C to C+L Bands Upgrade with Resource Re-provisioning in Optical Backbone Networks

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Abstract: Resource re-provisioning during network upgrade from C to C+L bands can optimize resource allocation and postpone upgrade cost. Results show re-provisioning shorter lightpaths to L band leads to a more cost-effective upgrade.

1. Introduction

To accommodate traffic growth, operators need to upgrade network capacity at minimum cost. Recent studies recommend expansion of low-loss spectrum optical bands (e.g., L, O, E, S, U bands) beyond the current C band [1]. Initial step is expansion to L band [2], which is the second-lowest-loss wavelength band after C band. But L band has higher attenuation, chromatic dispersion, and noise figure compared to C band. Hence, deploying lightpaths in L band leads to lower optical signal-to-noise ratio (OSNR), higher optical power budget, and higher cost. So, we study moving lightpaths from C band to L band judiciously to free up valuable resources of C band.

We study efficient allocation of resources during upgrade of network links from C to C+L bands. After an upgrade, resource allocation may become sub-optimal, leading to lower utilization of spectrum resources. Such inefficient spectrum utilization can block future requests and require early upgrade, which leads to higher cost. Thus, we investigate pro-active re-provisioning of lightpaths to C+L bands after each upgrade for cost benefit. Prior works show benefits of lightpath re-provisioning for restorability of optical mesh networks [3,4], network capacity maximization [5], service chaining in optical metro networks [6], etc. But, to the best of our knowledge, our work is the first to study the benefits of lightpath re-provisioning during upgrade to C+L bands.

Our strategy locates highly-utilized links and upgrades them in batches. After each batch upgrade, existing traffic in C band is re-provisioned to L band using various methods. This re-provisioning frees up high-OSNR lightpaths in C band, leading to improved quality of future transmissions, delayed upgrades, and cost benefits. Results show that re-provisioning of a shorter lightpath provides the most cost-effective upgrade strategy.

2. Background on Upgrade Strategy and Cost Model

We use an upgrade strategy based on two steps [7], forming the basis of our re-provisioning strategy in Section 3.

- **Link-Selection Technique:** We employ a multi-period strategy where, periodically, a batch of 'highly-utilized links' are selected for upgrade, as this leads to most cost efficiency [7].
- **Upgrade-Time-Selection Technique:** To handle traffic growth, when to upgrade (Year/Quarter?) is an important question. We perform a statistical analysis with a target blocking probability, e.g., 0.1%.

Cost Model: We model the upgrade cost in each year until all links are upgraded to C+L bands. Two cost elements are considered in the model: (i) equipment cost with yearly depreciation; and (ii) CAPEX deferral benefit. Total cost is calculated by adding equipment cost and subtracting CAPEX deferral. Details of the upgrade strategy and cost model can be found in [7]. In this work, we focus on the impact of re-provisioning on an upgrade strategy.

3. Cost-Efficient Re-Provisioning Strategy

We propose and compare different lightpath re-provisioning strategies applicable during a multi-period batch upgrade. During each upgrade, a batch of C band links are upgraded to L band, causing network links to be in mix of C and L bands. Re-provisioning moves lightpaths from C band to L band when triggered by a batch upgrade. We assume routes to remain unchanged when moved to L band, so all links of a lightpath need to be upgraded to L band to be re-provisioned. After upgrade, OSNR of re-provisioned lightpaths and lightpaths in C band affected by inter-channel stimulated Raman scattering (ISRS) from extension to L band are re-calculated.

Three lightpath re-provisioning strategies based on lightpath length are investigated: **(1) Re-provision All Lightpaths (R):** This strategy re-provisions (from C band to L band) all lightpaths which are routed on links already upgraded to L band; **(2) Re-provision Longer Lightpaths (R^{long}):** This strategy re-provisions (from C band to L band) lightpaths whose path length is longer than median path length of already-allocated lightpaths; and **(3) Re-provision Shorter Lightpaths (R^{short}):** On the contrary, this strategy re-provisions (from C band to L band) lightpaths whose path length is shorter than median path length of already-allocated lightpaths.

