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Architectures and buffering for all-optical packet-switched cross-connects

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Abstract This paper considers the performance of an all-optical packet-switched cross-connect. All-optical header processing and all-optical routing are implemented in the cross-connect architectures. The main metric considered to measure the performance is the packet loss ratio for the buffering. This is influenced primarily by three factors. The first is the cross-connect architecture: feedback or feed-forward buffering, incorporating wavelength domain contention resolution. The second is the selection of the fibre delay line distribution: degenerate or non-degenerate distributions. And the third is the traffic load together with the traffic model used for the performance analysis: a Poisson distribution or a self-similar model. It is shown that the optimal implementation of a feedback buffer requires a technique such as overflow buffering as well as the superior performance of an all-optical switch in order to maintain signal quality through multiple recirculations.

Keywords All-optical buffering · All-optical packet switch · Optical signal processing

Introduction

To achieve the higher processing speeds required by future-proof networks, all-optical switching technology provides a

superior solution to the hybrid electro-optic approach. The all-optical solution provides a much higher processing speed, provides transparency, and mitigates the optoelectronic conversion bottleneck. All-optical functions that have been developed include switching [1–3] header processing [4, 5], buffering methods [6–9], wavelength conversion [10–12] signal regeneration [13], and limited signal processing used for high-speed transmission such as multiplexing and demultiplexing [14–16], and for logic functions [17,18].

Optical cross-connects (OXC) are the basic network elements for routing optical signals. Currently two of the most important technological limitations of all-optical cross-connects are the implementation of optical buffering and optical signal processing. Hybrid optical packet switches have used electronic RAMs that have limited access speed, and use optical-to-electronic (O/E) and electronic-to-optical (E/O) conversions that add to the system complexity. Eliminating E/O and O/E conversions will also decrease the system cost.

Buffering is required when more than one input packet is destined for the same output port during the same time slot. Variable delays are required as multiple packets need to be delayed and processed one at a time. Both wavelength and time multiplexing are used to address the congestion. Optical buffering is done using fibre delay lines (FDLs), which are long lengths of fibre used to buffer packets of known lengths for specific times. A 512 byte packet (the average IP packet size) being transmitted at 10 Gbit/s, for example, requires 82 m of fibre per packet in the buffer. These FDLs cannot be accessed at any point in time, but comprise a FIFO system as the packets have to traverse the entire length of the FDL that they are buffered in. Space domain contention resolution (deflection routing) cannot be used in an all-optical implementation due to the complexity of the routing decision required in the routing node [19]. Although it can be used for low overall network loads, the performance depends on the

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network topology and routing matrix, and poor performance results from the excess consumption of network resources or the lack of alternate paths [20].

This paper discusses the relevant issues for an all-optical implementation. Considering the rudimentary state of all-optical technology, several implementation assumptions had to be made for the simulations in order to minimise the required optical signal processing. Various architectures are considered utilising all-optical concepts. The performance (measured in terms of packet loss ratio, PLR, as the effect of dropped packets is far more severe than the effect of queuing delay) of these architectures is analysed by looking at an all-optical buffering implementation. To facilitate the simulations, and in order to gain a clear perspective of the differences in performance, the architectures, and the influence of various parameters were analysed using a Poisson traffic model (a Bernoulli arrival process). It is, however, necessary to take the self-similarity of Internet traffic into account, so to obtain realistic values of how much buffering will be required, the final buffer sizes are analysed using a Pareto distribution to model the traffic. It is shown that the best performance is achieved using a feedback buffer architecture. Although this is often not feasible in an electro-optic implementation, the all-optical switches maintain signal quality through the recirculations, facilitating multiple recirculations required for a low packet loss ratio.

The original contributions of this paper are a new all-optical packet switch design based on all-optical switching and buffering as described in Ref. [21] (no electronic signal processing or control is assumed), fully shared buffers incorporating a buffer overflow algorithm in the wavelength domain is introduced, and these buffer architectures are investigated varying the following parameters: traffic load and models, the number of FDLs and FDL distributions, and the number of switch and buffer ports.

The paper is organised as follows. In the second section, optical switching is discussed. In Section ‘Traffic models’ the influence and selection of the appropriate traffic model is explained. Section ‘Architecture’ discusses the options for all-optical cross-connect architectures, while these architectures are evaluated according to the buffer implementations as analysed in Section ‘Travelling and recirculating buffers’.

