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Carrier-Grade Ethernet over WDM under Maximum Transmission Range (TR) Constraints of Signals

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Abstract: We study the problem of determining the optimal transmission range (TR) for high-rate carrier-grade Ethernet. We show that, since traffic grooming can be combined with signal regeneration, optimal TR value depends on the traffic volume.

OCIS codes: (060.4250) Networks

1. Introduction

Ethernet is an inexpensive, flexible, and widely-used technology, so it a strong candidate to be the transport technology for the carriers' backbone networks (carrier-grade Ethernet).

In a backbone network, Ethernet can be set up as a connection-oriented service with tunnels carrying Ethernet frames directly over a WDM network (Ethernet-over-WDM) with possibly high rates (100 Gbit/s) [1] where streams of Ethernet frames (Ethertunnels) are carried by lightpaths. These lightpths are established using Ethernet interfaces and are used to carry Ethernet traffic (term Etherpath is used to denote lightpath carrying only Ethernet traffic). Thus, several layers of other technologies (e.g., SONET/SDH) can be eliminated, and significant savings in Capital Expenditure (CapEx) and Operational Expenditure (OpEx) can be achieved.

Study [1] has found that CapEx and OpEx savings can be maximized by running Ethernet over WDM channels at high rates (up to 100 Gbit/s). With high rates of operation (100 Gbit/s) and since the signal may travel long distances in a backbone network, the effects of physical impairments may become prominent and the signal's quality may degrade. Hence, 3R (Re-amplification, Reshaping, and Retiming) signal regeneration may be needed. The maximum all-optical (rate-dependent) distance that a signal can travel is constrained. In addition to the TR dependence on the rate, the signal's modulation scheme performed at the source node governs the TR. Hence, to achieve higher TR; more intelligent (and more expensive) interfaces can be used. In this case, the interface's cost is TR-dependent [2]. Even though high TR may reduce the amount of 3R regeneration and reduce the network's cost, there may be a certain maximum TR value beyond which the network's cost may increase. Our objective is to determine this value, which is discussed next.

2. Node Architecture and Problem Statement

A) Node Architecture 3R Regeneration

Figure 1 shows the node architecture. It has two components: (1) the Optical Crossconnect (OXC) which switches signals optically at the Etherpath (lightpath) level and (2) the Ethernet Switch (ES). The ES initiates and terminates the Etherpaths (EPs). It can also perform other electronic functions such as grooming and 3R regeneration. Using this architecture, an EP must maintain a single wavelength along its path. If any of the electronic functions need to be performed on an EP, two interfaces are required, one transmitter for initiating the EP and one receiver for terminating. Now, if an Etherpath requires regeneration, it must be directed from OXC to ES (see Fig. 1), get regenerated, and then sent back to OXC and output fiber. Hence, an Etherpath (EP) originating from node X and destined to node Z (EP_{x-z}) requires regeneration at a third node Y, then since the EP must be terminated in the ES at node Y to perform regeneration, EP_{x-z} is segmented into two Etherpaths, namely, EP_{x-y} and EP_{y-z}. This will create a grooming opportunity into EP_{y-z} at node Y.

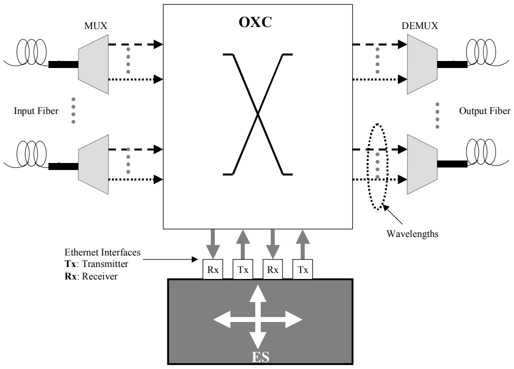

Fig. 1. Node architecture.

B) Problem description

The problem can be stated as follows. Given: (1) a network's physical topology represented by graph $G(N,E)$ where N represents the set of nodes and E represents the set of links, (2) traffic demand matrix composed of Ethertunnels with different bandwidth granularities, (3) number of interface slots on each node, (4) number of wavelength channels on each link, (5) set of different maximum transmission range values, and (6) Ethernet interface costs corresponding to the different maximum transmission range values. We need to provision all the traffic demands such that network cost (determined by the number of the Ethernet interfaces used) is minimized.

3. Transmission Range: Optimal Solution

To find the optimal TR, we can formulate the problem as an Integer Linear Program (ILP) where (1) TR selection, (2) Etherpath routing, (3) Etherunnel routing, and (4) resource constraints are captured. The ILP is as follows:

Given: (1) number of nodes $|N|$; (2) length of link (m,n) = d_{mn}; (3) number of wavelengths W on a link; (4) number of interface slots at node n = S_n; (5) throughput (maximum value of traffic a node can process at a time) of node n = G_n; (6) maximum number of Etherpaths that can be setup between any two nodes i and j = T_{ij} (T_{ij} = min $\{S_i, S_j\}$); (7) set R of possible transmission ranges where $r \in R$ is the index of transmission range with maximum un-regenerated distance D^r; (8) δ_{mn}, which takes value of 1 if link (m,n) exists; (9) μ^r: interface cost when TR = D^r is used; and (10) capacity of an Etherpath = C.

