RAMAN OPENS UP BANDWIDTH ON NON-IDEAL FIBRES FOR UN-REPEATERED SYSTEMS

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Abstract: In recent years the telecommunications industry has had to step away from bespoke designs for new cable systems. There have been a number of reasons why non-optimal fibre types have been considered for deployment, the usual driver being economics, but hand in hand come new development and scientific progress. The use of submarine cable for non-telecom applications is becoming more commonplace, groundbreaking redeployment of systems is being carried out, and the use of cable that has been pre-manufactured for alternative systems continues.

1 INTRODUCTION

This paper looks at which issues need to be addressed when considering the use of non-optimal fibre types for commercial applications, and the practical ways in which these issues can be tested in the laboratory prior to deployment. The relationship between fibre types and behaviour within the various optical bands is considered, along with the fibre / system performance when subjected to different types of amplification, in particular Raman. Which wavelengths within the spectral window will be most susceptible to non-linear effects and how can the wavelength grid be designed to reduce the effects? Furthermore, how will performance be affected if the fibre properties change once the system is deployed? We will review the constraints put on design, installation and maintenance of a system when non-optimal fibre is utilised, and explains how these are overcome. A case study is discussed, using Raman amplification on SMF-LS™ fibre to demonstrate how losses in the shore-end sections of a system due to re-design, can be compensated for. The effects of cable ageing and repair have been simulated in the laboratory and the ultimate capacity demonstrated. By fully considering these points before deploying new systems, economic and technically advanced scientific and commercial solutions are available to us all.

2 NON-IDEAL FIBRES

In this case we consider non-ideal fibres to be those which are not optimal in design or characteristics for the purposes in which they intend to be used; this could be due to their loss, their chromatic and polarization mode dispersion or their susceptibility to non-linear effects. One may ask how we find ourselves in a situation where we have to deploy non-ideal fibre types? In the case considered here the answer stems from the redeployment process, re-use of cable previously designed for a system of differing length, with different wavelengths employed, of a differing fibre plan designed to combat the effects of chromatic dispersion for example. The fibre plan could be further complicated by the fact that previous repair operations on a deployed cable may have added differing fibre types (in spare cable) in the repair sections. Another cause stems from the fact that when a cable is redeployed often the previous armouring types do not tie in with the required armouring determined by the new route survey. In this case the cable will need to be 'chopped and changed' to ensure that the correct armour type is deployed in the correct location on the seabed. And, as part of this process fibre types may be changed around such that the final design is non-optimal. For example, the fibre with the largest effective area is no longer located close to the high-power output of an amplifier. Furthermore the act of re-jointing the fibre after these changes have been made can induce additional loss in the shore end sections that needs to be overcome by the amplifiers.

3 KEY DESIGN CONSIDERATIONS

The sections below outline the key design considerations when utilizing non-ideal fibres for new systems. The effect of constraints, such as non-linear effects, need to be considered when determining how to equip a redeployed system. Additionally events which may have resulted in performance degradation during the system life to date and those that occur after its redeployment need to be fully understood.

3.1 System Capacity Expansion Via Raman Amplification And Transmission Window Re-Positioning

Legacy submarine systems were typically deployed with Dispersion Shifted Fiber (DSF), the fiber type of choice due to its low loss, approximately 0.2dB/km, and its zero dispersion at 1550nm. It allowed the simple implementation of single-channel, typically at 2.5Gb/s, unrepeated submarine systems using EDF amplifiers as boosters and/or pre-amplifiers. Distances bridged with such solutions were restricted to around 100km without amplification, to approximately 250-300km with both pre- *and* post-amplification. The maximum reach of these links could be extended with the use of Remotely-Pumped Optical Amplifiers (ROPAs). The carefully screened zero-dispersion wavelength prevented pulse broadening that impaired transmission at that wavelength in standard single mode fibers. DSF also made the implementation of these systems fairly cost-effective by eliminating the need for dispersion compensation. However, DSF is not well suited to support WDM transmission, at least in the wavelength range for which the systems were originally designed. In fact, because of their very low dispersion and their small effective area (~50μm^2), the presence of two or more wavelengths at power levels typically used in submarine applications would generate strong non-linear effects, such as Four Wave Mixing (FWM) and Cross Phase Modulation (XPM), that would drastically reduce the power budget of these installed links.

