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Synchronous optical packet switch architecture with tunable single and multi-channels wavelength converters

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ABSTRACT

In this paper, we propose a bufferless synchronous optical packet switch (OPS) architecture named the Limited-range wavelength conversion with Dynamic Pump-wavelength Selection (LDPS) architecture. LDPS is equipped with a dedicated limited-range wavelength converters (LRWCs, and a shared pool of parametric wavelength converters (PWCs) with dynamic pump-wavelength selection (DPS). The adoption of hybrid conversion types in the proposed architecture aims at improving the packet loss rate (PLR) compared to conventional architecture with single conversion types, while reducing (or at least maintaining) the conversion distance (d) of used wavelength converters. Packet contention in the proposed architecture is resolved using the first available algorithm (FAA) and the dynamic pump-wavelength selection algorithm (DPSA). The performance of the proposed architecture is compared to two well-known conventional architectures; namely, the *LRWC architecture* that uses dedicated LRWCS for each input wavelength, and the *DPS architecture* that uses a shared pool of dynamic pump-wavelength converters (PWCs). Simulation results show that, for the same value of d, the new architecture reduces the PLR compared to the LRWC architecture by up to 40% and 99.7% for traffic loads, 0.5 and 1; respectively. In addition, for $d = 1$, the new architecture reduces the PLR compared to the DPS architecture by up to 10% and 99.3% for traffic loads, 0.5 and 1; respectively.

1. Introduction

Emerging computing and communication applications over the last decade has increased the need to adopt high-speed broadband transmission and networking technologies. Wavelength division multiplexing (WDM) have been intensively deployed over the last two decades to provide broadband transmission capability in both backhaul and metro networks. As the deployment of WDM technologies increases so does the need for switching capabilities that deal with the data transmitted over WDM networks.

Optical Packet Switching (OPS) has received an increasing attention over the last few years as a potential solution for new high-speed system and network solutions [1–4]. OPS can be implemented with either synchronous or asynchronous technique. In the former, the optical packets have the same size and aligned together each one time slot, whereas in the latter, the packets may or may not have the same size, in addition, packets are not aligned.

A key challenge in both synchronous and asynchronous OPS networks is *contention* [9,11]. Contention occurs when two or more incoming packets require the same output wavelength channel at the same time. In such a case, one or more packets may need to be dropped or queued for long time, which may result in a considerable degradation in the overall performance of the network. In particular, contention increases the packet loss rate (PLR) of the switch, which result in overall poor switching performance [21,30].

Several several OPS architectures attempt to reduce the overall contention by using fiber delay lines (FDLs), wavelength converters (WCs), or a combination of both [17,18,10,18,19,22]. FDLs are used to delay packets until the desired output channels are free, where as WCs are used to allow the change of the wavelength of contend packets to another wavelengths that are free on the desired output. A considerable research effort has focused on designing OPS architectures with various FDLs and WCs capabilities. However, most known architectures adopt in one way or another WCs to reduce the impact of contention, and thus, improve the switching performance.

Using WCs to design effective OPS architecture can be challenging due to the fact that converters are still expensive devices in optical networks. The overall complexity, and hence, the cost of an OPS is largely dependent on the structure and capability of the used WCs. For instance, an OPS that adopts a flexible full-range WCs, which can convert any input wavelength to any other

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wavelength, can largely improve the switching performance; but with an increased, and sometimes prohibitive, cost.

One of the key parameters that determine the overall complexity of WCs, and hence the complexity of the OPS architecture, is the *conversion range* (d). Conversion range refers to the distance between the minimum and the maximum wavelengths a wavelength converter can convert. Conversion range impact complexity by increasing the requirements for the required range for pump power tunability for the converter.

Most existing design approaches; however, either focus on reducing the overall number of converters regardless their range, or they attempt to reduce range but at an increased cost in space switching and number of stages in the network. It is therefore, desired to design OPS architectures that can exploit the capability of the various WCs types and technologies in order to reduce the conversion, and hence the switching, complexity.

The conversion range and tunability of converters depend on the WC technology used. For instance, conventional single-channel WCs are capable of converting only one incoming wavelength to another at a time. Whereas, parametric wavelength converters (PWCs) [6,7] are capable of simultaneously converting multiple wavelengths. In PWCs, a pump-wavelength λ_p is used to define both the original, λ_w and the converted $\lambda_{w'}$ wavelengths, such that $\lambda_p = \frac{\lambda_w + \lambda_{w'}}{2}$. The conversion pairs of the PWC is defined as the set of pairs of the original and the converted wavelength such that the pump-wavelength of that PWC is set in the middle of those wavelengths.

