Economic and system impact of hybrid Raman–EDFA amplification in a 40 × 40 Gbps optical transmission network with DPSK modulation

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Abstract

Demands of modern high-bandwidth services drive the need to constantly improve existing optical amplification technology beyond its current bounds. In this paper, we demonstrate a hybrid broadband amplification scheme which is capable of improving the system performance of a wavelength-division-multiplexed (WDM) network. We present the study of optical signals with differential-phase-shift keying (DPSK) modulation at 40 Gbps and its transmission in a 50-GHz spaced, 40-channel WDM system over an 80-km link with hybrid optical amplification. A comparison of the system and cost impacts of a Raman-only amplification scheme with two hybrid Raman–erbium doped fiber amplifier schemes (Hybrids I and II) is performed. It is shown that one of the proposed hybrid schemes (Hybrid II) outperforms the other by (i) improving the tolerance to signal input power by 17 dB and (ii) increasing the system reach by 55 km for input signal power of 5 dBm, for a bit error rate (BER) performance of 10−12.

1. Introduction

With expanding broadband services such as video broadcast and high-speed internet, we need to utilize the supporting optical networks to their highest capacity. Essential factors that determine the performance of an optical network include the choice of amplification scheme, modulation format, channel spacing, and data rates. Amplification schemes which have broadband and low-noise properties at reasonable cost are required to extend bandwidth and reach in optical networks. In general, the high power conversion efficiency of erbium-doped fiber amplifiers (EDFAs) [1] and broadband tunability combined with low-noise properties of Raman amplifiers [2] are employed in hybrid amplifier configurations to yield highly performing WDM transmission systems. Although Raman-only amplifiers have demonstrated the capability to improve the system BER performance [3–7], Raman–EDFA hybrids have been found to be comparatively more power-efficient and cost-effective [8,9]. Consequently, WDM systems employing a variety of hybrid schemes which ultimately increase the transmission capacity have been proposed in recent publications [10–13]. Current schemes range from optimization techniques to equalize the EDFA gain spectrum by adjusting the Raman amplifier parameters [12] to recycling residual Raman pump power in order to improve the pumping efficiency [10,11]. Significant enhancement of gain and effective gain bandwidth were demonstrated with the use of a hybrid scheme where a Raman amplifier is cascaded with EDFA in [13]. Hybrid amplifiers are shown to not only give better performance in terms of noise figure, but also results in lower gain ripple [14,15].

The hybrid scheme proposed in this paper over and above combining the useful properties of EDFAs and Raman amplifiers to demonstrate superior gain and noise performance, also considers the following aspects, (i) the progressive upgrade from 10 to 40 Gbps of WDM technologies while aspiring to maintain a reasonable cost [16–19], and (ii) differential phase shift keying (DPSK) modulation format favored by 40 Gbps systems. DPSK is highly employed in recent systems [20] due to their resistance to nonlinearity, in particular, polarization mode dispersion (PMD) which is a major capacity-limiting factor in communication networks. The performance of the hybrid amplification schemes is compared using multiple metrics namely the average gain and noise figure, gain and noise ripples, bit error rate (BER), and cost. To the author’s best knowledge, there is no study in literature which compares the cost and system impact of hybrid Raman–EDFA amplification schemes in conjunction with DPSK modulation format and distributed amplification.

Given that experimental characterization of optically amplified WDM networks is snowed under the high cost of large numbers of optical sources required, an exhaustive experimental investigation...
is not viable or is highly restricted by the availability of resources. Hence, this study was designed using OptiSystem 9.0, which is a system level simulator that uses well established amplifier and transmission models. It will allow the evaluation of gain and noise profiles, system bit error rate (BER) performance, and cost comparison of optical amplification schemes for modern broadband wavelength division multiplexed (WDM) networks. This paper is presented as follows: In Section 2, the hybrid amplification schemes are presented and the system performance metrics are defined. Section 3 presents the results of comparison of gain and noise profiles and also the pumping cost of the amplifiers. In Section 4, the system impact of 40 Gbps DPSK modulation and span length for each of the schemes is presented.

