Throughput Maximisation in Ultra-wideband Hybrid-amplified Links

Henrique Buglia,[1] Eric Sillekens,[1] Lidia Galdino,[2] Robert Killey[1] and Polina Bayvel[1]

[1] *Optical Networks Group, Dept. of Electronic & Electrical Engineering, University College London, U.K.*
[2] *Corning Optical Communications, Ewloe, U.K*

henrique.buglia.20@ucl.ac.uk

Abstract: A semi-analytical, real-time nonlinear-interference model including ASE noise in hybrid-amplified links is introduced. Combined with particle-swarm optimisation, the capacity of a hybrid-amplified 10.5-THz 117x57-km link was maximised, increasing throughput by 12% versus an EDFAs-only configuration.

1. Introduction

To enable the exponential growth of data transmission required by new internet services, ultra-wideband (UWB) transmission technologies have been widely explored in optical fibre communication systems. Among these technologies, the use of hybrid-amplification schemes was almost universally applied in all the recent field trials achieving record throughputs over single-mode fibre (SMF), as shown in [1]. The increased throughput with hybrid amplification is due to the lower noise figure achievable with distributed Raman amplification in comparison to that possible using Erbium-doped fibre amplifiers (EDFA) alone. Distributed amplification also allows a reduction in the launch power and correspondingly - in the nonlinear interference (NLI) noise. To optimise this type of system, pump optimisation is required to find the best wavelength and power allocation to maximise the system throughput. To achieve this, real-time estimation of the nonlinear interference (NLI) noise in Raman-amplified links is required, enabled by recently-developed semi-analytical expressions of the Gaussian noise (GN) model in the presence of Raman amplification (RA) [2–5]. Together with this, the amplified spontaneous emission (ASE) noise generated by Raman amplifiers needs to be taken into account in this model to obtain a complete estimation of the total received signal-to-noise ratio (SNR).

In this paper, for the first time, we have included the ASE noise generated by Raman amplifiers in the model [2–4]. This new step allowed the design of a capacity-achieving backward-pumped hybrid amplifier. Using particle swarm optimisation (PSO) algorithm to optimise the total launch power, pump powers and pump wavelengths resulted in a maximum system throughput within a 10.5 THz transmission bandwidth, corresponding to the utilisation of the C- and L-band, where backward Raman pumps are placed in the S-band. The results are finally compared with the same system optimised to operate with EDFAs alone. This work represents the first complete (ASE + NLI) semi-analytical model which allows the calculation of the received SNR & throughput in real time for any UWB Raman-amplified link setup.

2. The GN Model in the Presence of RA and the Raman ASE Noise Generation

For an ideal transceiver, the SNR for the i-th channel at the end of the span, after amplification, can be estimated as $\text{SNR}_i^{-1} \approx \text{SNR}_{\text{NLI},i}^{-1} + \text{SNR}_{\text{ASE},i}^{-1}$, where $\text{SNR}_{\text{NLI},i}$, $\text{SNR}_{\text{ASE},i}$ originate from fibre nonlinearity and amplifier noise, respectively. In this work, ideal amplification was assumed, so that the transmitted power is fully recovered at the receiver. For Raman amplifiers, the evolution of the channel of interest (COI) power along the fibre distance ($P_i(z)$) is coupled with the ASE noise, generated by the remaining channels and the pumps, and is written as

$$\begin{aligned}\pm\frac{\partial P_i}{\partial z} = &-\sum_{k=i+1}^{\text{N}_{\text{ch}}} \frac{f_k}{f_i} g(|\Delta f|)(P_k + P_{\text{ASE},k})P_i - \sum_{p:f_i>f_p} \frac{f_p}{f_i} g(|\Delta f|)(P_p + P_{ASE,p})P_i + \\ &\sum_{k=1}^{i-1} g(|\Delta f|)(P_k + P_{\text{ASE},k})P_i + \sum_{p:f_i<f_p} g(|\Delta f|)(P_p + P_{\text{ASE},p})P_i - \alpha_i P_i,\end{aligned} \tag{1}$$

