PREDICTING THE UNPREDICTABLE

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Abstract: Today's upgrades usually aim to expand the capacity of existing systems as much as possible. This in turn means that the power budget for an upgrade needs to be as precise as possible, since including large margins will reduce capacity. Accordingly, minimising the uncertainties regarding the actual parameters of an existing system is a prime focus.

Non-intrusive measurements of optical spectra can give information about noise performance and system bandwidth and long-term performance, as logged by FEC and wet-plant monitoring provide insight into ageing and repairs. However, there are usually uncertainties in some of the data and there are a number of practical constraints which must be considered.

This paper discusses some of the issues and some of the techniques which can be used to reduce uncertainty.

1 INTRODUCTION

The fundamentals of optical transmission are clearly the same for a new build or an upgrade. A power budget or computer simulation must consider noise accumulation, propagation impairments and time-varying effects. It must also include margins to cover repairs, ageing and other factors.

For a new build the objective is to produce a line design meeting a specific target capacity and performance for the worst case of ageing and repairs. For an upgrade, however, the line design already exists and the aim is to determine how much capacity can be achieved with the latest terminal technology – or even with future technology! As might be expected, pushing the boundaries of the system design creates issues.

Computer simulations play an important role both in designing new systems [1,2] and in evaluating the upgrade capabilities of installed systems [3]. However for such simulations to be meaningful and precise the input data has to be complete and accurate; this can be difficult for a number of reasons:

- The original power budget often contains nominal, rather than actual values for fibre and repeater parameters. Sometimes these are deliberately a little pessimistic to ensure that contractual targets are met – this is particularly the case after a new technology has just been introduced.
- Getting precise details of ageing is not easy.
- Achieving the maximum capacity requires exploiting the extremes of the optical bandwidth: the original design, however, would probably have aimed to avoid using the band edge and there would be little detailed measurement data in this region.

A complication, in some cases, is a requirement to maintain the existing wavelengths. Since repeater power is fixed, adding new channels must involve finding some available optical power. If there are loading channels then these may be turned down/off and the existing channel power may be reduced providing that there is some operating margin. More difficult to assess is what interference might result from placing new channels close to existing ones, as terminal equipment designed for wide channel spacing generally doesn't use narrowband filters; this can be determined only by testing or on the basis of past experience.

Additionally, there are a number of practical constraints which must be considered. Although computation might suggest a particular channel plan as "optimal", most suppliers are obliged to place channels on some form of grid, typically at 30-50 GHz spacing, and also avoiding any existing channels which are to be retained. In a very few cases Line Monitoring Equipment (LME) channels may provide an additional constraint; in any event the signals used must be considered in the power budget, although the penalties they contribute are usually small.

The simulation accuracy depends on the length of the bit sequence used [4], with the precision increasing with the sequence length. However, this also increases the computation time required, as does increasing the number of channels and the number of repeater spans, In practice, a number of simulations will need to be run and the total time required may become a significant issue, particularly for long, nonlinear systems. There are a number of techniques for reducing the time needed, but ultimately there may be some compromise on accuracy.

2 OBTAINING INFORMATION

For obvious reasons traffic-affecting measurements are usually not welcome, but some data can be obtained in non-intrusive ways.

Data such as repeater separation and dispersion maps are usually readily available, as are the standard parameters of the optical power budget. The design budget, however, must be treated with caution, as values are often nominal and the reality may be a little different.

Optical spectra can usually be obtained at transmit and receive monitor ports, giving an idea of OSNR and the system bandwidth; this also confirms the precise location and power of existing channels in the case where they are to be retained. With a fine spectral resolution this can give an indication of nonlinear effects – for example, if the spectra show evidence of chirped modulation at the transmitter, or spectral broadening at the receiver.

The amplifier gain shape and tilt must be considered with such measurements, as a system operating with a few channels only will behave differently to one with the entire bandwidth filled [5] – the analysis of such measurements is quite challenging.

Performance data from the existing SLTE(s) are also useful. Comparing measured Q with that predicted from simple OSNR calculations gives an indication of propagation effects, while long-term error-correction statistics can provide a measure of line fluctuations – an example is shown below.

