# PRE-EMPHASIS-BASED EQUALIZATION STRATEGY TO MAXIMIZE CABLE PERFORMANCE

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**Abstract:** The procurement of modern cable systems is evolving towards an open cable model, where performance must be defined independently of specific modems, while maintaining the primary goal of maximizing the total achievable capacity. Historically, subsea systems have been defined and deployed with optical signal-to-noise ratio (OSNR) equalization as the key method for performance optimization. However, modern subsea systems have evolved from very narrow to very wideband repeater designs, where gain shape and delivered OSNR have a high degree of wavelength dependency, calling OSNR equalization into question as the ideal optimization method. Additionally, a significant change in the degree to which nonlinearity plays a role has occurred in recent years, which also affects the ideal equalization strategy. In this paper, we explore the impact of various pre-emphasis equalization strategies, including flat launch conditions, receive (RX) OSNR equalization, average power equalization, with the goal of maximizing cable capacity, both theoretically, and with real world limitations. We also explore the benefits of the evolving granularity available in variable rate modems, and its impact on optimal equalization strategies.

## 1. INTRODUCTION

The modem performance in the submarine power budget table (PBT) [1] outlined in ITU-T G.977 is referenced to an OSNR for the worst case. OSNR equalization has been used since the first wavelength-division multiplexed (WDM) submarine cables which had narrow bandwidths and large gain variations [2]. Historically, deployments performed OSNR equalization in an attempt to provide the minimum OSNR defined in the PBT for all channels to ensure system performance was achieved.

The process of equalizing OSNR can be a time-consuming process and requires specific equipment to measure the OSNR with adequate resolution. For example, in a system with 35 Gbaud QPSK signals arranged in a 50 GHz fixed grid spacing, the noise floor of each channel is easily observed and the measurement of OSNR is trivial. In a flexible grid configuration, however, with near Nyquist channel spacing, the technique of “channel plucking” is typically employed: where the given RX channel signal power is measured, the channel is blanked, and the noise floor is measured. This process is then repeated for every channel in the spectrum, resulting in a significant time-investment when equalizing for OSNR.

Implementing an equalization procedure that is based on optical power at the input and output of a modern wetplant with relatively flat gain variation across the bandwidth provides operational efficiencies for the operator, since the optical power can be measured with Optical Channel Monitors (OCM) that are common within the Submarine Line Terminal Equipment (SLTE). The use of the optical power-based procedures, while simpler, are only useful if they result in system performance equal to or greater than the performance that is achieved with OSNR equalization to ensure cable capacity is maximized.

## 2. EQUALIZATION METHODS

Three different equalization strategies are evaluated in this paper, and they are defined as follows:

- **OSNR Equalization**, where the receive OSNR of each channel was matched via the control of transmit (TX) powers;
- **Flat TX Equalization**, where the TX power of each channel was matched; and
- **$P_{fib}$ Equalization**, where the average of the TX and RX power of each channel was matched, given by $P_{\mathrm{fib}} = \frac{1}{2}(P_{\mathrm{in}} + P_{\mathrm{out}})$.

In a system that delivers a completely flat gain shape, the TX spectrum of flat TX equalization and $P_{fib}$ equalization is identical. Employing flat TX equalization results in a RX spectrum that matches the gain shape of the wetplant. In wetplants that have point losses at the start or end of the link, there are special equalization conditions that should be considered [3], but further exploration of this topic is outside the scope of this paper.

A simulation was performed to determine the effective signal-to-noise ratio (eSNR) penalty averaged across the C-band – where the eSNR is the system SNR when measured through a coherent modem – of the equalization strategies at various system gain tilts for a high positive dispersion fiber of 6,000 km (Figure 1). In addition, simulations were performed to determine the maximum capacity based on a “brute force” method; by iteratively adjusting the TX power spectrum using a generic multidimensional optimization algorithm.

