EFFICIENCY OF ROPA AMPLIFICATION FOR DIFFERENT MODULATION FORMATS IN UNREPEATERED SUBMARINE SYSTEMS

Nataša B. Pavlović (Nokia Siemens Networks Portugal SA, Instituto de Telecomunicações), Lutz Rapp (Nokia Siemens Networks Optical GmbH)
Email: natasa.pavlovic@nsn.com

Nokia Siemens Networks Portugal, SA, Estrada do Casal do Canas, Amadora, 2720-092, Portugal.

Abstract: Performance of links using remote optically pumped amplifiers (ROPAs) strongly depends on the position of the erbium-doped fibre (EDF) in the transmission link. Based on experimental data and simulation results, it is shown that the EDF should be generally placed farer away from the fibre end when using modern phase modulated signals as compared with 10 Gbit/s on-off-keying (OOK). Differences between first order and third order (cascaded) pumping schemes are detailed, and the impact of this dependency on link planning is discussed. In particular, scenarios such as greenfield installations and upgrades of legacy links are considered.

1. INTRODUCTION

Bridging long distances without intermediate amplification provides a cost efficient solution for submarine applications, since no electrical energy supply via the cable is required. Such installations are based on advanced amplification technologies. For bitrates up to 10 Gbit/s, conventional counter-directional Raman amplification with high power pumps is sufficient in most cases. Performance can be further enhanced by using more elaborated technologies such as higher order Raman pumping and codirectional Raman amplification [1-2]. But maximum transmission length is achieved by employing remotely pumped amplifiers (ROPAs), which can also be operated with higher order pumping schemes [3-4]. Recently, it has been shown that the transmission distance can be increased by about 20km with a third order pumping scheme, also called cascaded ROPA [5-6]. In this way, high capacity and ultra-long data transmission without inline amplifiers was achieved [6-8].

With the demand for higher bitrates, new challenges are arising also for unrepeatered links. Transponders providing higher data rates typically make use of more complex modulation formats and employ more advanced forward error correction (FEC) schemes. Currently, existing 10 Gbit/s based terrestrial links are upgraded to 40 Gbit/s or even 100 Gbit/s transmission by making use of coherent-detected polarization-multiplexed quadrature phase-shift keying (CP-QPSK) format. Similar requests are also imposed for unrepeatered submarine links by operators. Nevertheless, the maximum span length is smaller for higher data rates, which leads to an increased interest in ROPA assisted links. Therefore, it is of major importance to analyse the performance of single span links operated at high data rates with advanced modulation formats and to optimize amplifier parameters for this

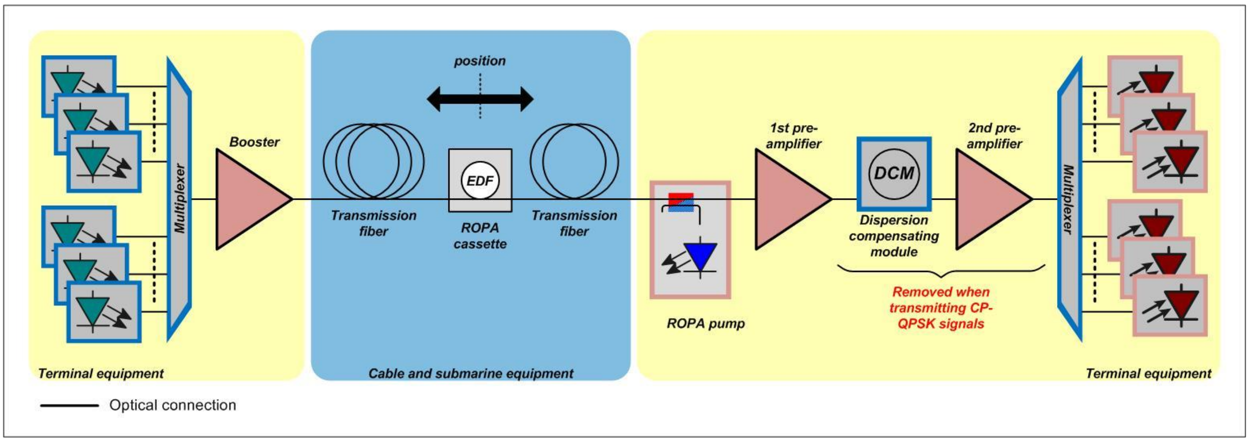

Figure 1: Setup of the investigated long single span system for submarine applications

mode of operation in order to be prepared for future upgrades.