With carriers now facing the challenge of cost-effectively increasing the capacity of these still viable systems past that for which they were originally designed *without* having to replace the cable, Raman amplification is gaining momentum as the technology of choice to upgrade existing repeaterless transmission systems. Distributed Raman amplification, as an alternative or in conjunction with ROPA, is already viewed as a cost effective solution to extend the reach of new or legacy systems. So far, however, repeaterless applications have made little use of the very broad-band gain spectrum allowed by Raman amplification. An all-Raman based system, with distributed and discrete amplification, would easily support the reach bridged by legacy un-repeatered system. At the same time, it would allow an increase in capacity by transmitting in a spectral window shifted with respect to the C-band (for instance in the L or L+ bands), thus alleviating the impairments resulting from the propagation of signals close to the zero-dispersion wavelength of DSF. The appropriate choice of gain medium in the discrete Raman amplifiers also compensates for the accumulated chromatic dispersion experienced at transmission wavelengths away from the zero-dispersion wavelength. Another advantage of transmitting at longer wavelengths results from the increase in mode-field diameter with wavelength, leading to lower penalty from non-linear effects. In fact, even if FWM is not an issue in this wavelength region, other non-linear effects such as Stimulated Brillouin Scattering (SBS), inter-channel Stimulated Raman Scattering (SRS), Self Phase Modulation (SPM), and XPM can still adversely affect system performance. The increased effective area due to the higher MFD helps in keeping these effects under control. Finally, the lower noise figure achieved by distributed Raman amplification allows required OSNR values to be obtained with lower channel power compared to an EDFA-based system; this helps in reducing the eye closure caused by SPM.

3.2 Change In Fibre Characteristics After Deployment

Modern fibre-optic submarine cables are designed to sustain and survive an environment several kilometers deep. Cable design has advanced such that the effects of "hydrogen ingress", accelerated ageing, and higher loss, have been reduced. As a result, and over the lifetime of an undersea system, the fibre loss increase due to the OH^- ions penetration is minimal, if not negligible. Therefore, fiber degradations post-deployment are primarily caused by:

- Excessive jointing during the cable lay, in particular in beach segments and in armored cable sections.
- Cable suspension and cable kinks.
- Cable repair operations.

All three types of degradation would appear as a lump loss, with increased distribution densities closer to the shore ends due to the higher probability of installation difficulties and the increase in likelihood of repairs. The "beach segment" and very shallow water fiber joints should not account for more than 0.2dB/splice of additional loss. However, these losses are critical because of their proximity to the launching point of the distributed pump power and therefore could impair the transmission performance more significantly than losses induced in the middle of the span. Cable suspension and cable kinks are typically a consequence of less then perfect deployment on hostile terrain and hence could in an ideal world be avoided. Many un-repeatered systems are deployed on the continental shelf and hence in shallow water for which the typical repair depth would be approximately 200m. Although the allocation in terms of repair loss for such system is lower, the frequency of cable breaks is higher and thus, a higher number of repair operations should be anticipated over the system lifetime. Such repairs should not result in more than 0.3dB of additional loss per repair (which equates to the additional cable loss corresponding to twice the depth of the repair plus 2 splice losses).

3.3 Power Budget

In un-repeatered links with distributed gain, the induced lump losses due to jointing and repairs do not degrade the signal OSNR and Q in a linear fashion (i.e., dB by dB). An additional loss in the line not only affects the signal power, but it also reduces the distributed gain in the line and thus, effectively increases the overall Noise Figure of the link. Such "double effect" is particularly pronounced when the induced lump losses are located close to the receive terminal (within last 20km or so). In systems with "adaptive" distributed pump power, the effect of the "near terminal" lump losses can be mitigated to a large extend at the transmit end. However, adaptive pumping does not help much at the receive end where the line operates in an unsaturated amplification regime, in which a degradation in the Noise Figure cannot be recovered by just increasing the counter propagating pump power. For the purpose of this discussion, "shore end" repairs and joints are defined as joints/repairs located within about 30km from either the transmit or receive terminals. "Mid segment" repairs are located further than 30km from a terminal. Qualitatively, and assuming adaptive distributed gain pumping, a "shore end" lump loss of 0.1dB induces a Q degradation of 0.3dB or less at the receive end, and 0.1dB or less at the transmit end. This asymmetry has been confirmed experimentally. In comparison, "Mid segment" lump losses can be accounted for in linear manner, i.e., 0.3dB loss will induce 0.3dB of Q penalty.