Simulation results show that in systems with a flat gain shape, all equalization methods provide equal capacity. As the magnitude of gain tilt increases, either in the positive or negative direction, the use of $P_{fib}$ equalization yields the lowest eSNR penalty. Here, positive gain tilt is defined as a linear trendline fitted across the gain spectrum, with higher gain evolution at longer (red) wavelengths. Similarly, negative gain tilt is defined as high gain evolution at shorter (blue) wavelengths.

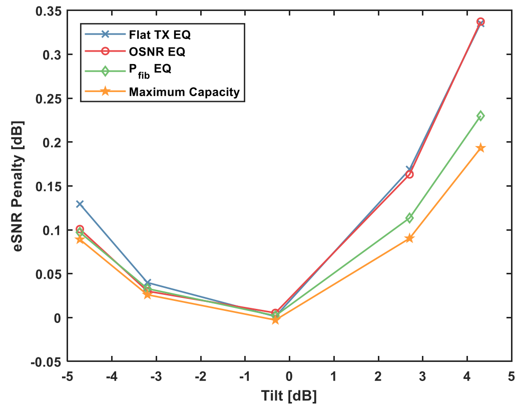


**Figure 1: The simulated effect of gain tilt on eSNR penalty averaged across the C-band for different equalization strategies. Max capacity equalization is based on a "brute force" method determined through iterative optimization techniques.**

## 3. EXPERIMENTAL SETUP

We experimentally study one of the simulated high-tilt scenarios using a recirculating loop system. The recirculating loop comprised of hybrid spans of roughly 150 and 130 μm$^2$ effective core area high positive dispersion fiber and totaling 2,100 km of linear length. Each fiber span was 70 km in length and was separated by repeaters with a total output power (TOP) of 18 dBm. The link was populated with 35 Gbaud QPSK channels across the system bandwidth on a 50 GHz grid. The modem performance was measured across the C-band for the different equalization strategies, at trans-Atlantic and trans-Pacific distances.

## 4. MEASUREMENT PROCESS

The signal-to-noise ratio (SNR) refers to any performance related metric or noise contributor, such as linear SNR ($SNR_{ASE}$), nonlinear SNR ($SNR_{NL}$), and modem implementation SNR ($SNR_m$). The total system SNR of a cable is given by the sum of reciprocals for each noise contributor,

$$\frac{1}{\mathrm{SNR}} = \frac{1}{\mathrm{SNR}_{\mathrm{ASE}}} + \frac{1}{\mathrm{SNR}_{\mathrm{NL}}} + \frac{1}{\mathrm{SNR}_{\mathrm{m}}}. \qquad (1)$$

Measurements of the SNR through an optical spectrum analyzer typically only capture the linear noise component (i.e., the $SNR_{ASE}$) of the cable system. A coherent modem can directly measure an effective SNR (eSNR) of the cable system, which can be related to the total system SNR and other SNR performance metrics via

$$\frac{1}{\mathrm{eSNR}} = \varepsilon\left(\frac{1}{\mathrm{SNR}_{\mathrm{ASE}}} + \frac{1}{\mathrm{SNR}_{\mathrm{NL}}} + \frac{1}{\mathrm{SNR}_{\mathrm{m}}}\right), \qquad (2)$$

where ε is the modem implementation distortion. In some cable environments, the modem distortion and implementation ($SNR_m$) can vary as a function of propagation. In the definition of Equation 2, these propagation penalties are lumped together with the nonlinear SNR ($SNR_{NL}$) term. Both ε and $SNR_m$ are measurable quantities determined by optically noise loading the modem under back-to-back conditions.

The eSNR can be used to estimate the theoretical capacity of a perfectly coded channel using the relation

$$C = 2 \cdot \mathrm{BW} \cdot \log_2(1 + \mathrm{eSNR}), \qquad (3)$$

where *C* is the theoretical capacity, BW is the bandwidth of the channel, and eSNR is the effective SNR reported by the modem.

