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Lightpath-Level Protection versus Connection-Level Protection for Carrier-Grade Ethernet in a Mixed-Line-Rate Telecom Network

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Abstract: Ethernet is a success story in Local Area Networks (LAN). Efforts for extending its boundaries beyond LAN to the carriers' backbone networks are in progress. We study the problem of designing reliable and cost-efficient high-rate (100 Gbit/s) carrier-grade Ethernet in a multi-line-rate telecom network under signal transmission-range constraints. Reliability is achieved using shared-path protection at two levels: (1) Protection-at-Connection (PAC) level, or (2) Protection-at-Lightpath (PAL) level. We study the two cases for their impact on network cost and other performance parameters. We construct a graph, called Mixed Topology (MT), using which it is possible to: (1) identify traffic grooming possibilities, (2) select a path which requires the minimum amount of 3R regeneration, and (3) effectively choose the data rate of a lightpath to be established. Our algorithms, tested on the 17-node German network, lead to the following findings: (1) for both PAL and PAC, our MT-based algorithm resulted in lower network cost and higher lightpath utilization compared with other schemes; and (2) in general, PAL incurs slightly higher cost than PAC.

Key Words: *Ethernet, Carrier-Grade, Multi-Line Rate (MLR), Signal Transmission Range, 3R Regeneration, Network Design, Shared Protection, Survivable Traffic Grooming (STG).*

I. INTRODUCTION

Being the dominating LAN technology, around 90% of Internet traffic is generated by end systems with Ethernet interfaces. Hence, efforts for extending Ethernet usage beyond LANs to Metropolitan Area Networks (MAN) and Wide Area Networks (WAN) are in progress. The future mode of operation is to carry native Ethernet frames directly over Wavelength-Division Multiplexing optical backbone networks (Ethernet-over-WDM). Thus, several layers of other technologies can be eliminated, and significant savings in Capital Expenditures (CapEx) and Operational Expenditures (OpEx) can be achieved.

In a backbone network, Ethernet can be set up as a connection-oriented service and tunnels carrying Ethernet frames. Three forwarding technologies for such tunnels are being explored: Virtual-LAN Crossconnect (VLAN-XC), Provider Backbone Transport (PBT), and Transport Multi-protocol Label Switching (T-MPLS) [4]. Studies [4] [7] have found that CapEx and OpEx savings can be maximized by running Ethernet over WDM tunnels (i.e., lightpaths [5]) at high rates (up to 100 Gbit/s).

Our study focuses on Ethernet-over-WDM inside the carrier's backbone (carrier-grade) network, so Ethernet now requires carrier-level reliability. Also, since the lightpath data rate can be high (100 Gbit/s) and it may travel long distances (for backbone links), 3R (Re-amplification, Retiming, and Reshaping) [9] [10] signal regeneration may be needed for a lightpath.

Wavelengths on different links may operate at different rates (multi-line-rate network). This gives the network operator more flexibility in choosing the lightpath's rate according to the available links' rates in the network. The operator may also want to operate links with different rates based on their location in the network.

The problem addressed in this paper is a special case of survivable traffic grooming (STG). The STG problem was considered in previous studies [6] [8]. In dynamic STG [6], performance metrics include wavelength and port usage for Protection-at-Connection (PAC) level and Protection-at-Lightpath (PAL) level. Unlike previous studies, our problem also considers the multi-line-rate nature of the network, i.e., different links may operate at different rates. We also consider the signal's maximum transmission range constraints, which depend on the signal bit rate. In a recent work [2], we studied the carrier-grade Ethernet problem using PAC. In our present paper, we extend the work in [2] in two dimensions: (1) carrier-grade Ethernet using PAL versus one using PAC, and (2) study various design parameters against different traffic matrices. Note that, even though the motivation behind this study is carrier-grade Ethernet, the general concepts and solution methods discussed here apply to connections carrying traffic other than Ethernet.

Section II explains the node architecture, explains 3R regeneration, and formally states the problem. Section III presents the design algorithms. Section IV discusses the experimental results. Section V concludes the study.

