Reach-Optimized Design for ULH Mesh Networks

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Abstract: The goals for ULH mesh network design should be reach optimization of the whole network and preparation for the future growth. We propose an approach that designs each ROADM-to-ROADM section independently with minimized OSNR penalty.

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1. Introduction

As dense-wavelength-division-multiplexing (DWDM) transport technology evolves from opaque long-haul (LH) point-to-point systems to transparent ultra-long-haul (ULH) mesh systems, link-engineering design of the optical network becomes a challenging problem. The newer transparent optical networks are different from the traditional opaque optical networks [1-3]. In an opaque LH network, a DWDM section is bounded by two end terminals (ETs). A circuit is terminated at both ETs with optical transponders (OTs). If a circuit must go beyond a DWDM section, it will be regenerated using back-to-back OTs or regenerators and manually cross-connected to other fiber directions. That is, each DWDM section is optically isolated from the rest of the network. Therefore, each DWDM section can be designed independently for cost optimization.

This design methodology of cost optimization of individual sections cannot be applied to the newer transparent ULH mesh network where a DWDM section is bounded by two reconfigurable optical add/drop multiplexers (ROADMs). A circuit does not necessarily terminate at one or both ROADMs with OTs. It may express into other DWDM sections via wavelength selective switches (WSSs) without OTs. That is, a transparent DWDM section is optically connected to the rest of the network. Therefore, when designing a DWDM section or a collection of DWDM sections (a subnet), one must consider the rest of the existing network and all the possible directions of future growth. A cost optimized design for an individual section may not be optimal for the whole network and for the future.

As the cost of OTs becomes more and more dominant in newer DWDM technologies, it is increasingly important to avoid back-to-back OTs or regenerators. Therefore, one should design a transparent mesh network for reach optimization of the whole future network. However, when designing a DWDM section or a subnet, information about the rest of the network usually is uncertain or not yet available.

A network transport equipment supplier usually provides a design tool for link-engineering a network with its product. A carrier relies on the supplier's design tool to design and build its own network with the technology, because only the supplier has the best knowledge of capabilities and limitations of its products. This is especially true for the modern transparent DWDM technologies, since many of their transmission characteristics are not standardized and are supplier proprietary. Although developing the link-engineering tool is the supplier's responsibility, the supplier has limited knowledge of the carrier's network and may not fully understand the network design goals. This paper is focused on defining the design goals of the tool from a carrier's prospect. We first discuss the challenges of the design tool for transparent mesh networks, and then propose a methodology to overcome those challenges.

2. Challenges in Transparent Optical Mesh Network Design

A network planning tool from a supplier typically starts with the input of a matrix of forecasted traffic demands. The tool then produces an optimal network design that supports all the forecasted demands at the least cost. This theoretical green-field approach is hardly useful in the real world. A carrier usually already has an existing network of various technologies. Building new DWDM sections is driven by capacity exhaustion. The choices of fiber routes are usually limited. A traffic forecast may exist, but it is not reliable and keeps changing [4]. Furthermore, a nationwide traffic forecast is not useful in predicting the traffic load on the DWDM sections being planed, since there are many ways to route the traffic across a mesh network.

In the real world, a design tool usually handles project after project, driven by capacity exhaustion. The tool starts with an input file of the fiber map of a project. The fiber map defines a set of add/drop sites (required ROADM sites), the junction sites of the fiber segments connecting those add/drop sites, and the properties of each fiber segment. The fiber properties include the fiber length, fiber type and vintage, chromatic dispersion, polarization mode dispersion (PMD), optical return loss (ORL), etc. The junction sites of the fiber segments can be assigned as fiber-through sites, in-line amplifier (ILA) sites, dynamic gain equalization (DGE) sites, regeneration sites, additional ROADM sites, etc. The detailed site types are technology dependent. Usually a regeneration site and a ROADM are of the same configuration, and a DGE site can be upgraded to a ROADM without service interruption. The assignment of the junction sites to various site types may be flexible or with restrictions and preferences. For example, some sites are limited to fiber-through due to lack of power and space. Some sites are preferred regeneration sites due to the availability of space/power and the potential for future traffic add/drop.

