Pump-Constrained Capacity Maximization: to Flatten or not to Flatten?

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Abstract *We show by simulation that, for power-efficient achievable information rate maximization, properly-operated links with gain-flattening filters (GFF) are superior to links without GFFs.*

Introduction

The recent advent of rate-adaptive, capacity-approaching transceivers for power-constrained submarine systems has renewed the interest in revisiting the design of the line erbium-doped fiber amplifiers (EDFA). In this context, there were reports based on machine-learning where better power efficiency (i.e., capacity at EDFA fixed pump power) was achieved by removing (or partially removing) the usual gain flattening filters (GFF)[1,2]. Those studies were timely, in line with recent concerns about the optimization of power constrained subsea systems, but unfortunately they only gave a limited view of the picture. In this paper we wish to add to the debate, by exploring the settings where the unfiltered system is more power efficient than the system with GFFs. We show that, if the launch power is optimized such that the line EDFAs work close to their optimal inversion[3,4], then the GFF system is always more power efficient than the unfiltered one.

System model

Fig. 1 sketches the studied link model. It consists of M single-mode fiber spans with span attenuation $A > 1$ followed by a single-stage EDFA. All EDFAs have the same physical characteristics and same optical pump power P_p. As in[1], we consider a transmitted (TX) WDM signal composed of N_c =40 channels with bandwidth B_c=50GHz, spaced by 100GHz, with carrier wavelengths from 1532.64 to 1563.80 nm, covering a total 4THz bandwidth. Each EDFA is possibly followed by a GFF that chops off all the gain in excess of A. This requires a different GFF at each EDFA, differently from[1]. As in[3,4], the EDFA is simulated by the homogeneously-broadened Saleh gain model[5] with amplified spontaneous emission (ASE) noise self-saturation[6], i.e., forward and backward ASE generated inside each EDFA over a broad bandwidth from 1470 to 1670 nm is considered for calculating each EDFA inversion. Then only the WDM signal range is propagated down the line. Having in mind transmission in a *deeply linear* space division multiplexed submarine link[1,7], of which our single-mode link represents one spatial mode, we assume that only ASE impairs transmission, so that for a given input WDM power distribution $[P_1, ..., P_{N_c}]$ the achievable information rate (AIR) is

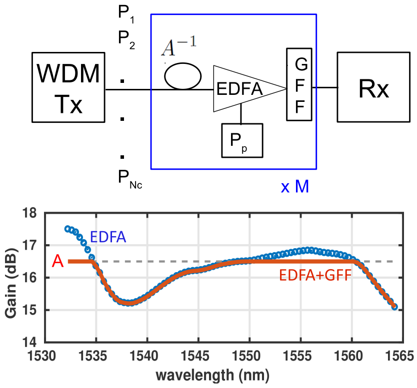

Fig. 1: (Top) Single-mode WDM link with $N_c = 40$ channels and M spans, span attenuation A and identical single-stage EDFAs with optical pump power P_p, with or without GFF. (Bottom) Sketch of a typical EDFA unfiltered gain at channel locations (circles), and gain after GFF (solid line). Dashed horizontal line at level A.

$$AIR = 2B_c \sum_{j=1}^{N_c} \log_2(1 + SNR_j) \tag{1}$$

where SNR_j is the received (RX) signal to noise ratio (SNR) at channel j. For some selected values of the EDFAs common pump, we wish to compare the AIR of this link without and with GFFs as we vary the inversion x_1 of the first EDFA, which induces that of the remaining line EDFAs[3,4]. For the purpose of AIR comparisons, we assume a Constant Input Power (CIP) distribution, where all 40 WDM channels have the same power P_c. It was shown in[3,4] that for GFF links

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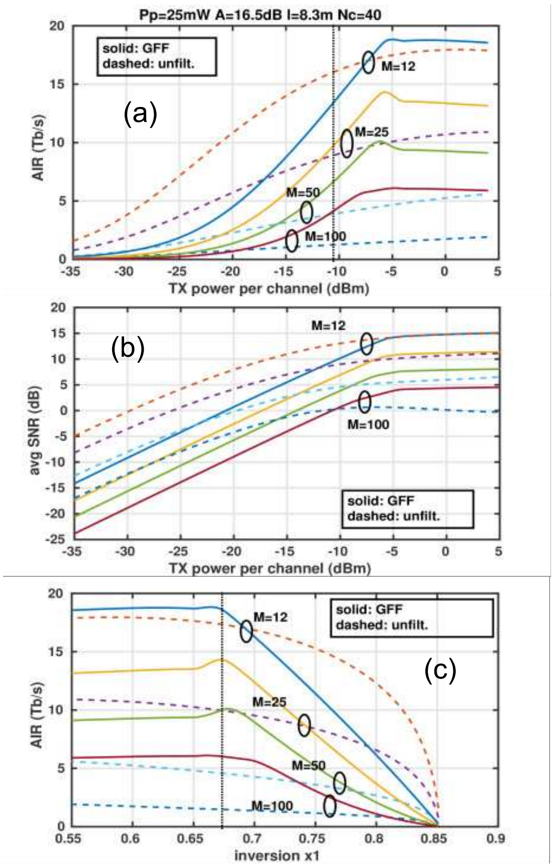

