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State aggregation-based model of asynchronous multi-fiber optical switching with shared wavelength converters

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ABSTRACT

This paper proposes new analytical models to study optical packet switching architectures with multi-fiber interfaces and shared wavelength converters. The multi-fiber extension of the recently proposed Shared-Per-Input-Wavelength (SPIW) scheme is compared against the multi-fiber Shared-Per-Node (SPN) scheme in terms of cost and performance for asynchronous traffic. In addition to using Markov chains and fixed-point iterations for modeling the mono-fiber case, a novel state aggregation technique is proposed to evaluate the packet loss in asynchronous multi-fiber scenario. The accuracy of the performance models is validated by comparison with simulations in a wide variety of scenarios with both balanced and imbalanced input traffic. The proposed analytical models are shown to remarkably capture the actual system behavior in all scenarios we tested. The adoption of multi-fiber interfaces is shown to achieve remarkable savings in the number of wavelength converters employed and their range. In addition, the SPIW solution allows to save, in particular conditions, a significant number of optical gates compared to the SPN solution. Indeed, SPIW allows, if properly dimensioned, potential complexity and cost reduction compared to SPN, while providing similar performance.

1. Introduction

In recent years, optical switching technology has entered a mature phase to support the ever growing bandwidth demands of user applications [1]. At the same time, emerging and future Internet-based services [2,3] to support these user applications call for enhanced flexibility and reconfigurability in transport networks. Packet-based optical networking based on either optical packet switching or optical burst switching, is the most suitable solutions to achieve high network reconfiguration capability and flexibility and has been widely studied and demonstrated as feasible in the last decade [2,4].

One of the main drawbacks of packet-based optical networking is represented by contention which arises as a consequence of the need for resource sharing for optical packets within the network nodes. In conventional electronically switched networks, packet contention is solved in time domain by queuing packets and allowing resource sharing on a time division multiplexing basis. Unfortunately, queuing is not straightforward in optical switching with current optical technologies and contention is instead typically addressed by exploiting wavelength and space domains. Wavelength Converters (WCs) are employed in optical packet/burst switching to exploit the wavelength domain with the purpose of contention resolution. As a matter of fact, when two or more optical packets simultaneously need the same forwarding resource (optical gate, fiber interface, splitter/combiner, etc.) within a node, different wavelengths are used to encode them, by wavelength converting some of the optical signals, thus avoiding wavelength contention [5].

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However, in spite of the progress in optical fabrication technology, all-optical WCs are still considered complex and expensive components [1]. For this reason, it is important to limit the number of WCs employed and try to exploit as simple WCs as possible in terms of implementation. In particular, WCs differ on the basis of their tunability and wavelength conversion range. In general, it can be assessed that fixed WCs are simpler to be fabricated with respect to tunable ones [6]. Furthermore, it has been demonstrated that the quantity and type of WCs employed to obtain a given packet loss performance are related to the specific switch architecture [7].

In order to reduce the number of WCs employed, different schemes for sharing WCs inside an optical switching node have been proposed in the past [8]. In particular, the Shared-Per-Node (SPN) sharing scheme provides the best packet loss performance since WCs are shared among all the incoming packets [8,9]. However, SPN requires tunable-input/tunable-output WCs, being the most complex type of WC, and also a relatively large number of optical gates to connect them. To simplify the complexity of the SPN scheme, the Shared-Per-Input-Wavelength (SPIW) optical switching architecture has been introduced which employs fixed-input/tunable-output WCs [10]. In this architecture, for each wavelength, there is a separate pool of WCs that can be used by all optical packets arriving on this particular wavelength. The SPIW architecture has been demonstrated to have superior properties in regards with its feasibility (fewer optical gates required) [11], power consumption [12] and complexity [9], while performing quite close to the shared-per-node architecture [7,9], as demonstrated in recent research studies [13,14].

The conversion range required by each WC is related to the number of wavelength channels supported by each fiber interface. The adoption of multi-fiber interfaces allows to repeat the same wavelength as many times as the number of fibers allocated at each interface, being them spatially separated [15]. This solution was studied in the past in WDM circuit-switched networks to optimize resources in transport networks [16,17]. Recently, multi-fiber solutions based on the SPN and SPIW sharing scheme have been presented [9] in synchronous setting. Even though the synchronous operation mode guarantees better packet loss performance within a node than the asynchronous one, it requires expensive and complex synchronizers at the input channels. Moreover, synchronous operation requires in general a more complex management at network level. Hence, it is crucial to analyze the performance of the SPN and SPIW schemes in the simpler asynchronous operation. To the best of our knowledge, the study of the multi-fiber SPIW has not yet been performed in asynchronous context in the existing literature. Only the multi-fiber SPN solution has been studied with asynchronous operation [18], so the present paper proposes an analysis of the multi-fiber SPIW and a comparison between the two. Multi-fiber SPIW architecture seems to be attractive in asynchronous operation since it has promising properties in terms of feasibility and power consumption, together with the possibility to limit the conversion range [19]. In the remainder of this paper, the two architectures considered will be referred to as A-MF-SPN (Asynchronous Multi-Fiber Shared-Per-Node) and A-MF-SPIW (Asynchronous Multi-Fiber Shared-Per-Input-Wavelength).

Based on previous motivations, the A-MF-SPIW switch architecture which shares fixed-input WCs is investigated in this paper to analytically obtain the packet loss performance. A similar kind of comparison was presented in [7] for the mono-fiber case whereas the current paper concentrates on the impact of multi-fiber switch interfaces. The assumptions behind the analytical model are:

- Optical packet arrivals to the switch are Poisson.
- Packet lengths are exponentially distributed.
- Packet traffic is allowed to be imbalanced across destination interfaces.
- Packet traffic is balanced across incoming wavelengths.

This paper is an extension of a recently published work in [14] where the analytical model for packet loss evaluation of the A-MF-SPIW scheme has been briefly presented. Compared with the work in [14], in this study:

- A complete description of a novel state aggregation technique to cope with multi-fiber interfaces is presented. Although various state aggregation schemes are available for studying large Markov chains, a state-aggregation method, specifically applied to the problem of interest, is proposed.
- The model is extended to cover the imbalanced input traffic case and to the analysis of the A-MF-SPN scheme as well.
- Validation section is provided where both A-MF-SPIW and A-MF-SPN models are compared with simulation, highlighting the accuracy achieved.
- Relying on the analytical models, the two architectures are extensively compared in terms of both packet loss performance and complexity, highlighting how the A-MF-SPIW not only exploits fixed-input WCs but also requires fewer optical gates in different configurations.
- Again, using the analytical model only, the achievable throughput for both architectures as a function of the number of fibers per interface is evaluated.

The paper is organized as follows. Section 2 describes the A-MF-SPN and A-MF-SPIW architectures and introduces related formulas for complexity evaluation. Section 3 presents the state aggregation-based methodology to calculate the packet loss probability in A-MF-SPN and A-MF-SPIW. Section 4 discusses model validation, performance comparison and complexity evaluation with respect to the main switch parameters. Finally, Section 5 provides the conclusions of this work.

2. A-MF-SPN and A-MF-SPIW architectures

This section provides the description of the two multi-fiber architectures considered in this paper. Section 2.1 introduces the A-MF-SPN architecture and Section 2.2 describes the A-MF-SPIW architecture.