Selective Transparency in Optical Networks

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Abstract -- Core optical networks can benefit from lower costs and increased speed by reducing O-E-O conversions through use of ultra long reach optical transport, and bit-rate and wavelength transparent cross-connects. While pure optical transparency avoids the high cost of deploying optical termination units (OTUs) for each wavelength channel, it incurs new costs with additional fiber requirements and reduced provisioning capability. This paper describes an intermediate option, selective transparency that uses small pools of wavelength converters at cross-connect nodes, which combines the advantages of reduced OTU count, minimal additional fiber, and high reconfigurability to support changing traffic patterns.

Index terms – optical cross-connect, transparency, ultra long reach optical systems, wavelength conversion, O-E-O, regeneration

A. INTRODUCTION

Future core optical networks are expected to transmit data at unprecedented rates due to rising demand, and enabled by the high-speed DWDM (Dense Wavelength Division Multiplexing) technology. However, an impeding factor for optical signals is imposed by the need for conversion to electronics, which destroys wavelength and bit-rate transparency, and increases network costs. This is typically due to opto-electronic switching at the nodes, needed for both wavelength conversion and signal regeneration. However, the introduction of all-optical switches, MEMS-based [7] for instance, and ultra long haul (ULH) optical transport, make this requirement obsolete. These two technologies can thus be leveraged to increase use of longer transparent paths resulting in elimination of a large number of OTUs. However, this form of *pure transparency*, as developed, for example, in the MONET research project [5], typically requires additional fiber resources, resulting in more “stranded capacity”. But more significantly, pure transparency reduces flexibility needed for changing traffic demands.

To mitigate these shortcomings, we explore an intermediate option that we term as *selective transparency*. This refers to the option of selective deployment of equipment that is not wavelength/bit-rate transparent--in particular wavelength converters--that can translate the wavelength of light on which a given optical signal is carried. This approach allows a trade-off between *opaque* design, which requires the least fiber resources, and *transparent* design, which requires no wavelength conversion. In addition to reducing network cost, such a selectively transparent design also increases the flexibility of the network to changes in traffic demands, and attempts to keep the number of network components manageable by reducing cross-connect sizes and wavelength conversion pools at pre-specified nodes.

In the rest of this paper, we provide quantitative comparisons between these three design options, opaque, transparent and selectively transparent, on example networks ranging from moderate to large sizes carrying variable amounts of traffic. The comparison is performed in terms of equipment required, wavelength converters, regenerators, fibers, *etc*., and not directly in terms of cost, since the relative costs of network components are not yet stable and decisive. For the same reason, we do not fully explore the trade-off between fiber resources and wavelength conversion equipment, as the optimal trade-off would depend on these relative costs. Instead, we evaluate one possible operating point for selective transparency, i.e. wavelength conversion requirements to support the traffic with the least fiber resources (obtained from opaque design). Already, this choice demonstrates substantial gains, suggesting that the optimal trade-off would be much preferable to the extremes of opaqueness and pure transparency.

B. SELECTIVE TRANSPARENCY

The principal differences between opaque design and pure transparent design are summarized in Table 1.

OPAQUE	TRANSPARENT
- Large no. of OTUs (regens+WLCs)	+ Few OTUs (regens only)
+ Low stranded capacity	- Higher stranded capacity
- ULH systems effective only for very long links	+ ULH systems effective if links are short but paths are long
+ Flexible and simple to operate	- Inflexible and complex to operate

Table 1. Comparison of opaque and transparent networks

As Table 1 shows, there is a large penalty associated with use of opaque designs. Typically, O-E-O components comprise the larger part of the total network cost. Elimination of that cost can reduce the total network cost by a significant amount. However, loss of flexibility due to pure transparent design has motivated much discussion and proposed remedies [6]. Selective transparency is an intermediate solution between these extremes, and a generalization of the *Islands of Transparency* discussed in [6]. Figure 1 gives a schematic of both the islands of transparency and the proposed selective transparency designs. Clearly, islands of transparency constitutes a special case of selective transparency in which only a pre-specified set of nodes carry converter pools.

