A Dynamic-Programming-Based Cost Analysis of 100G, 200G, and 400G Transmission Rates

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Abstract: We propose an efficient algorithm to analyze the costs for 100G, 200G and 400G transmission rates in next-generation networks. We apply our method to a sample network and study sensitivity to transponder reach and cost.

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1. Introduction

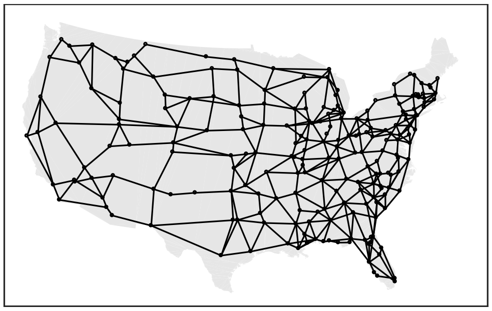

Fig. 1: An example fiber network.

The increasing bandwidth demand and diverse quality of service requirements from rapidly emerging new applications have put forward the development of optical technologies that enable higher transmission rate. Recently, 400G technology has been demonstrated experimentally in field tests [1–3], showing its capability to achieve higher network capacity while improving spectral efficacy.

On the other hand, the new 400G technology has a shorter reach and a higher transponder cost compared with the current 100G and 200G technologies. Given the new flexibility of optical technologies, it is critical to choose the one having the greatest cost advantage for a fiber network. In this paper, we propose a new methodology to analyze the relative cost of deploying new wavelength technologies. There are two major challenges to solving this problem. First, we need a model to accurately reflect the hardware cost of building a wavelength in the network, which will be described in Section 2. Second, to minimize wavelength cost, we must determine optimal regenerator positions on the path of the wavelength. Since the reach and cost continue to evolve, the analysis has to be performed under a large variety of cost and reach assumptions. An efficient algorithm to solving the optimal regenerator positioning problem and computing the minimum wavelength cost is presented in Section 3 and applied in an example network in Section 4.

2. Model

The fiber network is represented by a set of reconfigurable optical add-drop multiplexer (ROADM) nodes and fiber links. Fig. 1 shows an example network modeled from a U.S. highway map, which will be used in the following study. Wavelengths may connect any two nodes in the network, and we assume that every wavelength should be routed on the shortest path in the network. In this paper we consider 100G, 200G and 400G wavelengths, whose typical reaches are summarized in Table 1. If the distance between the source and destination exceeds the reach at the given rate, then a regenerator has to be placed at a ROADM site in the middle. Note that if there are two adjacent ROADM nodes on the path whose distance is larger than the reach, then it is impossible to connect the source-destination pair along this path using the given transmission rate.

To study the cost impact of using wavelengths with different transmission rates in a fiber network, we propose a cost model of a wavelength between a given source-destination pair. In our model, the cost of a wavelength includes the cost of transponders and regenerators, along with the amortized cost of fibers, amplifiers and ROADMs. We introduce the following notations: C_T and C_R are the cost for a transponder and a regenerator, respectively. C_F and C_A are the cost for fiber and amplification per 100 km, respectively. Here we assume that the amplifiers are placed on the fiber at a regular interval (80 km), so the cost of amplifiers is approximately proportional to length of the fiber. C_C is the cost to add/drop a channel to the ROADM, and C_E is the cost for a wavelength to pass through a ROADM node without regeneration.

A sample of the normalized cost values for different wavelengths is given in Table 1 and Table 2. Note that in Table 2, the cost C_F, C_A C_C and C_E are estimated under the assumption that the fiber is fully occupied by 96 standard

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Table 1: Example physical parameters and cost values for different wavelengths. Here the cost of a pair of 100G transponders is normalized to be 1.

Rate (Gbps)	Reach (km)	Channel Bandwidth (Hz)	Cost of Transponder (C_T)	Cost of Regenerator (C_R)
100	2400	50	0.50	0.80
200	800	50	0.85	1.50
400	300	75	1.65	2.70

Table 2: Example cost of fibers, amplifiers and ROADMs amortized on a 50 Hz channel.

