further increase the scalability of the proposed novel optoelectronic switching fabric a UTC-based (coordinated universal time) time driven switching or fractional lambda switching (FλS) architecture is proposed. This novel low-complexity switching architecture capitalizes on the ubiquitous of UTC from GPS and Galileo. FλS architecture is especially suitable to support high capacity streaming media applications over the Internet.

Keywords-optical networks; optical switching, sub-lambda switching; fractional lambda switching, time-driven switching, optical interconnect, scheduling, streaming media (key words)

I. Introduction

Despite recent slow-down in the telecom industry, the Internet traffic is still doubling roughly 12-18 months. Driven by the proliferation of services such as online interactive entertainment, voice/video/TV over IP and various other real-time streaming media applications, the high-speed Internet access to homes and businesses is becoming a reality. These new applications are projected to be a major source of revenue growth in the networking businesses. Thus, streaming media applications are the main driving force determining the technologies that should be adopted to ensure the continuous profitability of the telecom business.

This paper proposes a low cost optoelectronic switch design. The switch architecture guarantees deterministic QoS for streaming media over the Internet and is scalable to 10-100 Terabit per second. In order to achieve such performance pipeline forwarding of IP packets is used (see Section II). Pipeline forwarding is a method known to provide optimal performance independent of specific implementation. Invented by Henry Ford, pipeline forwarding is still the most efficient manufacturing process today. All computers today operate using pipelines, a simple extension of Ford's assembly line.

Optical transmissions in the form of wavelength division multiplexing (WDM) have allowed a huge capacity increase. While WDM solves the link bottleneck, the continuous exponential traffic growth, which has to be routed through the Internet backbone, constitutes a major switching bottleneck. The only possible exception is whole wavelength (or lambda) switching, which allows the provisioning of a whole wavelength (WDM optical channel) between source and destination. The whole lambda switching approach suffers from poor scalability, since it requires $O(N^2)$ lambdas, where N is the number of access nodes. Consequently, the whole wavelength switching approach is inefficient (i.e., wasteful) and expensive in the manner in which WDM optical channels are used.

In order to achieve switching size and wavelength scalability while minimizing the number of wavelengths per link, a hybrid design is proposed with low cost optoelectronic switching fabric. Using this novel switching architecture, capitalizing on the availability of global time, it is possible to satisfy the continuous growth in bandwidth demand and to guarantee a deterministic quality of service and thereby to solve the Internet packet switching bottleneck. The proposed approach combines

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electronic switching elements with optical interconnects. Though optical interconnects is receiving renewed interest in recent years [1][2] using such interconnects for IP switching received little attentions. The potential benefits of optical interconnect for ultra scalable switching in discussed in Section III. Section IV discusses the use of pipeline forwarding for streaming media over the Internet.

I.A Related Works

Optical burst switching (OBS) [7], was proposed as a middle stage towards the realization of optical packet switching (OPS). A burst accommodates a possibly large number of packets. In some OBS designs, control packets are forwarded in a control channel to configure switching nodes before the arrival of corresponding bursts, hence reducing the requirement of optical buffers. Though OBS is interesting and some protocols were defined for it [8][9], 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. Besides, grooming traffic into bursts at ingress nodes of OBS networks is another difficult issue. In general, an asynchronous optical packet switching network may be the ultimate goal for all-optical networking. However, two key technologies have still long way for maturity: realizing asynchronous optical random access memory and asynchronous optical packet header processing.

Fractional lambda switching (FλS) utilizes common time reference (CTR), which can be realized with UTC (coordinated universal time). UTC provides phase synchronization or 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 systems with UTC, TDM systems are using only frequency (or clock) synchronization with known bounds on frequency drifts. Early results on how UTC is used in packet switching were published in [10][12]. In addition, there are major challenges for implementing SONET/SDH TDM in the optical domain. Nevertheless in the past ten years there were number of works on combining WDM with TDM [13]-[15]. None of these works was using UTC with pipeline forwarding, as discussed in Section II, and lack of the detailed treatment of critical timing issues. Specifically, regarding the accumulation of delay uncertainties or jitter and clock drifts, which is solved by using UTC with pipeline forwarding.

