SPECTRAL HOLE BURNING EFFECTS AND SYSTEM ENGINEERING RULES FOR SYSTEM UPGRADES

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Abstract: The massive capacity potential of submarine systems is rarely exploited on installation. Loading channels are typically applied to maintain the traffic channels within their desired operating limits until the system is equipped to full capacity. Initially, the power density across the spectrum may differ from the End Of Life design, and this gives rise to Spectral Hole Burning. We discuss how these effects can be minimised and engineering rules are proposed that may be applied if a system is to be upgraded towards its ultimate capacity. Examples are presented based on real systems, simulation tools, and test bed measurements.

1 INTRODUCTION

As submarine system traffic continues to grow, it is becoming evermore popular to upgrade sub-equipped legacy systems with new terminal equipment. Advanced equipment technologies allow these systems to be upgraded beyond their original design capacity [1, 2]. Such systems typically comprise of both partially populated fibres and dark fibres. Initial upgrade requirements can be quite modest compared to the potential maximum capacity and so a well managed upgrade strategy is essential. Not only must existing channels be unaffected by the equipment overlay but newly installed channels must have the correct operating margin and should allow future upgrades with minimal operational impact.

Loading channels are deployed when a system is partially populated so that both the total EDFA output power and traffic channel power are maintained at their optimal levels. Maintaining the correct total power ensures minimal gain tilt whilst the correct traffic channel power ensures the optimum balance between OSNR and nonlinear penalties. For cost reasons, loading channels have typically been deployed in small numbers, and as a consequence, the power level of each loader is normally several times higher than the traffic channel power. Loaders will be gradually removed as the traffic channel count is increased towards the full capacity of the link. Clearly, it is important that any loading channel solution is reliable, configurable and inexpensive, the latter being of note since at full capacity, all loading channel will have been discarded.

Even with gain flattening filters, however, the gain spectrum can be far from flat for partially populated systems when incorrect loading channel strategies are used, due to Spectral Hole Burning (SHB) effects [3]. These effects can lead to exaggerated OSNR and non-linear penalties for some channels, and limit channel power adjustment sensitivity during upgrade procedures.

In this paper we discuss the effects of loader wavelength positioning and power on neighbouring traffic channels based on experimental and simulation results. A set of simple system engineering rules are developed to show how SHB effects can be suppressed through an Equal Power Density (EPD) concept. A working example is demonstrated by applying the rules to an ultra-long distance test-bed, and the results are compared to simulations. Application of the rules demonstrates good pre-emphasis sensitivity and good agreement between simulation and measurement is possible without recourse to a simulator which includes SHB.

2 SPECTRAL HOLE BURNING DEPENDENCE ON LOADING CONDITIONS

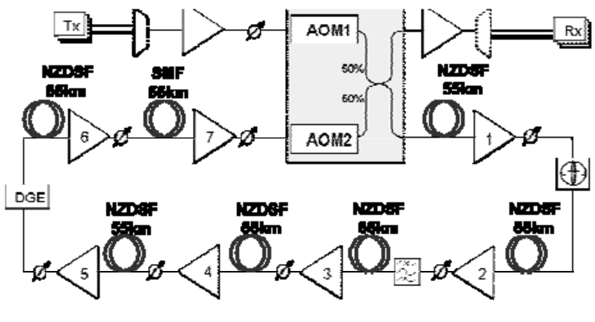

Figure 1 Loop Schematic

A 3400km re-circulating loop test-bed with 55km span length was configured to explore the SHB dependence on the loading channel plan. The loop is illustrated in Figure 1. The loop amplifiers were set up at the gain and low noise figure point typical of modern generation systems with a working bandwidth of 30nm. A comb of ~3nm spaced loading channels was used to set up the loop. The total repeater output power was +6dBm and the nominal traffic channel power -7dBm. A tuneable Gain Flattening Filter (GFF) was included within the loop orbit to maintain a flat gain spectrum and noise floor at the receive side. A low frequency polarisation scrambler was used to mitigate polarisation dependent gains effects in the loop amplifiers.

Figure 2 shows the ideal received spectra from the loop, with 8 loading channels, labelled A to H. This can be contrasted with the 2 traces in Figure 3 which illustrate the effect of sparsely allocated loading channel schemes.