Note that, after upgrade, new requests are allocated (if possible) in L band first in all cases.

No Lightpath Re-Provisioning (NoR, NoR_C): We compare the above strategies with two strategies with no re-provisioning: (i) NoR, i.e., no re-provisioning, assuming new requests after upgrade are routed in L band first and (ii) NoR_C, i.e., no re-provisioning, but assuming new requests after upgrade are routed in C band first.

OSNR re-calculation is required for all existing C band lightpaths whose links are in both C and L bands. If new OSNR requires to scale down the modulation format of lightpaths in C band, capacity of these scaled-down lightpaths will decrease. Two situations are now possible: **(i) Re-route C band Lightpaths:** It might not be possible to serve some of the requests in the scaled-down lightpaths (overflow requests). Therefore, overflow requests need to be re-routed to a new lightpath; and **(ii) Re-adjust C band Lightpaths:** If the scaled-down modulation format of a lightpath can still support all the previously-existing requests, then the OSNR is re-adjusted without needing any request to be re-routed. Below, we provide a formal description of the proposed re-provisioning algorithms.

Algorithm:

Given parameters:
- $G(V,E)$: Network topology; V set of nodes, E set of links.
- T: Traffic matrix.
- α: Yearly increment in traffic in percentage.
- γ: Blocking probability target.
- L_{seq}: Set of links in sequence of upgrade priority.
- L_C: Set of links in C band.
- L_{C+L}: Set of links in C+L bands, where $E = L_C \cup L_{C+L}$.
- R_p: Set of connection requests in a lightpath p.
- N: Number of upgrade batches.
- B: Set of links to be upgraded (batch size) at each batch, where $b \in B$.
- S: Set of re-provisioning strategies, where $s \in S$.
- M_p: Modulation format of a lightpath p.
- O_p: OSNR of a lightpath p.
- P_C: Number of lightpaths in C band.
- P_L: Number of lightpaths in L band.
- $Cost_s$: Cost of an re-provisioning strategy.
- $Cost_S$: Set of costs for all re-provisioning strategies.
- S_{best}: Best re-provisioning strategy with minimum cost.
- K_{best}: Set of upgrade times obtained from strategy S_{best}.

Algorithm 1 Cost-efficient re-provisioning for C to C+L upgrade.

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1: Input: $G(V,E)$, $N$, $B$ $T$, $\alpha$, $\gamma$, $L_{seq}$;
2: Output: Best re-provisioning strategy, upgrade times, cost;
3: while ($N > 0$) do
4:     $k_N \leftarrow$ Find upgrade times for given $\gamma$;
5:     $L_{C+L} = L_{C+L} \cup b(N)$;    ▷ Upgrade first un-upgraded $b(N)$ links from list sequence $L_{seq}$ to $L_{C+L}$ at $k_N$;
6:     for each re-provisioning strategy $s$ in $S$ do
7:         for each lightpath in $p$ in $P_C$ do
8:             if (All links of $p$ are upgraded to L band) then
9:                 if (Bandwidth available in L band) then
10:                    Update $O_p$ and $M_p$;
11:                    Allocate requests $R_p$ in L band, $p \in P_L$;
12:                    Remove $p$ from C band, update $P_C$;
13:        for each lightpath in $p$ in $P_c$ do
14:            if (Links of $p$ is upgraded to L band) then
15:                Update $O_p$ and $M_p$;
16:                if Capacity of $R_p$ overflows $p$ then
17:                    Re-route requests;
18:                    Update $P_C$ with new lightpaths;
19:    $N = N$ - 1;
20:    Find $Cost_s$;
21:    $K = K \cup k_N$;
22: $Cost_S = Cost_S \cup Cost_s$;
23: $min\_Cost_S \leftarrow$ Find minimum value in $Cost_S$
24: $S_{best} \leftarrow$ Re-provisioning strategy $S_{min}$ associated to $Cost_S$
25: $K_{best} \leftarrow K$ associated with $S_{best}$
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Algorithm 1 finds the minimum-cost re-provisioning strategy. Batch size (number of links per batch) is found by dividing the number of links in the network by the number of upgrade batches, N. While N is greater than 0, the algorithm finds current upgrade time (lines 3-4). A batch of B un-upgraded links from E is upgraded from set of link sequence L_{seq} (line 5) provided by the upgrade strategy. For each re-provisioning strategy in S, algorithm re-provisions lightpaths (from C to L band) whose links are upgraded to L band, if possible (lines 6-12). After re-provisioning, OSNR of remaining lightpaths in C band whose links are upgraded to L band are re-calculated (lines 13-15). If a request in a path overflows path capacity due to new OSNR, it is re-routed (lines 16-18). Otherwise, the request remains in the same path with re-adjusted OSNR. After first upgrade, requests are allocated in L band first. Now, the algorithm checks if there are more batches to upgrade (line 19); if so, it goes to step 3 and continues to upgrade batches of un-upgraded links until all links are upgraded. Else, cost calculation is performed (line 20). This algorithm finds cost of individual strategies in S and finds the minimum-cost strategy S_{best} (line 24) and associated set of upgrade times K_{best}.