2. Performance measures of hybrid amplification schemes

Hybrid amplifier configuration refers to a combination of two or more optical amplifier types in one optical transmission link. The most commonly used hybrid configuration is the Raman–EDFA scheme which consists of Raman amplifier and a cascaded erbium doped fiber (EDF) section. This configuration was primarily designed for low noise figure and also for flat gain bandwidth while enjoying high power conversion efficiency. They help to realize ultra-long haul telecommunications systems that require large gains. Amplification is employed effectively in three stages of an optical transmission link, namely, a power booster, for in-line amplification, and for pre-amplification [2] as shown in Fig. 1.

Power booster is used to amplify the signals transmitted to provide high input power to the fiber span before fiber loss is experienced. In-line amplification is to compensate for fiber loss in the transmission span and is done by Raman amplifiers as stimulated Raman scattering is intrinsic to all fibers. Pre-amplification is used to boost the receiver performance by amplifying the signals before it falls on the photo-detector. All amplification stages must be designed to have a high gain and low noise figure, so that it does not degrade the signal-to-noise ratio of the amplified signals [21].

Since hybrid Raman/EDFA consists of Raman amplifier and erbium doped fiber (EDF) section, the overall gain and effective noise figure of the system is contributed by both amplifiers, distributed Raman amplifier and lumped EDFA. By considering the Raman net gain, \( G_n \), the EDFA net gain, \( G_{EDFA} \), and the overall insertion loss, \( T_c \), for the signals, the overall gain of hybrid Raman/EDFA can be computed using [21,22]

\[ G_{overall}[dB] = G_n[dB] + G_{EDFA}[dB] - T_c[dB]. \]

The gain can also be expressed in terms of the 'on–off gain', defined as the ratio of the amplifier output with the ‘pumps on’ to that with the ‘pumps off’, and can be written as

\[ \text{On–off gain [dB]} = G_{overall}[dB] + T_c[dB]. \]

Assuming that signal-spontaneous beat noise is the dominant source of noise added by the optical amplifier, an approximate expression for the noise figure of the \( n \)th stage of amplification of a transmission system is [4].

\[ \text{NF}_n = \frac{2P_{ASE}}{h
ight v b_n} + \frac{1}{G_n}. \]

where \( G_n \) is the gain and \( P_{ASE} \) is the total amplified spontaneous emission (ASE) noise power in the optical bandwidth \( b_n \) of the \( n \)th stage, \( h \) is the Planck’s constant and \( v \) is the frequency of the channel. The overall noise figure calculation for an \( n \)-stage cascaded system is expressed as [23]

\[ \text{NF}_{overall} = \text{NF}_1 + \frac{\text{NF}_2 - 1}{G_1} + \frac{\text{NF}_3 - 1}{G_1 G_2} + \cdots + \frac{\text{NF}_n - 1}{G_1 G_2 \cdots G_{n-1}}. \]

In WDM systems, it is important to maintain nearly equal gain and noise figure across all channels thereby permitting uniform reach. The gain ripple and noise figure ripple are measures of non-uniformity in gain and noise figure profiles and are defined as the difference between the maximum and minimum magnitudes of gain and noise figure respectively. When the WDM channels are data modulated, Q-factor is used as a measure of the system degradation which for a simple on–off keyed system is defined as [24]

\[ Q = \frac{(i_1) - (i_0)}{\sigma_1 + \sigma_0}, \]

where \((i_1)\) and \((i_0)\) are the mean photocurrents for the ones and zeros, respectively. The quantities \( \sigma_1 \) and \( \sigma_0 \) are the standard deviations of the photocurrents for the ones and zeros respectively. BER is computed as a final measure of the transmission quality and is related to Q-factor by the following relationship [25]:

\[ \text{BER} = \frac{1}{2} \text{erfc}(Q/\sqrt{2}), \]

where \( \text{erfc} \) is the complementary error function. However, for a DPSK modulated system, limited by inter symbol interference and noise in OptiSystem, Q-factor and BER are computed using numerical analysis or semi-analytical techniques [26–28].

