Dimensioning of Combined OBS/OCS Networks

(Invited Paper)

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***Abstract*—To cope with ever-increasing traffic demands in transport networks, all-optical switching is currently perceived as a potential solution to remove bottlenecks caused by opto-electronic conversions. An effective realization of this concept must support a wide range of traffic patterns, while remaining feasible to construct and deploy both in an economical and practical sense. In this paper, we propose 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 main goal of this work is to motivate the use of multi-granular switching, as this can reduce total network installation costs. To this end, we introduce an Integer Linear Programming model, and our evaluation demonstrates 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.**

I. 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. 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 can not match the bandwidths currently offered in the form of 40 Gbps and higher. For this reason, 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 essentially reserve one or more full wavelengths between end points. For instance, Lambda Grids are 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. However, novel applications are appearing which demand a much more fine-grained access to bandwidth capacity, as is demonstrated for instance in consumer Grids [1]. 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 to be 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 hybrid optical switch architecture, which supports both circuits (wavelength level) and bursts (sub-wavelength level).

Previous work on hybrid optical switching can be classified in two main research tracks. First, several efforts propose performance models for hybrid optical nodes, focused on achieving accurate and scalable logical (as opposed to physical layer) performance calculation [2], [3], [4], [5]. Further research has targeted the possible improvements by using hybrid optical in contrast to single-technology approaches [6], [7]. However, only recently work has appeared which shows initial studies on the architecture and design of such hybrid optical switches [8]. In contrast, this work presents an attractive motivation to deploy hybrid optical switching, as we demonstrate that it allows important cost-savings in comparison to single-technology switching solutions.

Our results can be used as guideline for the design and optimization of optical transport networks. To this end, our work starts from a generic model for an MG-OXC, allowing us to to make very general assumptions while still drawing important conclusions, valid for a wide range of switch designs. This is achieved by developing an Integer Linear Program (ILP) model, accurately captures wavelength and sub-wavelength routing. We propose two objective functions to minimize either the total network installation cost, or the cost of the largest node. Results indicate multi-granular switching to be a cost-effective solution, and

The rest of this paper is structured as follows. In Section II we discuss in detail the problems related to construction and performance optimization of an optical switch, and present a generic model for the design of a hybrid optical switch. We proceed in Section III by discussing the problem statement as considered in this paper, i.e. network-level cost optimization to support multi-granular demands. The subsequent section presents our Integer Linear Programming model, and discussed its complexity and applicability for various switch designs. In Section V we evaluate the model for in a number of scenarios, while our conclusions are presented in Section VI.

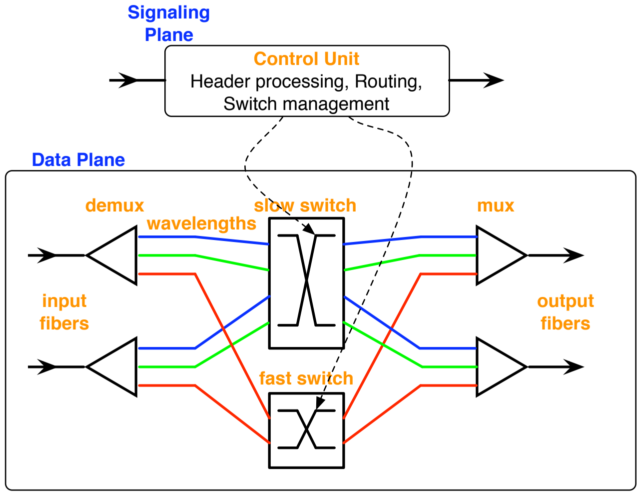

Fig. 1. Multi-granular optical switch supporting wavelength and sub-wavelength switching

II. Multi-Granular Optical Switching

In a previous section, we have motivated that multi-granular switching supports various application and QoS requirements on a common transport network infrastructure. In our previous work, we have demonstrated that an MG-OXC can offer improved blocking performance for even a small number of fast ports [9].