4 CASE STUDY

To better understand the effects of all these parameters on an optical link power budget a case study was performed. A simplified design of a un-repeatered link to investigate was agreed upon. The fiber type for the entire link was to be SMF-LS$^{(TM)}$. The Beginning-Of-Life (BOL) cable loss was agreed to be 62dB (at 1550nm) with an End-Of-Life (EOL) cable loss of 66.2dB (taking into account repair and Purchaser margins).

An in-house system design tool was used to simulate the link, with the objective to maximize its capacity. It was agreed to test the link with 45x10Gb/s channels with a margin equating to the EOL loss. The channels are spread over a spectral window ranging between 1614.39nm (first channel) and 1593.37nm (thus, in the L- and extended L-bands), with the first 40 channels spaced 50GHz apart and the remaining channels 100GHz apart, limited by Four-Wave-Mixing. To verify this design, the link was emulated in the laboratory by inter-connecting six sections of SMF-LS$^{(TM)}$ (Fig. 1) for a total a fiber loss of 56.7dB (at 1550nm). The dispersion of the line was measured to be 1,080ps/nm at 1620nm. Attenuators distributed over the span were set to adjust the total span loss to 66.8dB (including 0.4dB of equipment connector loss at each end), to match the EOL loss of the link under investigation.

Xtera's Nu-Wave XLS Terminals were connected at both ends of the span. The Transmit Terminal consisted in two shelves with a total of 25 10G transponders (XP, with E-FEC capability) whose signals were combined together via a multiplexing stage (Odd and Even MUX modules followed by a 50/50 coupler) and fed into an all-Raman Ingress amplifier. The Ingress amplifier combines a discrete stage and a distributed stage that pumps the line in the forward direction. To complement the number of channels, banks of 13 fixed wavelength DFB lasers and 7 External Cavity lasers (ECL), operated CW, were "bolted" onto the Terminal equipment and combined with the transponders channels. Data (a 2^{31}-1 pseudo-random bit sequence) are encoded on the DFB laser and on the ECL multiplexes by separate Ti:$LiNbO_3$ Mach-Zehnder modulators. Stimulated Brillouin Scattering was suppressed by applying on each CW source a sine-wave modulation (modulation depth =3%, frequency between 7 and 15kHz) to broaden the spectrum.

The Receive Terminal consisted in an all-Raman, 3-stage, Egress amplifier that combines a distributed stage that pumps the line fiber in the backward direction, and two discrete stages. The Egress amplifier is followed by a narrow-band (25nm) all-Raman single-stage amplifier, used as a pre-amplifier. An interleaver splits the aggregate channels into 2 multiplexes (Odd and Even) with a channel spacing of 100GHz. Each multiplex is then fed into an array-waveguide grating-based demultiplexer (Demux) and the individual channels are then detected by the transponders. The combined Raman amplifiers provide compensation for about 97% of the chromatic dispersion introduced by the line fiber. The residual chromatic dispersion is adjusted via a low-loss Dispersion Compensation unit placed between the Egress amplifier and the pre-amplifier. The list of test cases carried out to validate the system design is detailed below. For each test, the Optical Signal-To-Noise ratio (OSNR) of all channels and the Q-factor were recorded. The success criterion was for the measured Q value to be greater or equal to the target Q value required to ensure the specified EOL Bit Error Ratio (BER).