4. Simulation Setup

A custom-built event-driven Java simulator is used to emulate a realistic upgrade environment from C to C+L bands. The physical layer model in [8] is used to find OSNR of a lightpath for different bands (C band only, C and L in C+L bands). BT-UK network with 35 links and 22 nodes is considered. An incrementally-growing traffic is assumed, with a growth factor of 30% per year. 3000 connection requests of 100 Gbps are generated by selecting the source and destination from a bias traffic matrix of BT-UK. Elastic transponders with five modulation formats (QPSK, QAM, 16QAM, 32QAM, and 64QAM) with corresponding five bit rates (100, 150, 200, 250, and 300 Gbps) are considered. An uniform channel launch power of 0 dbm and ROADM loss of 18 dB are assumed. k-shortest path is used for routing, first-fit for spectrum allocation, and OSNR threshold in [8] for modulation format assignment. The upgrade time horizon has years as periods of time.

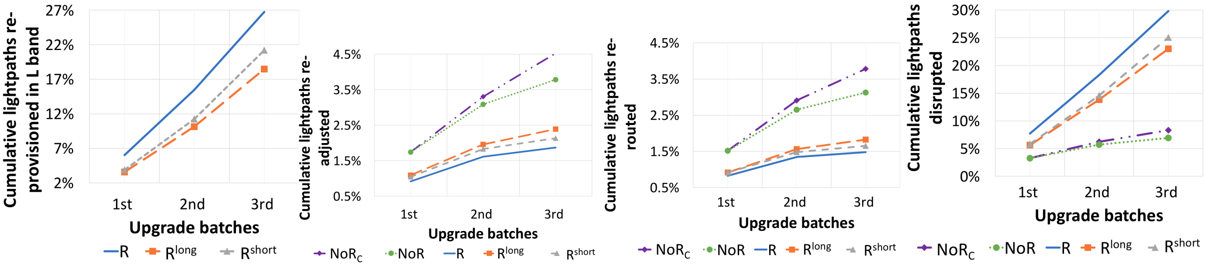
5. Results and Discussion

In this section, we compare total cost of upgrading all links among different re-provisioning strategies. We assume 10% yearly equipment depreciation, equipment cost to upgrade one link from C to C+L as 5 units, yearly CAPEX budget for upgrade of 20 units, and yearly CAPEX deferral benefit of 15%.

Table 1 lists total cost of upgrade, upgrade years of three batches, and percentage of requests in C and L band for all strategies. It is observed that NoR_C costs the highest (108 units) while R^{short} costs the least (78.8 units). Note that NoR_C upgrades links without re-provisioning while allocating requests in C band first leading to earlier capacity exhaustion in C band (75.7% requests in C band), needing earlier upgrades (years: 3, 4, 6).