In this paper, long single span links with ROPA and cascaded ROPA amplifiers are optimized when operated at different modulation formats and bit rates. The position of the ROPA cassette is optimized for a “greenfield” scenario. Simulation results and experimental data are presented. A major problem arises from the fact, that the optimum position of the ROPA cassette depends on the modulation format, but can no longer be changed once the system has been installed.

2. SYSTEM SET-UP

The unrepeatered submarine system used for this analysis is shown in Fig. 1. The wavelength division multiplexing (WDM) system is operated with up to 21 channels located in the conventional wavelength band (C-band) at channel spacing of 100 GHz. The simulation analysis is done for four different combinations of modulation format and bit rate: 100 Gbit/s CP-QPSK, 40 Gbit/s CP-QPSK, 40 Gbit/s differential phase-shift keying (DPSK) and 10 Gbit/s on-off keying (OOK). The maximum output power of the booster amplifier is sufficient to reach the nonlinear power limit with respect to nonlinear fibre effects. The WDM signals are transmitted over 350 km of pure silica core fibre (PSCF) with an attenuation of 0.177 dB/km and an effective area of 115 µm^2.

The ROPA consists of a ROPA cassette embedded into the transmission fibre and a ROPA pump. The ROPA cassette mainly consists of a piece of erbium doped fibre (EDF) placed at about 100 km from the receiver end. The pump with an emission wavelength of 1480 nm is located at the receiver terminal and provides the pump power to the EDF via the transmission fibre. Before reaching the doped fibre, it also amplifies the signal through stimulated Raman amplification.

In addition to the described conventional pumping scheme, the performance of a third-order pumping (cascaded) setup is also analysed. It is based on the successive energy transfer from a primary wavelength at 1276 nm to longer wavelengths (1360 nm, 1450 nm and finally the signal at 1550 nm) that takes place during their propagation over the transmission fibre [1].

At the end of the link, the power of the channels is restored by making use of preamplification. When using modulation formats with direct detection, a second preamplifier is installed in order to

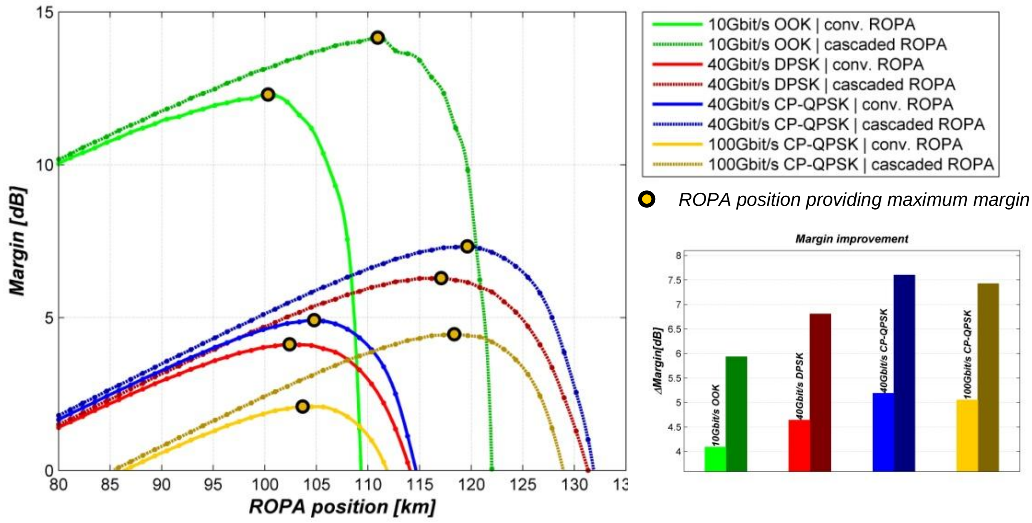

Figure 2: ***Left side:*** **OSNR margin versus ROPA position for different modulation schemes and ROPA types for a WDM system with 20 channels.** ***Right side:*** **OSNR improvement for conventional ROPA (left bar) and cascaded ROPA (right bar) for different modulation schemes.**

accommodate a dispersion compensation module (DCM).

