Amplifier Considerations in ROADM–free Space–Switched Nonlinear Optical Links

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Abstract: Power fluctuations accumulate in ROADM–free space–switched networks. Thousands of randomized nonlinear transmissions demonstrate that capacity with an inventory of {5,10,15,20} dB gain amplifiers is within 10 % of optimal and triple that with {10,20} dB amplifiers over 1,000 km. © 2020 The Authors

1. Introduction

To cope with exponential traffic growth, operators must increase capacity between major nodes. This paper considers a space division multiplexing (SDM) approach that utilizes existing C–band technologies over many fiber pairs and switches entire fiber cores rather than wavelengths. This removes reconfigurable optical add–drop multiplexers (ROADMs) from the transmission chain effectively turning the network into many point–to–point links and reduces opportunities for power equalization. This can result in significant variation between the power received by different channels. Recent investigations [1,2] show the importance of modelling erbium–doped fiber amplifiers (EDFAs) in submarine and wavelength routed networks, respectively. Both achieve periodic power equalisation in subsea by fabricating custom gain flattening filters (GFFs) every 5–10 amplifiers and terresrial by ROADMs. We consider ROADM–free terrestrial networks with non–uniform span lengths necessitating variable launch power within a link. When done naïvely, gain adjustments cause significant tilt across the C–band due to the underlying physics of erbium–doped fiber [3]. Incorrigible traffic growth requires installed fibers to be maximally utilised meaning reduced system margins and necessitating investigation into EDFA requirements. This paper considers three possible EDFA procurement strategies, shown in Fig. 1, which operators could consider. Option a) implies that operators buy an amplifier with a design gain close to that required by each span; the exact gain is achieved by varying EDFA pump power, inducing tilt. The smaller the inventory of amplifiers, the larger the worst–case tilt. Option b) uses an expensive dual–stage EDFAs which sandwich a variable optical attenuator (VOA) between pre– and power–amp stages to produce a flat output at any gain. Option c) uses the same fixed gain amplifier for every span adjusting the launch power with a VOA.

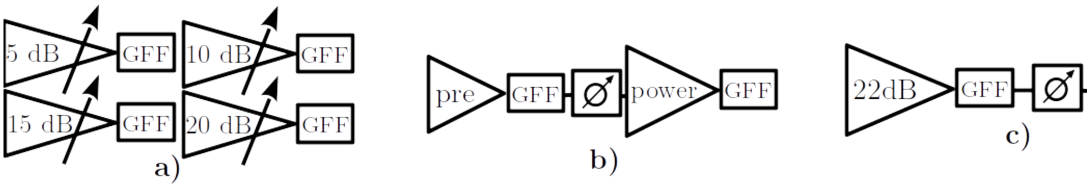

Fig. 1. Possible EDFA procurement strategies, a) a large inventory of EDFAs with different design gains; b) a dual–stage, actively flattened amplifier; c) a fixed gain amplifier with a variable attenuator on the output.

In Table 1 we summarise some properties of the various approaches. Operators must choose between large inventories of amplifiers with different design gains and the accumulated ripple of identical GFFs in addition to balancing unit cost, gain tilt, and the ability to launch optimal power.

Table 1. EDFA Deployment Options: 1) Each span has an EDFA specific to the gain required; 2) a dual–stage EDFA with a VOA; 3) a fixed gain EDFA with an Output VOA to avoid saturation

	Option a)	Option b)	Option c)
Inventory Complexity	High	Low	Low
Single Unit Cost	Low	High	Low
Tilt at non–design gain	Yes	No	No
Output Power Limited	No	No	Yes
Ripple for different gains	Indepedent	Identical	Identical

2. The Model

In deployed topologies, spans vary significantly in both their length and the age of the fiber. We therefore randomly sample both span length and fiber attenuation to mimic links in real networks. We then model the noise along these links with the linear contributions based on [3] and the nonlinear from [4].

2.1. Spans and their fiber

We sample span lengths discretely from 10 to 100 km, uniformly in steps of 10 km. We accept this distribution is not truly representative however it is a useful standin as the true distribution is unknown.

