A Comparative Analysis of Multi-Band Upgrade and Regeneration for Capacity Enhancement in Optical Networks

Ruoxuan Gao
University of California, Davis, USA
rxgao@ucdavis.edu

Sifat Ferdousi
University of California, Davis, USA
sferdousi@ucdavis.edu

Massimo Tornatore
Politecnico di Milano
Milan, Italy
massimo.tornatore@polimi.it

Biswanath Mukherjee
University of California, Davis, USA
bmukherjee@ucdavis.edu

***Abstract*—This paper explores the joint impact of two capacity enhancement schemes in optical backbone networks: multi-band expansion from C+L to C+L+S bands and varying 3R regeneration (no, selective, and full). Using a pay-as-you-grow batch upgrade framework that considers deferral benefits, we evaluate their interaction. In the short-haul BT-UK network, S-band upgrade consistently improves throughput and cost efficiency, with the greatest economic gain with no regeneration. In the long-haul USNET network, S-band upgrade reduces throughput because K-least-loaded routing does not consider path distance, yielding low-quality lightpaths with high blocking probability. Thus, C+L bands with full regeneration are more cost-effective.**

***Index Terms*—Optical networks, multi-band upgrade, 3R regenerator, capacity enhancement**

I. Introduction

The relentless growth of data traffic continues to drive the need for capacity enhancement in optical backbone networks [1]. Without deploying new fibers, operators can enhance capacity through: (i) spectral expansion, e.g., adding S band to existing C+L systems, and (ii) improving spectral efficiency via 3R (Re-amplification, Re-shaping, Re-timing) regeneration. Spectral expansion reuses existing fibers but suffers from physical impairments (especially when expanding to the S band), such as Stimulated Raman Scattering (SRS), which reduces the Quality of Transmission (QoT) and shortens signal reach [2]. Conversely, deploying 3R regenerators overcomes these impairments and improves spectral efficiency but entails substantial capital and operational expenditure (CapEx and OpEx, respectively). Depending on network configuration, regeneration can be either opted out or deployed selectively at intermediate nodes or fully at every node.

While prior studies have explored the performance trade-offs between multi-band upgrade and regeneration [3], they have often simplified the network upgrade process, thus neglecting the deferral benefits of batch upgrade. This work advances the investigation by employing a detailed cost model that captures critical aspects of real-world operator planning. We employ a pay-as-you-grow batch upgrade framework [4] combined with a lifecycle cost model that accounts for these deferral benefits. We evaluate how S-band upgrade and regeneration capabilities interact to influence cost and performance efficiency across two topologies: short-haul BT-UK and long-haul USNET network. Our results show that short-haul networks benefit most from S-band upgrade especially with no regeneration, while long-haul networks gain more from increasing regeneration in the C+L bands.

II. Upgrade and Regeneration Schemes

We perform a lifecycle analysis of cost and throughput efficiency of multi-band upgrade with varying regeneration capabilities. Spectral expansion from C+L to C+L+S bands is modeled using a batch-upgrade strategy [4] and performance is evaluated across three network configurations: no, selective, and full regeneration.

A. Upgrade Framwork

The upgrade framework in [4] adopts a pay-as-you-grow batch-upgrade strategy, whereby the network is incrementally upgraded in response to traffic growth. The process is detailed in Algorithm 1. In this study, we use K-least-loaded routing and first-fit for Routing and Spectrum Assignment (RSA) to balance the network load.