4.1 Stability Test

With the span set in its EOL configuration, both in terms of loss and capacity, the stability test was carried out to baseline the system performance. The plot in Figure 2 shows the average Q and OSNR after 18 hours of operation. For the transponder channels, the Q was derived from the pre-FEC corrected error count whereas for all CW source channels (except 2), the Q performance was calculated from the instantaneous BER recorded at the end of the testing period. The performance of the remaining 2 CW source channels is derived from the cumulative BER recorded on a Sonet test set. The minimum $Q_{measured}$ value was ≥ 9.8dB with a min/max fluctuation across all channels ≤ 0.4dB, resulting in a BER better than 10^{-15} after Forward Error

Correction. The worst channel OSNR was ≥ 11.6dB. The worst performing channels were located at both ends of the channel plan

4.2 Sensitvity Analysis Of Capacity As A Function Of Span Loss

This test case was devised to assess the impact of the cable loss on the number of channels that could be supported.

Starting from the EOL span configuration (66.8dB, 45 channels), a lump loss of 1dB was inserted at the end of the span and the performance of all channels was recorded. Channels that did not meet the Q_{target} of 9.5 dB required to meet a EOL BER of 10^{-15} were de-provisioned. This 1dB increase in the EOL span loss resulted in a decrease of the maximum capacity to 37 channels (with a minimum $Q_{measured}$ of 9.8 dB). The span loss was further increased by adding 2 dB of discrete attenuation at 101 km from the receive Terminal (refer to Fig. 1), resulting in a total span loss of 69.5dB, or a 3dB higher loss compared to the baseline EOL span loss. The maximum number of channels that could be accommodated dropped to 21. These results are in close agreement with the system design simulations that predicted a maximum capacity of 15 channels for a span loss 3dB greater than the baseline span loss (Fig. 3).

4.3 Effect Of System Repairs

The effects of land cable and submarine repairs on the link performance were analyzed as a function of the repair location and the incremental loss. Table 1 below summarizes the repair scenarios that were investigated.

As a baseline, the BOL Q-performance for all transponder channels and for the 1st channel (CW source) is shown in Fig. 4a. 1dB repairs, in the form of either (fiber +connector) loss or lump loss, were emulated at both the input and output of the span, where the effect on the distributed pump power would be the most pronounced. For scenarios 1, 2, 5, and 6, all channels remained error-free after FEC. The maximum Q-penalty of 2dBQ was observed on the first channel.

Similarly, in scenario 3, all channels were error-free after FEC. Once again, the first channel is suffering the highest penalty (1.8dBQ). However, in scenario 4, a few channels at both ends of the channel plan were no longer error-free after FEC, even after adjustment of the backward distributed pump power. Figure 4b shows the Q-penalty with respect to the baseline span loss. Large lump losses close to the receive Terminal drastically reduce the reach of the pump power into the line and reduces the OSNR seen at the input of the Egress amplifier. Such losses (in excess of 0.5dB) should thus be reworked.

4.4 Impact Of Point Losses

In this last test case, the system impact of an excessive amount of point losses (splices) in the "shore-end sections" of the span was assessed. Starting from the BOL span loss configuration with EOL capacity, four sets of splices were successively added to the line, 2 sets within the first 35 km and 2 within the last 35km, respectively. The table of Figure 5 details the quantity of splices in each set, their location in the span, and their estimated loss. After the addition of each set of point losses, the performance of all channels was recorded. The addition of about 0.7dB of "distributed" point losses, either at the beginning or/and at the end of the span, has little impact on the system performance. The line was then switched around (beginning of the span becoming the end of the span) and the same measurements were repeated. The same observations could be made. The "reserve" of distributed pump power, both in the forward and backward directions, accounted for during the design phase, can compensate for a large number of point losses that could arise during cable deployment

5 CONCLUSIONS

The theoretical and experimental works outlined in this paper demonstrate that it *is* possible to deploy state of the art systems using non-ideal fibre types if the correct care and consideration is given to selecting equipment which provides the necessary optimal transmission capability.

The paper surmises that not only the original system performance needs to be considered in the design but also what has happened to the fibre in the period from initial installation through to end of life of the redeployed system. The performance sensitivity stemming from the fibre type, location of lump losses, amplification type and non-linear effects has been highlighted, and ways to overcome these constraints provided.

