Design Strategies Exploiting C+L-band in Networks with Geographically-dependent Fiber Upgrade Expenditures

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Abstract: This paper proposes a framework leveraging next-generation interfaces and C+L-band to design transport networks where fiber-based capacity upgrade is geographically-dependent. Simulation results highlight the effectiveness of the proposal and the possible trade-offs between number of line interfaces and fibers. © 2020 The Author(s)

1. Introduction

The growth trajectory of Internet traffic is expected to continue, if not even accelerate as a result of key events such as the roll-out of 5G and massive Internet of Things (IoT) [1]. This will inevitable translate into the need to augment capacity also in transport networks. Traditionally, this increase has been possible via the deployment of consecutive generations of optical interfaces, each superseding the previous by providing both higher capacity and higher spectral efficiency. However, fundamental limits dictate that only minor spectral efficiency improvements are to be expected in the future and capacity per interface will be increased mostly via using more spectrum [2]. As a result, network operators will face the prospect of using more spectrum of the optical fiber (e.g. S- and L-band), light additional single-mode fibers or deploy novel multi-core/mode fibers. In the short to medium-term, exploiting C+L-band and lighting additional fibers are the only commercially available options [3-5]. Particularly, line systems can be deployed such that initially only the C-band is available but the network elements are prepared to accommodate, on a per need basis, the L-band subsystems without the need to overhaul these elements or disrupt traffic. Nevertheless, even the widespread exploitation of C+L-band will eventually not be enough to meet the capacity increase, at which point additional fibers are mandatory. Importantly, the expenditures associated to using additional fibers can vary significantly, not only from network to network, but also within the same network. For instance, a transport network operator often owns dark fiber in some countries/regions, while leasing fiber in the remaining ones where it is established. Therefore, in some cases using an additional fiber is possible at a reasonable cost and with a moderate turn-up time, whereas in others it can be a very expensive and lengthy process, if not impossible at all (e.g. due to shortage of dark fiber in a duct or as a consequence of licensing or regulatory aspects).

This paper presents a novel network planning framework which (i) models geographically-depend fiber upgrade expenditures; (ii) is customizable in terms of giving preference to use additional fibers versus line interfaces; and (iii) minimizes the number of L-band subsystems required. Simulation results obtained in a reference transport network validate the effectiveness of the approach in minimizing the total cost of ownership (TCO).

2. Network and Traffic Scenario

Tier 1 operators are present in several countries. Their operation in each country comprises not just a single optical network, but several ones in different segments (e.g. metro, aggregation and national). This means that the need for capacity upgrades is not uniform. Moreover, each country has its own situation and the position in such market varies from operator to operator. Fiber cost is a key parameter and one of the main reasons to consider rolling out C+L-band systems. Relative fiber abundancy is realistic in countries where the operator is incumbent, which is the case of Telefónica in Spain, BT in UK or DT in Germany. However, Telefónica operations in UK rely on leasing fiber from third-party companies, which is a major operational expenditure. In addition, aspects such as legislation promoting the efficient utilization of fiber, like in UK with a fiber tax, also have to be accounted for. This work assumes a scenario where the operator is not incumbent in the country and optimizing fiber usage is mandatory. Particularly, the operator is running a national backbone network in Italy and the cost of upgrading the infrastructure by adding additional fibers is not the same across the entire country: links in more densely populated areas are a premium resource (e.g. due to increased competition and higher traffic growth). For modelling purposes, Italy's population density map shown in Fig. 1(a) was used to identify 20 bidirectional links that have a fiber rental cost much higher than the remaining ones [6]. Figure 1(b) illustrates the 44-node, 71-link physical topology and the location of premium links.