In [13], an optical time slot interchange (TSI) utilizing sophisticated optical delay lines is described with no detailed timing analysis. In [14] and [15] 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 to immediate forwarding (see Section II.B), however, no timing analysis and no consideration of non-immediate forwarding (see Section II.B).

II. FλS - Basic Principles

II.A FλS Timing Principle

Sub-lambda or fractional lambda switching (FλS) was proposed as an effort to realize highly scalable dynamic optical networking [3]-[6], which requires minimum optical buffers. FλS has the same general objectives as in OBS and OPS: gaining 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 (TFs). TFs can be viewed as virtual containers for multiple IP packets that are switched at every FλS switch, based on and coordinated by the UTC signal. As shown in Figure 1, a group of K TFs forms a time-cycle (TC); L contiguous time-cycles are grouped into a super cycle (SC), for example, in Figure 1, $K=1000$ and $L=80$. To enable FλS, TFs are aligned at the inputs of every FλS switch before being switched. After alignment, the delay between any pair of adjacent switches is an integer number of TFs, as discussed in Section III.C.

The central element of FλS is the method of pipeline forwarding with the necessary requirement for common time reference – e.g., UTC. In FλS, a fractional lambda pipe (FλP) p is a predefined schedule for switching and forwarding TFs along a path of subsequent FλS switches. 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 Gb/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 Mb/s or 125 Kb/s, respectively.

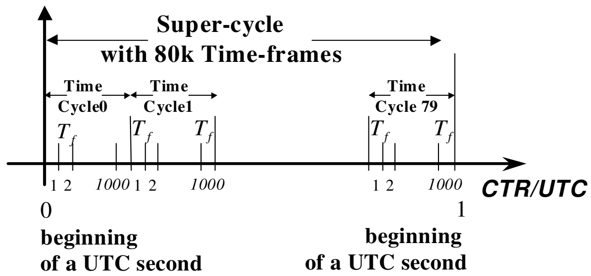


Figure 1. Division of an UTC second in FλS

II.B FλS Forwarding Principle

FλS defines two possible types of forwarding, as shown in

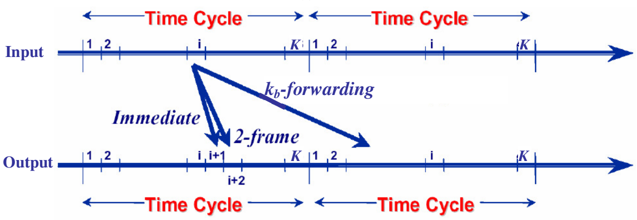


Figure 2. The first one is immediate forwarding (IF): upon the arrival of each TF to an FλS switch, the content of the TF (e.g., IP packets) is scheduled to be “immediately” switched and forwarded to the next switch during the next TF. Hence, the buffer that is required is bounded to one TF and the end-to-end transmission delay is minimized.

The other type of packet forwarding is called non-immediate forwarding (NIF). NIF requires buffers at FλS switches. Let us assume that, at each switch, there is a buffer of B TFs at each input channel. The content of each TF arriving to the FλS switch can be buffered for an arbitrary number k_b of TFs ($1 \le k_b \le B$) before being forwarded to the next switch. NIF offers greater scheduling feasibility than IF.

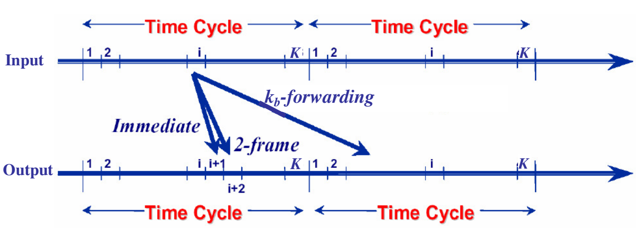


Figure 2. Illustration of IF and NIF in time domain

II.C Switch Architecture

Figure 3 shows the general architecture of an FλS switch. The optical alignment system shown therein operates on all the wavelengths carried by each optical fiber. The optical alignment system is based on a programmable optical delay line guaranteeing that the overall delay experienced through the optical fiber and the delay line is an integer number of time frames. As a result, when data units—that have left the switch at the transmitting end of the fiber aligned with UTC—arrive at the WDM DMUX at the receiving end they are still aligned with respect to UTC. The alignment system comprises a controller that detects time frame delimiters and adjusts the delay by using a programmable optical delay line (note that the alignment changes only when the propagation delay on the optical link changes).