Optical switching

All-optical technology is aimed at application in routing nodes that require high bandwidth, fast switching, and transparency. Packet switching is required to handle the burstiness of Internet traffic because of its fine granularity and effective utilisation of link capacity.

Processing complexity must be kept to a minimum in the all-optical routing nodes, which means that there are several

networking functions that must be implemented in the edge routers, such as maintaining packet sequence integrity. In optical packet switching, the route that a packet will follow through the network can be specified in the packet header, or the packet may specify the destination and the routing nodes will select the path. In an all-optical implementation considered as the context of this discussion, the processing overhead is minimised in the routing nodes thus it is assumed that the path (i.e., the output port of a packet from a node) will be specified in the packet header. For this reason it is assumed that one of the $N \times n_{\text{ext}}$ output channels (N is the number of input and output fibres, n_{ext} is the number of transmission wavelengths used on each of the N fibres outside the switch) is defined in the header, and each of the buffers thus outputs to one of these channels.

Ref. [22] describes how either fixed length packets (FLP) or slotted variable length packets (SVLP) can be handled successfully depending on the scheduling algorithm used. In this paper, a slotted architecture is assumed, with a fixed packet length. Although in practice this requires complex synchronisation, a slotted network performs better than an unslotted network, facilitating traffic shaping, load balancing, flow control, and most importantly queuing. Although variable length packets can be handled in an asynchronous manner through techniques such as void filling described in Ref. [23], these techniques are very complex to implement, especially within the context of an all-optical implementation as assumed in this work. Because IP packets are variable length packets, this means that the edge routers will have to segment and reassemble packets, and perform grooming. To select the length of the packets, in other words the units used to dimension the buffers with, there is a trade off between the time resolution and the amount of delay provided by the buffer as discussed in Ref. [24].

Traffic models

Because of the self-similar nature of Internet traffic, a Poisson traffic model is not appropriate to model the network traffic [25]. The heavy-tailed file size distribution of application layer files is transformed by the transport and network layer. This manifests as self-similar traffic at the link layer. This means that when viewed at different scales the correlational structure of the traffic remains unchanged. When using a self-similar model to describe long-range dependence, a single parameter is required: self-similarity is characterised by the Hurst parameter, H , which relates linearly to the shape parameter, α , of the heavy-tailed file size distribution in the application layer [26, 27]. $0.5 < H < 1.0$, and as H approaches 1, both self-similarity and long-range dependence increases. $0 < \alpha < 2$, and if $\alpha < 2$ then the distribution has infinite variance, and if $\alpha \leq 1$ then the distribution has

infinite mean. According to Ref. [26] a typical value for α is 1.2.

It has been shown that buffers cannot deliver desirable performance when accommodating self-similar traffic [28, 29]. Traffic shaping at the edge router is one possible solution to mitigate the adverse effects of self-similar traffic in optical packet-switched networks. It is important to note that with self-similarity, traffic aggregation is not a solution because the burstiness of a multiplexed stream is not less than that of its constituent individual streams. Traffic shaping can be done either through the use of an optical packet assembly mechanism that groups packets thus reducing the burstiness [30], or using flow control [31]. Flow control through a protocol such as TCP is able to reduce the degree of self-similarity of network traffic, but is not able to eliminate the self-similar nature of the traffic. This means that it will only decrease the Hurst parameter, H . It is however interesting to note that TCP can also contribute to the self-similarity of network traffic. It is possible to decrease the self-similarity in these cases by using queue management [32], but once again, self-similarity is not eliminated. Ref. [21] mentions strategies such as multiserver queues, reducing the link load, and implementing multiple-path routing schemes to reduce the degree of self-similarity.

In the following simulations, the simplest heavy-tailed distribution to use is the Pareto distribution. Alleviated self-similarity in a TCP environment with applicable queue management is assumed, where the ON times are more heavy-tailed than the OFF times: $\alpha_{\text{ON}} = 1.5$, $\alpha_{\text{OFF}} = 1.7$. The Pareto distribution is continuous, and to use this in the discrete simulations, the values obtained are simply rounded up to the next integer.

