Fiber Routing, Wavelength Assignment and Multiplexing for DWDM-Centric Converged Metro/Aggregation Networks

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Abstract *The planning problem of novel DWDM-centric converged metro/aggregation networks is solved by algorithms based on intelligent wavelength assignment and an auxiliary-graph approach that exploits load-balanced routing and the optical-multiplexing capability of WSSes.*

Introduction

Dense-wavelength-division multiplexing (DWDM)-centric metro/aggregation networking is defined as predominantly using packet aggregation at the edges of the aggregation domain (e.g., access sites, such as cell sites, and service edge sites), while using DWDM at the center of the network. Conversely, a packet-centric solution would predominantly use packet aggregation also at the center of the network. As traffic demand and granularity increase and the cost of optics continues to fall, the paradigm of metro/aggregation networks may change dramatically when the capital expenditure (CapEx) of the DWDM-centric solution becomes lower than packet-centric. In some sense, the DWDM-centric solution has the similar motivation and opportunity as long-reach passive optical networks (PON)[1, 2], but using DWDM wavelength switching. In this study, a DWDM-centric architecture is proposed and its planning problem is solved by algorithms based on intelligent wavelength assignment (WA) and an auxiliary-graph approach exploiting load-balanced routing and the optical-multiplexing capability of wavelength selective switches (WSSes).

Network architecture

Figure 1 shows the proposed network architecture. Two hubs (connecting to the core networks) are geographically separated in the metro area for the purpose of mutual protection. Multiple central-office (CO) nodes and the two hubs form a general metro *mesh* topology. A CO (composed of a 1:N WSS, with the '1' port called de-multiplexing port and the 'N' ports called multiplexing ports) is connected to multiple aggregation networks (assuming ring topologies), forming an *aggregation domain*. Optical amplifiers can be placed at COs. Each CO is responsible for aggregating/distributing wavelengths from/to its aggregation domain to/from the hubs. Wavelengths demands are bidirectional, which is possible because of bidirectional amplifiers[3] and WSSes. There are multiple access add/drop (AAD) nodes in each aggregation network, which are used for adding/dropping wavelengths from/to access ports (APs). Each AAD node is a mini-ROADM (Reconfigurable Optical Add/Drop Multiplexers[4]) that can switch *any* wavelength to/from the aggregation ring from/to *any* add/drop port. Wavelength demands within the same aggregation domain must be assigned different wavelengths to avoid wavelength collision at the CO. An optical splitter is used to replicate wavelengths to achieve 1+1 protection. Alternatively, two WSSes can be placed at each CO to avoid optical-splitting impairment and provide node resiliency (this option is not considered in this paper, but the proposed algorithms are also applicable to it with only minor difference). The wavelengths from a CO (e.g., CO 1 in Fig. 1) can either *bypass* an intermediate CO (e.g., CO 2) or be *optically multiplexed* with the wavelengths originating from an intermediate CO (e.g. CO 3), using its WSS (e.g., the WSS at CO 3), if there are spare multiplexing ports of the WSS and no wavelength collision. This function of optical multiplexing with an intermediate CO is called *'wavelength multiplexing' (WM)* in this study. Unnecessary duplicate wavelengths can be blocked by WSSes.

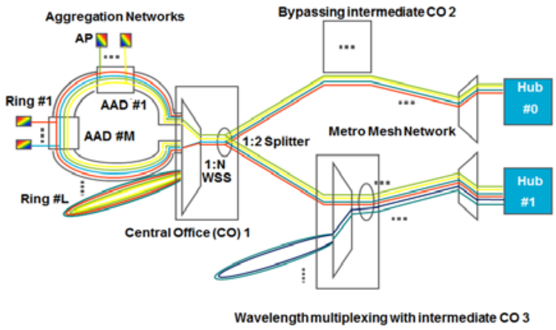

Fig. 1: Network architecture

Problem formulation

Given a metro mesh topology, formed by two hubs, COs, and links (e.g., underground ducts, through which multiple fibers may traverse), and wavelength demands from each aggregation domain (or CO) to the hubs, our objective is to minimize the maximum number of fibers deployed in any link (since we tend to deploy the same type of cable containing the same number of fibers in each link), while establishing all wavelength demands with 1+1 protection. Fiber deployment and wavelength assignment are outputs of the planning problem. All wavelengths from each CO are split and go through two link-disjoint paths to the two hubs. So the wavelength demands from CO *s* can be represented by only two demands (*s, p*) (p = 1 or p = 0 indicating the two link-disjoint paths).