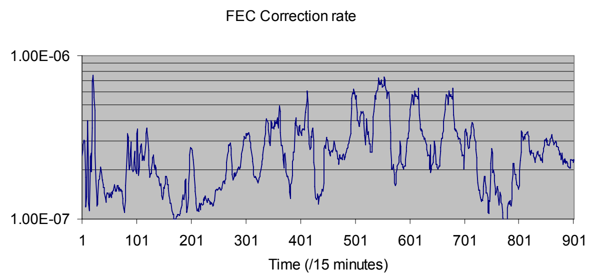

Figure 1: Example of System Performance Fluctuations

This data can potentially show long-term degradations, but the source of degradations may not be obvious, since they can be induced by various line effects [1], or by degraded terminal performance. Ideally one needs data from several channels across the band, but this may not be possible in all cases. Such measurements are particularly critical when one wishes to retain the existing channels, as they provide a good measure of current margins.

Long-term system supervisory data may show up degradations, but most are incapable of resolving section changes smaller than ~1 dB and some techniques only provide relative changes since the last calibration/repair – insufficient for precise budgeting, although capable of showing an individual repair or repeater degradation.

3 ITERATION AND DEDUCTION

The prediction process consists of first running simulations of the current system configuration and adjusting parameters whose values are not well known to produce results which mimic the actual system performance. The next step is to modify the inputs to represent the upgrade case i.e. a different channel plan and terminal equipment.

The first step seems somewhat problematic if one has several unknowns, but in reality the parameters of dispersion maps and fibre types used in submarine systems are quite well known. Given the target capacity and date of design an experienced engineer can estimate the values of the missing parameters and then test these values by attempting to predict current performance.

In addition to the iterative process just described, deduction can play a useful role. For example, if one channel shows signs of degradation while others do not, then the problem is clearly channel specific: if all the channels are affected, it is more likely that the effect is due to the line – although one would clearly also consider other common elements such as line amplifiers and optical mux/demux units. There is often a wealth of operational evidence which is worth examining.

4 PARAMETERS AND THEIR RELATIVE SIGNIFICANCE

Given the difficulty of obtaining accurate information, what impact does this have on the accuracy of the resulting power budget and capacity prediction? Received Q depends largely on:

- Noise accumulation
- Nonlinear effects
- Time-varying effects

The following sections attempt to explore the relative importance of different factors.

4.1 Amplifier Noise Accumulation

Noise accumulation depends essentially on the amplifier noise figure and the span loss between amplifiers.

The noise figure is an important parameter in modelling the noise build-up over the line. Although usually treated as a single number it has an intrinsic wavelength dependence [7], which is in the order of 0.1 dB/nm for submerged repeaters, i.e. 3 dB over a 30 nm bandwidth. Additionally there is a significant dependence on the amplifier gain shape, particularly at the edges of the band where the final channels may be added. Figure 2 shows an example of noise figure derived from non-intrusive spectral measurements.

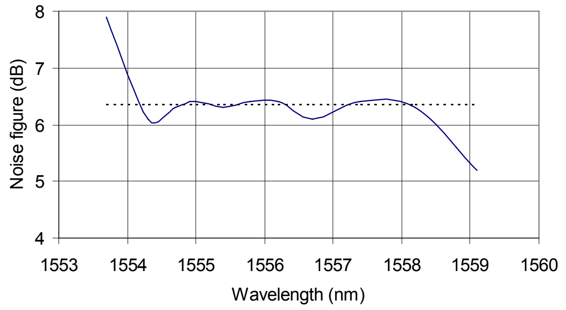

Figure 2: Noise figure dependence of an optical amplifier

Amplifier gain shape also has a significant impact on the achievable performance of a system – particularly for older systems without gain-flattening filters. Not only are the edges challenging to operate channels, it can also be difficult to get accurate details of the gain shape of an already installed system. Given a non-ideal gain shape, the obvious way to deal with it is by applying pre-emphasis. Here it is very important that the simulation is realistic for two reasons:

- If large levels of pre-emphasis are required (typically at the edges of the band), these channels will need a lot of power, which reduces the power (and consequently the OSNR) of all other channels.
- Large local channel powers also mean that nonlinearities become more significant.