where, P_i, f_i are the power and frequency of the COI, P_k, f_k are the power and frequency of the remaining WDM channels, P_p, f_p are the power and the frequency of the pumps, $g_r(|\Delta f|)$ is the polarisation averaged, normalized (by the effective core area A_{eff}) Raman gain spectrum for a frequency separation $|\Delta f| = |f_i - f_j|$, $j = k, p$ and α_i is the frequency-dependent attenuation coefficient. The symbol $\pm$ represents the pump under consideration, i.e., $+$ for forward pump and $-$ for backward pump configurations. $P_{\text{ASE},i}$, $P_{\text{ASE},k}$ and $P_{\text{ASE},p}$ are the ASE noise respectively in the COI, channel k and pump p. The $\text{SNR}_{\text{NLI},i}$ is calculated in closed form using the model in [2,3], which is derived from the integral ISRS GN model [6], by using a suitable semi-analytical expression to express

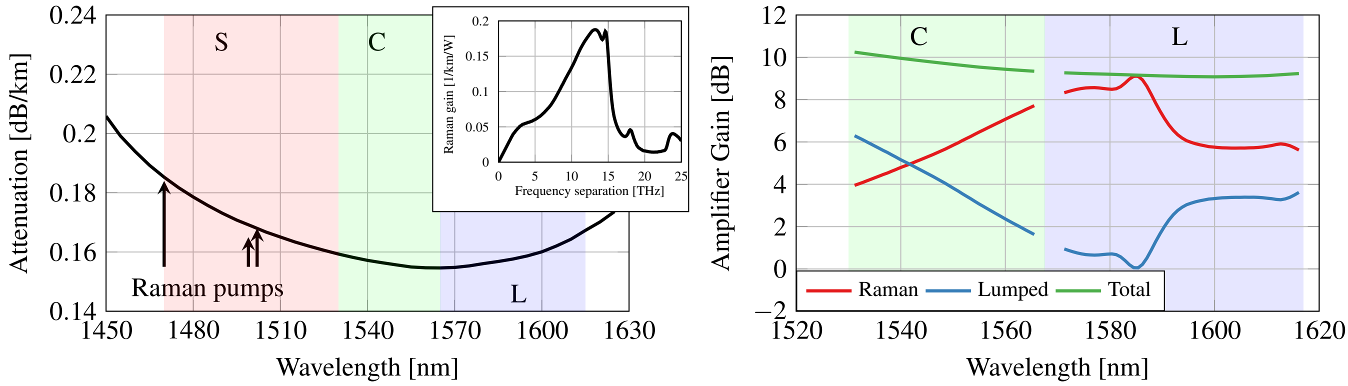

Fig. 1. (a) Fibre attenuation coefficient and Raman gain spectrum for the fibre used; and optimised pump wavelength allocation. (b) Optimised hybrid amplifier gain for backwards distributed Raman amplification stage (red) and ideal lumped (EDFA) stage (blue).

the normalised power profile evolution along the fibre distance, given by $\rho(z,f_i) = P_i(z)/P_i(0)$ (see Appendix A of [2]), where $P_i(z)$ is obtained from Eq (1). The ASE noise generated in channel i ($P_{\mathrm{ASE},i}$) is obtained as [7]

$$\frac{\partial P_{ASE,i}}{\partial z} = -\sum_{k=i+1}^{\mathrm{N_{ch}}} \frac{f_k}{f_i} g(|\Delta f|)(P_k + P_{ASE,k})(P_{ASE,i} + 2h\kappa B_i f_i) - \sum_{p:f_i>f_p} \frac{f_p}{f_i} g(|\Delta f|)(P_p + P_{ASE,p})(P_{ASE,i} + 2h\kappa B_i f_i) + \\ + \sum_{k=1}^{i-1} g(|\Delta f|)(P_k + P_{ASE,k})(P_{ASE,i} + 2h\kappa B_i f_i) + \sum_{p:f_i<f_p} g(|\Delta f|)(P_p + P_{ASE,p})(P_{ASE,i} + 2h\kappa B_i f_i) - \alpha_i P_{ASE,i}, \tag{2}$$