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Fig. 1. Optical amplification schemes in WDM networks.
3. Comparison of gain, noise, and cost performance

The test system operates in configurations utilizing a single mode fiber (SMF) span of 80-km with counter-directional Raman amplification and a single stage EDFA. The amplifier configurations for a conventional Raman-only amplifier and two hybrid schemes, Hybrids I and II, are shown in Fig. 2. Raman amplifier is used in a typical distributed Raman amplifier (DRA) configuration with a counter-pumped geometry. Hybrid I is Raman–EDFA hybrid with residual pump recycled into a cascaded EDF section which is placed after the DRA for pre-amplification. Hybrid II also utilizes residual pump recycling, but with the EDFA cascaded prior to the DRA as a power booster. All configurations employ Raman amplifier for in-line amplification and both hybrids recycle residual pump powers for increased pumping efficiency.

The WDM transmitter is set to 40 channels across the C-band, from 1545 nm to 1560 nm on a 50 GHz grid. Each channel has a continuous power of $-22 \text{ dBm}$ with no modulation. In both Hybrids I and II, an optimal length of 10 m of EDF was used. In the Raman-only configuration, four pumps at frequencies 1445 nm, 1450 nm, 1455 nm, and 1460 nm were counter-pumped into the 80-km SMF span. The power required from each pump is obtained by carrying out an optimization process with the objective of supplying an approximately uniform gain of 15 dB to all 40 channels. This was achieved at powers of 272 mW, 261 mW, 157 mW, and 50 mW at wavelengths 1445 nm, 1450 nm, 1455 nm, and 1460 nm respectively. Similar optimization was carried out for Hybrids I and II. For Hybrid I, the pump powers used for the DRA were reduced to 90 mW, 70 mW, 30 mW, and 20 mW at wavelengths 1445 nm, 1450 nm, 1455 nm, and 1460 nm respectively. An additional pump at 1480 nm and supplying 20 mW was launched into EDF section for pre-amplification. For Hybrid II, it was possible to achieve average gain of 15 dB with pump powers of 160 mW, 130 mW, 60 mW, and 40 mW at wavelengths 1445 nm, 1450 nm, 1455 nm, and 1460 nm respectively for the DRA section.

A 1480 nm pump at 15 mW was used to pump the EDF section used as power booster. Pump powers used for the three amplification schemes are summarized in Table 1.

For each of the amplifier configurations, the gain and noise figure are computed as a function of channel wavelength and the resulting profiles are illustrated in Fig. 3. It is seen that when the gain is approximately 15 dB across the channels, which has been intentionally maintained for fair noise comparison, Hybrid II exhibits better noise performance than Hybrid I and Raman-only amplification. The amplification of the signal prior to transmission in Hybrid II reduces the gain required from the DRA in comparison with the Raman-only configuration. This causes the noise figure to be lower. The drawback could well be introduction of non-linear
penalties due to high signal powers in the fiber if one is not cautious. Hybrid I on the other hand has the worst noise performance. This is due to the fact that majority of the amplification is taking place in the pre-amplifier EDFA section. The signal and the noise accumulated in the fiber span are amplified by the pre-amplifier EDFA. Hence, despite the lower pump power requirements from the Raman pumps, this configuration is less preferred.

Another important measure of the amplification quality of WDM networks is the gain and noise figure ripple. **Fig. 4** shows a comparison of the average gain, gain ripple, average noise figure, and noise figure ripple for the three configurations under test. Raman-only amplifier is found to have the smallest gain ripple of 0.6 dB. This is due to the well-known capability of Raman amplifiers to tune the gains using optimized pump power and wavelength assignment. Hybrid II has the lowest average noise figure of 6.6 dB with the Raman-only and Hybrid I being considerably higher at 14.7 dB and 19.2 dB respectively.

Although gain ripple and noise ripple of Hybrid I are comparatively small, it is of no significant advantage since its average noise figure is much higher than that of both Raman-only and Hybrid II schemes. Although the noise ripple in Hybrid II is the highest, it far outdoes the Raman-only and Hybrid I configurations by its considerably lower noise performance. **Fig. 5** shows a comparison of the cost of pumping the three amplifier schemes for similar gain performance. Since lasers are priced at dollars per mW, total pump power required for each scheme can be used as a direct translation of the cost of amplification, assuming that the price of the EDF is small in comparison with the cost of the pump lasers. It can be seen from **Fig. 5** that the Raman-only amplifier has the highest pumping cost compared to both Hybrids I and II. Hybrid I require the least total pump power, but is of no benefit in the light of its poor noise performance.