Algorithm 1 Batch Upgrade Framework

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Input: Optical backbone network G(V,E), chronological list of traffic requests R, spectrum utilization (SU) threshold T_SU
for all r ∈ R do
    Provision r on G.
    Update SU for all links in E.
    if max(SU) ≥ T_SU and there exist unupgraded links in E and a cooldown period has passed then
        Rank and select an upgrade batch B ⊂ E based on a defined strategy, subject to the network connectivity constraint and budget
        Release resources of affected requests R_a on B.
        Define residual network G' ← G − B.
        Identify requests R_u arriving during upgrade.
        Attempt to provision R_a ∪ R_u on G'.
        Upgrade links in B to support the S band.
        Re-provision R_a ∪ R_u on the upgraded G.
    end if
end for
```

B. Network Configuration

We evaluate three network configurations defined by their regeneration capabilities as outlined below. QoT is assessed differently in each case, which in turn affects RSA results and spectral efficiency. The General Signal-to-Noise Ratio (GSNR) is adopted to measure the QoT of each lightpath.

- **No Regeneration.** No 3R regenerators are deployed in the network and all lightpaths must be established transparently end-to-end. For a lightpath L traversing through k links, its GSNR is computed as:
$$\frac{1}{GSNR_L} = \sum_{i=1}^{k} \frac{1}{GSNR_i}, \quad (1)$$
where $GSNR_i$ represents the GSNR of the i-th link.
- **Full Regeneration.** Every node is equipped with a 3R regenerator. All lightpaths are terminated at each intermediate node and are regenerated. For a lightpath L,
$$GSNR_L = \min_{\forall i \in 1,2,\ldots,k} GSNR_i \quad (2)$$
- **Selective Regeneration.** Every node is capable of regenerating lightpaths, while regeneration is selectively applied when the transparent reach of a lightpath is insufficient for the path length. For a lightpath L,
$$\frac{1}{GSNR_L} = \sum_{i=n}^{k} \frac{1}{GSNR_i}, 1 < n < k \quad (3)$$
where n represents an intermediate node along the L, breaking L into two fragments.

C. Cost Model

We consider a backbone optical network $G(V, E)$ with $|V|$ nodes and $|E|$ links, initially operating in C+L bands and provisioning requests sequentially. A lifecycle CapEx model is used to evaluate the total cost for G, including both initial network deployment costs in C+L bands and dynamic upgrade costs over the whole upgrade period. The relative costs of the network components in cost units (CU) are listed in Table I.

TABLE I: Relative Costs of Network Components [5]

Component	Notation	Cost (CU)
C+L Amplifier Pair (per span)	$C_{amp,CL}$	2.0
C+L Transceiver (per site)	$C_{trx,CL}$	6.0
C+L Regenerator (per site)	$C_{reg,CL}$	13.0
Regenerator Chassis (per site)	$C_{chassis}$	2.0
S Amplifier (per span)	$C_{amp,S}$	1.2
S Transceiver (per site)	$C_{trx,S}$	4.0
S Regenerator (per site)	$C_{reg,S}$	10.0

The Total Network Cost (C_{total}) is calculated as the sum of the initial deployment cost and the lifecycle upgrade costs.

*1) **Initial Network Cost** ($C_{initial}$):* This is the CapEx required at Year 0 to build the C+L-band network. It consists of the link cost and the initial regeneration cost.

- **Link Cost** (C_{link}). This includes the cost of amplifiers and transceivers for all links in the network: $C_{link} = \sum_{l \in E} 2 \times ((N_{spans,l} + 1) \cdot C_{amp,CL} + 2 \cdot C_{trx,CL}$, where $N_{spans,l}$ is the number of 80 km spans for link l.
