Performance Evaluation of Time Driven Switching for Flexible Bandwidth Provisioning in WDM Networks

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Abstract — This work further studies blocking issues that are related to Time Driven Switching (TDS). TDS is a novel and promising technology for the realization of low complexity and high scalability switches in the electrical and optical switching domains. TDS is unique in enabling the implementation of all-optical fractional wavelength switching with current state-of-the-art components. Furthermore, TDS provides deterministic QoS guarantees for all streaming media applications. Being a new technology, TDS requires investigation, especially regarding its performance and efficiency. The performance in this paper considers multiple scenarios with variety of optical transmission and switch parameters. The performance results show that blocking does not compromise the efficiency in most cases, even with elevated offered traffic load with the restrictive scheduling of Immediate Forwarding.

I. INTRODUCTION

Modern telecommunication networks use light to transport information; in WDM systems multiple colours travel on optical fibers increasing the total bandwidth. All optical networks are being studied to avoid conversion from optical to electric signal every time a switch is crossed, in order to forward it towards the proper destination.

Present optical switches however can only divert entire wavelengths: all the data on a colour should be switched and forwarded from the same source to the same destination. This leads to some constraints in the network itself, that is:

• a source needs a different colour for each destination it addresses; if the network has N access points and they have to be all connected to each other, the number of wavelengths needed can grow up to N^2 (N^2 problem [1]).
• no aggregation/separation of multiple flows on/from a single wavelength can be operated: the wavelength travels unchanged switch by switch.
• it is not possible to connect fast sub-networks to slow ones (unless using more than one colour) because the capacity of a single wavelength cannot fit into that of the crossed link.

All these problems limit the extension of an all-optical network core, because of wavelengths growth and bandwidth mismatch between sub-networks. Therefore it is advisable to provide directly the availability of fractions of the wavelength capacity, so as to support “sub-lambda” end-to-end connections. Time Driven Switching (TDS) provides a solution to make available a capacity equal to a fraction of that transported by a wavelength in order to permit the above mentioned operations; for this reason, a switch operating according to TDS is called Fractional Lambda Switch [2-5].

Even though TDS has similarities with SONET/SDH, its basic working principle, pipeline forwarding [2-5], is fundamentally different. TDS is based on UTC (Universal Coordinated Time) to enable pipeline forwarding of large data units, each with multiple IP packets of variable length, in the network. UTC provides phase synchronization with identical frequencies everywhere, while SONET/SDH is using only frequency synchronization with known bounds on frequency drifts. In order to overcome possible data loss SONET/SDH is using a complex of overhead information to accommodate: (1) the accumulation of various delays and jitter and (2) continuous clock drifts from a nominal value. The SONET/SDH solution is a sophisticate forwarding of 1-byte data units, which takes, in 10 Gbps, about 1 nanosecond. Consequently, it is not possible to realize the sophisticated SONET/SDH in the optical domain. TDS enables pipeline forwarding of large data units of a few Kbytes with no accumulation of jitter, with no data loss and without the overhead complexity of SONET.

There are several other “sub-lambda” protocols for supporting end-to-end connections [6-12]. In [6], an optical time slot interchange (TSI) utilizing sophisticated optical delay lines is described with no detailed timing analysis. In [7] and [8] two experimental optical system with in-band master clock distribution and optical delay lines are described, with only limited discussion timing issues. In [9] a system with constant delays and clocks is described, which can be viewed as a close model to immediate forwarding (see Section II), however, no timing analysis and no consideration of non-immediate forwarding. The blocking probability analysis in [10] and [11] model a network with TSI switches while ignoring timing issues, such as, delays and timing errors. Thus, it is not possible to determine whether the analysis is applicable to network with UTC with non-immediate forwarding. The analysis in [11] provides some details regarding timing issues in the network model, specifically, a synchronizer that aligns incoming time slots while ensuring that the delay between nodes is an integer number of time slots. The issue in this case, is how the alignment is performed, e.g., how to align
when one incoming time slot start exactly in the middle of another incoming time slot. How the synchronizer “decides” what time reference to use.

The principles of Time Driven Switching and allocation procedures are described in section II, whereas section III provides traffic performance results for a single switching fabric.

II. TIME DRIVEN SWITCHING

Time Driven Switching uses time division multiplexing and framed structures in order to give flexibility to optical networks. Time is actually divided into time frames (TFs) with equal duration ($dT$), grouped in time cycle (TCs), all containing the same number ($T$) of TFs. According to the extent of these temporal intervals and to the link bandwidth, the amount of data which can be sent during a TF can be simply calculated. It could be used, for instance, the structure represented in Figure 1, with 1000 TFs per TC and with 64 cycles in one UTC second (or super-cycle).

