LINEAR Vs NONLINEAR SUBMARINE SYSTEMS

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Abstract: The remarkable improvements in fiber and coherent technologies has enabled a remarkable growth in capacity-distance products and spectral-efficiency. It has also stimulated the planning of ultra-long-haul routes of 15,000 km and beyond. This imposes severe constrains in the powering of the systems, which still desire to be single-end fed to secure maximum reliability against shunt faults. To overcome this limitation, "linear systems" were proposed to increase the capacity-distance product in power limited systems. This paper analyzes in detail how to designs these systems and the trade-offs with traditional "nonlinear systems" where the capacity per fiber pair is maximized.

1. INTRODUCTION

The expansion of data center (DC) capacity to address the capacity requirements of next generation IT applications is taking place at a considerable pace.

This growth in DC size and number requires a proportional growth in connectivity, in particular for geo-replication, which relays significantly in submarine fiber optic networks. To address this capacity growth, the submarine networks industry has proposed solutions recently to overcome the limitations that system powering imposes to the total capacity. These limitations are imposed mainly by ensuring system reliability against cable faults.

One way to increase capacity under powering limitations is to design the submarine transmission lines in a different way. Traditionally, the submarine line was designed to optimize the system capacity in a fiber-pair basis. These designs operate at the optimum repeater power, where an optimum balance between linear noise and nonlinear distortions are achieved (theoretically, a 3dB difference between linear and nonlinear noise in the GN model). These can be regarded as nonlinear systems.

Although nonlinear systems enable the most efficient power/space/cost LTE upgrades, it has been proven that they do not necessarily maximize the cable capacity under powering constrains. Instead, systems where the nonlinear noise is reduced and the traffic bandwidth increased, can provide larger capacity numbers at the expense of sacrificing spectral efficiency. These are linear systems and they have been proposed recently [1-3] to boost the design capacity of submarine systems of 15000+km and they are now in manufacturing stages.

This paper analyzes in detail the differences between linear and nonlinear systems providing design trade-offs, system optimizations and most importantly, the implications of this trend in future technology developments such as fiber, rep

2. NONLINEAR TRANSMISSION IN OPTICAL FIBERS: LINEAR AND NONLINEAR REGIMES

Recently, the GOSNR is being proposed to determine the performance of transmission lines in a transponder independent way [4]. The GOSNR is defined as follows,

$$GOSNR = \frac{P}{P_{ASE}+P_{NL}} \quad (1)$$

Where the effects from fiber nonlinearity are included in P_{NL} . This assumes that the effects of fiber nonlinearity accumulate similarly to the ASE noise.

This power is obtained by using the GN model formalism, as described in (ref 2), where P_{NL} is proportional to the power spectral density of the nonlinearity contribution defined as:

$$G_{NL}(f) = \iint_{\pm\infty} g(f_1)g(f_2)g(f_1+f_2-f)\times \cdots \rho(f_1,f_2,f)\times\chi(f_1,f_2,f)df_1df_2 \quad (2)$$

For this study, we will use 45 carriers with a Baud-Rate (BR) of 96 GBaud and 100 GHz spacing in the C-band with 4.5THz bandwidth. The transmission line is 10,000km with a fiber of 150um2 of effective area and 0.152 dB/km attenuation. Spans of 75km are considered.