We assume all fiber is standard single mode but installed over many years from different manufacturers. Fibre was sampled using Eq. (1) where λ_{Ral}, λ_{IR}, and α_{IR} were normally distributed with means 980, 1779, 52500 nm, respectively, and standard deviations 10, 10, and 100 nm, respectively. Loss from OH^- ions was assumed to be highly skewed, generated using the pearsrnd(·) method in Matlab, that gave insignificant (∼0.01 dB/km) values for α_{OH} for most fibers with a 0.3 % chance of a peak above 0.1 dB/km.

$$\alpha_{dB}(\lambda) = \left(\frac{\lambda_{Ral}}{\lambda}\right)^4 + \alpha_{OH} \cdot \left(1 + \frac{(\lambda - \lambda_{OH})^2}{\Delta\lambda_{OH}^2}\right)^{-1} + \exp\left(\alpha_{IR} \cdot \left(\frac{1}{\lambda_{IR}} - \frac{1}{\lambda}\right)\right) \tag{1}$$

All fibers where within G652D specifications [5] meaning especially large water peaks where unlikely to pass the 0.4 dB/km maximum loss from all sources at 1383 nm. We show the minimum fiber loss distribution in the left plot of Fig. 2 where the overall distribution is fairly Gaussian with a slight positive skew due to the water peak. Dispersion is identical for all fibres with D(1550nm) = 16.1 ps/(nm.km) and S_0 = 0.086 ps/(nm^2.km). Combined with discrete span lengths this provides a somewhat peaky span loss but the required gain is much more flat. This is because the next span length is also random and is likely to have a different optimal launch power.

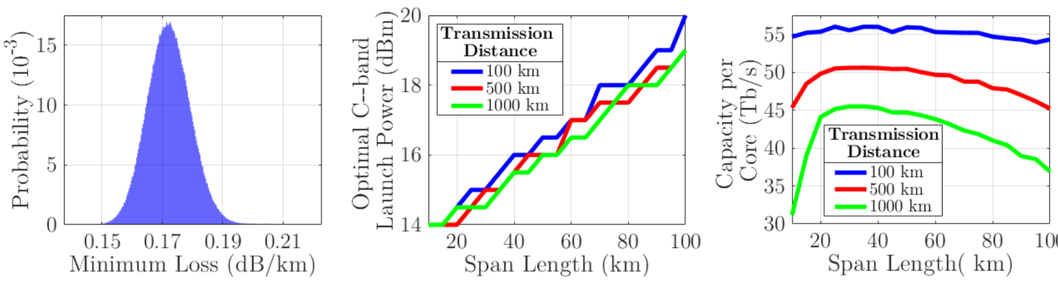

Fig. 2. left) Distribution of minimum fiber loss; centre) Optimum Launch Power for different span lengths and transmission distances; right) C–band capacity for different span lengths and transmission distances.

2.2. Transmission Simulations

EDFA gain profiles were calculated using eq. (2.125) of [3] with the noise figure calculated from eq. (2.120) using cross–sections from [6]. The 980 nm pump absorption assumed to be 5 dB/m. EDFAs of different design gains were chosen to minimise the total power output given flat power spectral density input. When operating at gains away from their design gains, we guarantee the total input power increases by the user–specified gain, post–GFF. Ripple was generated as per [7] with a sine wave with 2 THz wavelength that provided slowly varying imperfections to an otherwise perfect GFF. The phase of this sine wave was randomly generated for each link and design gain. We assume VOAs are flat across the C–band.

Nonlinear interference (NLI) was calculated using a closed form approximation of the GN model from [4] without the EGN correction terms. This underestimates GSNR by 0.5–1 dB due to the pessimistic nature of the standard GN model. We feel this provides a reasonable cushion on top of which any system margin can be added.

We assume transceiver technology beyond that currently available with a symbol rate of 125 GBd with a 137.5 GHz spacing. This enables 32 channels within 4.4 THz total whilst respecting the ITU-T grid. We assume probablistic constellation shaping with a fixed 20 % forward error correction and 1 bit in 25 is overhead. Based on [8] we assume a 1.75 dB gap to Shannon capacity although we extrapolate across all SNRs for simplicity.

The central plot of Fig. 2 shows optimal launch powers for links of 100, 500, and 1,000 km with fixed span lengths. The fiber core capacity is shown in the right plot of Fig. 2. This assumes 22.5 dB SNR back–to–back, and EDFAs which are flat every 1 dB with no ripple.