By varying the equalization strategy and measuring the eSNR and $SNR_{ASE}$ spectrum across the band, Equation 3 can be used to determine the total system capacity. In addition, the $SNR_{NL}$ profile can be calculated using Equation 2.

It should be noted that the SNR is the ratio of signal power to noise power, both of which are measured over the channel bandwidth. In contrast, the optical signal-to-noise ratio (OSNR) is defined as the ratio of the signal power measured over the channel bandwidth to the noise power measured over 0.1 nm (~12.5 GHz) of bandwidth. Since the modem reports eSNR, we have opted to cast the results in terms of SNR for consistency.

## 5. PERFORMANCE AT 6,300 KM

For each equalization strategy, the $SNR_{ASE}$ spectrum was measured after 3 orbits of propagation over the recirculating loop (Figure 2). Under flat TX conditions, that the system experiences roughly -3 dB of $SNR_{ASE}$ tilt. Figure 3 shows the corresponding TX channel power profile for each equalization strategy. Flat TX and $P_{fib}$ equalization are nearly identical pre-emphasis scenarios due to the flatness of the system gain shape. However, for OSNR equalization the blue-most channels are under-launched roughly 3 dB below flat launch and the mid- to red-band channels are pre-emphasized about 1 dB above flat launch to account for the system tilt.

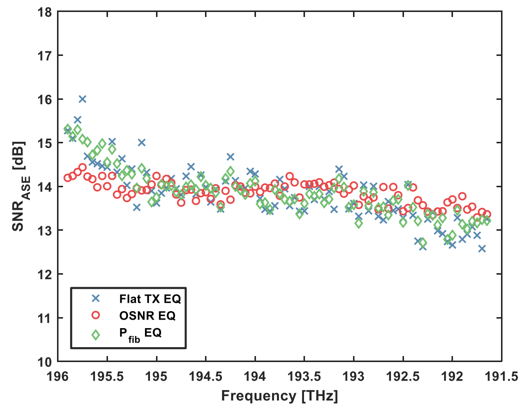


**Figure 2: The measured $SNR_{ASE}$ across the C-band after 6,300 km of propagation for various equalization methods.**

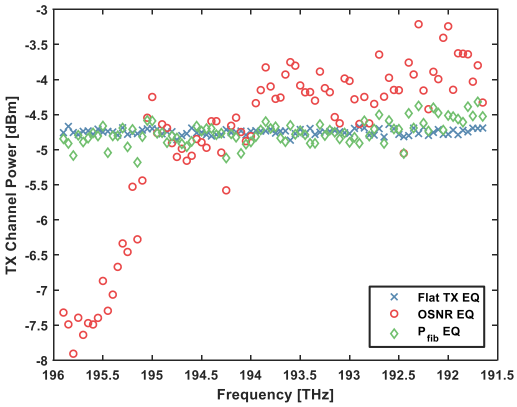


**Figure 3: The TX channel power spectrum of the different equalization methods for 6,300 km of propagation.**

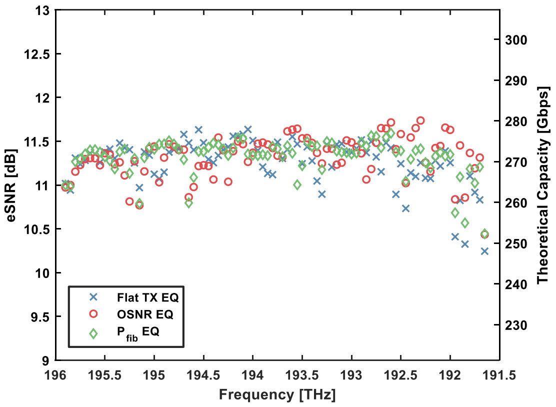


**Figure 4: The measured eSNR, as reported by the modem, across the C-band for various equalization strategies after 6,300 km of propagation.**

