XTERA®

Generalized SNR for Submarine Systems

Calculating performance in repeatered open line systems

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Introduction

Xtera has developed an Open System architecture to allow the sharing of bandwidth and/or fibers while allowing multiple SLTE vendors access to the line system gateway. With potentially different channel plans and line cards on the repeatered system, a method to calculate channel independent performance is required.

In this White Paper, we show how the GN model [1] can be used to separate the line system performance from the SLTE, allowing simple calculations for various channel spacing and baud rates. The methodology is very similar to the Open Cables Working Group approach [2], with the following differences:

- Frequency dependent SNR to account for variations in performance versus wavelength.
- Defining per-channel power by repeater output power and tilt to allow a linear pre-emphasis transmit spectrum.
- Using noise figure instead of OSNR to separate the channel power and baud rate from the line system parameters.

Optical Performance

The simplest metric of an amplified line system is the Optical Signal-to-Noise Ratio which in linear units is:

$$OSNR(f) = \frac{P(f)}{F_{total}(f)\,hf\,\Delta f} \qquad (1)$$

Where h is Planck's constant and Δf is the noise bandwidth, usually defined as 0.1 nm (~ 12.5 GHz in frequency) and F is the linear noise figure of the link. It is more convenient to consider setting Δf to the channel bandwidth, B_{ch}, which defines the optical SNR, or inverse optical SNR as

$$1/SNR_O(f) = \frac{F_{total}(f)\,hf\,B_{ch}}{P(f)} \qquad (2)$$

Relative to a 34 GBaud transponder, the SNR is 4.35 dB lower than the OSNR per 12.5 GHz. For 34 GBaud PM-QPSk, this might correspond to a pre-FEC SNR threshold of about 6 dB. If the noise figure of each span is the same and if each span gain is 1.0 (0 dB), then the total noise figure (F_{total}) can be calculated from the single-span noise figue (F_1):

$$F_{total}(f) = F_N(f) = N \cdot F_1(f) - (N-1) \approx N \cdot F_1(f) \qquad (3)$$

This noise figure equation does not include the effect of ASE build-up and signal power reduction. However, a good link-level simulation will capture this and result in a more accurate F_{total} derived from the simulated final OSNR. Alternatively, we can note that for fixed repeater output power and Nyquist channel spacing, the last span will have reduced signal power by the accumulated ASE power ($P - P_{ASE}$) and on average through the link ($P - P_{ASE}/2$). Therefore, SNR_{O_SD} (with signal droop) becomes (SNR_O – ½).

$$1/SNR_{O\_SD}(f) = \left[\frac{P(f)}{F_{total}(f)\,hf\,B_{ch}} - 0.5\right]^{-1} = \frac{F_{total}(f)\,hf\,B_{ch}}{P(f) - 0.5 \cdot F_{total}(f)\,hf\,B_{ch}} \qquad (4)$$

It is preferable that the noise figure be calculated as a function of frequency which captures the variation in fiber attenuation and distributed Raman amplification. The Xtera C-band repeater has an effective noise figure as shown in Fig. 1.

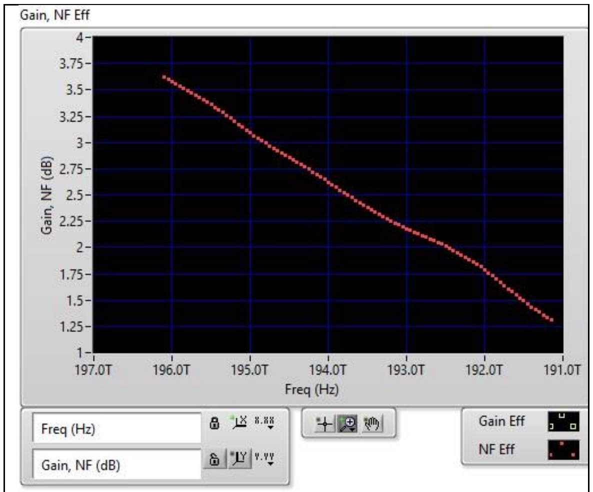

Fig. 1. Effective NF of Xtera's C-band Repeater (defined as NF of span + amplifier minus span loss in dB).

Similarly, the GN formula [1] can be used to define a nonlinear SNR (setting $\Delta f = B_{ch}$):

$$1/SNR_{NL}(f) = K_{NL}(f)\frac{P(f)^2}{B_{ch}^{\ 2}} \quad (5)$$

Note that the nonlinear power (P_{NL}) is proportional to P^3, but $1/SNR_{NL} = P_{NL}/P$ is proportional to P^2. For more general cases where the nonlinear factor, K_{NL}, varies with frequency, it is useful to consider it a function of frequency rather than just a simple constant. A more general method to calculate the channel dependent nonlinear factor is published in [3]. K_{NL} should include the effect of Raman amplification which can be incorporated from reference [4] or [5].

Note that $K_{NL}(f)$ depends on the channel plan and channel bandwidth which is not explicitly shown. Due to this fact, it could be defined for a common situation such as a maximum channel capacity with 34 GBaud channels spaced at 37.5 GHz. Potentially, it could be defined for several common cases including full capacity 100% Nyquist channels.