with $\kappa = 1+\eta = 1/(1-exp(-h\Delta f/k_B/T))$, where η is the phonon occupancy factor, h is the Planck constant, T is the temperature of the system and k_B is Boltzmann's constant. Note that Eq. (1) should be written for each channel k and pump p by replacing $i = p,k$, whereas Eq. (2) is written for each channel k by replacing $i = k$. Together, they represent a set of $2N_{ch} + N_p$ coupled differential equations describing the signal evolution and the ASE noise generation in Raman-amplified links. This equation is solved for each span, where the accumulated ASE noise at the end of each span is used as the initial condition for the following span. For hybrid-amplified links, the ASE generated by distributed Raman amplification, obtained from Eq. (2), is amplified by the ideal EDFA gain (G_i) placed at the end of the fibre. The total ASE noise is then given by $P''_{\mathrm{ASE},i} = G_i P_{\mathrm{ASE},i} + P'_{\mathrm{ASE},i}$, where $P'_{\mathrm{ASE},i} = 2(G_i-1)n_{sp}hf_iB_i$, with $n_{sp} \approx \mathrm{NF}/2$ the spontaneous emission factor and NF the EDFA noise figure. The per-channel SNR contribution from the total ASE noise is then calculated as $\mathrm{SNR}_{\mathrm{ASE},i} = P_i/P''_{\mathrm{ASE,i}}$.

3. Transmission Setup and System Optimisation

The transmission system is assumed to use a hybrid amplification technology, consisting of two stages: a backward-distributed Raman amplifier followed by an ideal EDFA. It was assumed to amplify a WDM signal with N_{ch}=105 Nyquist-spaced channels centred at 1571 nm, where each channel was modulated at the symbol rate of 100 GBd, with Gaussian symbols. This setup results in a total bandwidth of 10.5 THz, ranging from 1530 nm to 1615 nm, corresponding to the full utilisation of the C- and L- bands. Signal transmission was evaluated over 117 x 57 km (a total distance of 6669 km). The transmission optical fibre under consideration is assumed to have wavelength-dependent attenuation and the Raman gain profile compliant with Fig. 1.a, and an effective area of 150 μm^2, resulting in a nonlinear coefficient $\gamma = 0.55$ W^{-1}km^{-1}. Dispersion parameters considered are $D = 21$ ps nm^{-1}km^{-1}, $S = 0.067$ ps nm^{-2}km^{-1}. The NFs of the EDFAs were assumed to be 5 dB and 6 dB, for the C- and L- bands, respectively. For the distributed Raman amplification, pumps were placed in the S-band, as shown in Fig. 1.a, and their wavelengths and powers, as well as the total transmitted launch power are optimised to maximise the system throughput.

The optimised hybrid amplifier was designed, based on a PSO algorithm, where a spectrally uniform launch power profile and 6 backward pumps, limited to 500 mW each and placed in the S-band (1470 nm - 1520 nm) are considered. The total launch power and the pump wavelengths and powers are optimised to maximise the cost function $C = \sum_{i=1}^{N_{\mathrm{ch}}} 2\cdot\log_2(1+\mathrm{SNR}_i)$, such that the total throughput is maximised. The PSO algorithm has 7 variables to be optimised (6 pumps + total launch power). The number of particles was chosen to be 50 with a maximum of 50 iterations selected as the stopping criterion. For the algorithm bounds, we let the total channel launch power vary between 15 dBm and 25 dBm, and the power of each pump at the end of the fibre from 0 mW to 500 mW. The optimisation resulted in a total launch power of 20.4 dBm, corresponding to 0.49 dBm per

