Hybrid Optical WDM Networks Utilizing Optical Waveband and Electrical Wavelength Cross-connects

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Abstract: We propose an optical waveband and electrical OTN hybrid-HOXC node configuration, and a suitable network design algorithm. The proposed hybrid-HOXC network is verified as being very cost effective over a wide range of parameter values.
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1. Introduction

Recent advances in WDM technologies and related optical technologies have significantly increased network capacities. To meet the rapid growth of Internet traffic driven by the penetration of broadband access including ADSL and FTTx, single layer optical path networks that utilize wavelength path routing made possible with optical cross-connects (OXCs) and ROADMs have been proposed [1], and a large number of ROADM ring networks have been deployed in North America and Japan. The deployment of OXCs (multi-degree ROADMs) is, however, still limited due to the high cost of fabricating large-scale optical switches. Future video-centric broadband services, which include ultra-high definition TV and 3D-TV, are expected to trigger a further traffic explosion. The requirement of cost-effective networks that can support the ever-increasing traffic will become more and more critical. One important approach to cost-effectively enhancing optical switching capacity is the introduction of a higher-order optical path, the waveband path (a group of multiple wavelength paths), along with hierarchical OXCs (HOXCs) that are capable of switching optical signals at different granularities [2-5]. In HOXC architectures, the optical cross-connect switch scale required for switching wavebands is very small [5]. This differs from the wavelength paths cross-connect (WXC) portion, which needs only relatively large scale. Regarding the optical wavelength path cross-connect portion, the size is determined by the waveband add/drop ratio imposed by grooming. Wavelength path cross-connects with reduced switch scale can be attained by a new HOXC architecture [6] in which a large common-purpose switch is replaced by small dedicated-purpose switches and a novel network design algorithm [7] that incorporates the add/drop ratio restriction. Although electrical switches are expensive, they can naturally provide wavelength conversion and 3R regeneration functions since they use OE/EO converters at the inputs and outputs of the electrical switching matrices. The previously analyzed hybrid-hierarchical switch [8] that uses an electrical TDM switch for both originating/terminating and grooming traffic demands requires very large switch scale with costly electrical ports.

Based on this observation, we investigate here the effectiveness of hybrid-hierarchical optical cross-connect architectures (hybrid-HOXCs) that combine electrical cross-connects (EXCs) for wavelength path level cross-connection with optical waveband cross-connects (BXCs). We separate the wavelength adding/dropping and grooming functions at the WXC layer to minimize the switch scale. For intermediate grooming of just the wavelength paths, the proposed hybrid-HOXC uses a small scale EXC, and independent add/drop interfaces are directed to a BXC. The add/drop interface part is similar to that of a single layer OXC, which may use WSSs or optical space switches. The EXC may provide sub-lambda (ODU) level switching capability when it is necessary [9], but this is not discussed here for simplicity. EXC cost depends on the switch granularity needed, so EXC port cost is parameterized in this evaluation. Because of the high EXC port cost (which includes OE/EO), network-wide optimization that considers EXC cost is critical. In order to maximize the advantages of the proposed hybrid-HOXC, we carefully restrict the use of expensive electrical switch ports. For hybrid-hierarchical optical path network design, a near-optimal ILP approach was developed [10]. It divides the design problem into 2 separate sub-problems and solves them step-by-step. It is computationally expensive and applicable only to small networks. To design large-scale networks, we propose a heuristic algorithm that directly establishes highly utilized waveband paths while grooming only the sparse wavelength paths that cannot be accommodated within the wavebands. Simulation experiments prove that the proposed algorithm can create hybrid-HOXC based networks that are up to 70% cheaper than the corresponding single layer networks. We also analyze the effectiveness of the hybrid-hierarchical optical path networks with respect to network parameters and waveband capacities.

