Optimal Pay-As-You-Grow Deployment on S+C+L Multi-band Systems

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Abstract: We investigate the best band upgrade order on an S+C+L system in a pay-as-you-grow approach, aiming to maximize the end-of-life system capacity under the constraint of not disrupting already running services.

1. Introduction

Multi-band (MB) transmission is an attractive solution to support the continuous growth in bandwidth demand. It postpones costly fibre roll-outs, maximizes existing infrastructures' capacity, and is compatible with other spatial division multiplexing (SDM) solutions [1]. For example, the widely deployed ITU-T G.652D fibre offers a low-loss transmission spectrum of ∼54 THz – from the O- to the L-band. Another advantage of MB is that it supports modular upgrades. Thus, the enabling of additional transmission bands can follow a pay-as-you-grow approach, i.e., specific hardware required to enable particular transmission bands can be deployed just when the respective bands are necessary [2]. However, due to the interchannel stimulated Raman scattering (ISRS) effect, the deployment order of the transmission bands is not trivial since an additional transmission band might significantly impact the bands that are already operating. By default, in an S+C+L-band transmission system, the order of band deployment would probably be C→L→S, prioritizing the utilization of bands that have lower costs and present more mature and better-performing components. However, such a strategy may not be the optimum one concerning network capacity in each period and, consequently, may not maximize the return on investment of the upgrade process.

In this work, we focus the analysis on the best (in terms of capacity) pay-as-you-grow order of band deployment on an S+C+L MB transmission system occupying 15.5 THz. We also analyze the potential capacity limitation in each period resulting from restrictions such as the requirements that previously deployed bands remain in-service when adding a new band, the operating point of previously deployed amplifiers cannot change, and the maximization of end-of-life (EoL) system capacity (i.e. the fully occupied S+C+L-band system).

2. Launch Power Optimization and Upgrade Scenarios

In this work, the generalized signal-to-noise ratio (GSNR) – calculated using the GNPy library [3] – is set as quality of transmission of a lightpath (LP) metric. The launch power profile of an S+C+L system is optimized for 75-km fibre spans followed by an amplifier for each band with a noise figure of 5 dB. The fibre characteristics and the optical channel formats are the same as those considered in [4].

We consider deploying one transmission band at a time. However, we include the band DEMUX/MUX insertion losses of 2/1 dB, respectively, since day one to avoid future network disruptions. The average power level and power tilt for each band [5] are optimized to maximize the average GSNR and minimize the per band GSNR variation. Two upgrade scenarios are considered: i) in the ideal scenario, where the operating points of the amplifiers deployed in previous periods are freely re-optimized when upgrading the system with new transmission bands. In this case, the launch power profile is optimized to maximize the current system capacity. ii) in the "previous-fixed" scenario, the operating points of previously deployed amplifiers are fixed, and the launch power profile is optimized to maximize the end-of-life system capacity.

The optimized launch power profiles for current and EoL maximum capacity of single-band transmission and the resulting GSNR are depicted in Fig. 1. The L-band is the best-performing one when optimizing the system capacity (its minimum GSNR exceeds the C- and S-bands by 0.5 and 1 dB, respectively). On the other hand, the L-band is the most penalized one when optimizing the network for EoL transmission conditions. This higher penalty is a consequence of the high optimum launch power difference when optimizing for EoL (average difference of 2.53 dBm, 0.53 dBm and 1.19 dBm per channel for the L-, C- and S-band, respectively). The higher impact on the L-band results from assuming the simultaneous transmission of all bands in the EoL transmission scenario. In that case, the L-band receives power from both the C- and S-band through the ISRS effect and, therefore, the optimal average launch power is significantly lower than for the single-band transmission case. The inverse occurs for the

S-band. In this case, the optimal average launch power for the EoL transmission scenario is higher than for the single-band transmission. The smallest penalty when changing from current to EoL optimization occurs for the C-band, because it receives optical power from the S-band through ISRS but also transfers power to the L-band via the same effect.

