Investigating the Impact of Hybrid Raman-EDFAs in the Cost and Energy Efficiency of C+L Wideband Optical Networks

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***Abstract*— This paper investigates the impact of using hybrid Raman EDFAs in the total number of required transponders and power consumption of a wideband C+L optical network. Results are obtained through ILP modeling.**

Keywords—wideband, hybrid EDFA-Raman, ILP, optical amplifiers, optimization

I. Introduction and Related Work

In recent years the bandwidth demands have grown at an explosive rate, and this has been intensified by the advent of 5G services and the establishment of teleworking across the globe. In order to cope with the demands, instead of deploying new fiber cables which is a costly and time consuming process, exploiting the bandwidth of already deployed fibers, beyond the conventional C-band, is a more realistic and cost-effective option. The L-band is expected to be the next band that is going to be added to legacy WDM networks [1] but experiments have shown the potential of using the S band [2] and even the E and O bands [3] in the future. Moreover, works in [4] and [5] evaluate the cost efficiency of a wideband optical network when compared to a multi-fiber network of equivalent throughput.

Nevertheless, by extending the usable bandwidth, stimulated Raman scattering (SRS) becomes a significant physical impairment issue as the power of shorter wavelength channels is transferred to those of longer ones and thus, power depletion is caused to the first ones and signal distortion to the latter [6]. However, the same effect can be used for amplification, through high power pump signals that amplify the co-propagating lightpaths in a fiber span. The pump signals can propagate in the same direction (forward) or opposite (backward propagation) to those of the transmitted signals and Raman amplification can be applied in a distributed way (across the whole fiber span) or a discrete one (in a segment of fiber that is several kilometers long and is attached at the beginning or the end of a fiber span).

Even though Raman amplifiers have an advantage over widely deployed erbium doped fiber amplifiers (EDFAs) in terms of noise figure, it is unlikely that they will replace the latter entirely, for long haul scenario at least, since Raman amplifiers offer lower energy efficiency and achievable gain [7]. However, Raman amplification can be used in conjunction with EDFAs, in the form of hybrid Raman EDFAs (HR-EDFAs), which can lower the noise figure of existing EDFAs and eventually increase the transmission reach of the lightpaths. Experiments have validated the benefit of HR-EDFAs in the optical reach and the throughput of a fiber link for C+L transmission [8][9]. Furthermore, the authors in [10] examine the merit of HR-EDFAs in minimizing the need for 3R regeneration. The authors in [11] address the problem of optimal placement of HR-EDFAs in a mesh network topology whereas the authors in [12] assess the effect of optimal launch power with the presence of HR-EDFAs in an elastic optical network.

This paper extends previous works by investigating the impact that the usage of HR-EDFAs can have on a C+L wideband network. Specifically, the goal is to provide a techno-economic insight in terms of number of required transponders and total power consumption. At first, the method of calculating the OSNR of a lightpath is described which is then applied to the examined physical topologies of NSFNET and JPN-12. The obtained OSNR values for each route and wavelength are given as input parameters to the integer linear programming (ILP) model that is presented in this paper. Comparison results are then shown between an EDFA-only and HR-EDFA network architecture.

II. Methodology

A. OSNR Estimation

The modeling of the network is crucial for the validity of the results. Firstly, the two assumed amplification schemes are i) typical lumped amplification with two types of EDFAs operating separately on the C and L band, and ii) hybrid amplification where distributed Raman amplification is applied at the end of each fiber span, through backward propagation, and prior to the EDFAs. Secondly, for a given physical route in a network, it is important to provide an accurate OSNR estimation in order to determine whether a lightpath can be established or not. The $OSNR_l$ for a single fiber link l is calculated as [12] [13]:

$$\text{OSNR}_l = \frac{P_o}{N_l(P_{\text{ASE}}+P_{\text{NLI}})} \quad (1)$$

where P_o is the launch power of the transmitted signal, P_{ASE} the amplified spontaneous emission (ASE) noise of a single fiber span, $P_{\text{NL},l}$ the non-linear interference in the same span, which is assumed to be added incoherently, and N_l the number of spans in that fiber link. The P_{ASE} in the case of a single EDFA can be calculated by the known formula:

$$P_{\text{ASE}} = 2n_{\text{sp}}hf_o(G-1)B_o \quad (2)$$

where n_{sp} is the spontaneous emission factor, h the Planck constant, fo the frequency of the propagating signal, G the gain of the amplifier and Bo the optical bandwidth of the receiver. For the case of a HR-EDFA with backward propagation, the ASE noise is equal to [14] [15]:

$$P_{\text{ASE,HR}} = \text{NF}_{eff}hf_o(G-1)B_o \quad (3)$$

where NF_{eff} is the effective noise figure for an HR-EDFA and in the case of distributed backward Raman amplification is equal to [14] [15]:

$$\text{NF}_{eff} = \text{NF}_{\text{R}} + \frac{(\text{NF}_{\text{EDFA}}-1)}{G_{\text{R}}} \quad (4)$$

where NF_{R} the noise figure of a distributed Raman amplifier, NF_{EDFA} the noise figure of a single EDFA and G_{R} the on-off gain of the Raman amplifier. The value of NF_{R} is calculated according to [12]. The calculation of P_{NL}, is based on a closed formula provided in [16] that offers an approximation of non-linear interference with the presence of inter-band SRS. The formula is used on the assumption that the whole spectrum of C and L band is occupied on every link and thus, the worst-case non-linear interference is estimated. It is also worth mentioning that even though the Raman pump can increase the non-linear interference of a span, for backward propagation and low power level, the increase is insignificant and thus, neglected [17]. A more precise calculation of non-linear P_{NL} however, that assumes both inter-band SRS and Raman amplification, is left for future work. In addition to the ASE noise produced by the deployed amplifiers across a fiber link, when an optical signal goes through a re-configurable optical add-drop multiplexer (ROADM) node n, ASE noise is introduced by the embedded amplifiers and the OSNR_n is calculated as [12] [13]:

$$\text{OSNR}_n = \frac{P_O}{P_{\text{ASE},n}} \quad (5)$$

where $P_{\text{ASE},n}$ is the ASE noise that is added by the ROADM amplifiers. Eventually, the OSNR_p along a given path p is equal to [12] [13]:

$$\text{OSNR}_p = \left(\sum_{l\in p}(\text{OSNR}_l)^{-1} + \sum_{n\in p}(\text{OSNR}_n)^{-1}\right)^{-1} \quad (6)$$

Based on the above formula, and for a given path p, wavelength w and modulation scheme m, it is possible to define whether a lightpath is feasible or not and how many regenerations are required along the path. If the OSNR in a single fiber link of that path is below the threshold value of the particular modulation scheme then the lightpath cannot be established. The precomputed data set is given as input for the ILP formulation that is presented next.

B. ILP Formulation

In this ILP model one type of bandwidth variable transponder (BVT) is assumed that is used for both transparent connections as well as for 3R regeneration in a back-to-back configuration. The BVT is also assumed to have two operating modes of one and two carriers that occupy 50 and 100GHz spectrum respectively. Finally, four modulation schemes are assumed to be supported, specifically DP-BPSK, DP-QPSK, DP-8QAM and DP-16QAM. Based on these assumptions the ILP formulation is as follows:

