Dynamic Reconfiguration in WDM Packet Networks with Wavelength Limitations

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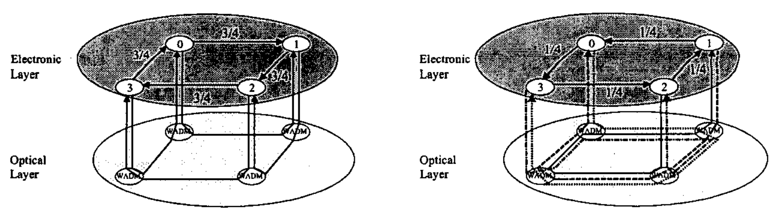
I. Introduction

In metropolitan and wide area Wavelength Division Multiplexed (WDM) networks, most connections are multihop, i.e., most of the traffic is processed by intermediate electronic routers between the source and destination [1]. Electronically processing each wavelength at each network node is prohibitively expensive as well as inefficient since much of the traffic traveling through a node may be destined for a downstream node. Optical Add/Drop Multiplexers (ADMs) and cross-connects may be used to allow individual wavelength signals to be either *dropped* to the electronic routers at each node or to pass through the node optically.

The passive or configurable optical nodes and their fiber connections constitute the *physical topology* of the network. The *logical topology*, which describes the lightpaths between the electronic routers, is determined by the configuration of the optical ADMs and tunable transceivers on each node. Configurable components allow the network's logical topology to be changed. This capability can be used to reduce traffic loads on electronic routers in accordance with the traffic pattern. Consider, for example, the traffic matrix shown in Figure 1(a) in which a four node ring network has 1/4 units of traffic between nodes i and $(i+3)$ mod 4. Figure 1(b) shows the four node network configured in the clockwise direction. With this configuration, each logical link has a load of 3/4 units. By reconfiguring the logical topology to the one shown in Figure 1(c), the logical link load is reduced by a factor of 3, thereby reducing the amount of traffic that must be processed by each electronic router and hence the queuing delay.

$$S = \begin{matrix} 0 & 0 & 0 & 1/4 \\ 1/4 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \end{matrix}$$



(a) Traffic Matrix (b) Fixed Configuration (c) Optimal Configuration

Fig. 1. Comparison of the load on the electronic routers under fixed and optimally reconfigured logical topologies. The solid, dashed, dash-dot, and dotted lines in the optical layer represent the multiple wavelengths used to set up the electronic layer lightpaths.

As network traffic changes with time, the optimal logical topology varies as well. With a connected physical topology and an unlimited number of wavelengths, it is possible to implement any logical topology. However, changing the logical topology can be disruptive to the network since the traffic at each node must be buffered or re-routed while the topology is being reconfigured.

In [5], a reconfiguration strategy was proposed, the Dynamic Single Step Optimization (DSSO) algorithm, that at regular intervals, makes a minimal change to the logical topology in order to reduce the network load. Since the network disruption is limited, reconfiguration can be employed more regularly allowing the logical topology to track dynamic traffic patterns. It was shown that reconfiguring the logical topology via the DSSO algorithm significantly reduces maximum link load and that the DSSO algorithm closely tracks the optimal logical topology when the traffic is time-varying. These results assumed that sufficiently many wavelengths were available to implement any logical topology. In this work, we examine a scenario where the number of wavelengths, W, in the system is less than the number of lightpaths, i.e., $W < PN$, where N is the number of nodes and P is the number of transceiver ports per node. With wavelength limitations, the set of logical topologies that can be established is a function of the physical topology. We show that with a bidirectional ring topology, most of the benefits of reconfiguration can be obtained with significantly less than PN wavelengths.

II. Dynamic Single Step Optimization (DSSO) Algorithm

The DSSO algorithm is an iterative local search algorithm. At regular intervals, small changes to the logical topology reduce the network's maximum link load. The DSSO maintains a connected logical topology, thus ensuring that traffic between every source and destination pair can be continually supported. In networks with one port per node, this implies the logical topologies are unidirectional rings. For single port per node networks, the DSSO utilizes a *3-branch exchange* at each step to maintain network connectivity while minimizing network disruption and maximizing the number of reconfiguration options. In a 3-branch exchange, three links (lightpaths) in the current topology are selected and numbered 0, 1, and 2, in the order that they appear in the ring. These three links are rearranged such that source of link i is connected to the destination of link $(i+1)$ mod 3. When $P \geq 2$, the DSSO employs *2-branch exchanges*, in which the destinations of two links are exchanged. Only 2-branch exchanges that retain ring connectivity are allowed. Minimum hop routing is used to route traffic when multiple paths exist between source and destination.