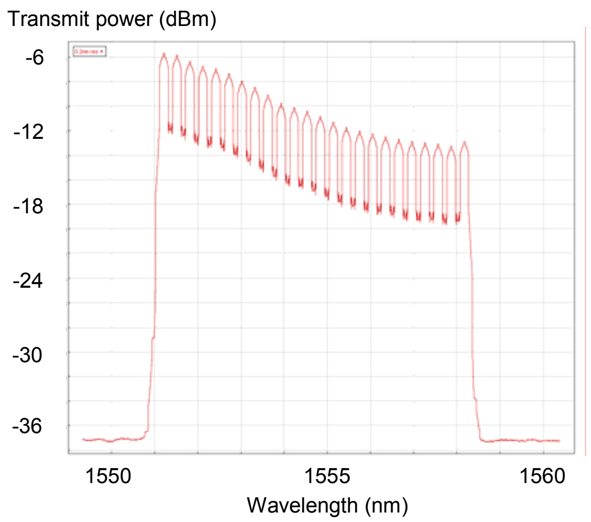

Figure 3: Channel pre-emphasis

Figure 3 (based on modelling of a real system) shows that channels at one extreme of the band need to be 8 dB higher than those at the other extreme, so this effect becomes rapidly more important as channels are added at the low gain end of the band.

4.2 Nonlinear effects

Fibre nonlinearities – either localised or broadband – become more significant as system power increases past the point where light-material interactions leave the harmonic regime. Up to this point Q increases as the power is raised: beyond this point it starts to decrease. For systems operating at 10 Gbit/s line rate the relevant nonlinear effects can be single channel (such as SPM) or multi-channel effects (e.g. XPM) and they depend not only on optical power, but also on fibre parameters such as effective area and dispersion. Multi-channel interaction may be particularly relevant to an upgrade because in general the channel separation will be reduced compared to the original design. The following graph shows non-linearity at the extremes of the band (for Noise Figure = 5dB with gain-flattened amplifiers); in this case the higher wavelength end has rather less dispersion, leading to greater effects.

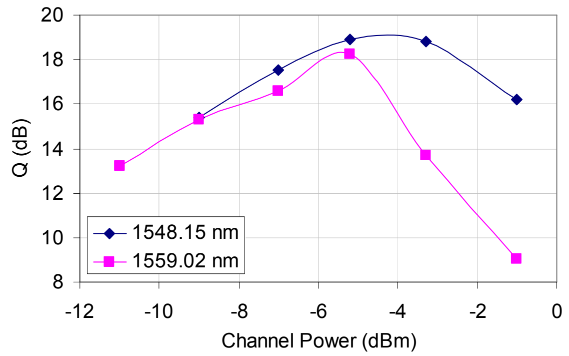

Figure 4: Q as a function of optical power (from a 32 x 10 Gbit/s system)

There are a number of ways to mitigate nonlinear effects and operate at higher power levels, the most popular being the use of sophisticated combinations of different fibres which vary the chromatic dispersion along the overall link and phase modulating the transmitted pulses; additionally there will normally be both pre-compensation and post-compensation.

Most recent undersea systems utilise Large Effective Area Fibre (LEAF) in order to keep nonlinearities low. Because most LEAF has a chromatic dispersion with strong wavelength dependency it is often used close to the amplifier output (where power is high), with other fibres elsewhere to optimise overall dispersion and losses. In reality, there are often significant deviations from the ideal dispersion map, e.g. due to manufacturing imperfections or wet-plant installation problems. Furthermore, repairs often create a further deviation from the initial map assumed in the original power budget.

The following figures show what impact deviations from an ideal dispersion map can have. The results are based on modelling a generic trans-Atlantic system with typical nonlinear effects, but no degradation other than the repairs. It's worth remarking that one of the examples matches a real repair and that the simulation is a good fit to the observed effects.

