Throughput Maximization in (C+L+S) Networks with Incremental Deployment of HFAs and 3Rs

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Abstract *We optimize HFA and 3R deployment to avoid lightpath degradation and maximize throughput in (C+L+S) networks. We show that our proposed strategies can lead up to around 64% fewer HFAs and 20% higher throughput compared to baseline solutions. ©2023 The Author(s)*

Introduction

Multi-band transmission is among the most prominent solutions to enable capacity in optical networks. Upgrading transmission to (C+L+S)-bands has been demonstrated to increase capacity up to four times compared to traditional C-band transmission[1]. However, transmitting in (C+L+S) leads to lightpaths' degradation in C and L bands due to Inter-channel Stimulated Raman Scattering (ISRS)[2]. To avoid such degradation when serving incremental traffic, an emerging solution is to deploy hybrid EDFA/Raman amplification (HFA) and 3R regeneration (3Rs)[3]. While 3Rs allow to regenerate the lightpath, HFA upgrade allows to compensate for propagation losses and to reduce the overall amplifier noise figure. We have previously investigated the optimized HFA placement in (C+L) networks[4],[5], and showed that we can avoid lightpath degradation while minimizing number of HFA upgrades. However, in (C+L+S) networks, SNR degradation in C and L band is more severe, leading to unacceptable performance. As a result, deploying *both HFAs and 3Rs* becomes essential for mitigating lightpath degradation, therefore compounding the complexity of the optimization problem. Previous works in the literature have investigated the deployment of Raman amplifiers[6],[7] and 3R regenerators[8] in (C+L+S) networks. However, these works assume that HFA are deployed in every candidate location and do not consider joint HFA and 3R deployment. Differently from previous literature, we consider planning in (C+L+S) networks under incremental traffic, i.e., how to strategically place HFAs and 3Rs over time to maximize throughput and minimize ligthpath degradation.

Problem statement

The problem of optimizing HFA and 3R deployment can be stated as: **Given** a network topology, an initial set of traffic demands (with source-destination nodes and data-rate), an increase rate of the traffic, a baseline deployment of EDFAs for C- and L-band, and TDFAs for S-band, a set of candidate spans to deploy HFAs and a set of node candidate locations for 3Rs, **decide** Routing, Modulation format, and Spectrum Assignment (RMSA) of all traffic demands, and the deployment of HFAs and 3Rs at each step of traffic increase, **constrained by** *i)* minimum lightpath SNR and received power, *ii)* spectrum continuity and contiguity, and *iii)* fiber capacity, with the **objective** of avoiding lightpaths' degradation and maximizing throughput while minimizing the number of HFAs and 3Rs.

Physical layer modelling

We assume that all network links support (C+L+S) transmission and that EDFAs for C and L bands, and TDFAs for S-band are placed in the same cabinet location. Regarding the deployment of Raman amplifiers, we define a fiber span as *eligible* for HFA upgrade if its length is at least 70 km. We assume that HFA amplification operates at a moderate pumping regime with a counter-propagating pumping scheme and that Raman amplification recovers 60% of the span loss[9]. We assume noise figure values for EDFA in C- and L-band, and TDFA for S-band as in[1], and that introducing Raman amplification reduces amplifier noise figure by 5 dB[5],[9],[10]. We utilize the closed-form Generalized Gaussian Noise model to estimate the Signal-to-Noise Ratio (SNR), accounting for ISRS[2],[11]. We assume links operate with ASE loading, i.e., worst-case scenario in terms of interference, and channels operate at optimal power according to LOGO[12]. A lightpath is defined as *feasible* if its SNR and received power are higher than a threshold[13].

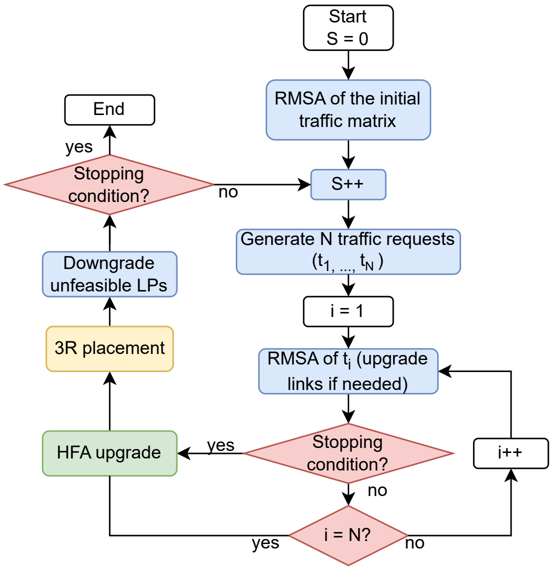
Optimized placement of hybrid EDFA/Raman amplifiers and 3R regenerators

We investigate two approaches for deployment of HFA and 3Rs with different objectives: 1) *MinDeg*: it ensures no lightpath degradation (and modulation formats are set according to achievable lightpaths' SNR), and 2) *MaxTHR*: in addition to ensuring no lightpath degradation, it assumes the availability of an extra budget to maximize network throughput by deploying additional 3Rs such that the modulation format that matches the traffic demands' data-rate is assigned (i.e., all traffic demands are served with minimum spectrum).