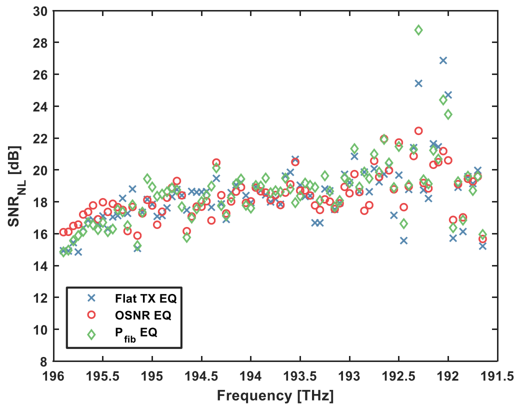


**Figure 5: The calculated $SNR_{NL}$ across the C-band for various equalization strategies after 6,300 km of propagation.**

Similarly, the eSNR was measured across the C-band (Figure 4) and the $SNR_{NL}$ was calculated (Figure 5). The eSNR was used to calculate the theoretical capacity for each channel using the capacity formula (Equation 3) and converted to a total system capacity for both an idealized modem capable of infinitely granular client capacity, as well as for modems subject to quantized capacity constraints (Figure 6). It was found that there was little difference in total capacity, theoretical or quantized, between the various equalization strategies. Flat TX yielded a theoretical total capacity within 1% as compared to OSNR or $P_{fib}$ EQ, without the operational complexity.

The quantization of the line rates offered by the modem have a more significant impact on delivered capacity than the equalization. It should be noted that the impact of quantization is heavily dependent on the eSNR margin above each quantization step.

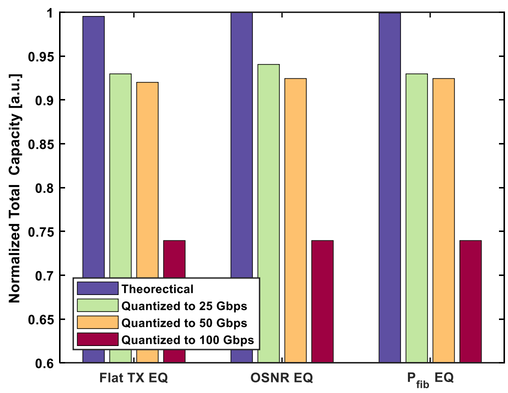


**Figure 6: Normalized total system capacity based on the measured eSNR for various equalization strategies, and quantization step sizes after 6,300 km of propagation.**

We also study the effects of baud rate on total system capacity. The measured eSNR data was interpolated and converted to represent channels with a baud rate of 17.5 Gbaud and 70 Gbaud, compared with the original 35

Gbaud. The interpolated eSNR was then used to calculate the total system capacity using the new baud rate under flat TX equalized conditions (Figure 7). When a higher baud rate modem is used under the same system conditions, the results show that the effect of quantization on total system capacity are reduced. This result is as expected when quantization is considered in terms of spectral efficiency (SE). For example, 50 Gbps step at 17.5 Gbaud gives an arbitrary SE step of A, whereas 50 Gbps step at 35 Gbaud gives a SE step of A/2, and so forth. Thus, higher a baud rate modem inherently provides finer granularity when quantized to increments of 50 Gbps client rates.

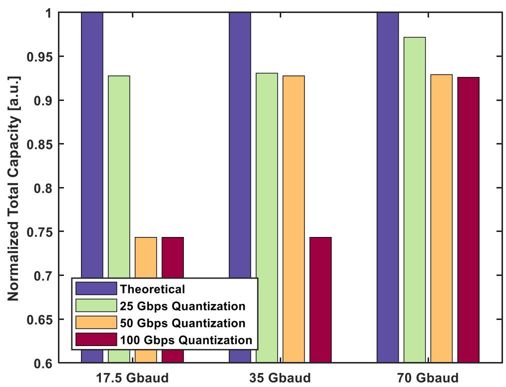


**Figure 7: Total system capacity interpolated for different baud rates under flat TX equalized conditions after 6,300 km of propagation. Normalizations are relative to the theoretical capacities.**