2. Hybrid-Hierarchical Optical Path Network

Figure 1 shows that the proposed hybrid-HOXC node architecture consists of 2 switching layers: waveband and wavelength path switching layers. The former is an optical waveband cross-connect (BXC). The latter is divided into 2 separate functional parts for dedicated adding/dropping and grooming operations with wavelength path granularity, in which EXCs are utilized. The usage of EXCs, besides grooming wavelength paths, also offers wavelength conversion and 3R functions. The wavelength path added/dropped operations can be done with optical supplemental devices (i.e. WSSs) or they can be integrated in the switch portions required for attaining colorless/directionless capabilities (as in a single layer OXC), which may be realized with optical or electrical space switches (or in combination with ODU cross-connects if necessary). These issues are not discussed herein. In the proposed architecture, as mentioned before, the large switch scale reduction is attained by utilizing switches specialized for grooming compared to the HOXC approach of implementing both grooming and add/drop functions in one large WXC switch [6,8]. In the proposed hybrid-hierarchical optical path networks, a wavelength path in an incoming waveband path that must be groomed is routed to the EXC, regenerated and/or converted into a new wavelength index, and then aggregated (merged) into an outgoing waveband path, while added/dropped wavelength paths do not pass through the EXC (see Figure 2), which reduces EXC switch scale. The hybrid-HOXC switches bypass-waveband paths only at the BXC layer.

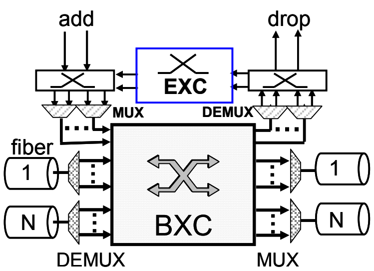

Figure 1. Hybrid-HOXC Architecture

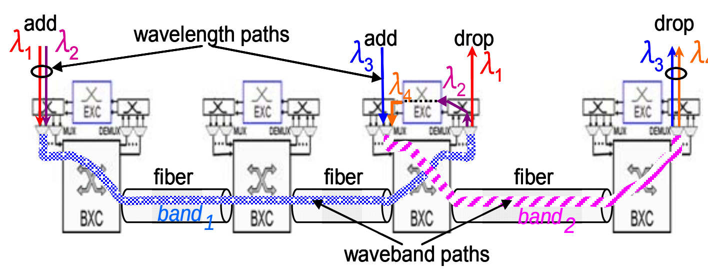

Figure 2. Wavelength paths and waveband paths

The total network cost of the hybrid-hierarchical optical path network is calculated using link cost and node cost [7]. The node cost including optical/electrical switch port cost can be reduced by encouraging waveband path level cross-connection and minimizing EXC operations. EXC layer operations although costly, can increase link utilization efficiency or reduce link cost. A tradeoff exists between link cost and node cost.

3. Hybrid-Hierarchical Optical Path Network Design

Given physical topology $G(\mathbf{V};\mathbf{E})$, where **V** is a set of nodes, **E** is a set of fiber edges; a set of traffic demands **C** in which a demand request between source s and destination d is defined as $C_{s,d}$ and maximum waveband/fiber capacity is W/B: a fiber can carry up to B wavebands and each waveband consists of W wavelengths. The design goal is to minimize the total network cost required to accommodate all traffic demands.

To minimize the total network cost while fully utilizing the advantages of the hybrid-nodes, the direct establishment of highly utilized waveband paths is encouraged while grooming operations should be used only to accommodate the sparse wavelength paths that cannot be carried by wavebands to improve the utilization of waveband paths, since electrical EXC ports are expensive. The developed design algorithm is briefly described as follows:

<Hybrid-Hierarchical Optical Path Network Design based on Auxiliary Waveband/Wavelength Graphs>

Step 0- Selection of parameter value

Select proper value of the waveband construction threshold, denoted as X_{wb}, for establishing an end-to-end waveband path ($X_{wb} \in (0,1]$).

Step 1- Routing and Assignment of high capacity Waveband Paths

Search for node pair $(s,d) \in \mathbf{V}\text{x}\mathbf{V}$ in descending order of hop(s,d) such that $C_{s,d} \geq X_{wb}W$ where hop(s_0,d_0) is the minimum hop count between node pair (s_0,d_0). Find the shortest waveband path (including route and waveband index) on an auxiliary multi-layer waveband graph of the network where its arcs are weighted to encourage sharing of unoccupied wavebands in established fibers. Establish the corresponding end-to-end waveband path from s to d to carry the traffic demand. Repeat until no such node pair is found.

