

Impairments and Other Constraints on Optical Layer Routing

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Abstract

Optical networking poses a number challenges for Generalized Multi-Protocol Label Switching (GMPLS). Fundamentally, optical technology is an analog rather than digital technology whereby the optical layer is lowest in the transport hierarchy and hence has an intimate relationship with the physical geography of the network. This contribution surveys some of the aspects of optical networks that impact routing and identifies possible GMPLS responses for each: (1) Constraints arising from the design of new software controllable network elements, (2) Constraints in a single all-optical domain without wavelength conversion, (3) Complications arising in more complex networks incorporating both all-optical and opaque architectures, and (4) Impacts of diversity constraints.

Table of Contents

1.	Introduction	2
2.	Sub-IP Area Summary and Justification of Work	3
3.	Reconfigurable Network Elements	3
3.1.	Technology Background	3
3.2.	Implications for Routing	6
4.	Wavelength Routed All-Optical Networks	6
4.1.	Problem Formulation	7
4.2.	Polarization Mode Dispersion (PMD)	8
4.3.	Amplifier Spontaneous Emission	9
4.4.	Approximating the Effects of Some Other Impairments Constraints	10
4.5.	Other Impairment Considerations	13

4.6.	An Alternative Approach - Using Maximum Distance as the Only Constraint	13
4.7.	Other Considerations	15
4.8.	Implications for Routing and Control Plane Design	15
5.	More Complex Networks	17
6.	Diversity	19
6.1.	Background on Diversity	19
6.2.	Implications for Routing	23
7.	Security Considerations	23
8.	Acknowledgements	24
9.	References	25
9.1.	Normative References	25
9.2.	Informative References	26
10.	Contributing Authors	26

1. Introduction

Generalized Multi-Protocol Label Switching (GMPLS) [Mannie04] aims to extend MPLS to encompass a number of transport architectures, including optical networks that incorporate a number of all-optical and opto-electronic elements, such as optical cross-connects with both optical and electrical fabrics, transponders, and optical add-drop multiplexers. Optical networking poses a number of challenges for GMPLS. Fundamentally, optical technology is an analog rather than digital technology whereby the optical layer is lowest in the transport hierarchy and hence has an intimate relationship with the physical geography of the network.

GMPLS already has incorporated extensions to deal with some of the unique aspects of the optical layer. This contribution surveys some of the aspects of optical networks that impact routing and identifies possible GMPLS responses for each. Routing constraints and/or complications arising from the design of network elements, the accumulation of signal impairments, and the need to guarantee the physical diversity of some circuits are discussed.

Since the purpose of this document is to further the specification of GMPLS, alternative approaches to controlling an optical network are not discussed. For discussions of some broader issues, see [Gerstel2000] and [Strand02].

The organization of the contribution is as follows:

- Section 2 is a section requested by the sub-IP Area management for all new documents. It explains how this document fits into the Area and into the IPO WG, and why it is appropriate for these groups.

- Section 3 describes constraints arising from the design of new software controllable network elements.
- Section 4 addresses the constraints in a single all-optical domain without wavelength conversion.
- Section 5 extends the discussion to more complex networks and incorporates both all-optical and opaque architectures.
- Section 6 discusses the impacts of diversity constraints.
- Section 7 deals with security requirements.
- Section 8 contains acknowledgments.
- Section 9 contains references.
- Section 10 contains contributing authors' addresses.

2. Sub-IP Area Summary and Justification of Work

This document merges and extends two previous expired Internet-Drafts that were made IPO working group documents to form a basis for a design team at the Minneapolis IETF meeting, where it was also requested that they be merged to create a requirements document for the WG.

In the larger sub-IP Area structure, this merged document describes specific characteristics of optical technology and the requirements they place on routing and path selection. It is appropriate for the IPO working group because the material is specific to optical networks. It identifies and documents the characteristics of the optical transport network that are important for selecting paths for optical channels, which is a work area for the IPO WG. The material covered is directly aimed at establishing a framework and requirements for routing in an optical network.

3. Reconfigurable Network Elements

3.1. Technology Background

Control plane architectural discussions (e.g., [Awduche99]) usually assume that the only software reconfigurable network element is an optical layer cross-connect (OLXC). There are however other software reconfigurable elements on the horizon, specifically tunable lasers and receivers and reconfigurable optical add-drop multiplexers

(OADM). These elements are illustrated in the following simple example, which is modeled on announced Optical Transport System (OTS) products:

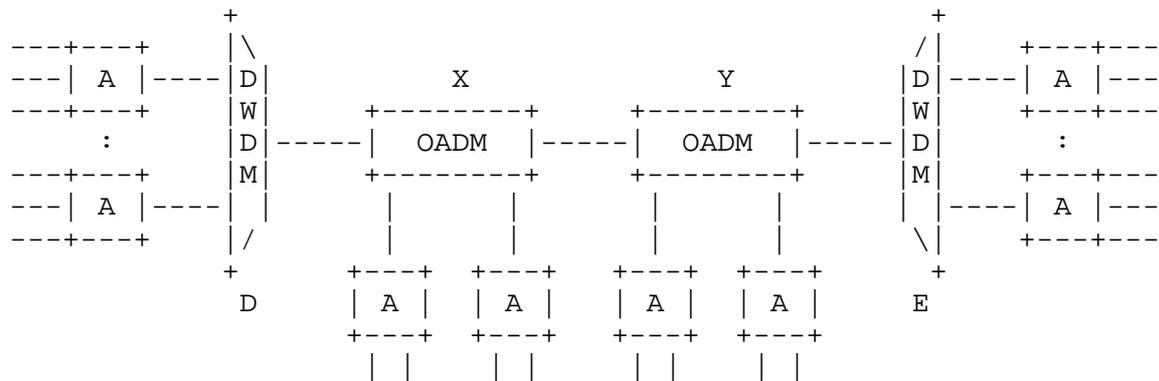


Figure 3-1: An OTS With OADMs - Functional Architecture

In Fig. 3-1, the part that is on the inner side of all boxes labeled "A" defines an all-optical subnetwork. From a routing perspective two aspects are critical:

- Adaptation: These are the functions done at the edges of the subnetwork that transform the incoming optical channel into the physical wavelength to be transported through the subnetwork.
- Connectivity: This defines which pairs of edge Adaptation functions can be interconnected through the subnetwork.