Then the generalized SNR is simply the sum of these two terms:

$$1/SNR_G(f) = 1/SNR_O(f) + 1/SNR_{NL}(f) = \frac{F_{total}(f)\, hf\ B_{ch}}{P(f)} + K_{NL}(f)\frac{P(f)^2}{B_{ch}^{\ 2}} \quad (6)$$

The channel powers are constrained by the total repeater output power such that $P_{ave}(f) = P_{total}/N_{ch}$. Considering that it may be advantageous to allow for a linearly tilted channel spectrum, we can more generally write the channel power as:

$$P_{dBm}(f) = P_{total}\ (dBm) - 10\log_{10}(N_{ch}) + T_{dB}\frac{(f - f_{mid})}{(f_{\max} - f_{\min})} \quad (7)$$

where T is the (max – min) tilt. For example, a tilt of 3 dB would result in an offset of +/- 1.5 dB of relative channel power at the spectrum edges and 0 dB in the middle of the spectrum.

Given the characterization of the link may result in a SNR_G that varies with frequency, the sharing of fiber spectrum between different customers can take this into account in order to share capacity in the most equitable manner.

Commissioning Measurements

Using the formulas above, the link performance can be computed for any transponder and channel plan given the repeater output power, the transponder $Q(SNR_{B2B})$ back-to-back characterization, the link $F_{total}(f)$ and link $K_{NL}(f)$ [for a reasonably close channel plan]. The last two factors are simulated during the design phase and should be measured during commissioning. The NF can be measured by measuring the link OSNR as a function of frequency. A measurement of commissioning Q at several points across the spectrum allows the SNR_{NL} to be inferred by setting the $SNR_{B2B}(Q) = SNR_G$. Note that there may be additional penalties in the transponder Q measurement due to PDG, PMD and CD that don't appear in the back-to-back characterization. This might be referred to as a modem SNR [6] such that the SNR formula becomes

$$1/SNR_{B2B}[Q_{measured}(f)] = 1/SNR_O(f) + 1/SNR_{NL}(f) + 1/SNR_{modem} = 1/SNR_{Total}(f) \quad (8)$$

Ideally, the modem penalties would be characterized separately and then subtracted in order to get a better measured estimate of $K_{NL}(f)$. Also note that the optical SNR is the dominant factor and the easiest to measure, so the uncertainty in the $K_{NL}(f)$ characterization is of slightly lower concern.

One additional discrepancy can arise from the propagation of gain ripple through the system which affects per-span P(f). Operating somewhat in the linear regime and having the ability to pre-emphasize the transmit P(f) spectrum will minimize this effect.

Examples

The following examples will consider a baseline link and simulation to calculate $NF_{total}(f)$ and $K_{NL}(f)$. The SNR_G will be recalculated for different channel and baud rate cases according to equation (6) and compared to a new simulation (the modem SNR will be ignored). Consider the following baseline repeatered link:

25 spans x 140 km = 3500 km (25.6 dB span loss) SMF-28e+ LL fiber
Xtera Raman Repeater, C-band
100 chan x 50 GHz spacing, P_{total} = 18.0 dBm, Tilt = T_{dB} = 4.0 dB, B_{ch} = 34 GHz

The baseline simulation SNR values are shown in Fig. 2. At this point, the recalculated SNR is an exact match.

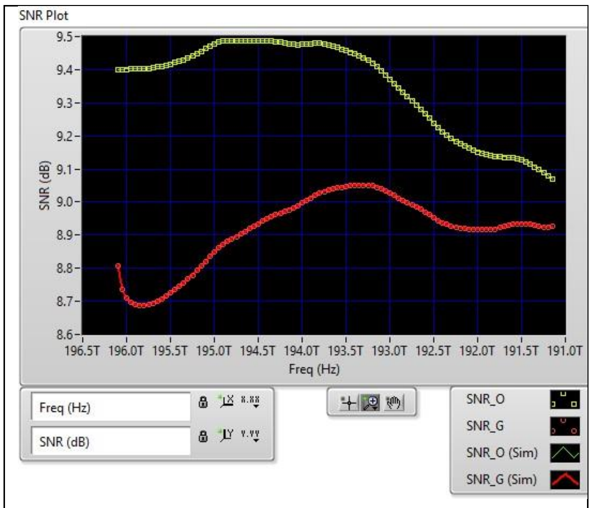

Fig. 2. Baseline link simulation. Lines are from simulation and symbols are from SNR_G equation.

The next case (A) to consider is changing the channel plan to 133 chan x 37.5 GHz spacing, Tilt = 4.0 dB at the same P_{total}. The channel power is now 1.24 dB lower resulting in lower SNR values. Note that $F_{total}(f)$ is fairly insensitive to channel plan such that SNR_O matches the new simulation, but $K_{NL}(f)$ is slightly sensitive such that SNR_G has a small mismatch. These curves are shown in Fig. 3.