Cost for fiber per 100 km (C_F)	0.032
Cost for amplification per 100 km (C_A)	0.024
Cost to add a channel (C_C)	0.040
Cost to express through a ROADM (C_E)	0.030

50 Hz channels. Because the 400G wavelength occupies a 75 Hz channel, the cost parameters need to be adjusted proportionally when we calculate the cost for a 400G wavelength.

Assume that for a given wavelength of rate T(Gbps), its length is L(km), and there are M ROADMs nodes and K regenerators on the path. Then the total cost (per Gbps) C of this wavelength can be simplified as

$$C = (\alpha L + \beta M + \gamma K + \delta)/T, \tag{1}$$

where

$$\alpha = (C_F + C_A)/100 \times B/50, \quad \beta = C_E \times B/50, \quad \gamma = C_R + (2C_C - C_E) \times B/50, \quad \delta = 2C_T + (2C_C - 2C_E) \times B/50.$$

Here $B = 50$ GHz if the rate is 100 Gbps or 200 Gbps and $B = 75$ GHz if the rate is 400 Gbps.

3. Method

Our main objective is to determine which wavelength speed has the minimum cost for a given source-destination pair. Since by assumption the wavelength is always routed on the shortest path in the network, the path itself is fixed but we still have the freedom to choose where to put regenerators along the path. By (1), minimizing the total cost for a fixed path is equivalent to minimizing the number of regenerators on the path.

For a given path, define $F(k)$ to be the required reach to serve the path using at most k regenerators, and $G(r)$ to be the minimum number of regenerators required under reach constraint r. Obviously, the functions $F(k)$ and $G(r)$ are related by

$$G(r) = \min\{k | k \geq 0, F(k) \leq r\}. \tag{2}$$

Then the minimized cost for a wavelength with reach constraint R is

$$(\alpha L + \beta M + \gamma G(R) + \delta)/T. \tag{3}$$

If $F(k)$ has already been computed for each possible k, we can efficiently calculate the minimized cost for a wavelength under arbitrary reach and cost assumptions using equations (2) and (3).

It turns out that the function $F(k)$ can be computed by dynamic programming. Let M be the number of ROADM nodes on the path and s_i be the distance from the source node to the ith node on the path (where the first node is the source). We define $F(i,k)$ to be the minimum reach such that the ith node on the path can be reached from source using at most k regenerators. $F(i,k)$ has the following recursive formula:

$$F(i,k) = \min_{j=1,\dots,i-1} \max\{F(j,k-1), s_i - s_j\}, \ 1 < i \leq M-2, k > 0,$$

with the base cases $F(1,k) = 0$ and $F(i,0) = s_i$.

4. Analysis Result

In this section, we apply the proposed method to the example network in Fig. 1 with the reach and cost structure specified in Table 1 and Table 2. Fig. 2a shows the total cost for each of 200 representative source-destination pairs and each of the three transmission rates (if such a transmission rate is feasible). For clarity, Fig. 2b shows an expanded view for the regional source-destination pairs with shorter distance. Under the given cost structure, 200G and 400G transmission rates are optimal only if the distance of the source-destination pair is within the reach of that rate (i.e., if regeneration is not needed).

To see how the optimal solution will change if 200G and 400G wavelengths become cheaper or their reach is extended, we can perform sensitivity analysis on the reach and cost structure. Specifically, we consider the reasonable cases where the reach decreases and the costs of transponder C_T and regenerator C_R increase as the transmission rate goes from 100G to 400G. Fig. 2c shows which transmission rate has the minimum cost for a long-haul source-destination pair (3000 km) when the reach of 200G and 400G wavelength is varied while keeping the reach of 100G fixed. The same analysis is carried out for a regional source-destination pair (500 km) in Fig. 2e. In Fig. 2d and Fig. 2f, we decrease the cost parameters C_T and C_R of 200G and 400G wavelength by the factors shown, while keeping the other parameters fixed and show how the optimal solution changes for the same long-haul and regional source-destination pairs. From the analysis, we can see that for the long-haul pair 200G will soon become advantageous when its reach increases to around 1000 km or its cost decreases by 10%.