TABLE 1 ILP MODEL

Input Parameters	
$G = (V, E)$	Physical topology of the network with node set V and fiber link set E.
$\Lambda_{s,d}$	Bandwidth demands between node pair s and $d \in V$.
P	Set of all k-shortest routes between all pairs of nodes in the network's topology.
$P_{s,d}$	Set of all k-shortest routes between node pair s and $d \in V$. $P_{sd} \subseteq P$.
K_p	Set of routes (including p) that have at least one common link with route $p \in P$.
W_{C}	Set of available wavelengths in C- band.
W_{L}	Set of available wavelengths in L- band.
M	Set of available modulations schemes that a BVT can use.
$R_{m,h}$	Parameter equal to the transmission rate when modulation scheme $m \in M$ is used with spectrum width equal to $h \in \{50, 100\}$GHz.
$f_{p,w,m}$	Boolean parameter that that is equal to 1 if a lightpath with modulation scheme $m \in M$ is feasible on a given path $p \in P$ and wavelength $w \in W_{\text{C}} \cup W_{\text{L}}$.
$D_{p,w,m}$	Integer parameter that shows the number of times a lightpath with modulation scheme $m \in M$ and wavelength $w \in W_{\text{C}} \cup W_{\text{L}}$ needs to be regenerated on a given path $p \in P$.(If $D_{p,w,m} = 0$ then the lightpath is infeasible, else if $D_{p,w,m} = 1$ then a transparent connection is possible, else if $D_{p,w,m} > 1$ it includes the number of regeneration points)
$L_{p,i,j}$	Boolean parameter that is equal to 1 if path $p \in P$ traverses link $(i, j) \in E$.
Variables	
$X_{p,w,m,h}$	Boolean variable that is equal to 1 if path $p \in P$ is utilized by a lightpath with wavelength $w \in W_{\text{C}}$, modulation scheme $m \in M$ and spectrum width equal to $h \in \{50, 100\}$GHz.
$Y_{p,w,m,h}$	Boolean variable that is equal to 1 if path $p \in P$ is utilized by a lightpath with wavelength $w \in W_{\text{L}}$, modulation scheme $m \in M$ and spectrum width equal to $h \in \{50, 100\}$GHz.

Objective
Minimize:

$$\sum_{p}^{P}\sum_{w}^{W_C}\sum_{m}^{M}\sum_{h\in\{50,100\}} 2\cdot X_{p,w,m,h}\cdot D_{p,w,m} +$$

$$+\sum_{p}^{P}\sum_{w}^{W_L}\sum_{m}^{M}\sum_{h\in\{50,100\}} 2\cdot Y_{p,w,m,h}\cdot D_{p,w,m} \quad (7)$$

Constraints
Requested bandwidth constraint:

$$\sum_{p}^{P_{s,d}}\sum_{w}^{W_C}\sum_{m}^{M}\sum_{h\in\{50,100\}} X_{p,w,m,h}\cdot f_{p,w,m}\cdot R_{m,h} +$$

$$+\sum_{p}^{P_{s,d}}\sum_{w}^{W_L}\sum_{m}^{M}\sum_{h\in\{50,100\}} Y_{p,w,m,h}\cdot f_{p,w,m}\cdot R_{m,h} \geq \Lambda_{s,d} \quad (8)$$

for every source and destination node pair (s, d), where $s, d \in V$ ($s \neq d$).
Wavelength continuity and non-overlapping constraints:

$$\sum_{p}^{P}\sum_{m}^{M}\sum_{h\in\{50,100\}} X_{p,w,m,h}\cdot f_{p,w,m}\cdot l_{p,i,j} +$$

$$+\sum_{p}^{P}\sum_{m}^{M} X_{p,w-1,m,100}\cdot f_{p,w,m}\cdot l_{p,i,j} \leq 1 \quad (9)$$

for every wavelength $w \in W_C$ and every link $(i, j) \in E$.

$$\sum_{p}^{P}\sum_{m}^{M}\sum_{h\in\{50,100\}} Y_{p,w,m,h}\cdot f_{p,w,m}\cdot l_{p,i,j} +$$

$$+\sum_{p}^{P}\sum_{m}^{M} Y_{p,w-1,m,100}\cdot f_{p,w,m}\cdot l_{p,i,j} \leq 1 \quad (10)$$

for every wavelength $w \in W_L$ and every link $(i, j) \in E$.
The objective function (7) is equal to the total number of transponders deployed in the C+L bands. Each variable is multiplied by two because it is assumed that the bandwidth demands are symmetrical and served through bidirectional fiber links. Constraint (8) ensures that all bandwidth requests are served whereas constraints (9) and (10) forbid the assignment of a wavelength in a link to more than one lightpath.