3. Multi-Fiber C+L Network Design Framework

The need to support massive bandwidth growth will lead to the deployment of C+L-band systems in the short term, particularly in congested links where lighting new fibers is very expensive. In this context, state-of-the-art line systems are being prepared to support both bands on a per need basis (i.e. by introducing L-band when needed and without affecting running traffic). This demands a customized service-provisioning framework to optimize the deployment of L-band subsystems, postponing the extra expenditures with amplifiers and ROADMs. However, the exploitation of C+L-band will eventually not be sufficient to transport all the traffic, leading to the need to install/lease new fibers. As discussed, geographically-dependent fiber upgrade expenditures also need to be accounted for when determining how to more cost-effectively scale fiber capacity. Consequently, a robust service provisioning framework must model all these requirements such that the design solution obtained has the lowest TCO. This can be achieved by optimally selecting in which links to add extra fibers based on their specific costs and on fine-tuning the solution such that a minimum number of L-band subsystems has to be deployed in both existing and new fibers.

The proposed framework combines an integer linear programming (ILP) model with a heuristic algorithm in order to balance optimality and scalability. The ILP model routes and grooms traffic demands as to minimize the total cost with fiber deployment, modelling the differentiated fiber upgrade costs, and having as an extra objective to minimize the number of line interfaces that have to be acquired. Note that the ILP model is executed under the assumption that both C- and L-band become available whenever a new fiber is deployed. Based on the resulting grooming, routing and fiber assignment solution, the heuristic algorithm assigns spectrum to optical channels such that the deployment of L-band subsystems is minimized. It gives priority to using the C-band and choosing the frequency that provides the best-fit in terms of adjacent network links already occupied, hence optimizing spectrum usage by avoiding to have frequencies available only in short links, which would otherwise lead to an increased impact of the spectrum continuity constraint and the need to use a wider set of frequencies. The ILP model and the heuristic are defined as:

ILP: Service-Provisioning with Geographically-dependent Fiber Upgrade Expenditures

$$\min \varphi + \frac{\sigma}{M} \tag{1}$$

subject to:

$$\sum_{l \in L_{i,j=v}} \beta_{d_{(s,t)}}^{l_{(i,j)}} - \sum_{l \in L_{i=v,j}} \beta_{d_{(s,t)}}^{l_{(i,j)}} = \begin{cases} -P_d, & v = s \\ P_d, & v = d \\ 0, \forall v \in V \backslash \{s, d\} \end{cases} \quad \forall d \in D \tag{2}$$

$$\sum_{d \in D} B_d \times \beta_d^l \leq B_l \times \theta_l \qquad \forall l \in L \tag{3}$$

$$\sum_{l \in L_e} \boldsymbol{F_l} \times \theta_l \leq F \qquad \forall e \in E \tag{4}$$

$$\sum_{l \in L} 2 \times \theta_l = \sigma \tag{5}$$

$$\sum_{l \in L_e} \boldsymbol{F_l} \times \theta_l \leq F \times \boldsymbol{\xi_l} \qquad \forall e \in E \tag{6}$$

$$\sum_{e \in E} T_e \times C_e \times \boldsymbol{\xi_l} = \varphi \qquad \forall e \in E \tag{7}$$

Heuristic: L-Band Min Spectrum Assignment

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INPUT: Set of optical channels that have to be deployed $\boldsymbol{O}$ and
       spectrum with all fibers available $\boldsymbol{S}$.
1.  While $\boldsymbol{O}$ is not empty
2.      From the $\boldsymbol{O}$ list select the optical channel that has an
        available frequency in spectrum (giving priority to C-band)
        with highest score in terms of the following priority:
        1) Best neighbor fit: the frequency already in use in the
           largest number of adjacent network links of the path.
        2) Relative capacity loss: the frequency that can
           accommodate the largest number of future channels in their
           available network links.
3.      Assign the channel to selected frequency and remove
        channel from $\boldsymbol{O}$.
4.  Return $\boldsymbol{S}$
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Variables

$\boldsymbol{\beta_{d_{(s,t)}}^{l_{(i,j)}}} \in \mathbb{N}^{\mathbf{0}}$- number of traffic demands from type $d \in D$ between source node s and destination node t using the optical channel $l \in L$ with source node i and destination node j.