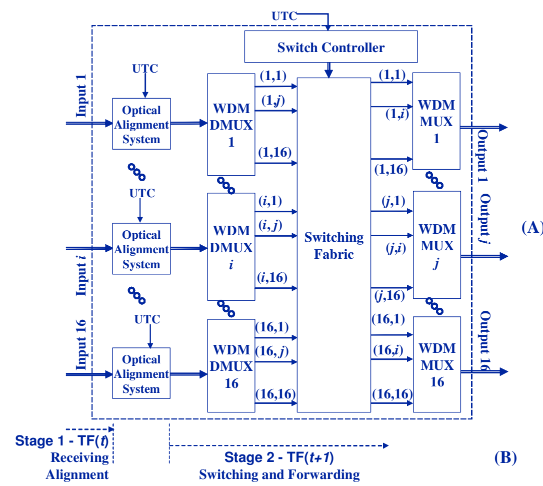


Figure 3. Optical Fractional λ Switch Architecture

III. Why FλS is Ultra Scalable

To cope with the present Internet growth rate, an IP routing capacity of multi Tb/s is required. Existing architectures can handle a maximum load of about only one Tb/s (in a single chassis), however much higher switching capacities are required. To get beyond the limitations of conventional electrical switch technologies, alternative architectures based on optical interconnects are proposed (see, for example, [1][2]). Optical interconnects allow, at least in principle, any desired interconnection topology without introducing crosstalk, thus minimizing noise sources. On the other hand, electrical switching with electrical interconnects cannot support the huge information flow from optical networks, while suffering from increased wire resistance, residual wire capacitance and inter-wire crosstalk as the length and/or the density of the electrical interconnections increases.

Given the clear limitations of both "all-optical" and "all-electrical" switching approaches, we briefly introduce a hybrid switching solution that is a "best-of-breed," since it combines the best of:

1. Electronic based switching (and buffering) with
2. Optical interconnects

In order to understand the rationale of this optoelectronic FλS architecture the discussion is divided into three parts:

1. Section III.A is brief comparative analysis of electric wires versus optical interconnections, in order to motivate why it is desired to use optical interconnection.
2. Section III.B is a brief discussion of the switching fabric topological design used for FλS and is based on Banyan interconnected network. Banyan has the lowest switching complexity but suffers from blocking. Though, beyond the scope of this paper, the use of FλS eliminates many aspects of this blocking problem [17].
3. Section III.C is a brief discussion of the buffering issue in packet switching. First it is explained that FλS minimizes the switch buffer requirements while using electronics, rather than optics, further reduces the complexity of the switch buffer implementation.

III.A Why Optical Interconnections

Summarizing, some of the problems that are typically associated with electric wire interconnection are stated in the following:

- A high wire resistance is responsible for large losses. Moreover, the resistance limits the signal rise time and consequently the channel capacity.
- When the length of electrical interconnection increases, effects such as overshoot, delay increase, and inductive crosstalk become critical.
- The problem associated with interconnect delay, cannot be solved by shrinking the whole system, as the RC time constant does not scale down when miniaturizing the architecture.
- As the interconnection wire density increases, sophisticated manufacturing and packaging techniques are required.