Fig. 2: **(a)** AIR (Tb/s) versus TX power per channel P_c (dBm), **(b)** average RX SNR (dB) vs. P_c, for a link of M spans, **(c)** AIR versus EDFA-1 inversion x_1, for both the GFF link (solid) and the unfiltered link (dashed). Data: pump power $P_p = 25$mW, span loss $A = 16.5$dB, doped fiber length $\ell = 8.3$m, 40 WDM equal-power input channels as in[1].

the CIP allocation (around the optimal EDFAs inversion) has AIR close to Capacity, i.e., the AIR maximum over all possible input WDM distributions subject to the constraint on x_1.

Results

We analyze a link similar to the one in[1] , with span attenuation $A = 16.5$dB. The 980nm co-pumped single-stage EDFAs we use have the same absorption and emission profiles as in [7, Fig. 7]. In order to reasonably match the WDM power values after $M = 12$ spans in the unfiltered chain in [1, Fig. 4b] with CIP input WDM total power 5dBm ($P_c = -11$dBm) into the first EDFA, we selected an EDFA length $\ell = 8.3$m, with optical pump levels $P_p = [25, 80, 170]$ mW roughly corresponding to the $[75, 150, 450]$mA reference currents in[1].

Fig. 2 shows: (a) the AIR versus TX power per channel P_c, (b) the average RX SNR, (c) the AIR vs. inversion x_1 of the first EDFA, at various number of spans M for both the GFF link (solid) and the unfiltered link (dashed). The average EDFA noise figure (not shown) increases for the GFF case from around 4dB to about 5dB as we move from low to high powers, while in the unfiltered case the average noise figure was always around 5dB.

We see from Fig. 2(a) that at all distances M the unfiltered link has larger AIR than the GFF link at all powers $0 \leq P_c \leq P_c^*$ up to a cross-point P_c^* above which the GFF link is superior. The reason is that in the GFF case at low powers the WDM signal weakly saturates the EDFAs, which have an almost signal-independent maximum gain and a minimum noise figure. That is the regime where GFFs uselessly "waste power in the over-performing channels"[8], so that the unfiltered case has larger AIR. Note that in the unfiltered link, even at low launched powers, right after the first EDFA power abruptly grows and saturates the downstream EDFAs, whence the slightly larger noise figure.

As power grows, in the unfiltered chain the channels with the largest EDFA gains grow faster than the others down the chain and mostly contribute to saturating the downstream EDFAs, driving their inversions towards a value such that the largest-gain channel has gain equal to the span attenuation, and all remaining channels have gain $\leq A$ and quickly fade away as we increase M.

Fig. 2(b) gives indirect evidence of this fact: it shows the WDM-averaged SNR versus power P_c for both the unfiltered and the GFF links. We see that for a link of $M = 12$ spans the average SNR of the unfiltered link dominates that of the GFF link, even at the largest powers, where AIR is instead larger for the GFF link. The reason is that the unfiltered link has a few channels with a "significant SNR", while the GFF link keeps most input channels at a significant SNR at all input powers. In fact, the AIR in eq. (1) is seen to linearly increase with the number of significant-SNR channels, while the SNR gives only a logarithmic increase. From Fig. 2(a) we also note that at $M = 12$ spans, $P_c = -11$dBm and $P_p =$25mW (akin to the 75mA pump current in[1] resulting in 1W of line electric pump power) the GFF link has $AIR \cong 14$ Tb/s, while the unfiltered link has a larger $AIR \cong 16$ Tb/s, as in [1, Fig. 16]. However, if power per channel is increased to the GFF-optimal value $P_c = -6$dBm, then the GFF link is markedly superior to the unfiltered line, and the AIR gap with the unfiltered link grows larger and larger as we increase the spans M. In fact the unfiltered link AIR decreases much faster than the GFF link AIR as M grows, since the number of