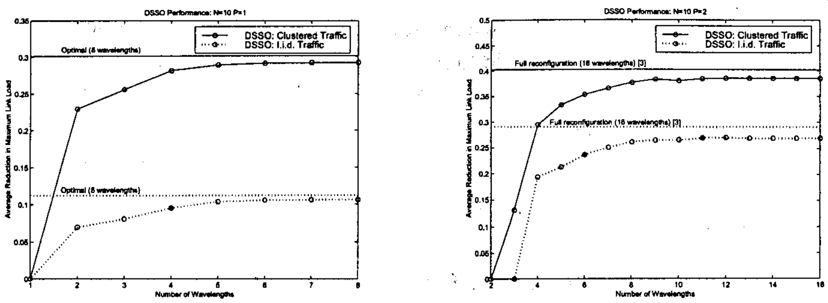
To evaluate the benefits of reconfiguration, two dynamic traffic models are utilized. For *I.i.d. Traffic*, the traffic between each pair of nodes is independent and identically distributed with a uniform distribution between 0 and 1. In *Clustered Traffic*, significant proportions of the traffic flow from a single source to multiple destinations or from multiple sources to a single destination.

III. Impact of Wavelength Limitations

With a ring physical topology, multiple lightpaths in a logical topology may be able to share wavelengths. However, if the physical topology is a unidirectional ring, the worst case logical topology still requires PN wavelengths. Below, we therefore consider a bidirectional ring physical topology. We first determine the total number of wavelengths required to implement all possible logical topologies and then examine the impact of further restricting the number of wavelengths on the DSSO algorithm performance.

We assume that each lightpath is routed using a deterministic shortest path routing scheme. For lightpaths requiring $N/2$ hops (when N is even), lightpaths from nodes i to $i+N/2$ and from $i+N/2$ to i are routed clockwise (counter-clockwise) if i is odd (even) for $0 \leq i \leq \frac{N}{2}$. Since shortest path routing minimizes resource utilization, it is conducive to future logical topology changes imposed by the DSSO algorithms which dynamically add and remove individual lightpaths from the logical topology.

For the bidirectional ring physical topology, we consider the total number of wavelengths required as the number of wavelengths required in the clockwise direction plus the number of wavelengths required in the counter-clockwise direction. It can be shown that in a single port per node network the worst case connected logical topology requires $N-2$ wavelengths. Thus, in a 10 node system, at least 8 wavelengths are required to implement all possible connected logical topologies. Any further restriction on the number of wavelengths implies that not all logical topologies are realizable. With a wavelength restriction, the DSSO algorithm is restricted to branch exchanges that do not require more than the appropriated number of wavelengths. Figure 2(a) shows, for a 10 node network, the average reduction in maximum link



(a) $N = 10$ nodes and $P = 1$ ports (b) $N = 10$ nodes and $P = 2$ ports

Fig. 2. Average reduction in maximum link load achieved by the DSSO algorithm as a function of the number of wavelengths. DSSO is compared to optimal reconfiguration (w/o wavelength restrictions) for the single port per node case and to full reconfiguration (w/o wavelength restrictions) for the 2 port per node case.

load provided by the DSSO algorithm as a function of the number of available wavelengths. DSSO is compared to the optimal reconfiguration strategy which requires full network reconfiguration and is not wavelength limited. These results show that the number of wavelengths required to achieve most of the possible link load reduction is quite small and that full network reconfiguration is unnecessary.

We next consider multiple port per node networks. If the physical topology is a bidirectional ring and the logical topology has no duplicate lightpaths, we show that there exist worst case logical topologies that require $P(N-P)$ wavelengths [1]. This implies that for a 10 node and 2 port network, at least 16 wavelengths are required to establish all logical topologies. The impact of limitations on the number of wavelengths is shown in Figure 2(b) where the reduction in maximum link load is shown for a 10 node and 2 port network as a function of the number of available wavelengths. DSSO is also compared to full network reconfiguration [3] in which the full logical topology is rearranged at each step and no wavelength limitation is imposed. Most of the gain in performance is achieved with far fewer than 16 wavelengths.

In conclusion, we find that by taking advantage of configurable WDM technology, the DSSO algorithm significantly reduces electronic processing loads. The substantial reduction in maximum link load is obtained even when the number of wavelengths available is limited.

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[1] For $P = 1$, a minimum of $N-2$ rather than $N-1$ wavelengths are required because of the network connectivity constraint.