III. SIMULATION AND RESULTS

A. Case Study

The examined topologies are the NSFNET with 14 nodes and 21 links, and the JPN-12 with 12 nodes and 17 links which are depicted in figures 1 and 2. In both topologies, a list of three shortest paths for every pair of nodes is pre-computed and given as the set P in the ILP model. In addition, every fiber link is assumed to have the capacity of 80 and 120 wavelengths of 50GHz spectrum width in the C and L band respectively. The traffic load that was simulated on each topology is distributed according to actual population estimates [18]. Regarding the power consumption of BVTs, it is assumed to be in the form [18]:

$$P_{\mathrm{BVT}} = P_{\mathrm{D}} + \alpha\cdot TR \quad (11)$$

where P_{D} is the static power consumption and TR the transmission rate. The values of P_{D} and α are set as 180 and 0.75 respectively so that the calculated power consumption approximates the values presented in [19]. The total power consumption of one EDFA is set as 30 W [20]. For Raman amplification, 5 Raman pumps are assumed to be optimally tuned to achieve a flat gain across the C+L spectrum [14] where the power consumption of each pump's semiconductor laser is assumed to be 10 W [15]. Additional parameters that were used for the OSNR estimation are listed in Table 2.

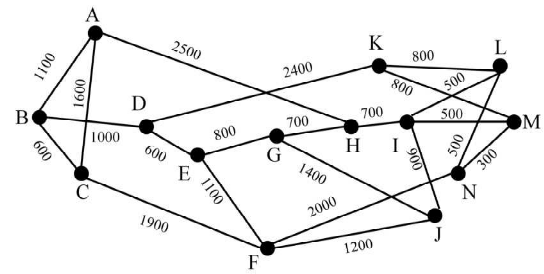

Fig. 1 NSFNET topology with the length of each fiber link given in km.

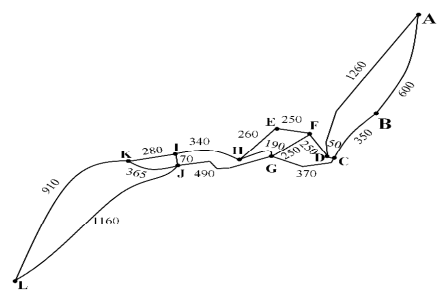

Fig. 2 JPN-12 topology with the length of each fiber link given in km.

TABLE 2 SIMULATION PARAMETERS

Fiber attenuation for both C and L bands	0.2 dB/km
Dispersion	17 ps/nm/km
Dispersion slope	0.067 ps/nm^2/km
Nonlinear parameter	1.2 W/km
Total channels in C band	80
Central frequency in C band	193.89 THz
Total channels in L band	120
Central frequency in L band	188.16 THz
Channel spacing	50GHz
Raman gain	0.4 /W/km
Symbol rate	32 GBd
Launch power	0 dbm
Fiber span length	80 km
Gain of EDFAs	20 dB
n_{sp} for C band	1.25
n_{sp} for L band	2
On-off gain of Raman amplifiers	10 dB
Gain of HR-EDFA	20 dB
DP-BPSK OSNR threshold	9 dB
DP-QPSK OSNR threshold	12 dB
DP-8QAM OSNR threshold	16 dB
DP-16QAM OSNR threshold	18 dB

B. *Numerical Resutls*

The numerical results were obtained through CPLEX 12.7 on a server with two 8-core CPUs and 32 GB of RAM. Computational times ranged from several minutes to one hour and peaked whenever the traffic load was close to the network's capacity. Results that are depicted in Figures 3 and 4 show an advantage of the network with HR-EDFAs in terms of transponders that are required for transmission as well as regeneration. The reduced noise figure has as a result the increased transmission reach of each modulation scheme which leads to less regeneration along the path and eventually a reduced number of transponders. The difference becomes more prominent as the traffic load increases and for the highest traffic load it is shown that the deployment of HR-EDFAs can boost the network's throughput, since the ILP solver could not return a feasible solution for the conventional EDFA-only network. On average, the number of transponders was 25% less for the NSFNET topology when HR-EDFAs were deployed and 14% for the JPN-12. Results for the total power consumption depicted in Figures 5 and 6 demonstrate again the benefit of HR-EDFAs. Despite the higher power usage of the Raman laser pumps, which corresponds to additional 28.8 kW and 9.4 kW for the NSFNET and JPN-12 topology respectively, the HR-EDFA network is proven to be more energy efficient since a transponder is quite more demanding in power consumption than an optical amplifier. In the case of NSFNET topology the power consumption dropped by 23% on average compared to the EDFA-only architecture, whereas in JPN-12 topology the average drop was 12%.