Figure 1 presents the generic design of a multi- granular optical cross-connect (MG-OXC). The switch is composed of two separate switching fabrics. Current optical switching technologies offer a broad range of switching speeds, but faster switching speeds generally have two distinct disadvantages: cost and scalability. For instance, micro-electromechanical switches (MEMS) have a typical switching time in the millisecond range, while it is technologically feasible to produce port counts of for instance 1000x1000. In contrast, Semiconductor Optical Amplifier technology (SOA) can only scale up to 32x32 port counts at very high cost, but at the same time can achieve switching speeds in the nanosecond range. Hence, cost-effectiveness is an important driver for MG-OXC designs requiring only a limited amount of expensive fast switching components. As our results show, even a minimal amount of fast switching fabrics can achieve considerable improvements in network performance.

A final note is related to the practical realization of the MG-OXC, where several architectural choices remain an open research challenge. For instance, a sequential design (where the fast switching fabric is cascaded behind the slow fabric), allows reconfiguration of the fast wavelengths, at the expense of an increase in dimensionality of the slow switch. The design depicted in Figure 1 places the two switching fabrics in parallel, and as such loses its reconfigurability for a slightly smaller slow switching matrix. In Section V, we will demonstrate that allowing reconfigurability of fast wavelengths has a negligable influence on the total network cost. Refer to [10] for further details regarding the architecture and performance of the multi-granular OXC.

In the following, we will show that multi-granular switching also provides economic advantages on the network level. For this, a model for dimensioning a multi-granular optical network will be proposed, and results are obtained that illustrate the possible reductions in total network cost and improvements with regard to node scalability.

III. Problem Statement

Assume the network is composed of OXCs, capable of switching circuits or slow bursts on millisecond scale (slow MEMS switch), and fast bursts or packets on a nanosecond scale (fast SOA switch). Likewise, traffic is generated by clients requiring both fast and slow switching. This corresponds to OBS for fast traffic, where multiplexing of different bursts on a single wavelength is allowed, and OCS for slow traffic, where end-to-end lightpaths are reserved exclusively for the endpoints. The question arises how to dimension the network for a static traffic demand and a pre-determined fraction of fast and slow traffic. The main objective is to minimize the network's cost, given a price ratio of slow over fast port costs. Another objective is to reduce the cost of the cross-connect with the highest cost, and as such obtain reduced node complexity.

The first reduction of the problem lies in the realization that we can split the network planning decision for slow and fast traffic. To reduce the number of fast ports (and thus minimize costs and scalability issues), slow traffic will be switched exclusively by slow switches, and thus this minimum cost network flow problem can be solved independently with known algorithms [11]. We do not consider this problem, and as such only need to plan the network for the remaining fast traffic. This fast traffic can be switched in one of the following ways: either on a fast switch, which can be shared between different demands[1], or on a slow switch which is then exclusively reserved for that particular demand.

Note that the proposed model does not incorporate wavelength assignment, mainly because of complexity issues. Thus, in principle this model assumes full wavelength conversion is available in each OXC, which has consequences for the economics of the obtained solutions [12]. Otherwise, an additional wavelength assignment step is required; an overview of optimal and heuristic approaches to this problem can be found in [13], [14]. We now proceed to the actual model, which has been formulated as a Linear Integer Programming model (ILP). The appeal of a linear model is that it allows the use of general purpose techniques (simplex and interior-point methods) to find optimal solutions.

IV. Linear Model

The following notations are introduced:

- directed graph $G(V, E)$, V the set of nodes, and E the set of directed links

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[1] Sharing bandwidth among different demands is usually denoted as *grooming*.

- each wavelength has a fixed bandwidth B, identical for all links and wavelengths
- Λ^{sd} is the fixed demand (fraction of bandwidth B) between source s and destination d
- C represents the cost ratio of fast over slow switches
- the possible paths between source s and destination d are determined in advance, and are represented by the boolean parameters $\pi^{sd}_{pl} = 1$ iff link l is part of path p between source s and destination d, 0 otherwise.

