# CORRELATION BETWEEN AGING MARGIN AND REPAIR MARGIN IN UNREPEATERED SUBMARINE SYSTEMS

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**Abstract:** It is shown that the system margin for fibre repair in single span systems can be accepted to be smaller than the expected increase of fibre attenuation during lifetime when upgrading links using remote optically pumped amplifiers (ROPAs). Different scenarios of fibre cuts and their impact on system margin are analysed for various modulation formats and bitrates over legacy fibres. The results reveal that ROPA based systems are typically quite tolerant to fibre cuts that occur before the erbium-doped fibre (EDF) cassette. Strategies to keep the overall cost of the installation as low as possible are presented.

## 1. INTRODUCTION

Unrepeatered submarine transmission systems bridge very long distances without active inline amplifiers by making use of quite sophisticated amplification technologies such as higher-order Raman amplification [1], remote optically pumped amplifiers (ROPAs) [2], or even codirectional Raman amplification [3]. Among all techniques installed at the end of the link, ROPAs provide maximum optical signal-to-noise ratio (OSNR) improvement [4] irrespective of the modulation format. Increasing the transmission distance or the system margin by a few decibels increases the complexity of the equipment and, therefore, system cost significantly when operating a system close to the maximum possible span length. Thus, operators are interested in keeping the system margin as small as possible. Nevertheless, it is required to hold enough margin available for component aging and fibre repair in order to guarantee correct operation of the system during lifetime.

Every year, around 100-150 cases of submarine cable damage are reported [5]. Although some damage is caused by

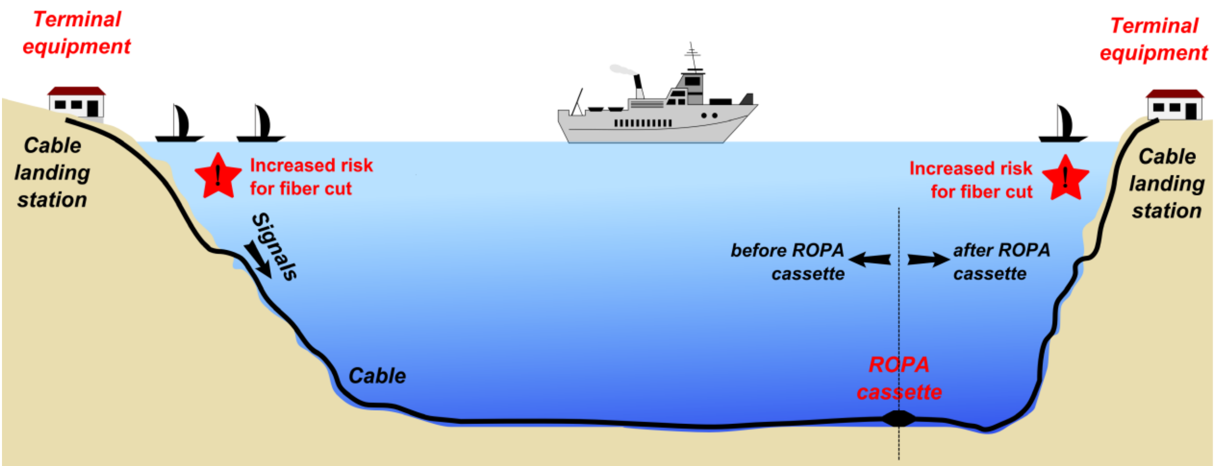


**Figure 1: Illustration of the long single span link under investigation**

 