In Fig. 3-1, D and E are DWDMs and X and Y are OADMs. The boxes labeled "A" are adaptation functions. They map one or more input optical channels assumed to be standard short reach signals into a long reach (LR) wavelength or wavelength group that will pass transparently to a distant adaptation function. Adaptation functionality that affects routing includes:

- Multiplexing: Either electrical or optical TDM may be used to combine the input channels into a single wavelength. This is done to increase effective capacity: A typical DWDM might be able to handle 100 2.5 Gb/sec signals (250 Gb/sec total) or 50 10 Gb/sec (500 Gb/sec total); combining the 2.5 Gb/sec signals together thus effectively doubles capacity. After multiplexing the combined signal must be routed as a group to the distant adaptation function.

- Adaptation Grouping: In this technique, groups of k (e.g., 4) wavelengths are managed as a group within the system and must be added/dropped as a group. We will call such a group an "adaptation grouping". Examples include so called "wave group" and "waveband" [Passmore01]. Groupings on the same system may differ in basics such as wavelength spacing, which constrain the type of channels that can be accommodated.
- Laser Tunability: The lasers producing the LR wavelengths may have a fixed frequency, may be tunable over a limited range, or may be tunable over the entire range of wavelengths supported by the DWDM. Tunability speeds may also vary.

Connectivity between adaptation functions may also be limited:

- As pointed out above, TDM multiplexing and/or adaptation grouping by the adaptation function forces groups of input channels to be delivered together to the same distant adaptation function.
- Only adaptation functions whose lasers/receivers are tunable to compatible frequencies can be connected.
- The switching capability of the OADMs may also be constrained.

For example:

- o There may be some wavelengths that can not be dropped at all.
- o There may be a fixed relationship between the frequency dropped and the physical port on the OADM to which it is dropped.
- o OADM physical design may put an upper bound on the number of adaptation groupings dropped at any single OADM.

For a fixed configuration of the OADMs and adaptation functions connectivity will be fixed: Each input port will essentially be hard-wired to some specific distant port. However this connectivity can be changed by changing the configurations of the OADMs and adaptation functions. For example, an additional adaptation grouping might be dropped at an OADM or a tunable laser retuned. In each case the port-to-port connectivity is changed.

These capabilities can be expected to be under software control. Today the control would rest in the vendor-supplied Element Management system (EMS), which in turn would be controlled by the operator's OSes. However in principle the EMS could participate in the GMPLS routing process.

3.2. Implications for Routing

An OTS of the sort discussed in Sec. 3.1 is essentially a geographically distributed but blocking cross-connect system. The specific port connectivity is dependent on the vendor design and also on exactly what line cards have been deployed.

One way for GMPLS to deal with this architecture would be to view the port connectivity as externally determined. In this case the links known to GMPLS would be groups of identically routed wavebands. If these were reconfigured by the external EMS the resulting connectivity changes would need to be detected and advertised within GMPLS. If the topology shown in Fig. 3-1 became a tree or a mesh instead of the linear topology shown, the connectivity changes could result in Shared Risk Link Group (SRLG - see Section 6.2) changes.

Alternatively, GMPLS could attempt to directly control this port connectivity. The state information needed to do this is likely to be voluminous and vendor specific.

4. Wavelength Routed All-Optical Networks

The optical networks deployed until recently may be called "opaque" ([Tkach98]): each link is optically isolated by transponders doing O/E/O conversions. They provide regeneration with retiming and reshaping, also called 3R, which eliminates transparency to bit rates and frame format. These transponders are quite expensive and their lack of transparency also constrains the rapid introduction of new services. Thus there are strong motivators to introduce "domains of transparency" - all-optical subnetworks - larger than an OTS.

The routing of lightpaths through an all-optical network has received extensive attention. (See [Yates99] or [Ramaswami98]). When discussing routing in an all-optical network it is usually assumed that all routes have adequate signal quality. This may be ensured by limiting all-optical networks to subnetworks of limited geographic size that are optically isolated from other parts of the optical layer by transponders. This approach is very practical and has been applied to date, e.g., when determining the maximum length of an Optical Transport System (OTS). Furthermore operational considerations like fault isolation also make limiting the size of domains of transparency attractive.

There are however reasons to consider contained domains of transparency in which not all routes have adequate signal quality. From a demand perspective, maximum bit rates have rapidly increased from DS3 to OC-192 and soon OC-768 (40 Gb/sec). As bit rates increase it is necessary to increase power. This makes impairments

and nonlinearities more troublesome. From a supply perspective, optical technology is advancing very rapidly, making ever-larger domains possible. In this section, we assume that these considerations will lead to the deployment of a domain of transparency that is too large to ensure that all potential routes have adequate signal quality for all circuits. Our goal is to understand the impacts of the various types of impairments in this environment.

Note that, as we describe later in the section, there are many types of physical impairments. Which of these needs to be dealt with explicitly when performing on-line distributed routing will vary considerably and will depend on many variables, including:

- Equipment vendor design choices,
- Fiber characteristics,
- Service characteristics (e.g., circuit speeds),
- Network size,
- Network operator engineering and deployment strategies.

