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Raman Pumping as an Energy Efficient Solution for NyWDM Flexible-grid Elastic Optical Networks

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ABSTRACT

This paper investigates transparent wavelength routed optical networks using three different fiber types NZDSF, SMF and PSCF - and validates the effectiveness of Hybrid Raman/EDFA Fiber Amplification (HFA) with different pumping levels, up to the moderate 60% pumping regime. Nodes operate on the basis of flexible-grid elastic NyWDM transponders able to adapt the modulation format to the quality-of-transmission of the available lightpath, exploiting up to five 12.5 GHz spectral slots. Results consider a 37-node Pan-European network for variable Raman pumping level, span length and average traffic per node. We show that HFA in moderate pumping regime reduces the power consumption and enhances spectral efficiency for all three fiber types with particular evidence in NZDSF. In essence to that, introduction of HFA is also beneficial to avoid blocking for higher traffic loads.

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1. INTRODUCTION

Worldwide IP traffic will undergo a significant increase of up to 23% in the years to come, as estimated in [1]. Therefore, operators are keen to improve the capacity of currently deployed Dense Wavelength Division Multiplexing (DWDM) infrastructure. A cost effective solution is to enhance the capacity without replacing the installed equipment [2].

Numerous investigations reveal three promising solutions for capacity improvement: the achievement of elasticity at the grid level [3], the use of advanced modulation formats [4] and the introduction of hybrid Raman/EDFA fiber amplification (HFA) [5] to lower ASE noise figure [6] [7]. We investigate the merits of incorporating aforementioned techniques in the network design problem. Approaching the problem from a transmission-level point-of-view [8], multilevel modulation formats with DSP-based Tx/Rx permit to maximize the spectral efficiency (SE) enabling Nyquist-WDM (NyWDM) transmission [9]. Moreover, they enable the use of flexible transponders to trade-off the bit-rate (R_b) with the lightpath quality-of-transmission (QoT).

A major current focus for transmission level is the improvement of the amplification quality. The seamless solution in currently deployed networks turns out to be the use of HFA, i.e. adding Raman pumping to EDFAs. Indeed, it has been shown in [5] that HFAs operated in moderate pumping regime are a feasible solution for upgrading re-configurable point-to-point optical links. Using multilevel modulation formats, linear propagation impairments such as chromatic dispersion and polarization mode dispersion (PMD) are fully recovered by the Rx DSP implementing a blind equalizer compensating for lightpath degradations. Therefore, links are not tailored for a specific transmission technique, and transponders may adapt the delivered (R_b) to the lightpath QoT, while nodes may perform transparent wavelength routing. As a consequence, the entire network can be configured on the basis of a

Table 1. Parameters for the fiber types

Fiber Type	Loss	Dispersion	Effective Area
	α_{dB}	D	A_{eff}
	[dB/km]	[ps/(nm · km)]	[μm^2]
NZDSF	0.222	3.8	70
SMF	0.200	16.7	80
PSCF	0.167	21.0	135

Table 2. Pan-Eu Topology

Parameters	Pan-Eu		
	mean	min	max
Fiber Distance (km)	648	218	1977
Node Degree	3.08	2	5

unique QoT parameter for physical level lightpath: the generalized optical signal-to-noise ratio (OSNR), including both the ASE noise introduced by amplifiers and the non-linear interference (NLI) [10] generated by the Kerr effect in fiber propagation. It has been shown that a network control plane, named LOGO (Local-Optimization Global-Optimization), based on local OSNR maximization enhances lightpath QoT [11].

Much research in recent years has focused on approaching the network design problem with the introduction of detailed physical layer modelling for both fixed and flexible-Grid Networks [12] [13] [14]. In [15], we showed the advantages of using HFAs in fixed-grid networks. We extend such analysis to the flexible-grid scenario in [16] to show how HFA in moderate pumping regime reduces the spectral occupancy. In this work we perform a sensitivity study by changing i) physical layer characteristics like fiber type, Raman pumping level (RPL) and span length, and ii) network parameters such as average traffic per node ($R_{b,N}$). Results are analysed in terms of performance matrices like spectral efficiency, power consumption and number of blocked requests.

The remainder of this paper is organized as follows: Sec. 2., introduces the transmission layer model. Sec. 3., provides details on network layer model used. Sec. 4., shows the simulation scenarios and results obtained. Finally, sec. 5. gives a conclusion and highlights the possible future work.

