CAPACITY LIMITS OF SUBMARINE CABLES

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Abstract: Submarine cables play a fundamental role in global telecommunications. In recent years, the internet traffic is experiencing a remarkable growth due to the large number of resource hungry applications which often require large traffic between data centers. In parallel with this traffic growth, optical transmission technologies have experienced a remarkable transformation providing large improvements in terms of transmission rates, spectral efficiency or OSNR tolerance.

1. INTRODUCTION

Submarine cables play a fundamental role in global telecommunications. In recent years, the internet traffic is experiencing a remarkable growth due to the large number of resource hungry applications which often require large traffic between data centers. In parallel with this traffic growth, optical transmission technologies have experienced a remarkable transformation providing large improvements in terms of transmission rates, spectral efficiency or OSNR tolerance.

Unlike terrestrial systems, the entire undersea equipage is powered from the landing locations, which can be as far as 10,000 km apart. The inability to supply electrical power locally prevents the use of full regenerators and results in very large number of amplifiers, which need to be powered from one or both ends. In addition, full powering from only one landing site is desired to prevent traffic disruption in the event of cable conductor damage or water ingress (shunt faults). These powering constraints have a fundamental impact in the cable design, imposing restrictions in the repeater output power, the maximum number of fiber pairs and, in consequence, in the net cable capacity.

This paper aims to determine an upper bound of the cable capacity under end-to-end voltage constrains. In order to detach this study from SLTE technologies, the Shannon limit for the spectral efficiency is considered to estimate the capacity as a function of the electrical-to-optical conversion efficiency of submarine repeaters and the cable resistance. Similar studies have been published before [1] as a function of some design parameters, but without providing an upper bound for the cable capacity.

In this work, an absolute capacity maximum of the system is obtained when OSNR (including fiber nonlinearity penalties) is optimized for that purpose. In other words, the repeater spacing and the repeater output power (ROP) are optimized to provide the maximum achievable Shannon capacity at a given end-to-end voltage. The fiber transmission is modelled through the full integration of the GN model, where practical carrier spacing is assumed. The GN model provides a generalized OSNR which includes the contribution of fiber nonlinearity. From this generalized OSNR, the Shannon Spectral efficiency can be determined and subsequently, the design capacity.

This paper is organized as follows: First, the transmission model is explained. Second the capacity calculation procedure is introduced. Finally, the results are presented and discussed.

2. FIBER TRANSMISSION AND POWERING OF SUBMARINE CABLES

In this section, both the optical transmission model together with the powering characteristics of submarine cables is discussed.

Nonlinear Fiber Optic transmission

The full integration of the GN model is used in this paper to obtain the generalized OSNR of the system [2]. The generalized G-OSNR is defined as:

$$G-OSNR=\frac{P_{ch}}{P_{ASE}+P_{NL}} \qquad (1)$$

Where P_{NL} is obtained from the power spectral density of the nonlinearity contribution defined as:

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

Where ρ includes fiber parameters and it is integrated over the propagation distance (in a sort of generalized effective length, which takes into account dispersive effects). Finally, χ includes a phase-array factor from frequency mixing. It is not the purpose of this paper to detail the full integration of the GN model. For detailed explanations of the GN model, including the integration of Equations (1-2) and the parameters therein, please refer to [2].

In order to simulate a more realistic scenario that the typical approximations of the GN model (flat and constant power spectrum), this work is assuming a spectral power distribution compatible with realistic WDM technologies. A spectrum of $N_{ch}=135$ channels with $R_s=32$ Gbaud and $B=33.3$ GHz channel bandwidth is assumed for this simulation. This results in an effective repeater bandwidth of 4.5THz. The normalized spectrum power is shown in Figure 1.

