Research Article | Vol. 13, No. 7 / July 2021 / Journal of Optical Communications and Networking 193

JOURNAL OF
Optical Communications
and Networking

C+L-band upgrade strategies to sustain traffic growth in optical backbone networks

Tanjila Ahmed,[1,*] Abhijit Mitra,[1,2] Sabidur Rahman,[1] Massimo Tornatore,[1,3] Andrew Lord,[4] and Biswanath Mukherjee[1,5]

[1] University of California, Davis, California 95616, USA
[2] Indraprastha Institute of Information Technology, New Delhi, India
[3] Politecnico di Milano, Milano, Italy
[4] British Telecom, Ipswich, UK
[5] Soochow University, Suzhou, China
*Corresponding author: tanahmed@ucdavis.edu

Received 9 April 2021; revised 24 May 2021; accepted 25 May 2021; published 23 June 2021 (Doc. ID 427097)

We investigate cost-efficient upgrade strategies for capacity enhancement in optical backbone networks enabled by C+L-band optical line systems. A multi-period strategy for upgrading network links from the C band to the C+L band is proposed, ensuring physical-layer awareness, cost effectiveness, and less than 0.1% blocking. Results indicate that the performance of an upgrade strategy depends on efficient selection of the sequence of links to be upgraded and on the time instant to upgrade, which are either topology or traffic dependent. Given a network topology, a set of traffic demands, and growth projections, our illustrative numerical results show that a well-devised upgrade strategy can achieve superior cost efficiency during the capacity upgrade to C+L enhancement.

https://doi.org/10.1364/JOCN.427097

1. INTRODUCTION

Global IP traffic volume with a compound annual growth rate (CAGR) of 26% has been forecast by the Cisco global visual networking index (VNI) for 2017–2022 [1]. Long-term capacity scaling in optical backbone networks is necessary to accommodate this fast-growing traffic. Studies have debated multiple solutions, among which spatial-division multiplexing (SDM) [2] and low-loss spectrum optical bands (L, O, E, S, and U bands) of single-mode fibers (SMFs) such as G.652.D fibers [3,4] have emerged as potential solutions. It should be noted that not all fibers can be used for multi-band (MB) transmission. SDM consists of transmitting over multi-fibers (MFs), multi-core fiber (MCF), and few-mode fiber (FMF). MF technology requires rolling out new optical fiber infrastructure by either installing new fibers or lighting up existing dark fibers, both being expensive options. MCF technologies require the deployment of novel types of fibers possibly with complex multiple-input–multiple-output (MIMO) transceivers, which are not yet commercially available. FMF technology poses challenges due to cross talk between the modes. Therefore, expansion of the operating band of existing SMFs beyond the C band [5,6] is considered a nearer-term viable solution to handle the capacity crunch. This solution maximizes return on investment of already-deployed optical infrastructure. A gradual progression from the C band to L, O, E, S, and U bands (MB) is envisioned to be a longer-term solution as technology matures for all bands. Submarine networks already have active C+L-band systems to extend the cable lifetime [7].

As a first step towards MB transmission, C+L-band expansion allows the use of existing technologies available for the C band, maximizing return on capital expenditure (CapEx) [8]. Moreover, the attenuation coefficient variation between the C and L bands is negligible, and the in-line erbium-doped fiber amplifier (EDFA) used in the C band can be tuned to amplify the L band as well [8,9]. Overall fiber capacity increases from 5 THz to 10 THz while using the L band. However, transmission in the L band induces additional nonlinear interference (NLI) penalties due to inter-channel stimulated Raman scattering (ISRS) [10,11]. Our work shows how a well-devised upgrade strategy should account for quality of transmission (QoT) degradation of lightpaths, interoperability issues between the C and L bands, and unwanted connection blocking.

Network upgrade can be done either all at once or periodically (the latter being more practical, as it allows the deferment of upgrade investments and more gradual management of possible traffic interruptions). Operators might choose to upgrade all links of the network as soon as possible to absorb benefits of the C+L band early or delay the upgrade process for cost benefits. Continuous traffic growth, technology developments, and equipment cost depreciation require proper timing of the upgrade. Therefore, an optimal upgrade strategy is a complex

1943-0620/21/070193-11 Journal © 2021 Optical Society of America

problem. Studies [5,8] compare SDM techniques by quantifying the amount of added capacity in the network. No study, to the best of our knowledge, has explored cost-effective, multi-period upgrade from the C to C+L band. In this work, we assume that all links are initially in the C band. Then, as traffic grows, link capacities are exhausted, and an upgrade decision to the L band needs to be made following an incremental capacity upgrade from the C to C+L band. A multi-period batch upgrade strategy [12] is considered, which upgrades batches of links at a time over multiple years. We propose two types of upgrade planning: long-term planning, which remains fixed based on the general network state, and short-term planning, which changes based on the current network state. We also explore different upgrade batches (i.e., the number of links that can be upgraded at the same time) for two traffic types (see below). As multi-period network planning with batch upgrade can provide cost-efficient upgrade solutions [13], our work provides a detailed analysis of different multi-period upgrade strategies for C to C+L band and evaluates their performance in two networks (BT-UK and US-24).

We propose upgrade strategies for two types of traffic: known and unknown. Known traffic provides information on exact arrival times of future requests, whereas unknown traffic does not have this information. For known traffic, as connection requests and their arrival times are known, the links to be exhausted at future times can be determined. In contrast, for unknown traffic, we devise the upgrade link sequence and times to upgrade using a statistical analysis to obtain our target blocking (near zero) for unknown traffic. Both cases guarantee that the expected blocking rate will be below the targeted maximum rate during the network upgrade process.

The rest of this study is organized as follows. In Section 2, related works are reviewed. In Section 3, the physical-layer model is described. Section 4 provides a detailed description of multi-period batch upgrade strategies from the C to C+L band, and introduces some baseline strategies for comparison. Section 5 introduces the cost model. Section 6 proposes cost-efficient upgrade algorithms for both known and unknown traffic (long- and short-term planning). Section 7 introduces simulation settings and the traffic matrices considered in this study. Section 8 shows numerical results with explanations. Section 9 concludes the study.

2. RELATED WORKS

Researchers are investigating how to conduct gradual expansion from the C band to other bands to solve the capacity crunch problem in backbone networks.

Reference [14] investigated several MB and MF upgrade strategies. The authors showed that the total capacity served by a MB system is slightly better than that of MF systems. Reference [15] shows optical degradation in terms of the generalized signal-to-noise ratio, on different bands (C, L, S, U, E, and O), resulting from successive channel upgrades until the complete low-loss window is occupied. Given these limitations, [5,8] build a strong motivation for C+L expansion over lighting dark fiber or 2C fiber (two fibers). Simulation results show that a C+L-band system does not exhibit capacity penalties compared to parallel C-band systems; rather, it can unlock more capacity. Moreover, in the past few years, clear advancements in industrial implementation of the C+L band have been observed [16–18]. In light of the above studies, we incorporated noise penalties observed by the C+L band and analyzed capacity gain accordingly.

A critical aspect of C+L-band expansion is a practical physical-layer model. The authors of [9,19] investigated C+L-band systems, accounting for ISRS and amplified spontaneous emission (ASE) noise generated by in-line amplifiers. They use frequency-dependent dynamic spectral occupancy to account for NLI, which may lead to sub-optimal decisions, especially for an on-going migration process. Similarly, [20] proposes frequency-dependent power control strategies for the C+L band. For every lightpath, there exists an optimal power maximizing optical signal to noise ratio (OSNR) and transmission capacity. According to [9], the ideal range of launch power is -1.5 dBm to -3 dBm. We choose a frequency-independent, fully filled, worst-case NLI at -1.5 dBm launch power, as it provides maximum capacity while assuming maximum NLI.

