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Performance Analysis of an Optical Packet Switch with Shared Parametric Wavelength Converters

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Abstract—Wavelength conversion capability has been shown to significantly improve the blocking performance of all-optical networks. In order to transport payloads that may be of different bit-rates and modulation formats, a transparent wavelength conversion method is desirable. Recently, parametric wavelength converters, that are capable of multi-channel wavelength conversion for heterogeneous optical services, have been experimentally demonstrated for optical circuits. In this letter, we analyse the performance of an asynchronous optical packet-switch (OPS) architecture that exploits such devices. A sensitivity analysis of the number of converters, as a function of the main switch design parameters, demonstrate a significant reduction in the number of converters when compared with architectures employing single-channel wavelength conversion.

Index Terms—Parametric wavelength conversion, optical packet switching, contention resolution.

I. INTRODUCTION

NETWORKS are experiencing continual growth in traffic demands leading to the development of new network architectures such as optical circuit-switched (OCS), burst-switched (OBS) and packet-switched (OPS) networks. In OPS networks, one of the main challenges is resolving packet contention in which two or more coincident packets are to be forwarded to the same output port of an optical packet switch. Several methods of resolving contention have been proposed, such as the use of fiber delay-lines (FDL), deflection routing and wavelength conversion which exploit the time, space and wavelength domain, respectively. Although these methods can be combined, it is generally accepted that wavelength conversion is the most effective technique [1].

For maximum benefit, an optical packet switch should be capable of transporting payloads consisting of heterogeneous services that may be of different bit-rates and modulation formats. Considering that wavelength conversion is the preferred method of contention resolution, three key design criteria can be identified: wide wavelength conversion range, multi-wavelength conversion capability and strict signal transparency. All-optical wavelength conversion can be accomplished using several methods, including: cross-gain modulation (XGM), cross-phase modulation (XPM), four-wave-mixing (FWM) and difference frequency generation (DFG)

[2]. Currently, only FWM and DFG match the above criteria. However, both techniques require the introduction of guard bands around the pump to suppress degradation of signals by parametric crosstalk [3]. Using FWM, the simultaneous wavelength conversion of 32 channels at 10Gb/s with a 12.8nm guard band (16 channels) was demonstrated [4]. Compared to FWM, DFG typically exhibits lower crosstalk over a wider wavelength range and hence smaller guard bands can be used. Recently, the use of DFG has been demonstrated for multi-channel wavelength conversion using quasi-phase-matched LiNbO₃ (QPM-LN) waveguides for 64 and 103 10Gb/s channels using guard bands less than 8nm [5],[6].

Although the above experiments were conducted in the context of optical circuit switching, the same concept can be applied to OPS networks. Several OPS node architectures have been proposed that support single-channel wavelength conversion [7]. When considering a space-switched architecture, a full wavelength convertible (FWC) architecture is usually assumed in which each wavelength at each input (or output fiber) has a dedicated tunable wavelength converter. This implies that a switch with F input (or output) fibers and W wavelengths per fiber would require FW wavelength converters. Although this architecture provides the best blocking performance, a large quantity of devices is required for large F and W . Depending on traffic conditions, it may not always be necessary for each optical packet entering the switch to be wavelength converted. In order to reduce the number of devices, it has been proposed that the optical packets that require wavelength conversion are switched to a pool of single-channel wavelength converters; these can be shared on a per-link (SPL) or per-node (SPN) basis [7].

In this letter, we propose and analyse a shared-per-node OPS architecture with parametric wavelength converters (PWC). The results demonstrate a significant reduction in the required number of converters when compared to equivalent architectures utilising conventional single-channel wavelength converters (CWC). The impact on the switch performance of the requirement for guard bands in the PWCs is also analysed.

II. SHARED-PER-NODE ARCHITECTURE WITH PARAMETRIC WAVELENGTH CONVERTERS (SPN-PWC)

Fig. 1 shows the proposed architecture with M parametric wavelength converters. To maximise the utilisation of the converter, x ($x \leq W$) outputs of the switch are aggregated by an $x : 1$ coupler allowing multiple packets to be admitted and simultaneously converted in the PWC. Although the packets exiting from the PWC could be demultiplexed before the switch, this has been avoided in order to minimise the number

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of optical components. Consequently, packets from the same parametric wavelength converter will be switched to the same output fiber. If M is the number of converters in the node, the proposed switch size will follow $(FW + M) \times (FW + xM)$.

To convert the wavelength of arriving packets, a continuous wave (CW) pump wavelength, λ_p is applied to the non-linear material (fiber/waveguide) resulting in a down-conversion to $\lambda_p/2$, by the parametric process. This mixes with the signal at λ_s to produce a wavelength converted signal at $2\lambda_p - \lambda_s$. The parametric conversion process is instantaneous and the conversion efficiency is symmetric in both directions.

Fig. 1 illustrates the mode of operation for a scenario in which four packets on λ_1 and λ_2 asynchronously enter the switch on fibers 1 and 2 and are to be forwarded to output fiber 1. The first two packets to arrive on InF_1 are switched directly through without conversion. The first packet to arrive on InF_2 contends with the λ_1 packet from InF_1 and wavelength conversion is required. Suppose PWC_M is unoccupied and a decision is made to convert this packet to λ_7 using PWC_M by setting $\lambda_p = \lambda_4$, as shown in Fig. 2(a). When the second packet arrives on InF_2 , PWC_M could also be used to convert the packet from λ_2 to λ_6 if λ_6 is available on $OutF_1$. Otherwise, another PWC must be allocated.