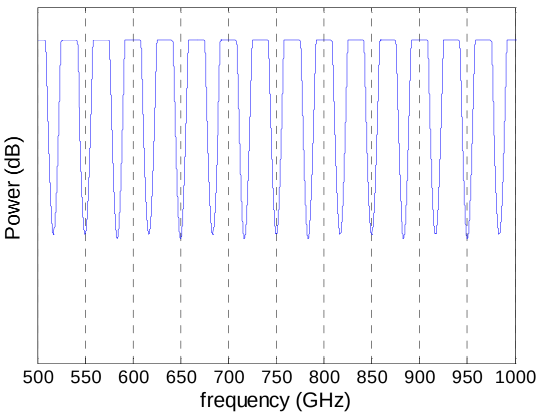

Figure 1: Subset of the power spectrum integrated in the GN model

The repeaters are assumed to have a 4.5dB noise figure. The fiber is assumed to have a nonlinear coefficient of $n_2=2.3\times10^{-20}\,\mathrm{m}^2/\mathrm{V}$ and a dispersion parameter of 22ps/km/nm. For this study, a transmission distance of 10,000km is considered with a fiber attenuation of 0.155dB/km and an effective area of 150 $\mu\mathrm{m}^2$.

The power per channel and the span length is optimized during the process of obtaining the maximum achievable capacity under end-to-end voltage constraints.

Cable Powering

In order to feed the repeaters with their operating current, $\mathrm{I}_{\mathrm{rep}}$ the landing station must be equipped with Power Feeding Equipment (FPE) capable of supplying a voltage large enough to compensate the voltage drop of the cable and the repeaters.

The repeater current depends on the characteristics of the EDFA, namely: Gain, output power, bandwidth and flatness. Also, it depends on the pumping scheme, which includes pump redundancy and control circuitry. The end-to-end voltage drop of a submarine cable is the sum of the contributions of cable and repeaters,

$$V_{total} = V_{cable} + V_{reps} . \qquad (3)$$

Where, $V_{cable} = I_{rep} \times R_{cable} \times L_{cable}$ is the cable voltage drop and R_{cable} is the cable resistance. The resistance varies depending of the cable diameter and conducting properties. In this paper, we are assuming a cable resistance of $0.75\,\Omega/\text{km}$.

The submarine repeater can be modelled as the diagram shown in Figure 2.

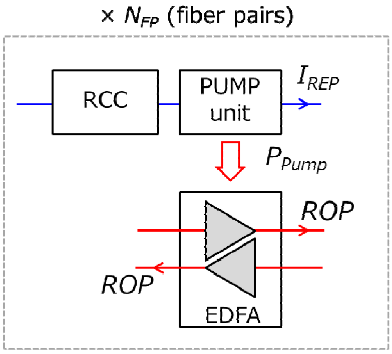

Figure 2: Functional diagram of an amplifier unit (one fiber pair) in a submarine repeater. RCC stands for Repeater Control Circuit.

The energy efficiency of the submarine repeater can be determined from the two following parameters, namely:

$$\eta_{EO} = \frac{N_{FP} \times P_{pump}}{V_{rep} \times I_{rep}} \qquad (4)$$

And

$$\eta_{EDFA} = \frac{2 \times ROP}{P_{pump}} \qquad (5)$$

The parameter η_{EO} represents an Electrical-to-Optical energy efficiency parameter which depends of the total number of fiber pairs, N_{fp}, the total pump power per fiber pair, P_{pump} divided by the voltage drop per repeater and the repeater current product. Alternatively, η_{EDFA} represents the pump conversion efficiency into signal power.

This parameter accounts for the EDF efficiency as well as the gain flattening losses, making this parameter dependent of the repeater gain. Typical values of the repeater efficiencies range between 5% and 25% for both parameters depending of system design.

3. SHANNON CAPACITY

In order to stablish an upper bond for the capacity, the Shannon limit for optical communication systems is considered. Figure 3 shows the well-known Shannon limit for the symbol size (M) as a function of the signal to noise ratio [3]. For a dual-polarization optical channel, the SNR translates to the G-OSNR as follows,