For example, a metropolitan network that does not intend to support bit rates above 2.5 Gb/sec may not be constrained by any of these impairments, while a continental or international network that wished to minimize O/E/O regeneration investment and support 40 Gb/sec connections might have to explicitly consider many of them. Also, a network operator may reduce or even eliminate their constraint set by building a relatively small domain of transparency to ensure that all the paths are feasible, or by using some proprietary tools based on rules from the OTS vendor to pre-qualify paths between node pairs and put them in a table that can be accessed each time a routing decision has to be made through that domain.

4.1. Problem Formulation

We consider a single domain of transparency without wavelength translation. Additionally, due to the proprietary nature of DWDM transmission technology, we assume that the domain is either single vendor or architected using a single coherent design, particularly with regard to the management of impairments.

We wish to route a unidirectional circuit from ingress client node X to egress client node Y. At both X and Y, the circuit goes through an O/E/O conversion that optically isolates the portion within our domain. We assume that we know the bit rate of the circuit. Also, we assume that the adaptation function at X may apply some Forward Error Correction (FEC) method to the circuit. We also assume we know the launch power of the laser at X.

Impairments can be classified into two categories, linear and nonlinear. (See [Tkach98] or [Kaminow02] for more on impairment constraints.) Linear effects are independent of signal power and affect wavelengths individually. Amplifier spontaneous emission (ASE), polarization mode dispersion (PMD), and chromatic dispersion are examples. Nonlinearities are significantly more complex: they generate not only impairments on each channel, but also crosstalk between channels.

In the remainder of this section we first outline how two key linear impairments (PMD and ASE) might be handled by a set of analytical formulae as additional constraints on routing. We next discuss how the remaining constraints might be approached. Finally we take a broader perspective and discuss the implications of such constraints on control plane architecture and also on broader constrained domain of transparency architecture issues.

4.2. Polarization Mode Dispersion (PMD)

For a transparent fiber segment, the general PMD requirement is that the time-average differential group delay (DGD) between two orthogonal state of polarizations should be less than some fraction a of the bit duration, $T=1/B$, where B is the bit rate. The value of the parameter a depends on three major factors: 1) margin allocated to PMD, e.g., 1dB; 2) targeted outage probability, e.g., 4×10^{-5} , and 3) sensitivity of the receiver to DGD. A typical value for a is 10% [ITU]. More aggressive designs to compensate for PMD may allow values higher than 10%. (This would be a system parameter dependent on the system design. It would need to be known to the routing process.)

The PMD parameter (D_{pmd}) is measured in pico-seconds (ps) per $\sqrt{\text{km}}$. The square of the PMD in a fiber span, denoted as span-PMD-square is then given by the product of D_{pmd}^2 and the span length. (A fiber span in a transparent network refers to a segment between two optical amplifiers.) If D_{pmd} is constant, this results in an upper bound on the maximum length of an M -fiber-span transparent segment, which is inversely proportional to the square of the product of bit rate and D_{pmd} (the detailed equation is omitted due to the format constraint - see [Strand01] for details).

For older fibers with a typical PMD parameter of 0.5 picoseconds per square root of km, based on the constraint, the maximum length of the transparent segment should not exceed 400km and 25km for bit rates of 10Gb/s and 40Gb/s, respectively. Due to recent advances in fiber technology, the PMD-limited distance has increased dramatically. For newer fibers with a PMD parameter of 0.1 picosecond per square root of km, the maximum length of the transparent segment (without PMD

compensation) is limited to 10000km and 625km for bit rates of 10Gb/s and 40Gb/, respectively. Still lower values of PMD are attainable in commercially available fiber today, and the PMD limit can be further extended if a larger value of the parameter a (ratio of DGD to the bit period) can be tolerated. In general, the PMD requirement is not an issue for most types of fibers at 10Gb/s or lower bit rate. But it will become an issue at bit rates of 40Gb/s and higher.

If the PMD parameter varies between spans, a slightly more complicated equation results (see [Strand01]), but in any event the only link dependent information needed by the routing algorithm is the square of the link PMD, denoted as link-PMD-square. It is the sum of the span-PMD-square of all spans on the link.

Note that when one has some viable PMD compensation devices and deploy them ubiquitously on all routes with potential PMD issues in the network, then the PMD constraint disappears from the routing perspective.

4.3. Amplifier Spontaneous Emission

ASE degrades the optical signal to noise ratio (OSNR). An acceptable optical SNR level (SNR_{min}), which depends on the bit rate, transmitter-receiver technology (e.g., FEC), and margins allocated for the impairments, needs to be maintained at the receiver. In order to satisfy this requirement, vendors often provide some general engineering rule in terms of maximum length of the transparent segment and number of spans. For example, current transmission systems are often limited to up to 6 spans each 80km long. For larger transparent domains, more detailed OSNR computations will be needed to determine whether the OSNR level through a domain of transparency is acceptable. This would provide flexibility in provisioning or restoring a lightpath through a transparent subnetwork.

Assume that the average optical power launched at the transmitter is P . The lightpath from the transmitter to the receiver goes through M optical amplifiers, with each introducing some noise power. Unity gain can be used at all amplifier sites to maintain constant signal power at the input of each span to minimize noise power and nonlinearity. A constraint on the maximum number of spans can be obtained [Kaminow97] which is proportional to P and inversely proportional to SNR_{min} , optical bandwidth B , amplifier gain $G-1$ and spontaneous emission factor n of the optical amplifier, assuming all spans have identical gain and noise figure. (Again, the detailed equation is omitted due to the format constraint - see [Strand01] for details.) Let's take a typical example. Assuming $P=4dBm$, $SNR_{min}=20dB$ with FEC, $B=12.5GHz$, $n=2.5$, $G=25dB$, based on the

constraint, the maximum number of spans is at most 10. However, if FEC is not used and the requirement on SNR_{min} becomes 25dB, the maximum number of spans drops down to 3.