II. NODE ARCHITECTURE, 3R REGENERATION, AND PROBLEM FORMULATION

A) Node Architecture and 3R Regeneration

Figure 1 shows the Ethernet-over-WDM switch architecture. It has two components: (1) Optical Crossconnect (OXC) which performs switching at the lightpath level and (2) Ethernet Switch (ES). The Ethernet Switch initiates and terminates lightpaths using Ethernet Interfaces (EI), namely Ethernet Transmitter (ET) and Ethernet Receiver (ER). ES performs electronic functions of grooming Ethernet connections onto the lightpaths, and regeneration. OXC must have enough I/O ports (linecards) to support fiber connections with neighboring nodes as well as for local add/drop with the ES.

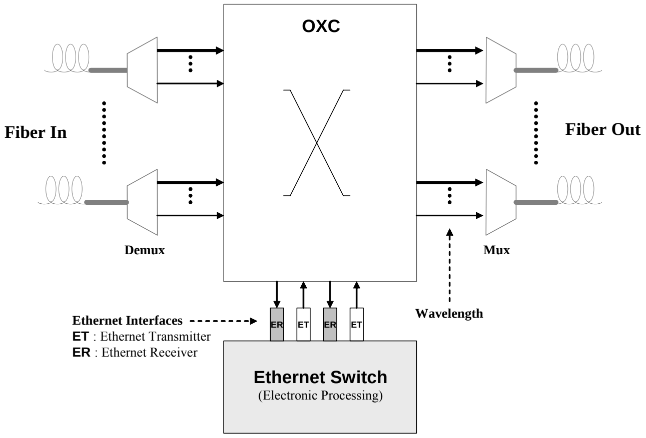

Fig. 1: Node architecture.

To perform in-node electronic 3R regeneration (used here), a number of Optical-Electronic-Optical (OEO) transponders (Ethernet interfaces in our case) must be allocated. Now, if a lightpath needs regeneration, it must be directed from OXC to ES (see Fig. 1), get regenerated, and then sent back to OXC and output fiber.

B) Problem Formulation

The cost-efficient and reliable carrier-grade Ethernet network design problem is formulated as follows:

Given:

- Network topology represented by graph $G(V,E)$ with set of edges E representing links and set of vertices V representing nodes.
- Traffic demand matrix composed of Ethernet connections with different bandwidth requirements.
- All nodes have regeneration and traffic grooming capabilities.
- The network can have mixed line rates.

Transmission Constraints:

- Number of wavelengths on a link and wavelength capacity.
- Number of Ethernet interfaces at each node.
- Signal's maximum transmission range, i.e., maximum distance a lightpath can travel before regeneration is required.
- Wavelength continuity is assumed for each lightpath.

Need to:

- Route all Ethernet connections.
- All Ethernet connections must be protected. Shared-path protection is used to protect the Ethernet connections against single link failures.

Objectives:

- Satisfy all Ethernet connections.
- Reduce the solution's CapEx: determined by the number and rates of Ethernet interfaces used.

III. DESIGN ALGORITHMS

An efficient algorithm must address the following issues:

(1) Shortest path, where edge weight is the link's length, does not imply that the path is a minimum-regeneration path (requiring minimum amount of 3R regeneration).

(2) Establishing a lightpath over a set of links running at rate R implies that the transmitter and receiver at the ends of the lightpath must operate at a *minimum* rate of R.

(3) If a lightpath (LP) originating from node X destined to node Z ($\text{LP}_{\text{X-Z}}$) requires regeneration at a third node Y, then since the LP must be terminated in the ES at node Y to perform regeneration, $\text{LP}_{\text{X-Y}}$ is segmented into two lightpaths, namely, $\text{LP}_{\text{X-Y}}$ and $\text{LP}_{\text{Y-Z}}$. This will create a grooming opportunity into $\text{LP}_{\text{Y-Z}}$ at node Y. It is also possible that the two lightpaths use different wavelengths.