$\boldsymbol{\theta_l} \in \mathbb{N}^{\mathbf{0}}$- number of optical channels required from type $l \in L$.

$\boldsymbol{\xi_l} \in \mathbb{N}^{\mathbf{0}}$- total number of additional fibers deployed for link $e \in E$.

$\boldsymbol{\varphi}$ - total cost of fiber deployed per kilometer.

$\boldsymbol{\sigma}$ - total number of line interfaces that have to be acquired.

Parameters

$\boldsymbol{V}$ - set of nodes; $\boldsymbol{E}$ - set of network links

$\boldsymbol{D}$ - set of traffic demands; $\boldsymbol{L}$ - set of optical channels; $\boldsymbol{L_e}$ - set of optical channels that traverse the network link $e \in E$.

$\boldsymbol{B_d}$ - number of ODU slots to groom $d \in D$; $\boldsymbol{B_l}$ - number of ODU slots supported by optical channel $l \in L$.

$\boldsymbol{P_d}$ - total number of traffic demands from type $d \in D$.

$\boldsymbol{F}$ - number of frequency slots available per network link; $\boldsymbol{F_l}$- total number of frequency slots used to deploy the optical channel $l \in L$.

$\boldsymbol{T_e}$ - total number of fiber kilometers deployed in network link $e \in E$; $\boldsymbol{C_e}$ - multiplier factor that differentiates the kilometers of fiber deployed according to the geographical area.

(1) consists of minimizing the total cost with fibers deployed and also has a secondary objective to minimize the total number of line interfaces.

(6-7) calculate the number of fibers deployed per network link and the total cost, respectively.

(2) guarantee the general flow conservation for the set of demands.

(3) ensure the optical channel capacity restrictions.

(4) guarantee that the total number of frequency slots used does not exceed the link capacity.

(5) compute the total number of line interfaces required.

4. Simulation Results and Discussion

The simulation results assume four design scenarios: (i) the proposed framework considering the differentiated fiber rent (FR) cost with C+L-band (Min FR-C+L); (ii) assuming the simple minimization of fiber length (FL), i.e. without geographical-dependences (Min FL-C+L); (iii) primarily minimizing line interface (LI) count and minimizing the fiber cost in best-effort (Min LI-C+L) and (iv) using the proposed framework but restricted to C-band (Min FR-C). For simplicity it is assumed premium links have a 100 times higher upgrade cost per km. The performance model uses the Gaussian noise approach to estimate the impact of nonlinear interfaces (NLI) and a noise figure of 6 and 7 dB for the amplifiers in the C- and L-band, respectively. Next-generation line interfaces operating at 64 Gbaud and supporting modulation formats between QPSK and 64-QAM are utilized [2]. The study comprises five different optimization runs with an increase of 26% traffic load between consecutive runs, following the yearly growth forecast of [1]. The 100/200/400G traffic demands are randomly generated between 20% of the node pairs.