Table 1: Upgrade cost, years of upgrade batches, and requests in C and L band for all five strategies.

Upgrade strategy	Cost (units)	Year: 1^{st} batch	Year: 2^{nd} batch	Year: 3^{rd} batch	Requests in C	Requests in L
NoR_C	108.0	3	4	6	75.7%	24.3%
NoR	94.7	3	4	8	44.4%	55.6%
R	84.6	3	5	9	32.5%	67.5%
R^{long}	90.7	3	5	8	35.2%	64.8%
R^{short}	78.8	3	5	10	34.1%	65.9%



(a) Re-provisioned in L band. (b) Re-adjusted in C band. (c) Re-routed in C band. (d) Lightpaths disrupted.

Fig. 1: Cumulative number of lightpaths (a) re-provisioned, (b) re-adjusted, (c) re-routed, and (d) disrupted in all upgrade batches of all strategies.

Instead, R^{short} upgrades links with re-provisioning while allocating traffic in L band first leading to later C band exhaustion (34.1% requests in C band), needing later upgrades (years: 3, 5, 10) which gains cost benefits due to yearly equipment cost depreciation and CAPEX deferral. R^{short} costs less compared to R^{long} (90.7 units) due to overall less disruption in C band lightpaths created by shorter lightpath re-provisioning. Shorter lightpath re-provisioning causes less disruption by affecting fewer links and lower fragmentation which eventually delays capacity exhaustion and upgrade in C band.

To understand the reasons that lead R^{short} to outperform R and R^{long}, in Fig. 1 we provide a detailed analysis of lightpath disruption at different upgrade batches. This helps to understand the trade-off of re-provisioning between creating disruption in the network and reducing the overall cost. Fig. 1a shows percentage of lightpaths re-provisioned in L band at the end of upgrade period for the three re-provisioning strategies. For all strategies, a higher number of re-provisioning occurs for later upgrade batches, as more links are already upgraded to L band and hence more re-provisioning options are available. R re-provisions more lightpaths (27%) compared to other two strategies as all lightpaths in L band are candidate to be re-provisioned. R^{long} re-provisions only longer paths in L, which require bandwidth availability in higher number of links in L band compared to shorter paths. This results in higher number of lightpath re-provisioning in R^{short} (21%) compared to R^{long} (18%).

Fig. 1b and 1c show cumulative number of lightpaths re-adjusted and re-routed in C band, respectively. For all strategies lower number of lightpaths are re-adjusted and re-routed in C band during later upgrade batches, due to more lightpaths assigned in L band. Overall number of re-adjusted lightpaths (Fig. 1b) is higher than re-routed lightpaths (Fig. 1c). Higher number of lightpaths are re-adjusted and re-routed by NoR_C (4.5%, 3.7%) and NoR (3.8%, 3.1%), due to larger number of lightpaths located in C band. Among the re-provisioning strategies, R re-provisions more lightpaths in L, thus fewer lightpaths are left in C band to re-adjust (1.9%) and re-route (1.5%). R^{short} compared to R^{long} re-adjusts (2.1%) and re-routes (1.6%) slightly less lightpaths as the fewer requests in C.

Fig. 1d shows the cumulative number of lightpaths disrupted at each upgrade batches. Here, disruption is the sum of number of lightpaths re-provisioned, re-adjusted, and re-routed. It is observed that, all re-provisioning strategies disrupts more number lightpaths compared to strategies without re-provisioning. NoR causes the least (total 7%) whereas R causes the highest (total 30%) disruption.

Conclusion: Benefit of re-provisioning lightpaths in L band in terms of cost and disruption is shown in a C to C+L bands upgrade scenario. Although re-provisioning disrupts a large amount of traffic (25% in R^{short}), it decreases the number of re-adjusted (2.1% in R^{short}) and re-routed (1.6% in R^{short}) lightpaths and improves the resource allocation leading to lower cost of upgrade.

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