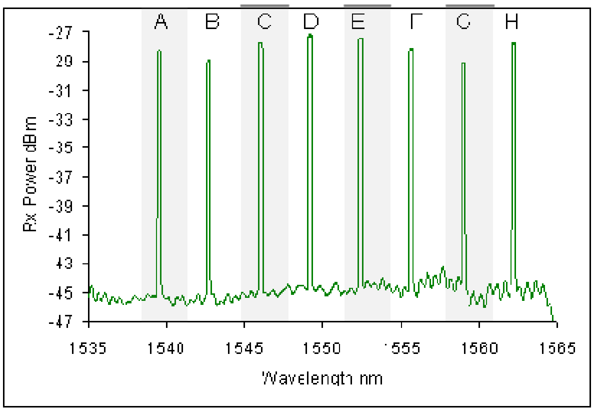

Figure 2 Baseline optical spectra with 8 evenly spaced loading channels

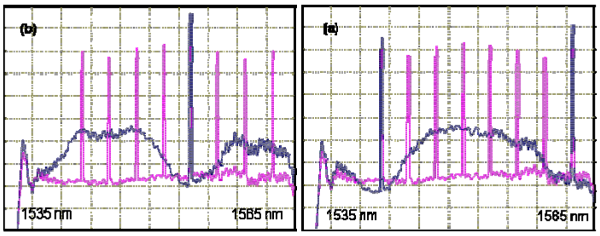

Figure 3 Received optical spectra (a) 2 loaders at the edges of the band, (b) 1 loader at the centre of the band

Figure 3a shows the effect of placing 2 loading channels at the edges of the band. This loading scheme may appear promising because the loading channels can be kept away from the traffic channels, freeing up the whole of the central operating region for traffic channels. However, the noise level in the centre of the band is significantly higher than the uniform loading comb trace. When a few nominal power traffic channels are inserted into the centre of the band with this loading condition these would exhibit higher gain than expected when fully loaded.

Figure 3b shows the effect of placing a single loading channel in the centre of the band. A spectral hole is formed in the gain profile near the loading channel affecting the local gain in the region. A similar affect would be found if a group of closely spaced traffic channels were placed in the centre of the band without using loading channels [4]. This latter scenario may appear promising from an economic point of view, particularly if sufficient performance margin is available. However transmission performance may differ at full capacity when more channels are added giving migration problems (see next section).

SHB effects are localised and occur over a few nm. In order to minimise SHB gain distortions, the concept of maintaining an Equal Power Density (EPD) is introduced. Loading channels and groups of traffic channels are adjusted such that the power is equally distributed across the entire system bandwidth, within a few nanometres resolution. EPD is a system specific parameter which should be maintained from the initial upgrade, until maximum traffic capacity has been reached. Therefore a fully tuneable multi-channel loading source is required. Despite the perceived additional upfront cost, this provides the lowest overall cost solution – improving performance through life and minimising the impact at upgrade events.

3 TRANSMISSION PERFORMANCE

In this section, we demonstrate how to achieve band independence during upgrade procedures and illustrate the concept through examples of replacing a single loading channel with 1 or 5 traffic channels within a band. These two extremes serve to illustrate the realistic effects of partial band upgrades.

Figure 4 shows the effect of replacing 1of the 8 loading channels by traffic channels. Two traces are shown. First, 1 traffic channel was inserted into band B then the group of 5 channels was interchanged with the single channel. The launched traffic channel power was the same for both cases.

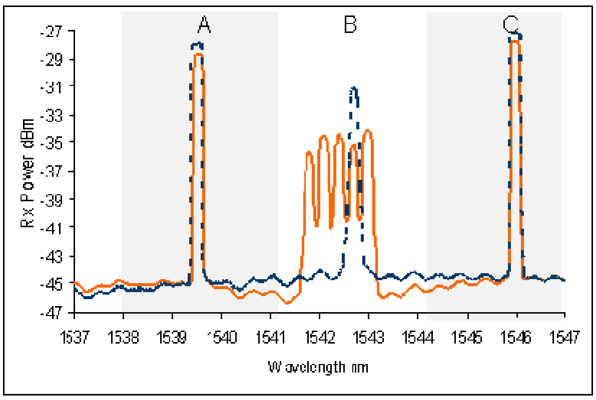

Figure 4 Received optical spectra with one loader removed. One trace with 5 traffic channels inserted into band B (solid line), and one trace with 1 traffic channel in band B (dashed).

With just a single traffic channel occupying band B, the energy density is 4dB less than the EPD case causing the noise floor to rise slightly in the vicinity. When 5 traffic channels occupy the band, the energy density is 3dB greater than the initial loading case and a spectral hole is formed.

To investigate the transmission performance effects further, transmit channel power sweeps were carried out. The OSNR and BER performance were measured for both the single channel and 5 channel cases. The lower wavelength band B was chosen for the experiment since SHB effects were strong in that region.

Figure 5 shows the received OSNR and Q performance for the two cases. The nominal channel power (-7dBm) is highlighted with a dashed line.