(4) If a lightpath originating from node X destined to node Z ($\text{LP}_{\text{X-Z}}$) uses links X-Y, Y-Z, where link X-Y is running at rate $R1$ and link Y-Z is running at a different rate $R2$, then $\text{LP}_{\text{X-Z}}$ must be segmented into two lightpaths, namely, $\text{LP}_{\text{X-Y}}$ and $\text{LP}_{\text{Y-Z}}$. $\text{LP}_{\text{X-Y}}$ runs at rate $R1$, and $\text{LP}_{\text{Y-Z}}$ runs at rate $R2$. Again, this will create a grooming opportunity into $\text{LP}_{\text{Y-Z}}$ at node Y. The two lightpaths may use different wavelengths.

(5) Once a lightpath is terminated in the Ethernet switch, electronic functions are accessible. For example, grooming can be performed, and wavelength conversion is possible [9]. In addition, regeneration is *always* performed.

To address the above issues, we construct an auxiliary graph called Mixed Topology (MT). The term Mixed is used since the edges of MT might be physical links, virtual links (already established lightpaths), or both. The MT is constructed on a per-Ethernet-connection basis, i.e., for each connection, its MT is constructed. The MT contains all possible virtual and physical links over which a specific lightpath can be routed. Moreover, establishing the MT for finding a protection path must address the resource-sharing constraints. Hence, risk information must be maintained.

In this study, the rules in Table 1 are used for constructing the MT for the connection's working and protection paths.

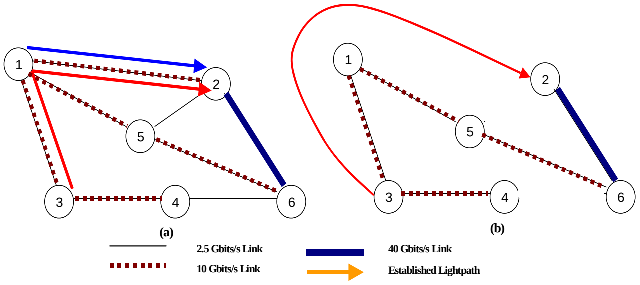

Fig. 2: MT construction.

Figure 2 shows an example for constructing MT. In this example, all links have two wavelengths. In Fig. 2(a), LP 1-2 is fully used and only 2.5 Gbit/s is used in LP 3-2. Consider a 5 Gbit/s connection from node 4 to node 2; the corresponding MT for this connection is shown in Fig. 2(b). All links running below 5 Gbit/s are eliminated. LP 1-2 is removed since it has no free capacity. Link 1-2 is removed since it is saturated. (Note that free capacity available in link 1-2 is reflected through the inclusion of LP 3-2.) All remaining links and LPs are included in MT.

In this example, we may establish a LP between nodes 4 and 3, and then groom the LP onto LP 3-2.

Constructing MT for Finding Working Path

The MT includes all physical and virtual links except:

- All links running at rates below connection's rate.
- All LPs reserved for protection.
- All saturated LPs or LPs with free capacity below the connection's rate.
- All saturated links (saturated = all wavelengths in use).

Constructing MT for Finding Protection Path

The MT includes all the physical and virtual links except:

- All links running at rates below the connection's rate.
- All physical links on the connection's primary path.
- All protection LPs for connections sharing the same risk with the current connection if the aggregate capacity of the connections exceeds each LP capacity.
- All working LPs.
- All protection LPs that have reached the maximum allowed sharing, if any.
- All links saturated with working traffic.

Table 1: Rules for constructing the MT.

For a connection with certain granularity it is possible to carry it over LPs with different rates. If we simply use a shortest-path algorithm to route the connection, then the algorithm may not recognize this. To increase the possibility of picking the minimum-cost path, we use the concept of link stretching. Under this concept, the link's weight is multiplied (stretched) by factor α that depends on both the link's rate and the connection's granularity. Factor α is defined as:

$$\alpha = \text{Link Rate / Connection's Rate.}$$

Using link stretching, we can set higher weights on links with high line rates. Hence, the probability of generating low-rate (cost-efficient) paths will increase. In addition, generating low-rate paths means higher transmission reach and less 3R regeneration. To enable grooming on established LPs, weights on the MT's virtual links (already established LPs) are set to zero.