Variables: (1) α^r, binary variable takes value of 1 if TR = D^r is used; (2) $V_{ij}^{r,t}$, binary variable takes value of 1 if the t-th Etherpath ($t \in T_{ij}$) between nodes i and j is established and has a TR = D^r; (3) $V_{ij,mn}^{r,t}$ binary variable takes value of 1 if Etherpath $V_{ij}^{r,t}$ uses link (m,n); (4) V_{ij}^{r}: number of Etherpaths between nodes (i,j) when max TR = D^r; (5) $\lambda_{ij}^{sd,z,y}$, binary variable takes value of 1 if the z-th Ethertunnel with granularity y ($y \in \{1,10,40,100\}$ Gbit/s) between nodes (s,d) uses Etherpath (i,j); (6) V^r: total number of Etherpaths when TR = D^r; and (7) number of transmitters T_n and receivers R_n at node n.

Constraints:

$$\sum_r \alpha^r = 1$$

$$\sum_{m,n} d_{mn} \times V_{ij,mn}^{r,t} \le D^r$$
$$\forall i, j, t, r.$$

$$V_{ij,mn}^{r,t} \le \delta_{mn} \times \alpha^r$$
$$\forall i, j, m, n, t, r.$$

$$V_{ij}^{r} = \sum_t V_{ij}^{r,t} \quad \forall i, j$$

$$\sum_m V_{ij,mi}^{r,t} = 0 \quad \forall i, j, t, r$$

$$\sum_n V_{ij,jn}^{r,t} = 0 \quad \forall i, j, t, r$$

$$\sum_t \sum_m V_{ij,mj}^{r,t} = V_{ij}^{r} \quad \forall i, j, r$$

$$\sum_t \sum_n V_{ij,in}^{r,t} = V_{ij}^{r} \quad \forall i, j, r$$

$$\sum_m V_{ij,mk}^{r,t} = \sum_n V_{ij,kn}^{r,t}$$
$$\text{if } k \ne i, j \ \forall i, j, k, r, t$$

$$V_{ij,mn}^{r,t} + V_{ij,nm}^{r,t} \le 1$$
$$\forall i, j, m, n, r$$

$$\sum_r \sum_{i,j} \sum_t V_{ij,mn}^{r,t} \le W \quad \forall m, n$$

$$\sum_r C \times V_{ij}^{r} \le G_i \ \forall i, j$$

$$\sum_r C \times V_{ij}^{r} \le G_j \ \forall i, j$$

$$\sum_i \sum_r V_{ij}^{r} \le T_j \quad \forall j$$

$$\sum_j \sum_r V_{ij}^{r} \le T_i \quad \forall i$$

$$T_n + R_n \le S_n \quad \forall n$$

$$\sum_i \lambda_{id}^{sd,z,y} = 1 \ \forall s, d, z, y$$

$$\sum_j \lambda_{sj}^{sd,z,y} = 1 \ \forall s, d, z, y$$

$$\sum_i \lambda_{is}^{sd,z,y} = 0 \ \forall s, d, z, y$$

$$\sum_j \lambda_{dj}^{sd,z,y} = 0 \ \forall s, d, z, y$$

$$\sum_i \lambda_{ik}^{sd,z,y} = \sum_j \lambda_{kj}^{sd,z,y}$$
$$\text{if } k \ne s, d \ \forall s, d, z, y$$

$$\sum_{s,d} \sum_y \sum_z y \times \lambda_{ij}^{sd,z,y} \le \sum_r C \times V_{ij}^{r}$$
$$\forall i, j$$

Objective:

$$\text{Minimize} \sum_r \left(\mu^r \times V^r\right)$$

Linear programming methods are often not scalable for large (and sometimes even for moderate) size networks. Hence, solution algorithms may be needed. Our previous study [3] used an auxiliary graph called Mixed Topology (MT) to perform routing/grooming with signal's TR constraints. Our MT-based algorithm (MT-based) can reflect the traffic grooming opportunities when 3R regeneration is performed.

4. Illustrative Numerical Examples

We apply the ILP model above on the network in Fig. 2. The average traffic demand among node pairs is 10 Gbit/s. Link weights are distances in kilometers. Each link has two 100 Gbit/s wavelengths. For this network, three possible TR's are considered {300, 500, 700} km with relative interface costs {1, 1.2, 1.5}, respectively. The optimal TR using ILP is 300 km. The same output is generated using our MT-based algorithm. For scalability constraints, we use our algorithm to study the cost-TR relationship for the network in Fig. 3. Each link is running at 100 Gbit/s. The number of wavelengths on each link 160. The number of Ethernet interfaces at each node is 128. Links are bidirectional. Etherpaths are unidirectional. Network cost is equal to the number of interfaces used times the cost of an interface. The following TR values are considered: 750, 1000, 1250, 1500, 1750, 2000, 2250, and 2500 kilometers with relatives interface costs of 1.0, 1.1, 1.2, 1.4, 1.6, 1.8, 2.0, and 2.2, respectively. Traffic is uniform among all (source, destination) node pairs.