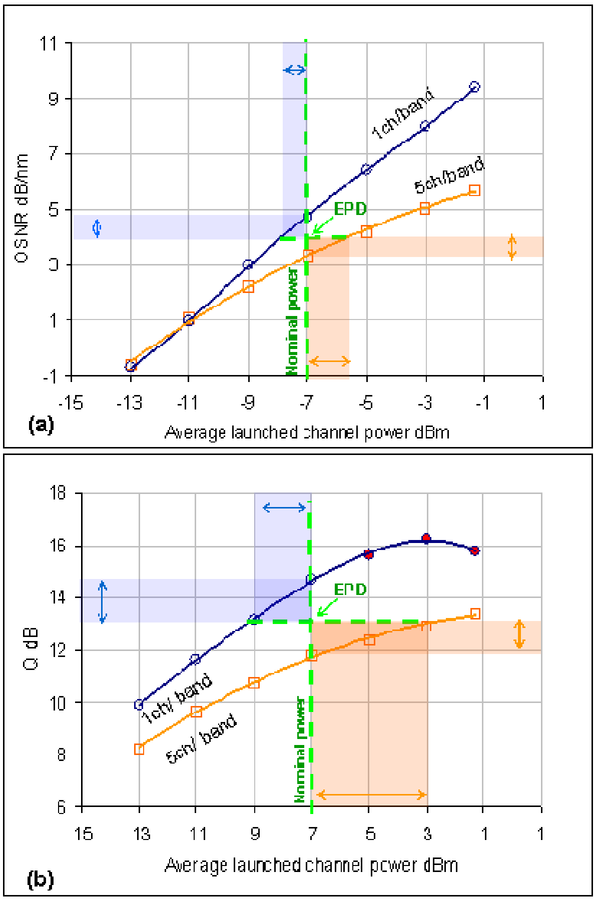

Figure 5 Average launch power sweeps for 1 and 5 traffic channels per band for (a) received OSNR, and (b) received Q performance

In Figure 5a, the OSNR is observed to be ~1dB higher when the single channel occupies the band and ~1dB lower when 5 channels occupy the band. In addition to these 1dB offsets, the slope of the curves is also significant. When the power density is greater than the EPD, the OSNR slope is reduced and therefore the pre-emphasis sensitivity is reduced [5]. Clearly the slope would be even shallower if more traffic channels were placed in the band.

Figure 5b shows the effect of SHB on the received Q. Here the reduced pre-emphasis sensitivity is even more marked than for the OSNR due to nonlinearities. To recover the Q performance by 1dB, the average channel power would have to be increased by 4dB. Changes in pre-emphasis of this magnitude would tend to starve the other upgrade channels of power.

4 SYSTEM ENGINEERING RULES

Based on the observations above, a simple set of system engineering rules has been devised for the allocation of loading channels so that SHB effects can be suppressed for Start Of Life (SOL) upgrades, allowing channels to be operated at nominal settings with margin, and minimal impact throughout upgrades. The rules take into account the loading channel power and wavelength position for the particular number of traffic channels applied.

Firstly, the system is split into bands, with 1 loading channel allocated per band to keep the EPD constant. The loading channel wavelength separation is ~3nm. The total power of the traffic channels is set to within ~±3dB of the EPD per band, at the nominal launched channel power.

For systems operating below their full traffic capacity we recommend the following rules:-

- The entire useable bandwidth of the system should be split into **~3nm regions or less** with **the power density in each band adjusted to a value within ~±3dB of each other.**

- Each **non-traffic carrying band should include at least 1 loading channel** to maintain EPD across the system bandwidth.

- The **power of the loading channels** should be adjusted such that **the traffic channels are operating near the middle of their adjustment range at the nominal channel power** for the system.

The physical structure of the erbium doped fibre within the optical amplifiers causes the lower wavelength region of the gain spectrum to be most sensitive to SHB effects. The 3nm loader spacing is considered prudent for this reason. This pragmatic approach is also consistent with the banded dispersion compensation architecture typically used.

A flexible Multiple Line Loader module with variable wavelength and channel power which is compatible with these rules is pictured in Figure 6.

Figure 6 Multiple Line Loader module

4.1 Working example

The system engineering rules were then applied to a 9800km link. The design capacity of the system was 32 channels over a 12nm bandwidth with a nominal EOL channel power of -4dBm. The initial upgrade capacity was 6 channels. From the SHB suppression rules above, a minimum of 3 loaders are required.

Table 1 summarises the key parameters for the system example reflecting the SHB rule constraints.

Line design capacity (no. channels)	32
System bandwidth (nm)	12
Number of bands allocated	4
Initial number of loaders allocated	3
Initial number of working channels	6
Band separation (nm)	3.0

Table 1 Key system parameters for a 6 channel upgrade considering SHB rules

Figure 7 shows the number of loading channels required for a given number of traffic channels. The curves correspond to the ±3dB tolerance between the total traffic power and the nominal EPD band power. Any channel plan that falls within this region should have low SHB penalties and good pre-emphasis sensitivity.

