The Use of Raman Amplification to Increase the Reach of Short Undersea Optical Systems

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Abstract **– Upgrading a system from 2.5Gbits/s to 10Gbits/s requires enlarging the pulse energy by a factor of four. This could be difficult to achieve due to optical signal to noise ratio and nonlinear degradation. In this paper we show that in these situations the use of distributed amplification is advantageous and in the present state of technology the Raman amplification is a suitable technique.**

I. INTRODUCTION

Long haul undersea optical cable systems are working in Atlantic and Pacific oceans since 1980's [1, 2] connecting continents and countries. Such systems need regeneration in the middle even when operating with low bit rates, due to the fibers intrinsic loss (around 0.2dB/km).

In short distances, up 200km, typically between islands or connecting sites along the coast, for systems operating at moderates speeds (up to 2.5Gbit/s) amplification in the middle of the link can be avoided. This reduces the installation and maintenance cost of the systems. At this moderate bit rates chromatic dispersion is also not a relevant factor.

The purpose of this work is to study the possibility of upgrading such links to 10Gbit/s. Due to the specificities of the system we only have access to the end points of the fiber, therefore amplification or other type of compensating modules at the middle is precluded.

The analysis focuses on optical to signal noise degradation and nonlinear degradation.

Chromatic dispersion is compensated with a dispersion compensating module composed by a span of dispersion compensating fiber (DCF) just before the foto-detector.

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II. NOISE IN LUMPED AND DISTRIBUTED AMPLIFICATION

The Heisenberg's uncertainty principle precludes the incoherent amplification of a signal without noise,

$$\Delta p \Delta x \geq \hbar / 2 \qquad (1)$$

where Δp and Δx are the uncertainty of momentum and position respectively. Expression (1) can be applied to the optical field considering $p = \hbar k = \hbar\omega/c = E/c$, where k is the wave vector, E is the photon energy, $\hbar$ is the Planck constant divided by 2π, and c is the speed of the light. With $\Delta t = \Delta x/c$, and considering $E = h\nu n$, where ν is the central frequency of light and n the number of photons, and $\Delta\varphi = 2\pi\nu\Delta t$, that is the phase uncertainty, equation (1) can be rewriting as [3]

$$\Delta n \Delta\varphi \geq 1/2 \qquad (2)$$

Considering a linear noiseless amplifier, one can say that $n_o \pm \Delta n_o$ is an input photon stream that after the amplifier has a number of photons $Gn_o \pm G\Delta n_o$. It means that at the amplifier output we have $\Delta n = G\Delta n_o$, and $\Delta\varphi = \Delta\varphi_o$. Assuming one ideal detector with unity quantum efficiency, meaning that every photon incident is accounted, and considering the smallest possible uncertainty, $\Delta n\Delta\varphi = 1/2$, the uncertainty of the input signal is given by [3]

$$\Delta n_O \Delta\varphi_O = 1/2G \qquad (3)$$

As G is by definition grater than one, it represents a violation of the uncertainty principle, see equation (2), meaning that the amplifier described can not exist. This missing uncertainty must be compensated by a source of noise intrinsic to the amplifier. Such noise will reduce the optical signal-to-noise ratio.

Optical noise figure (NF) is one way to compare systems and measure the influence of noise in a system. NF can be defined as $NF = SNR_o(0)/SNR_o(L)$. Where

$SNR_o(0)$ is the input signal-to-noise ratio and $SNR_o(L)$ is the output signal-to-noise-ratio. NF is always greater than one.

Desurvire [3] calculate the NF in lumped and distributed amplified systems. To this purpose he considered lumped amplifiers with gain G=exp(αL), where α is the loss coefficient (at 1.5μm α = 0.2dB/km), and L is the length of the link. It was considered the ideal case with complete inversion of population of each amplifier, so, the spontaneous emission factor is considered $n_{sp}=1$.

