Analysis of extended range variable gain hybrid Raman-EDFAs in systems using Nyquist-WDM 100/200G PM-QPSK/16QAM

W. Forysiak(1,3), D.S. Govan(2), I. McClean(2), B.K. Nayar(1), O.A. Olubodun(3), N.J. Doran(3) ,
1Oclaro Technology Ltd, Caswell, NN12 8EQ, UK
2Oclaro Technology Ltd, Paignton, TQ4 7AU, UK
3Aston Institute of Photonic Technologies, Aston University, UK
e-mail: wladek.forysiak@oclaro.com

Abstract

We use the GN-model to assess Nyquist-WDM 100/200Gbit/s PM-QPSK/16QAM signal reach on low loss, large core area fibre using extended range, variable gain hybrid Raman-EDFAs. 5000/1500km transmission is possible over a wide range of amplifier spans.

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1. Introduction

Digital coherent technology and soft-decision FEC have enabled the deployment of 100Gbit/s wavelengths in conventional EDFA-amplified WDM systems, for distances in excess of 1500km on existing G.652 fibre [1,2]. Recently, the first generation of flexible bit-rate transponders has been developed, supporting PM-BPSK, PM-QPSK, and PM-16-QAM, and capable of transporting 50/100/200Gbit/s per optical carrier [3,4]. In the near future, it is expected that 400Gbit/s and 1Tb/s transponders will become available, based on multi-carrier super-channels, with carrier spacing close to the baud-rate, and DAC-enabled Nyquist pulse-shaping [3-5].

To date, large increases in FEC coding gain have offset the increases in OSNR demanded by higher order modulation formats, so that the reach of today's "de facto standard" 100G transponder using PM-QPSK (28-32Gbaud) is comparable to that of the widely deployed 10G NRZ transponders, with G.709 FEC. However, prospects of further reach improvements via increases in coding gain are limited, even if FECs with much higher overhead are now being investigated [6,7]. Moreover, due to the increased OSNR required, it is clear a substantial reach reduction must be accommodated even for the anticipated upgrade from 100G PM-QPSK to dual-carrier 400G PM-16-QAM, and that reaching the oft-cited *sweet spot* of 1500km will be challenging.

To help to mitigate these reach reductions, it is expected that low noise amplification will become increasingly important in future optical network design. In the near future, we expect a greater penetration of hybrid Raman-EDFA amplification [8-13], particularly since recent advances in pump technology have made high-power 980/1480nm pumping increasingly cost-effective. In this paper, therefore, we consider the combination of hybrid Raman-EDFA amplification with low loss, high effective area fibre [11,12], as two possible enablers for low noise optical fibre transmission lines. We use results from the recently-developed Gaussian-Noise (GN) model [14-16] to compare "span budgets" calculated for systems based on extended reach variable gain EDFA-only and hybrid Raman-EDFA amplification, showing the feasibility of support of super-channels based on 100/200G PM-QPSK/16QAM over long distances, with therefore the potential for widespread deployment.

2. The Gaussian Noise Model

The Gaussian Noise (GN) model [14] has been established in recent years as an accurate predictor of system performance for PM-m-QAM signals transmitted over uncompensated fibre links [15]. The effects due to nonlinear interference can be modelled as excess additive Gausssian noise, leading to a simple modification of the usual equation for the optical signal-to-noise ratio (OSNR) according to

$$OSNR = \frac{P_{Tx}}{P_{ASE} + P_{NLI}} \tag{1}$$

Here P_{Tx} is the per channel power, P_{ASE} is the power of ASE noise, expressed as,

$$P_{ASE} = G_{ASE} B_N = N_s NF(G-1)h\nu B_N \tag{2}$$

where G_{ASE} is the dual-polarisation ASE noise power spectral density, B_N is the noise bandwidth, N_s is number of spans (each of length L_s), and G and NF are amplifier gain and noise figure, respectively. P_{NLI} is the additional term representing the power of the nonlinear interference, which varies as the third power of P_{Tx} and can be approximated as,

$$P_{NLI} = N_s a_{NLI} \gamma^2 P_{Tx}^3 \quad (3)$$

where γ is the nonlinear fibre coefficient in (1/W.km), and the dimensionless coefficient a_{NLI} is given by

$$a_{NLI} = \left(\frac{2}{3}\right)^3 L_{eff} \frac{log(\pi^2 |\beta_2| L_{eff} N_{ch}^2 R^2)}{\pi |\beta_2| R^3} B_N \quad (4)$$