The problem can be divided into the following three interacting sub-problems: 1) Fiber routing problems: how to route fibers through links. Note that *a fiber* is defined to start from a de-multiplexing port of a WSS and end either at a hub or a multiplexing port of another WSS; 2) WA: given the maximum number of wavelengths supported in each fiber and the wavelength-continuity constraint, a set of wavelengths have to be assigned to the demands from each CO; 3) WM problem: how to decide whether wavelengths should bypass an intermediate CO or be multiplexed by the WSS at the CO? Also, routing and WM must make sure that each wavelength demand has two link-disjoint paths to the hubs.

Algorithms

We propose the following algorithms to tackle the network-planning problem.

1. *Shortest-Path Routing (SPR)*

SPR is proposed as a baseline: two link-disjoint fibers originating from each CO, *bypassing* all intermediate COs, are routed directly to the two hubs. A *routing graph* is created by adding a dummy node to the metro-topology graph and connecting it to the two hubs. The route of the primary path is derived by running a shortest-path algorithm between the source CO and the dummy node. The backup path is also calculated in the same way but with the links and the hub node in the primary path deleted in the routing graph.

2. *Load-Balanced Routing with Random wavelength assignment and Wavelength Multiplexing (LBR-R-WM)*

The problem of *SPR* is that there are bottleneck links (intuitively, the links near the hubs) carrying more fibers than others. So, load-balanced routing schemes are needed to alleviate the bottleneck effect. We propose an auxiliary-graph approach to solve the fiber-routing and WM problems in one step. Figure 2

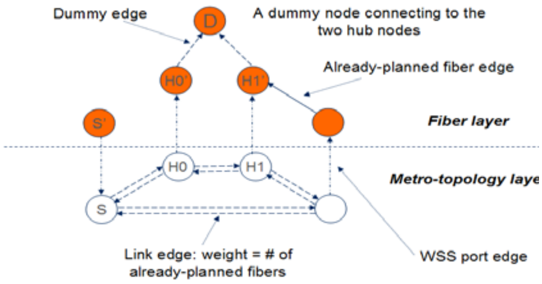

Fig. 2: Auxiliary graph

shows an exemplary auxiliary graph for a 4-node metro topology. An auxiliary graph, which has a metro-topology layer and a fiber layer, is constructed for each source CO *s* and its two associated demands. The metro-topology layer corresponds exactly to the physical metro topology. Each node in the fiber layer corresponds to a CO or hub. The two fiber-layer hubs (e.g., H0' and H1') are both connected to a dummy node through *dummy edges*.

There is a *WSS port edge* from a metro-topology-layer node to its corresponding fiber-layer node if there is a spare multiplexing port at the WSS. In this study, we assume that there are always enough WSS multiplexing ports. There is also a *WSS port edge* from the source CO *s*' corresponding fiber-layer node to its metro-topology-layer node, or from a metro-topology-layer hub to its corresponding fiber-layer hub. Each link in the metro topology corresponds to a pair of *link edges* with opposite directions in the metro-topology layer.

There is an *already-planned fiber edge* corresponding to each *fiber* that has already been planned in the processing of demands from previous COs before processing the current CO *s*, if the fiber carries a non-overlapping set of wavelengths with that from CO *s*. The current demand (*s, p*) may be multiplexed onto the already-planned fiber.

In *LBR-R-WM*, wavelengths are first *randomly* assigned to each CO, which is adopted as a benchmark WA scheme. Then, we sort the COs according to their distances to the hubs (the distance from a CO to the hubs is defined as its shortest distance to the closer hub) and process *'nearer'* COs (to hubs) earlier. An auxiliary graph is established for the current sorted CO and a shortest-path algorithm is run between the source fiber-layer CO and the dummy node to derive the primary path. If the derived path goes through an *already-planned fiber edge,* the demand is then multiplexed onto the corresponding fiber. If the path goes through *link edges*, new fibers are deployed through the corresponding links. The backup path is also derived in the same way but with certain edges in the auxiliary graph deleted, e.g., an edge should be deleted if it is an *already-planed fiber edge* and its corresponding fiber traverses at least one link through which the primary path travels, or it is a *link edge* that is traversed by the primary path. If the backup path is derived successfully, the next sorted CO is to be processed. If not, we derive the primary and backup paths in the same way as SPR: directly routing two fibers to the two hubs without WM.