3. Results

We generated links for 100 to 1,200 km transmission distances, with span lengths sampled uniform randomly from 10 to 100 km in steps of 10 km. Fibre parameters for each span were sampled in the manner described above. We consider 5,000 links for each distance with different EDFA procurement solutions. Opt. a) is represented with 3 different inventory sizes of single–stage amplifiers of: {1,2,...,21,22} dB gains, {5,10,15,20} dB gains, and simply {10,20} dB gains. Opt. b) uses a dual–stage amplifier with 10 and 12 dB gains for pre and power stages, respectively. Opt. c) uses a 22 dB gain amplifier. All EDFAs had a maximum output power of 20 dBm. This was repeated for peak–to–peak ripple of 0 to 1.5 dB in steps of 0.25 dB. Launch powers into each span were adjusted to the average of those shown in Fig. 2:centre where possible and 1 dBm higher than that with dual–stage EDFAs given the higher ASE. The tilt of the variable gain amplifiers is expected to uniformly distributed and hence should have standard deviations of 0.29, 1.44, and 2.89 for the 3 options listed above. The actual results were 0.29, 1.47, and 2.96, showing good agreement. We show our results in Fig. 3. The left plot shows the 99$^{\text{th}}$ of

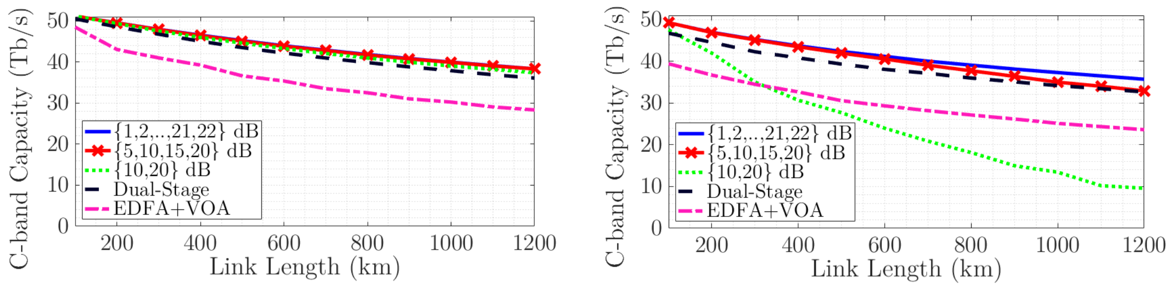

Fig. 3. left) The 99$^{\text{th}}$ percentile and right) the 1$^{\text{st}}$ percentile of capacity with the various EDFA solutions with 0.5 dB pk–pk ripple. We see that accumulated tilt from a limited EDFA inventory results in severe performance degredation in the worst cases.

capacity achieved in the 5,000 random links generated for each link length and EDFA procurement option, whilst the right shows the 1$^{\text{st}}$ percentile of the same data. We see that in a near–optimal sequence of span lengths, there is very little difference between the different solutions, with the exception of the compromised launch power of the EDFA+VOA design. This is because EDFAs with specific design gains can provide flat gain when a series of spans require exactly that amount of gain. This contrasts with the case when the spans require gains that are maximally far away from the design gain of the amplifiers. This can result in accumulated tilt and a significant performance penalty when this tilt is large, as seen in the right plot with just 2 variable gain amplifiers. When the gain is close to the design gain, of 10 or 20 dB, performance is equivalent to any other solution however the tilt from a 5 dB difference between required gain and design gain can result in performance below that of even the EDFA+VOA option beyond 400 km. The best option, as expected, is to have a large inventory of EDFAs and choosing the best one, to within 0.5 dB, of the requirements for a given span. A more reasonble inventory size of 4 amplifiers results in a worse case 2.5 dB difference to the desired gain and we can see performs within 10 % of an impractical EDFA inventory numbering nearly 20 different models. A dual–stage solution performs middlingly due to higher ASE. Over longer distances and large accumulated ripple, this results in significant performance degredation, even approaching that the launch power comprimised Opt. c.

4. Conclusion

We have shown the effect of different EDFA procurement solutions for space–switched networks which allow power variations to accumulate due to the lack of ROADMs. A reasonable inventory size of just 4 amplifiers achieves capacities close to that possible with an unwieldy number of different amplifier designs. An inventory of just 2 variable gain amplifiers significantly degrades fiber capacity due to large gain tilts in the worst case. Other solutions — expensive dual–stage EDFAs with high noise floors and output power compromised EDFA plus VOA designs — performed worse than a 4 EDFA inventory but better than a 2 EDFA inventory on longer links.

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