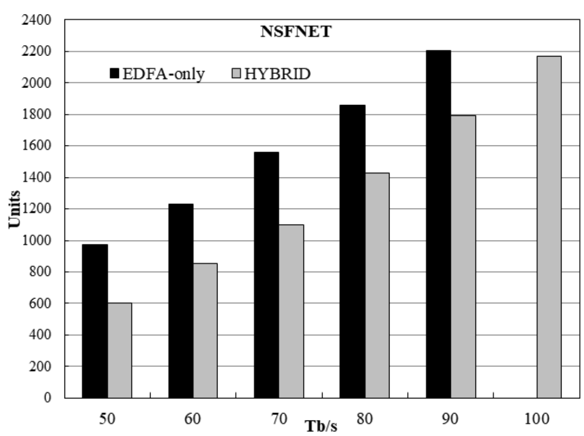

Fig. 3 Total number of required transponders for NSFNET.

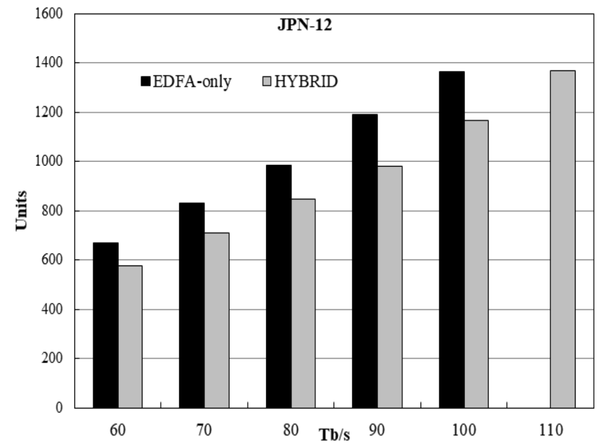

Fig. 4 Total number of required transponders for JPN-12

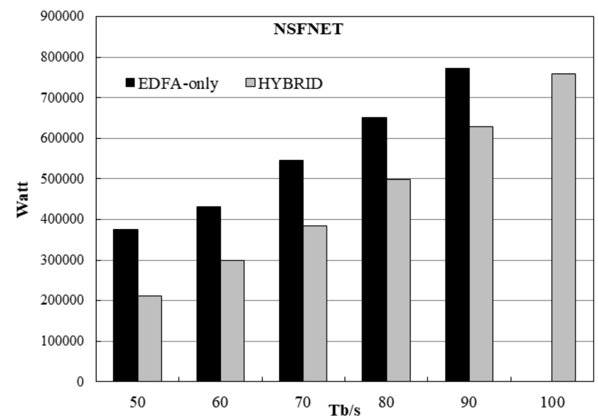

Fig. 5 Total power consumption for NSFNET.

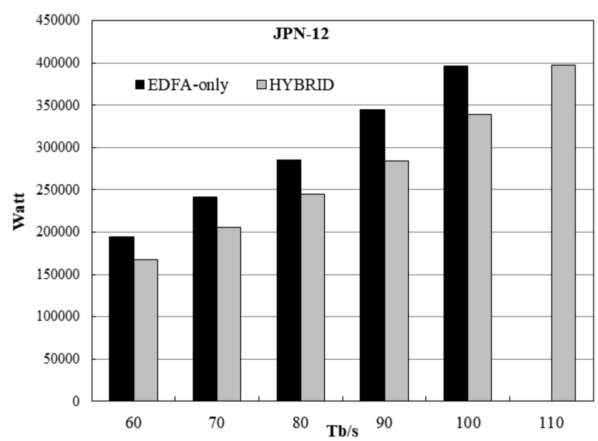

Fig. 6 Total power consumption for JPN-12.

IV. CONCLUSION

This paper investigated the impact of HR-EDFAs in the cost and energy efficiency of a wideband C+L optical network. A comparison was conducted with an EDFA-only network in terms of required transponders and power consumption. The numerical evaluation was based on strict OSNR estimation that considered the inter-band SRS as well as the different noise figure of EDFAs and HR-EDFAs. Then, the estimated OSNR values were used as input in an ILP formulation to obtain the optimal value. Results showed a clear advantage of the network with hybrid amplification in both comparison criteria. This work can be further extended in the future by examining more bands as well as more amplification schemes.

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