On setting up a connection for a new couple source-destination, a free TF is searched in the cycles associated to the link bandwidth, the amount of data which can be sent during a TF can be simply calculated. It could be used, for instance, the structure represented in Figure 1, with 1000 TFs per TC and with 64 cycles in one UTC second (or super-cycle).

The sequence of TFs on each link from source to destination can be chosen according to three pipeline forwarding modes:

- **Immediate Forwarding** (IF): data arriving at a switch during a TF must exit during the next one; and
- **Full Forwarding** (FF): data arriving at a switch during a TF can leave the switch in any time frame, that is during a TF between the next one and the corresponding one in the next cycle.
- **D-frame Forwarding** (D-F) or non-immediate forwarding: in this case a TF can be selected up to $D$ TFs later (see figure 2). In other words, the selection of the forwarding time frame from the switch may be $1, 2, \ldots, D$ after the time of arrival to the switch.

Immediate Forwarding gives more restrictions on finding free TFs and hence causes more connection blocking. Nevertheless, it grants minimum delay between transmission and reception, as packets don't have to wait in the switches until the proper TF. For this same reason it minimizes buffer capacity within the switches. Full Forwarding has the complementary advantages: minimum connection blocking and larger delay. Switches must also store packets for a longer time (larger buffers). The D-Frame Forwarding (D-F) performance ranges from those of Immediate Forwarding to those of Full Forwarding.

Figure 1: time division in TDS

The connection is lost if free TFs cannot be found, otherwise the sequence of TFs on the links will form a Synchronous Virtual Pipe (SVP): each packet put by the source on the SVP will pass from TF to TF until the destination is reached. Every crossed switch will be set to route the content of the arriving TF to the proper outgoing TF in the outgoing link.

The whole network must be synchronized to recognize the time division, using a worldwide global system providing the standard time reference, UTC (Universal Coordinated Time), with given accuracy. A typical example is given by the GPS system, which globally provides the standard time with an accuracy up to 1 µs. In this way switches will forward all packets contained in a TF in the right direction, without needing to read any header.

Dividing a single wavelength into independent temporal fractions solves the problems mentioned about optical networks:

- each fraction of the same wavelength can be used for a different destination;
- TFs can come from different up-links and go to different down-links (multi/demultiplexing); and
- fast links can use short TFs and slow links longer ones, so that the amount of data transmitted is the same and the content of a TF can be exchanged between them.

Figure 2: D-frame (pipeline) forwarding

Another restriction to TDS operations can derive from the operations of the switch fabric. It can be cost efficient not to allow that a TF arriving on one colour (wavelength) to be forwarded on a different colour: this mode will be called No Wavelength Interchange (NWI). If no restriction applies in...
terms of wavelength, the operation is referred to as Full Wavelength Interchange (FWI). FWI and NWI can be combined with both Full Forwarding, Immediate Forwarding and D-F forwarding according to the characteristics of the switch fabric and the traffic performance desired, as we will see in the following. 

III. PERFORMANCE EVALUATION

The performance of TDS is now evaluated through computer simulation. The following symbols are introduced to define the switch characteristics:

- \( T \): number of time frames in a cycle
- \( C \): maximum number of concurrent connections in a time frame
- \( W \): number of wavelengths per fiber
- \( N \): number of inlets and outlets of the switch
- \( V \): number of different Synchronous Virtual Pipes that can be set up on a given inlet-outlet couple of the switch.

In particular \( T \) must be such that at least a TF is available for every possible connection in the switches; since the number of wavelengths for fiber is \( W \), \( W* T \) (all the TFs on a fiber) has to be greater than the number of connections that is possible to set-up through any switch port. The parameter \( V \) indicates how many different transmitter-receiver couples in the whole network have to share the same inlet-outlet couple of the switch (in different time frames, obviously): for each of these inlet-outlet couples a different SVP is reserved.

The values \( N=16 \), \( T=50 \) have been selected in this study. All the charts shown in this study express the blocking probability as a function of the offered traffic, normalized to the capacity of the switch, i.e., the quantity \( T*W*C \), that represents the maximum number of connections that can be concurrently supported by every input of the switch.