On the other hand, optical interconnections have the potential to facilitate the following. Optical transmission lines, whether guided or free space, exhibit a small amount of losses in comparison with traditional electrical wires:

- The non-interacting nature of free space optical channels allows the design of low noise, crosstalk free interconnections.
- The low interacting nature of guided optical channels allows the design of high density, low power loss, low noise, and low crosstalk interconnections.
- The ability of optoelectronic devices to be optically matched while still providing no electrical wave reflections, allows reducing power dissipation.
- The density of optical interconnects is only limited by the maximum allowed power dissipation.
- Complete electrical isolation that avoids multitudes of noise sources (e.g., ground loops) and in turn provides the capability for interconnecting a very large number of electronic switching elements (or cross-connects) without increasing in any way the overall system noise.
- Because the bandwidth of the modulated carrier can be up to a few percent of the carrier frequency, optical interconnections allow an information capacity 10,000 larger than that carried by electrical systems.

No physical breakthrough is required to design dense optical interconnects, although there are many technical challenges. The advantages offered by optical interconnections do not preclude conventional electrical interconnections as well. In order to make the best of both approaches, switches should be designed by using electrons for switching data, and photons to deliver data.

III.B Optoelectronic Switching Fabric Design

In order to maximize the switching fabric scalability it is necessary to minimize the switching fabric complexity. The lowest complexity fabric are multistage Banyan interconnection networks, with switching complexity of O(a*N*$lg_a N$), where N is the number of input/output and a is the size each switching block.

Switching elements	Multistage $a*N*\lg_a N$	Crossbar N^2	
For N=256, a=4	4K	64K	(factor of 16)
For N=1024, a=4	20K	1,000K	(factor of 50)

Figure 4, is a switching complexity comparison between a multistage Banyan and a crossbar.

Switching elements	Multistage $a*N*\lg_a N$	Crossbar N^2	
For N=256, a=4	4K	64K	(factor of 16)
For N=1024, a=4	20K	1,000K	(factor of 50)

Figure 4: Switching fabric complexity

The main disadvantage of Banyans is *space blocking*, which means that a connection between an available input and an available output may not be possible because there is no available pass (route) through the switch interconnection network.

One of the interesting properties FλS is that it significantly reduces the blocking phenomenon of Banyan based switching fabrics. Intuitively, In order to connect an available input to an available output there is another degree of freedom in the time domain. Namely, it is possible to select one of the *K* time frames (TFs), which mean that there are *K* possible choices. Figure 5 shows the blocking of a Banyan as a function of the number time frames, *K*, per time cycles: *K* = 1, 4, 16, 32, 64 and 1000. Clearly, as the number of time frames per time cycle increases the blocking probability decreases (see a more detailed performance study in [17]).

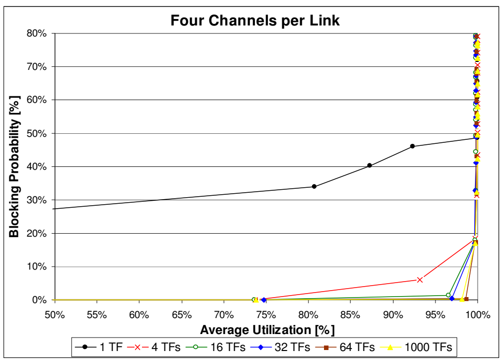


Figure 5: Blocking probability

FλS enables the construction of Banyan based fabrics, which are the most scalable switch design (in the next subsection it will be shown that FλS also minimizes buffer requirements).

Figure 6 and

Figure 7 are two design examples of Banyan based fabrics with switching capacities of 10Tb/s and 40Tb/s, respectively. The two designs are based on commercially available electrical switching blocks from Mindspeed Inc. that are interconnected either electronically or optically.

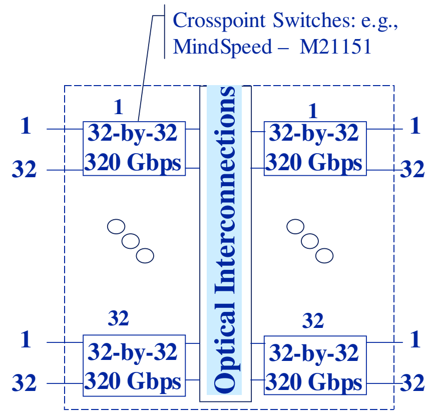


Figure 6. 10Tb/s switching fabric

In comparison, optical switches with below 1µs switching have lower capacity, larger physical size and are much more expansive. The main challenge in constructing the large switching fabrics shown Figure 6 and

Figure 7 is interconnection. Electronic interconnection will not scale given their inherent problems as discussed in Section III.A. Consequently, the most promising approach is a hybrid opto-electronic switching fabric. As discussed in the next section, electronic may be also the most suitable approach for buffering.