By fully considering all these points before re-deploying a system, it has been demonstrated that economic and technically advanced scientific and commercial solutions are available to us all.

6 FIGURES AND TABLES

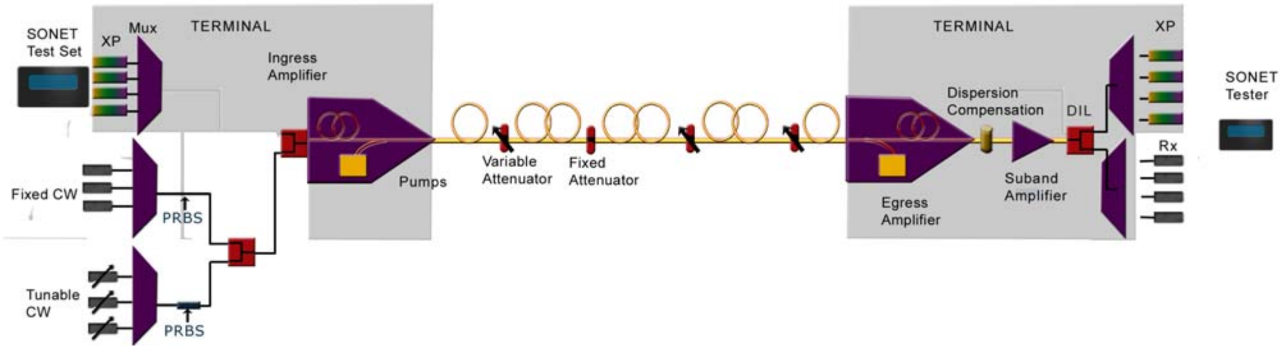

Figure 1. Set-up of the emulated link

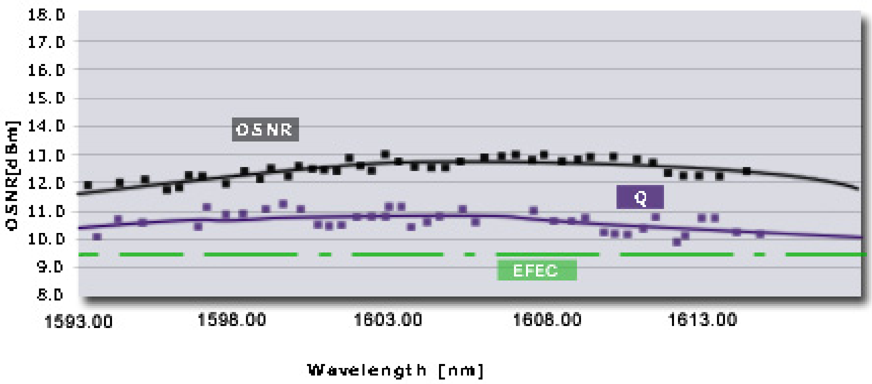

Figure 2. Stability test Average Q and OSNR

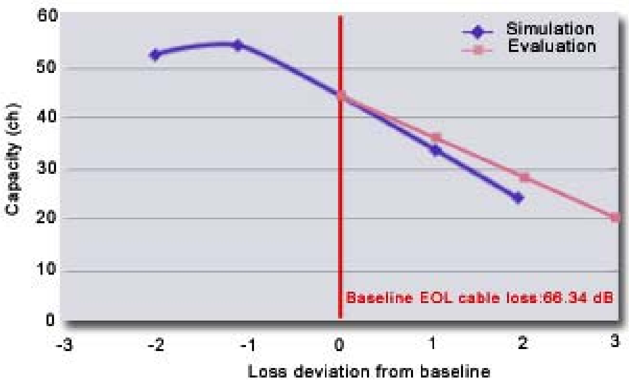

Figure 3. Capacity vs. Loss Devtion from the Baseline

	Scenario	Measured Span los (dB)	Methodology / Configuration
0	BOL (baseline)	63.7	
1	BOL+1dB at beginning of span	65.4	Add section of 4km fiber (connectorized) at the very beginning of the BOL span configuration
2	BOL+2dB at beginning of span	66.4	Add 1dB attenuator (connectorized) at the beginning of the scenario 1 configuration
3	BOL+1dB at end of span	65.5	Add section of 4km fiber (connectorized) at the very end of the BOL span configuration