A. Performance with different forwarding types

The different types of forwarding have been compared in figure 3, ranging from immediate forwarding (IF) to full forwarding (FF) by examining also the intermediate cases of D-F with \( D=2,4,6,8,10,12 \); \( V=2 \) and \( C=10 \) have been chosen in this case. It can be seen that the blocking probability significantly improves passing from IF to FF especially at low loads. When the normalized offered traffic is 0.3 the improvement spans over several orders of magnitude. D-frame forwarding gives intermediate results between the two cases, showing that \( D=12 \) gives results very close to FF (\( D=50 \)).

B. Blocking probability varying the number of TF per SVP

The most important aspect of the Time Driven Switching is how time is considered: it is the basic building block of the protocol, more then packets and connections. This means that the behaviour of the switch can be studied under the aspect of the forwarding of whole TFs, rather than single packets. This also implies that: (1) intermediate switches do not have to decode packet headers and (2) only a small amount of buffers are required.

Different parameters influence the switch performance, particularly the number of concurrent connections that is possible to establish through a single input of the switch. On setting up a new path through the switch, a couple of TFs are searched in both sides of the connection: so it is useful to grant a TF for each possible SVP that passes through the same port, or for the greater part of them. We have made the hypothesis that up to \( V \) different SVPs are possible between the same inlet and the same outlet of the switch. Every inlet can be connected with all the outlets, and so the total number of TF on all the wavelengths of the fiber (\( T*W \)) has to be greater then (\( N*V \)).

![Figure 3: Comparison of the routing techniques](image)

We first evaluate how the parameters \( N \), \( T \) and \( V \) affects the blocking performance by keeping the same number of TFs per SVP, given by \( T W/NV \). As shown in figures 4, 5, 6, where each of these parameters is varied, the switch performance do not change significantly. However, from figure 4 we observe that when \( N \) grows, by keeping the same ratio \( T/N \), blocking decreases. This is easily explained considering that TFs grows with \( N \). Furthermore figure 6 confirms that FF outperforms IF when the number of TFs per SVP is larger than 1, still under low traffic values.

C. Behaviour of the switch in a WDM environment

The last aspect to be considered is the effect of varying the wavelengths \( W \) per fiber number by still keeping constant the ratio \( T W/NV \). We consider the two cases of \( W=1,4 \) by keeping the same ratio \( T W/NV=2.5 \).

Figure 7 shows that under FWI (Full Wavelength Interchange) assumption a larger number of wavelengths improves the performance, since increasing \( W \) implies there is a larger pool of TFs where to choose for an idle one. Thus, notice that with FWI the improvement is such that immediate forwarding with \( W=4 \) is better than full forwarding with \( W=1 \).
D. Different classes of offered traffic

We consider now different types of sources loading the switch, whose calls are received according to a specific traffic model: the generation of the calls is modelled as a Poisson process, and the time between two arrivals will be exponentially distributed.

Constant bit rate (CBR) sources are assumed for three different types: phone calls, videophone calls and Video-on-Demand (VoD). The three types of sources are characterized in the following way:

- **Phone calls**: 64 kbit/s PCM voice, with average duration of 3 minutes.
- **Videophone calls**: they request a bandwidth which depends on different factors; here we assume capacity equal to 384 kbit/s. The average duration will be equal to that of phone calls that are 3 minutes.
- **Video-on-Demand (VoD)**: they request a bandwidth equal to 1.5 Mbit/s with an average duration of 1.5 hours.

The following parameters will be assumed:

1. The duration of a time frame is $d_T = 125 \mu s$.
2. The time cycle is composed from $T=100$ time frames, and its duration is therefore 12.5 ms.
3. The capacity $C$ of a time frame is calculated as the ratio between the capacity of a time frame and the smallest data block to send during a cycle.
4. The link capacity is 153.6 Mbit/s, or multiple or fractions of it: this capacity will be indicated as $L_c=B$.

We note that:

1. If the link capacity is, for instance, equal to 153.6 Mbit/s, multiplying it by the time frame duration gives the quantity of data that can be sent in each TF (in this case 19.2 kbits).
2. The number of bits (subsequently indicated as "tile") needed by a call in a time cycle, whose duration is of 12.5 ms can be computed for every different traffic type. For voice traffic, at 64 kbit/s, the bits to be sent
are 64 kbit/s * 12.5 ms = 800 bit. Since the system can send 19.2 kbits in a TF, the capacity will be equal in this case to $C = 19,200 / 800 = 24$

For videophone traffic, with a capacity of 384 kbit/s, we obtain that 4800 bits per time cycle should be sent. The capacity is therefore equal to $C = 4$. For Video-on-Demand connections running at 1.5 Mbit/s, 18,750 bits per time cycle will be necessary to be sent and therefore $C = 1$ must be selected.