Reference [3] presents a lightpath-provisioning scheme for MBs with different upgrade scenarios (C only, C+L, C+L+S, C+L+S+E, C+L+S+E+O) showing significant capacity increase. However, it does not provide any multi-period plan for upgrade. Some studies have discussed the importance of careful link selection for C+L upgrade. The authors of [21] presented a network design framework to exploit the C+L band, focusing on geographically dependent fiber upgrade expenditures. Simulation results show that optimizing L-band usage and carefully selecting the links to be upgraded can lead to cost-effective upgrade. Compared to [21], our link-selection technique considers not only the geographical locations of links (network topology), but also the traffic matrix, and yearly traffic growth. Moreover, we propose a multi-period batch upgrade strategy with associated cost estimation, which was not considered in [21].

3. PHYSICAL-LAYER MODEL

C+L-band transmission can cause significant physical-layer signal impairments. To evaluate the performance of our proposed C+L-band upgrade strategy, a lightpath OSNR estimation model is employed to account for the noise contribution due to in-line equipment and the effect of ISRS on NLI among C+L-band channels. ISRS involves power transfer from the C to L band due to the Raman effect, and NLI occurs due to phase-mismatch nonlinear interactions between non-degenerate frequency triplets [19]. These signal impairments limit the OSNR of lightpaths, which determines the set of feasible modulation formats and hence the capacity of the lightpaths.

We assume a worst-case scenario for both spectrum bands (C and L) while calculating the OSNR. This is based on a fully filled spectrum, where more NLI interactions occur due to the higher number of active channels, which degrades the OSNR of the active C-band channels. Therefore, as a link is upgraded to include operations over the L band, the OSNR of existing C-band lightpaths degrades due to higher NLI and ISRS process interactions. The following equation [9] shows the OSNR with its noise components:

$$\frac{1}{\mathrm{OSNR}(f)} = \sum_{i=0}^{N_L-1} \frac{P_{\mathrm{ASE}}^i(f) + P_{\mathrm{NLI}}^i(f)}{P_{\mathrm{ch}}} + \frac{P_{\mathrm{ASE}}^R}{P_{\mathrm{ch}}} N_R, \quad \textbf{(1)}$$

where $P_{\mathrm{ASE}}^i(f)$ is the total ASE noise from in-line EDFAs, and $P_{\mathrm{NLI}}^i(f)$ is the cumulative NLI due to ISRS in the ith optical link. $P_{\mathrm{ASE}}^R(f)$ is ASE noise generated in a reconfigurable optical add-drop multiplexer (ROADM), post amplification. N_L is the number of links traversed by the lightpath, and N_R is the total number of traversed intermediate ROADMs.

In this work, we assume that NLI is accumulated incoherently across multiple spans. The following equation is used to calculate the noise power (P_{NLI}) for all intermediate links based on their current state of spectral occupancy [9]:

$$P_{\mathrm{NLI}}^i(f_z) = P_{\mathrm{ch}}^3 N_s^i \eta_1(f_z), \quad \textbf{(2)}$$

where P_{ch} is the channel launch power, N_s^i is the number of spans in the ith link, η_1 is the NLI coefficient for a single span, and $P_{\mathrm{NLI}}^i(f_z)$ is the NLI power of the ith link for the channel of interest (COI) f_z. η_1 denotes the total noise contribution across all the active interfering channels [9], which is given by

$$\eta_1(f_z) = \eta_{\mathrm{XPM}}(f_z) + \eta_{\mathrm{SPM}}(f_z), \quad \textbf{(3)}$$

where η_{XPM} is due to cross-channel and η_{SPM} is due to self-channel interference. For the C+L band, cross-channel interference dominates. A closed-form expression of the above total NLI contribution due to η_{XPM} [22] is given by

$$\eta_{\mathrm{XPM}}(f_z) \approx \frac{32}{27} \sum_{k=1,k\neq z}^{N_{\mathrm{ch}}} \left(\frac{P_k}{P_{\mathrm{ch}}}\right)^2 \frac{\gamma^2}{B_k \phi_{z,k} \bar{\alpha}(2\alpha + \bar{\alpha})}$$
$$\left[\frac{T_k - \alpha^2}{\alpha} a\tan\left(\frac{\phi_{z,k} B_z}{\alpha}\right) + \frac{A^2 - T_K}{A} a\tan\left(\frac{\phi_{z,k} B_z}{A}\right)\right], \quad \textbf{(4)}$$

where N_{ch} is the total number of active channels. The higher the value of N_{ch}, the more significant will be $\eta_{\mathrm{XPM}}(f_z)$. P_k is the power of the kth interfering channel, γ is the fiber nonlinear coefficient, $\phi_{z,k}$ is the phase mismatch term between the kth channel and the COI, and T_k is the frequency-dependent constant of the kth channel for ISRS power transfer [22]. Another solution, but not in closed form, can be found in [11].

4. MULTI-PERIOD BATCH UPGRADE FOR THE C+L BAND

We explore multi-period batch upgrade strategies under two different traffic cases: If the traffic is known, then upgrade decisions are relatively simple. But both the magnitude and exact time of occurrence of future traffic are not available easily [23], so we also study unknown traffic upgrade strategies. For unknown traffic, we explore both long-term and short-term planning.

A. Upgrade Strategies for Unknown Traffic

Unknown traffic does not provide any information on connection request arrivals ahead of time. So, we use insights from the initial traffic matrix, network topology, and a large set of simulations representing a stochastic evolution of network spectrum occupancy. The goal is to upgrade links at the right time that are likely to be exhausted in capacity to avoid future blocking. Incorrect selection of links and untimely upgrade can cause cost inefficiency and blocking. Below, we propose link-selection techniques to be used during upgrade for unknown traffic. Figure 1 shows a five-node sample network topology with link spectrum utilization and node traffic generation probability to explain these strategies. Here we use randomly generated biased traffic generation probabilities.

Link-selection techniques. Each link is given a weight according to the following parameters:

1. spectrum utilization of the link,
2. number of highly utilized links in the shortest paths containing the link,
3. number of highly utilized nodes in the shortest paths containing the link,
4. number of high-joint-probability node-pairs in the shortest paths containing the link,
5. betweenness centrality of the link.

Each link-selection along with upgrade-time selection technique leads to a different strategy, i.e., a different sequence of links to upgrade. Then, a cost analysis of each strategy lets us identify the best strategy among all. Below, we describe each link-selection technique.

1. **Link spectrum utilization.** Links with higher spectrum utilization are given priority for upgrade. Higher utilization indicates a higher probability to exhaust capacity, eventually requiring upgrade to the L band. Spectrum utilization of link L is calculated as follows:

$$W_u(L) = \frac{\text{Spectrum occupation of link } L \text{ at } t}{\text{Total spectrum of link } L}, \quad \textbf{(5)}$$

where t is the connection request time at which the utilization is calculated, and $W_u(L)$ is the spectrum utilization of link L. In Fig. 1, the link sequence based on spectrum utilization is {B (0.7), D (0.6), A (0.4), C (0.3), E (0.2)}.