The following boolean decision variables are introduced to determine the path p to use for demand Λ^{sd}, and whether to use slow or fast switching:

$$\delta^{sd}_p = \begin{cases} 1 & \text{demand (s,d) uses slow switching on path p} \\ 0 & \text{otherwise} \end{cases}$$

$$\epsilon^{sd}_p = \begin{cases} 1 & \text{demand (s,d) uses fast switching on path p} \\ 0 & \text{otherwise} \end{cases}$$

The integer variables x_l and y_l represent the number of slow and fast switching wavelengths on link l, and are given by:

$$\forall (s,d), p: \quad x^{sd}_p \geq \Lambda^{sd}\delta^{sd}_p \tag{1}$$

$$\forall l: \quad x_l = \sum_{sd}\sum_{p} \pi^{sd}_{pl} x^{sd}_p \tag{2}$$

$$\forall l: \quad y_l \geq \sum_{sd}\sum_{p} \pi^{sd}_{pl} \Lambda^{sd} \epsilon^{sd}_p \tag{3}$$

The auxiliary variables x^{sd}_p (integer-valued) represent the number of slow wavelengths required to carry the demand Λ^{sd}. Clearly, slow switching corresponds to reserving end-to-end circuits that are exclusively accessed by the source and destination, while fast switching allows grooming of traffic on a link-by-link basis. The following contraints enforce two requirements: (1) each demand can only use a single path, thereby excluding solutions based on multi-path routing, and (2) a demand is either switched slow *or* fast, but not both.

$$\forall (s,d): \sum_p (\delta^{sd}_p + \epsilon^{sd}_p) = 1. \tag{4}$$

The final step to obtain total network cost is to transform the variables for the wavelength count on each link $l = (u, v)$ (u and v represent nodes), into ports counts for each node n. For the slow port count, this is achieved as follows (similar equations are necessary for the fast port counts y_n):

$$\forall n \cdot x_n = \sum_m (x_{(m,n)} + x_{(n,m)}). \tag{5}$$

The first objective we propose is to minimize the total installation cost of the network, which in large part depends on the total number of installed switching ports:

$$\min \sum_n (x_n + Cy_n). \tag{6}$$

A related objective function is to minimize the cost of the most expensive cross-connect. This objective is motivated by the limited scalability of OXC designs, especially when based on fast switching fabrics. This objective can be stated more formally as:

$$\min z \quad \text{where } \forall n \cdot z \geq x_n + Cy_n. \tag{7}$$

A. OXC Architectures

In this section, we demonstrate how the proposed model can be adapted to support the different OXC architectures that were presented in [10] . More precisely, we show how slow only, fast only and the MG-OXC alternatives (parallel vs. sequential) can be incorporated in the model.

First of all, note that the model captures two related ILP problems, corresponding to scenarios in which either only slow or only fast switching is used. Indeed, in case $\forall (s,d), p: \epsilon^{sd}_p = 0$, all demands will be served by a slow only connection (i.e. $y_l = 0$). Likewise, in case $\forall (s,d), p: \delta^{sd}_p = 0$, only fast ports will be used ($x_l = 0$).

Furthermore, observe that in case slow only switching is used, the objective function (6) can be simplified to:

$$\begin{aligned} \sum_n (x_n + Cy_n) &= \sum_n x_n \qquad (8) \\ &= \sum_{n,m}\sum_{sd}\sum_{p} \lceil \Lambda^{sd} \rceil (\pi^{sd}_{p(n,m)} + \pi^{sd}_{p(m,n)}), \end{aligned}$$

which corresponds to the use of shortest path routing for all demands. This is however not the case when objective function (7) is used.

To differentiate between the parallel and sequential MG-OXC approaches, the number of slow ports in the latter case is given by:

$$\forall n: x^*_n = x_n + 2\sum_m y_{(m,n)}. \tag{9}$$

This corresponds to the allocation of additional slow ports for each incoming fast wavelength that is introduced in a cross-connect. In the following section, we will demonstrate that network cost is only slightly increased, as a limited number of additional slow ports suffice to allow the configurability offered by the sequential switch designs (see [10] for more details).

B. Complexity

Table I summarizes the complexity of the different ILP models. Here, N represents the number of OXC nodes, L the number of network links, D the number of demands (at most $N \cdot (N-1)$), and P the number of paths that are considered for each demand (assumed identical for all demands). Observe that MG parallel and MG sequential have an identical complexity. The table lists the complexity when objective function (6) is used. When minimizing the highest node cost, the number of variables is increased by 1, and an additional N constraints are introduced.

