# REPEATER OUTPUT POWER FOR FUTUREPROOF UNDERSEA TRANSMISSION

Dmitriy Kovsh, Alexei Pilipetskii, Georg Mohs (SubCom)
Email: dkovsh@subcom.com

SubCom, 250 Industrial Way West, Eatontown NJ 07724 USA.

**Abstract:** This paper demonstrates undersea system design methodologies to take advantage of available higher repeater Total Output Power (TOP). The market development for systems optimized at the overall cable level allow optical power to be distributed over more fiber pairs in the SDM design approach, leading to systems with higher fiber pair counts. Alternatively, the increased resilient to fiber nonlinearity penalties in next generation coherent transponders can support system designs with higher optimal repeater Total Output Power (TOP), providing higher capacity in the future. Higher optimal TOP can also allow system suppliers to reduce system cost for a fixed fiber pair capacity. In all cases, repeaters with higher TOP will be in demand in the future.

## 1. INTRODUCTION

Modern undersea cable projects can be placed in three main categories based on customer requirements. These categories can strongly impact the design specifications of the system, and the method used for system acceptance.

The first system type is the large high-capacity "data pipes" developed by one or several Internet Content Providers (ICPs). The key performance metric for these systems is typically cost-per-bit of capacity, as computed for the entire cable. The number of fiber pairs in the system and capacity per FP are optimization variables in the overall cable design. There may be no hard target on single fiber pair capacity, although expected capacity targets are often provided.

The second, more traditional system purchasing group consists of multiple owners in a consortium group. The design specifications for these systems are typically based on a fixed fiber pair capacity, with separate ownership for each fiber pair.
A final system type, typically for regional applications, calls for a modest FP count and low overall system cost. The driving system design factor for these systems is low initial system price, providing that a minimum target capacity per FP is achieved.

## 2. SYSTEM DESIGN APPROACHES

The type of system ownership has a significant impact on the method that is selected to specify system performance for the initial design and for the test procedures to accept the system after installation.

The systems offered to ICP customers are typically designed with an "Open Cable" design philosophy, with the customer providing fiber pair design requirements based on Optical Signal-to-Noise Ratio (OSNR) and Generalized OSNR (G-OSNR) values [1]. These systems are then commissioned based on these requirements. Fiber pair capacity estimates can then be made derived from the commissioning OSNR and G-OSNR values, based on the forecasted capabilities of future modem technology.

Consortium systems are instead typically designed based on an agreed upon set of specifications for a modem technology that is expected to be available at the time of system Ready for Provisional Acceptance (RFPA). The capability of the system to support the required design capacity is then demonstrated by the Full Capacity Testing (FCT) during system commissioning.

Cost-optimized systems are typically based on a “Turn Key” design approach with guaranteed modem performance for the contracted terminal equipment during system commissioning.

## 3. EVOLVING SYSTEM DESIGNS

The traditional approach to high performance undersea cable system is based on amplifiers with high Total Output Power (TOP). The overall combination of repeater TOP, Noise Figure and fiber span parameters, can be selected to achieve higher modem performance (Q-factor) and fiber pair capacity.

There have been recent developments in the submarine industry that are changing this traditional design philosophy. The recent introduction of pump-sharing and Spatial Division Multiplexing (SDM) methodologies into system design support more efficient transfer of optical and electrical power into cable performance/capacity and lower cost/bit [2]. The operation of individual fiber pairs at a more linear operating point allows more fiber pairs to be supported in the cable, although with lower capacity per fiber pair and increasing total system cost.

The applicability of this SDM approach to a particular system depends on the overall customer goals, as described in the above section. In this paper, we will review how the system design process can take advantage of higher repeater TOP to optimize any of the system types, whether for a lower cost-per-bit, a larger total capacity or a lower system cost, depending on customer requirements.

Throughout the paper, we will use the term repeater TOP as total output power delivered into a single fiber.

## 4. DEFINITIONS

It has been proposed that performance of an Open Cable Design can be expressed in terms of Signal-to-Noise Ratio following GN Theory for uncompensated links [3].

$$SNR = \frac{P_{sig}}{P_{ASE}+P_{NL}}, \qquad (1)$$

Where contributions of both linear and nonlinear noise terms are included with Gaussian distributions. There were several modifications of the GN theory that extend the formalism to include effects including modulation scheme and Raman interaction within fiber spans.

Performance as defined by SNR can be translated to the achievable Capacity (C) using the modified Shannon formula [4], as scaled by a margin that is intended to cover imperfections in the Submarine Line Termination Equipment (SLTE) and the undersea transmission path (“wet-plant”) implementation:

$$C = 2 \cdot BW \cdot log_2(1 + a \cdot SNR) \qquad (2)$$

The inclusion of the scaling factor *a* provides capacity values estimated closer to what is expected from available modem providers. One can think of *a* as the penalty of a given modem relative to the theoretical performance expressed by the Shannon curve, with added implementation and operation margins.