2. **Highly utilized links.** Links that are in a shortest path containing any highly utilized links are prioritized for upgrade. Highly utilized links are specified by a threshold obtained from average link utilization. Any link with higher utilization than this threshold is considered as a highly utilized link. The number of times a link appears in the shortest paths containing any of these highly utilized links is counted as the weight for this link. Links with higher weights are given higher upgrade priority. The weight of link L is calculated as

$$W_{\mathrm{hl}}(L) = \sum_{U_L} \frac{C(U_L|L)}{C(U_L)}, \quad \textbf{(6)}$$

where U_L is the set of highly utilized links, $C(U_L)$ is the set of shortest paths containing highly utilized links, $C(U_L|L)$ is the set of shortest paths containing both link L and one or multiple highly utilized links, and $W_{\mathrm{hl}}(L)$ is the weight of link L from this strategy. The set of shortest paths contains the shortest paths for each node-pair of the traffic matrix. If there are two connections between a node-pair, the shortest path is counted twice. From Fig. 1, we obtain the average link utilization to be 0.4. Therefore, the highly utilized link set is {B (0.7), D (0.6)}. Now, we calculate the number of times each link of the topology appears in the shortest paths containing any of these highly utilized links. With the assumed traffic matrix, these values are (5, 6, 2, 3, 4) for links (A, B, C, D, E), respectively. Therefore, the link sequence obtained from this technique will be (B, A, E, D, C).

3. **Highly utilized nodes.** Links that are in a shortest path containing highly utilized nodes are prioritized. Utilization of a node is calculated from the traffic-generation probability of that node. The number of times a link lies in the shortest paths containing any of these highly utilized nodes is considered as the weight of that link. Links with higher weights are given upgrade priority. The weight of link L is calculated as follows:

$$W_{\mathrm{hn}}(L) = \sum_{U_N} \frac{C(U_N|L)}{C(U_N)}, \quad (7)$$

where U_N is the set of highly utilized nodes, $C(U_N)$ is the set of shortest paths containing highly utilized nodes, $C(U_N|L)$ is set of shortest paths containing both link L and one or multiple highly utilized nodes, and $W_{\mathrm{hn}}(L)$ is the weight of link L from this strategy. From Fig. 1, we find that the average utilization of the node is 0.2. Therefore, the highly utilized node set is {1 (0.3), 5 (0.35)}. We assume the number of times each link lies in the shortest paths containing any of these highly utilized nodes is (5, 7, 4, 6, 2) times for links (A, B, C, D, E), respectively. Therefore, the link sequence obtained from this technique will be (B, D, A, C, E).

4. **High-joint-probability node-pairs.** Links that are in a shortest path containing any high-joint-probability node-pairs are prioritized for upgrade. The joint probability of a node-pair is obtained by multiplying individual traffic-generation probabilities mentioned in the parentheses (Fig. 1). Node-pairs are considered to be high-joint-probability node-pairs if their joint probabilities exceed the threshold obtained by the average multiplied probability among all node-pairs. The number of times a link lies in the shortest path containing any of these high-joint-probability node-pairs is counted as the weight of this link. Links with higher weights are given higher upgrade priority. The weight of link L is

$$W_{\mathrm{hj}}(L) = \sum_{U_J} \frac{C(U_J|L)}{C(U_J)}, \quad (8)$$

where U_J is the set of high-joint-probability nodes, $C(U_J)$ is the set of shortest paths containing high-joint-probability node-pairs, $C(U_J|L)$ is the set of shortest paths containing both link L and one or multiple high-joint-probability node-pairs, and $W_{\mathrm{hj}}(L)$ is the weight of link L from this strategy. From Fig. 1, for all node-pairs, we find the average joint probability to be 0.03724.

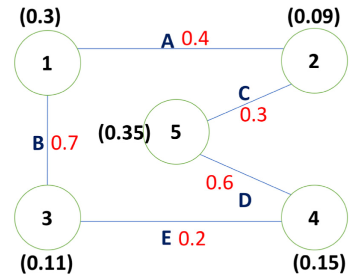

Fig. 1. Sample network with link spectrum utilization (in red) and traffic generation probability in parenthesis.

Therefore, the high-joint-probability node-pairs are {(1, 4), (1, 5), (3, 5), (4, 5)}. The number of times each link lies in the shortest paths containing any of these high-joint-probability nodes is (5, 7, 6, 3, 2) times for links (A, B, C, D, E), respectively. Therefore, the link sequence obtained from this technique will be (B, C, A, D, E).

5. **High-betweenness centrality.** Frequently traversed links by most lightpaths between nodes are prioritized for upgrade [24]. The betweenness centrality of link L is

$$W_b(L) = \sum_{A,B \in V, A != B,} \frac{C(AB|L)}{C(AB)}, \quad (9)$$

where V is the set of nodes, $C(AB)$ is the number of shortest paths between A and B, $C(AB|L)$ is the number of those paths passing through link L, and $W_b(L)$ is the weight of link L using betweenness centrality. From Fig. 1, we find links (A, B, C, D, E) lie between all node-pairs for (0.3, 0.5, 0.7, 0.6, 0.1) times, respectively. Thus, the betweenness centrality of all the links is in the sequence (B, D, A, C, E).

Upgrade-Time-Selection Techniques: The above link-selection techniques help an operator to determine which links should be prioritized for upgrade. However, operators also need to know the probable time of blocking of these links to determine when to upgrade them (upgrade time). Upgrading links early or later can have a significant effect on cost. Upgrading later in time provides cost efficiency due to reduced equipment cost and CapEx deferral benefits (explained in Section 5). However, upgrading later in time might incur connection blocking. So, a cost-efficient upgrade-time-selection technique is critical.

Our study performs a statistical analysis to anticipate the time of occurrence of future blocking. To explain how this time is calculated, we refer to an example of finding the earliest blocking time. Earliest blocking refers to the very first connection request blocking before each batch upgrade has been performed. This is to ensure no blocking occurs before this earliest blocking instance. Figure 2 plots the statistical distribution of earliest blocking instances for a large number of independent simulations before any upgrade is done, simulating possible future traffic evolution for the BT-UK network. Future traffic evolution is calculated for the same node-pair distribution but

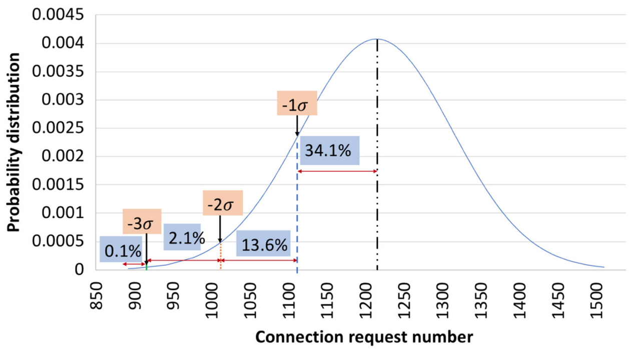

Fig. 2. Normal distribution of blocking for the BT-UK network.

with higher levels of traffic. These values follow a normal distribution with finite mean and variance. Depending on targeted blocking probability, an operator can choose an upgrade time.

In Fig. 2, the normal distribution has a mean at connection request number 1241 and standard deviation (σ) of 98. According to the 3-σ rule of 68-95-99.7, 68% of data drawn from this distribution falls within one σ, 95% of data falls within two σ, and 99.7% data falls within three σ away (both negative and positive sides) from the mean. For a 0.1% blocking probability target, the upgrade time will reside within three negative sigma values (connection request number 920) from the mean, which guarantees the least probability of occurrence of any connection request. Any connection request less than 920 has a probability of occurrence of 0.1% or less. Therefore, if upgrade to the C+L band is done before connection request number 920, there will be 0.1% or less probability of occurrence of any blocking.