Step 2- Grooming Sparse Wavelength Paths

Construct an auxiliary full-mesh virtual wavelength path graph based on established waveband paths with spare capacities or new direct end-to-end waveband paths. Find the shortest path on the virtual wavelength path graph to route each traffic demand in descending order of the hop count between its source and destination. Update the graph and repeat this step until all the traffic demands are accommodated.

4. Simulation Results

We assumed the following parameter values for the numerical evaluation; pan-European network COST266 consisting of 26 nodes and 51 links [11]; randomly distributed traffic demands represented as the average number of wavelength paths between each node pair; each fiber accommodated up to 64 wavelengths with B wavebands and W wavelengths per waveband (BxW=64); parameter β is defined as the ratio of the cost of an electrical switch port (including OE/EO) to that of an optical switch port.

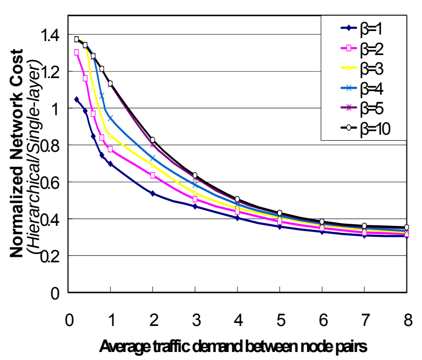

Figure 3. Network cost versus traffic demand

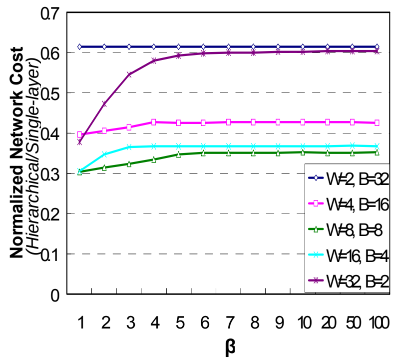

Figure 4. Network cost versus β

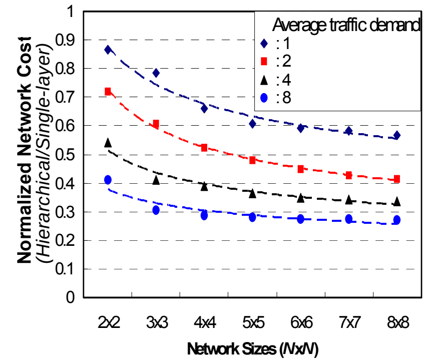

Figure 5. Impact of network size

Figure 3 plots the normalized network costs achieved by the heuristic algorithm where the average traffic demand is changed, and both B and W are set to 8. The costs are normalized by that for the comparable single layer optical path network that uses single layer OXCs. The results show that the hybrid-hierarchical optical path network can offer up to 70% lower cost than the corresponding single layer network, and the cost reduction is enhanced as the traffic demand increases or the cost of EXC ports falls. The dependence of the network cost on β at the average traffic demand of 8 with different waveband capacities (W=2, 4, 8, 16, and 32) is illustrated in Figure 4. Grooming is encouraged as β decreases, the exact characteristics depend on waveband capacity. Figure 5 shows the normalized network costs for NxN regular mesh networks (N=2-8) when B=W=8, β=2, and the average traffic demand between each node pair is 1, 2, 4 and 8. The normalized network cost reduction is improved as network size or traffic demand increases. The larger the network size, the greater the role of EXC cut-through, and the larger the traffic demands, the higher the link utilization becomes; both of which play important roles in reducing total network cost.

5. Conclusions

We have introduced a hybrid-HOXC node architecture consisting of a waveband cross-connect to switch high-order optical paths (wavebands), and an electrical cross-connect for grooming lower-order optical paths (wavelength paths). We then proposed a network design algorithm based on auxiliary waveband/wavelength graphs. Simulation results proved that the proposed algorithm offers up to 70% cost reduction. It was also verified that the hybrid-HOXC approach is especially cost-effective for large networks, cheaper EXC ports, and large traffic demand areas.

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6. References

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