2. TRANSMISSION LAYER MODEL

We consider a uniform, uncompensated and amplified network topology, and suppose the distance between the amplifiers - the fiber span L_s - is the same for all network links as well as the amplifiers gain $G_{dB} = \alpha_{dB} \cdot L_s$ and noise figure F_{dB}. We assume the network is operating in C-Band exploiting flex-grid transponders based on variable symbol rate R_{SG}. On this transmission scenario we may apply a detailed model for the evaluation of the lighpaths QoT. It uses the incoherent Gaussian noise model (IGN) [10] to evaluate the amount of NLI on each lighpath that together with the ASE noise determines the related OSNR. Consequently, the generalized OSNR for a lightpath directly connecting no intermediate nodes node *i* to node *j*, with N_s amplified spans is:

$$SNR_{i,j} = \frac{P_{ch}}{N_s \left[P_{ASE} + \eta_{NLI} P_{ch}^3\right]} \quad (1)$$

where η_{NLI} and P_{ch} are the NLI efficiency and optimal LOGO-defined power per channel [11], respectively. Both values refer to the worst-case scenario represented by the full spectral load, that in general is close to be realistic in any case thanks to the weak dependence of NLI generation on the spectral occupation [17]. For the optimal power, we considered a hard-limit of 20 dBm given by the maximum power that the amplifier may deliver on the entire C-band, but the LOGO value never induced to exceed such a limit. P_{ASE} is the ASE noise generated by a single amplifier EDFA or HFA whose expression is:

$$P_{ASE} = h \cdot f_0 \cdot F \cdot (G - 1) \cdot R_{SG} \quad (2)$$

where h is the Planks constant, f_0 is the C-band center frequency. G and F are the gain and noise figure in linear units. For pure EDFA amplification we suppose F_{dB} = 5 dB, while introducing some Raman pumping F_{dB} decreases as shown in [5]. As we are focusing on a dynamic network scenario, we limit Raman amplification to the moderate pumping scenario, roughly corresponding to up to 60% of fiber loss recovered by Raman gain. Hence, according to [5], the related HFA behaviour is practically independent of the channel add/drop and does not modify the NLI impairments with respect to the ones given by the use of pure EDFA, and the only effect of Raman is the beneficial noise figure reduction.

We analyze the possible use of three typical fiber types: Single Mode Fiber (SMF), Pure-Silica Core Fiber (PSCF) and Non-zero Dispersion-Shifted Fiber (NZDSF). The main fiber parameters are shown in table 1.We

Table 3. Physical layer details for flexible-grid

Modulation Format	$OSNR_{min,m}$ (dB)			R_b (GBpS)				
		BpS↓	No. of Slots →	1	2	3	4	5
PM-BPSK	4.323	2		20	40	60	80	100
PM-QPSK	7.334	4		40	80	120	160	200
PM-16QAM	13.887	8		80	160	240	320	400
PM-64QAM	19.709	12		120	240	360	480	600

assume to operate with Nyquist-WDM (NyWDM) transponders, implementing a spectrally sliceable technology, attainable using variable symbol-rate (R_s) DSP. According to [18], B_{slot}=12.5 GHz and laser sources must be tunable on a B_{slot}/2 grid. Transponders are assumed to be able to occupy up to 5 slots. Thus, the R_{SG} , the lightpath spectral occupation, may vary from 12.5 up to 62.5 Gbaud. Assuming a typical 25% protocol and coding overhead (OH), the net symbol rate R_s is tunable from 10 to 50 Gbaud, step 10 Gbaud. The full optical C-band (B_{opt} = 4 THz) is assumed to be available. Therefore, each point-to-point link has 320 spectral slots available.