We also assume a realistic upgrade completion time (τ). This is the duration to upgrade a batch of links. So, the upgrade time can be calculated as follows:

$$M_T = B_T - \tau, \tag{10}$$

where B_T is the earliest blocking time obtained from the 3-σ rule, τ is the upgrade completion time of one batch of links, and M_T is the obtained upgrade time to upgrade batches of links to the C+L band. Here, time refers to the connection request number.

Now, we introduce two upgrade planning proposals.

Long-term upgrade. This upgrade planning finds the best link-selection technique based on the network state at the beginning of the upgrade time period. It is a one-time selection technique with no changes made to the link selection before all links of the network have been upgraded. However, upgrade times are selected based on the current network state.

Short-term upgrade. This upgrade planning finds the best link-selection technique based on the current network state before each batch upgrade. Changes to the link-selection technique and corresponding link sequence may occur before each batch is upgraded. Upgrade times are selected based on the current network state.

Next, we present two baseline strategies that may follow the link-upgrade sequence of any of the above-mentioned link-selection techniques. However, from simulation results, the highly utilized links technique produces the lowest-cost solutions. Therefore, we use the link sequence from the highly utilized links technique for both of these baseline strategies. Although these strategies follow the generated link sequence, they do not follow the above-mentioned statistical process of upgrade-time-selection techniques.

Early upgrade. This strategy upgrades all links at the beginning without optimizing the time of upgrade, which causes additional costs due to higher early equipment cost and no CapEx deferral benefits to the operator (explained in Section 5). However, no blocking is observed before the upgrade process is done due to early upgrade.

Blocking un-aware upgrade. This strategy also upgrades all links from the highly utilized links sequence without knowledge of stochastic upgrade times. To keep the cost low, the upgrade occurs later, causing some blocking.

B. Upgrade Strategy for Known Traffic

This strategy upgrades links in advance to avoid any future blocking, relying on known future traffic request arrival times. It is assumed that known traffic provides information on future requests and their arrival times (in terms of connection request numbers). Hence, both the link sequence to be upgraded and their upgrade times can be deduced from this information. The upgrade completion time is considered using Eq. (10) to calculate the time of upgrade. Finally, strategies are formulated to avoid any blocking before all links of the network are upgraded to the C+L band.

The following example explains how the upgrade strategy for known traffic works for the BT-UK network shown in Fig. 3. Table 1 shows a snapshot of connection requests blocked in the C band along with their request number. For a

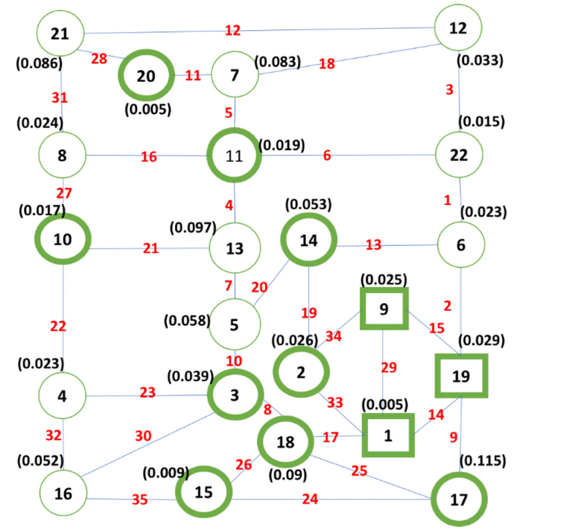

Fig. 3. BT-UK network with the link sequence from the highly utilized links strategy (in red) and traffic generation probability in parentheses.

Table 1. Connection Requests Blocked in the C Band

Connection Request Number	Links in the C Band
1147	**8-11, 11-22, 22-6**
1149	**12-22**, 22-6, **6-19, 19-17, 17-18**
…	………………
2308	**16-3**, 3-5, 5-14, 14-6

predetermined set of connection requests, connection blocking and their blocking occurrence times are fixed. Therefore, link sequence and their upgrade times can be deduced from this table. For example, first blocking in the C band appears at connection request number 1147, which consists of links 8-11, 11-22, and 22-6, which are all in the C band. Similarly, second blocking appears at connection request 1149, which consists of links 12-22, 22-6, 6-19, 19-17, and 17-18 in the C band. To avoid connection blocking at 1147 and 1149, associated links need to be upgraded before they are exhausted. So, the sequence of links to be upgraded until connection request 1149 will be (shown in bold in Table 1): 8-11, 11-22, 22-6, 12-22, 6-19, 19-17, and 17-18. The time of upgrade will be just before (including upgrade completion time) each link is about to be blocked. The last connection request blocked is at request number 2308, before which all the links of the network need to be upgraded to the C+L band to avoid any blocking.

5. UPGRADE COST MODEL

An upgrade cost is formulated by summing up the cost of upgrade at each year until all the links are upgraded to the C+L band. Three cost elements are considered in the model.

1. **Equipment cost.** This cost is associated with the equipment required for C+L-band upgrade. Modifications in transceivers, amplifiers, and filters are required to accommodate the C+L band, which results in additional cost. However, as technology matures over the years, the equipment cost decreases. Therefore, depreciation is included in the equipment cost calculation. The following is the equation used to calculate the equipment cost ($C_E()$) with yearly depreciation:

$$C_E(y) = E * (1 - d\%)^y * l, \tag{11}$$

where E is the cost to upgrade one link from the C to C+L band, d is the yearly equipment cost depreciation value, y is the year at which the equipment cost is calculated, and l is the number of links upgraded in year y.
2. **Workforce cost.** This cost is associated with the workforce needed to upgrade links from the C to C+L band. It depends on the number of links that need to be upgraded at a certain time. The following is the equation for workforce cost ($C_W()$) calculation:

$$C_W(y) = W * l, \tag{12}$$

where W is the workforce cost to upgrade one link from the C to C+L band, y is the year at which the workforce cost is calculated, and l is the number of links upgraded in year y.
3. **CapEx deferral benefit.** Our study applies multi-period upgrade planning taking the time horizon into account. Multi-period planning approaches have the objective to minimize network cost. But, a realistic consideration is that a network operator allocates a budget per period, which can be used to build and upgrade the network or, if not used up in the specific period, it can be used in alternate investments. Hence, companies prefer to invest money in upgrade later rather than now, i.e., "CapEx deferral," and it is a common strategy to effectively use a given budget. The following is the equation to calculate the CapEx deferral benefit ($B_\delta()$) for a given year:

$$B_\delta(y) = \sum_{y=1}^{y_n} C * \delta\%, \tag{13}$$

where C is the CapEx budget for each year, which is fixed regardless of the year, δ is the yearly CapEx deferral discount rate earned in alternative investments, and y_n is the year at which the cost is calculated.

The total cost is calculated by adding the equipment and workforce costs and then subtracting the CapEx deferral. The following is the total cost of upgrade after Y years:

$$C_T = \sum_{y=1}^{Y} C_E(y) + \sum_{y=1}^{Y} C_W(y) - \sum_{y=1}^{Y} B_\delta(y). \tag{14}$$

6. ALGORITHMS FOR UPGRADE TO THE C+L BAND

Now, we describe the algorithms for our proposed multi-period batch upgrade strategy to the C+L band for both unknown (long-term and short-term planning) and known traffic.