The fiber map of a project defines a subnet with one or several DWDM sections in a linear or mesh configuration. The subnet is optically connected to the existing network of the same technology and must be prepared for growth in all directions, including adding new branches from any ROADM site. How to design such a subnet without complete knowledge of the rest of the network is the focus of this paper.

Consider a trivial example first. The reach of a DWDM technology depends on the distribution of span lengths or span losses. (A span is referred to as the fiber span between adjacent ILA or ROADM sites. It may consist of several fiber segments.) The optimal span loss for the maximum reach is technology dependent. A technology usually can support larger span losses with the trade-off of reduction in reach. Let's suppose that a certain technology can reach 20 spans of 20 dB (20x20dB), but reach only one span of 40 dB (1x40dB). For a fiber with a loss coefficient of 0.25 dB/km, it corresponds[1] to a reach of 1600 km for 80-km spans, but a reach of 160 km only for 160-km spans. Now assume we are given a project of a single DWDM section from A to B with two fiber segments of 80 km and 20 dB each. Without knowing the rest of the network, a traditional design tool with the goal of cost optimization would recommend to "fiber-through" the junction of the two fiber segments and to create a long 40 dB span of 160 km. This design would be very correct for the given project if the AB section never grows. However, once the AB section grows in any direction, any circuit beyond AB would require regeneration, a very expensive operation. With the future in mind, one would abandon the short-term cost optimization goal and invest in an ILA at the midpoint of AB. In this way, a circuit could go another 1440 km beyond AB without regeneration. The challenge here is that the user of the design tool usually does not have complete information on future projects. How can the tool design a subnet of a given project and make sure that it is optimized for the unknown future network?

3. Reach Optimization Design for Individual Sections

A wavelength is transmitted through an ULH mesh network section by section, accumulating optical signal noise ratio (OSNR) penalty along the path. When the cumulated OSNR penalty reaches the allowed OSNR budget, regeneration is required. Note that, the OSNR penalties are cumulative but not added up linearly. For example, the PMD penalty is cumulative as the root of the sum of the squares (RSS). Nevertheless, reducing the OSNR penalty of a section always results in a reduction of the total OSNR penalty along the path. In other words, to realize the goal of reach optimization of the whole mesh network, we must design each section with a minimum OSNR penalty within the section itself. Then the network design problem is reduced to optimal design of each ROADM-to-ROADM section with the goal of the minimum OSNR penalty within the section.

Within a ROADM-to-ROADM section, there are a finite number of fiber segments and their associated junction sites. The task of link-engineering design is assigning each junction site to the appropriate site type. There are finite types of sites for a DWDM technology, such as fiber-through, ILA, DGE, regeneration, and ROADM sites. If a ROADM-to-ROADM section defined in the original fiber map of the project is longer than the maximum reach of the technology, regeneration sites are required and those sites can also serve as ROADM sites for add/drop traffic. Since a regeneration site must regenerate every express wavelength and support potential add/drop traffic, the site must allocate enough space and power for all the future transponders. If there are several junction sites that can serve as the regeneration site to fulfill the transmission requirements, the designer should ask the project manager to assign one of the potential regeneration sites as the additional ROADM site. The project manager probably wants to pick a larger office site that has enough space and power and may need add/drop traffic in the future.

Once the fiber map is modified with the additional ROADM sites, the fiber junctions within each section can only be assigned as fiber-through, ILA, or DGE sites. There are a finite number of ways for link-engineering design of a section. A simple approach is exhaustive search: First find all the possible combinations when every junction site is assigned to every possible site type. (For example, if there are 3 junction sites and 3 site types, there are 3x3x3=27 ways of combinations or designs.) Then calculate the OSNR penalty for each combination and identify the minimum-penalty combination as the best design. In reality, we usually have some simple rules to reduce the search space and need to consider only a small number of possible designs. For example, some technologies have simple rules for DGE assignment. Transmission engineers of the supplier may have more sophisticated ways to quickly identify the design that minimizes the OSNR penalty within each section.