Now, based on the MT construction rules and the concept of link stretching, we propose the following two algorithms: (1) MT-Based algorithm for Reliable and Cost-Efficient Carrier-grade Ethernet Design using PAC and link stretching, or simply PAC/s, (2) MT-Based algorithm for Reliable and Cost-Efficient Carrier-grade Ethernet Design using PAL, or simply PAL/s.

A) PAC/s

For each (source, destination) Ethernet connection, do following:

A. Determine connection's working path:

1. Establish MT for connection's working path (Working MT).
2. Stretch the links.
3. Generate set of K minimum-weight paths (KMWP) over established MT. If set contains zero paths, block connection.
4. For each path in KMWP, calculate cost of using that path. Path cost is equal to the number of Ethernet interfaces of certain rate times the Ethernet interface's price of that rate.
5. Pick path with minimum cost, route connection and update usage information on the network resources.

B. Determine connection's protection path:

1. Establish MT for connection's protection path (Protection MT) and perform link stretching.
2. Generate set of KMWP. If set contains zero paths, block connection.
3. For each path in KMWP, find cost of routing the connection. (Cost is determined as in Step A-4)
4. Pick path with minimum cost, reserve resources over that path and update the network's state.

B) PAL/s

For each (source, destination) Ethernet connection, do following:

Determine connection's working path:

1. Establish MT for connection's working path (Working MT).
2. Stretch the links.
3. Generate set of KMWP. If set contains zero paths, block connection.
4. For each path in KMWP, calculate its cost.
5. Pick path with minimum cost.
6. Determine number of new lightpaths that need to be established to route connection over path generated in Step 5. Number of new lightpaths equals number of non-zero segments of selected route, where a non-zero segment is a set of adjacent physical links (edges with non-zero weights).
7. For each new lightpath, determine protection path as follows:
    a. Establish MT for the lightpath's protection path, and perform link stretching.
    b. Generate set of KMWP over established MT. If set contains zero paths, block connection.
    c. For each path in KMWP, find cost of routing the lightpath.
    d. Pick path with minimum cost, reserve resources over that path and update the network's state.

In these algorithms, routing and wavelength assignment (RWA [3] [5] [13]) are combined, i.e., as soon as a path is found, the number (and rate) of LPs to be established are determined; and for each LP a single (wavelength-continuous) path is searched along its route. If such a path is not found, the connection is blocked.

IV. EXPERIMENTAL RESULTS

The proposed solution methods were experimented with on the German network topology shown in Figure 3. Each link is associated with the two numbers (R, D) where R is the link's rate in Gbit/s and D is the link's distance in km. The number of wavelengths on each link is 64. The number of Ethernet interface slots at each node is 256. Links are bidirectional. Lightpaths are unidirectional in this study. A link has a single rate, same in both directions. Ethernet connections are 1 Gbit/s, 10 Gbit/s, or 100 Gbit/s. Traffic is asymmetric among different (source, destination) pairs (see [2]). The aggregate traffic is scaled up (multiplied) by a factor from the set {1, 1.35, 1.85, 2.35, 2.85, and 3.35}. Lightpaths running at 10 Gbit/s and 100 Gbit/s have maximum transmission distances of 3000 km and 500 km, respectively, after which regeneration is required. Ethernet interface rates are 10 Gbit/s and 100 Gbit/s with relative costs of 1 and 5 respectively. Network cost is equal to the number of Ethernet interfaces of each rate times the Ethernet interface's cost for that rate. This includes Ethernet interfaces used for setting up *working* lightpaths and *protection* lightpaths

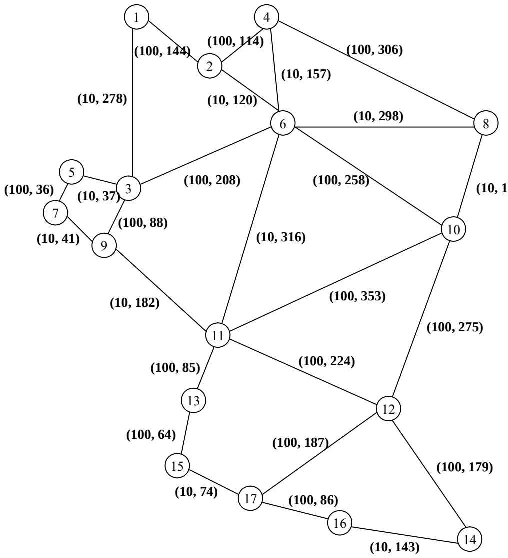

Fig. 3: German network topology.