For simplicity going forward we will ignore noise contributions from the SLTE and from GAWBS [5]. In the following examples, capacity is computed for the entire C-band of Erbium Doped Fiber Amplifiers (EDFAs), and ideal amplifier gain equalization is assumed.

One of the objectives of system design is to utilize the available technology and to minimize the required equipage (and therefore system cost) required to reach the performance targets defined by System Purchasers. A common method for such optimization requires power sweep curves that represents performance as function of repeater TOP for a chosen characteristics of fiber spans. This "optimization curve" helps to match peak performance supported by maximum available repeater TOP to the required performance target. This curve can be generated for the Beginning-of-Life (BOL) or the End-of-Life (EOL) condition of a system depending on what is required by the Customer, where EOL considers expected aging and repairs.

## 5. EXAMPLE CONFIGURATION

For our design examples, we will consider a 7000km EDFA-based transmission link implemented with Pure Silica Core (PSC) fiber. We can plot performance expressed as GN theory SNR as a function of repeater TOP as shown in Figure 1.

For a repeater TOP of 19dBm, we chose the repeater spacing to be 100km so that peak performance would take place exactly at this power level. The decrease in performance for repeaters with lower TOP performance will follow the optimization curve.

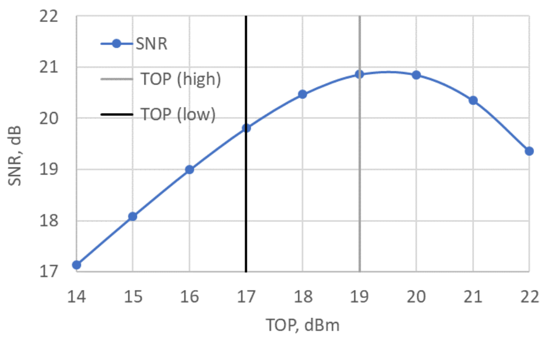


**Figure 1. SNR versus repeater TOP for 100km repeater spacing**

## 6. REPEATER TOP FOR FIBER CAPACITY ADVANTAGE

For our first example, we will consider capacity optimization on a fiber pair with a fixed span length, perhaps for a regional cost-optimized system.

For the fiber pair with 100km spans, lowering the repeater TOP by 2dB to 17dBm will lead to 1dB of SNR degradation. Note that there is not a one-for-one correlation between the change in repeater TOP and in OSNR. Figure 2 re-plots the optimization curve in terms of capacity rather than SNR. Increasing the repeater TOP from 17 dBm to 19 dBm results in a 1dB increase in SNR, and a 2 Tbps (~10%) increase in fiber pair capacity for the same fiber span design.

In summary, higher repeater TOP can be translated to higher performance or increase in Design Capacity, within the limits of the given modem characteristics.

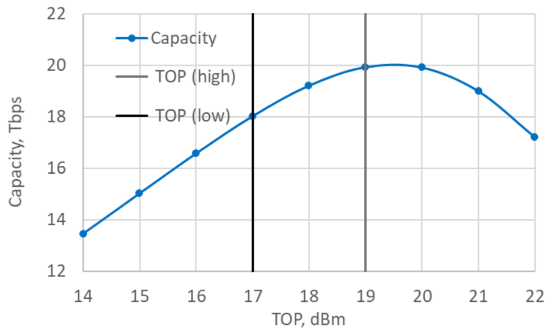


**Figure 2. Total Capacity versus TOP for 100km repeater spacing**

## 7. REPEATER TOP FOR SPAN LOSS ADVANTAGE

For our next example, consider the case where individual fiber pair capacity of 20 Tb/s is the system design specification. This approach could apply to a consortium system with a firm target for fiber pair capacity. In this case, higher repeater TOP can be used to optimize repeater spacing and span loss at the target capacity.

Figure 3 shows fiber pair capacity as a function of TOP for a design that utilizes the same fiber type as in Figure 1, but with the repeater spacing reduced from 100km to 90km. The target capacity can be met with 100km spans for 19dBm TOP, but 90km spans are needed with 17dBm TOP. The availability of 2dB higher TOP leads to difference in repeater spacing of 10km.

Stretching the repeater spacing leads to fewer repeaters and a lower overall wet plant cost. Alternatively, a less expensive fiber type with higher loss characteristics could be used, resulting in higher span losses.

In summary, higher repeater TOP can be translated into a system design for a required design capacity with fewer repeaters and a lower system cost.

