

Dynamically Concatenated Wavelength Converters

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Abstract—An architecture is proposed for a wavelength-division-multiplexed (WDM) optical packet or circuit switch in which a bank of limited-range wavelength converters is shared among all input fibers, and in which any subset of converters can be dynamically concatenated (cascaded) to yield a wider conversion range for a packet that would otherwise be dropped because all unused wavelengths in its desired output fiber lie outside the range of a single converter. A probabilistic model of a switch is used to numerically determine the improvement in packet-drop probability achieved by dynamically concatenating converters.

Index Terms—Dynamic concatenation, packet-drop probability, shared wavelength conversion.

I. INTRODUCTION

WAVELENGTH conversion has been studied for well over a decade now as an approach to resolve wavelength contention in wavelength-division-multiplexed (WDM) optical packet and circuit switches. Wavelength converters are costly devices [2]; therefore, a particular effort has been devoted to designing cost-effective switch architectures by minimizing the number of converters constrained to a prescribed packet-drop probability.

A fairly well-popularized architecture that was first proposed in [4] relies on a bank of converters that is *shared* among all input fibers. Probabilistic models developed in [3], [6], and [7] have shown that sharing a bank of converters among all input fibers can achieve a packet-drop probability that rivals earlier architectures in which a converter is *dedicated* to each wavelength channel of each input fiber, but with significantly fewer converters. The reason for this saving is simple: not all packets need conversion because not all packets encounter wavelength contention, so those packets not needing conversion should be switched directly to their desired output fiber rather than unnecessarily passed through a dedicated converter.

On the downside, a shared converter must be capable of converting *any* arbitrary wavelength switched to its input; whereas, a converter dedicated to a specific wavelength can be of a simpler fixed-input type [2]. A more complex switching arrangement is also required to allow a packet to be switched either directly to its desired output fiber, in the case that it does not encounter wavelength contention, or otherwise to a shared converter, after which it is then switched via a second switch to its desired output fiber.¹

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¹It should be remarked that a packet is dropped if and only if it requires conversion but arrives to find all shared converters in use simultaneously, or if it requires conversion but arrives to find that all wavelength channels that lie within the range of a converter are in use in its desired output fiber.

Some techniques used to realize all-optical wavelength converters impose a conversion range limitation. Thus, conversion range limitations can forbid conversion of a wavelength beyond its immediate neighboring wavelengths [2].

This letter proposes a modification to the switch architecture presented in [4] in which a bank of converters is shared among all input fibers and shows that this modification achieves a significant reduction in packet-drop probability. This reduction comes at the cost of a more complex switching fabric.

In particular, this letter proposes an architecture in which any subset of shared converters can be dynamically concatenated in series to yield a wider conversion range for a packet. Therefore, two or more unused converters can be concatenated to salvage a packet that would otherwise be dropped because all unused wavelengths in its desired output fiber lie outside the maximum conversion range of a single converter. A switch architecture proposed in [1] could potentially allow concatenation of certain subsets of converters; however, it is unclear whether concatenation was, in fact, considered in [1].

Passing an optical signal through a series of concatenated wavelength converters will generally result in an appreciable degradation in the signal-to-noise (SNR) ratio [2]. SNR degradation is not explicitly considered in this letter. However, we note that 3R regeneration wavelength converters have been concatenated up to 2500 times [5].

Henceforth, fixed shared conversion (FSC) refers to a switch architecture in which a bank of converters is shared among all input fibers (as was proposed in [4] and analyzed in [3], [6], and [7]), while dynamic shared conversion (DSC) refers to a switch architecture in which a bank of converters is shared among all input fibers *and* any subset of these shared converters can be dynamically concatenated in series to effect a wider conversion range for a given packet (as proposed in this letter).

The next section specifies a possible DSC architecture and quantifies its complexity. To numerically compute packet-drop probability for an FSC and DSC architecture, Section III models a single switch as a multidimensional Markov process. This model is not tractable for a switch of realistic dimensions, and thus we use simulation to determine the improvement in packet-drop probability yielded by DSC relative to FSC for a switch of realistic dimensions. A switch control policy for DSC is also presented in Section III.

II. SWITCH ARCHITECTURE

Consider a WDM optical packet switch with M input fibers, K output fibers, and a bank of J converters that is shared among all input fibers. Each fiber supports C wavelength channels. Let λ_i be the wavelength associated with channel i , $i = 1, \dots, C$, and assume the natural ordering $\lambda_1 < \lambda_2 < \dots < \lambda_C$.

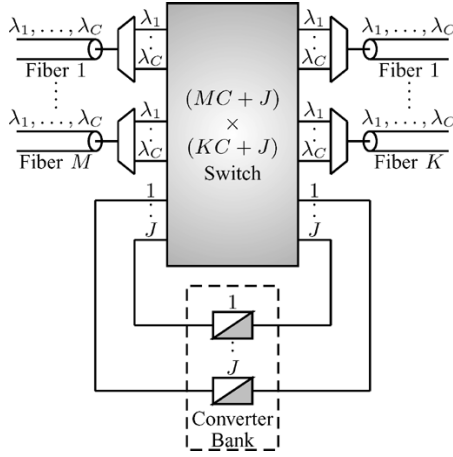


Fig. 1. Schematic of DSC switch architecture with control logic and delay buffering omitted.