Furthermore, “OSNR preemphasis” providing equal optical signal to noise ratio (OSNR) to all channels is applied. The required OSNR is calculated by assuming amplified spontaneous emission noise loading with target bit error ratio (BER) of 10^{-3} for all modulation formats. The performance is obtained for the wavelength channel at 1550 nm. The different cards are connected by pigtails with a loss of 0.2 dB per connection.

3. RESULTS AND DISCUSSION

On the left side of Fig. 2, the OSNR margin is indicated as a function of the ROPA position for different modulation schemes and ROPA types. For each scenario, the optimum transmission and receiver input power are calculated and applied together with the ROPA position optimization. A WDM system with 20 channels is considered.

The impact of two limiting effects determining the optimum ROPA position can clearly be seen from Fig. 2. Shifted from the optimum position towards the fibre end, the ROPA cassette has higher pump power available due to the counter-directional pumping, but the minimum signal power in the transmission fibre decreases, which finally results in a reduced margin. When shifted further away from the receiver, amplification is provided to the signals at higher power levels, which is in principle beneficial with respect to the OSNR. But, on the other hand, the pump power is limited, which again decreases the ROPA gain and leads to a decreased OSNR.

As illustrated in Fig. 2, the optimum ROPA position (marked by ‘○’) depends on the modulation format and the bit rate used. Among all modulation schemes, maximum OSNR margin is achieved for the 10 Gbit/s OOK format since the smaller bandwidth occupancy results in a significant larger tolerance towards nonlinear fibre effects.

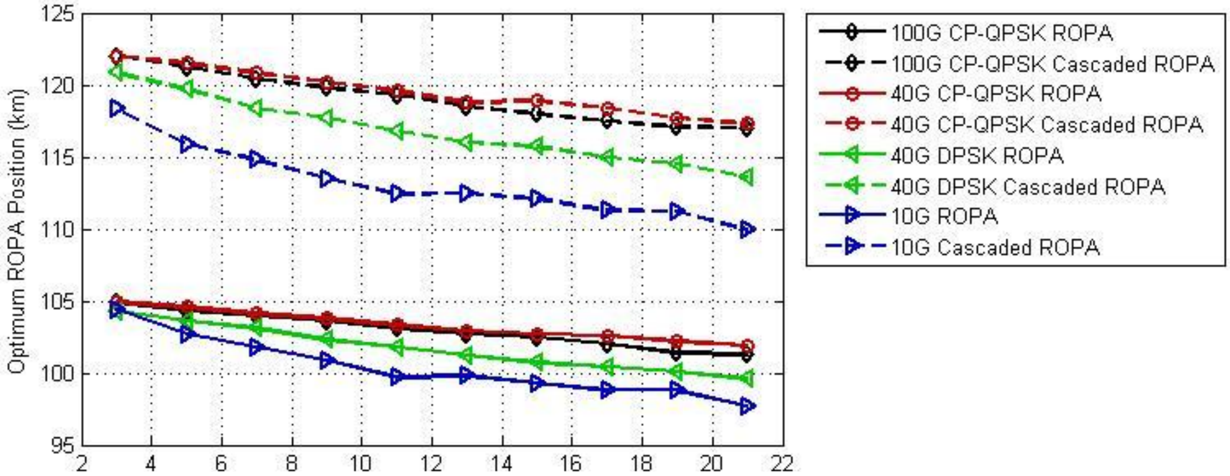

Figure 3: **Optimum ROPA position as a function of number of channels for different modulation schemes and ROPA types**

In an attempt to quantify the efficiency of the ROPA, the OSNR measured at optimum position is compared with the OSNR that would be achieved with a 1st order Raman amplifier and without the ROPA cassette. There is only negligible pump depletion by the signal, so that the provided gain is independent of the modulation scheme. The bar plot on the right side of Fig. 2 indicates the OSNR improvement. For each modulation format, a left bar provides the improvement achieved with a conventional ROPA, whereas the improvement resulting from the use of a cascaded ROPA is represented by a bar on the right. In summary, the OSNR improvement achieved by use of a ROPA technology is by around 1 dB larger for CP-QPSK as compared with 10Gbit/s OOK. This statement is valid for both ROPA types. For 40 Gbit/s DPSK, the improvement equals approximately 0.5 dB for the conventional ROPA as well as for the cascaded ROPA.