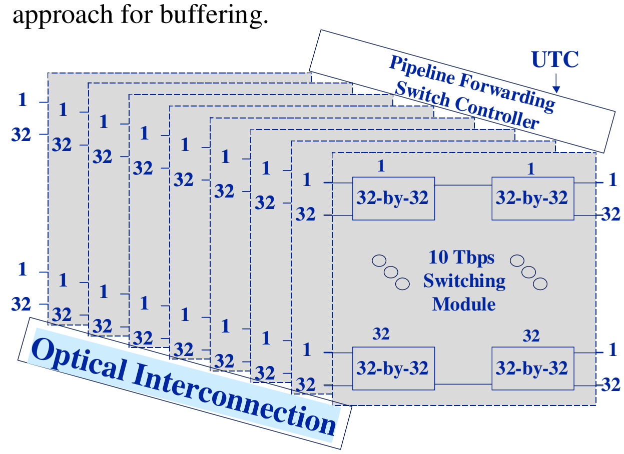


Figure 7. 40Tb/s switching fabric

III.C Ultra Scalable Buffer Requirements

FλS enables the switching of IP packets in time frames (TFs) without decoding the headers of each packet. Namely, FλS eliminates the need for header processing. FλS is based on the setting of a switching schedule of IP packets in TFs along a predefined route in the network.

Clearly, if the IP packets in TFs arrive to the switch at the exact time no buffers are required. However, since the delay between FλS switches may not be an integer number of TFs it is necessary to align the incoming TFs on the optical links with the UTC TFs. Alignment consists in aligning the beginning and end of each time frame on each optical channel with the beginning and end of the UTC time frames. Realizing the alignment operation requires some buffers.

Such buffer can be realized in the optical domain using programmable optical delay line, as shown, for example, in Figure 8. Skipping the detailed analysis of such programmable delay line, it is based on a non-trivial dynamic optical switch, which may introduce significant amount of power loss. In addition, such programmable optical delay lines are expensive.

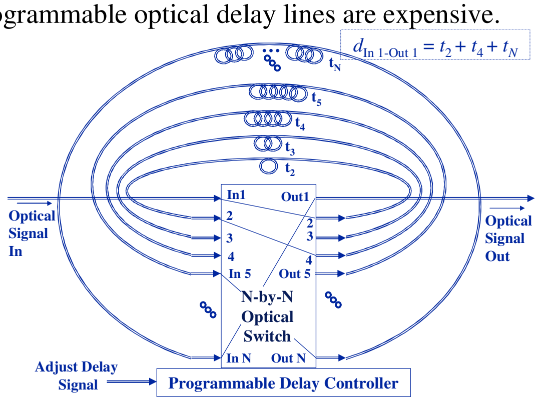
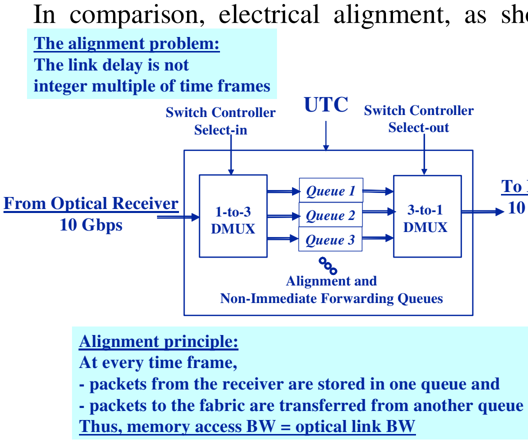


Figure 8. Optical alignment

In comparison, electrical alignment, as shown in



, is simple with no power loss and low cost. Obviously, the electrical alignment matches the use of electronic switching. The electrical alignment is based on buffers implemented with electronic memory. An electrical alignment consists of a number of queues (usually 3) in which arriving IP packets are stored and IP packets to be switched are retrieved.