For ASE the only link-dependent information needed by the routing algorithm is the noise of the link, denoted as link-noise, which is the sum of the noise of all spans on the link. Hence the constraint on ASE becomes that the aggregate noise of the transparent segment which is the sum of the link-noise of all links can not exceed $P/\text{SNR}_{\text{min}}$.

4.4. Approximating the Effects of Some Other Impairment Constraints

There are a number of other impairment constraints that we believe could be approximated with a domain-wide margin on the OSNR, plus in some cases a constraint on the total number of networking elements (OXC or OADM) along the path. Most impairments generated at OXCs or OADMs, including polarization dependent loss, coherent crosstalk, and effective passband width, could be dealt with using this approach. In principle, impairments generated at the nodes can be bounded by system engineering rules because the node elements can be designed and specified in a uniform manner. This approach is not feasible with PMD and noise because neither can be uniformly specified. Instead, they depend on node spacing and the characteristics of the installed fiber plant, neither of which are likely to be under the system designer's control.

Examples of the constraints we propose to approximate with a domain-wide margin are given in the remaining paragraphs in this section. It should be kept in mind that as optical transport technology evolves it may become necessary to include some of these impairments explicitly in the routing process. Other impairments not mentioned here at all may also become sufficiently important to require incorporation either explicitly or via a domain-wide margin.

Other Polarization Dependent Impairments

Other polarization-dependent effects besides PMD influence system performance. For example, many components have polarization-dependent loss (PDL) [Ramaswami98], which accumulates in a system with many components on the transmission path. The state of polarization fluctuates with time and its distribution is very important also. It is generally required that the total PDL on the path be maintained within some acceptable limit, potentially by using some compensation technology for relatively long transmission systems, plus a small built-in margin in OSNR. Since the total PDL increases with the number of components in the data path, it must be taken into account by the system vendor when determining the maximum allowable number of spans.

Chromatic Dispersion

In general this impairment can be adequately (but not optimally) compensated for on a per-link basis, and/or at system initial setup time. Today most deployed compensation devices are based on Dispersion Compensation Fiber (DCF). DCF provides per fiber compensation by means of a spool of fiber with a CD coefficient opposite to the fiber. Due to the imperfect matching between the CD slope of the fiber and the DCF some lambdas can be over compensated while others can be under compensated. Moreover DCF modules may only be available in fixed lengths of compensating fiber; this means that sometimes it is impossible to find a DCF module that exactly compensates the CD introduced by the fiber. These effects introduce what is known as residual CD. Residual CD varies with the frequency of the wavelength. Knowing the characteristics of both of the fiber and the DCF modules along the path, this can be calculated with a sufficient degree of precision. However this is a very challenging task. In fact the per-wavelength residual dispersion needs to be combined with other information in the system (e.g., types fibers to figure out the amount of nonlinearities) to obtain the net effect of CD either by simulation or by some analytical approximation. It appears that the routing/control plane should not be burdened by such a large set of information while it can be handled at the system design level. Therefore it will be assumed until proven otherwise that residual dispersion should not be reported. For high bit rates, dynamic dispersion compensation may be required at the receiver to clean up any residual dispersion.

Crosstalk

Optical crosstalk refers to the effect of other signals on the desired signal. It includes both coherent (i.e., intrachannel) crosstalk and incoherent (i.e., interchannel) crosstalk. Main contributors of crosstalk are the OADM and OXC sites that use a DWDM multiplexer/demultiplexer (MUX/DEMUX) pair. For a relatively sparse network where the number of OADM/OXC nodes on a path is low, crosstalk can be treated with a low margin in OSNR without being a binding constraint. But for some relatively dense networks where crosstalk might become a binding constraint, one needs to propagate the per-link crosstalk information to make sure that the end-to-end path crosstalk which is the sum of the crosstalks on all the corresponding links to be within some limit, e.g., -25dB threshold with 1dB penalty ([Goldstein94]). Another way to treat it without having to propagate per-link crosstalk information is to have the system evaluate what the maximum number of OADM/OXC nodes that has a MUX/DEMUX pair for the worst route in the transparent domain for a low built-in margin. The latter one should work well where all the OXC/OADM nodes have similar level of crosstalk.

Effective Passband

As more and more DWDM components are cascaded, the effective passband narrows. The number of filters along the link, their passband width and their shape will determine the end-to-end effective passband. In general, this is a system design issue, i.e., the system is designed with certain maximum bit rate using the proper modulation format and filter spacing. For linear systems, the filter effect can be turned into a constraint on the maximum number of narrow filters with the condition that filters in the systems are at least as wide as the one in the receiver. Because traffic at lower bit rates can tolerate a narrower passband, the maximum allowable number of narrow filters will increase as the bit rate decreases.

Nonlinear Impairments

It seems unlikely that these can be dealt with explicitly in a routing algorithm because they lead to constraints that can couple routes together and lead to complex dependencies, e.g., on the order in which specific fiber types are traversed [Kaminow97]. Note that different fiber types (standard single mode fiber, dispersion shifted fiber, dispersion compensated fiber, etc.) have very different effects from nonlinear impairments. A full treatment of the nonlinear constraints would likely require very detailed knowledge of the physical infrastructure, including measured dispersion values for each span, fiber core area and composition, as well as knowledge of subsystem details such as dispersion compensation technology. This information would need to be combined with knowledge of the current loading of optical signals on the links of interest to determine the level of nonlinear impairment. Alternatively, one could assume that nonlinear impairments are bounded and result in X dB margin in the required OSNR level for a given bit rate, where X for performance reasons would be limited to 1 or 2 dB, consequently setting a limit on the maximum number of spans. For the approach described here to be useful, it is desirable for this span length limit to be longer than that imposed by the constraints which can be treated explicitly. When designing a DWDM transport system, there are tradeoffs between signal power launched at the transmitter, span length, and nonlinear effects on BER that need to be considered jointly. Here, we assume that an X dB margin is obtained after the transport system has been designed with a fixed signal power and maximum span length for a given bit rate. Note that OTSs can be designed in very different ways, in linear, pseudo-linear, or nonlinear environments. The X-dB margin approach may be valid for some but not for others. However, it is likely that there is an advantage in designing systems that are

less aggressive with respect to nonlinearities, and therefore somewhat sub-optimal, in exchange for improved scalability, simplicity and flexibility in routing and control plane design.

