Using tunable optical transceivers for reducing the number of ports in WDM/TDM networks

Eytan Modiano
Lab. for Information and Decision Systems, MIT, Cambridge, MA 02139, USA
modiano@mit.edu

Randall Berry
Dept. of ECE, Northwestern Univ., Evanston, IL 60208, USA
rberry@ece.northwestern.edu

Abstract: We consider the benefits of using tunable transceivers for reducing the required number of ports in WDM/TDM optical networks. We show that tunable transceivers can be used to efficiently "groom" subwavelength traffic and significantly reduce the number of ports compared to the fixed tuned case. We provide a new formulation for this "tunable grooming" problem and develop algorithms for designing such networks.

OCIS codes: (060.4250) Networks; (060.0060) Fiber optics and optical communications

1. Introduction

In a WDM/TDM optical network each fiber link supports multiple wavelength channels operating at a given bit rate, e.g., 2.5 Gbps (OC-48) and sub-wavelength traffic is time-division multiplexed onto a wavelength. A significant design consideration for such networks is reducing the number of ports required at each node in the network, where a port refers to the combination of optical transceivers and electronic terminal equipment needed to access a wavelength. There has been much interest in the reducing this requirement by efficiently *grooming* the low rate traffic so that only a subset of the available wavelengths must be electronically processed at any node, while the remaining wavelengths optically bypass the node. Most of the work on grooming has focused on the case where optical transceivers are fixed tuned and so a fixed subset of wavelengths are dropped at a each node; each dropped wavelength requiring an electronic port (e.g. a SONET ADM). The basic traffic grooming problem, as in [1-5], is then to assign a given traffic requirement to wavelengths so that the total number of needed ports is minimized. The general traffic grooming problem has been shown to be NP-complete [1]; however, optimal algorithms have been found for several special cases, and a variety of heuristic algorithms have also been presented.

We consider a different approach to designing WDM/TDM networks based on using tunable optical transceivers, where these transceivers can be tuned from TDM time-slot to time-slot. This complements work on *reconfigurable* WDM networks, where tunable components are used to change the virtual topology in response to traffic variations or for protection purposes. One goal of this work is to highlight a different advantage of tunable components - they can be used to to significantly reduce the required number of ports over an architecture with fixed tuned transceivers, even with a static traffic requirement. This approach requires transceivers to be tunable from time-slot to time-slot. Hence, with time-slots on the order of μs, these devices must be able to tune in sub-μs time. Presently fast-tunable transceivers are much more costly than their fixed tuned counterparts. It is reasonable to expect that as demand for tunable components increases their cost will continue to drop. Also, as we show in this paper, the use of tunable transceivers can reduce the total required amount of hardware in the network (both optical and electronic); this savings may justify their use.

2. Network Model

Consider a network with N nodes numbered $1, \ldots, N$. On each wavelength in the network, up to g low-rate circuits can be time division multiplexed; the parameter g is referred to as the traffic granularity. A static traffic requirement for the network is given by an $N \times N$ matrix $R = [R_{i,j}]$, where $R_{i,j}$ indicates the number of circuits required from node i to node j. For simplicity, we assume that all traffic requirements are *symmetric* , i.e., $R_{i,j} = R_{j,i}$ for all i, j; this represents the case where all connections are bi-directional. Each node i generates $W_i = \sum_j R_{i,j}/g$ (fractional) wavelengths of traffic. Hence, to support the traffic requirement, node i must have at least $\lceil W_i \rceil$ optical transceivers. Also for simplicity, we focus in this paper on the case of unidirectional rings; although, many of our results are applicable to general network topologies. Let W_{min} denote the minimum number of (fractional) wavelengths needed

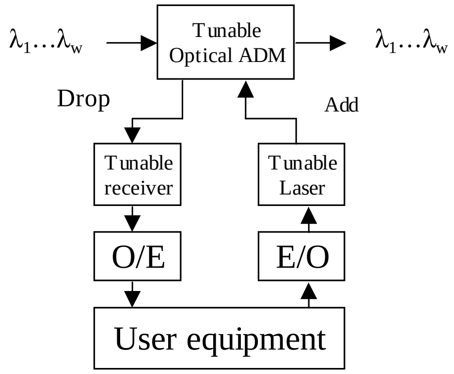

Fig. 1: An example node with tunable transceiver.