Given parameters:

- $G(V, E)$: network topology; V set of nodes, E set of links.
- L: set of links in sequence of upgrade priority obtained from any of the proposed strategies.
- L_C: set of links in the C band.
- L_{C+L}: set of links in the C+L band, where $E = L_C \cup L_{C+L}$.
- R: set of connection requests, where $r \in R$.
- R_l: set of path links of connection requests R.
- R_t: set of connection requests and their arrival times.
- N: number of upgrade batches.
- B: number of links to be upgraded for each batch; also called batch size, where $B = (\text{size of } (E))/N$.
- T: traffic matrix.
- α: yearly increment in traffic in percentage.
- γ: blocking probability target.
- S: set of link-selection techniques.
- K: set of upgrade times in terms of the connection request number, where $k_N \in K$.
- $Cost_s$: cost of an upgrade strategy.
- $Cost_S$: set of costs for all upgrade strategies.
- S_{best}: best upgrade strategy with minimum cost.
- L_{best}: set of links in sequence of upgrade priority obtained from upgrade strategy S_{best}.
- K_{best}: set of upgrade times in terms of connection request number obtained from strategy S_{best}.

Algorithm 1 takes the network topology, number of upgrade batches, traffic matrix, yearly increment in traffic, and blocking probability target from the operator as input. It finds the minimum-cost upgrade strategy in terms of link sequence and the set of upgrade times. For each upgrade strategy in S, the algorithm finds L-set of links in sequence of upgrade priority

Algorithm 1. Upgrade Strategy for Unknown Traffic (Long-Term Solution)

1: **Input:** $G(V, E), N, T, \alpha, \gamma$;
2: **Output:** Best upgrade strategy, sequence of links to be upgraded, set of upgrade times, cost of upgrade;
3: **for each** upgrade strategy s **in** S **do**
4: $L \leftarrow calc\_linkSeq(G(V, E), T, s)$; ▷ Find set of links ($L$) in sequence of upgrade priority obtained from (s);
5: **while** $N > 0$ **do**
6: $k_N \leftarrow$ find upgrade times from normal distribution with given γ;
7: **if** ($N == 1$) **then**
8: $L_{C+L} = E \cap L_{C+L}$; ▷ Upgrade all un-upgraded links from list sequence L to L_{C+L} at k_N;
9: Go to step 16;
10: **else**
11: $L_{C+L} = L_{C+L} \cup B$; ▷ Upgrade first un-upgraded B links from list sequence L to L_{C+L} at k_N;
12: **if** ($E >$ size of(L_{C+L})) **then**
13: $N = N - 1$;
14: Go to step 5;
15: **else**
16: Find $Cost_s$ using Eq. (14); ▷ Calculate total cost of upgrade strategy s;
17: $K = K \cup k_N$; ▷ Store the upgrade times for N batches of strategy s in K
18: $N = 0$;
19: $Costs_S = Costs_S \cup Cost_s$;
20: $min\_Costs_S =$ find minimum value in $Costs_S$ and associated strategy S_{min};
21: $S_{best} \leftarrow S_{min}$;
22: $L_{best} \leftarrow L$ associated with S_{best};
23: $K_{best} \leftarrow K$ associated with S_{best};

Algorithm 2. Upgrade Strategy for Unknown Traffic (Short-Term Solution)

1: **for each** batch $N > 0$ **do**
2: **for each** upgrade strategy s **in** S **do**
3: $L \leftarrow calc\_linkSeq(G(V, E), T, s)$; ▷ Find set of links ($L$) in sequence of upgrade priority obtained from (s);
4: $k_N \leftarrow$ find upgrade times with given γ;
5: **if** ($N == 1$) **then**
6: $L_{C+L} = E \cap L_{C+L}$; ▷ Upgrade all un-upgraded links from list sequence at k_N;
7: Go to step 10;
8: **else**
9: $L_{C+L} = L_{C+L} \cup B$; ▷ Upgrade first un-upgraded B links from list sequence at k_N;
10: Find $Cost_s$ using Eq. (14);
11: $Costs_S = Costs_S \cup Cost_s$;
12: $min\_Costs_S =$ find minimum value in $Costs_S$ and associated strategy S_{min};
13: $S_{best} \leftarrow S_{min}$;
14: $N = N - 1$;

Algorithm 3. Upgrade Strategy for Known Traffic

1: **Input:** $G(V, E), N, T, \alpha, \gamma, R_t$;
2: **Output:** Sequence of links to be upgraded, set of upgrade times, cost of upgrade;
3: $(R, R_l) \leftarrow calc\_connLink(R_t)$; ▷ Find set of connection requests R and their path links R_l that will be blocked;
4: $L \leftarrow calc\_linkSeq(R, R_l)$; ▷ Find set of links ($L$) in sequence of upgrade priority;
5: **while** $N > 0$ **do**
6: $k_N \leftarrow calc\_upgradeTime(R, R_l)$; ▷ Find set of upgrade times (k_N) in sequence of upgrade priority;
7: **if** ($N == 1$) **then**
8: $L_{C+L} = E \cap L_{C+L}$; ▷ Upgrade all un-upgraded links from link sequence L to L_{C+L} at k_N;
9: Break;
10: **else**
11: $L_{C+L} = L_{C+L} \cup B$; ▷ Upgrade first un-upgraded B links from list sequence L to L_{C+L} at k_N;
12: **if** ($E >$ size of(L_{C+L})) **then**
13: $N = N - 1$;
14: Go to step 5;
15: **else**
16: Break;
17: Find $Cost$ using Eq. (14); ▷ Calculate total cost of upgrade;

using *calc_linkSeq()* (line 4). While the number of upgrade batches, N, is greater than zero, the algorithm finds the current upgrade time, k_1, using normal distribution with given γ. If N is one, which indicates two cases—the operator asked for only one upgrade batch or this is the last remaining batch to upgrade—then all the un-upgraded links will be upgraded to the C+L band at k_1. The next step is to calculate the cost at line 16.

If N is not one, a batch of B un-upgraded links from E is upgraded to L_{C+L} from this set of link sequence L (line 11) at k_N. B is calculated by dividing the total number of links by the number of upgrade batches, N. This algorithm keeps upgrading B number of links for each upgrade batch until all links are upgraded. It checks whether the number of links in C+L is less than the total number links E; if so, it goes to step 5 and continues to upgrade batches of un-upgraded links until all links are upgraded. Else, if E number of links is being upgraded to C+L, cost calculation is performed using Eq. (14). N is set to zero (if not zero), as there is no more link to be upgraded. This algorithm finds the cost of individual strategies in S and stores them in $Costs_S$ (line 19). Finally, it finds the minimum-cost strategy S_{best}, associated link sequence L_{best}, and set of upgrade times K_{best}.

Algorithm 2 has the same input and output as Algorithm 1; the only difference is in finding minimum-cost strategy S_{best}. Algorithm 2 finds S_{best} after each batch upgrade. Thus, each batch may have different S_{best} and corresponding L_{best}. This is selected by evaluating all strategies at each batch upgrade based on the current network state. More computation is required in this case.