4.5. Other Impairment Considerations

There are many other types of impairments that can degrade performance. In this section, we briefly mention one other type of impairment, which we propose be dealt with by either the system designer or by the transmission engineers at the time the system is installed. If dealt with successfully in this manner they should not need to be considered in the dynamic routing process.

Gain Nonuniformity and Gain Transients For simple noise estimates to be of use, the amplifiers must be gain-flattened and must have automatic gain control (AGC). Furthermore, each link should have dynamic gain equalization (DGE) to optimize power levels each time wavelengths are added or dropped. Variable optical attenuators on the output ports of an OXC or OADM can be used for this purpose, and in-line devices are starting to become commercially available. Optical channel monitors are also required to provide feedback to the DGEs. AGC must be done rapidly if signal degradation after a protection switch or link failure is to be avoided.

Note that the impairments considered here are treated more or less independently. By considering them jointly and varying the tradeoffs between the effects from different components may allow more routes to be feasible. If that is desirable or the system is designed such that certain impairments (e.g., nonlinearities) need to be considered by a centralized process, then distributed routing is not the one to use.

4.6. An Alternative Approach - Using Maximum Distance as the Only Constraint

Today, carriers often use maximum distance to engineer point-to-point OTS systems given a fixed per-span length based on the OSNR constraint for a given bit rate. They may desire to keep the same engineering rule when they move to all-optical networks. Here, we discuss the assumptions that need to be satisfied to keep this approach viable and how to treat the network elements between two adjacent links.

In order to use the maximum distance for a given bit rate to meet an OSNR constraint as the only binding constraint, the operators need to satisfy the following constraints in their all-optical networks:

- All the other non-OSNR constraints described in the previous subsections are not binding factors as long as the maximum distance constraint is met.
- Specifically for PMD, this means that the whole all-optical network is built on top of sufficiently low-PMD fiber such that the upper bound on the mean aggregate path DGD is always satisfied for any path that does not exceed the maximum distance, or PMD compensation devices might be used for routes with high-PMD fibers.
- In terms of the ASE/OSNR constraint, in order to convert the ASE constraint into a distance constraint directly, the network needs to have a fixed fiber distance D for each span (so that ASE can be directly mapped by the gain of the amplifier which equals to the loss of the previous fiber span), e.g., 80km spacing which is commonly chosen by carriers. However, when spans have variable lengths, certain adjustment and compromise need to be made in order to avoid treating ASE explicitly as in section 4.3. These include: 1) Unless a certain mechanism is built in the OTS to take advantage of shorter spans, spans shorter than a typical span length D need to be treated as a span of length D instead of with its real length. 2) Spans that are longer than D would have a higher average span loss. In general, the maximum system reach decreases when the average span loss increases. Thus, in order to accommodate longer spans in the network, the maximum distance upper bound has to be set with respect to the average span loss of the worst path in the network. This sub-optimality may be acceptable for some networks if the variance is not too large, but may be too conservative for others.

If these assumptions are satisfied, the second issue we need to address is how to treat a transparent network element (e.g., MEMS-based switch) between two adjacent links in terms of a distance constraint since it also introduces an insertion loss. If the network element cannot somehow compensate for this OSNR degradation, one approach is to convert each network element into an equivalent length of fiber based on its loss/ASE contribution. Hence, in general, introducing a set of transparent network elements would effectively result in reducing the overall actual transmission distance between the OEO edges.

With this approach, the link-specific state information is link-distance, the length of a link. It equals the distance sum of all fiber spans on the link and the equivalent length of fiber for the network element(s) on the link. The constraint is that the sum of

all the link-distance over all links of a path should be less than the maximum-path-distance, the upper bound of all paths.

4.7. Other Considerations

Routing in an all-optical network without wavelength conversion raises several additional issues:

- Since the route selected must have the chosen wavelength available on all links, this information needs to be considered in the routing process. One approach is to propagate information throughout the network about the state of every wavelength on every link in the network. However, the state required and the overhead involved in processing and maintaining this information is proportional to the total number of links (thus, number of nodes squared), maximum number of wavelengths (which keeps doubling every couple of years), and the frequency of wavelength availability changes, which can be very high. Instead [Hjalmtysson00], proposes an alternative method which probes along a chosen path to determine which wavelengths (if any) are available. This would require a significant addition to the routing logic normally used in OSPF. Others have proposed simultaneously probing along multiple paths.
- Choosing a path first and then a wavelength along the path is known to give adequate results in simple topologies such as rings and trees ([Yates99]). This does not appear to be true in large mesh networks under realistic provisioning scenarios, however. Instead significantly better results are achieved if wavelength and route are chosen simultaneously ([Strand01b]). This approach would however also have a significant effect on OSPF.