### 4. System impact for 40 Gbps DPSK modulation

In order to measure the system impact for each type of amplifier, data modulation was introduced and BER measurements were performed. A single NRZ-DPSK modulated transmitter at 1552.5 nm (test channel) multiplexed with a 40-channel WDM transmitter comprising of wavelength between 1552 nm and 1580 nm were used in this experiment. **Fig. 6** presents a schematic of the set up used for BER performance comparison.

The test channel was intensity modulated at 10 and 40 Gbps and coupled into the amplifier system under test. A photodetector was used to perform conversion from optical to electrical domain followed by a filter to limit the noise spectrum before the BER is computed. The simulation was carried out at different input powers of the signal channels and also at different lengths of transmission span. At each input power and transmission length, the BER of the test channel was observed. The BER values at different input powers for each of the amplification scheme are shown in **Fig. 7**. For the test channel of 1552.5 nm, the use of Hybrid II exhibited the best performance. A BER performance of $10^{-12}$ was achieved at an input power level of $-25$ dBm at 10 Gbps modulation. At 40 Gbps modulation, the input power tolerance was reduced by merely fractional dB. Similar BER performance can be delivered by Raman-only scheme if input power is $-13$ dBm for 10 Gbps modulation.

However, at 40 Gbps modulation, the input power tolerance reduces by almost 3 dB. Hybrid I, as expected from its poor noise performance, exhibits a BER performance inferior to both Raman-only and Hybrid II amplifiers. It is found to be able to perform at a BER of $10^{-12}$ only if input power is $-8$ dBm or higher for 10 Gbps modulation. The scheme, however, does not perform very differently at 40 Gbps modulation. The observations also indicate that using

### Table 1

<table>
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<tr>
<th>Pump wavelength (nm)</th>
<th>RP1-1445 nm Power (mW)</th>
<th>RP2-1450 nm Power (mW)</th>
<th>RP3-1455 nm Power (mW)</th>
<th>RP4-1460 nm Power (mW)</th>
<th>EDF-1480 nm Power (mW)</th>
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<td>261</td>
<td>157</td>
<td>50</td>
<td>0</td>
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<tr>
<td>Hybrid I</td>
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<td>70</td>
<td>30</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Hybrid II</td>
<td>160</td>
<td>130</td>
<td>60</td>
<td>40</td>
<td>15</td>
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</tbody>
</table>

**Fig. 3.** Gain and noise figure profile of a 40-channel WDM network with Raman-only, Hybrid I, and Hybrid II amplification schemes.

**Fig. 4.** Average noise figure, gain and NF ripple comparison for 40 channels.

**Fig. 5.** Cost comparison for Raman-only, Hybrid I, and Hybrid II amplification schemes. $X$ is the price of the pump laser per mW.
the power booster EDFA stage in Hybrid II has not driven the signal into the non-linear operating regime for the parameters under test. The dependence of the amplifier performance on span length is illustrated in Fig. 8. With increased span lengths, BER performance is expected to worsen due to increased non-linearity and noise in the transmission system.

At an input power of 5 dBm, Hybrid II is able to realize a 200 km reach delivering a BER of $10^{-10}$. In comparison, the reach for similar BER performance is 165 km for Raman-only and 145 km for Hybrid I.

5. Conclusion

The system BER performance and amplification cost of an NRZ-DPSK WDM system in which losses are compensated by hybrid Raman/EDFA amplifiers has been numerically studied. Comparison of the hybrid amplification schemes was established by applying 40 Gbps modulation at 50-GHz channel spacing in a 40-channel WDM network. The Raman–EDFA hybrid that uses an EDFA for power booster was shown to have superior noise and BER performance at reasonable cost, made possible by combining the high power conversion efficiency of EDFAs and low-noise, flat gain properties of Raman amplifiers, and residual pump recycling.

References