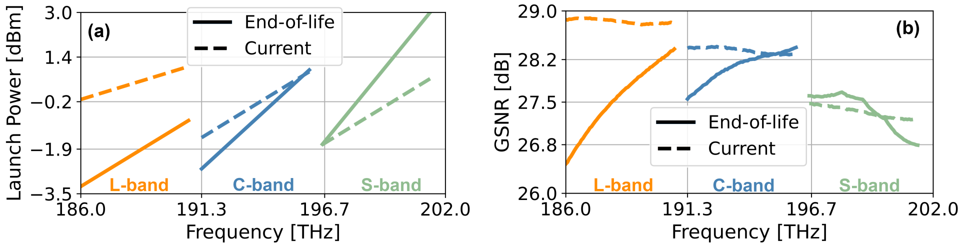

Fig. 1: (a) Optimized launch power for current and for EoL maximum capacity and (b) resulting GSNR profiles for a 75-km fibre span.

Table 1 and Table 2 present the minimum GSNR for each band (i.e., the lowest GSNR among all channels in that band) in the ideal and in the previous-fixed transmission scenarios. For the ideal scenario, the optimum order of deployment of the transmission bands is L→C→S because this is the case that best explores the available GSNR while still guarantees that previously deployed bands remain in-service. For the previous-fixed scenario, the optimum order of deployment of the transmission bands is C→L→S where the C-band provides a minimum GSNR of 27.5 dB against 26.4 dB and 26.7 dB for the L- and S-band, respectively. However, if the C-band is deployed first, existing LPs operating close to the performance limit may not remain in service when adding the L-band (the C-band minimum GSNR decreases from 27.5 to 27.1 dB when adding the L-band to a C-band system and from 28.3 to 27.8 dB when adding the L-band to an S+C-band system). The most conservative approach that guarantees that previously deployed LPs remain in-service when performing network upgrades is to deploy C→L→S, but assuming that the GSNR of the C-band only system is already the one that will be measured in the C+L system, i.e., to consider an available GSNR of 27.1 dB instead of 27.5 dB. This strategy may reduce the system's capacity in the first period but still provides higher capacity than starting data transmission in the L- or S-band only. One solution that keeps the maximum capacity on the first period and does not disrupt previously deployed bands is going directly from a C-band-only system to an S+C+L-band system by simultaneously deploying the S- and L-band. However, this solution requires an early deployment of the three bands and possibly incurs a sub-utilization of the deployed infrastructure, while the demand for capacity only justifies using two bands.

Table 1: Minimum per band GSNR for the ideal scenario.

Bands	Min. GSNR [dB]		
	L	C	S
L	28.7	–	–
C	–	28.2	–
S	–	–	27.2
C+L	28.7	27.6	–
S+L	29.1	–	26.2
C+S	–	28.1	26.8
S+C+L	29.1	27.8	25.8

Table 2: Minimum per band GSNR for the previous-fixed scenario.

Deployment Order	First Deployment Min. GSNR [dB]			Second Deployment Min. GSNR [dB]			Third Deployment Min. GSNR [dB]		
	L	C	S	L	C	S	L	C	S
C→L→S	–	27.5	–	27.4	27.1	–	29.1	27.8	25.8
C→S→L	–	27.5	–	–	28.3	26.6			
L→C→S	26.4	–	–	27.4	27.1	–			
L→S→C	26.4	–	–	28.4	–	26.3			
S→C→L	–	–	26.7	–	28.3	26.6			
S→L→C	–	–	26.7	28.4	–	26.3			

3. Network Analyzes and Results

The statistical network assessment process (SNAP) [6] is used to analyze the impact of using different bands and power optimization strategies on the capacity of the US reference transport network (Fig. 2a). SNAP enables taking into account limitations resulting from the control-plane such as the routing algorithm and the spectrum assignment (SA) policy, and parameters to simulate the behaviour of the network, such as the traffic model and distribution, as well as the characteristics of the transceivers used to calculate each LP capacity. We performed a progressive traffic analysis with 1000 Monte Carlo iterations, k-shortest path algorithm with $k_{max} = 3$ as routing and First-Fit as SA policy. We considered connection requests of 400 Gbps each, randomly distributed among the network nodes. The transceivers characteristics are described in [7], supporting the transmission of 64-GBaud signals in the 75-GHz WDM grid and three modulation formats, namely 16QAM, 8QAM, and QPSK. Each transmission band is assumed to support the transmission of 64 channels in each fibre link.