We assume transponders are able to tune the delivered bit-per-symbol (BpS) switching modulation formats as shown in Table 3. In particular, we assume to use polarization- division multiplexed (PM) multilevel modulation formats in the following set of square constellations with coherent receivers: Binary Phase-Shift Keying (PM-BPSK), Quadrature Phase- Shift Keying (PM-QPSK), 16 Quadrature Amplitude Modulation (PM-16QAM) and 64-Quadrature Amplitude Modulation (PM-64QAM). Hence, the net bit-rate R_b per lightpath may vary from 20 to 600 Gbps. The parameter enabling the use of a specific modulation format is the lightpath OSNR that must exceeds the value required by each format, as display in Table 3, second column.Considering possible transparent wavelength routing in nodes, the OSNR for a given lightpath crossing N_{Nodes} is:

$$SNR = \frac{1}{\sum_{i=1}^{N_{nodes}-1} \frac{1}{OSNR_{i,i+1}}} \tag{3}$$

Furthermore, table 3 depicts information about multilevel modulation formats used with their minimum required SNR $SNR_{min,m}$, the number of Bits-per-Symbol (BpS) and the bit rate C_m. The $OSNR_{min,m}$ is derived from the target BER defined by the forward error correction (FEC) code as follows:

$$SNR_{min,m} = \phi_m^{-1}(BER_{target}) \tag{4}$$

where ϕ_m is the function giving the BER for modulation format m. In the paper, we assume $BER = 10^{-2}$.

3. NETWORK LAYER MODEL

We consider an IP network over an optical WDM infrastructure with a flexible distribution of the spectrum grid [19]. The physical topology of the network can be represented as a directed graph in which vertices representing nodes are connected with edges representing physical links existing in the network. We assumed to have an IP router and an Optical Cross Connect (OXC) installed at each node in the network.

Each physical link from i to j is characterized by a physical length D_{ij}, expressed in km and such that $D_{ij} = D_{ji}$.

The traffic demands are transmitted from the source to the destination node using lightpaths, which are optical logical channels that can span over one or more physical links. A traffic demand can use one or more consecutive lightpaths to reach the final destination. In this case, the IP router electronically switches the demand between two consecutive lightpaths.

The set of all the established lightpaths forms the logical topology (LT). Each lightpath is generated at the source node and terminated at the destination node by dedicated flexible transponders. A flexible transponder can use any modulation format among the available ones and it is characterized by a maximum transmitting capacity C_{Max} equal to 300 Gbps. At intermediate nodes the lightpath is transparently switched by the flexible-grid OXC. Since optical switching devices working in a gridless fashion are not yet available, the spectrum is usually divided in spectrum slots with a much finer granularity than the coarse ITU grid. The optical spectrum on each link is divided in slot of size 12.5 GHz [18], which results in 320 slots per link by dividing the C-band (4 THz) by the slot size. It is also assumed that two empty slots are left as guard-band between two lightpaths so that the OXC can correctly switch the lightpaths.

A given modulation format and a given number of spectrum slots are associated to each lightpath. Each modulation format m is characterized by a maximum bandwidth capacity C_m of a single spectrum slot and by a maximum optical reach in km. The modulation formats considered in this work, their transmission rate and their optical reach are listed in Table 3. Depending on the modulation chosen, it is thus possible to create either lightpaths for long distances operating at low bit rate or lightpaths for short distances characterized by very high bit rate. The maximum among the optical reach distances of the available modulation formats corresponds to the maximum reach of the flexible transponder. The maximum number of slots that can be associated to a lightpath with modulation format m is equal to $\lfloor C_{Max}/C_m \rfloor$.

The network design initially defines the set of lightpaths that can satisfy the traffic demands, i.e., the design of the LT, while optimizing a given design target. When deciding which lightpaths have to be established, it is required to choose for each lightpath the most suitable modulation and the correct number of slots according to the distance that the lightpath has to cover and the amount of traffic that it has to carry. Finally, slots in the spectrum are assigned to each lightpath, with the constraints that the same set of consecutive slots is assigned to a lightpath over all the physical links that the lightpath is flowing on. Obviously, each slot on a physical link can be assigned only to one lightpath.

3.1. Design of Flexible-Grid Networks Under a Detailed Transmission Layer Model

We face the problem of designing a logical topology and mapping it to a physical infrastructure, the classical Logical Topology Design-Routing and Spectrum Assignment (LTD-RSA). This family of problems is defined by an integer linear program (ILP), which is NP complete. Because of the complexity of the problem the use of heuristic algorithms is justified and it is a common approach to solve it. Thus, we use a very simple greedy heuristic, named Direct Lightpath Heuristic (DLH), to define a set of lightpaths satisfying the traffic matrix [19]. We choose a simple heuristic because the focus of the work is to discuss the influence of physical layer parameters like the use of HFA and different fiber types on network performance metrics, with no major emphasis on resource allocation policies. A brief summary of the DLH heuristic is provided, whereas a more detailed description can be found in [19]. DLH satisfies node-to-node traffic requests beginning from the largest one. Each node-to-node traffic request is transported on the number of lightpaths depending on the ratio between traffic request and lightpath capacity. Differently from [19], we include a detailed physical layer model performing the computation of the SNR values to better define the transmission reach for different modulation formats for each lightpath.