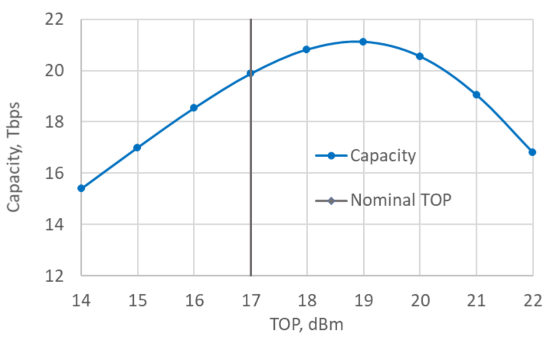


**Figure 3. Total Fiber Capacity versus TOP for 90km repeater spacing**

## 8. REPEATER TOP FOR CABLE CAPACITY ADVANTAGE

In the SDM design approach, electrical and optical pump power are distributed across more fiber pairs. This approach is applicable for ICP systems that target high total cable capacity at lower cost-per-bit rather than in individual fiber pair capacity.

This requirement leads to modifying the fiber pair operating point to a more linear condition so that the remaining repeater power can be used to support additional fiber pairs as shown in Figure 4.

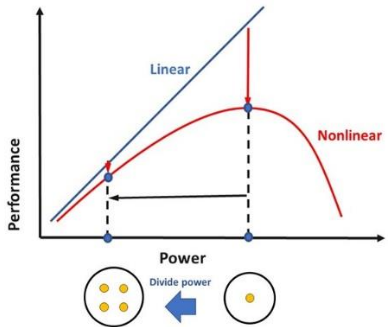


**Figure 4. Illustration of SDM approach**

In the specific example of Figure 2 above, one fiber pair with 19 dBm TOP can support 20 Tbps capacity. If the pump power is instead distributed to support two fiber pairs with 16 dBm TOP, then the overall capacity provided by the pump power increases to approximately 33 Tbps.

Figure 5 illustrates how the SDM power sharing design approach leads to overall increase in cable capacity by allowing a fixed electrical power budget to support more fiber pairs, with a somewhat lower capacity per fiber pair.

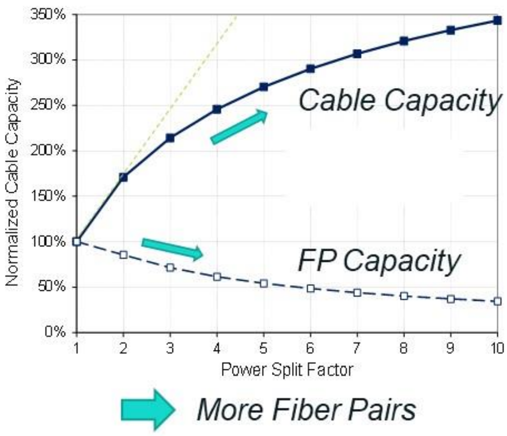


**Figure 5. Illustration of increasing cable capacity as more fiber pairs are added, using the SDM design approach.**

## 9. REPEATER TOP FOR FUTURE PROOF DESIGN

Future generations of coherent modems are expected to include Nonlinearity Compensation (NLC). Higher repeater TOP can be used to "future-proof" a system design to take advantage of this expected improvement. Figure 6 illustrates how the system design point can be shifted past the peak performance of the current modem generation so that additional capacity is available with future DSP technology.
Here we should note that peak performance repeater TOP depends on modem modulation format, and may be different than what is predicted by GN theory even for well-known formats (e.g. QPSK). To fully take advantage of NLC design optimization, one should include the anticipated change of peak performance TOP from the current to future modem with NLC.

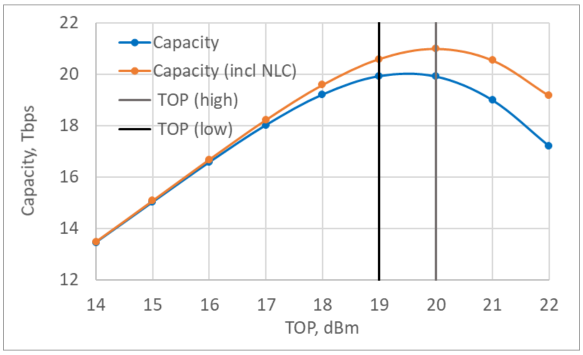


**Figure 6. Capacity increase from NLC**

## 10. CONCLUSION

The four examples discussed here illustrate the advantages of repeaters with high TOP. The undersea system designer can use these approaches to translate the performance benefit into cost savings, higher capacity or better futureproofing of the design based on customer requirements.

## 11. REFERENCES

[1] V. Kamalov et al., "Lessons Learned from Open Line System Deployments," OFC (2017), M2E.2

[2] R.-J. Essiambre and R. Tkach, "Capacity Trends and Limits of Optical Communication Networks," Proc. IEEE, vol. 100, no. 5, pp. 1035–1055, 2012

[3] P. Poggiolini, "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," Journal of Lightwave Technology, vol. 30, no. 24, pp. 3857–3879, Dec. 2012.

[4] C.E. Shannon, "Communications in the Presence of Noise," 1949., Proceedings to IEEE

[5] M.A. Bolshtyansky et al "Impact of Spontaneous Guided Acoustic-Wave Brillouin Scattering on Long-haul Transmission," in Proc. Optical Fiber Communication Conference (OFC), March 2018, p. M4B.3.