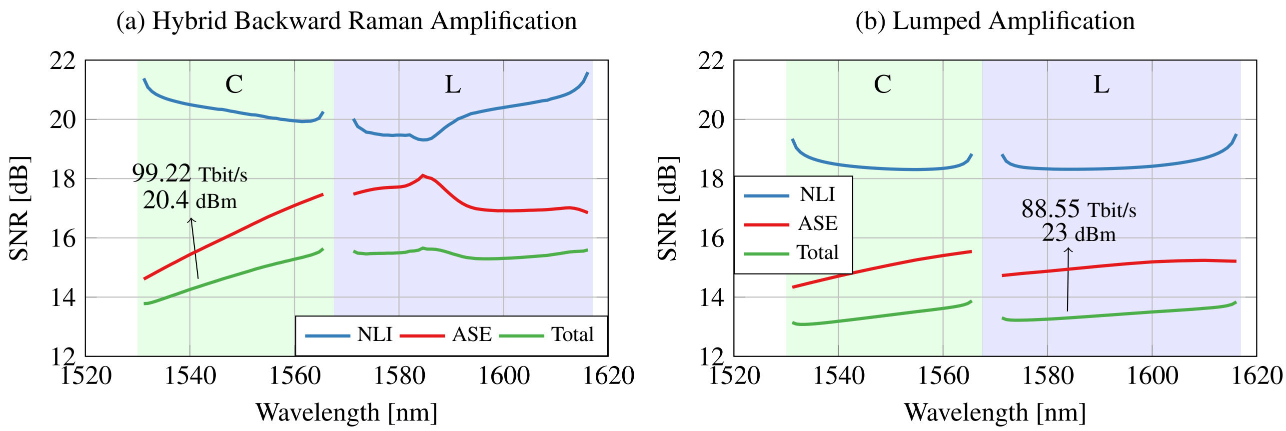

Fig. 2. Performance in terms of SNR for the system in Sec. 3 operating with an optimised (a) hybrid amplification and (b) full lumped amplification.

channel, and 3 pumps with non-negligible power, with wavelengths 1470 nm, 1499 nm and 1502 nm, and powers of 433 mW, 107 mW and 113 mW, respectively as shown in Fig. 1.a. The optimised hybrid amplifier gain is shown in Fig. 1.b where the lumped (EDFA) gain is assumed to be ideal to completely recover the transmitted power.

4. Throughput Maximisation Results

Fig 2.a shows the transmission system performance of the capacity-achieving hybrid amplifier in terms of SNR. Because the majority of Raman gain occurs at the shorter wavelengths of the L band (see Fig. 1.b), the NLI noise is worst in this region, due to the increased power levels propagating through the fibre, which reduces the SNR_{NLI}. On the other hand, the better ASE performance of Raman amplifiers when compared to EDFA reduces the ASE noise in this same region increasing the SNR_{ASE}; this is because for those channels almost all the fibre loss is compensated with RA, whereas in the remaining part of the spectrum, greater EDFA gain is required.

To compare the benefits of using hybrid amplification schemes, Fig 2.b show the performance results in terms of SNR for the same transmission system described in Sec. 3 using a fully lumped amplification scheme, i.e, without any distributed Raman pumps injected in the transmission fibre. The results are calculated using the model in [8] and the total launch power was also optimised to maximise the throughput, resulting in a value of 23 dBm, corresponding to 3.09 dBm per channel. The increased ASE noise values for this case when compared to the hybrid amplification case are a result of the lower performance of EDFAs in comparison to Raman amplifiers in terms of NF. In the case of NLI noise, despite pump powers also being injected into the transmission fibre for the hybrid amplification case, the increased channel launch powers optimising the system with lumped amplification make this case also worse in terms of NLI noise. Indeed, with optimised hybrid amplification, a total throughput of 99.22 Tbit/s was obtained with the total channel launch power of 20.4 dBm, while for the system with optimised lumped amplification, this value was 88.55 Tbit/s with 23 dBm total launch power.

5. Conclusions

The first semi-analytical, real-time nonlinear-interference model capable of predicting the performance of hybrid-amplified (EDFA + Raman) systems was developed. The key new step was the inclusion of the Raman ASE noise in this model. Enabled by this, the throughput of a 10.5-THz 6669-km link was maximised by using a particle-swarm optimisation (PSO) algorithm. A total throughput of 99.22 Tbit/s was achieved, corresponding to a 12 % increase when compared to the same system operating with EDFAs only.

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