The algorithm works as follow on each traffic request. Initially, the shortest path from source to destination is analysed. The path is feasible if its physical length is less than the maximum admissible optical reach of the transmitter using the lowest modulation format, i.e. BPSK, based on the OSNR. If feasible, the heuristic selects the highest modulation format among the available ones that can be supported on the path, to use as few as possible spectrum slots. The availability of the spectrum slots on the selected path is verified. If sufficient slots are available, the lightpath is established and the traffic request is allocated to the lightpath. Otherwise, the same operations are repeated for the next feasible shortest path from source to destination, until the request is satisfied. When the request is satisfied, the heuristic moves to the next traffic request repeating the same procedure, until all requests are satisfied, providing a set of lightpaths and spectrum slot allocation. When all traffic demands have been assigned, spectrum slots are associated with each lightpath. If a slot assignment is possible, the solution is validated, otherwise it is rejected.

4. RESULTS

4.1. Network Simulation Scenarios

In this section, we present the results of using HFA with different fiber types. In a previous contribution [16] only one performance metric was considered for simplicity: the spectral occupancy (SO) defined as the total number of used spectral slots divided by the total number of available slots. Obviously, a decrease in SO reflects a better efficiency in spectrum utilization. Differently from [16], here we analysed the performance against the matrices like power consumption, number of blocked requests and spectral efficiency. We use the following expression

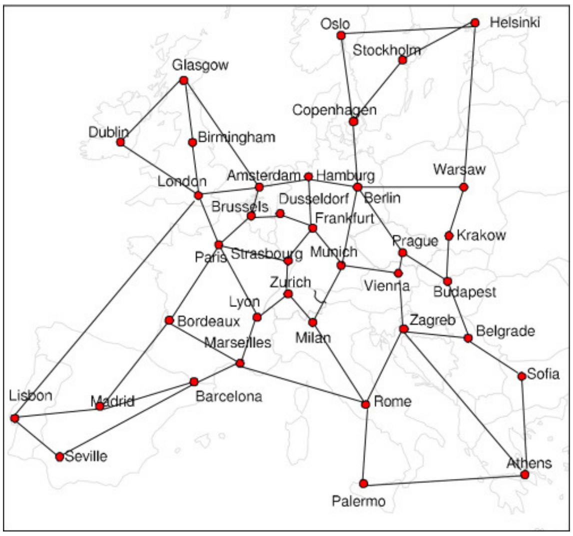


Figure 1. [Pan-EU Topology]

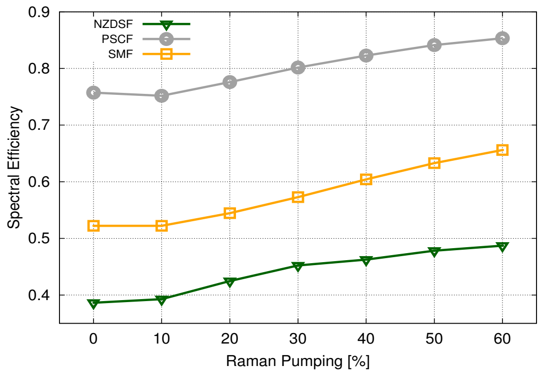


Figure 2. Spectral efficiency vs. Raman pumping level for different fiber types (traffic = 1500 Gbps, number of nodes = 37, span length = 100km and average connectivity = 3.08)

for the spectral efficiency *SE*:

$$SE = BpS * \frac{R_s}{B_{ch}}[\frac{bit/s}{Hz}] \quad (5)$$

Several traffic matrices are generated, for variable average generated traffic per node. Traffic loads are analysed into two regimes: low load regime and high load regime. In the low load regime we mainly use the SE along with power consumption as a performance index, in the high load regime we focus on the number of blocked requests along with SE. We consider real topology of the Pan-European (Pan-Eu) network shown in Fig. 1, with the distance between nodes,calculated using Eq. 1 in [20], ranging from 218km to 1977km. The average node degree is 3.08. Detailed network characteristics are reported in Tab.2. We consider the non-linear interference (NLI)transmission model, introduced in Sec. 2. The design heuristic is investigated over : the fiber type, among SMF, PSCF and NZDSF, as in [15], Raman pumping level (RPL), span length L_s and traffic load $R_{b,N}$.