Architecture

The performance of optical packet switches strongly depends on the architecture and device technology. Important switch parameters include switching time, insertion loss (and loss uniformity), crosstalk, extinction ratio, and polarisation-dependent loss (PDL) [33]. The main limitations to the implementation of electro-optic switches in OXC architectures are optical loss, noise and crosstalk [34,35]. The all-optical architectures proposed in this paper are based on the $1 \times N$ all-optical switches and $N \times 1$ all-optical buffers as described in Ref. [21]. The $1 \times N$ switches are implemented in parallel planes, each element handling one packet per timeslot, which means that crosstalk is minimised. The all-optical wavelength converters used in these devices contribute to the regeneration of the signal, thus enhancing the signal quality by improving the extinction ratio as in other interferometric wavelength converters [10,11]. Ref. [36] shows that signal regeneration is imperative for cascading OXCs, and the

electro-optic architectures discussed in Ref. [36] cannot be cascaded without including additional optical regeneration in the network. This problem is addressed in an architecture employing all-optical switching and buffering devices, both of which have been demonstrated to output packets with high output powers and high contrast ratios.

Single-stage feed-forward and feedback switch architectures are considered in this paper. All-optical header recognition and all-optical routing is used, and all-optical signal processing is assumed. Because it is an all-optical implementation, the functionality implemented in the cross-connect is limited, and functions such as packet priority or packet sequence integrity are not catered for. Multiple wavelengths for transmission between nodes are assumed, and the internal use of wavelengths is imperative [37].

In Ref. [38] a generic node structure was presented for hybrid electro-optic packet-switches that consists of an input interface with synchronisation and header recovery, the switching fabric with the switch control, and an output interface with header updating and signal regeneration. All three sections consist of both an optical and an electrical part. The all-optical implementation of the generic structure (shown in Fig. 1) differs in that there is only optical signal processing and control, which means that the functional blocks differ slightly. The synchronisation of optical packets can be done using switchable delay lines for the coarse synchronisation, and wavelength converters with dispersive fibre for the fine synchronisation. This complex functionality has not been demonstrated without electronic control [38, 39].

Each of the $N \times n_{\text{ext}}$ output channels in the proposed architecture receives its packets from one of the $N \times n_{\text{ext}}$ buffers, but these buffers can all be implemented on a single set of fibres, realised on n_{int} different wavelengths. The implementation of FDLs is bulky and expensive. The other disadvantages of using FDLs for buffering is that they do not have random access capability (except in a specific implementation of a feedback buffer with single packet length FDLs), there could be signal degradation in the FDLs from traversing the switch in a feedback architecture, more FDLs are required for a higher traffic load, and the FDL lengths are dependent on the specific lengths of the packets. In this analysis, the biggest consideration is minimising the amount of buffering fibre required.

Travelling and recirculating buffers

The two architectures that can be used in an optical implementation are a travelling buffer architecture and a recirculating buffer architecture.

The results shown in this section were obtained using event-driven simulations of $1 \times (N \times n_{\text{ext}})$ buffers as shown in Fig. 2, with parameters as shown in Table 1 (unless otherwise

Fig. 1 Generic node structure. The switch fabric and contention resolution that form the main structure of the cross-connect architecture are all-optical implementations. There is no specific output interface function as header regeneration is not required

Fig. 2 The simulated optical buffers have $N \times n_{\text{ext}}$ input channels and one output channel. The traffic load on each of the input channels is $\rho / (N \times n_{\text{ext}})$ for an output buffer because of the uniform distribution to each output from each of the cross-connect inputs. The cross-connect has $N \times n_{\text{ext}}$ parallel buffers feeding each of the $N \times n_{\text{ext}}$ output channels. Each buffer has B FDLs and the lengths of these fibres depend on the selected (degenerate or non-degenerate) distribution

specified). For both architectures, the FDLs support multiple internal wavelengths (n_{int}), thereby decreasing the amount of fibre required for contention resolution.

The assumption is made that there is a uniform distribution of the traffic from all of the $N \times n_{\text{ext}}$ input channels to

each of the $N \times n_{\text{ext}}$ output channels. This means that each of the n_{int} parallel buffer planes has $N \times n_{\text{ext}}$ inputs, and only one output. The assumption of a uniform traffic distribution in the cross-connect improves the performance considerably, increasing throughput and limiting the buffering required. To obtain a uniform traffic distribution, load balancing would be required, resulting in a very complex switch structure [40]. The details of load balancing are beyond the scope of this paper.