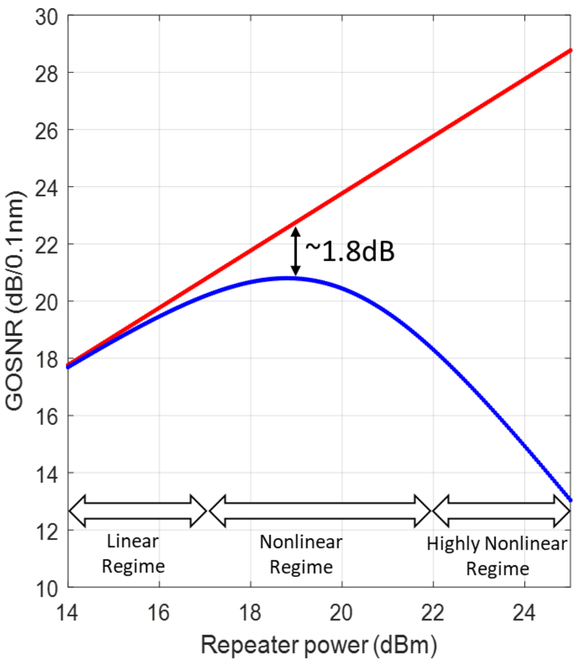

Figure 1: OSNR and GOSNR (45 carriers) vs Repeater Power in a 10000km system

The Figure 1 shows the GOSNR vs Repeater power for a 10000km system with high effective area fiber. The approximate linear and nonlinear regimes are shown.

In this paper we define a linear regime where the OSNR-GOSNR gap is around 1.0dB or less. The Nonlinear regime goes from 1.0dB to 5.0dB and the highly nonlinear regime for values beyond ~5dB. The maximum wet plant performance (i.e. Maximum GOSNR) happens at a gap of around 1.8dB. This can be easily derived by Eq. 1, assuming a cubic power dependency of P_{NL}. This is assuming that nonlinearity compensation techniques are not applied.

3. CABLE CAPACITY IN LINEAR AND NONLINEAR SYSTEMS

In this work, the Shannon capacity will be used as performance metric. The Shannon capacity of a submarine cable is defined as,

$$C = N \times B \times FR \times 2\log_2(1+GSNR) \quad (3)$$

Where N is the number of fiber pairs, B is the usable bandwidth and FR is the spectrum occupancy ratio. The GSNR is given by:

$$GSNR = GOSNR - 10\log_{10}\left(\frac{BR}{12.5}\right) \quad (4)$$

The power dependency of a submarine cable capacity is illustrated in the figure 2.

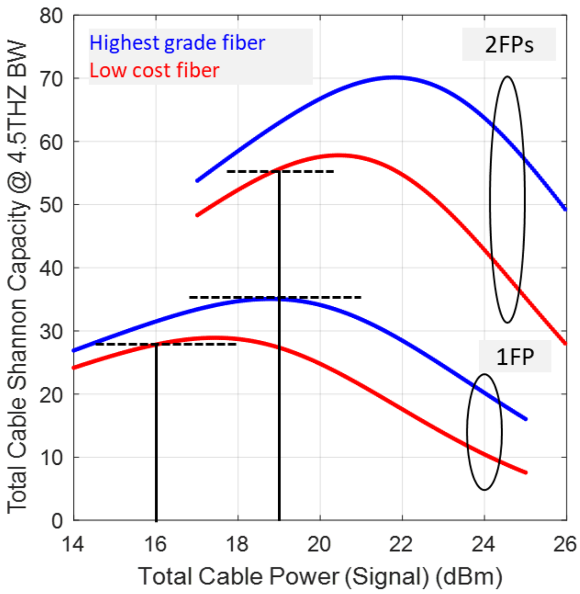

Figure 2: Cable Capacity vs Total Cable Signal Power

The total capacity of the cable for 1 and 2 fiber pairs is plotted as a function of the total cable power (signal power). Figure 2 shows results for two types of fibers. High-performance fiber (150/0.152) and low cost fiber (80/0.165) where the first item is the effective area in square microns and the second item is attenuation in decibels per kilometer.

Due to the logarithmic growth of capacity with power and the effects of nonlinearity, it becomes evident that, for the same total power and fiber, operating at the linear regime with two fiber pairs provides much larger capacity than operating at the maximum GOSNR on a single fiber pair. For the same total power, operating in the linear regime and doubling the fiber count provides 75% more capacity than operating at the maximum GOSNR in a single fiber pair.

These linear designs can be optimized by using lower grade fiber and optimize the cost/bit of the system. In this case, the capacity is increased by ~50%, but the fiber cost can be significantly reduced.