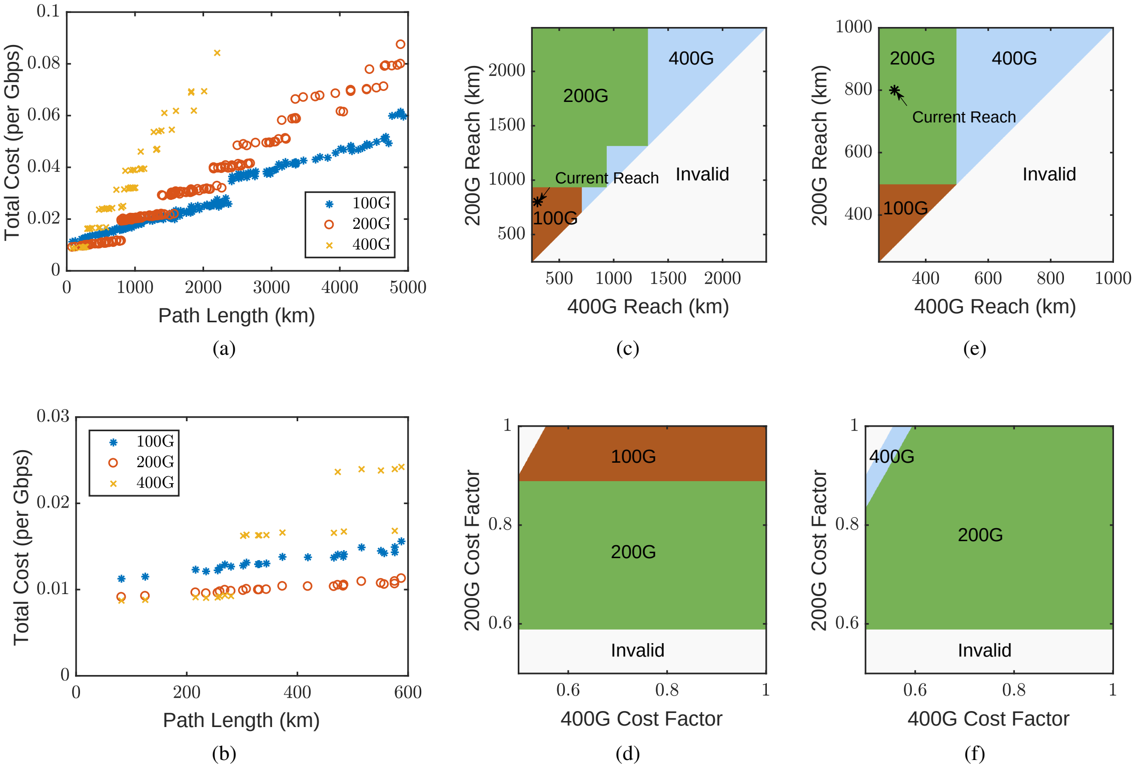

Fig. 2: Cost analysis results for the sample network: The total cost for representative long-haul source-destination pairs (a) and regional pairs (b). A sensitivity analysis on the reach and cost assumptions for a 3000 km source-destination pair (c)-(d) and for a 500 km pair (e)-(f).

5. Conclusion

We have presented an efficient algorithm based on dynamic programming for analyzing the cost and technological trade-offs between 100G, 200G, and 400G per-wavelength transmission rates. Assuming current cost numbers and reach constraints, we find that 100G technology is preferable for long-haul networks, while 200G and 400G technologies are more suitable for shorter distances that do not require re-generation, such as in metropolitan networks and for shorter sections of long-haul networks. However, as costs drop and reach constraints are relaxed, 200G and 400G technologies become more attractive.

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