## 6. PERFORMANCE AT 12,600 KM

The same set of measurements were repeated after 6 orbits of the recirculating loop (12,600 km). At twice the propagation distance, the system experiences almost -4 dB of $SNR_{ASE}$ tilt across the spectrum (Figure 8); a 1 dB increase relative to 6,300 km of propagation. As a result, the TX channel power profile requires greater dynamic range than before (Figure 9). The measured eSNR across the C-band maintains a similar profile but is reduced by 3 dB on average due to longer propagation (Figure 10). The $SNR_{NL}$ and total capacity were again determined (Figure 11 and Figure 12, respectively), and compared between the different equalization strategies, quantization step sizes, and baud rates (Figure 13).

The 12,600 km results further emphasis that the equalization strategy employed has little impact on the net system capacity. The effect of quantization and baud rate also has a smaller effect at this distance due to the nature of where the quantization steps lie relative to the measured eSNR.

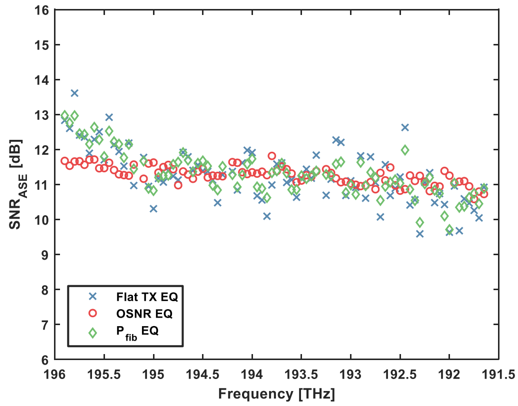


**Figure 8: The measured $SNR_{ASE}$ across the C-band after 12,600 km of propagation for various equalization methods.**

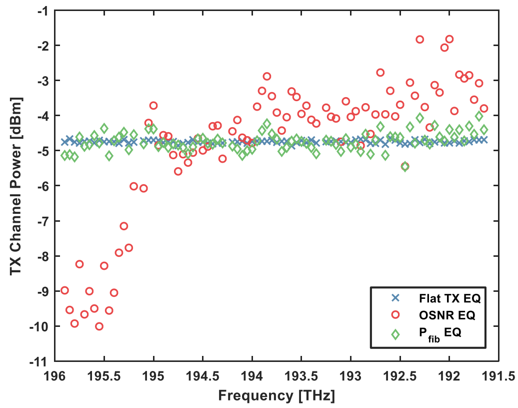


**Figure 9: The TX channel power spectrum of the different equalization methods for 12,600 km of propagation.**

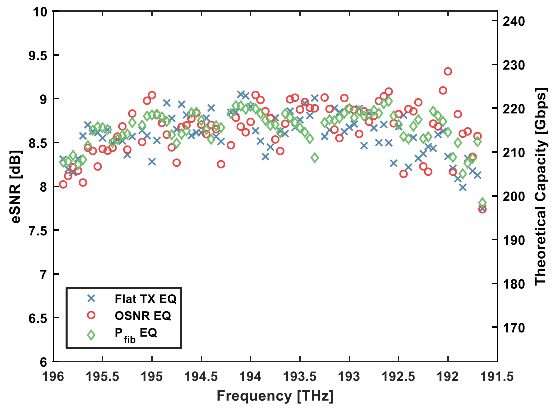


**Figure 10: The measured eSNR, as reported by the modem, across the C-band for various equalization strategies after 12,600 km of propagation.**