In eqn (4), L_{eff} is the effective length, β_2 is the fibre group velocity dispersion (GVD) coefficient, N_{ch} is the number of channels, and R is the baud rate, which in the Nyquist limit equals the channel spacing.
It can been shown [16] that the optimal transmit power, $P_{Tx,opt}$ is obtained when the ASE power is twice the power of the nonlinear interference, $P_{ASE} = 2P_{NLI}$, and given by

$$P_{Tx,opt} = \sqrt[3]{P_{ASE}/2N_{s,max}\alpha_{NLI}\gamma^2} \quad (5)$$

At the optimum transmit power, the maximum number of spans $N_{s,max}$ and maximum distance L_{max} are,

$$N_{s,max} = \frac{L_{max}}{L_s} = \frac{P_{Tx,opt}}{OSNR_{req}(GNF_{eq} h\nu B_N + a_{NLI}\,\gamma^2 P_{Tx,opt}^3)} \quad (6)$$

where $G \approx (G-1)$, NF_{eq} is the amplifier noise figure (defined below for a hybrid Raman-EDFA) and $OSNR_{req}$ is the required OSNR at the target BER for the modulation format of interest.

3. Reconfigurable Variable Gain Erbium Doped Fibre Amplifiers and Hybrid Raman-EDFAs

A typical commercial variable gain (VG) EDFA consists of two amplifier stages with a variable optical attenuator (VOA) between them [17,18]. Such EDFAs exhibit degraded noise figure (NF) in the low gain region, caused by the additional attenuation of the VOA, limiting the useable gain range and resulting in the need for a small number of amplifier variants with different (and overlapping) gain ranges as part of any WDM system. This is illustrated in Figure 1(a), where the NF as a function of gain is and plotted for a two sets of EDFAs, with 2 and 3 variants respectively, each covering a gain range of 10dB, but configured with different maximum gains and overlaps of 1dB and 3dB, respectively. A dual-EDFA set is shown with a minimum NF of 5dB and gain ranges of 11-21dB and 20-30dB; the triple-EDFA set has a minimum NF of 6dB and gain ranges of 10-20dB, 15-25dB, and 20-30dB. We note that a single reconfigurable gain EDFA can be designed that modifies the Er-doped fibre length using optical switches, with only a small NF penalty compared to individual units [19,20].

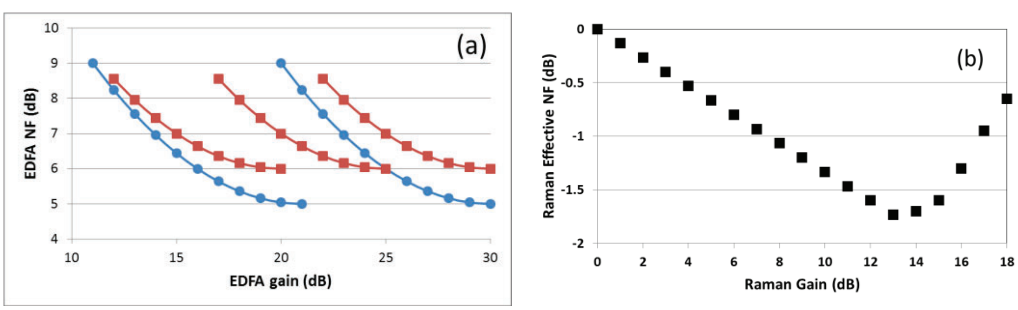

Figure 1: (a) EDFA NF in (dB) as a function of variable EDFA gain; dual-EDFA set (blue) and triple-EDFA set (red). (b): Raman noise figure as a function of Raman gain (after [11]).

We consider a practical situation in which the two EDFA sets and a single Raman pump unit characterised by Figure 1 are available to the system designer to configure systems with span losses ranging from 12-30dB. Figure 1(b) shows a reduced model of the effective NF of the Raman gain, including the effects of Rayleigh scattering which lead to an increase in NF for gains greater than 14dB. The NF of the hybrid EDFA-Raman amplifier is given by $NF_{eq} = NF_{Raman} + (NF_{EDFA} - 1)/G_{Raman}$, where NF_{Raman} is the "effective" NF of the Raman amplifier, NF_{EDFA} is the NF of the EDFA and G_{Raman} is the Raman gain. The gain partitioning between EDFA and Raman is chosen to minimise the added noise by maximising the Raman amplifier gain, subject to the constraints of minimum EDFA gain (12dB) and the turning point in the Raman noise figure (14dB).