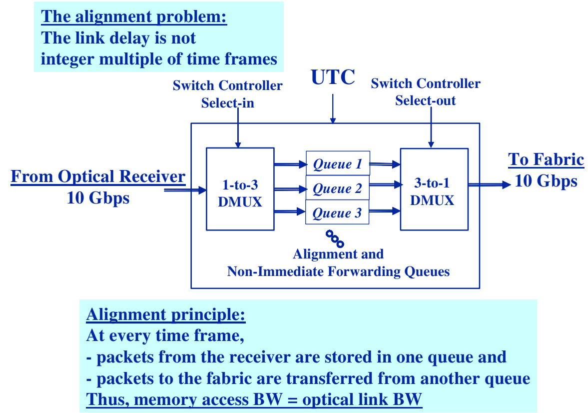
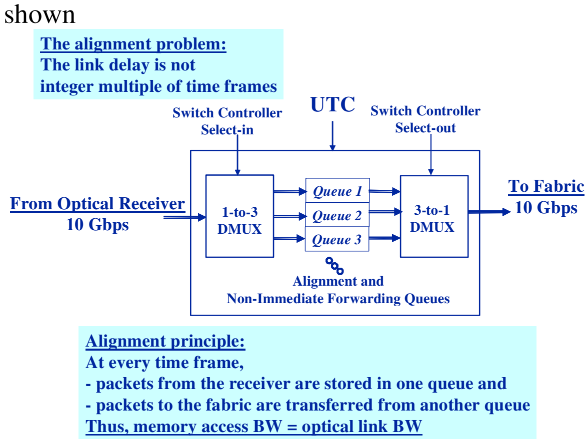
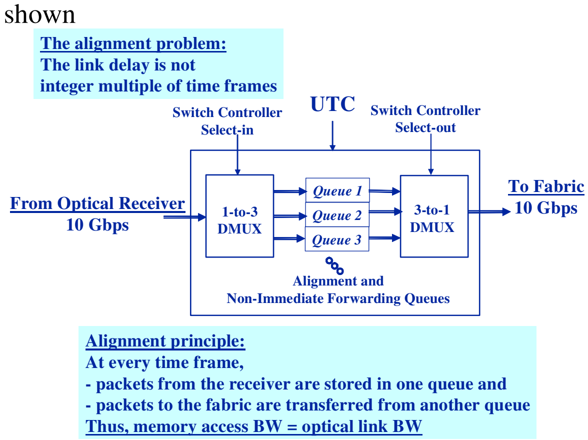


Figure 9. Architecture of electrical alignment

Note that the switch controller, which controls the electrical switching fabric, is also responsible for changing the configuration of the electrical alignment responsive to the current value of UTC. The alignment buffering requirements of the electronic alignment, shown in



, are three queues each contains the bits transmitted during one time frame. For example, for 10Gb/s optical channel and 8µs TF is only 3*80,000/8=30KB. Note the structure of electrical alignment buffer, shown in



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can be easily extended to support non-immediate forwarding (as discussed in Section II.B).

In essence, the switch controller, the switching fabric and the electronic alignment buffers are all what is needed for implementing ultra scalable FλS switch.

IV. FλS for Streaming Media

As discussed in Section III, with FλS it is possible to construct ultra scalable switches: lowest complexity fabric (with Banyan interconnection) and very low buffer requirements (1-3 time frames). The simplicity and scalability are due to switching the content (IP packets) of each time frame as a whole with a predefine schedule that is derived from global time (UTC). This section briefly discusses why FλS is suitable for streaming media applications. Streaming media is projected to be the primary traffic type over the Internet. Note that FλS can support "best effort" traffic" as well.