It has been shown in the literature that, as the conversion range increases, so dose the complexity; and hence, cost of the converter [5,7,9]. Thus, reducing the conversion range is one of the main goals when designing OPS architectures. Accordingly, in this paper, we attempt to achieve this goal by proposing a new OPS architecture with reduced PLR without increasing the conversion distance d. In particular, we propose a bufferless synchronous optical packet switch (OPS) architecture named the Limited-range wavelength conversion with Dynamic Pump-wavelength Selection (LDPS) architecture. LDPS is equipped with a dedicated limited-range wavelength converters (LRWCs, and a shared pool of parametric wavelength converters (PWCs) with dynamic pump-wavelength selection (DPS). Packet contention in the proposed architecture is resolved using the first available algorithm (FAA) and the dynamic pump-wavelength selection algorithm (DPSA). The performance of the proposed architecture is compared to two well-known conventional architectures; namely, the *LRWC architecture* that uses dedicated LRWCS for each input wavelength, and the *DPS architecture* that uses a shared pool of dynamic pump-wavelength converters (PWCs).

The reminder of the paper is organized as follows. Section II reviews known techniques for the contention resolution and basic concepts of WCs and PWCs. The proposed OPS architecture (LDPS) is presented in Section III. In Section IV, the matching algorithm used for packet scheduling in the proposed architecture is introduced. Simulation results and comparison with conventional architectures are resented in Section V. Conclusions are given in Section VI.

2. Background and basic concepts

In this section, we review key common techniques used for contention resolution in the conventional OPS architectures, and provide a brief overview of PWCs and its various types.

A common way to alleviate the cost of WCs in OPS architectures is to share converters among fibers or wavelengths. It has been shown that sharing can result in a considerable reduction in the used number of WCs. If the WC can be used by all incoming packets, it is called full sharing structure; whereas if each WC can only be used through a subset of the incoming packets, it is called partial sharing structure [8]. In Full sharing structure we have a dedicated tunable WC (TWC) for each output wavelength channel. Whereas in partial sharing structure, we have TWC shared among a number of wavelength channels.

TWC can be realized using two types of sharing: share-per-node (SPN) or share-per-link/fiber (SPL/SPF) [9]. In SPN, all WCs are collected in a converter pool, which can be shared by all the packets forwarded to any fiber. As a result, SPN structure can be implemented using Tunable-input/Tunable-output WCs. In SPF, as a special case, a share-per-input-fiber (SPIF) structure allows each input fiber to have a dedicated converter pool that can be only shared by those packets coming from that particular fiber. Contrariwise, a share-per-output-fiber (SPOF) structure allows each output fiber to have a dedicated converter pool that can be only shared by those packets going to that particular fiber. In [10], authors proposed a comparative study on scheduling algorithms for SPIF and SPOF architectures. Fixed wavelength converters are more common than tunable ones because they save tuning power resulting in a reduced implementation cost. A shared per wavelength (SPW) as a special case, a share-per-input-wavelength (SPIW) was proposed where Fixed-input/Tunable-output WCs (FTWC) are shared by the packets coming from the same input wavelength. Contrariwise, a share-per-output-wavelength (SPOW) was proposed where Tunable-input/Fixed-outputs WCs (TFWC) are shared by the packets going to the same output wavelength [11].

Also, the above segmentations can be combined together to form new architectures. For instance, fixed WCs with SPW structure and partial sharing degree was proposed and analyzed in [12,13]. Also, two switching models of tunable WCs, one was implemented with SPF partial sharing and another with SPN full sharing structures were first proposed in [14]. The above combined segmentations were all of synchronous single stage structure type. Recently, a trend to investigate the performance obtained by using multi-stage (e.g., Clos-type) switching networks has started. For this purpose, an architecture was proposed and analyzed in [15] with fixed WCs based on SPW structure, where all output channels on the same wavelength have a fixed WCs pool that can be fully shared by any packet needs to be converted to that specific wavelength.

OPS networks may support unicast traffic [16] or multicast traffic [17] or broadcast traffic [18], and Wavelength converters can be configured as Feed-Forward (FF) [10] or Feed-Back (FB) [18,19]. In [17], the authors provided a comparison between the multicast performance of the network with limited wavelength conversion to that with no wavelength conversion and full wavelength conversion capability.

TWCs can be classified according to their tuning ranges to Full Range TWCs (FR-TWC) and Limited Range TWCs (LR-TWC). FR-TWC can convert an input wavelength to any other wavelengths in the same network. By using LR-TWC, an input wavelength can be converted to a limited set of wavelengths on both upper and lower sides of its input wavelength. For synchronous networks, authors in [20] demonstrated that LR-TWCs can achieve almost the same performance as FR-TWCs. In [9], the authors proposed two architectures equipped with both limited-range wavelength converters and shared full-range wavelength converters.

Due to their lower complexity compared to FR-TWCs, LR-TWCs received more attention in the literature. Generally speaking, LR-TWCs can be classified into two basic types according to the conversion boundaries relationship; namely, circular-type and non-circular-type WCs. In circular-type, the converter allows wrap-around boundary wavelengths so that wavelengths near the upper boundaries are allowed to be converted to wavelengths on the lower boundaries and vice versa. That is, wavelengths near the