NF, was redefined in terms of gain G. To lumped cases, amplifier before or after fiber, discrete gain compensates the fiber losses. The distributed case was considered with constant gain matching the fiber losses. A complete description of the calculations can be seen on reference [3-5]. The mathematical results to noise figure are shown in equation (4)

$$
\begin{aligned}
NF_{distributed} &= 1 + 2\alpha L \\
NF_{lumped\,before} &= 1 + 2[1 - \exp(-\alpha L)] \qquad (4) \\
NF_{lumped\,after} &= 1 + 2[\exp(\alpha L) - 1]
\end{aligned}
$$

Noise figure of a system with an amplifier before the link is always smaller than the noise figure when the same amplifier is placed after link. It is because the fiber losses attenuate the noise generated by the amplifier in the first case, when the amplifier is placed after fiber, it does not occur. In the distributed case noise in the beginning of the link experiences the most attenuation, while in the last portion the least attenuation. Therefore noise figure to distributed amplifiers must fall in between noise figure of both lumped cases.

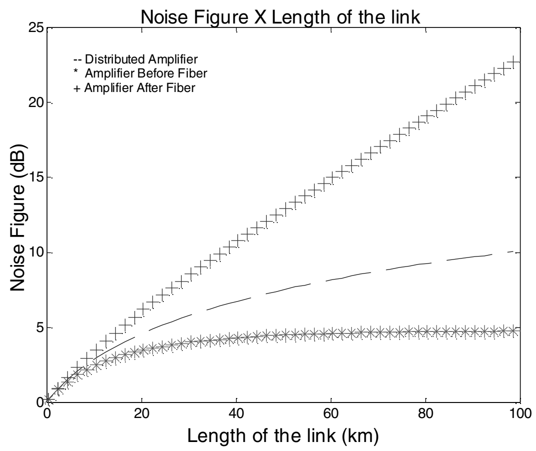

Figure 1. Noise figure comparison between lumped and distributed amplifiers.

Frequently, the NF figure is expressed in decibels as (5).

$$
\begin{aligned}
NF_{distributed}(dB) &= 10 * \log 10(1 + 2\alpha L) \\
NF_{lumped\,before}(dB) &= 10 * \log 10\{1 + 2[1 - \exp(-\alpha L)]\} \\
NF_{lumped\,after}(dB) &= 10 * \log 10\{1 + 2[\exp(\alpha L) - 1]\}
\end{aligned} \qquad (5)
$$

The behavior of (5) is shown on figure 1.

III. SIMULATION AND RESULTS

A. *Description of the systems*

In this section, we report a scheme of the transmission system used for the simulation.

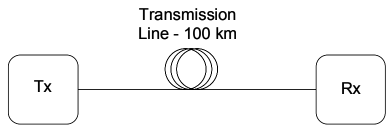

Figure 2. Schematic of a 100km system working at 2.5Gbit/s

Figure 2 shows the schematic of the system used in the simulations at 2.5Gbits/s. Tx generates the optical signal to be transmitted. The transmission line is composed of a 100km span of single mode fiber (SMF) with attenuation of 0.2dB/km. Rx is the receiver. The receiver has a sensitivity that is proportional to the bit energy. Energy per bit can be written as

$$P_{average} = \frac{E_{per\,bit}}{T_{bit}} \qquad (6)$$

where $P_{average}$ is the average power per bit received, and T_{bit} is the period of the bit. If one system is working at 2.5Gbits/s the bit has an energy $E_{2.5}$, when bit rate increase to 10Gbits/s, T_{10} decreases four times. So, maintaining an average power per bit equal to the transmission at 2.5Gbits/s, E_{10} has to decrease four times, as it can be seen in equation (6). In the situation under analyze we are operating under the same optical average power at 2.5 and 10Gbit/s.

Figure 3 shows the schematic for 10Gbits/s with the purposed solutions to compensate losses with chromatic dispersion module integrated in the receiver.

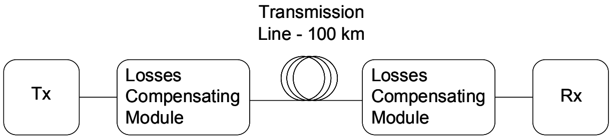

Figure 3. Schematic of the 100km purposed system at 10Gbits/s

The losses compensating modules represent Raman pumps or EDFAs. This work will show the behavior of the different configurations of this system and available solutions to compensate losses. For Raman amplification it is shown counter-propagating, co-propagating, and bidirectional configurations. For EDFAs, it will be considered compensation before fiber, after fiber, and both together. Dispersion management is included at receiver.