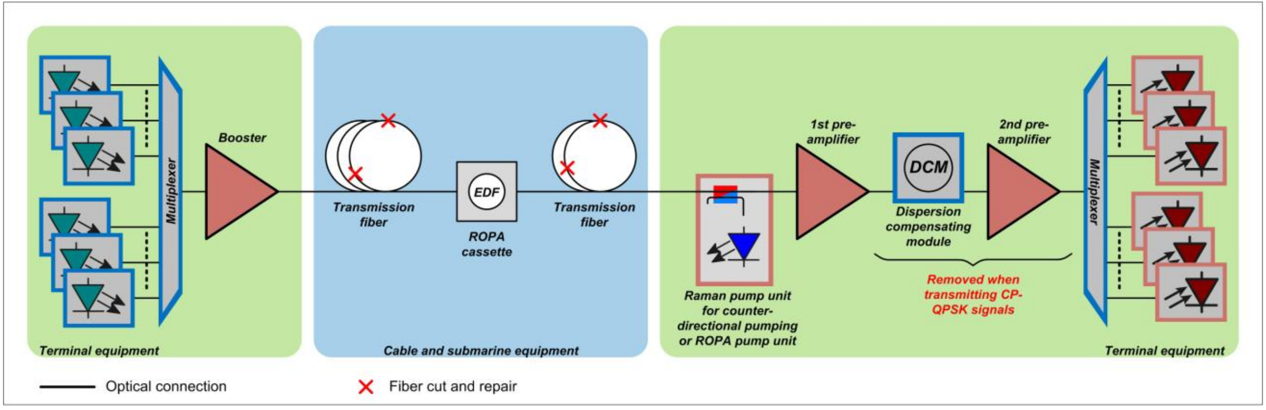


**Figure 2: System setup including ROPA**

natural sources, the overwhelming majority (~80 %) of cases is caused by human interaction such as fishing, dredging, and maritime transportation [6]. Despite cable burial, the majority of the faults still occur in water depths of 200 meters or less, with about 40 % of faults taking place in less than 100 meters. Except for very shallow water, fibre repair typically increases the length of the transmission fibre by 2.5 times the depth of water [7].

Commonly, available margins that can be exhausted by component aging or fibre repair are defined with reference to the noise loading technique [8]. When planning a long single span system, operators typically request a system margin for repair that is equal to the expected increase in span attenuation during lifetime. This approach is suitable for links with codirectional Raman amplifiers that are not operated in saturation. However, it is shown in the following that this approach leads to unnecessary increase of cost in links making use of ROPAs.

First, the considered system setup is presented. In the main part of the paper, different scenarios are analysed with respect to their impact on system margin taking into account various modulation formats and bitrates. Suitable scenarios to keep system cost small are explained. Finally, some conclusions are drawn.

## 2. SYSTEM SETUP

An illustration of the link under consideration is provided in Fig. 1. In typical installations, the ROPA cassette embedded into the transmission path is located significantly closer to the recipient side than to the transmit side. As shown in Fig. 2, up to 20 data channels having identical modulation formats and data rates are multiplexed at the input of the system. Their carrier frequencies are found in the conventional wavelength band (C-band) with channel spacing of 100 GHz between neighbouring channels. The connection to the transmission fibre is provided by a high-power erbium-doped fibre amplifier (EDFA) acting as a booster. The energy required for the amplification process in the doped fibre is provided by a ROPA pump located at the recipient side via the pure silica core transmission fibre (PSCF). Its emission wavelength equals 1480 nm.

During the investigation, four different modulation formats using direct or coherent detection are considered. In case of direct detection, there is an additional dispersion compensating module (DCM) embedded between two preamplifiers at the end of the transmission link. With this module, the residual dispersion is set to the optimum value.

## 3. INSTALLATION SCENARIOS

It is essential to distinguish between two installation scenarios. In most cases, the link is already running at a lower data rate, e.g. 10 Gbit/s, and shall now be upgraded to higher data rates, such as 40 Gbit/s or 100 Gbit/s ("brownfield deployment"). Unfortunately, some of the link parameters such as the position of the ROPA cassette can no longer be changed, which imposes some limitations on the performance of the system. Sometimes, a link is designed from scratch ("greenfield deployment").

For the purposes of illustration, let us consider an example. A link is currently running with 20 channels at 10 Gbit/s using on-off-keying (OOK). The position of the ROPA cassette has been optimized for this modulation format. The carrier intends now to upgrade this link to 40 Gbit/s CP-QPSK and anticipates an increase of the fibre attenuation due to repair activities by 2 dB. Link planning reveals a total margin of 1.39 dB for the new modulation format and the original fibre length, which is at a first glance too small in view of the anticipated fibre repair.