A limited-range converter is characterized by its maximum conversion range in wavelength channels. In cross-gain modulation conversion [2], the down-conversion range is slightly wider than the up-conversion range. However, it is assumed they are equal in this letter. Let a d converter denote a converter with conversion range d . A d converter is capable of converting wavelength λ_i , $i = 1, \dots, C$, to any of the wavelengths in the set

$$\mathcal{F}_d(i) = \{\lambda_{\max(1, i-d)}, \dots, \lambda_{i-1}, \lambda_i, \lambda_{i+1}, \dots, \lambda_{\min(C, i+d)}\}.$$

Packets randomly arrive at each wavelength channel of each input fiber. The purpose of the switch is to route each packet from the wavelength channel upon which it arrives to an appropriate unused wavelength channel in its desired output fiber, either directly or via one or more converters.

One possible DSC architecture, which is based on an $(MC + J) \times (KC + J)$ nonblocking switch, is shown in Fig. 1. A bank of converters comprising a quantity J of d converters, abbreviated to $J \times d$ henceforth, is shown in Fig. 1. The input and output of each converter is connected to an input and output port, respectively, of the switch. This allows each converter to direct its output to the input of any other converter, as dictated by a switch control policy. Thus, any permutation comprising $\nu = 1, \dots, J$ unused d converters can be concatenated to yield a maximum conversion range νd .

In Fig. 1, wavelengths requiring conversion are each directed to the input of an unused converter, provided a sufficient quantity of unused converters are available. The output of a converter can be either directed to an output fiber, in the case that an unused wavelength in that output fiber lies within the maximum conversion range, or otherwise to the input of any other unused converter to further widen the maximum conversion range. Wavelengths not requiring conversion are directly switched to their desired output fiber. Control logic as well as delay buffering mandatory to an optical packet switch is omitted in Fig. 1.

It may be necessary to impose a restriction on the number of conversions a wavelength can undergo in a switch to maintain an acceptable SNR as well as to preclude a single packet from “hogging” all J converters, possibly resulting in a situa-

tion in which several packets requiring only a few converters are dropped to cater for a single packet requiring all J converters.

The next section shows that DSC requires far fewer converters than FSC to achieve a prescribed packet-drop probability. This comes at the cost of a more complex architecture. It is, thus, important to compare the complexity of DSC and FSC.

We quantify the complexity of a switch architecture by a so-called *input-to-output port count*, defined as the sum (over all input ports) of the number of output ports to which an input port can be switched. The input-to-output port count of DSC is $(MC + J)(KC + J)$ because *any* input port can be switched to *any* output port. The input-to-output port count of FSC is $(MC + J)(KC + J) - J^2$ because each of the J input ports connected to a converter can only be switched to the KC output ports connected to a multiplexor, but not to the J output ports connected to a converter. Note that the input-to-output port count of an architecture in which converters are *dedicated* to each wavelength of each input fiber is MKC^2 .

III. PACKET-DROP PROBABILITY

The purpose of this section is to quantify the improvement in packet-drop probability achieved through DSC relative to FSC and to present a switch control policy.

To this end, we consider a switch with K output fibers, each of which leads to a different neighboring switch. We assume packet arrivals at the switch are Poisson distributed; a packet is equally likely to arrive on any one of C wavelengths; also, a packet is equally likely to desire to be switched to any one of the K output fibers. The Poisson assumption was also made in [6] and [7] and implies $M \gg K$, which is a reasonable model given that input fibers may originate from edge routers *as well as* neighboring switches. A packet that is not dropped uses a wavelength channel and possibly a subset of converters too, for a random holding period. Let a denote the offered traffic load, defined as the mean number of packet arrivals to the switch during an average holding period.

To study the effect of imposing a restriction on the maximum number of converters that can be devoted to a single packet, we introduce a *maximum concatenations parameter*, denoted by h and defined as the maximum number of conversions a single packet can undergo in a switch.

Given switch dimensions K ($\ll M$), C , and J , offered load a , maximum conversion range d , and maximum concatenations h , packet-drop probability can be computed numerically by modeling a switch as a multidimensional Markov process. We consider $K = 1$ and then use simulation for $K > 1$. For $K = 1$, a suitable state description is given by $(\mathbf{x}, \mathbf{y}) = (x_1, \dots, x_C, y_1, \dots, y_C)$, where $x_i = 1$ if wavelength channel λ_i , $i = 1, \dots, C$ is used; otherwise, $x_i = 0$, and y_i is the number of converters used by wavelength channel λ_i , $i = 0, \dots, C$. For DSC, the corresponding state space is then

$$\left\{ (\mathbf{x}, \mathbf{y}) \mid \mathbf{x} \in [0, 1]^C, \mathbf{y} \in [0, \dots, J]^C, \sum_{i=1}^c y_i \leq J, y_i \leq \beta(i) \right\}$$

where $\beta(i) = \min(h, \max(\lceil i/d \rceil, \lceil (C - i)/d \rceil))$. For FSC, this state space is further constrained to $\mathbf{y} \in [0, 1]^C$ because a wavelength channel cannot use more than one converter.