It is clear that, under power limitations, linear cables deliver much higher capacity than nonlinear cables. However, operating at the linear regime sacrifices spectral efficiency, which results in less power efficient terminal equipment per unit of bandwidth. The role of terminal equipment in the comparison of linear and nonlinear systems is out of the scope of this paper.

4. ULTIMATE CAPACITY IN VOLTAGE LIMITED SYSTEMS

The analysis in section 3 compares the cable capacity as a function of signal power. However, submarine cable powering is limited by voltage constrains rather than wall-plug power.

In order to supply current to the repeaters in the submarine network, large voltage is required from the landing stations. The ability to supply voltage to the entire transmission segment is critical to preserve traffic availability in case of cable shunt faults. This is the so-called Single-End Feeding of a submarine line and it is illustrated in the Figure 3.

Figure 3: Powering of a submarine line with SEF capabilities

The Voltage drop of a submarine line is the sum of cable voltage drop and repeater voltage drop, i.e, $V_{total} = V_{cable} + V_{reps}$. The cable voltage drop depends of the cable resistance and it is given by,

$$V_{cable} = I \times DCR \times L \quad (5)$$

Where I is the line current, DCR is the Distributed Cable Resistance and L is the cable length. The line current typically depends of the bandwidth, pump power and repeater gain (span length). In this paper, typical values are assumed for state-of-theart pumps. The repeaters voltage drop is defined as follows;

$$V_{reps} = N_{FPs} \times V_0 \times N_{reps} \qquad (6)$$

Which is proportional to the number of fiber pairs, the number of repeaters and the voltage per fiber pair. The voltage drop per fiber pair, V_0, depends of the pumping scheme as well as the voltage drop of control circuits. In general, this value depends on the total number of pumping units in the repeater. Each pumping unit contains N_{pumps} and supplies power to a number of fiber pairs given by, N_{FPs} . In this pump sharing arrangement, we define the Pump Sharing Index (PSI) as,

$$PSI = N_{FPs}/N_{pumps} \qquad (7)$$

This work attempts to obtain the maximum capacity as a function of the available voltage. The following parameters are fixed for this study:
Transmission distance of 10000km; repeater bandwidth of 4.5THz, repeater noise figure of 4.5dB, Fiber types, WDM (45x96Gbaud at 100GHz spacing)

Ultimate Capacity in Linear Systems

To determine the ultimate capacity in linear systems, the following 4 parameters are optimized: Span length, repeater output power, number of fiber pairs and PSI.

These four parameters are optimized to maximize the total capacity as a function of a given end-to-end Voltage. Both total Voltage and total Shannon capacity are obtained as function of four parameters. Then, fixing the total voltage, the combination providing the highest capacity is selected.

It is worth noting that the amount of fiber is optimized in this case together with the repeater characteristics. This means that the amount of fiber pairs depends, trivially, on the available voltage budget but also on the repeater efficiency to deliver the optimum GOSNR at that particular Voltage budget.

Ultimate Capacity in Nonlinear Systems

In this case, the repeater output power and the repeater spacing are optimized, for a given fiber type, to maximize the GOSNR value and therefore the Shannon Capacity. In this case, only fiber count and PSI are optimized for a given Voltage budget.

5. RESULTS AND DISCUSSION

Figure 4 shows the results of the optimization of capacity as a function of Voltage for a fiber type (150/0.152).

The capacity is shown for both linear and nonlinear designs, showing the corresponding the GOSNR values for each case. For reference, the number of fiber pairs is shown for the linear case. The advantage of linear systems is clear from the Shannon capacity analysis. It is worth stressing that linear systems are optimized to operate in the very linear regime, where the nonlinear penalty is around 0.1dB. This confirms that the maximum capacity is achieved when negligible power is used to “generate” nonlinear noise.