The K value to generate the KMWP is 2. The design algorithms compared against each other are the following:

<u>PAC/s</u>: Algorithm uses shared Protection-at-Connection (PAC) level and is based on constructing the MT and performing link stretching.

<u>PAC/ns</u>: Algorithm uses shared protection at connection level and is based on constructing the MT but <u>no</u> link stretching is used.

<u>PAC-KSP</u>: Algorithm uses shared protection at the connection level. In this case, neither MT nor link stretching is used. It simply generates the K shortest paths (KSP) based on the links distances.

<u>PAL/s, PAL/ns, PAL-KSP</u>: Same as above but Protection-at-Lightpath (PAL) level is used.

We discuss the results in the following two dimensions: (1) comparison of PAC versus PAL; and (2) comparison of the performance of MT-based approaches versus non-MT approaches.

A) PAC versus PAL

Figure 4 shows the performance of the six cases in terms of their impact on the network cost. To make a fair comparison, each approach is compared to the relevant one, e.g., PAC/s versus PAL/s. In addition, the cost comparison is tied to the traffic-blocking ratio (TBR) shown in Figure 7. This is because, in a network design problem, all traffic must be satisfied, and a higher TBR may lead to higher cost (in order to reflect the cost of the blocked traffic). If we consider PAC/s and PAL/s, PAC/s results in lower cost (5-15% cost saving) for all traffic values. Considering the TBR in Fig. 7, PAC/s has higher TBR (around 5%). The difference in TBR does not scale with the difference in cost, which may suggest that PAC/s is more cost-efficient than PAL/s.

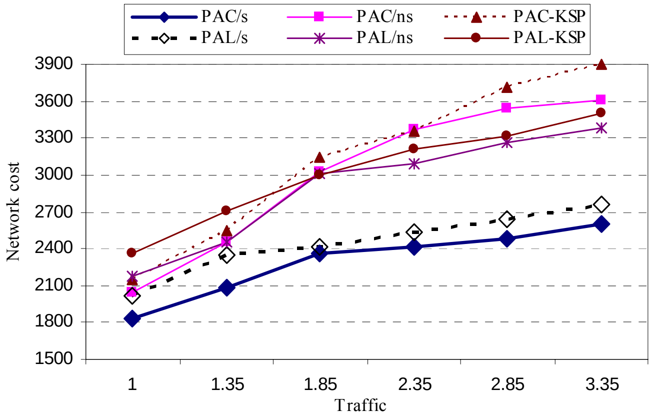

Fig. 4: Network Cost.

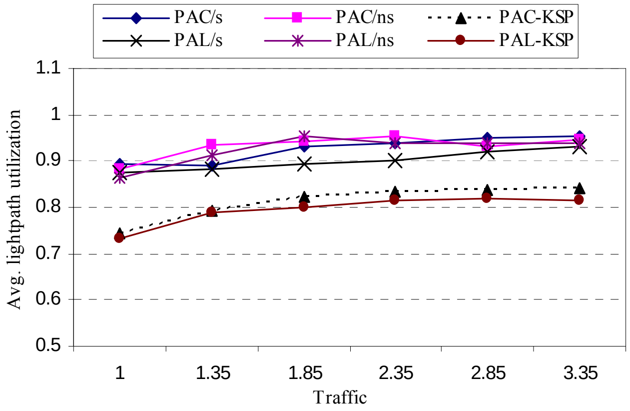

Fig. 5: Avg. utilization of the 100 Gbit/s lightpaths.

For the other schemes that do not use link stretching (PAC/ns, PAL/ns), or may not use MT (PAC-KSP, PAL-KSP), PAC-based approaches have higher cost than PAL-based schemes, but TBR is higher for PAL-based schemes.