Streaming media, e.g., IP/TV and videoconferencing, rely on continuous playing at the receiver of samples acquired at a fixed rate at the sender (just like the "old" telephony system). Samples of video frames are captured by a camera and digitized and processed by a frame grabber.

When circuit switching is used to transfer video frames, the encoder is operated in such a way that it produces a constant bit rate flow. This is required in order to fully utilize the channel allocated to the session. Consequently, the transmission delay of a single video frame is the time between two successive video frames. This is because the transmission of the current video frame should continue, in a constant rate, until the next video frame is ready. For example, if the sampling rate is ten video frames a second, the transmission delay alone is 100 ms, which is unacceptable in interactive streaming applications.

With FλS switching it is possible to eliminate such a long transmission delay by transmitting the captured video frame as a short burst as shown in Figure 10. The combination of FλS with IP packet switching allows burst transmission of video frames in packets, i.e., a video frame is captured, put into an IP packet, and then transmitted as a burst into FλS network.

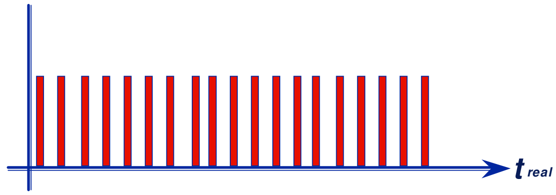

Figure 10: Periodic-bursty transmission

The next question is how to ensure that each transmission of a video frame will reach its destination with no loss and with minimum delay bound. Since video frames are captured periodically, in order to minimize the delay bound, periodic resource allocation with periodic transmission synchronized with their capture are required. Switching based on global time is the only known way to satisfy those requirements, while guaranteeing no loss with minimum delay bound, as shown in Figure 11.

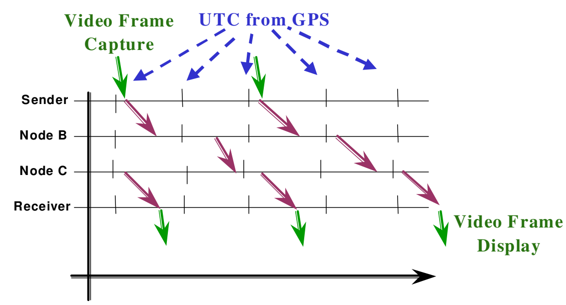

Figure 11: Periodic Capture, Transmission and Display

It is worth noting that even though all the video frames are not encoded with exactly the same amount of bits, the capacity reserved on the links is not wasted since it used to forward "best effort" (i.e., non-reserved) traffic. No loss due to congestion is guaranteed to all the video frames, provided that the amount of bits encoding them does not exceed the reservation.

Some video encoding schemes, like MPEG, encode frames with significantly different amounts of bits in a periodic fashion. MPEG encodes pictures in one of two different ways:

Intra-frame Coding eliminates spatial redundancy inside pictures and the resulting encoded picture is called *I-frame*.

Predictive Coding eliminates temporal redundancy between a picture and the previous one through motion estimation. The obtained encoded picture is called *P-frame* and it is typically from 2 to 4 times smaller than an I-frame.

It may be inefficient to transfer such a compressed video stream over a constant bit rate channel, e.g., the one provided by a circuit switched network (see [10] for a detailed discussion). If the encoder is operated in such a way that it produces a constant bit rate flow, it can introduce a delay up to the time between two successive I-frames; such a delay, which can be on the order of 500 ms, is obviously unacceptable for interactive streaming media applications.

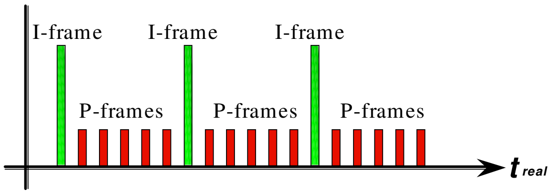

Figure 12: Complex periodicity scheduling

Complex periodicity scheduling, as shown in Figure 12, allows MPEG video frames to be transmitted as soon as they are encoded, analogously to what was previously described for fixed size video frames. UTC facilitates the realization of complex periodicity scheduling, which provides deterministic quality of service guarantees to variable bit rate traffic. In complex periodicity scheduling the amount of transmission capacity reserved on the links traversed by a connection varies in a repetitive manner.