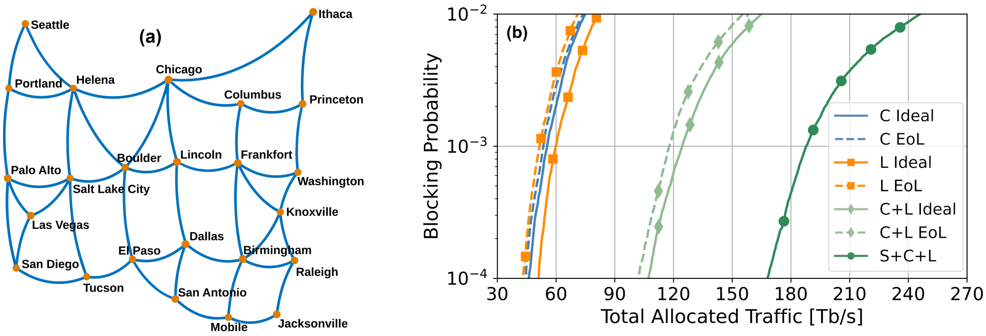

Fig. 2: (a) Representation of the US network and (b) total allocated traffic for different system upgrades, considering current or EoL power optimization.

Fig. 2b depicts the network behaviour for C-, L-, C+L-band transmission in the ideal and previous-fixed (EoL power optimization) scenarios and S+C+L-band system in terms of total allocated traffic versus blocking probability. Fig. 2b shows that the deployment of the C-band only in the ideal case supports 55 Tb/s capacity at the blocking probability (BP) of 0.1%. However, when maximizing the EoL capacity, it drops by 2 Tb/s. At the same BP value, but using the L-band only, the difference between ideal and EoL scenarios grows to about 9 Tb/s (from 60 Tb/s to 51 Tb/s). Fig. 2b also shows that the total capacity is approximately doubled when comparing C+L-band with a single C- or L-band. In this case, the total allocated traffic is 124 Tb/s and 117 Tb/s, for the ideal and EoL scenarios, respectively. According to Table 2, the minimum GSNR is similar for the S+C+L system at both the ideal and EoL scenarios. Consequently, the total allocated traffic is about 190 Tb/s for both scenarios, at the BP of 0.1%. These results show that fixing the operation point of previously deployed amplifiers results in having to trigger band upgrade slightly earlier on. It also shows that the difference between deploying first the C- or the L-band is small for the previous-fixed scenario. The total traffic supported in the first deployment period is just 2 Tb/s higher when starting with the C-band. This difference will become even smaller if considering the GSNR limit of 27.1 dB instead of 27.5 dB to avoid service disruption on the C-band.

4. Conclusions

We analyze the best deployment order of transmission bands (in terms of capacity) in a pay-as-you-grow approach of an S+C+L-band system occupying 15.5 THz. For the ideal case, in which the operating point of previously deployed amplifiers may be changed, the best deployment order is L→C→S. When the amplifiers' operating point must remain fixed, and the launch power profiles are optimized to maximize the end-of-life capacity of the system, we show that, even under the optimistic assumption that the amplifiers have the same characteristics for all three bands, the best order of deployment is C→L→S, but a margin of 0.4 dB in the GSNR of the C-band only has to be included to guarantee that there will be no service disruption in future band deployments. One alternative to maintain the maximum capacity on the first period and avoid service disruption is to go directly from the C-band to the full S+C+L-band transmission system. However, this solution requires an early deployment of the third band and possibly incur a sub-utilization of the optical infrastructure. For even broader transmission bands, the obtained results suggest that the central bands should be deployed first, since the capacity penalty resulting from using the EoL optimum launch power is smaller in this case (but further work is needed to sustain this hypothesis).

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