To achieve load-balanced routing, the weight of each *link edge* is assigned as the number of already-planed fibers in the link. Also, WM should be encouraged by assigning a much smaller weight (e.g., 0.0001 * the number of links the fiber goes through) to an *already-planned fiber edge* than to a *link edge*. The weights of *WSS port edges* are set to one and the weights of *dummy edges* are set to 0.0001.

3. *Load-Balanced Routing with Depth First Search wavelength assignment and Wavelength Multiplexing (LBR-DFS-WM)*

WM is possible only when there is no wavelength collision at a WSS. Intuitively, if neighboring COs are assigned non-overlapping sets of wavelengths, there are more opportunities for their wavelengths to be multiplexed together. In *LBR-DFS-WM*, we iteratively assign non-overlapping sets of wavelengths to the neighboring COs in the depth first search (DFS) pre-ordering starting from any of the hubs in the metro topology. For example, with each fiber supporting 10 wavelengths (1-10), if the DFS pre-ordering is (CO 1, CO 2, and CO 3) and their demanded wavelength numbers are 2, 4, and 6 respectively, CO 1 would be assigned wavelengths 1-2, CO 2 would be assigned wavelengths 3-6, and CO 3 would be assigned wavelengths 7-10 and wavelengths 1-2. After WA is done, load-balanced routing and WM are done in the same way as *LBR-R-WM*. As we process 'nearer' COs earlier, DFS pre-ordering encourages 'further' demands to be multiplexed onto 'nearer' already-planned fibers.

Illustrative Numerical Examples

We study the performance of the algorithms for a 38-node (including 2 hubs) metro network shown in the Fig. 3. Each fiber can support 360 wavelengths with 25 GHz spacing. The number of wavelength demands from each CO is uniformly distributed in [a, b], where *a* and *b* are parameters to control the traffic load.

Figure 4 shows the maximum numbers of fibers deployed in any link. We can observe that: load-balanced routing alone can reduce the maximum number of fibers from 17 (derived by

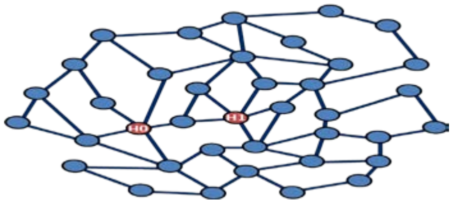

Fig. 3: 38-node metro topology

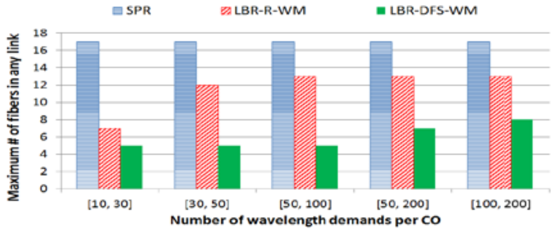

Fig. 4: Maximum number of fibers in any link

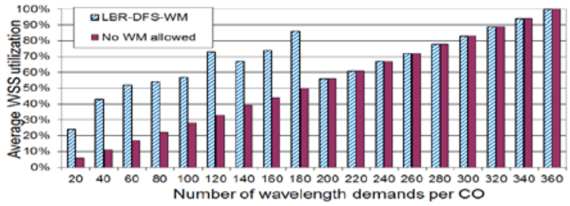

Fig. 5: Average WSS utilization

SPR) to 13 (derived by *LBR-R-WM* at high loads when WM is not possible for random WA). As intelligent DFS WA is adopted by *LBR-DFS-WM*, we can get much more significant fiber savings (up to 70% compared to *SPR)*. So, the effect of WM largely depends on WA.

We also study the average WSS utilization, which is defined as the average (over all WSSes) ratio of the number of incoming wavelengths to a WSS over WSS capacity (360 wavelengths). Figure 5 shows the average WSS utilization derived by *LBR-DFS-WM*, compared to the case when WM is not allowed (by deleting all *already-planned fiber edges* in the auxiliary graph). It is observed that when WM is possible (load < 180) for *LBR-DFS-WM*, its WSS utilization is much better than that if WM is not allowed.

Conclusions

In this study, we introduced a new architecture of DWDM-centric converged metro/aggregation networks. It is found that load-balanced fiber routing can significantly reduce the maximum number of fibers in any link. WM, which is largely affected by WA, is beneficial for reducing both the maximum number of fibers and for increasing WSS utilization.

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