4. System reach estimates via "span budget tables"

To estimate the reach improvements due to hybrid Raman-EDFA amplification, we combine the results of the GN model of section (2) and the NF models of section (3). We consider transmission of Nyquist-WDM PM-

QPSK and PM-16QAM signals at 32Gbaud, with OSNR requirements of 16dB and 20.5dB for a pre-FEC BERs of $2x10^{-3}$ and $2x10^{-2}$, assuming HD-FEC and SD-FEC respectively [19]. The dual and triple EDFA variant sets are considered separately for PM-QPSK and PM-16QAM, respectively. The low loss, high effective area fibre parameters [12] were α= 0.166dB/km, γ=1.3*(80/143) (1/W.km) scaling the G.652 fibre nonlinearity according to the ratio of effective area, D =20.5ps/nm/km, and the total optical bandwidth was 4.6THz (N_{ch}=144). The results are summarised in Figure 2, which shows $P_{Tx,opt}$ and L_{max} for systems with uniform span losses from 12-30dB. The reach of EDFA-only and hybrid Raman-EDFA systems is shown in blue and red, respectively.

Two key results are immediately visible via this analysis. First, the optimum transmit power of these systems rises with span loss, and is lower for hybrid Raman-EDFA systems than for EDFA-only systems, by an amount which grows with L_s to more than 2dB. Note the step-wise transisions in $P_{Tx,opt}$ for the EDFA-only cases, as the switch in EDFA variants occurs at span losses of 22dB, and 20/25dB. Second, the improvement due to Raman amplification grows with L_s, allowing peak reaches in excess of 6000/2000km for span losses of ~20dB, greater than ~13dB for EDFA-only systems [20], and more than doubling the reach for span losses of 25-30dB.

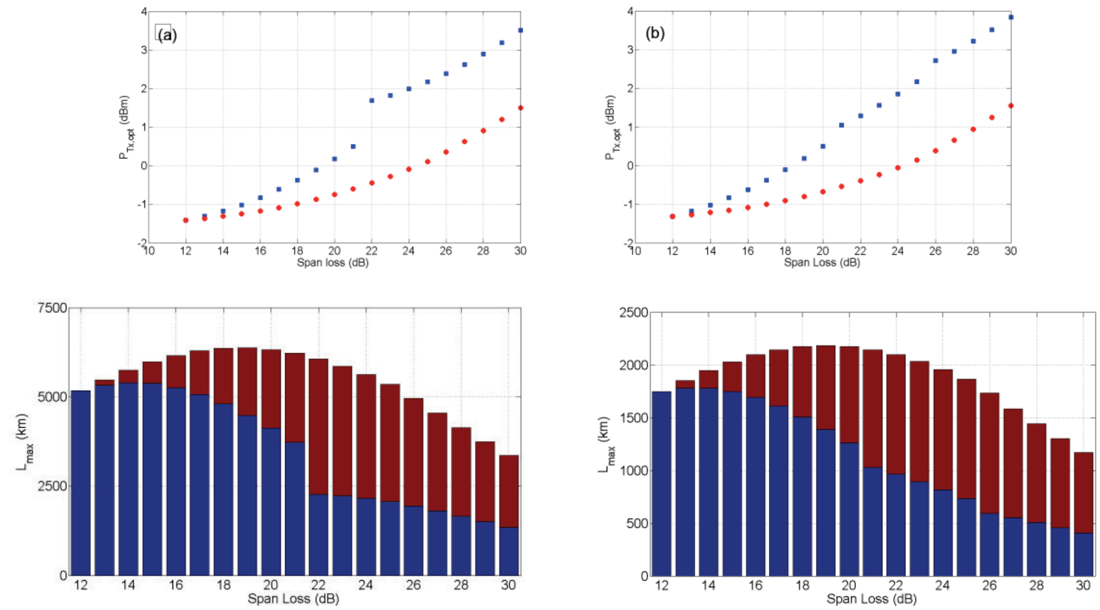

Figure 2(a,b): $P_{tx,opt}$ (dBm) versus L_s for EDFA-only (upper, blue) and hybrid Raman-EDFA (lower, red) dual (a) and triple (b) variable gain EDFA systems. Figure 2(c,d): L_{max} (km) versus L_s for PM-QPSK (c) and PM-16QAM (d) EDFA-only (lower, blue) and hybrid Raman-EDFA (upper, red) systems. Note VG EDFA-only stepwise transitions at 21dB (a,c) and 20/25dB (b,d)

5. Conclusion

The optical channel power requirements and transmission reach of 14.4/28.8Tbit/s Nyquist-WDM systems based on PM-QPSK/16QAM modulation at 32Gbaud, low loss, high effective area single-mode fibre, and extended range variable gain hybrid Raman-EDFA amplifiers have been assessed using the GN model. Span budget calculations indicate a wide range of 5000km/1500km+ links can be supported in future systems.

Acknowledgements

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