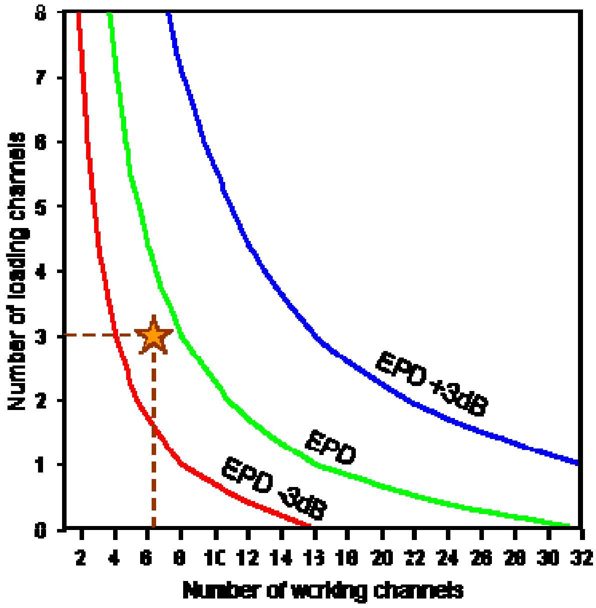

Figure 7 Loading channel count requirements for a partially populated system with a maximum capacity of 32 channels

The figure shows that for an initial deployment of 6 working channels, a minimum of 3 loading channels are required. Clearly as the traffic channels count increases, a lower number of loading channels are required, tending towards zero for the fully populated system.

To verify the system engineering rules and to show the benefit to facilitate more efficient modelling, the loop test-bed was used. The average channel power was swept by changing the total loading channel power, using the same procedure as in the previous section.

A state-of-the-art transmission software package was used to compare simulated with measured results. The model was set-up in a flat gain mode with SHB disabled, to verify that a good match could be achieved when the system engineering rules were applied.

The results are shown in Figure 8 for the initial 6 channels under test. The dashed lines show the received OSNR and the solid lines show the Q performance versus average channel power.

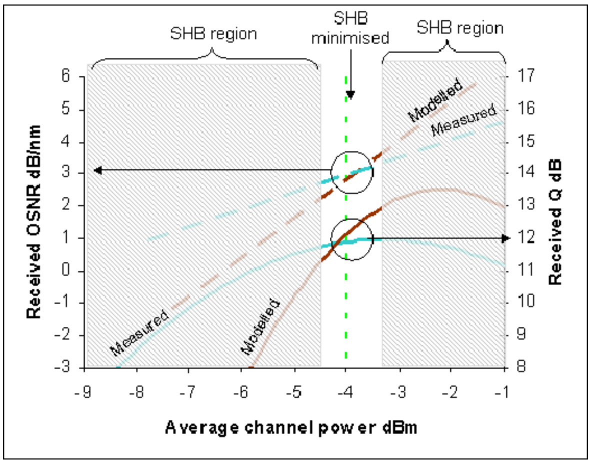

Figure 8 Received OSNR (dashed) and Q (solid) performance for a 6 channel upgrade system example comparing measured results with a simple, flat-gain model

Using SHB suppression rules it is possible to calculate the number of loading channels required for a given number of traffic channels, at the nominal operating power for the system. Figure 8 shows that at a nominal channel power of -4dBm, there is a good match between simulation and experiment, indicating that SHB has been minimised.

For other channel powers, SHB effects are clearly present. The Q performance trends between the loop and the model differ due to the OSNR difference and the nonlinearities (which is a function of path averaged power).

The channel count can be increased within the same traffic band to increase capacity by a few channels with minimal impact. Further traffic channels can be added to the other bands by readjusting or removing the loading channels in accordance with the system engineering rules. In all cases the installed channels will operate close to their nominal channel power with the correct operating margin throughout.

5 CONCLUSIONS

Spectral Hole Burning is a complex phenomenon that up until now has required sophisticated modelling techniques to design systems containing a mixture of loading and data channels on partially lit submarine links. This paper has described how SHB effects can affect the installed operating margin and upgrade potential of submarine systems if the available bandwidth is incorrectly balanced by traffic and loading channels. By designing systems following the system engineering rules outlined here, SHB can be largely neglected and the simulation times significantly reduced.

From a practical point of view, equipment vendors have been mindful that loaders are essentially “throw away” products. This has tempted these to use as few loaders as practically feasible. Whilst these undoubtedly work we have shown that this approach does not lead to seamless upgrades. We have proposed a simple set of design rules, that when used in conjunction with low cost loaders, can lead to the superior operation of a partially populated system which can be rapidly upgraded with little additional and complex transmission work.

6 REFERENCES

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