To verify this conclusion, link planning is repeated with increased fibre length in order to evaluate performance after fibre repair. Since fibre cuts occur mainly in less than 200 m of fibre depth, we can assume that the length increase becomes effective in equal measure before and after the ROPA cassette. On this assumption, the performance calculation reveals a margin of 0.18 dB, which means that the system is running correctly even after fibre repair. The reason for this apparent contradiction is explained in the following section.

## 4. PERFORMANCE ANALYSIS

Performance of ROPA based systems strongly depends on the position of the ROPA cassette. In order to achieve maximum OSNR, the preamplification mechanism should be pushed deep into the transmission fibre. On the other hand, the available pump power reduces with growing distance from the recipient side and the gain of the EDF goes down. As a consequence, there is a clear optimum of the ROPA position.

System design becomes even more complex due to the fact that this optimum

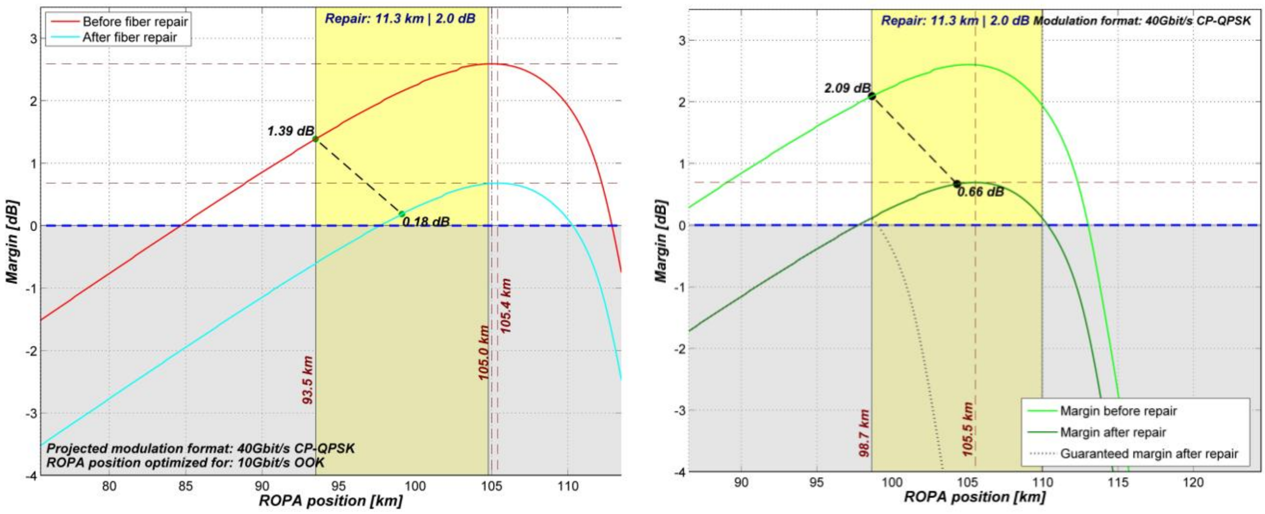


**Figure 3: OSNR margin of a 40Gbit/s CP-QPSK channel versus ROPA position for system upgrade (left side) and greenfield application (right side). The upper curve shows the situation at begin of life (BOL), whereas the lower curve shows the remaining system margin after fiber repair.**

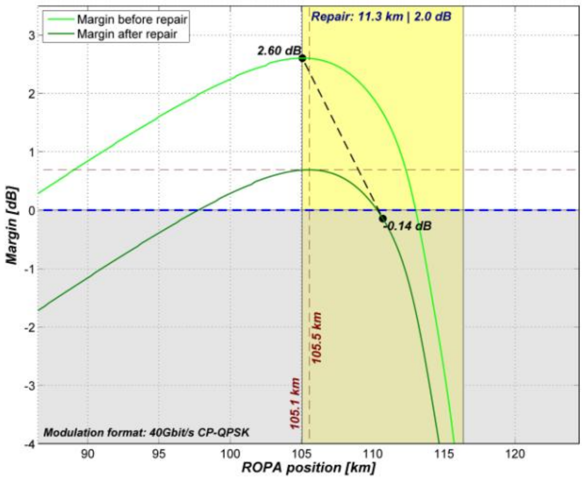


**Figure 4: Bad example: initially, the ROPA cassette is set to the position providing maximum margin at BOL.**

also depends on modulation format, since different modulation formats show significant differences in view of their tolerance towards nonlinear fibre effects. The optimum launch power is typically smaller for data rates of 40 Gbit/s or higher as compared with 10 Gbit/s OOK. Since the gain provided by the EDF decreases with increasing signal power, the optimum position of the ROPA cassette is smallest for 10 Gbit/s OOK. Due to the same reason, the optimum position also depends on channel count when the cable has been laid.