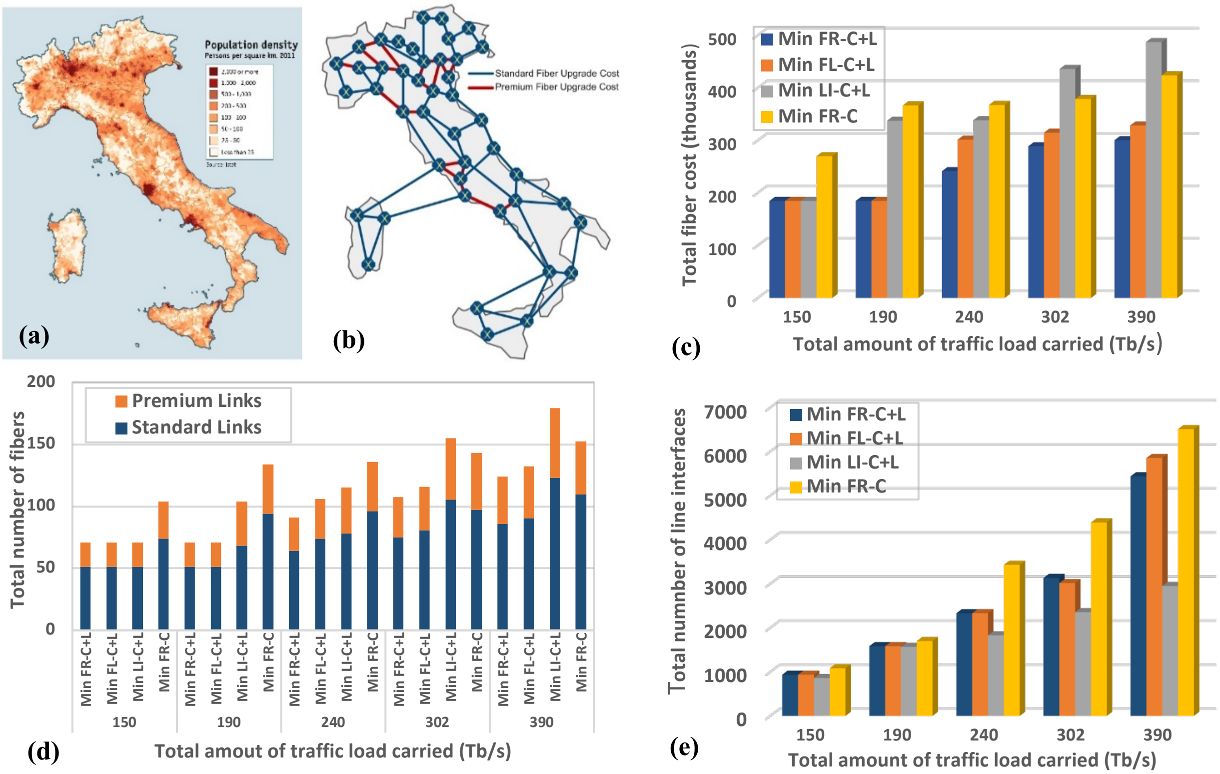

Fig. 1. (a) Italy population density [6], (b) Network physical topology, (c) Total cost of fiber deployed, (d) Total number of fibers that have to be assigned and (e) Total number of line interfaces that have to be acquired for the different optimization scenarios.

Figure 1(c) plots the total cost with fibers installed based on the total number of kilometers deployed and fiber rent cost, whereas Fig. 1(d) presents the total number of fibers utilized. As can be seen, being aware of geographically-dependent fiber upgrade expenditures, Min FR-C+L minimizes fiber cost by reducing the number of fibers deployed in the regions with highest population density (premium links). Moreover, this can be achieved without compromising the number of line interfaces that have to be acquired when compared to the scenario that does not take into account this geographical-dependence, as visible in Fig. 1(e). Importantly, the deployment of C+L-band is critical to postpone any fiber roll-out until at least 190 Tb/s of carried traffic load, as shown in Fig. 1(c-d) when comparing Min FR-C+L with Min FR-C. In addition, the latter strategy also requires deploying more line interfaces (e.g. as a consequence of using longer paths to avoid deploying even more fibers). As expected, the number of line interfaces deployed is the minimum when this is the main optimization objective (Min LI-C+L). Nevertheless, this can only be accomplished by deploying significantly more fibers in both standard and premium links, as can be seen in both Fig. 1(c) and (d). This provides evidence that the usual approach of focusing primarily on minimizing line interface count is ill-suited for future transport network scenarios where C+L-band and multi-fiber deployments are an increasingly important part of the design.

5. Conclusions

This paper presented a network design framework to exploit C+L-band and taking into account that the fiber upgrade expenditures are geographically-dependent. The simulation results over a reference transport network highlight the savings that can be realized by optimizing the usage of L-band and carefully selecting the fiber links to be upgraded.

Acknowledgments

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