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[1] This example is simplified for illustration only. In a real link-engineering design, the designer must consider additional margins, such as maintenance, aging, intra-office losses, etc.

4. Discussions

As mentioned earlier, the cost of the transponders is becoming increasingly dominant in the newer DWDM technologies. The cost of common equipment, including optical amplifiers, mux/demux, and WSS, is nearly independent of the transmission speed of the wavelength. (This is the beauty of optical transport!) Actually, the cost of common equipment decreases as the technology progresses. On the other hand, the cost of the transponders increases almost linearly with the speed of wavelength. (A carrier usually starts to deploy a higher-speed technology when the cost per bit is 75% lower than the previous one, e.g., when a 10G transponder costs less than three 2.5G transponders or a 40G transponder costs less than three 10G transponders.) In the 2.5G/10G era, a ROADM degree may cost more than 10 transponders. However, in the 40G/100G era, the cost of a ROADM degree may drop below that of a single transponder. The cost of common equipment may account for only a few percent of the total system cost at full load. Therefore, it is very important to avoid regeneration as much as possible and design the network with reach optimization.

Nevertheless, we should not overdesign a network when the return in OSNR improvement is diminishing. For example, suppose a technology supports both 30x12dB and 15x24dB configurations. Even if the 30x12dB design exhibits a marginally better OSNR, we may prefer the 15x24dB design to save the cost of 15 ILAs. To systematically avoid this type of overdesign, we propose adding an effective OSNR penalty that represents the cost of common equipment to the total OSNR penalty of the section. The conversion factor from the cost of common equipment to the effective OSNR penalty shall be in the order of one dB per million dollars. For example, the carrier may not want to invest an additional $100K in a section if the improvement of OSNR penalty in the section is less than 0.1 dB. The exact conversion factor shall depend on the details of the DWDM technology and the infrastructure of the carrier's network.

Another scenario that one may want to avoid is building a long DWDM section that is a significant portion of the maximum reach. For example, consider a project with 4 ROADMs at A, B, C and D, in a linear chain with 1000 km spacing, and the system reach is 1500 km. Designing the 3 sections, AB, BC, and CD, individually would not require any regeneration sites. However, when we route a wavelength from A to D, it must be regenerated twice at B and C. If we had put a regeneration site, i.e., an additional ROADM, at the middle of BC, then a wavelength from A to D would only require regeneration once. In view that the cost of a transponder is comparable or less than that of a ROADM degree, it is certainly cost effective to add a ROADM at the middle of BC to the design. That is, after designing the DWDM sections individually for a project, one should examine all possible ROADM-to-ROADM paths, including the paths connecting to the ROADMs in the existing network, to see if adding ROADMs in long sections would reduce the number of regenerations of possible paths.

Preparing for the unknown future is more difficult. In the above example, if only the BC section is given in the current project without knowing about the AB and CD sections, how can one know that it is beneficial to add a ROADM at the middle of BC? We propose a rule of thumb that, if a section length is 1/2 to 2/3 of the reach, one should check if there exists an upgradable DGE within the section or if an additional ROADM should be added at a middle point. Such long DWDM sections are not encountered frequently in modern ULH systems where the system reach usually much exceeds the typical ROADM spacing. Note that it is acceptable if the length of a DWDM section already approaches the reach limit, since transponders are needed at both ends anyway.

5. Conclusion

Link-engineering design of new sections in a transparent ULH mesh network is different from the design of an opaque LH network. Since transponders are the dominant cost of the total system, the design goal should be reach optimization of the whole network and preparation for any future growth. In this paper, we propose an approach that first designs each ROADM-to-ROADM section independently to minimize the OSNR penalty in each section. Then we examine the whole network to see if adding ROADM sites to long sections would be beneficial for reducing the number of regenerations in all possible paths.

6. References

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