B. *Results*

It was evaluated one system without amplification, considering chromatic dispersion and attenuation caused by intrinsic properties of the fiber. A single channel was transmitted through 200km of a SMF. It was evaluated to 2.5Gbits/s and after to 10Gbits/s. Comparison was made utilizing a definition to Eye Opening Penalty (EOP) [6]

$$\mathrm{EOP} = -10\log_{10}\left[\frac{\min(1_R) - \max(0_R)}{\min(1_{btb}) - \max(0_{btb})}\right] \qquad (7)$$

where 1_R and 0_R are the amplitudes of the received marks and spaces, respectively, and 1_{btb} and 0_{btb} are the amplitudes of marks and spaces in back-to-back.

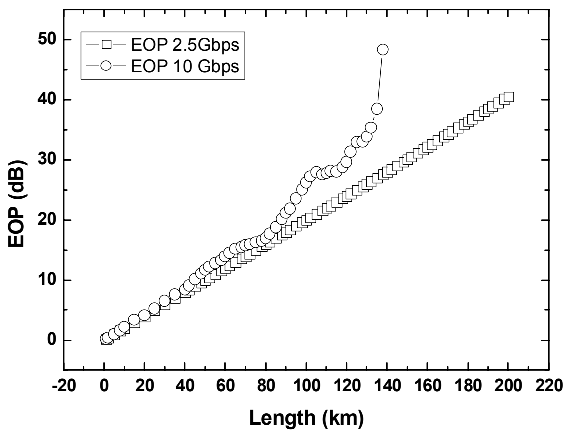

Figure 4. Comparison of EOP along the length for 2.5Gbits/s and 10Gbits/s. Detail shows the behavior after 80km

Figure 4 shows the EOP at 2.5Gbits/s and 10Gbits/s along 200km. It can be seen that at 2.5Gbits/s the most important influence along the length is attenuation, EOP varies linearly along the length, for example, for 60km EOP has a value of 12dB, which correspond to the value of attenuation times the distance. For 10Gbits/s chromatic dispersion takes a dominant role after 80km. The degradation of the eye is strong enough to change the linearity of the EOP, as it can be seen on figure 4. Therefore to operate at 10Gbits/s we need to use some sort of chromatic dispersion techniques for distances above 80km. This is why in the considered system receiver integrates a DCF module.

Considering a scheme working at 2.5Gbits/s and another 10Gbits/s, the eye opening diagrams in the end of 100km are presented on figures 5(c) and 5(d), respectively. It was included attenuation, dispersion and fiber nonlinearities in these simulations. On figure 5(c), dispersion occurs but does not affect system performance, attenuation plays a major role as it can be seen in figure 5(a), eye opening back-to-back at 2.5Gbits/s. The eye opening, basically, only changes its amplitude.

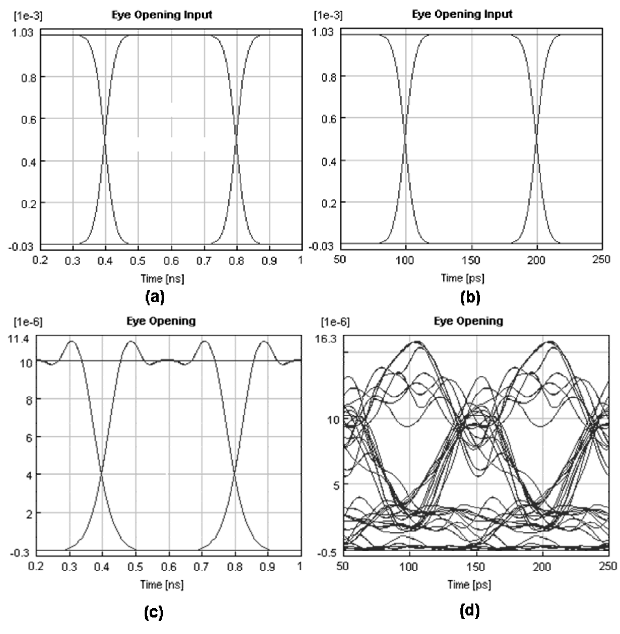

Figure 5. Eye opening diagram of a link of 100km at (a) 2.5Gbits/s back-to back, (b) 10Gbits/s back-to-back, (c) 2.5Gbits/s in the end of the link, and (c) 10Gbits/s in the end of the link.