4.2. Effect due to change in Raman Pumping Level RPL

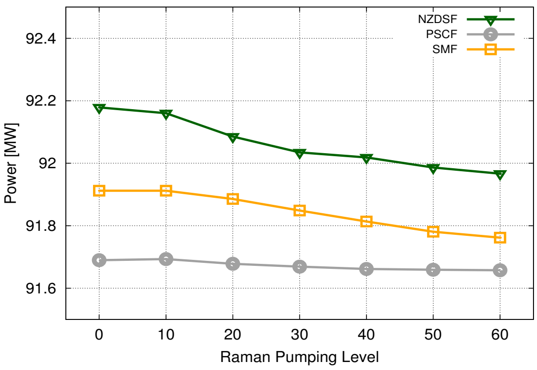
Fig. 2 shows the spectral efficiency respectively vs. RPL, for traffic load $R_{b,N}$ = 1500 Gbps, L_s = 100 km, N_{num} = 37 nodes and $N_{Conn.}$ = 3.08 and three different fiber types. It is evident that SE increases with the increase in RPL. This is because the amplifier noise figure decreases with the increase in RPL. PSCF shows the highest SE due to its physical properties which help it to cater the non-linearities more efficiently. while increasing RPL from 0-6 (i.e. from pure EDFA upto 60% Raman pumping) NZDSF shows an SE improvement of upto 12%. This improvement is 9% and 7% for SMF and PSCF respectively.

Fig. 3a shows the power consumption vs. RPL, for traffic load $R_{b,N}$ =, 1500 Gbps, L_s = 100 km, N_{num} = 37 nodes and $N_{Conn.}$ = 3.08 and three different fiber types. The power consumption decreases as the RPL increases due to the low power consumption of IP routers the Raman improvement varies fiber by fiber. Out of three finer types, here NZDSF enjoys the maximum benefit due to the used of HFA with respect to other two fiber types. PSCF, already being energy efficient, takes the least advantage of the phenomena.

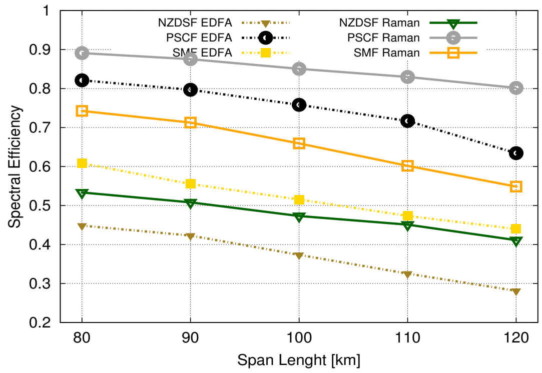
For the remaining investigations, two RPLs are used: EDFA only, RPL=0% (RA0) and RPL=60% (RA60).

4.3. Effect due to change in the span length L_s

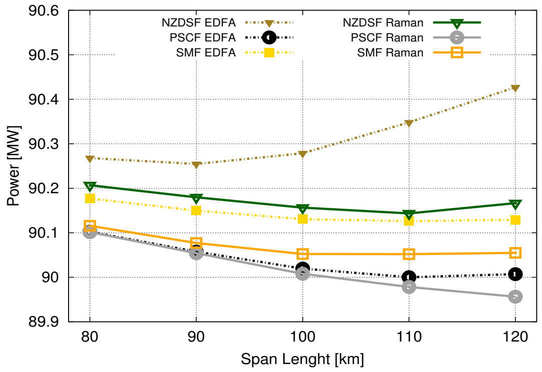
Fig. 3b shows the spectral efficiency vs. the L_s at $R_{b,N}$ = 1000 Gbps, N_{num} = 37 nodes $N_{Conn.}$ = 3.08 and three different fiber types. As the the span length increases from 80km to 120 km, we notice a decrease in the spectral efficiency. This is because of the increase in physical distance between the amplifiers which adds more linear and non linear impurities to the system. Since higher order modulation formats are used for shorter distances which transforms into the use of lower order modulation formats by increasing the distance. Therefore as the