Design	**Variables**	**Constraints**
Slow only	$2 \cdot D \cdot P + L + N$	$D \cdot (1 + P) + L + N$
Multi-granular	$3 \cdot D \cdot P + 2 \cdot L + 2 \cdot N$	$D \cdot (1 \cdot P) + 2 \cdot L + 2 \cdot N$
Fast only	$D \cdot P + L + N$	$D + L + N$

TABLE I

COMPLEXITY OF ILP MODEL FOR DIFFERENT OXC DESIGNS

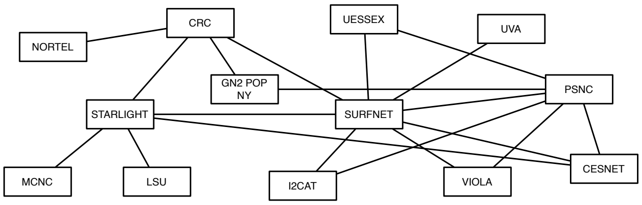

Fig. 2. Phosphorus topology

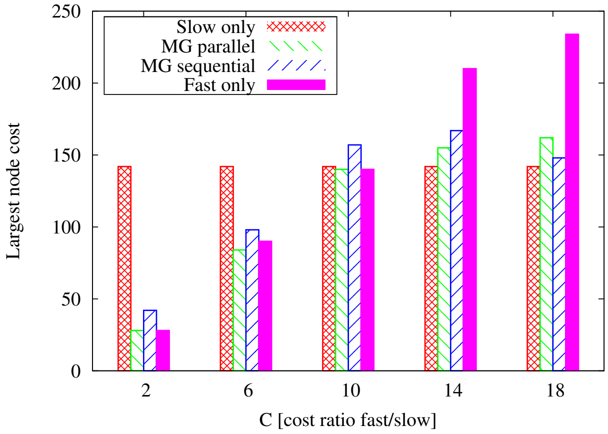

Fig. 3. Largest node cost for minimized total network cost

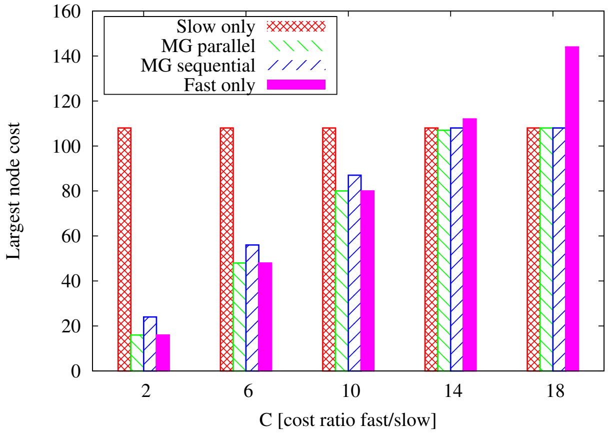

Fig. 4. Minimized largest node cost

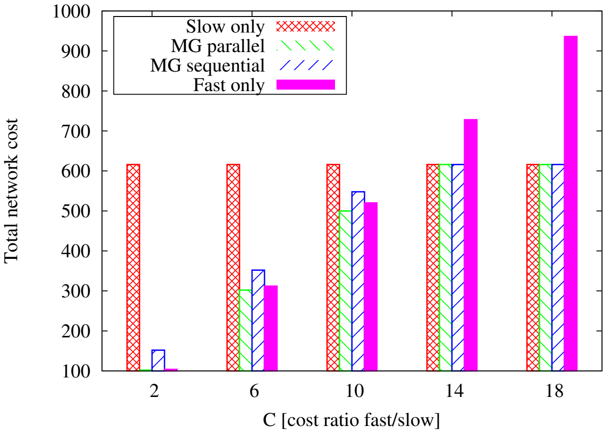

Fig. 5. Minimized total network cost

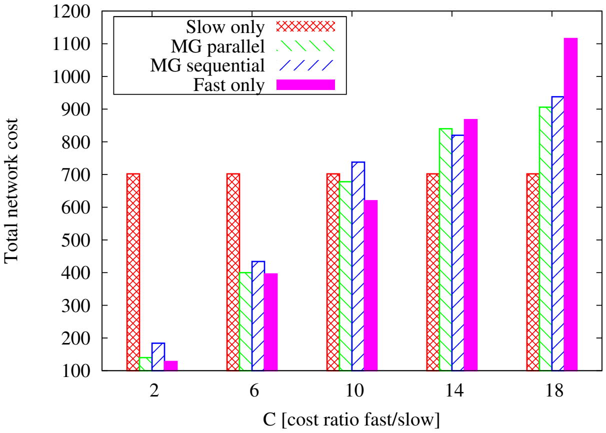

Fig. 6. Total network cost for minimized largest node cost

V. EVALUATION

The ILP-formulated problems were implemented and solved through the use of the ILOG CPLEX library. All OXC design approaches are evaluated, including slow only, fast only, and both multi-granular (parallel and sequential) architectures. Results are obtained for a specific scenario, defined by the Phosphorus topology depicted in Figure 2. The traffic demand matrix is fixed, and consists of uniformly generated traffic between all source-destination pairs with average $\Lambda = .05$. The low traffic demands are established in order to maximize the influence of traffic grooming; observe that when shortest path routing is used for the given topology, the maximum number of demands making use of the same link is 15. To reduce computational complexity, we only considered the 5 shortest paths for each demand; this suffices for the topology considered, as the maximum distance between any node pair is 4 hops. Results show the total network cost and highest node cost, for both objective functions (6) and (7).

Comparing the total network cost when minimizing either total network cost (Figure 5) or highest node cost (Figure 6), a number of interesting observations can be made. First, note that slow only returns constant network costs, due to its independence of cost ratio C. As expected, minimizing the highest node cost slightly increases total network cost when compared to objective (6). Furthermore, MG sequential produces total network costs at least as large as MG parallel when minimizing network cost, although this is not the case when minimizing the highest node cost. Finally, for high values of C, the multi-granular approaches return identical results as the slow only design when using objective (6). In summary, significant cost savings are possible when using multi-granular optical switching, in comparison to slow only or fast only switching. Also, introducing reconfigurable fast wavelengths through the MG sequential design will only slightly increase total network cost.