4.8. Implications For Routing and Control Plane Design

If distributed routing is desired, additional state information will be required by the routing to deal with the impairments described in Sections 4.2 - 4.4:

- As mentioned earlier, an operator who wants to avoid having to provide impairment-related parameters to the control plane may elect not to deal with them at the routing level, instead treating them at the system design and planning level if that is a viable approach for their network. In this approach the operator can pre-qualify all or a set of feasible end-to-end optical paths through the domain of transparency for each bit rate. This approach may work well with relatively small and sparse networks, but it may not be scalable for large and dense networks where the number of feasible paths can be very large.

- If the optical paths are not pre-qualified, additional link-specific state information will be required by the routing algorithm for each type of impairment that has the potential of being limiting for some routes. Note that for one operator, PMD might be the only limiting constraint while for another, ASE might be the only one, or it could be both plus some other constraints considered in this document. Some networks might not be limited by any of these constraints.
- For an operator needing to deal explicitly with these constraints, the link-dependent information identified above for PMD is link-PMD-square which is the square of the total PMD on a link. For ASE the link-dependent information identified is link-noise which is the total noise on a link. Other link-dependent information includes link-span-length which is the total number of spans on a link, link-crosstalk or OADM-OXC-number which is the total crosstalk or the number of OADM/OXC nodes on a link, respectively, and filter-number which is the number of narrow filters on a link. When the alternative distance-only approach is chosen, the link-specific information is link-distance.
- In addition to the link-specific information, bounds on each of the impairments need to be quantified. Since these bounds are determined by the system designer's impairment allocations, these will be system dependent. For PMD, the constraint is that the sum of the link-PMD-square of all links on the transparent segment is less than the square of (a/B) where B is the bit rate. Hence, the required information is the parameter "a". For ASE, the constraint is that the sum of the link-noise of all links is no larger than P/SNR_{min} . Thus, the information needed include the launch power P and OSNR requirement SNR_{min} . The minimum acceptable OSNR, in turn, depends on the strength of the FEC being used and the margins reserved for other types of impairments. Other bounds include the maximum span length of the transmission system, the maximum path crosstalk or the maximum number of OADM/OXC nodes, and the maximum number of narrow filters, all are bit rate dependent. With the alternative distance-only approach, the upper bound is the maximum-path-distance. In single-vendor "islands" some of these parameters may be available in a local or EMS database and would not need to be advertised.
- It is likely that the physical layer parameters do not change value rapidly and could be stored in some database; however these are physical layer parameters that today are frequently not known at the granularity required. If the ingress node of a lightpath does path selection these parameters would need to be available at this node.

- The specific constraints required in a given situation will depend on the design and engineering of the domain of transparency; for example it will be essential to know whether chromatic dispersion has been dealt with on a per-link basis, and whether the domain is operating in a linear or nonlinear regime.
- As optical transport technology evolves, the set of constraints that will need to be considered either explicitly or via a domain-wide margin may change. The routing and control plane design should therefore be as open as possible, allowing parameters to be included as necessary.
- In the absence of wavelength conversion, the necessity of finding a single wavelength that is available on all links introduces the need to either advertise detailed information on wavelength availability, which probably doesn't scale, or have some mechanism for probing potential routes with or without crankback to determine wavelength availability. Choosing the route first, and then the wavelength, may not yield acceptable utilization levels in mesh-type networks.

5. More Complex Networks

Mixing optical equipment in a single domain of transparency that has not been explicitly designed to interwork is beyond the scope of this document. This includes most multi-vendor all-optical networks.

An optical network composed of multiple domains of transparency optically isolated from each other by O/E/O devices (transponders) is more plausible. A network composed of both "opaque" (optically isolated) OLXCs and one or more all-optical "islands" isolated by transponders is of particular interest because this is most likely how all-optical technologies (such as that described in Sec. 2) are going to be introduced. (We use the term "island" in this discussion rather than a term like "domain" or "area" because these terms are associated with specific approaches like BGP or OSPF.)

We consider the complexities raised by these alternatives now.

The first requirement for routing in a multi-island network is that the routing process needs to know the extent of each island. There are several reasons for this:

- When entering or leaving an all-optical island, the regeneration process cleans up the optical impairments discussed in Sec. 3.
- Each all-optical island may have its own bounds on each impairment.

- The routing process needs to be sensitive to the costs associated with "island-hopping".

This last point needs elaboration. It is extremely important to realize that, at least in the short to intermediate term, the resources committed by a single routing decision can be very significant: The equipment tied up by a single coast-to-coast OC-192 can easily have a first cost of \$10**6, and the holding times on a circuit once established is likely to be measured in months. Carriers will expect the routing algorithms used to be sensitive to these costs. Simplistic measures of cost such as the number of "hops" are not likely to be acceptable.

Taking the case of an all-optical island consisting of an "ultra long-haul" system like that in Fig. 3-1 embedded in an OEO network of electrical fabric OLXCs as an example: It is likely that the ULH system will be relatively expensive for short hops but relatively economical for longer distances. It is therefore likely to be deployed as a sort of "express backbone". In this scenario a carrier is likely to expect the routing algorithm to balance OEO costs against the additional costs associated with ULH technology and route circuitously to make maximum use of the backbone where appropriate. Note that the metrics used to do this must be consistent throughout the routing domain if this expectation is to be met.

The first-order implications for GMPLS seem to be:

- Information about island boundaries needs to be advertised.
- The routing algorithm needs to be sensitive to island transitions and to the connectivity limitations and impairment constraints particular to each island.
- The cost function used in routing must allow the balancing of transponder costs, OXC and OADM costs, and line haul costs across the entire routing domain.

Several distributed approaches to multi-island routing seem worth investigating:

- Advertise the internal topology and constraints of each island globally; let the ingress node compute an end-to-end strict explicit route sensitive to all constraints and wavelength availabilities. In this approach the routing algorithm used by the ingress node must be able to deal with the details of routing within each island.