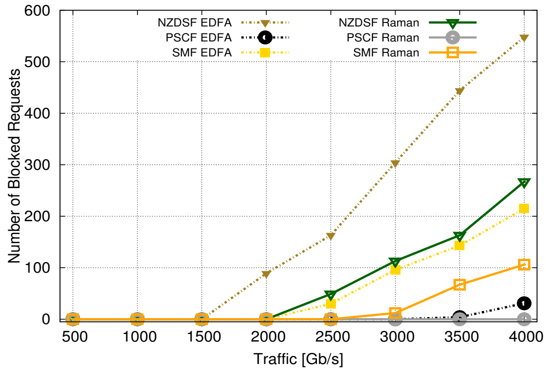
(a) Power consumption vs. Raman pumping level for different fiber types (traffic = 1500 Gbps, number of nodes = 37, span length = 100km and average connectivity = 3.08)



(b) Spectral efficiency vs. Span Length for different fiber types (traffic = 1000 Gbps, number of nodes = 37 and average connectivity = 3.08)



(c) Power Consumption vs. Span Length for different fiber types (traffic = 1000 Gbps, number of nodes = 37 and average connectivity = 3.08)



(d) Number of blocked requests vs. Traffic for different fiber types (number of nodes = 37, span length = 100km and average connectivity = 3)

Figure 3

distance increases OSNR decreases due to the use of lower order modulation formats. Resulting in the decrease of spectral efficiency.This decrease in SE is well addressed by increasing RPL especially for NZDSF. The explanation for this behaviour is related to the comments to results of Fig. 2. We are observing improvement in SE enabled by RPL, the fiber hierarchy already observed in Fig. 2.

Fig. 3c reports the power consumption vs.the L_s at $R_{b,N}$ = 1000 Gbps, N_{num} = 37 nodes $N_{Conn.}$ = 3.08 and three different fiber types to discuss the effect due to physical distance L_s between in-line amplifiers. Except for NZDSF, it is evident that power consumption reduces with the increase in span length. Which is due to involvement of lesser electronic equipment, especially in-line amplifiers. The variation shown by each fiber is different as the L_s increases from 80 km to 120 km. In particular, NZDSF displays a much larger advantage as compared other two fibers. Since we notice an over all decrease in the power consumption of a system even for the longer spans. Therefore introduction of HFA is also beneficial in reducing the energy requirements of a network.

4.4. Effect due to change in Load Level

Number of blocked requests depicted in Figs. 3d explains the network performance under heavy traffic loads for $L_s = 100$ km, $N_{num} = 37$ nodes and $N_{Conn.} = 3.08$ and three different fiber types. In the provided static solution, spectrum resources can not allocated due to to unavailability slots in one or more than one fiber in a link. Which results in blocking of traffic requests. It is evident that the the number increases with the increase in traffic load. In case of NZDSF for pure EDFA, we face blocking starting from 2000 Gbps that increases upto the count of 548 i.e 41% of total requests generated. (Total number of requests = N_{num} * N_{num} - N_{num}). This implies that network with pure EDFA may not carry heavy traffic loads using NZDSF. But the same network with the same fiber can be improved upto the one using SMF by introducing HFA. This is an improvement of almost 20%. in case of SMF and PSCF the reduction in the number of blocked requests is 8% and 2% respectively.

5. CONCLUSIONS

Prior work has documented the effectiveness of detailed physical layer modelling for both fixed and flexible-Grid Network. However a proposed solution to reduce spectral occupancy has to be the use of Hybrid Raman/EDFA Fiber Amplification. In this study we tested the impact of different fiber types and moderate Raman pumping as a complement to EDFA in flexible grid optical networks. We considered three typical fiber types NZDSF, SMF and PSCF and evaluated the benefit of Raman pumping against traffic load and span length. we found that the maximum considered percentage of Raman amplification - 60% of the span loss in dB - permits to increase SE and reduces power consumption. In addition, the improvement noted in our study is a significant decrease in number of blocked request as a result of HFA introduction. Furthermore,as observed for fixed-grid networks [15], the fiber experiencing the largest benefit from Raman pumping is the one experiencing the largest transmission impairments, i.e., the NZDSF in our case.

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