Algorithm 3 takes connection requests and their arrival times as additional inputs from an operator compared to Algorithm 1. Using these inputs, it finds the link sequence to upgrade with the corresponding set of upgrade times and cost of upgrade. Algorithm 3 works in a way similar to Algorithm 1, except it obtains the set of links in sequence of upgrade priority and set of upgrade times from a previously known set of connection requests and their arrival times (R_t). Therefore, it does not need to compare different link-selection techniques to find the minimum-cost strategy.

For all three algorithms, physical-layer modeling comes into action during connection request provisioning. At the arrival of each connection request, the algorithms check whether the request is to be allocated in the C band only, C in the C+L band, or L in the C+L band. The OSNR and modulation formats vary according to this connection request allocation in different bands.

7. SIMULATION SETTING

A. Simulation Setup

A custom-built event-driven Java simulator is used to emulate an accurate upgrade environment from the C to C+L band with accurate physical-layer modeling. The BT-UK network (Fig. 3) is primarily considered for our simulations; it consists of 35 bi-directional links and 22 nodes, with an average link distance of 147 km. We also evaluated the US-24 node network. A G.652.D fiber with a flexible grid is considered with a slot width of 37.5 GHz and forward error correction (FEC) of 12%. A uniform channel launch power of -1.5 dBm and ROADM loss of 18 dB are assumed [9]. Routing, spectrum, and modulation format selection is done based on availability on the k-shortest path, first-fit spectrum allocation, and OSNR threshold parameters [19]. We assume yearly equipment depreciation $d = 10\%$, equipment cost to upgrade one link from C to C+L as $E = 1$ unit, workforce cost for one link upgrade $C_w = 1$ unit, yearly CapEx budget for upgrade $C = 20$ units, and yearly CapEx deferral benefit $B_\delta(y) = 15\%$.

The network simulator takes a network topology and a traffic matrix as inputs and allocates connection requests with the highest modulation format achievable based on physical-layer modeling of different spectrum bands (C and C+L). Initially, connections are provisioned in the C band, then to the L band if the C band does not have the needed spectrum. Connections remain fixed after they are added, i.e., the route, wavelength, and modulation format of the existing connections all remain the same as new traffic is added. The upgrade time horizon has years and corresponding four quarters as periods of time. An upgrade completion time (τ) of 40 connection requests, or one quarter, is assumed for each batch upgrade. Therefore, an upgrade needs to be performed at least 40 connection requests ahead of the connection request that is about to be blocked.

B. Traffic Matrix

Incrementally growing traffic is assumed, with a growth factor of 30% per year. Core networks typically exhibit an incremental demand model, i.e., once a lightpath is routed, it stays in the network over all considered periods of time. Three thousand connection requests of 100 Gbps are generated by selecting the source and destination from a biased traffic matrix. This traffic matrix is based on connected users in the BT-UK network (Fig. 3) and corresponding node traffic-generation probability. Similarly, for the US-24 network, we assume a population-based traffic matrix.

Table 2. Blocking and Modulation Format Variation in the C and C+L Band

Topology	Bands	1st Blocking	Most-Used Modulation Format
BT-UK	C	1281	16QAM
BT-UK	C+L	2714	8QAM
US-24	C	980	QPSK
US-24	C+L	1590	BPSK

8. RESULTS AND DISCUSSION

This section is divided into three subsections: analysis, results for unknown traffic, and results for known traffic.

A. Analysis

The following results show the benefits and drawbacks of the C+L band compared to the C band only. We calculate the difference in first blocking while all links of the network are in the C band and in the C+L band. The first blocking occurs much later [at connection request 2714 (BT-UK) and 1590 (US-24)] in the C+L band compared to the C band [at connection request 1281 (BT-UK) and 980 (US-24)]. Table 2 shows the most-used modulation formats in both networks. When all links are operated in the C band, most connection requests are provisioned with 16 quadrature amplitude modulation (QAM) (BT-UK)/quadrature phase shift keying (QPSK) (US-24). But, when all links are in the C+L band, an increase in the number of 8QAM (BT-UK)/BPSK (US-24) is observed, as the OSNR decreases when the L band is added at each link due to ISRS.

B. Results for Unknown Traffic

Table 3 lists the total cost of different upgrade strategies for unknown traffic where the number of upgrade batches is two, which is the least number of batches. Each upgrade strategy (each row) is a combination of a link-selection and an upgrade-time-selection technique. Batch size (number of links per batch) is calculated by dividing the number of links in the network by the number of upgrade batches. It is observed that the early-upgrade strategy costs the most (65.2 units) and the blocking-unaware strategy costs the least (37.7 units) among all the strategies. The early-upgrade strategy upgrades (years 1 and 2) all 35 links before the upgrade time obtained from the statistical process mentioned in Fig. 2, which causes a high cost, as no yearly equipment cost depreciation or capacity deferral benefits are leveraged. In contrast, the blocking-unaware strategy upgrades (years 5 and 7) all links after the obtained statistical upgrade time, which gains cost benefits due to yearly equipment cost depreciation and CapEx deferral but incurs blocking before all links are upgraded. In contrast, none of the other six strategies experiences any blocking before all links are upgraded. Our proposed five approaches schedule the time of the first batch's upgrade (17 links) at year 3 based on the statistical upgrade time, maintaining less than 0.1% blocking. However, the second batch's upgrade (18 links) times vary for the five strategies due to differences in link sequences, which eventually differentiates the total upgrade cost. We notice that

Table 3. Upgrade Cost for Unknown Traffic (Two Batches, CAGR 30%, and Long-Term Planning)

		1st Batch	2nd Batch
Upgrade Strategy	Cost	Year	Year
Early upgrade	65.2	1	2
Highly utilized links	48.6	3	5
Highly utilized nodes	52.9	3	4
High-joint-probability node-pairs	52.9	3	4
High-betweenness centrality links	57.4	3	3
High-spectrum-utilized links	57.4	3	3
Blocking-unaware upgrade	37.7	5	7

the high-betweenness-centrality and high-spectrum-utilized-links strategies upgrade both batches at the same time (year 3), which is a cost-inefficient upgrade plan causing high expenditure in a single year and no benefit from yearly equipment cost depreciation or CapEx deferral. High betweenness centrality depends on the topology and ignores the influence of traffic load. The high-spectrum-utilized-links strategy ranks links based on their spectrum usage only, not considering any associated links.

Highly utilized nodes and high-joint-probability node-pairs upgrade the second batch of links one year later than the first batch; hence, a lower cost of upgrade is observed. Both strategies consider the influence of only high-traffic generating nodes/node-pairs while prioritizing links to upgrade. Both strategies are based on only node traffic information, which does not correctly identify the bottleneck links.

Finally, among our proposed strategies, minimum upgrade cost is achieved by the highly utilized link based strategy, with a cost of 48.6 units. This strategy is able to postpone the second batch of upgrades (year 5) more than other strategies without causing any blocking. By definition, the highly utilized links strategy prioritizes links in a shortest path containing any highly utilized links. In practice, upgrading individual links or node-pairs does not ensure that the entire lightpath will operate in the L band. Therefore, upgrading links associated with highly utilized links makes the upgrade decision more optimal.

Table 4 shows the effect of different numbers of batches and traffic growth for the highly utilized links strategy. The CAGR is shown in parentheses in the first column of Table 4. Here, we list the cost of two types of batch upgrades: two and three. For most of the traffic growth scenarios, more batches achieve the least cost (44.6 and 54.3 units) due to a fewer number of average link upgrades in each year and postponing the last batch upgrade to a later time. However, for 20% CAGR, two batches have much lower cost than three batches. For 40%, the difference is negligible. For 50% CAGR, only the scenario with two batches achieved less than 0.1% blocking. Moreover, as expected, the cost of upgrade increases with increasing CAGR. Higher yearly traffic growth leads to more rapid network capacity exhaustion, which requires an earlier upgrade. Therefore, with a CAGR of 50%, the operator can upgrade only in two batches to maintain the target near-zero blocking.