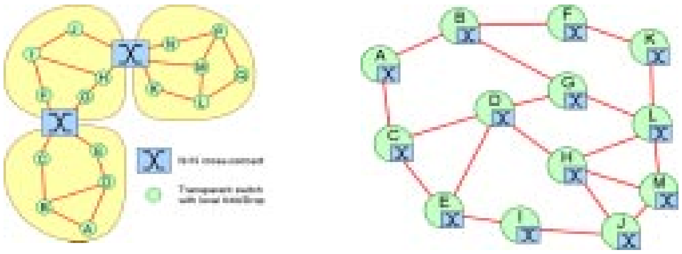

Figure 1. Islands of transparency (left) as a special case of the proposed selective transparency (right).

Selective transparency therefore combines the best features of opaque design (low stranded capacity and flexibility) with the best features of pure transparency (few OTUs and leveraging ultra long haul transport). However, the reduction in the OTU counts needs to be quantified. Small overall reductions will not influence designs in practice, but substantial reductions in both components and costs can justify departures from established methods. We demonstrate the latter to be the case for selective transparency, using both moderate to large traffic loads on typical optical backbone networks. We precede this with an outline of the methodology we follow to obtain selective transparent designs.

C. DESIGN METHODS

Mathematical optimization of the selective transparency design is a hard problem, both from computational and implementation points of view. The well-know routing and wavelength assignment problem [4] is only a small part of the optimal design, which is in itself hard, even to approximate to within reasonable error. Furthermore, we must deal with protection and restoration issues that further complicate even the opaque design methods [1,2]. With these considerations in mind, we follow a feasible and scalable approximation that is outlined in the diagram of Table 2.

- Do optimal opaque design [1,2] with protection as needed
- Assign wavelengths to lightpaths given by step 1 [3] as follows
- Process lightpaths in order of decreasing hop counts
- Index wavelengths
- If current lightpath is primary
  - o Choose lowest indexed available wavelength
  - o If none available, choose the wavelength with largest hop span to destination
- If lightpath is protection, for shared protection, do as above and
  - o Allow sharing of wavelengths with other single-failure non-coincident protection lightpaths
- Add wavelength converters at each node, as necessary

Table 2: Outline of selective transparent design heuristic

References [1,2,3,4] could be consulted for detailed description of these approximations and their performance.

D. NUMERICAL EXPERIMENTS

To quantify the advantages due to selective transparency, we examined several real networks of which two representative samples are discussed in detail. The key characteristics of these networks are summarized in Table 3.

Attribute	**Network 1 (Large Load)**	**Network 2 (Moderate Load)**
No. of nodes	120	40
No. of links	210	55
Link lengths	2-4000km(mean ~350)	1-2000km (mean ~600)
Diameter	15 links/6500km	17 links/9000km
No. of neighbors per node	mean 3.5	mean 2.5
Number of node-pairs with non-zero demand	4000	600
Demand (in λs) per node-pair	mean ~10 λs	mean ~1.4 λs
Demand (in λs) in total	42K λs (84K λs with protection)	800 λs (1600 λs with protection)
Primary path lengths	~8 links, mean 2500km	~6 links, mean 3037km
Back-up path lengths	Mean ~9 links, ~3000km	Mean 9 links, ~4904km
URL system reach	2000-4000km or 20-40 spans with 50-100 km per span	2000-4000km or 20-40 spans with 50-100 km per span
Fiber	80 λs	80 λs

Table 3. Attributes of the sample networks studied

Two facts are particularly worth noting. First, in both networks, typical path lengths are in the range ~2000-3000km, about the same as the ULH reach, with the distribution primarily skewed towards the shorter paths. This implies good use of ULH systems can be made to eliminate OTUs. Second, a large number of links are traversed by each path, typically 6-8 links for primary paths. This makes the wavelength assignment challenging as intersections with multiple other paths are common. Tables 4 & 5 summarize key metrics for each of the three design options for Networks 1 & 2, respectively.