Moreover, the 3rd order cascaded ROPA improves the margin of all signals. However, this requires placing the ROPA cassette 10-15 km further away from the recipient end as compared with the 1st pumping scheme, which increases, for almost the same amount, the total maximum span length of unrepeatered submarine links.

As indicated in Fig. 3, the optimum ROPA position also depends on channel count. For this analysis, channel counts from 3 to 21 are considered for the modulation schemes already used in Fig. 2. Fibre launch powers and receiver input powers are optimized at the same time as the ROPA position for each scenario.

Obviously, the differences among the considered modulation schemes with respect to the optimum ROPA position increase with increasing channel count. Irrespective of the modulation scheme, the optimum ROPA position moves towards the fibre end when the number of channels increases. This is caused by the higher total fibre input power and thus higher input power into the ROPA cassette.

For the direct-detection format, the optimum ROPA position shifts deeper into the transmission fibre with increasing data rate due to the smaller launch power. This is again a consequence of the reduced tolerance to nonlinear fibre effects. The coherently detected formats with different bit rate have almost the same optimum ROPA position for all scenarios due to the similar signal tolerance to the nonlinear effects. Again, the optimum ROPA position is farer away from the recipient side due to the poorer tolerance to the nonlinear effects as compared with the direct-detection formats.

For verification purposes, experimental results obtained with a 16 x 40 Gbit/s WDM system with DPSK and CP-QPSK formats using 1st order ROPA have been compared with the simulation results. As for the simulation results, the position of the ROPA has been optimized also in the experiment. Optimum ROPA positions of 108 km and 106 km, respectively, for DPSK and CP-QPSK formats have been observed, which is in good agreement with the simulation results.

So far, it has been assumed that the ROPA position can be optimized for each scenario. However, this is not possible when performing upgrades of legacy 10 Gbit/s OOK submarine links. The presented results indicate that the optimum position for the phase modulated signals is by 5-8 km larger as compared with the 10 Gbit/s OOK signals. As a consequence, link upgrades suffer from an additional penalty caused by a non-ideal position of the ROPA cassette in the order of magnitude of 0.5 dB. In addition, the results reveal that upgrading an existing link to a cascaded ROPA solution does not provide any noteworthy benefit as long as the ROPA position is not changed.

4. CONCLUSIONS

Remote optically pumped amplifiers (ROPAs) are the technology of choice to achieve maximum transmission distance in unrepeatered links. In this work, the ROPA position was optimized for different bit rates, ROPA amplification types, and modulation formats using direct or coherent detection.

Based on experimental data and simulation results, we demonstrate in this paper that the optimum position of the ROPA strongly depends on the used modulation format by comparing 10 Gbit/s OOK signals with 40 Gbit/s DPSK, 40 Gbit/s CP-QPSK, and 100 Gbit/s CP-QPSK signals. The observed dependency is mainly due to the different maximum launch powers into the link governed by the tolerance of the modulation format to nonlinear fibre effects, but also depends on the different sensitivity values. First, it was found that the OSNR improvement achieved by use of a ROPA technology is by around 1 dB larger for CP-QPSK as compared with 10 Gbit/s OOK. Besides, the results show that the optimum position for the phase modulated signals is by 5-8 km larger as compared with 10 Gbit/s OOK signals. A strong impact of the modulation formats on the optimum ROPA position is observed for WDM systems with large numbers of channels. As a consequence, link upgrades suffer from an additional penalty caused by a non-ideal position of the ROPA cassette.

Moreover, 1st and 3rd pump provisioning to the ROPA cassette has been analysed. This work showed that the optimum ROPA position strongly depends of the pumping scheme used (1st or 3rd order cascaded ROPA). The maximum OSNR margin is reached with a 3rd order remote amplifier at the receiver end whatever the modulation format is. However, the results reveal that upgrading an existing link to a cascaded ROPA solution does not provide any noteworthy benefit as long as the ROPA position is not changed.

5. REFERENCES

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