Figure 4 shows the annual cost break-down of the highly utilized links strategy for two- and three-batch upgrades for 30% CAGR. This information helps an operator to distribute the upgrade budget over years. In a two-batch upgrade, costs of the first batch (24.8 units/51%) and second batch (23.8 units/49%) are substantial. In contrast, in a three-batch upgrade, costs of the first batch (13.9 units/31%), second batch (16 units/36%), and third batch (14.7 units/33%) are less on average. Given the upgrade cost and annual budget requirement of both batch upgrades, operators have the flexibility to decide which upgrade plan is the best. To obtain lower cost, an upgrade plan that takes advantage of CapEx deferral, equipment-cost depreciation, and lower yearly workforce cost would be the best. Otherwise, for a shorter overall upgrade period and longer time between upgrades, a plan that upgrades links in bulk (larger batch size) is the best.

Table 5 shows a comparison between short-term and long-term planning. Among all strategies, the highly utilized link upgrade provides the least cost. Short-term planning is based on the current network state, which postpones upgrades more (up to year 11 for the fourth batch), achieves a higher number

Table 4. Highly Utilized Links Upgrade Strategy with Various Batches and Traffic CAGR for BT-UK

		1st Batch		2nd Batch		3rd Batch	
Batches	Cost	Year	#Links	Year	#Links	Year	#Links
2 (20%)	35	4	17	8	18	—	—
3 (20%)	39.1	4	11	5	11	7	13
2 (30%)	48.6	3	17	5	18	—	—
3 (30%)	44.6	3	11	4	11	6	13
2 (40%)	54.4	2	17	4	18	—	—
3 (40%)	54.3	2	11	3	11	4	13
2 (50%)	58.9	2	17	3	18	—	—

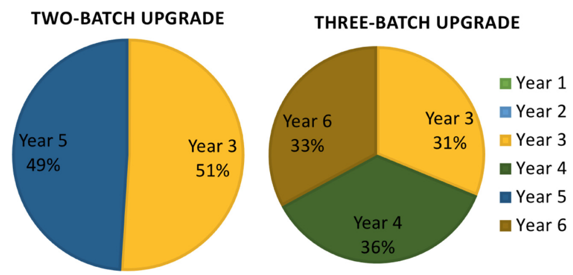

Fig. 4. Annual cost of the highly utilized links strategy with CAGR of 30% and long-term planning.

Table 5. Long-Term and Short-Term Planning with Various Batches for BT-UK with CAGR 30% and the Highly Utilized Links Strategy[a]

		1st Batch		2nd Batch		3rd Batch		4th Batch	
Batches	Cost	Y	#l	Y	#l	Y	#l	Y	#l
2 (long)	48.6	3	17	5	18	—	—	—	—
3 (long)	44.6	3	11	4	11	6	13	—	—
2 (short)	48.6	3	17	5	18	—	—	—	—
3 (short)	40.8	3	11	4	11	7	13	—	—
4 (short)	40.4	3	8	4	8	5	8	11	13

[a]Y = year, #l = number of links.

Table 6. Upgrade Cost of Unknown Traffic for the US-24 Network (Two Batches, CAGR 30%, and Long-Term Planning)

Upgrade Strategy	Upgrade Cost (units)
Early upgrade	80.8
Highly utilized links	68.9
Highly utilized nodes	73.8
High-joint-probability node-pairs	73.8
High-betweenness centrality links	78.7
High-spectrum-utilized links	78.7
Blocking-unaware upgrade	50.31

Table 7. Highly Utilized Links Upgrade Strategy with Various Batches for US-24, CAGR 30%, and Long-Term Planning

		1st Batch		2nd Batch		3rd Batch	
Batches	Cost	Year	#Links	Year	#Links	Year	#Links
Two	68.9	2	21	4	22	—	—
Three	64.8	2	14	3	14	5	15

of batches (four), and provides the least cost (40.4 units) compared to long-term planning (44.6 units). However, short-term planning requires more computation compared to long-term planning.

Table 6 lists the total cost of upgrade strategies for unknown traffic where the number of upgrade batches is two for the US-24 network. Similar to the BT-UK network, the blocking-unaware upgrade strategy costs the least (50.31 units), as it does not maintain the target blocking. Among our five proposed strategies, the minimum upgrade cost is again achieved by the highly utilized link based strategy, with a cost of 68.9 units.

Table 7 compares different batch sizes for the highly utilized links strategy in a US-24 network. The highly utilized links strategy costs the least among all upgrade strategies for the US-24 topology as well. From Tables 4 and 7, we observe that the cost of upgrade in the BT-UK network is less compared to the US-24 network. The average link lengths and highest used modulation formats of the BT-UK and US-24 topologies are 147 km with 16QAM versus 996 km with QPSK, respectively. A longer link length with a lower modulation format leads to lower spectral efficiency and earlier capacity exhaustion in US-24 compared to BT-UK. This is reflected in the overall higher upgrade cost (68.9 and 64.8 units) in US-24.

C. Results for Known Traffic

Table 8 compares the total cost of upgrade and the number of batches achievable for known and unknown traffic. As the highly utilized link strategy performs the best among all link-selection techniques, here we refer to it as an "unknown traffic upgrade strategy." It is observed that known traffic strategies result in lower cost (39, 38.3, 34.6 units) and more batches (four) compared to unknown traffic strategy costs (48.6, 44.6 units) and fewer batches (three) due to the known connection requests and corresponding arrivals times. However,

Table 8. Upgrade Cost Comparison between Known and Unknown Traffic Upgrade Strategies for BT-UK with CAGR 30% and Long-Term Planning[a]

			1st Batch		2nd Batch		3rd Batch		4th Batch	
Upgrade Strategy	Batches	Cost	Y	#l	Y	#l	Y	#l	Y	#l
Known	2	39.0	4	17	7	18	—	—	—	—
Known	3	38.3	4	11	6	11	7	13	—	—
Known	4	34.6	4	8	5	8	7	8	8	11
Unknown	2	48.6	3	17	5	18	—	—	—	—
Unknown	3	44.6	3	11	4	11	6	13	—	—

[a]Y = year, #l = number of links.

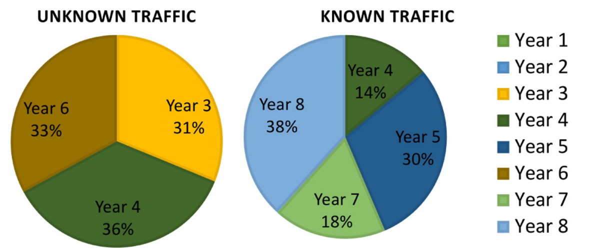

Fig. 5. Annual cost comparison of the known and unknown traffic upgrade strategies with CAGR of 30%.

more than four batches could not be formed without overlapping two batch upgrades in the same year for a known traffic upgrade.