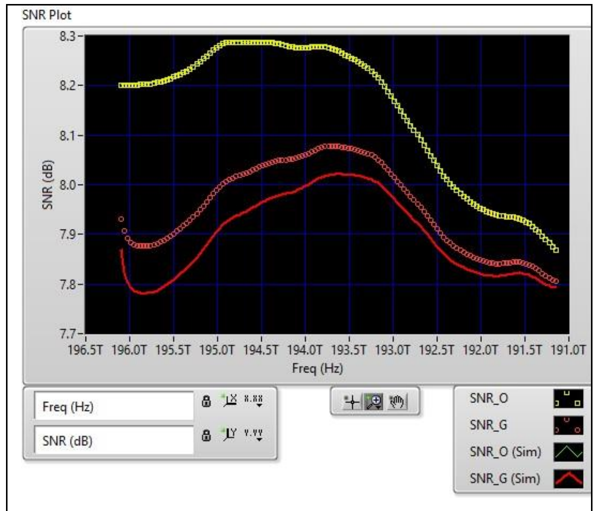

Fig. 3. Case A recalculated SNR values. Lines are from simulation and symbols are from SNR_G equation.

The next case (B) decreases the number of channels to 67 at 75 GHz spacing with a Tilt of 2.5 dB at the same P_{total} (+1.74 dB/ch) with the results plotted in Fig. 4.

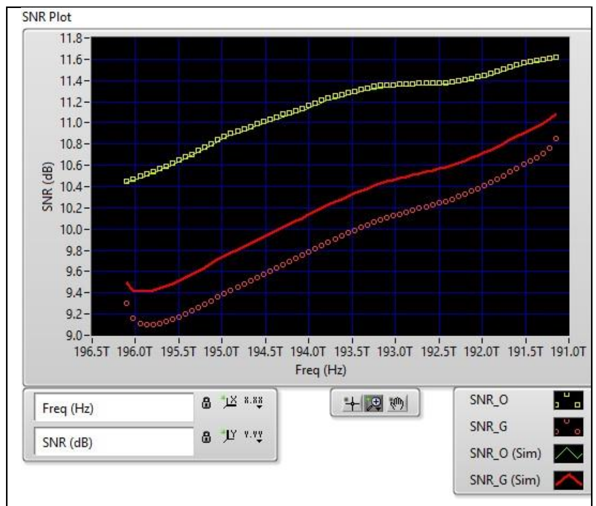

Fig. 4. Case B recalculated SNR values. Lines are from simulation and symbols are from SNR_G equation.

Thus, the effect of changing channel spacing results in an over-estimation of SNR_G for denser channel spacing and an under-estimation of SNR_G for wider channel spacing. But, the shape of the SNR curves closely match.

Returning to the baseline 100 channel case at 50 GHz spacing and changing the channel baud rate to 50 GHz results in a larger noise bandwidth (lower SNR_O) and a lower power spectral density (higher SNR_{NL}). The increase in baud rate in this example represents a 1.67 dB increase in capacity. These results (case C) are shown in Fig. 5.

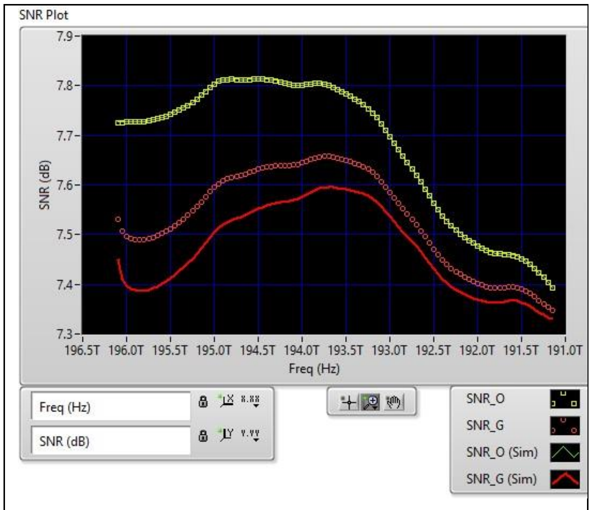

Fig. 5. Case C recalculated SNR values. Lines are from simulation and symbols are from SNR_G equation.

Further Work

It should be possible to add a factor to equation (5) that accounts for variations in nonlinear power from the simple PM-QPSK case based on geometric or probabilistic shaped constellations or for nonlinear compensation.

$$\frac{1}{SNR_{NL}(f)} = \beta \cdot K_{NL}(f)\frac{P(f)^2}{B_{ch}^{\;2}} \qquad (9)$$

In this case, β would equal 1.0 for the PM-QPSK case and would be experimentally measured for any other case. For example, a direct measurement comparing the new case to PM-QPSK in the lab or field could result in a value of β < 1.0 which could be used to compare to other transponder technologies.

Conclusion

This white paper has developed a simple frequency dependent formula to calculate the SNR values of a repeatered submarine link as a function of changing channel plans and channel baud rates. The methodology presented herein result in a close match to re-simulated values. A measurement of the required parameters during commissioning would validate the proposed simulation and allow customers a simple method to compare performance of different transponders on the submarine link.

References

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