Figure 4 shows the network's cost versus TR. For this figure, the amount of traffic between any node pair is 100 Gbit/s. The minimum cost value is achieved at TR = 1250 km. (Note that this value is half the distance between various parts of the network, i.e., 2500 km.) In the TR interval {750, 1000, and 1250} km, the increase in TR reduces the cost, mainly due to the reduction in the amount of 3R regeneration required. For TR values beyond 1250 km, cost increases as TR increases. In this case, it is possible that the amount of regeneration is reducing, but the increase in the interface cost dominates the network's cost.

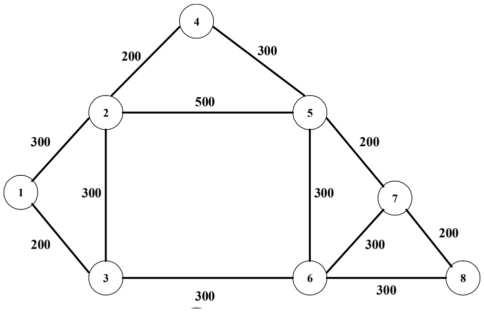

Fig. 2. 8-node network.

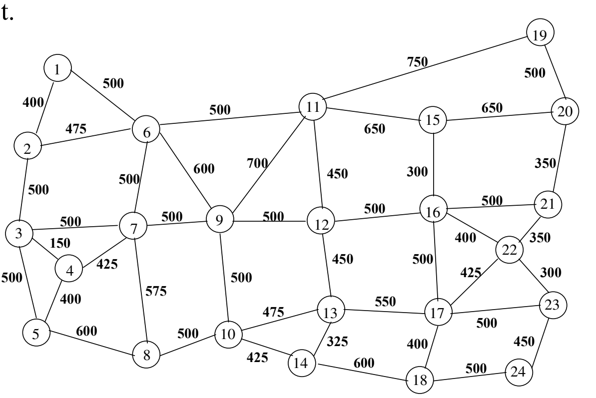

Fig. 3. US nationwide backbone network.

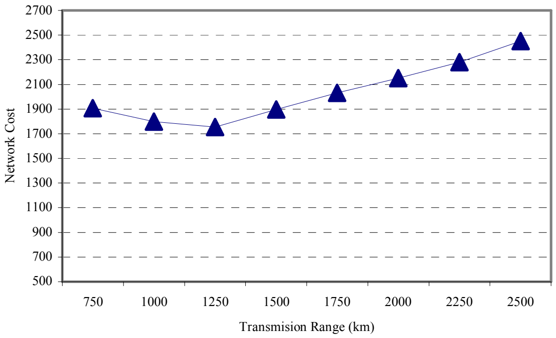

Fig. 4. Network cost versus TR.

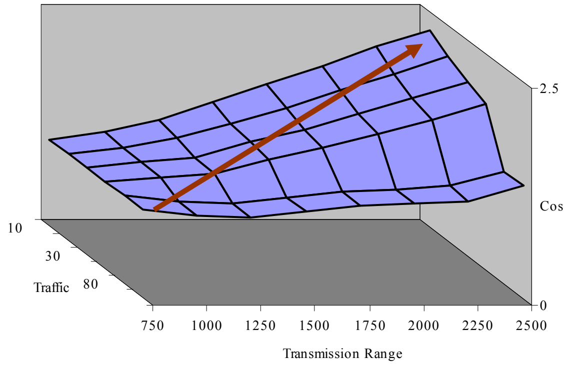

Fig. 5. Network cost –TR versus Traffic.

Since 3R regeneration can create grooming opportunities, we study the network's cost sensitivity against TR with different traffic scenarios. This three dimensional relationship is captured in Fig. 5. The following values of traffic between any node pair are considered: 10, 20, 30, 40, 80, and 100 Gbit/s. Note that, for each scenario, the cost is normalized to that captured at TR = 750 km. Based on Fig. 5, we make the following observations. First, as we go into the direction of the arrow, the cost increases. This direction is characterized by increase in TR and decrease in the amount of traffic. This is explained as follows: as the TR increases, less regeneration is performed, and hence, we may not groom other traffic onto the Etherpaths (that require regeneration with a shorter TR). In this case, we need to establish new Etherpaths to satisfy this traffic, i.e., more resources are used (cost increase). Second, at low traffic values, the decrease in TR reduces the cost. Again, this is because lower TR means more grooming points, since grooming is more relevant when traffic is low, it may be desirable to operate at (moderately) low TR in this case. (Note that, at low traffic values (10, 20, 30, and 40), best TR = 750 km.) Finally, at high traffic values, increasing the TR to certain value reduces the cost (1250 km for traffic values 80 and 100 Gbit/s). In addition, further increase in TR increases the cost, but this increase is very small compared with the case of low traffic. This is because grooming is less relevant in this case and higher TR may be desirable.

5. Conclusion

Careful selection of the TR is important as it affects the network's cost. In addition to its dependence on distance, TR selection is also dependent on the traffic volume.

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