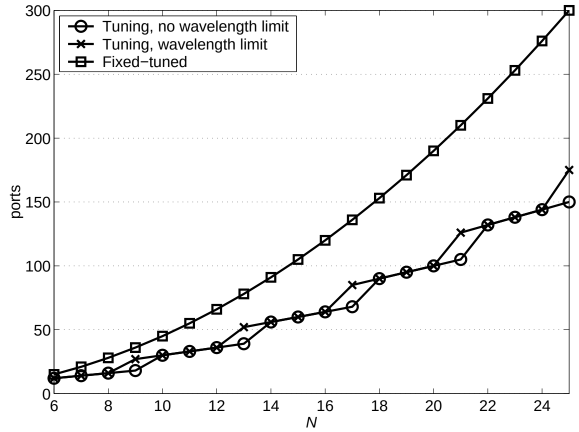

Fig. 2: Number of ports vs. N for a ring with uniform demand of $r = 1$ circuits and $g = 4$.

to support the given traffic requirement. In a unidirectional ring with symmetric traffic, each symmetric traffic demand $R_{i,j} = R_{j,i}$ uses exactly $R_{i,j}$ circuits around the ring, and so $W_{\min} = \sum_{i \neq j} R_{i,j}/2g = \sum_{i=1}^{N} W_i/2$.

Each node in the network is assumed to have a set of tunable transceivers. An example of such a node is shown in Fig. 1; however, many different implementations are possible. As shown, each tunable transceiver consists of a tunable optical ADM, a tunable receiver and a tunable laser. In addition, the node must also be equipped with optical-to-electrical (OE) and electrical-to-optical (EO) converters. The specific implementation of such tunable transceivers are not of interest in this paper. However, we require the nodes to be synchronized at the slot level. Moreover, in a ring network as a slot propagates around the ring it should return to its source on a slot boundary. This can be taken care of by adding extra delay with fiber delay lines or by framing transmissions so that synchronization is maintained. In the following we use the term “port” to refer to all of the optical and electronic equipment required to receive and transmit on one wavelength. From the above discussion, for symmetric traffic, each node requires at least $\lceil W_i \rceil$ tunable ports.

To illustrate the potential advantages of tunablity consider the following simple example of a unidirectional ring with $N = 4$ nodes, $g = 3$, and assume there is a uniform demand of one circuit between every pair of nodes, i.e. $R_{i,j} = 1$ for all $i \neq j$. In this case the minimum number of wavelengths, $W_{min} = 2$ and there is a total of $N(N-1) = 12$ circuits that need to be assigned to the wavelength. With $g = 3$, as many as 6 circuits can be assigned to each wavelength; this can be accomplished by assigning both circuits for each duplex connection to the same time-slot. The traffic demand can then be supported by finding an assignment of each duplex connection to one of the g time-slots in the TDM frame, on one of the wavelengths in the ring. Without the possibility of tunable transceivers the assignment of circuits to wavelengths corresponds to the standard traffic grooming problem; for which an optimal solution is given in Table 1 requiring a total of 7 transceivers. However, if nodes are equipped with tunable transceivers, then the number of transceivers can be further reduced. For example, notice in the traffic assignment in Table 1 node 3 only transmits and receives on one wavelength at any time (i.e. λ_2 in slots 1 and 3 and λ_1 in slot 2). Hence if node 3 were equipped with a tunable transceiver, it would only need one transceiver, rather than two. An optimal traffic assignment using tunable transceivers is shown in Table 2; this requires each node to only transmit on one wavelength during each slot and hence each node need be equipped with a single tunable transceiver.

Table 1: Optimal traffic assignment for fixed tuned transceivers.

	λ_1	λ_2
Slot 1	(1-2)	(2-3)
Slot 2	(1-3)	(2-4)
Slot 3	(1-4)	(3-4)

Table 2: Optimal traffic assignment with tunable transceivers.