Figure 5(d) shows the same system working at 10Gbits/s without any dispersion compensation scheme. The eye opening diagram changed its form, besides the attenuation that occurs in both configurations. The pulse shape degradation is completely compensated by the

DCF module. Therefore, accounting losses will be only caused by attenuation and nonlinear effects.

A span of DCF inserted after link can compensate chromatic distortion but such DCF span insertion generates additional attenuation. To compensate these losses and to compensate the reduction by a factor of four of the bit energy, it is necessary some kind of amplification. The available solutions are EDFAs or Raman amplification.

Simulations with EDFA placed before link, after link, and in both sides were done. Raman counter-pump, co-pump, and bidirectional amplification were evaluated in the same way. Figure 6 show results of EDFA after fiber (a), EDFA before fiber (b), Raman counter-pump (c), and Raman co-pump (d). It can be seen that the worst case, taking account noise degradation, is (a) EDFA after fiber. This results are in accordance with (4), to the same gain and same length, an amplifier placed after link will have a greater noise figure than the one placed before, as it can be seen on (b), and than the distributed case (c) and (d). It can be seen that noise is less relevant in (b), EDFA before fiber, than in (d) Raman co-pump.

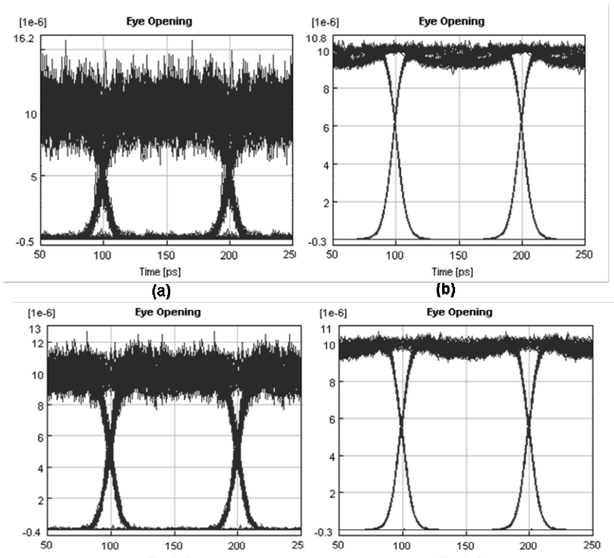

Figure 6. Eye opening diagrams of 100km at 10Gbits/s. (a) EDFA placed after link, (b) EDFA placed before link, (c) Raman with counter-pump, and (d) Raman with co-pump.

Nonlinear effects take a major role when the amplification happens before transmission link. Therefore, EDFA before, (b), and Raman co-pump (d) have more influence than the other ones. EDFA has more influence of nonlinearities because the amplification is done in the beginning of the fiber. Power is amplified before transmission link, and as nonlinearities increase with the intensity of power, the pulses suffer a strong distortion right after the EDFA. In the Raman co-pumped scheme this is less critical, because amplification occurs along the fiber link.

III. CONCLUSIONS

Transmission through a repeaterless system with 100km at 10Gbits/s is possible with Raman amplification or EDFAs. Raman amplification has a better behavior because induces low noise and low nonlinear degradation. All configurations of Raman amplifiers have Q > 7 (quality factor). EDFAs have good performance when placed before the fiber, but can induce strong nonlinear penalties. Pump power used in the Raman schemes was 270mW and 271mW, respectively, for counter-pumping and co-pumping, considering the signal co-polarized with the pump. Even considering the polarization effects it is possible with the technology available nowadays to achieve these values with robust and affordable high power semiconductor lasers.

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