4	BOL+2dB at end of span	66.2	Add 1dB attenuator (connectorized) to the scenario 3 configuration, 4km away from the Receive Terminal
5	BOL+1dB in first 30km of span	65.9	Add section of 4km fiber (connectorized) after 25 km of the BOL span configuration
6	BOL+1dB in first 30km of span + 1dB at end of span	66.4	Add 1dB attenuator (connectorized) at the very end of the scenario 5 span configuration

Table 1: Repair scenarios

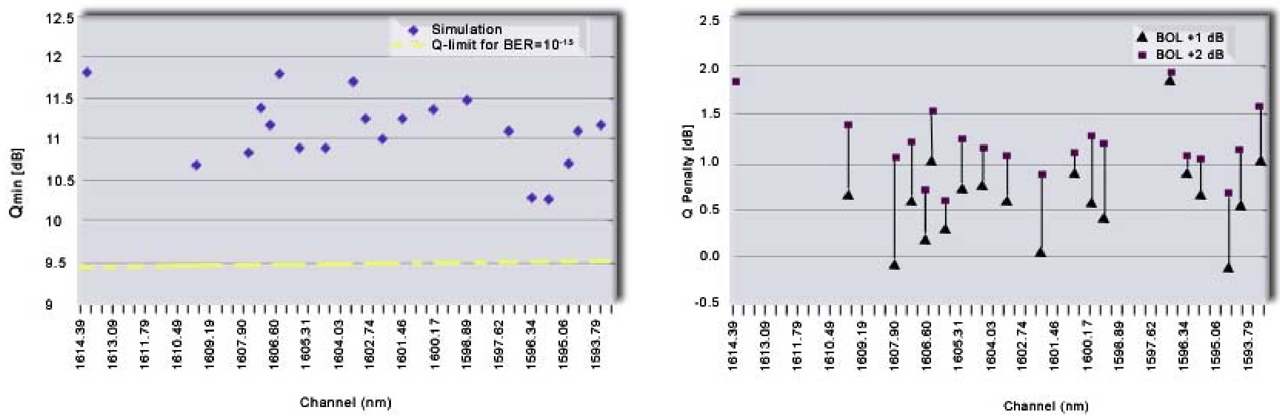

Figure 4: a) BOL Q-performance; b) Q-penalty with respect to baseline in scenario 4

	Splice #	Dist. From Beg of Span (km)	Splice Loss (dB)
1st Set	s1	10.9	0.11
	s2	13.8	0.17
	s3	19.7	0.05
4th Set	s10	22.6	0.05
	s11	28.4	0.07
	s12	31.2	0.10
	s13	31.5	0.15
avg. splice loss (dB):			0.10

	Splice #	Dist. From End of Span (km)	Splice Loss (dB)
2nd Set	s4	15.3	0.15
	s5	17.7	0.10
	s6	21.2	0.11
3rd Set	s7	24.1	0.13
	s8	29.9	0.08
	s9	32.8	0.09
avg. splice loss (dB):			0.11

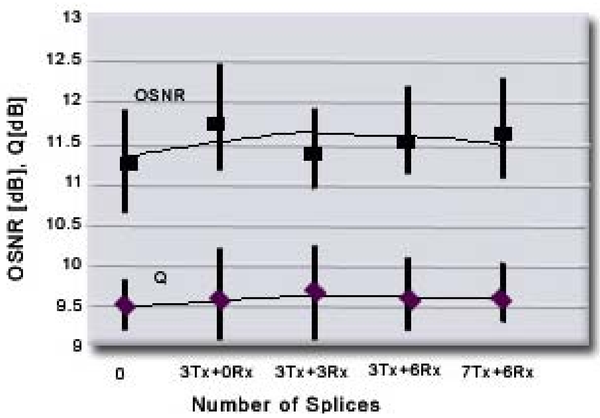

Figure 5: Impact on performance of point losses in shore-end sections