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Performance analysis and dimensioning of multi-granular optical networks☆

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ABSTRACT

Recent years have demonstrated the limited scalability of electronic switching to realize transport networks. In response, all-optical switching has been identified as a candidate solution to enable high-capacity networking in the future. One of the fundamental challenges is to efficiently support a wide range of traffic patterns, and thus emerges the need for equipment that is both practical and economical to construct and deploy. We have previously proposed the use of multi-granular optical cross-connects (MG-OXC), which support switching on both the wavelength and sub-wavelength level. To this end, the MG-OXCs are equipped with cheap, highly scalable slow switching fabrics, as well as a small number of expensive fast switching ports. The goal of this work is two-fold: first to demonstrate that a small number of fast switching ports suffices to support a wide range of traffic requirements, and second that multi-granular optical switching can offer cost-benefits on a network-wide scale. The first objective is studied through simulation analysis of a single switching node, and results indicate that a limited number of fast switching ports can significantly improve burst blocking performance over slow only switches. Furthermore, under certain circumstances, the MG-OXC can even approach the performance of a fast only switch design. Secondly, we introduce an Integer Linear Programming model for the total network installation cost, and our evaluation indicates that multi-granular optical switching can be a cost-effective solution on the network level, in comparison to slow only or fast only approaches. Furthermore, we can achieve reduced costs of individual OXC nodes, which allows us to minimize scalability problems corresponding to emerging fast switching fabrics.

1. Introduction

Optical networks have a proven track-record in long-haul, point-to-point networking, where large amounts of data are transported in a cost-effective way. An enabling technology is Wavelength Division Multiplexing (WDM), as it allows multiple signals (wavelengths) concurrent access to a single fiber. However, interest is growing to use optical networks in edge and even access networks (e.g. Fiber To The Home or FTTH), mostly because of the predictable performance of photonic technology (i.e. high bandwidth, low latency). A major issue is O/E/O (optical/electronic/optical) conversions in the network, because the speed of electronic processing cannot match the bandwidths currently offered in the form of wavelengths of 40 Gbps and higher. For this reason, most current research is focusing on all-optical networking solutions.

As of today, it is possible to create all-optical networks through the use of circuit-switched paths, which essen-

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tially reserve one or more full wavelengths between end points. For instance, Lambda Grids is a general term to refer to Grid applications making use of wavelengths (i.e. lambdas) to connect high-performance computing sites over an optical network [1]. However, novel applications are appearing which demand a much more fine-grained access to bandwidth capacity, as is demonstrated for instance in consumer Grids [2]. In such a scenario, data sizes become smaller, since aggregation of multiple data sources is much harder, and the bandwidth utilization would drop dramatically if full wavelengths were used by these applications. Consequently, the network must support reservation and allocation of bandwidth on a sub-wavelength scale. In this paper, we propose a generic multi-granular optical switch architecture, which supports both circuits (wavelength level) and bursts (sub-wavelength level).

This paper will investigate the specific details of realizing optical networking solutions that allow efficient transfer of both large (circuit) and small scale (burst or packet) data sizes. This is useful for future optical (possible Grid) deployments, which must support a new and emerging generation of distributed network-based applications that combine scientific instruments, distributed data archives, sensors, computing resources and many others. Each application has its own traffic profile, resource usage pattern and different requirements originating in the computing, storage and network domains [3]. Dedicated networks do not offer sufficient flexibility to satisfy the requirements of each application type, nor are they economically acceptable. Hence it is vital to understand and redefine the role of networking, to support applications with different requirements and also offer service providers a flexible, scalable and cost effective solution. A dynamic optical network infrastructure with the ability to provide bandwidth granularity at different levels is a potential candidate. In this way, the network can adapt to application requirements and also support different levels of Quality of Service (QoS). However, care must be taken to devise a solution that remains scalable and cost effective.

More specifically, we define a *multi-granular optical switched network* as a network that is able to support dynamic wavelength and sub-wavelength bandwidth granularities with different QoS levels. As such, the network will support the three basic switching technologies in WDM networks; optical circuit switching (OCS), optical packet switching (OPS) and optical burst switching (OBS). In order to support these switching approaches, optical switching fabrics with speeds in the millisecond range down to the nanosecond range must be considered. As we will demonstrate in the following section, OCS can utilize millisecond switching technologies efficiently, whereas this switching speed causes bandwidth inefficiency and unpredictability for the performance of OBS. This is mainly caused by the high overhead incurred by the large offset times required to configure slow switches. Consequently, fast switching fabrics should be introduced in the network.

The ideal solution would thus consist of deploying fast switches of large dimension; however current technology can only realize fast fabrics of limited scalability at a very high cost (for more details, a review of existing switching technologies is provided in [4,5]). Therefore, one possible solution is an optical cross-connect (OXC) which combines both slow and fast switching elements, with careful consideration of scalability and cost properties. Furthermore, users and applications can decide on slow or fast network provisioning, and additionally the network service provider can optimize bandwidth utilization by allocating wavelengths or lightpaths according to the traffic's switching needs.

In summary, the multi-granular OXC (MG-OXC) has a number of distinct advantages over traditional single-fabric switches:

- Bandwidth provisioning and switching capability at fiber, wavelength and sub-wavelength granularities;
- Agility and scalability of switching granularities providing a dynamic solution;
- Fast reconfigurability and flexibility on the electronic control of switching technologies;
- Cost-performance efficiency by offering an optimal balance between slow and fast switch fabric technologies.

A number of authors has previously investigated multi-granular optical networks, although these generally focused on granularities higher than a single wavelength. For instance, multiple proposals have advocated the use of a multi-layer cross-connect to allow wavelength, waveband and even fiber switching [6,7]. In contrast, this work is the first to introduce multi-fabric cross-connects supporting wavelength and sub-wavelength switching in a single network layer. Furthermore, our solution contrasts with multi-layer approaches, such as IP over WDM, where multiple layers of control are introduced to support the wide range of traffic parameters. A related subject is the design of the optical path layer in networks with cross-connects; this issue is usually denoted as the routing and wavelength assignment (RWA) problem [8,9]. The complexity increases when considering multi-granular traffic, and two important subproblems can be identified: traffic grooming in optical networks [10,11], and the RWA-problem for multi-granular traffic (wavelength-scale and higher, i.e. waveband and fiber) [12]. Other research has focused on technological design choices of node design [13], and dimensioning of individual nodes, such as [14]. In contrast, the algorithm presented in Section 4 focuses on optimizing total network and individual node costs, by appropriate routing decisions in a multi-granular (wavelength-scale and below) optical network.

The remainder of this paper is organized as follows. Section 2 further elaborates on the need for multi-granular switching, along with an indication of the most important challenges associated with the concept. Simulations are then used to evaluate a generic MG-OXC design for various traffic and design parameters in Section 3. A dimensioning study for the optimal design of a multi-granular optical network is presented in Section 4, while the concluding Section 5 summarizes our findings and discusses a number of remaining challenges.