- **Initial Regeneration Cost** ($C_{reg,init}$). This cost depends on the network configuration:
  - **No Regeneration.** $C_{reg,init} = 0$
  - **Selective Regeneration.** Every node installs a chassis to support possible regenerations in the future. $C_{reg,init} = N_{nodes} \times C_{chassis} + N_{activated} \times C_{reg,CL}$, where N_{nodes} is the total number of nodes and $N_{activated}$ is the set of nodes where regenerators are activated during the lifecycle.
  - **Full Regeneration.** Every node is equipped with a full C+L-band regenerator from the start. $C_{reg,init} = N_{nodes} \times C_{reg,CL}$.

The total initial cost is therefore: $C_{initial} = C_{link} + C_{reg,init}$.

*2) **Lifecycle Upgrade Cost** C_{life}:* This component captures all costs and deferral benefits of upgrading the network to S band, which occurs dynamically during the lifecycle.

- **S-Band Upgrade Cost** $C_{upgrade}$. This includes the cost of deploying new equipment to support the S band.
  - **Link Upgrade Cost** $C_{Link,S}$. This cost accounts for upgrading the amplifiers and transceivers of each link, incorporating a yearly depreciation rate calculated based on the year of upgrade [4], [6].
  - **Regenerator Upgrade Cost** $C_{reg,upg}$. $C_{reg,upg} = N_{reg,S} \times C_{reg,S}$. where $N_{reg,S}$ denotes the number of nodes requiring a S-band regenerator upgrade, which depends on the network configuration.
- **Budget Deferral Benefit** (B_{defer}). A financial benefit is accrued in years of zero upgrade expenditures, calculated as $B_{defer} = \sum_{y \in Y_{NoUpg}} (Budget \times Deferral\ Rate)$ where Y_{NoUpg} represents the years with no upgrade.

*3) **Total Network Cost**:* The final cost for each scenario is the sum of all components: $C_{total} = C_{initial} + C_{upgrade} - B_{defer}$. In scenarios without S-band upgrade, where only regeneration capabilities increase, the network remains in C+L bands and $C_{upgrade} = 0$ and $B_{defer} = 0$.

III. Numerical Evaluation

A. Simulation Setup

We developed an event-driven simulator to evaluate network performance over its entire lifecycle, which is 10 years in this work. Generalized Gaussian Noise (GGN) model [7] is adopted to pre-calculate the GSNR of each link with a fully-loaded assumption. Table II details the supported modulation formats and their required optical signal-to-noise ratio (ROSNR) to achieve a bit error rate (BER) of 2×10^{-2}, with ROSNR measured within a 12.5 GHz reference bandwidth.

TABLE II: Transceiver parameters [8]

Baud Rate (GBaud)	Modulation Format	Bandwidth (Gbps)	OSNR (dB)
64	DP-BPSK	100	12
64	DP-QPSK	200	16
64	DP-8QAM	300	21
64	DP-16QAM	400	24

We evaluate two network topologies: BT-UK and USNET [6]. The BT-UK network consists of 22 nodes and 35 bi-directional links, with an average link length of 147 km. In

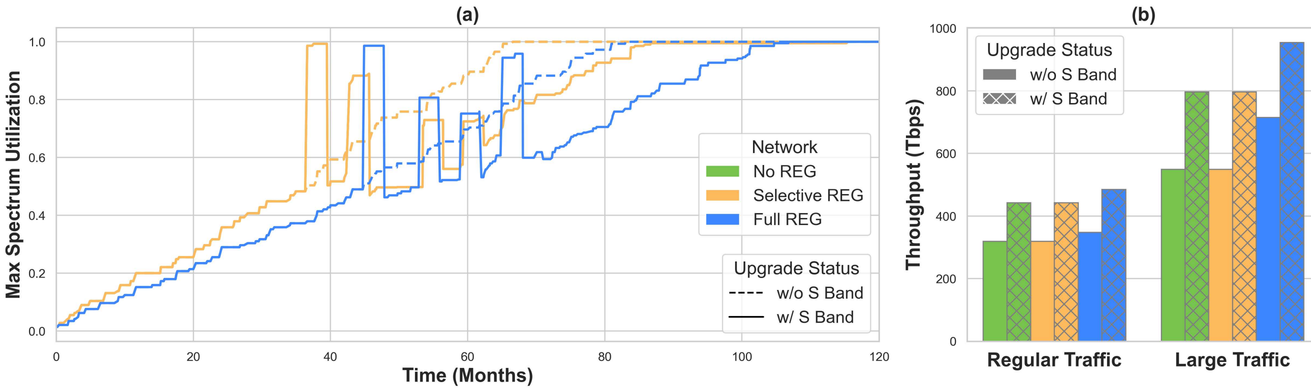

Fig. 1: Numerical results for BT-UK topology. (a) Maximum SU with large traffic model over a 10-year lifecycle. (b) Total network throughput under both traffic models.

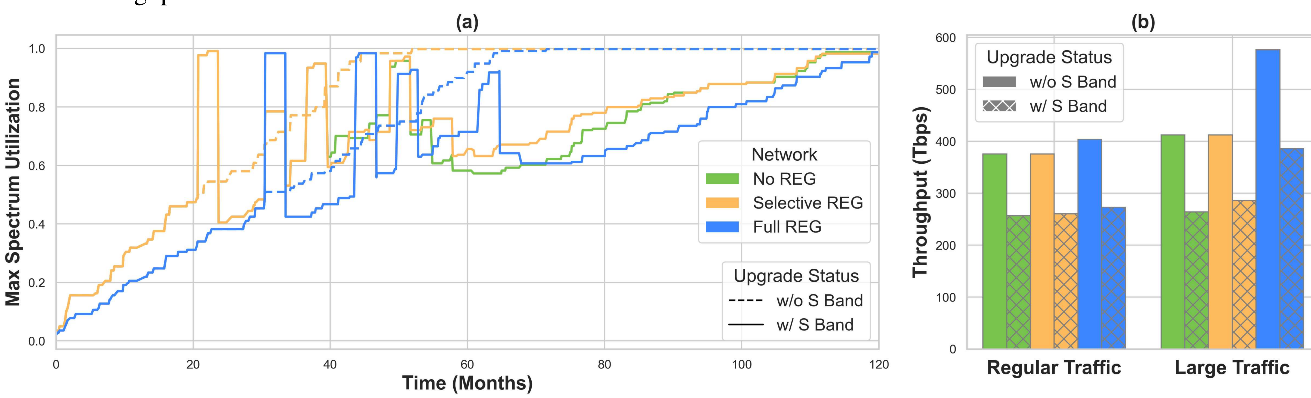

Fig. 2: Numerical results for USNET topology. (a) Maximum SU with large traffic model over a 10-year lifecycle. (b) Total network throughput under both traffic models.