- Have the EMS or control plane of each island determine and advertise the connectivity between its boundary nodes together with additional information such as costs and the bit rates and formats supported. As the spare capacity situation changes, updates would be advertised. In this approach impairment constraints are handled within each island and impairment-related parameters need not be advertised outside of the island. The ingress node would then do a loose explicit route and leave the routing and wavelength selection within each island to the island.
- Have the ingress node send out probes or queries to nearby gateway nodes or to an NMS to get routing guidance.

6. Diversity

6.1. Background on Diversity

"Diversity" is a relationship between lightpaths. Two lightpaths are said to be diverse if they have no single point of failure. In traditional telephony the dominant transport failure mode is a failure in the interoffice plant, such as a fiber cut inflicted by a backhoe.

Why is diversity a unique problem that needs to be considered for optical networks? Traditionally, data network operators have relied on their private line providers to ensure diversity and so have not had to deal directly with the problem. GMPLS makes the complexities handled by the private line provisioning process, including diversity, part of the common control plane and so visible to all.

To determine whether two lightpath routings are diverse it is necessary to identify single points of failure in the interoffice plant. To do so we will use the following terms: A fiber cable is a uniform group of fibers contained in a sheath. An Optical Transport System will occupy fibers in a sequence of fiber cables. Each fiber cable will be placed in a sequence of conduits - buried honeycomb structures through which fiber cables may be pulled - or buried in a right of way (ROW). A ROW is land in which the network operator has the right to install his conduit or fiber cable. It is worth noting that for economic reasons, ROWs are frequently obtained from railroads, pipeline companies, or thruways. It is frequently the case that several carriers may lease ROW from the same source; this makes it common to have a number of carriers' fiber cables in close proximity to each other. Similarly, in a metropolitan network, several carriers might be leasing duct space in the same RBOC conduit. There are also "carrier's carriers" - optical networks which provide fibers to multiple carriers, all of whom could be affected by a single failure in the "carrier's carrier" network. In

a typical intercity facility network there might be on the order of 100 offices that are candidates for OLXCs. To represent the inter-office fiber network accurately a network with an order of magnitude more nodes is required. In addition to Optical Amplifier (OA) sites, these additional nodes include:

- Places where fiber cables enter/leave a conduit or right of way;
- Locations where fiber cables cross; Locations where fiber splices are used to interchange fibers between fiber cables.

An example of the first might be:

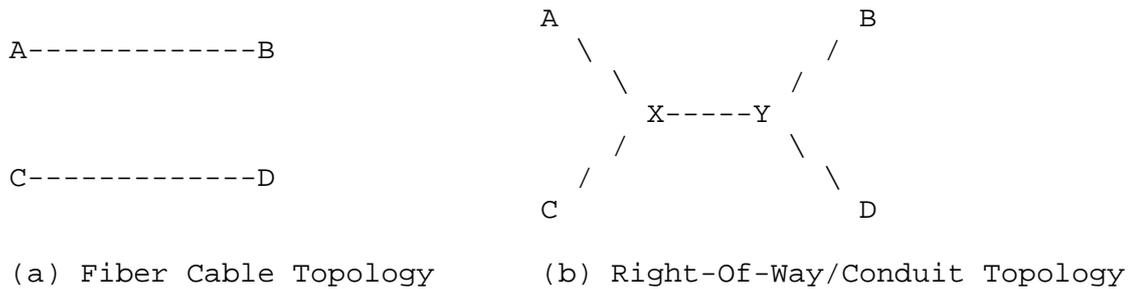


Figure 6-1: Fiber Cable vs. ROW Topologies

Here the A-B fiber cable would be physically routed A-X-Y-B and the C-D cable would be physically routed C-X-Y-D. This topology might arise because of some physical bottleneck: X-Y might be the Lincoln Tunnel, for example, or the Bay Bridge.

Fiber route crossing (the second case) is really a special case of this, where X and Y coincide. In this case the crossing point may not even be a manhole; the fiber routes might just be buried at different depths.

Fiber splicing (the third case) often occurs when a major fiber route passes near to a small office. To avoid the expense and additional transmission loss only a small number of fibers are spliced out of the major route into a smaller route going to the small office. This might well occur in a manhole or hut. An example is shown in Fig. 6-2(a), where A-X-B is the major route, X the manhole, and C the smaller office. The actual fiber topology would then look like Fig. 6-2(b), where there would typically be many more A-B fibers than A-C or C-B fibers, and where A-C and C-B might have different numbers of fibers. (One of the latter might even be missing.)

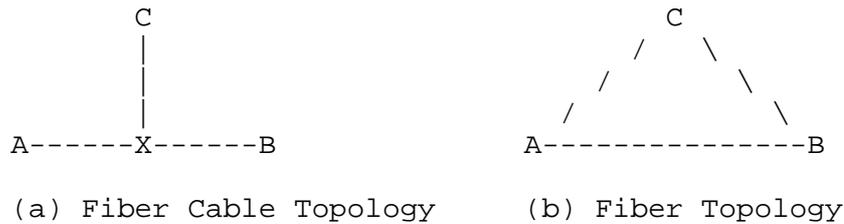


Figure 6-2. Fiber Cable vs Fiber Topologies

The imminent deployment of ultra-long (>1000 km) Optical Transport Systems introduces a further complexity: Two OTSes could interact a number of times. To make up a hypothetical example: A New York - Atlanta OTS and a Philadelphia - Orlando OTS might ride on the same right of way for x miles in Maryland and then again for y miles in Georgia. They might also cross at Raleigh or some other intermediate node without sharing right of way.