These differences in TBR and cost for PAC/s and PAL/s can be explained as follows: using link stretching, the algorithm is biased toward low-rate links; Ethernet connections tend to use low-rate wavelength channels. In this case, the low-rate channels are consumed quickly. Due to wavelength-continuity constraint, it is possible that some connections may not find a single wavelength channel available on all the low-rate links.

B) MT-based approaches versus other approaches

The MT-based approaches with link stretching result in lower cost than the other schemes at the expense of higher TBR. The increase in TBR is explained above. The important point is that the difference in TBR between

PAC/s and PAL/s is less than the improvement in cost achieved by PAC/s and PAL/s, especially at high traffic.

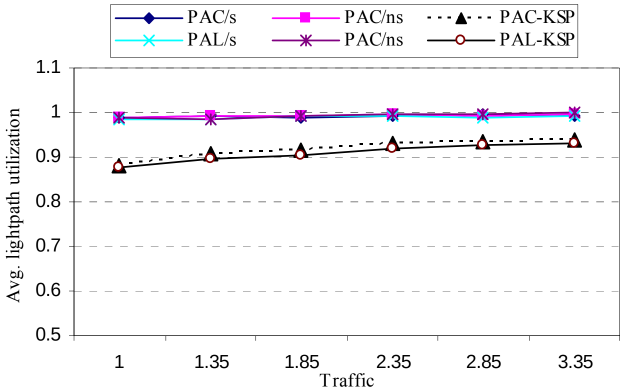

Fig. 6: Avg. utilization of the 10 Gbit/s lightpaths.

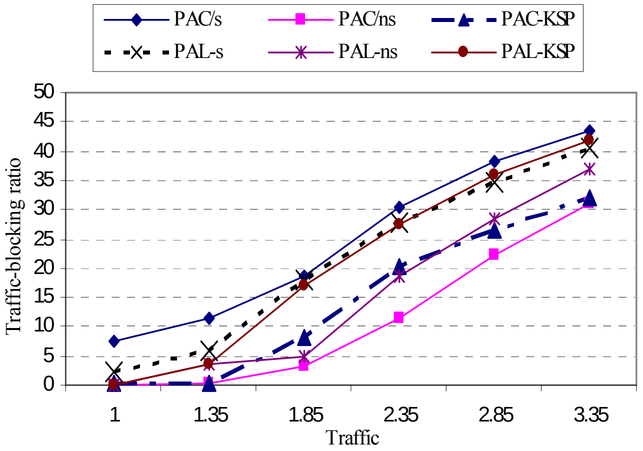

Fig. 7: Traffic-blocking ratio (TBR).

We comment on one more observation regarding the average lightpath utilization (Figures 5 and 6). Even though the network cost using link stretching (PAC/s, PAL/s) is lower, the average lightpath utilization in both cases is very close where we may expect PAC/s and PAL/s to achieve higher utilization than PAC/ns and PAL/ns. This is justified as follows.

(1) Since the algorithm sets zero weights on the MT's virtual (lightpath) edges, Ethernet connections will be forced to follow these lightpaths. In PAC/ns and PAL/ns, since more 100 Gbit/s LPs are established, these LPs will take longer to be filled, and hence PAC/ns and PAL/ns are more affected by the fake utilization phenomena.

(2) Since no link stretching is performed in PAC/ns and PAL/ns, the probability of selecting a path running at 100 Gbit/s is high. Hence, in a 100 Gbit/s lightpath, more Ethernet connections may coexist, so the number of connections sharing the same risk will reduce the number of backup lightpaths that can be shared for protection. As a result, we need to use more resources for protecting the connections, which will increase the network cost.

V. CONCLUSION

We studied the design of reliable and cost-efficient carrier-grade Ethernet in a multi-line-rate telecom network with signal-transmission-range constraints with high rates (100 Gbit/s). These constraints are very practical in a carrier's telecom network. In particular, we studied design algorithms using the Protection-at-Connection (PAC) level and Protection-at-Lightpath (PAL) level protection schemes. We proposed a graph-based soution, which depends on constructing the Mixed Topology (MT) and the novel concept of *link stretching*. The approach showed improved performance compared to non-MT-based approaches. Also, PAL costs a little more than PAC.

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