	λ_1	λ_2
Slot 1	(1-2)	(3-4)
Slot 2	(1-3)	(2-4)
Slot 3	(1-4)	(2-3)

This example shows that the number of transceivers can be reduced from 7 to 4 by proper slot assignment. In this case the optimal assignment can be found by inspection; however, as we show next, in larger networks this can be a non-trivial combinatorial problem.

3. Minimum tunable transceiver provisioning

We consider finding a time-slot assignment that minimizes the number of tunable ports needed for a ring with a given traffic requirement $R = [R_{i,j}]$ and $W \geq W_{min}$ available wavelengths. We refer to this as the *minimum tunable port (MTP)* problem. A solution to this requires specifying the number of ports at each node and specifying which wavelength each port must be tuned to during each time-slot, as in table 2. This problem can be formulated as an ILP where the objective is to minimize the $\sum_{i=1}^{N} X_i$, where X_i is an integer variable indicating the number of transceivers at node i. The constraints are given by a set of linear relations representing the conditions that (1) the traffic demand is satisfied, (2) no node can transmit or receive on more wavelengths than it has ports, and (3) each time-slot on each wavelength is not used more than once on any link in the ring. As stated next, this problem is in general NP-complete.

Theorem 1 *The MTP problem with $W = \lceil W_{min} \rceil$ available wavelengths is NP-complete.*

This can be shown by transforming the MTP problem into a graph edge-coloring problem [6]. Though the general MTP problem is NP-complete, the optimal solution can be found in several important cases. First we consider the case where there are sufficient available wavelengths so that the wavelength limitation is not binding.

Theorem 2 *If a network has no wavelength limitations, then each node requires $\lceil W_i \rceil$ tunable ports. Moreover, a time-slot allocation that achieves this can be found in polynomial time.*

Notice that $\lceil W_i \rceil$ tunable ports is the minimum number of ports required to support node i's traffic. Thus, removing the wavelength limitation allows each node to use the minimum possible number of ports and lets us solve an otherwise NP-complete problem in polynomial time. The proof of this also uses a correspondence with an edge coloring problem, however here the coloring is performed on a bipartite graph representing unidirectional circuits. In a bipartite graph an optimal edge coloring can be found in polynomial time [7]. The above solution applies to arbitrary network topologies (not necessarily rings).

When the wavelengths are limited, the above time-slot allocation will no longer be feasible and the circuits must be packed more efficiently onto the available wavelengths. In this case the network topology is important. First we consider a unidirectional ring with a uniform traffic requirement of r circuits between each pair of nodes and a wavelength limit of $\lceil W_{min} \rceil$ wavelengths. In this case if the number of nodes is even, then each node again need only be equipped with the minimum number of transceivers.

Theorem 3 *In a ring with uniform traffic, N even, and $\lceil W_{min} \rceil$ wavelengths, each node requires $\lceil W_i \rceil$ tunable ports. Moreover, an optimal time-slot allocation can be found in polynomial time.*

For a general traffic requirement, including the case of uniform traffic with N odd, we have developed heuristic algorithms for approximating the solution to the MTP problem. Moreover, these heuristics have bounded approximation error and exhibit good performance. An example of the performance of these algorithms is shown in Fig. 2. This figure shows the number of ports in a ring with $g = 4$ and a uniform demand of $r = 1$ circuits for different values of N. Three curves are shown. The top curve is a lower bound on the number of ports required in a ring with fixed-tuned transceivers given in [1]. The middle curve is the number of ports needed with tunable transceivers and W_{min} wavelengths. When N is even this is given by Theorem 3; when N is odd, our heuristic algorithms are used. The bottom curve is the number of tunable ports needed without any wavelength restrictions, as in Theorem 2. In the case with tunablity, the number of ports can be reduced by over 40% as compared to the lower-bound from [1] with fixed tuned transceivers. Also note that there is little difference between the case with wavelength limitation and without. Similar performance is attained for other parameters.

4. Conclusions

We show that using tunable transceivers can significantly reduce the required hardware in a WDM/TDM network. As the cost and capabilities of optical hardware improve, the ability to trade-off additional complexity in optical hardware for a significant reduction in electronic hardware may become extremely beneficial.

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