Diversity is often equated to routing two lightpaths between a single pair of points, or different pairs of points so that no single route failure will disrupt them both. This is too simplistic, for a number of reasons:

- A sophisticated client of an optical network will want to derive diversity needs from his/her end customers' availability requirements. These often lead to more complex diversity requirements than simply providing diversity between two lightpaths. For example, a common requirement is that no single failure should isolate a node or nodes. If a node A has single lightpaths to nodes B and C, this requires A-B and A-C to be diverse. In real applications, a large data network with N lightpaths between its routers might describe their needs in an NxN matrix, where (i,j) defines whether lightpaths i and j must be diverse.
- Two circuits that might be considered diverse for one application might not be considered diverse for in another situation. Diversity is usually thought of as a reaction to interoffice route failures. High reliability applications may require other types of failures to be taken into account. Some examples:
 - o Office Outages: Although less frequent than route failures, fires, power outages, and floods do occur. Many network managers require that diverse routes have no (intermediate) nodes in common. In other cases an intermediate node might be acceptable as long as there is power diversity within the office.

- o Shared Rings: Many applications are willing to allow "diverse" circuits to share a SONET ring-protected link; presumably they would allow the same for optical layer rings.
- o Disasters: Earthquakes and floods can cause failures over an extended area. Defense Department circuits might need to be routed with nuclear damage radii taken into account.
- Conversely, some networks may be willing to take somewhat larger risks. Taking route failures as an example: Such a network might be willing to consider two fiber cables in heavy duty concrete conduit as having a low enough chance of simultaneous failure to be considered "diverse". They might also be willing to view two fiber cables buried on opposite sides of a railroad track as being diverse because there is minimal danger of a single backhoe disrupting them both even though a bad train wreck might jeopardize them both. A network seeking N mutually diverse paths from an office with less than N diverse ROWs will need to live with some level of compromise in the immediate vicinity of the office.

These considerations strongly suggest that the routing algorithm should be sensitive to the types of threat considered unacceptable by the requester. Note that the impairment constraints described in the previous section may eliminate some of the long circuitous routes sometimes needed to provide diversity. This would make it harder to find many diverse paths through an all-optical network than an opaque one.

[Hjalmtysson00] introduced the term "Shared Risk Link Group" (SRLG) to describe the relationship between two non-diverse links. The above examples and discussion given at the start of this section suggests that an SRLG should be characterized by 2 parameters:

- Type of Compromise: Examples would be shared fiber cable, shared conduit, shared ROW, shared optical ring, shared office without power sharing, etc.)
- Extent of Compromise: For compromised outside plant, this would be the length of the sharing.

A CSPF algorithm could then penalize a diversity compromise by an amount dependent on these two parameters.

Two links could be related by many SRLGs. (AT&T's experience indicates that a link may belong to over 100 SRLGs, each corresponding to a separate fiber group.) Each SRLG might relate a single link to many other links. For the optical layer, similar situations can be expected where a link is an ultra-long OTS.

The mapping between links and different types of SRLGs is in general defined by network operators based on the definition of each SRLG type. Since SRLG information is not yet ready to be discoverable by a network element and does not change dynamically, it need not be advertised with other resource availability information by network elements. It could be configured in some central database and be distributed to or retrieved by the nodes, or advertised by network elements at the topology discovery stage.

6.2. Implications For Routing

Dealing with diversity is an unavoidable requirement for routing in the optical layer. It requires dealing with constraints in the routing process, but most importantly requires additional state information (e.g., the SRLG relationships). The routings of any existing circuits from which the new circuit must be diverse must also be available to the routing process.

At present SRLG information cannot be self-discovered. Indeed, in a large network it is very difficult to maintain accurate SRLG information. The problem becomes particularly daunting whenever multiple administrative domains are involved, for instance after the acquisition of one network by another, because there normally is a likelihood that there are diversity violations between the domains. It is very unlikely that diversity relationships between carriers will be known any time in the near future.

Considerable variation in what different customers will mean by acceptable diversity should be anticipated. Consequently we suggest that an SRLG should be defined as follows: (i) It is a relationship between two or more links, and (ii) it is characterized by two parameters, the type of compromise (shared conduit, shared ROW, shared optical ring, etc.) and the extent of the compromise (e.g., the number of miles over which the compromise persisted). This will allow the SRLGs appropriate to a particular routing request to be easily identified.

7. Security Considerations

We are assuming OEO interfaces to the domain(s) covered by our discussion (see, e.g., Sec. 4.1 above). If this assumption were to be relaxed and externally generated optical signals allowed into the

domain, network security issues would arise. Specifically, unauthorized usage in the form of signals at improper wavelengths or with power levels or impairments inconsistent with those assumed by the domain would be possible. With OEO interfaces, these types of layer one threats should be controllable.

A key layer one security issue is resilience in the face of physical attack. Diversity, as describe in Sec. 6, is a part of the solution. However, it is ineffective if there is not sufficient spare capacity available to make the network whole after an attack. Several major related issues are:

- Defining the threat: If, for example, an electro-magnetic interference (EMI) burst is an in-scope threat, then (in the terminology of Sec. 6) all of the links sufficiently close together to be disrupted by such a burst must be included in a single SRLG. Similarly for other threats: For each in-scope threat, SRLGs must be defined so that all links vulnerable to a single incident of the threat must be grouped together in a single SRLG.
- Allocating responsibility for responding to a layer one failure between the various layers (especially the optical and IP layers): This must be clearly specified to avoid churning and unnecessary service interruptions.

The whole proposed process depends on the integrity of the impairment characterization information (PMD parameters, etc.) and also the SRLG definitions. Security of this information, both when stored and when distributed, is essential.

This document does not address control plane issues, and so control-plane security is out of scope. IPO control plane security considerations are discussed in [Rajagopalam04]. Security considerations for GMPLS, a likely control plane candidate, are discussed in [Mannie04].

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