Since the selection of the appropriate PWC and the pump wavelength, (λ_p) define subsequent packet conversions, they are two important considerations that affect the overall switch performance. For the PWC selection, we assume that they are selected in a sequential order. Regarding the choice of pump wavelength, an important factor to be considered is the effect that the pump position has on the number of channels that can be converted. For example, when the pump is chosen to be in the middle of the transmission wavelength grid ($\lambda_p = \lambda_6$), as in Fig. 2(b), the maximum number of wavelengths can be converted (i.e. $\lambda_1 \Rightarrow \lambda_{11}$, $\lambda_2 \Rightarrow \lambda_{10} \dots$). However, as the pump wavelength approaches the edge of the grid as in Fig. 2(a), the number of possible conversions is reduced; this can severely impact the converter utilisation. For this reason, the pump selection algorithm attempts to set the pump wavelength as close as possible to the central wavelength.

A final consideration that has been examined in this letter is the impact of a guard band around the pump wavelength that is normally necessary due to crosstalk effects [6]. As illustrated in Figs. 2(a) and 2(b), the size of the guard band affects the number of usable wavelengths and the conversion range. For example, once λ_p has been set to λ_4 in PWC_M , λ_3 and λ_5 are not usable within PWC_M . The same is observed in Fig. 2(b) for λ_5 and λ_7 . The other implication is that the use of a guard band does not allow input signals to be converted to wavelengths that reside in the guard band. This has a similar effect as limited range wavelength conversion [7].

Given these considerations, blocking occurs when the wavelength (λ_w) of the arriving packet is occupied at the desired output fiber and no PWC is available to convert the signal to a free output wavelength. The availability of a PWC depends on whether it is occupied or not. An occupied PWC will be available if a) its output fiber coincides with the output fiber the packet is addressing; b) λ_w is outside the specified guard band; and c) the converted wavelength is free at the desired output fiber. An unoccupied PWC is available if the pump

Fig. 1. Shared-per-node architecture employing parametric wavelength converters.

Fig. 2. Parametric wavelength conversion process.

wavelength is appropriately allocated so that conditions b) and c) hold.

III. SIMULATION RESULTS AND DISCUSSION

A discrete event-driven simulator was constructed to investigate the performance of the proposed architecture. We simulated an OPS node with four input/output fiber ports ($F = 4$), each with 80 wavelengths ($W = 80$). The offered load is specified as the average traffic intensity per wavelength, where the capacity per wavelength is 10Gbps. The packet inter-arrival time and packet size are independent and exponentially distributed. The results are obtained using a load per wavelength of 0.6. In our analysis, incoming packets are not aligned in time and the traffic pattern is unicast i.e. any packet is destined to only one output fiber. Additionally, each

Fig. 3. Packet blocking probability as a function of the number of wavelength converters for different values of x , without guard band (guard band = 0) for SPN-PWC with respect to conventional architectures FWC and SPN-CWC. $F = 4$, $W = 80$ and $\rho = 0.6$.

Fig. 4. Packet blocking probability against the number of wavelength converters for $x = 8$ and different guard bands (guard band = 4, 8 and 16 channels) for SPN-PWC with respect to FWC and SPN-CWC. $F = 4$, $W = 80$ and $\rho = 0.6$.

arriving packet has the same probability to be sent to any output fiber.

Fig. 3 depicts the packet blocking probability for a given number of wavelength converters when $x = 2, 4, 8$ and 80 and no guard band assumed. To achieve the same performance as FWC (which requires $FW = 320$ CWCs), shared-per-node with conventional single-channel wavelength converters (SPN-CWC) require 50% fewer converters. The proposed SPN-PWC is shown to substantially reduce the number of converters required when PWCs are used and the number of inputs from the switch to the PWCs, x , is increased. For example, when $x = 2$, the number of PWCs required to achieve the same performance as SPN-CWC is 100, a 38% reduction in the number of converters. As x is increased to 4 and 8, it is observed that the required number of parametric converters is 70 and 60, a reduction of 56% and 63% respectively. As x tends towards W , the savings that can be achieved saturates at a value of 50 PWCs. Since x determines the size of the coupler and therefore the optical loss, $x = 8$ provides a good compromise for the number of inputs to the PWC.

We also analyse the impact on the switch performance when a guard band is considered around the pump to minimise crosstalk. As already discussed, the guard band reduces the number of possible conversion wavelengths and typical figures

are in the order of 4-8nm for DFG [6] and 12.8nm for FWM in fiber [4]. Assuming a channel spacing of 100-GHz, this corresponds to a range of 4 to 16 channels. Fig. 4 demonstrates the impact on performance of various guard bands for $x = 8$. It is interesting to note that when the guard band is 16, the blocking probability of the switch does not reach the achievable FWC blocking probability. This occurs due to the effect described in section II.

Clearly, the choice of the main switch design parameters and the PWC technology determine the overall switch performance. However, it is evident that such an architecture achieves similar blocking performance using fewer converters compared with architectures using single-channel wavelength converters.

IV. CONCLUSION

This letter presents the first attempt to analyse the performance of an OPS shared-per-node architecture employing parametric wavelength converters. The benefits of utilising multi-channel wavelength converters in an asynchronous optical packet-switch is verified through numerical simulations. The results demonstrate a reduction of 38 to 63% in the number of converters when compared with equivalent architectures employing shared single-channel wavelength converters. The blocking performance of the switch is shown to be sensitive to the width of the guard band associated with the parametric process and this will ultimately influence the choice of wavelength converter technology.

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