When comparing architectures and buffer compositions, a Poisson traffic model was used to simplify the simulation. When obtaining realistic performance values to calculate, for example, the amount of fibre required for an optical buffer, a Pareto distribution was used to take the self-similar nature of network traffic into account.

Travelling buffers

In the travelling buffer there are $N \times n_{\text{ext}}$ total buffers, which means that at most, $n_{\text{int}} = N \times n_{\text{ext}}$ to exploit the wavelength domain and not replicate the buffer fibres. For n_{ext} large, as is the case in a WDM implementation, this may be difficult to implement due to the dispersive quality of the fibre over such a wide bandwidth. There are $N \times n_{\text{ext}}$ switches, switch-

Table 1 Simulation parameters

Symbol	Parameter	Amount
	Number of events	10^7
n_{ext}	Number of transmission wavelengths in the network	32
n_{int}	Number of internal buffer wavelengths	256
N	Number of input and output ports (fibres)	8
	Packet length	128 Bytes
B	Number of FDLs in the buffer	Varies: 8–35
	Traffic type	Poisson and Pareto
ρ	Input channel traffic load, $0 < \rho < 1$	0.7
α_{ON}	Pareto ON-burst shape parameter	1.5
α_{OFF}	Pareto OFF-burst shape parameter	1.7

ing the packets from each of the input signals, and these are $1 \times (N \times n_{\text{ext}})$ switches, providing an input to each of the $N \times n_{\text{ext}}$ buffers. There is a wavelength conversion interface between the switching and buffering functions, placing each of the $N \times n_{\text{ext}}$ channels on one of the n_{int} buffer wavelengths.

The $(N \times n_{\text{ext}}) \times 1$ all-optical buffer simulated in this paper differs from an electrical or electro-optic implementation [41] because the header is only analysed in the switch, which means that no header information is known to the buffer. For an output travelling buffer this makes no difference, but for an input travelling buffer as shown in Fig. 3 this means that there is no intelligent way to distribute the input traffic in the queues (e.g., distributing the input traffic on different buffer wavelengths). This also means that head-of-line (HOL) blocking is not relevant [36], as the destinations of the packets are unknown to the buffering function. The reason for the poor input buffer performance in this implementation is because the input traffic load on each of the $N \times n_{\text{ext}}$ inputs to the buffer is ρ (not $\rho/(N \times n_{\text{ext}})$ as is the case for an output buffer), which means that a traffic load of only $\rho < 1/(N \times n_{\text{ext}})$ can be accommodated on a single wavelength. To try and alleviate the bottleneck between the buffer and the switch as shown in Fig. 3, header information

would be required to manage the wavelength dimension. For this reason, only an output travelling buffer architecture is considered, as shown in Fig. 4.

In the proposed travelling buffer, the FDL that a packet will be routed to is selected according to the following:

- (i) Assuming a specific delay line has a duration of τ (packet lengths), a packet cannot be routed to this FDL if there is already another packet in the buffer scheduled to be output in τ timeslots on the same output port.
- (ii) Of the available delay lines, the shortest one is chosen.

This means that fixed length delay lines cannot be used as (i) then determines that only one packet can enter the buffer during any given timeslot to prevent packet contention at the output of the buffer. The selection of the number and the length of the FDLs is equivalent to defining the entry points to a single buffer. The length of this single buffer is the length of the longest FDL in the buffer, and is referred to as the *buffer depth*.

Travelling buffers have two main drawbacks. One is that the PLR performance is far inferior to recirculating buffers

Fig. 3 Input travelling buffer architecture with N ($N \times n_{\text{ext}} \times 1$ input buffers and N $1 \times (N \times n_{\text{ext}})$ switches. The bottleneck between the buffers and switches cannot be successfully alleviated using wavelengths because no header (destination address) information is available in the buffer

Fig. 4 Output travelling buffer architecture with N input and output ports and n_{ext} transmission wavelengths. The cross-connect consists of $N \times n_{\text{ext}}$ parallel switching and buffering planes. With the ideal

$n_{\text{int}} = N \times n_{\text{ext}}$ internal buffer wavelengths, the amount of buffer fibre is minimised

for the same amount of fibre used for the FDLs, and the other, perhaps more important, problem is that the algorithm to write packets to the buffer is very complex to implement in an all-optical approach. This is because the entire content of the buffer needs to be considered to prevent contention at each output of the buffers.