V. Discussion

As the Internet exponential traffic growth continuous, in the foreseeable future, it will be due more and more to (all IP) streaming media applications. Streaming media applications will "fill-up" the optical "pipes." One of the main remaining challenges is how to efficiently switch this huge amount of IP traffic. UTC-based FλS provides the necessary switching solution, which has following desired requirements for streaming applications:

- Switch and forward IP packets as a whole (i.e., IP packets are remained intact at all times).
- Provisioning granularity from 1Mb/s to full optical channel capacity.
- Minimum delay with constant jitter and no packet loss.
- Multicast and broadcast of IP packets with any allocated capacity with the above mentioned properties.

Furthermore, UTC-based FλS facilitates the most scalable electronic design with optimal switch complexity (O[a*N*$lg_a N$]), minimum electronic buffers (1-3 time frames) and optimal switching speedup of one. However, in order to actually construct ultra scalable switches it is necessary to overcome the switching modules interconnection problem.

Since optical transmission has superior interconnection properties over electric wires, it has been proposed to use optical interconnects. However, such an approach is novel and requires further research and development. The optical interconnection objective of high-capacity electronic switching modules is:

> "*maximizing the density of optical interconnections, while minimizing power dissipation for a given distance bound among electronic switching modules (each consists of one or more electronic switching devices).*"

A UTC-based FλS switch prototype, shown in Figure 13, using Mindspeed cross-point devices (M21151) is being implemented at the University of Trento. Each of the M21151 cross-point is a single electronic chip with 144 inputs and outputs, each input/output has capacity of 3.2Gb/s or total raw capacity of 460Gb/s. The cost of such cross-point chip is around 500 USD or 1 dollar per (raw) Gb/s! Moreover, the switching time for changing the input/output permutation is less than 10ns. The switch prototype is using UTC-base time-driven priority software developed at the Politecnico di Torino.

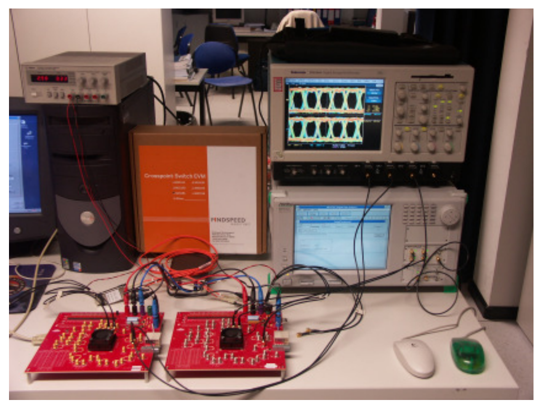

Figure 13: Early FλS prototype

Although UTC-based FλS is optimally designed to support streaming media applications it is straight forward how to combine its operation with "best effort" (non-scheduled) IP/MPLS, as shown in Figure 14. This is done by adding an IP packet filter before the alignment sub-system and then diverting non-scheduled IP packets to IP/MPLS switching module.

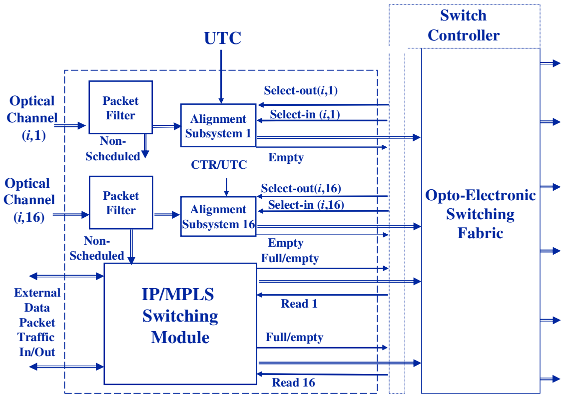

Figure 14: Hybrid IP/MPLS and FλS system

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