contrast, the USNET network is larger, featuring 24 nodes and 43 bi-directional links with an average link length of 998 km.

In this work, we consider two incrementally growing traffic models, with 100 initial requests in the first year, as follows:

- **Regular** traffic model consists of 100 Gbps (50%), 200 Gbps (30%), and 400 Gbps (20%) requests, growing at 30% annual growth rate (AGR).
- **Large** traffic model consists of higher bandwidth requests with 400 Gbps (50%), 800 Gbps (30%), and 1 Tbps (20%), growing at 10% AGR.

B. Numerical Results for Maximum SU and Throughput

Figs. 1 and 2 present numerical results of SU and network throughput for BT-UK and USNET topology, respectively. Network throughput is defined as the total volume of successfully provisioned traffic with a blocking probability (BP) below 0.1. The maximum SU in the network under various scenarios (different regeneration capabilities with and without S-band upgrade) with only large traffic is tracked for simplicity in both topologies over their lifecycle of 120 months. S-band upgrade is represented with solid lines (as opposed to dashed lines for C+L only), where the periodic spikes correspond to the upgrade instances (each upgrade duration is 3 months) that are triggered when SU reaches a threshold (T_{SU}) of 50%.

*1) **BT-UK Topology**:* As seen in Fig. 1a, adding the S band (solid lines) consistently lowers SU compared to C+L-only systems (dashed lines), hence delaying spectrum exhaustion. The selective regeneration case (orange lines and bars) performs identically to the no regeneration case (green lines and bars), as regeneration is only applied when a lightpath has insufficient QoT and given the short average link length of the BT-UK network, most lightpaths achieve sufficient QoT for transparent transmission without it. Network with full regeneration achieves the lowest SU, maximizing the budget deferral benefit by postponing the need for upgrades. This efficiency translates directly to the throughput shown in Fig. 1b. Characterized by short average link length, upgrading to S band uniformly improves network throughput across all regeneration capabilities. The largest relative improvement (44.9%) is seen for no/selective regeneration under the large traffic model. When comparing regeneration capabilities, full regeneration consistently achieves the highest throughput in both C+L bands and C+L+S bands, with the most significant gain (30.2%) occurring in the large traffic model without the S-band upgrade. Notably, the throughput of a C+L network with full regeneration (715 Tbps) approaches that of a C+L+S network with no regeneration (796 Tbps), highlighting that both schemes can yield comparable capacity gains.

*2) **USNET Topology**:* The numerical results of the long-haul USNET network are shown in Fig. 2. The selective regeneration case (orange) aligns with the no regeneration case (green) in C+L-only scenarios (dashed lines and solid bars). In C+L bands, most lightpaths meet the required QoT for transparent transmission even across the long distances of the

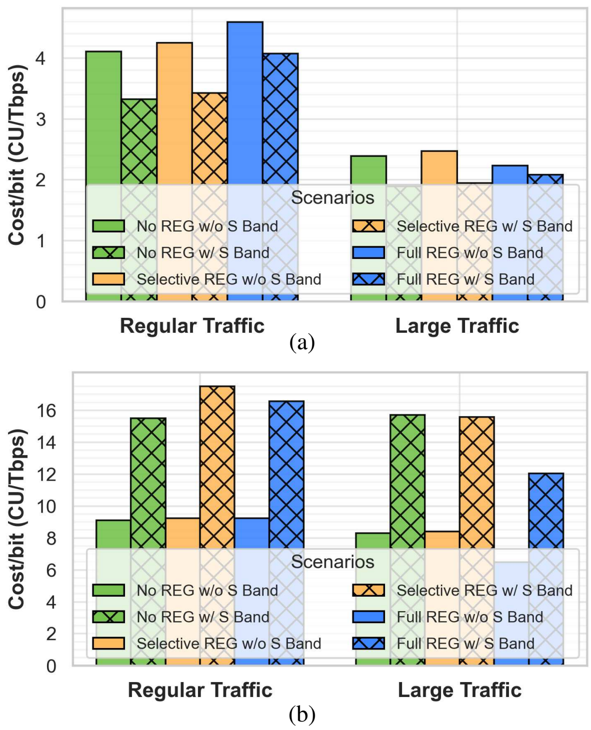

Fig. 3: Cost per bit analysis of (a) BT-UK topology. (b) USNET topology.