First, the above described **upgrade scenario** is analyzed. For sake of brevity, the term “ROPA position” is used throughout this paper to denote the distance between the ROPA cassette and the ROPA pump. Before the fibre repair takes place, the ROPA position equals 93.5 km, which has been determined to be the optimum position for 10 Gbit/s OOK signals.

Caused by fibre repair, 11.3 km of fibre are added to the link, which leads to a 2 dB increase of the fibre attenuation. Depending on the location of the assumed multiple fibre repairs, the ROPA position also increases by up to 11.3 km. In case all repairs take place in front of the ROPA cassette, this parameter remains unchanged. In contrast, maximum increase of the ROPA position occurs if all fibre cuts are located after the ROPA cassette. These extreme scenarios are very unlikely and the actual increase of the ROPA position will typically be half of the maximum value. However, this aspect will be discussed in more detail later.

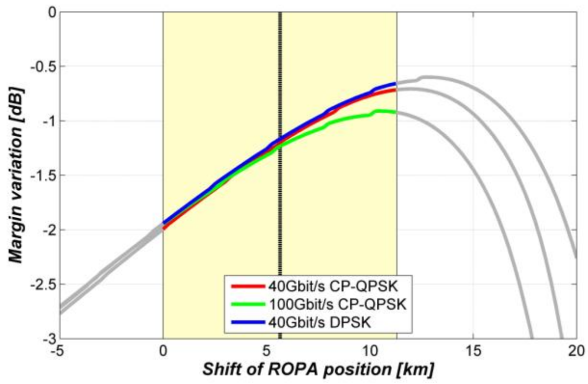


**Figure 5: Margin variation versus shift of ROPA position for different modulation formats.**

Graphs shown on the left side of Fig. 3 indicate system margin versus ROPA position before and after fibre repair. The yellow box delimits the possible range of the ROPA position after fibre repair. System margin increases monotonously with growing ROPA position due to the fact that the initial ROPA position has been optimized for 10 Gbit/s OOK operation. Assuming that the shift of the ROPA position equals half of the increase of fibre length, the system margin after fibre repair is still positive. In summary, a 2 dB increase of fibre attenuation induced by fibre cuts has led to a decrease of the system margin of 1.21 dB only.

Successful optimization of the ROPA position for **greenfield deployment** is shown on the right side of Fig. 3 for

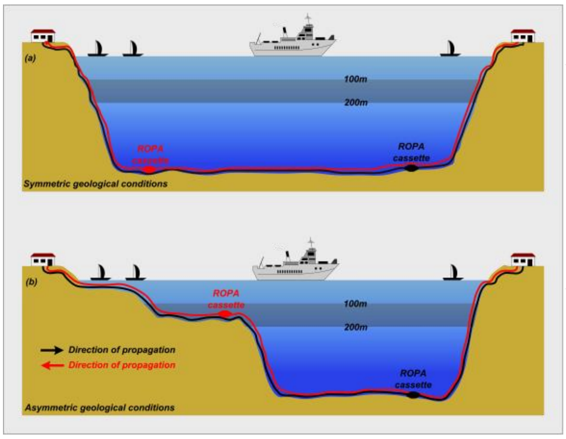


**Figure 6: Examples for the topography of the seabed.**

40 Gbit/s CP-QPSK operation. Intentionally, an initial ROPA position inferior to the ROPA position providing maximum margin has been chosen in order to guarantee maximum performance after fibre repair.

The idea of the optimization concept becomes clear when looking at the dotted curve. It indicates for each ROPA position the minimum margin that might be observed after fibre repair on the assumption that the shift of the ROPA position can cover the complete variation range (as described above). This approach can be illustrated by assuming that the yellow box is shifted horizontally. For each position of the left edge on the horizontal axis, the minimum of the margin values within the covered range of ROPA positions is determined. Finally, the ROPA position yielding the maximum of this curve is chosen as initial ROPA position. In the presented example, an increase of the fibre attenuation of 2 dB leads to a decrease of margin of 1.43 dB only for fibre repairs equally distributed before and after the ROPA cassette.