	Opaque	**Pure Transparent**	**Selective Transparent**
Total Regens	~1.5M/1M	~0.25M/0.2 M	~0.25M/0.2M
Total WLCs	~1.5M/1M	0/0	~50K/40K
Total fiber*hops	~8K/6K	~10K/8K	~8.3K/6.3K
Total fiber*km	2M/1.6M	~2.5M/2M	2M/1.5M
Fiber pairs/link	1-128/110	1-150/130	1-128/110
λ pairs/link	33-10K/8K	40-12K/10K	33-10K/8K

Table 4. Comparative results for Network 1, for 1+1 (left of slash) and shared mesh (right of slash)

	Opaque	Pure Transparent	Selective Transparent
Total Regens	~25K/20K	~1.8K/~1.8 K	~1.8K/1.7K
Total WLCs	~25K/18K	0/0	~1.8K/1.7K
Total fiber*hops	~155/140	~190/160	~155/140
Total fiber*km	~95K/75K	~110K/90K	~95K/75K
Fiber pairs/link	~3.2/2.5	~3.6/3.0	~3.2/2.5
λ pairs/link	~230/170	~270/200	~230/170

Table 5. Comparative results for Network 2, for 1+1 (left of slash) and shared mesh (right of slash)

There are a few assumptions made in the derivation of results in Tables 4 and 5. First, it is assumed that each node reduces the range of the optical signal by 1-2 spans. Thus, a light path that traverses 5 nodes end-to-end, loses 5-10 spans out of its 20-40 span budget. This accounting takes care of any signal degradation due to the optical switch at the node and is indeed conservative. Furthermore, the approximation used in Section C also errs on the side of caution in calculating the wavelength and fiber counts. These result in over-estimates of all relevant attributes tabulated above for both transparent and selective transparent designs.

Tables 4 and 5 shed light on several issues related to the three design methods. The following are the key findings

1. There is a substantial reduction in OTU counts in both networks for the transparent design options, roughly about an order of magnitude
2. Pure transparent design typically involves more fiber in the order of 10-20%
3. The number of wavelength converters is no more, and is typically much less, than the number of regenerators needed, both substantially fewer than OTUs in opaque designs
4. At each node only a small number of wavelength converters and regenerators are needed, typically in the order of 10-15 % of ports
5. Shared mesh is typically 20% lower in major attributes compared to 1+1 designs.
6. In both the large and intermediate traffic loads (Networks 1 &2) the results are qualitatively the same, namely, the % reductions are comparable

The quantification of flexibility afforded by selective transparency requires more complex models than the static load assumption we have made in this paper. In particular, the changing traffic patterns across the network require definition of dynamic traffic for node pairs. However, it is intuitively clear that dynamic traffic will typically *reduce* the size of the converter pools, even compared to item 4 above. This is due to the statistical multiplexing, or sharing, of converter pool across many fibers at each node. It is also interesting to determine the pool size if converters are limited to fixed output wavelengths. However, early simulations suggest that the converter pool continues to be an order of magnitude smaller than port counts. This is the subject of another investigation.

E. CONCLUSIONS

All-optical cross-connects and ultra long haul transport systems make it possible to design and manage networks in which wavelengths are not individually terminated at every node of the network, as is current practice today in what is referred to as opaque designs. Designs that take advantage of these new technologies are closely related to the “transparent” design envisioned in the DARPA work of the 1980s but are in many respects distinct from those. In particular, use of transparent switches augmented by a pool of wavelength converters and regenerators helps reduce the O-E-O needed in the network to near absolute minimum. The proposed selective transparency also maintains flexibility needed for changing traffic patterns without additional fiber requirements.

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