USNET topology, thus not triggering the need for selective regeneration. While adding S band lowers the SU (Fig. 2a, solid lines), it paradoxically degrades overall throughput across all network configurations (Fig. 2b), despite the additional capacity it provides in [9]. This counterintuitive result stems from K-least-loaded routing strategy used in our algorithm. This method selects links with minimum SU to compose the whole route and neglects total distance of the lightpaths. In a long-haul network like USNET, this leads to selection of longer paths which accumulates physical impairments causing their GSNR to degrade resulting in high BP.

Consequently, S-band expansion alone, even with regeneration, cannot guarantee higher throughput in long-haul networks like USNET, unless paired with a QoT-aware RSA Alternatively, increasing the regeneration capability (especially full regeneration) in the C+L bands delivers the highest throughput and avoids GSNR-related penalties, as shown in Fig. 2b.

C. Cost per Bit Analysis

Fig. 3 compares the cost per bit of the BT-UK and USNET topology across different scenarios for both traffic models.

For BT-UK topology, while increasing regeneration capability usually raises the cost per bit in both with and without S-band upgrade under regular traffic, full regeneration has the lowest cost per bit when handling large traffic in C+L bands, implying that regeneration can be economically justified when operators cope with large traffic in the C+L-band system. Additionally, the large traffic model has significantly lower cost per bit values, indicating greater cost efficiency for operators when handling higher traffic volumes over the same network configuration. The S-band upgrade reduces the cost per bit for all network configurations while no regeneration has the lowest cost per bit value for both traffic models. Moreover, as per Fig. 1b and Fig. 3a, upgrading a short-haul network with full regeneration to support the S band is particularly noteworthy. This upgrade reduces cost per bit from 2.2 to 2.1 CU/Tbps while achieving the highest throughput.

For USNET topology, S-band upgrade leads to high cost per bit values in all regeneration scenarios due to the QoT-driven throughput penalty. Although greater regeneration capability in large traffic model mitigates the issue, S-band upgrade remains too cost-inefficient for capacity enhancement. In contrast, increasing regeneration capabilities in C+L-band systems offers clear economic and performance benefits, particularly under large traffic loads. These findings suggest that, for long-haul networks, operators should prioritize investments in regeneration over S-band upgrade.

IV. Conclusion

This study evaluates the combined effects of spectral expansion from C+L to C+L+S bands and increasing regeneration capability for capacity enhancement in optical backbone networks. Using a detailed cost model with a pay-as-you-grow upgrade framework, we show that network scale and physical characteristics critically determine the optimal approach for operators. In short-haul networks, S-band upgrade consistently improves throughput and cost efficiency, with the greatest economic benefits achieved when combined with no regeneration. In long-haul networks, however, naive S-band upgrade can degrade performance when combined with K-least-loaded routing which neglects path distance leading to high blocking from GSNR degradation, making full regeneration a more cost-effective solution. Future work will explore a more comprehensive study with different routing strategies.

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