To show the effect of the selection of the fibre distribution, the travelling buffer has been simulated with both a degenerate (increasing uniformly) and non-degenerate distribution (increasing non-uniformly, often implemented with an exponential increase in fibre lengths) [42]. Fixed FDL lengths were not considered as it was shown in Ref. [22] that incremental FDLs exhibit better PLR performance, and also provide more buffer space using less switch ports.

Recirculating buffers

The feedback architecture is shown in Fig. 5. Depending on the selected FDL lengths, these buffers can provide the capability of random access, whereas the travelling buffer storage times are predetermined. A larger switch fabric is required as B switch input and output ports are required for the buffering. The number of wavelengths implemented in the buffer is n_{int} , and the number of parallel physical buffers is denoted by F_{buf} . When $n_{\text{int}} = N \times n_{\text{ext}}$, $F_{\text{buf}} = 1$ and the amount of fibre used is minimised. The implementation requires wavelength converters at each of the interfaces between the switch fabric and the buffering.

Apart from the reuse of the buffering fibre, recirculating buffers provide two distinct advantages. First, for the recirculating buffer, the algorithm to select a FDL in the buffer is much simpler than for a travelling buffer where the entire content of the buffer needs to be known. Only the positions at the end of each FDL need to be considered in order to see if there will be an open position at the beginning of the

FDL in the next time slot. It is necessary to be able to discern the amount of delay that a packet has experienced if maximum delay is used as the output packet selection criteria. It is however not necessary to know what the entire content of the buffer is thus decreasing the required optical signal processing for the buffer algorithm. In terms of the all-optical implementation, recirculating buffers provide a more feasible algorithm that can be implemented using, for example, a laser neural network [17], and the discrimination of packet delays in the FDLs could, for example, be done using wavelength conversion and demultiplexers as illustrated by the all-optical variable optical delay circuits described in Ref. [7, 8].

Second, all of the fibre in the recirculating buffer FDLs can be used at any given time, in contrast to the inefficient fibre utilisation in travelling buffers, because the condition of not writing a packet to a FDL of length τ (packet lengths) if there is already another packet in the buffer scheduled to exit in τ time slots, is not applicable.

A Poisson traffic model can be used to facilitate the comparison between, for example, different buffer configurations. Figure 6 shows the performance difference between different FDL configurations for both an output travelling buffer configuration, and a recirculating buffer configuration. In travelling buffer architectures, the non-degenerate distributions have superior performance relative to the total amount of fibre as well as the total number of FDLs, but this is also at the cost of an increased average delay as the buffer depths are, for example, Degenerate: 20, Non-degenerate3: 31 and Non-degenerate5: 41 for the travelling buffer. Of course the maximum delays experienced in the recirculating buffer far exceed these as packets experience delays equal to integer multiples of the FDL lengths, with an average packet delay of 300 time slots for a degenerate or non-degenerate feedback architecture with an average of 110 packet positions in the fibre, versus only about 5 time slots for a travelling

Fig. 5 Recirculating buffer where the cross-connect consists of $(N \times n_{\text{ext}} + B)$ switches with tunable wavelength converters (TWC) on each of the N output ports as well as on the B buffer ports

Fig. 6 (a) and (b) show the packet loss ratio for an output travelling buffer and a recirculating buffer, respectively. The performance is measured versus the total amount of fibre required for buffering, measured in the number of packets buffered in the fibre. It is clear that recirculating buffers outperform travelling buffers. In the travelling buffers, non-degenerate configurations outperform a degenerate buffer configuration. This is not the case in a recirculating buffer

Fig. 7 The dotted lines show the average delay per packet in the different FDL distributions. On the second axis, the solid lines show the average number of recirculations

buffer. This is shown in Fig. 7. In electro-optical applications, the maximum buffering time in recirculating buffering is limited because of the amplified spontaneous emission (ASE) noise and signal-fluctuation. But in the all-optical switch and buffer there is not significant loss in the switch or in the buffering implementation, and considerably less amplification is required, resulting in a superior signal quality.

Buffer performance under self-similar traffic

Figure 8 (c) shows the performance of the best recirculating buffers from Fig. 6, but using a realistic self-similar traffic model. Low PLRs are not attainable. The dilemma of buffering self-similar traffic satisfactorily is not limited to an optical implementation, and the probability of ATM cell loss does not decrease as the electronic buffer size increases either [43]. For the queuing in ATM switches, it has been shown that there is a lower bound on the buffer overflow probability, with the overflow probability being around 10^{-4} for an electronic buffer of size 10^4 [44]. In a shared-buffer improving switch throughput, the loss probability with a high-traffic load ($\rho = 0.9$) is between 10^{-1} and 10^{-2} , with acceptably low loss probabilities only achievable with $\rho < 0.5$ [45].