Figure 1 illustrates HFA and 3R deployment considering 30% incremental traffic at each step, until we meet 1% of blocked traffic (stopping condition). Depending on the objective, HFAs and 3Rs are deployed to avoid lightpath degradation, i.e., *MinDeg*, or to maximize throughput, i.e., *MaxTHR*. Once we perform RMSA of the initial traffic matrix, at each step (s_i) of traffic increase, we generate *N* traffic demands. If a demand can not be served due to insufficient available spectrum, transmission in links on its shortest path is extended to (C+L) if links are in C-band, or extended to (C+L+S), if links are operating in (C+L). If links are operating in (C+L+S) and there is no available capacity, then the traffic demand is blocked. If the ISRS-induced SNR degradation causes a lightpath's SNR to fall below the SNR threshold of the assigned modulation format, we define the lightpath as *unfeasible*. At the end of each step s_i of incremental traffic, in case of *unfeasible* lightpaths, we proceed with HFA and 3R deployment, and then proceed to step s_{i+1}. The objective of HFA deployment is to avoid that existing lightpaths become *unfeasible* after the traffic increment at step s_i. In case HFA upgrade does not enable the required SNR, we deploy 3Rs. In case signal degradation is severe and even 3Rs do not ensure sufficient SNR improvement, we consider that such lightpaths are *downshifted* to a lower modulation format.

In the following, we describe all the proposed strategies for HFA upgrade and 3R deployment.

HFA upgrade. We consider three strategies for HFA upgrade. *1) minHFA* is our proposed greedy algorithm that optimizes the deployment of Raman amplification with the objective of improving ligthpaths' SNR while minimizing the number of deployed HFAs. *2) HFA-all* deploys Raman amplification in all eligible spans, i.e., spans with length greater or equal to 70km, and *3) HFA-need* deploys Raman amplification in all eligible spans that have unfeasible lightpaths passing through.



Stopping condition: blocked traffic > 1%

Fig. 1: Flowchart for HFAs and 3R-regenerators placement.

minHFA is a two-step algorithm. In *Step-1*, it identifies links that carry unfeasible lightpaths and orders them based on the number of unfeasible lightpaths, from highest to lowest. Then, it deploys Raman amplification in the longest span of the link. Once upgraded, lightpaths' SNRs are recalculated and, if there are still unfeasible lightpaths and candidate locations for HFA upgrade, we repeat *Step-1*. Otherwise, we proceed with *Step-2*. In *Step-2*, we sort links by decreasing number of deployed HFAs and sequentially remove HFA from the first link of the list. If removing an HFA does not lead to unfeasible lightpaths, we check removing other HFAs from the same link, otherwise, we revert the action and move to the next link in the list. *Step-2* is repeated until all links in the list are considered.

3R placement. We assume a lightpath can be regenerated at its intermediate nodes. Regeneration implies establishing two new lightpaths: one from source node to regenerator node, and another from regenerator to the destination node. We propose two strategies for 3R deployment. 1) *3R-minSNR* selects the regenerator node in order to maximize the minimum SNR of the two new established lightpaths. 2) *3R-avgSNR* selects the regenerator node in order to maximize the average SNR of all lightpaths in the network.

Illustrative numerical results

We compare the HFA and 3R deployment strategies in terms of number of HFAs and 3Rs and network throughput, considering the 19-node European Network[5]. We assume that traffic at *Step-0*