We now consider the highest node cost when minimizing total network cost (Figure 3) or highest node cost (Figure 4). Again slow only produces constant results, but lower values are achieved by optimizing for objective (7). Observe that MG sequential returns highest node costs lower than MG parallel, only when minimizing the highest node cost. Multi-granular optical switching can thus clearly reduce the highest node cost, and consequently improve node complexity which is critical for scalability issues.

VI. CONCLUSIONS

This paper demonstrated the need for multi-granular optical switching, and described and analyzed a generic multi-granular optical cross-connect. This work positioned to motivate the concept, by demonstrating the possible advantages for total network cost and node complexity. To this end, an ILP-based network dimensioning algorithm was introduced, and results indicated that significant cost savings can be obtained when implementing multi-granular optical switching. Furthermore, reduced node costs can be achieved as well, in order to minimize scalability problems corresponding to emerging fast switching fabrics.

A number of research challenges remain before multi-granular switching becomes a practical technology for deployment in the field. An open research challenge is a protocol for wavelength assignment and reconfiguration on the network level. Relevant objectives could be to minimize the number of expensive, fast wavelengths, to improve bandwidth utilization, or to reduce the influence of wavelength reconfigurations on existing traffic. Furtermore, bandwidth efficiency could be improved even further by combining (sub-)wavelength switching with waveband or even fiber-based switching. Another point of interest is an extensive dimensioning study on MG-OXCs, investigating issues such as traffic variability, multiple (> 2) switch fabrics, physical layer constraints (e.g. signal loss, BER), etc. Finally, the presented network dimensioning algorithms are based on ILP which does not scale properly for larger networks. Heuristic techniques are thus required in order to plan and dimension either new or existing, large-scale optical networks.

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