The architecture used in the recirculating simulations is similar to the one described in Ref. [46], which provides an extensive analysis of contention resolution through various combinations of space, wavelength and time domain contention resolution. In Ref. [46] it is shown that a load threshold is observed under self-similar traffic conditions, and once the threshold is reached, neither deflection in the time nor the space domain is effective. A PLR of only 0.01 is attainable, even when the wavelength domain is also exploited, with a traffic load of 0.6.

Although PLRs of 10^{-9} or less are achievable in electronic systems, optical implementations typically require a PLR of < 0.01 because of the trade-off between PLR and wavelength utilisation [46].

Overflow buffering

The use of a self-similar traffic model results in unacceptably high PLRs. This can be addressed by implementing an overflow algorithm in the buffer, by routing overflow packets to available wavelengths within the buffer. Fig. 9 compares the performance of a degenerate recirculating configuration with and without internal cross-connect overflow buffering ($n_{\text{int}} = N \times n_{\text{ext}} = 16$).

Fig. 8 In recirculating buffers an important performance measurement is the number of switch ports required for buffering. Each FDL requires the use of a port. Against this consideration the non-degenerate configuration is slightly superior. The performance of the optical buffer with self-similar traffic (c) is distinctly worse than the buffers simulated using Poisson traffic (a) and (b), even at a lower load (c) shows results with both $\rho = 0.7$ and $\rho = 0.9$). It is also clear that buffer performance when analysed using a self-similar traffic model is not significantly influenced by the buffer configuration

To achieve a PLR of 0.01 with $\rho = 0.6$ with the degenerate distribution used to obtain the results in Fig. 9, 630 packet positions (35 delay lines) are required in the buffer. This translates to 12.9 km of fibre at a data rate of 10 Gbit/s and using a packet length of 128 Bytes. When buffer overflow is implemented with this buffer, the PLR can be brought down to 10^{-4} , or alternatively, a PLR of 0.01 can be achieved with only 200 m of fibre.

Fig. 9 Buffer performance can be significantly improved using overflow buffering. When the load is low ($\rho = 0.5$), the PLR can be eliminated. When $\rho = 0.9$, the PLR with flow control (dotted line) and without flow control (solid line) converge

Conclusion

Hybrid electro-optical cross-connect architectures are not applicable to all-optical implementations for two reasons. In all-optical routing nodes, the functionality is kept very simple as the signal processing is done in the optical domain, and thus functions such as packet priorities and packet sequence integrity are addressed at edge nodes. Furthermore, the all-optical switching and buffering devices differ from the electro-optical approach in that the control (packet routing) is in the optical domain, the header recognition is all-optical, and signal regeneration results from the implementation of wavelength conversion in the all-optical devices [10].

Of the two architectural approaches to an all-optical cross-connect, recirculating buffering provides a superior solution to travelling buffers. The main drawback of recirculating buffering in an electro-optic implementation is the loss resulting from traversing the switch multiple times. To compensate for this loss, amplifiers are used in the feedback loop resulting in ASE noise in the signal as it traverses the buffer multiple times. Furthermore, depending on the switch architecture, switch crosstalk can accumulate with multiple traversals of the signal. In electro-optic switches, feed-forward switches are preferred because of the limited attenuation in the switch fabric thus reducing the dynamic range of the signals that must be handled [39].

Utilising an all-optical switch fabric that consists of parallel $1 \times N$ all-optical switches, however, alleviates the influence of crosstalk as each individual switch has a single independent output packet per timeslot. Furthermore, implementing wavelength conversion within the switching and buffering functional units results in very good signal quality because of the signal regeneration inherent in the all-optical

architecture's building blocks [21]. An all-optical implementation of optical buffering is imperative to sustain good signal quality with a feedback architecture that will minimise the required buffer fibre.

The simulations described in this paper show that the performance of the selected architecture depends mostly on the buffer configuration and the traffic load. The self-similar nature of realistic traffic makes it very difficult to buffer efficiently, and the use of a techniques such as overflow buffering is required to exploit the wavelength domain properly.

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