Figure 5 shows the annual cost break-down of the unknown and known traffic upgrade strategies with three and four batches, respectively. The unknown traffic upgrade strategy costs more because of early upgrade (years 3, 4, and 6) and higher average batch size (11 links) compared to the later upgrade (years 4, 5, 7, and 8) and lower average batch size (8 links) of the known traffic upgrade strategy. Keeping initial batch sizes lower than later batches results in more benefits from equipment-cost depreciation. In known traffic cost distribution, the benefit of the CapEx deferral is observed significantly in years 4 (14%) and 7 (18%), as these upgrades were delayed (three and one years, respectively) from their immediate previous upgrades. Equipment-cost depreciation, workforce cost, and CapEx-deferral benefits could be exploited more in the known traffic scenario due to the exact knowledge of traffic arrivals.

9. CONCLUSION

We have investigated network upgrade strategies for optical backbone networks from the current C band towards the C+L band. A physical-layer-aware, cost-efficient, multi-period, batch upgrade strategy with less than 0.1% blocking was proposed for incrementally growing traffic. Two types of traffic were analyzed. The known traffic upgrade strategy costs less compared to unknown ones. However, we showed that the performance of the unknown traffic upgrade strategy could be improved by efficient link-selection and upgrade-time-selection techniques. These parameters are network topology and traffic dependent. We analyzed two topologies and various traffic CAGRs. A larger geographic network and higher traffic

CAGR showed earlier network capacity exhaustion and higher upgrade cost. We proposed two upgrade planning strategies: long-term and short-term. Short-term planning leads to lower upgrade cost compared to long-term with the cost of greater computation. Having an accurate link sequence enables us to postpone batch upgrades to later years, absorbing the benefits of equipment-cost depreciation and CapEx deferral. Our proposed strategy offers flexibility to an operator to choose different numbers of batches. Generally, more batches lead to less cost due to lower average batch size (lower workforce cost) and CapEx deferral.

Funding. National Science Foundation (1716945); Department of Science and Technology, Ministry of Science and Technology, India (DST/INSPIRE/04/2017/000089); United States—India Educational Foundation (2444/FNPDF/2019).

Acknowledgment. We acknowledge the contributions of Aniket Pradhan and Rana Kumar Jana in physical-layer modeling of our simulator. Abhijit Mitra was supported by a Fulbright Fellowship and a DST Inspire Faculty Award.

REFERENCES

1. "Cisco Visual Networking Index: Forecast and Trends, 2017–2022," Cisco White Paper, 2020, https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html.
2. C. Antonelli, M. Shtaif, and A. Mecozzi, "Modeling of nonlinear propagation in space-division multiplexed fiber-optic transmission," J. Lightwave Technol. **34**, 36–54 (2015).
3. N. Sambo, A. Ferrari, A. Napoli, N. Costa, J. Pedro, B. S. Krombholz, P. Castoldi, and V. Curri, "Provisioning in multi-band optical networks," J. Lightwave Technol. **38**, 2598–2605 (2020).
4. A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, A. D'Amico, J. Pedro, W. Forysiak, E. Pincemin, A. Lord, A. Stavdas, J. P. F.-P. Gimenez, G. Roelkens, N. Calabretta, S. Abrate, B. S. Krombholz, and V. Curri, "Assessment on the achievable throughput of multi-band ITU-T G.652.D fiber transmission systems," J. Lightwave Technol. **38**, 4279–4291 (2020).
5. E. Virgillito, R. Sadeghi, A. Ferrari, G. Borraccini, A. Napoli, and V. Curri, "Network performance assessment of C+L upgrades vs. fiber doubling SDM solutions," in *Optical Fiber Communication Conference (OFC)*, March 2020.
6. E. Virgillito, R. Sadeghi, A. Ferrari, A. Napoli, B. Correia, and V. Curri, "Network performance assessment with uniform and non-uniform nodes distribution in C+L upgrades vs. fiber doubling SDM solutions," in *Optical Network Design and Modeling (ONDM)*, May 2020.
7. D. Aguiar, G. Grasso, A. Righetti, and F. Meli, "EDFA with continuous amplification of C and L bands for submarine applications," in *International Microwave and Optoelectronics Conference (IMOC)*, November 2015.
8. M. Cantono, R. Schmogrow, M. Newland, V. Vusirikala, and T. Hofmeister, "Opportunities and challenges of C+L transmission systems," J. Lightwave Technol. **38**, 1050–1060 (2020).
9. A. Mitra, A. Srivastava, P. Bayvel, and A. Lord, "Effect of channel launch power on fill margin in C+L band elastic optical networks," J. Lightwave Technol. **38**, 1032–1040 (2020).
10. A. Mitra, D. Ives, A. Lord, S. Savory, S. Kar, and P. Wright, "Network equipment and their procurement strategy for high capacity elastic optical networks," J. Opt. Commun. Netw. **8**, A201–A211 (2016).
11. M. Cantono, D. Pilori, A. Ferrari, C. Catanese, J. Thouras, J.-L. Augé, and V. Curri, "On the interplay of nonlinear interference generation with stimulated Raman scattering for QoT estimation," J. Lightwave Technol. **36**, 3131–3141 (2018).
12. C. Meusburger, D. A. Schupke, and A. Lord, "Optimizing the migration of channels with higher bitrates," J. Lightwave Technol. **28**, 608–615 (2010).
13. C. Meusburger, D. A. Schupke, and J. Eberspacher, "Multiperiod planning for optical networks—approaches based on cost optimization and limited budget," in *International Conference on Communication (ICC)*, May 2008.
14. B. Shariati, P. S. Khodashenas, J. M. R. Moscoso, S. B. Ezra, D. Klonidis, F. Jiménez, L. Velasco, and I. Tomkos, "Investigation of mid-term network migration scenarios comparing multi-band and multi-fiber deployments," in *Optical Fiber Communication Conference (OFC)*, March 2016.
15. A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, J. Pedro, N. Sambo, E. Pincemin, B. S. Krombholz, and V. Curri, "Upgrade capacity scenarios enabled by multi-band optical systems," in *International Conference on Transparent Optical Networks (ICTON)*, July 2019.
16. https://www.infinera.com/press-release/windstream-deploys-infinera-c-l-solution-sets-foundation-double-fiber-capacity.
17. https://www.corning.com/media/worldwide/coc/documents/Fiber/R_OFC_Infinera-2018.pdf.
18. https://www.ciena.com/insights/white-papers/a-model-for-business-case-analysis-of-c-l-band-betwork-architectures.html.
19. A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C+L band elastic optical networks," J. Opt. Commun. Netw. **11**, C86–C93 (2019).
20. A. Ferrari, D. Pilori, E. Virgillito, and V. Curri, "Power control strategies in C+L optical line systems," in *Optical Fiber Communication Conference (OFC)*, March 2019.
21. D. Moniz, V. Lopez, and J. Pedro, "Design strategies exploiting C+L-band in networks with geographically-dependent fiber upgrade expenditures," in *Optical Fiber Communication Conference (OFC)*, March 2020.
22. D. Semrau, R. I. Killey, and P. Bayvel, "A closed-form approximation of the Gaussian noise model in the presence of inter-channel stimulated Raman scattering," J. Lightwave Technol. **37**, 1924–1936 (2019).
23. D. Applegate and E. Cohen, "Making routing robust to changing traffic demands: algorithms and evaluation," IEEE/ACM Trans. Netw. **14**, 1193–1206 (2006).
24. N. Kourtellis, G. D. F. Morales, and F. Bonchi, "Scalable online betweenness centrality in evolving graphs," IEEE Trans. Knowl. Data Eng. **27**, 2494–2506 (2015).