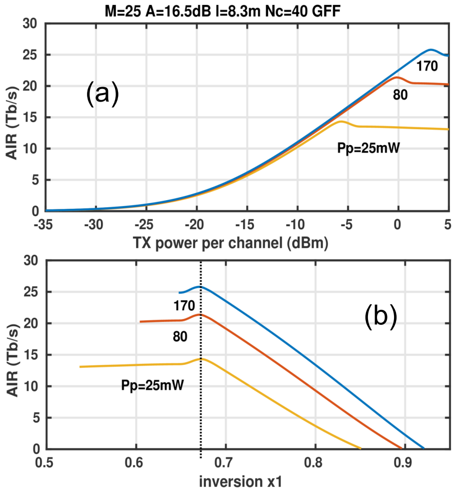

Fig. 3: (a) AIR vs. P_c and (b) AIR vs. EDFA-1 inversion x_1, for a GFF link of $M = 25$ spans, span loss $A = 16.5$dB, doped fiber length $\ell = 8.3$m, 40 WDM channels, at pump powers $P_p = [25, 80, 170]$mW.

channels with a significant SNR decreases way faster in the unfiltered link. This tells us that for very long links (like typical submarine links) the only way of preserving the RX WDM bandwidth is that of using GFFs.

Fig. 2(c) provides an alternative and equivalent way of portraying the AIR evolution with power. The figure shows AIR versus the inversion of the first EDFA x_1. For a given pump P_p, there is a 1-1 correspondence between x_1 and the input power P_c, as per Saleh equilibrium equation[3,4]. We see for instance that the maximum AIR for the GFF link occurs at an optimal inversion around $x_1^* \cong 0.68$ ($P_c = -6$dBm) which very slowly increases with increasing distance M. However, the shape of the AIR vs. x_1 curve, once normalized to its maximum, is weakly dependent on the pump power[3,4]. This is confirmed by Fig. 3, which shows both (a) AIR vs. P_c and (b) AIR vs. x_1 for a 25-span GFF link at the three reference pump powers $P_p = [25, 80, 170]$mW. We note that the optimal inversion is at $x_1^* \cong 0.68$ at all pumps. Note also that Fig. 3(a) resembles the shape of the Shannon capacity with nonlinearity, although here the AIR behavior is related to the EDFAs saturation at increasing power (nonlinearity will be present and significant at the shown AIR peaks in the 80 and 170mW pump cases, so these are upper-bounds to real performance). The coincidence of the three AIR vs P_c curves at low powers indicates the presence of a signal-independent noise figure, i.e., the GFF link has EDFAs working in their small-signal regime, up to a little before the AIR maximum. The AIR decrease after the maximum is due to the sharp power fading of channels with a link-average gain below the attenuation A, as will be better appreciated next. Fig. 4 shows the gain profiles versus wavelength of EDFA 1 and 50, and the link-average EDFA gain profile (AVG EDFA) for a GFF link at two operating points: the max-AIR one at $P_c = -6$dBm ($x_1 \cong 0.68$), dashed curves, and a suboptimal one at $P_c = -11$dBm ($x_1 \cong 0.73$). We see that the optimal inversion corresponds to a link-averaged EDFA gain profile which lays above the attenuation A at almost all WDM channels, with $G \cong A$ at the "gain dip" at 1538nm, with a minimum gain spread among the link EDFA profiles. This is a feature that we always find at the optimal inversion in GFF links with constant-pump EDFAs[4]. At powers beyond the one at the maximum, the dip at 1538nm sinks below A (Cfr. Fig. 1) and more and more signals in that spectral region, as well as the channels at wavelengths above 1563nm, have powers that fade more and more as the spans M increase.

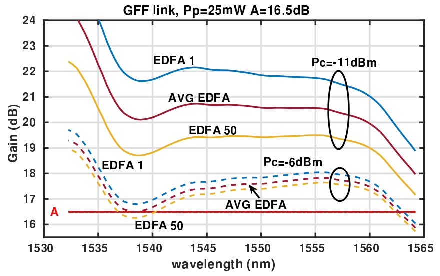

Fig. 4: EDFA Gain (dB) vs. wavelength (nm) at EDFA 1, EDFA 50, and span-averaged EDFA gain in a GFF link with $P_p = 25$mW, $A = 16.5$dB, doped fiber length $\ell = 8.3$m, at power $P_c = -11$dBm ($x_1 \cong 0.73$) (solid) and $P_c = -6$dBm ($x_1 \cong 0.68$) (dashed).

Conclusions

We showed by simulation that fixed-pump EDFA amplified links with GFFs have larger AIR than unfiltered links if operated at sufficiently large power. We proved that the GFF link has an optimum power-maximizing AIR, corresponding to an inversion such that the gain variations of EDFAs along the line are minimal. We compared GFF and unfiltered links using the WDM allocation in[1], but the range of powers/inversions where the GFF link dominates the unfiltered link increases when we fill entirely the bandwidth and extend it to encompass also the 1530nm gain peak. The comparison is even more in favor of GFF links when we reduce the span loss to standard values for submarine systems around 9-10dBs. Finally, the comparison is presented for a power-flat WDM input signal, although the qualitative conclusions do not change if we use optimized input allocations.

Acknowledgments

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