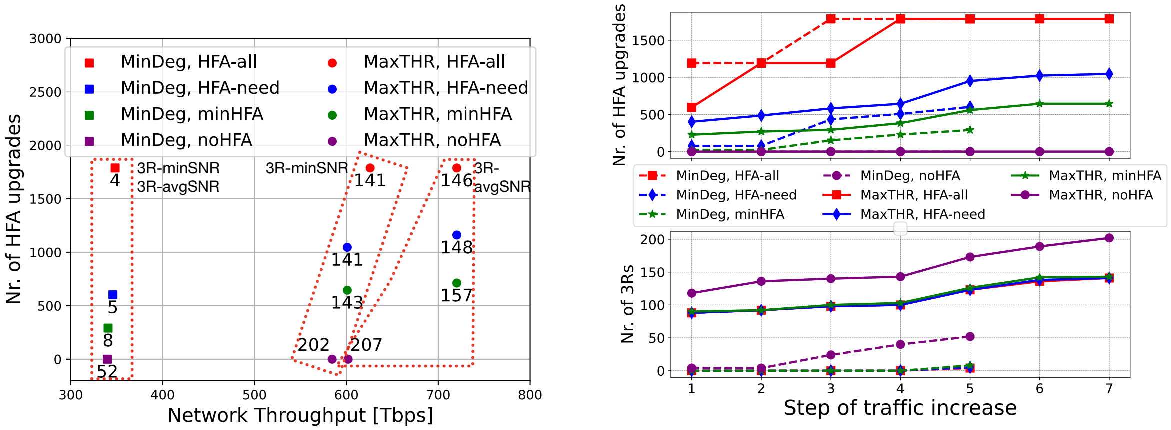


Fig. 2: a) Number of 3Rs, network throughput and number of HFA upgrades for all the HFA upgrade strategies in case of *3R-minSNR* and *3R-avgSNR*, and b) number of HFA upgrades and 3Rs in case of *3R-minSNR* for each step of traffic increase.

amounts to 114 Tbps and is distributed between node pairs according to the gravity model[14] (i.e., traffic between two nodes is proportional to the product between their populations). We consider PM-16QAM to PM-64QAM modulation formats, and 200 Gbps to 800 Gbps (with 100 Gbps step) transmission rates. The SNR threshold, baud rate and channel spacing are defined as in[13]. We consider that all demands are routed according to the k-shortest-path (k=3) algorithm with minimal loss[15],[16] and spectrum assignment according to first-fit policy. Figure 2.a shows the results for all the HFA upgrade strategies, for both *MinDeg* and *MaxTHR*. Each point on the plot reports the number of HFA upgrades, the network throughput and the number of 3Rs, represented by the numerical value. Figure 2.b shows the number of HFA upgrades and 3Rs at each step of traffic increase for all HFA upgrade strategies, in case of 3R-minSNR.

MinDeg. In *MinDeg*, the combined use of HFAs and 3Rs ensures that all the lightpaths are feasible at the end of traffic increase and no lightpath is *downshifted* (note also that results are the same for *3R-minSNR* and *3R-avgSNR*). Using *HFA-all, HFA-need and minHFA* we can deploy up to 84% less 3Rs compared to *noHFA* (down from 52 to 4, 5 and 8, respectively), and, in general, joint deployment of HFAs and 3Rs leads to a higher throughput compared to *noHFA*. In terms of HFA upgrades, *minHFA* deploys 84% and 51% fewer HFAs compared to *HFA-all* and *HFA-need*, while having a small impact on the 3Rs and on the network throughput, that ranges from 339 Tbps to 348 Tbps, depending on the HFA strategy.

MaxTHR. As shown in the right part of Fig. 2.a, *MaxTHR* allows to boost dramatically network throughput. In case of *3R-minSNR*, we observe that, depending on the HFA strategy, network throughput grows from about 350 Tbps to a number between 600 Tbps and 625 Tbps. As expected, *noHFA* leads to the highest number of 3Rs and lowest network throughput, but, by placing HFAs jointly with 3Rs, we can reduce the number of 3Rs up to 30% compared to *noHFA*. *minHFA* deploys 64% and 41% fewer HFAs compared to *HFA-all* and *HFA-need*, respectively, guaranteeing a network throughput of about 600 Tbps. To increase throughput by 25 Tbps (*HFA-all*), we need to place 64% more HFAs. Hence, it is important to explore different HFA and 3R deployment strategies to balance cost, complexity, and network throughput. For example, using *HFA-all* instead of *minHFA*, one could serve an additional 4% of traffic by paying for additional 64% Raman amplifiers (on top of 645 already deployed). We argue that our proposed *minHFA* offers a good trade-off to jointly save HFAs and achieve high throughput.

Similar considerations hold also for *3R-avgSNR*, but we observe that it achieves higher throughput than *3R-minSNR*; e.g., in case of *minHFA*, throughput in *3R-avgSNR* increases by 20% compared to *3R-minSNR*.

In conclusion, we numerically demonstrated how strategically placing 3Rs and HFAs is crucial for minimizing lightpath degradation, maximizing network throughput and to avoid uncessary HFA upgrades in (C+L+S) networks, especially when dealing with non-uniform traffic distributions.

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