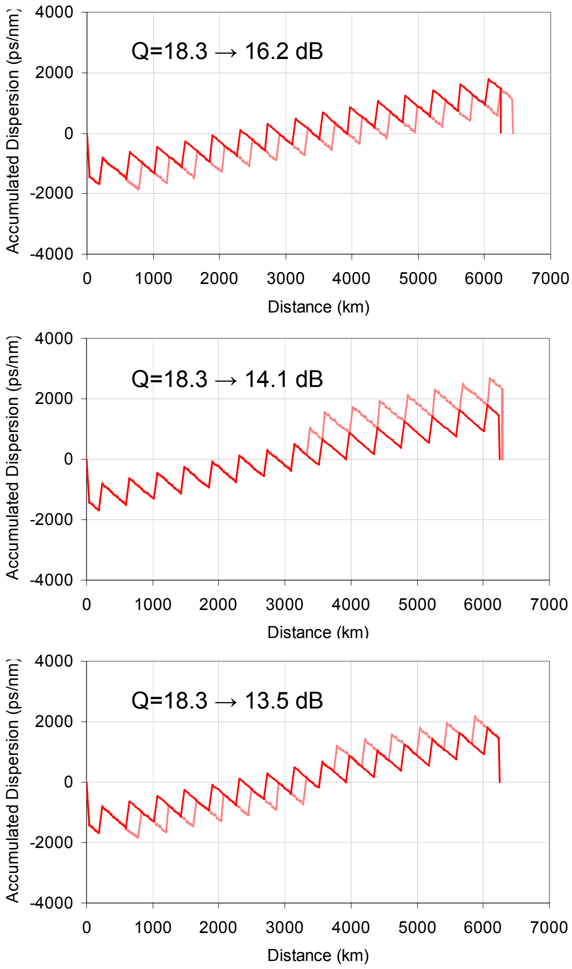

Figure 5: Effect of departures from the ideal dispersion map

The results show that the impact of the dispersion map can be very significant, which means that information regarding repairs is absolutely essential to make accurate predictions about upgradeability.

4.3 Time Varying effects

Experience has shown that the performance of WDM systems varies over time, one of the major reasons being relatively slow variations in the State Of Polarisation (SOP) of each individual channel coupled with a variety of Polarisation effects (PMD, PDL & PDG) in the line [6]. These variations can produce a penalty of 2 dB or more in extreme cases.

Computing the magnitude of this penalty is a very hard problem for which there is no well established solution so far. For an upgrade, however, one can use the long-term data from the existing terminals (described in section 2). While this data obviously applies to the specific loading plan of the existing configuration, the upgrade process will increase the number of channels and will probably reduce the number, or power, of loading channels. Both theory and experience show that this generally results in no increase in the penalty – in some cases there may be slight reductions. So while, the computation of this phenomenon remains a serious problem for new builds, for upgrades a good estimate can be made if one has access to long-term data of performance fluctuations.

5 DISCUSSION & SUMMARY

There are a large number of parameters need to make an accurate assessment of upgrade potential and there will inevitably be some degree of error / uncertainty regarding precise values. This paper has discussed a number of these and described processes which can refine the predictions, but clearly perfect accuracy is not possible. What then is the achievable accuracy? The following table attempts to summarise the individual contribution:

	Uncertainty		
Parameter	**Best case**	**Worst case**	**Comment**
Linear Effects (noise figure)	0.3	1	Better precision with careful non-intrusive tests
Linear Effects (gain shape)	0.3	0.7	Worst case if outside known band
Non-linear effects	0.5	1	Worse if unknown repair exists Better if channel power reduced
TVSP	-0.5	0.5	Penalty may reduce
Simulation accuracy	0.3	1	Depends on number of bits and the level of nonlinearity (not independent!)

	Uncertainty		
Parameter	**Best case**	**Worst case**	**Comment**
Sum of uncertainties	**0.9**	**4.2**	
Root of sum of squares	**0.7**	**1.9**	Assuming that uncertainties are uncorrelated

The "best" represents the case where all efforts have been taken to obtain and analyse data: the "worst case" assumes rather less effort. Clearly, accuracy will depend on the data available, so these numbers should not be taken as more than indicative of the authors' experience, based on results from a number of different systems.

While uncertainties will always exist, a comprehensive review of available data and good non-intrusive measurements can reduce the margin of error significantly. The process involves both iteration and a degree of reasonable deduction, making it more than a simple analytic procedure and one where the experience of the people involved can add value. Validation of the predictions by comparison with real systems can provide the feedback which leads to reliable predictions. Using this type of process can make a substantial reduction to the uncertainty of prediction, with our own experience over a range of systems supporting accuracy in the 1 dB range.

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