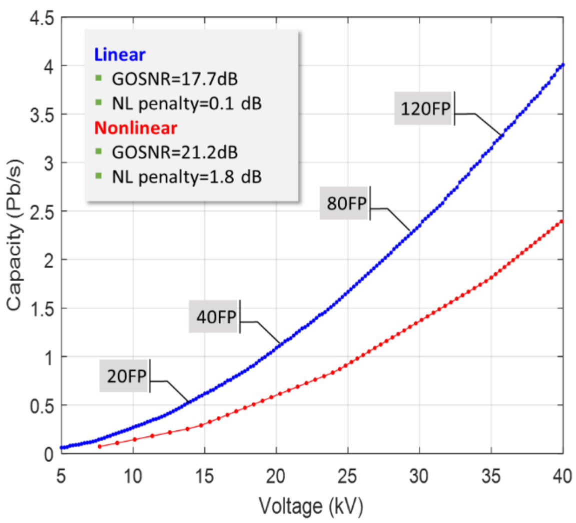

Figure 4: Ultimate Capacity as a function of Voltage for linear (blue) and nonlinear (red) systems.

Still, there is a 2.5dB difference in GOSNR, which translates in larger capacity per fiber pair for nonlinear systems.

Although more optimization parameters are included in this optimization, this trend was already shown first in works [ref 2 and ref 3] followed by other works [ref 4], where the concept SDM is used for these power/cost optimized systems.

The main purpose of this work is to analyze the impact of linear designs in technologies such as fiber, repeater or STLE.

Ultimate capacity and fiber types

Figure 5 shows the ultimate capacity against voltage for different types of fiber. The fiber type is changed only for the linear system, whereas 150/0.152 fiber is used for nonlinear design, for comparison purposes.

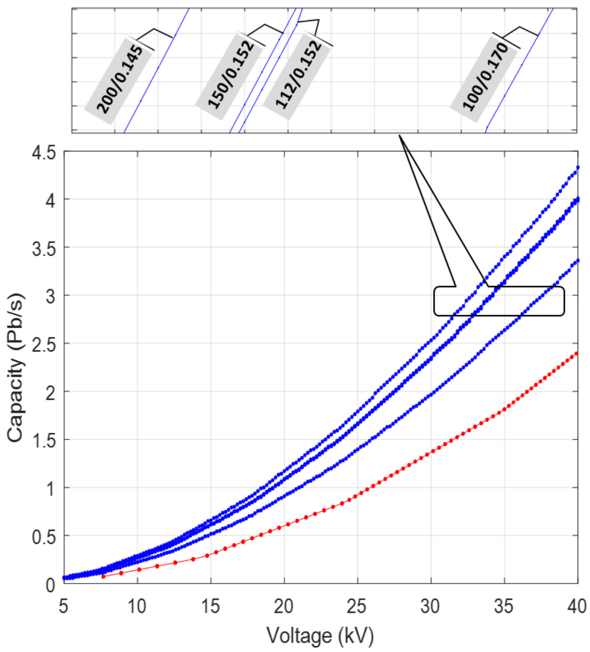

Figure 5: Fiber dependency on ultimate capacity vs voltage

As expected, large effective area plays a negligible role in the ultimate capacity for linear systems. As the systems operate at linear regimes, fiber attenuation has a larger impact because it is directly related to the optical power dissipation of the system. It is still worth reminding that in non-power limited system, the fiber effective area plays a major role to increase the spectral efficiency of the systems.

Linear systems and pump sharing

Another optimization item used in this analysis is the repeater configuration. In the figure 6, it is shown the capacity vs voltage for different pumping configurations.

The results show how the pumping scheme is optimized as the voltage budget grows. This analysis also shows the maximum capacity in case the pump power is capped to a certain value. As the voltage grows, the sharing index is increased as well as the optimum pump power.

It could appear counterintuitive at first to deploy more pumps in a voltage restricted environment. However, lower PSI allow a reduction of the pump power, and therefore the line current.