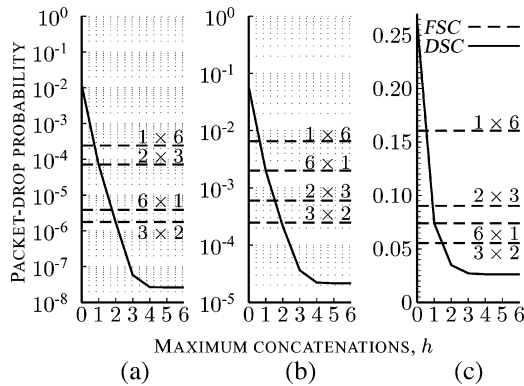


Fig. 2. Drop probability computed numerically for $C = 8$, $K = 1$, and $Jd = 6$: (a) $a = 0.1$, (b) $a = 0.5$, and (c) $a = 3$.

Due to space limitations, we do not specify the flow-conservation equations arising from this state space. Their solution can be computed numerically to determine the steady-state distribution, from which packet-drop probability can be obtained; see [8] for details.

We use this approach to calculate the packet-drop probability as a function of h for a small switch with $C = 8$ wavelength channels and $K = 1$ output fiber. A bank of converters comprising a quantity J of d converters, abbreviated to $J \times d$, where 6×1 is used for DSC, while all four integer combinations of $J \times d$ such that $Jd = 6$, is considered for FSC. This is to ensure an equitable comparison, because for FSC it is unclear if, for example, 2×3 is better than 3×2 . We remark that 6×1 is best for DSC since all other combinations satisfying $Jd = 6$ can be realized through concatenation.

In Fig. 2, packet-drop probability is plotted as a function of h for DSC and FSC, where all four integer combinations of $J \times d$ such that $Jd = 6$, are considered for FSC. Three different traffic loadings are shown in Fig. 2.

A prohibitively large state space limits this approach to a switch of small dimensions; that is, $K = 1$ and small C . As an aside, the number of states is bounded by $(J + 2)^C$ for DSC and 3^C for FSC. For $K > 1$, we therefore resort to simulation.

To confirm that trends exhibited in Fig. 2 remain pertinent to a switch of realistic dimensions, corresponding plots computed via simulation are shown in Fig. 3 for $C = 25$ wavelength channels, $K = 4$ output fibers, and $Jd = 20$, where 20×1 is used for DSC while the optimal $J \times d$, as found via an exhaustive search, is used for FSC.

Figs. 2 and 3 suggest that packet-drop probability is a non-increasing function of h that rapidly saturates to an asymptote. Therefore, to minimize packet-drop probability with the least possible degradation in SNR, h should be set equal to the point at which packet-drop probability just begins to saturate. For example, setting $h = 4$ is a good choice for the switch dimensions considered in Fig. 2. Choosing h as such gives rise to the following simple control policy for DSC.

Let the attributes (k, λ_i, j) identify a packet, where k is its desired output fiber, λ_i is the wavelength upon which it arrives,

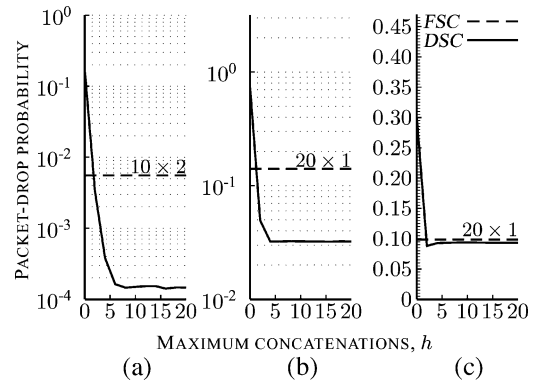


Fig. 3. Drop probability computed via simulation for $C = 25$, $K = 4$, and $Jd = 20$: (a) $a = 20$, (b) $a = 30$, and (c) $a = 45$.

and j is the number of unused converters at its arrival. Also, let (k, λ) denote wavelength λ of output fiber k .

DSC Switch Control Policy: At the arrival of a packet with attributes (k, λ_i, j) , if (k, λ_i) is unused, switch the packet directly to (k, λ_i) ; otherwise, for $\nu = 1, \dots, h$, if any (k, ω) is unused, where $\omega \in \mathcal{F}_i(\nu d)$, concatenate ν converters, switch the output of the endmost concatenated converter to any randomly chosen unused (k, ω) , switch the packet to the input of the first concatenated converter, update h such that $h \leftarrow h - \nu$, and break from the for-loop. Otherwise, block the packet.

IV. CONCLUSION

A marked improvement in packet-drop probability can be achieved by allowing shared converters to be dynamically concatenated. This improvement comes at the cost of a more complex switch architecture; specifically, complexity increases by 36%, as quantified by input-to-output port count, for the switch dimensions considered in Fig. 3.

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