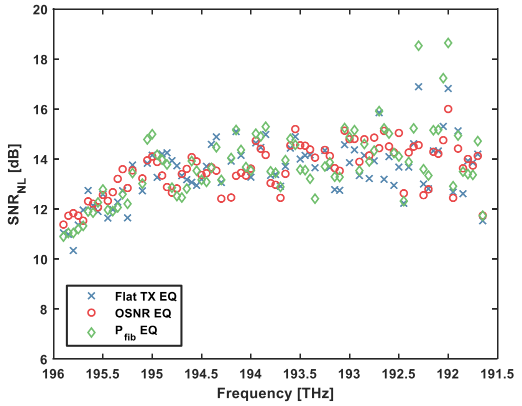


**Figure 11: The calculated $SNR_{NL}$ across the C-band for various equalization strategies after 12,600 km of propagation.**

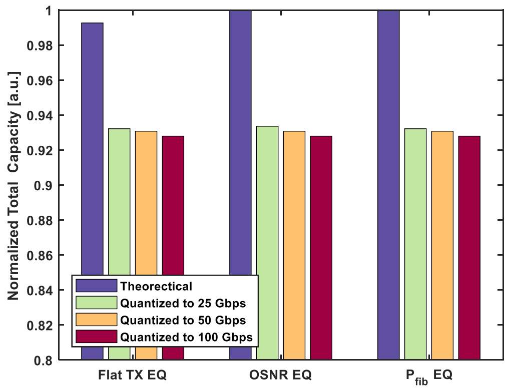


**Figure 12: The total system capacity based on the measured eSNR for various equalization strategies, and quantization step sizes after 12,600 km of propagation.**

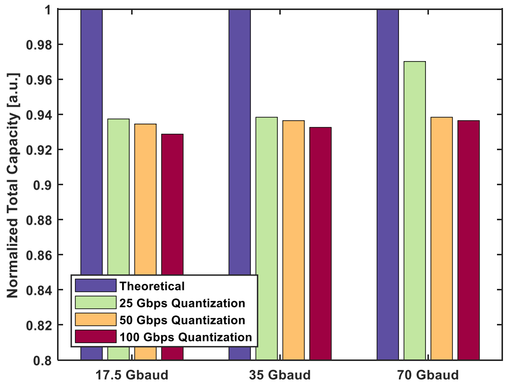


**Figure 13: Total system capacity interpolated for different baud rates under flat TX equalized conditions after 12,600 km of propagation. Normalizations are relative to the theoretical capacities.**

## 7. CONCLUSION

In a system where the delivered $SNR_{ASE}$ tilts by -3 to -4 dB, the three equalization methods evaluated provide nearly identical system capacity when measured experimentally. Even in extreme cases of ±5 dB of tilt, the simulations show that the difference in eSNR penalty between each equalization strategy is minimal.

The quantization of modem line rates is a more significant factor in achieving the maximum delivered system capacity. Differences between a 25 Gbps quantization and the theoretical limit are still greater than 7%. Until Flex Ethernet and Flex OTN become widely adopted, most line rates will be quantized to 50 Gbps for simplest alignment to 100G and 400G clients, which result in decreased system capacity. However, the effects of quantization can be mitigated using higher baud rate modems, which offer finer granularity of SE steps for a given line rate step allowing for better alignment between the offered line rates and the required client rates.

For a modern, high dispersion submarine cable system, the effect of pre-emphasis-based equalization has little impact on the total system capacity. Hence, flat TX or $P_{fib}$ equalization provides a method that is operationally simple with minimal impact on achievable capacity. It does not require significant impact on channel performance during equalization and is readily achievable with common SLTE equipment. With modems evolving towards smaller quantization client rates and higher baud rates, the effects of pre-emphasis-based equalization become less important in maximizing system capacity.

## 8. REFERENCES

[1] ITU-T G.971. Recommendation ITU-T G.971 (2010), "General features of optical fibre submarine cable systems".

[2] F. Forghieri et al, "Simple Model of Optical Amplifier Chains to Evaluate Penalties in WDM Systems", *Journal of Lightwave Technology, Vol 16, No. 9, September 1998*, pp 1570-1576.

[3] L. Berg et al, "Methods and Limits of Wet Plant Tilt Correction to Mitigate Wet Plant Aging", *Proc. SubOptic 2016*, WE1A.5.