An example for an improper link design is represented in Fig. 4. The initial placement of the ROPA provides maximum margin at BOL. However, the margin drops significantly after fibre repair if the fibre cuts do not happen uniquely in front of the ROPA cassette and link operation becomes impossible in case the majority of repair activities are after the ROPA cassette.

So far, upgrades to 40 Gbit/s CP-QPSK have been considered solely. However, the fundamental behaviour is identical for other modulation formats such as 40 Gbit/s DPSK and 100Gbit/s CP-QPSK, as demonstrated in Fig. 5. In this figure, the variation of the margin is shown versus the shift of the ROPA position relative to its initial position optimized for 10 Gbit/s operation.

As indicated before, the distribution of the fibre cuts has a major impact on system operation and needs some more thorough investigation. Fibre cuts are random events requiring a stochastic description. In particular, their distribution strongly depends on the topography of the seabed. Two examples for possible topographies are sketched in Fig. 6. Since the vast majority of fibre cuts occur in depths smaller than 200 m, the shape of the two shore areas is of major importance. Thanks to the quite symmetric shape of the upper topography, the peak of the probability distribution of the ROPA position is found in the centre of the variation range ("yellow box"), i.e. it is very likely that the lengths of fibres added before and after the ROPA cassette are identical. The situation is completely different for the lower topography. Let us first consider the communication from West to East shown in black. In this case, fibre cuts are much more likely on the left side than on the right side. As a consequence, the peak of the distribution is shifter towards the left side of the variation range.

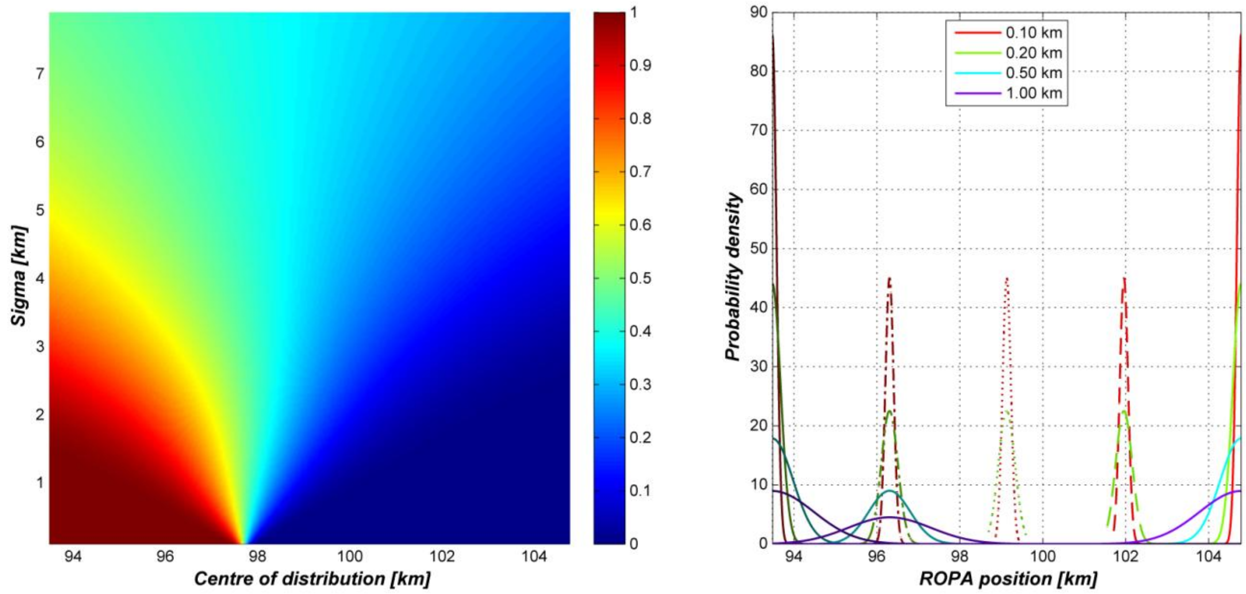


**Figure 7: Failure probability of the link versus standard deviation and centre of the distribution for the ROPA position after fibre repair for the upgrade scenario to 40 Gbit/s CP-QPSK (left side). On the right side, some examples for the distribution are shown.**