Only Immediate Forwarding will be studied here, which gives the best performances in terms of network delay. Naturally the blocking probability performances will improve using the Full Forwarding or the D-frame Forwarding, thanks to the greater scheduling flexibility. We will illustrate only the case of a switch with a single wavelength. We would like to outline that now the calls don't request a connection per time, but request for more than one, based on the type of traffic the calls belong to.

As previously stated, the link capacities are chosen so that an integer number of "tiles" can be sent in every time frame, to isolate the effect of the fragmentation of the capacity from the measure of the blocking probabilities. We evaluate first one type of connections, the telephone calls. The link bandwidths used is 307.2 Mbit/s ($C = 48$ tiles per TF), 153.6 Mbit/s ($C = 24$ tiles per TF), 76.8 Mbit/s ($C = 12$ tiles per TF), 51.2 Mbit/s ($C = 8$ tiles per TF), 25.6 Mbit/s ($C = 4$ tiles per TF), 6.4 Mbit/s ($C = 1$ tile per TF). In the charts a capacity equal to 153.6 Mbit/s will be identified with the symbol $Lc = B$, and, in the other cases, with multiple or fractions of it.

Figure 8 shows that the blocking performance improves when the link bandwidth grows and therefore when the time frame capacity increases: by augmenting the capacity of the TFs (and therefore of the SVP) it is possible to satisfy more and more call requests (with the same offered traffic) and to get better performance.

**E. Performance study of mixed traffic**

Based on the results presented before, we study the combined effect of "tiles" on mixed traffic. Our case study consists in a traffic mix with 75% of telephone calls, 15% of video-telephone calls and 10% of VoD connections. Figure 9 gives the blocking probability for the different traffic flows assuming a link bandwidth $Lc = B$ and multiples of it.

Starting from the case of a link bandwidth equal to 153.6 Mbit/s ($Lc = B$), we recall the TF capacity required for the different types of traffic: $C = 24$ for telephony, $C = 4$ for video-telephone and $C = 1$ for VoD. This means that a video-telephone connection occupies the bandwidth of 6 telephone connections and a Video on Demand connection is worth as 24 telephone connections.

The blocking performance of VoD calls is the worst one and it is easily explained considering that a VoD call occupies an entire time frame. Therefore, all TFs with at least one phone or video phone connection already set-up makes that TF unavailable for the VoD call. For the same reason Video-telephone traffic behaves better that VoD traffic but still worse than telephone traffic. In immediate forwarding, it is possible to have blocking of VoD or video-telephone calls even if the available capacity in the whole time cycle is enough for that call.

When the link capacity is set to 307.2 Mbit/s ($Lc = 2B$) the capacity of the TFs is doubled and it is therefore equal to $C = 48$. It is possible to notice a performance improvement of all traffic flows, but the blocking probability for VoD connections is still rather high. Much better results are obtained when the link capacity is set to $Lc = 4B$, $8B$.

![Figure 8: Effect of link bandwidth on the link utilization for telephone calls](image)

![Figure 9: Blocking probability for traffic classes and link bandwidths](image)
IV. CONCLUSIONS

This paper presents a detailed performance study of the scheduling efficiency of Time Driven Switching (TDS). In order to provide deterministic QoS guarantees for streaming media applications, resources are reserved as transmission capacity during a specific sequence of TFs to enable pipeline forwarding, which is a known optimal method. This work evaluates via simulation the relationship between blocking probability and utilization as a quantitative assessment of the efficiency of traffic shaping and forwarding with TDS.

Simulation results show that blocking does not compromise the efficiency and in most cases low blocking probabilities are obtained, even with elevated offered traffic and Immediate Forwarding. One interesting case is scheduling of VoD calls, which showed high blocking probability (figure 9). However, VoD performance can be easily improved significantly by dividing each VoD call into multiple sub-calls and by employing D-frame Forwarding (2-frame forwarding, see Figure 2, is likely to be sufficient).

The efficient and deterministic bandwidth provisioning with no loss and small constant jitter of TDS enables a network “nirvana” with IP/MPLS. Connections are realized in TDS network have the same deterministic characteristics as leased lines in SONET/SDH and circuit emulation in ATM with several advantages: (i) IP/MPLS packets are transferred through a TDS network with no format change, (ii) simple aggregation or grooming in the time domain, with no address decoding, is possible, (iii) IP/MPLS header processing is performed only at the edges, and (iv) TDS is uniquely suitable for all-optical fractional lambda switching [4].

REFERENCES