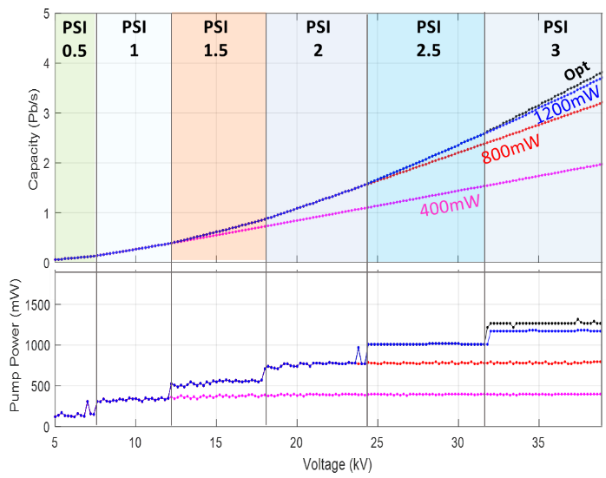

Figure 6: Pump scheme dependency on ultimate capacity vs voltage

This provides more budget for repeaters, and therefore, enables the addition of more fiber pairs. As the available voltage grows, less pumps are used per fiber pair to reduce the repeater voltage drop while gradually increasing the line current. Figure 6 shows a clear trade-off between the repeater voltage drop and the cable voltage drop. Therefore, results could slightly differ if the powering characteristics of the networks change.

Linear systems and SLTE

An interesting study to be done is the impact of linear designs in the SLTE definitions. We have shown so far that the ultimate capacity is obtained at significantly lower GOSNR values. This has an impact in the development of SLTE technologies.

One interesting aspect to analyze is the impact of Nonlinearity Compensation Techniques in the ultimate capacity of submarine cables.

Figure 7 shows an interesting result. In case of nonlinear systems, the implementation of Nonlinearity compensation actually reduces the total capacity of the system. The reason is the trade-off between repeater power and fiber count. When ideal SPM compensation is applied, the repeater power increases and the maximum capacity per fiber pair also increases.

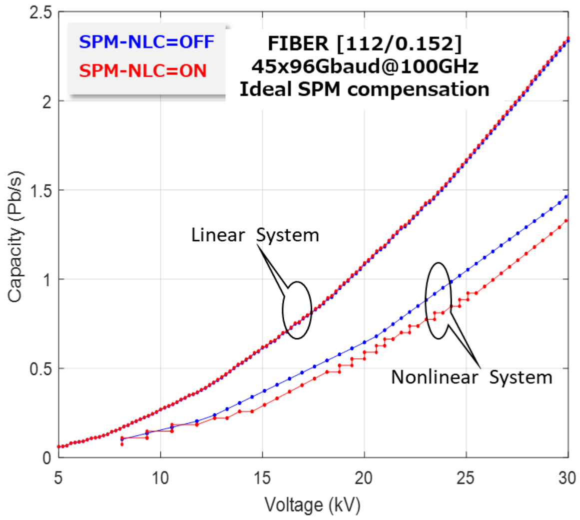

Figure 7: Ultimate capacity for linear and nonlinear systems with and without ideal SPM compensation

However, the line current also increases which leaves less voltage available for the repeater. Therefore, the number of fiber pairs needs to be reduced resulting in a capacity reduction.

6. CONCLUSION

We have analyzed the ultimate cable capacity of submarine cables under linear and nonlinear designs. This work provides a quantitative description of linear and nonlinear systems in terms of capacity per kilovolt. We have also analyzed the impact of linear vs nonlinear system in terms of fiber, repeater and SLTE technologies.

7. REFERENCES

[1] Pilipetskii et al. “High capacity submarine transmission systems” OFC 2015 W3G.5

[2] Mateo et al. “Capacity limits of submarine cables”, SubOptic 2016.

[3] Dar et al., "Submarine cable cost reduction through massive SDM," ECOC 2017, Tu.1.E.5.

[4] Kamalov et al., "Lessons learned from open line system deployments," 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2017, pp. 1-3.

[5] Poggiolini, P., “The GN model of nonlinear propagation in uncompensated coherent optical systems”, Lightwave Technology, Journal of, vol.30, no.24, pp.3857,3879, Dec.15, 2012.