In order to take the probability aspect into account, Gaussian distributions with variable average value and standard deviation that are truncated at the borders of the variation range are used for the following investigations. Some examples are shown on the right side of Fig. 7. The colour coded plot on the left side shows the probability that the link is not operable after fibre repair as a function of the centre of the distribution and the standard deviation for the upgrade scenario to 40 Gbit/s CP-QPSK. As expected from the results shown in Fig. 3, the failure probability is quite large if the centre of the probability distribution is shifted towards the input of the link, whereas quite small failure probabilities are observed if the peak of the distribution is in the centre of the variation range or shifted to the end of the link.

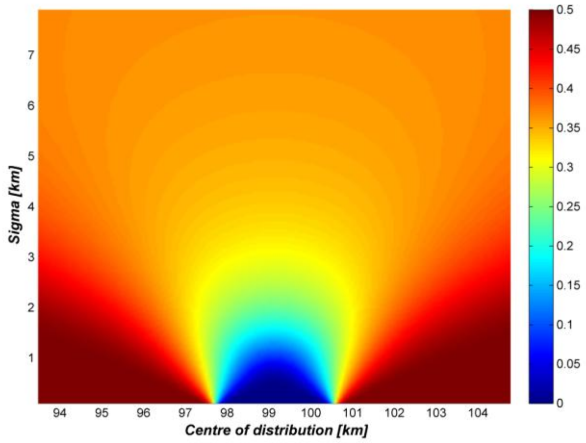


**Figure 8:** ***Average failure probability for the upgrade to 40Gbit/s CP-QPSK for bidirectional communication.***

So far, unidirectional data transmission has been considered. However, single span links typically provide bidirectional communication over fibre pairs. Typically, the distance from the ROPA cassette to the recipient side is almost identical for both fibre pair. Let us reconsider the lower topography in Fig. 6. The peak of the distribution is shifted towards the lower border of the variation range for the communication from West to East, whereas it is shifted to the upper border for the East-to-West communication shown in red. Such an asymmetric distribution of the fibre cuts is beneficial for one direction, whereas it is detrimental for the complementary one. In order to give an idea of the resulting reliability, the average failure probability of both directions is shown in Fig. 8. There is a small region centred around the point of equal distribution of repairs before and after the ROPA cassette for which the average failure probability is very small.

In contrast to the upgrade scenario, the specific probability distribution of the fibre cuts can be taken into account in order to improve the overall reliability of the link. In particular, different ROPA positions can be chosen for the two directions. Going back to the lower topography in Fig. 6, the initial ROPA position for the communication from West to East shown in black should be very close to the position providing maximum margin, since no significant change of the ROPA position during fibre repair is foreseen. In contrast, a significantly smaller initial ROPA position should be chosen for the East-to-West direction, since it is expected that significant length of fibre is added between the ROPA cassette and the corresponding pump.

## 5. Conclusions

The correlation between aging margin and repair margin has been investigated throughout this paper. Simulation results reveal that a single span system making use of remote optically pump amplifiers (ROPAs) can typically tolerate an increase of the fibre attenuation (measured in logarithmic units) that is larger than the determined aging margin. Taken into account during link design, this aspect helps to keep the overall cost of the installation as low as possible.

Performance degradation strongly depends on the location of the fibre repair. In particular, links that have been upgraded to higher data rates are quite tolerant to fibre cuts that occur before the erbium-doped fibre (EDF) cassette. In view of greenfield deployments, a technique to optimize the position of the ROPA cassette taking into account requirements for fibre repair has been presented and an example for a bad link design has been discussed. Furthermore, the impact of the topography of the seabed has been pointed out.

Fibre cuts are random events that require stochastic analysis. Failure probabilities of the link have been presented for assumed distributions of the fibre cuts with variable average position and standard deviation. Finally, some hints for the optimization of bidirectional links have been given.

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