$$G-OSNR = \frac{R_s}{B_{ref}} SNR . \qquad (6)$$

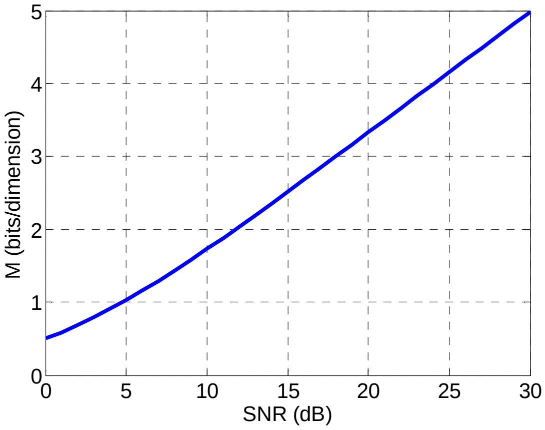

Figure 3: Shannon Capacity

Therefore, the G-OSNR defines the maximum achievable Capacity for a submarine cable with dual polarization digital coherent signal (4-dimensions), as follows,

$$C_{cable} = 4M \times R_s \times N_{ch} \times N_{FP} \qquad (7)$$

Where M depends of the G-OSNR obtained from the GN model at the reference bandwidth of B_{ref} =12.5 GHz.

Note that the above calculation does not consider compensation of fiber nonlinearities through back-propagation techniques.

4. CALCULATION PROCEDURE

In order to obtain the maximum achievable capacity that the PFE Voltage can provide, we have defined some cable, fiber and repeater characteristics. Also, the Shannon limit has been stablished as the upper bound for the modulation order. For that, we have left free the fundamental parameters that determine the G-OSNR for a given transmission distance, namely, the repeater power (ROP) and the repeater spacing (L).
First, by solving Eqs. (1-2), a matrix of G-OSNR values is obtained as function of the repeater output power and the span length. In order to reduce computation time, a subset of values is calculated and subsequent interpolation is performed.

This $m \times n$ matrix provides the G-OSNR for every possible (ROP, L) pair. For each (ROP, L) pair, the cable voltage can be obtained as a function of the number of fiber pairs. For that calculation, the repeater current is calculated based on typical values of η_{EDFA} and typical performance of high reliability laser diodes. After the repeater current is obtained, the repeater voltage drop is obtained based on typical values of the electro-optical efficiency, η_{EO} . Together with the cable resistance, the total voltage is obtained through Eq. (3). By changing the fiber pair count N_{FP} from 1 to p, a 3-dimensional matrix for $V_{cable}(ROP, L, N_{FP})$ is obtained.

Similarly, a 3-dimensional matrix for the cable capacity can be calculated by using Eq. (7).

Figure 4: **Graphic explanation of the calculation procedure** shows a diagram summarizing the calculation procedure explained above.

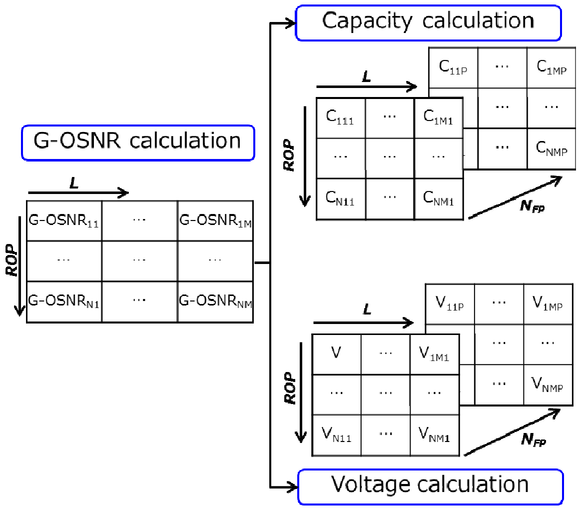

Figure 4: Graphic explanation of the calculation procedure

After the data is calculated, a search is performed to obtain the elements of the matrices that fall within a given Voltage limit. Amongst these values, the maximum capacity is found.

This calculation procedure completely optimizes the wet plant design (including the G-OSNR) as a function of the electrical properties of the repeaters and cable. Therefore, it provides an upper bound for the cross sectional capacity limited by the end-to-end voltage.

5. RESULTS AND DISCUSSION

Figure 5 shows the maximum achievable capacity of a 10,000km submarine cable under Voltage constraints. The ROP and L values are a result of the maximization of the capacity. Current PFE supplies a typical maximum voltage of around 15kV. According to our results, a single-end feeding system would be capable of support a 300Tb/s system of 10,000 km with a maximum of 12 fiber pairs.

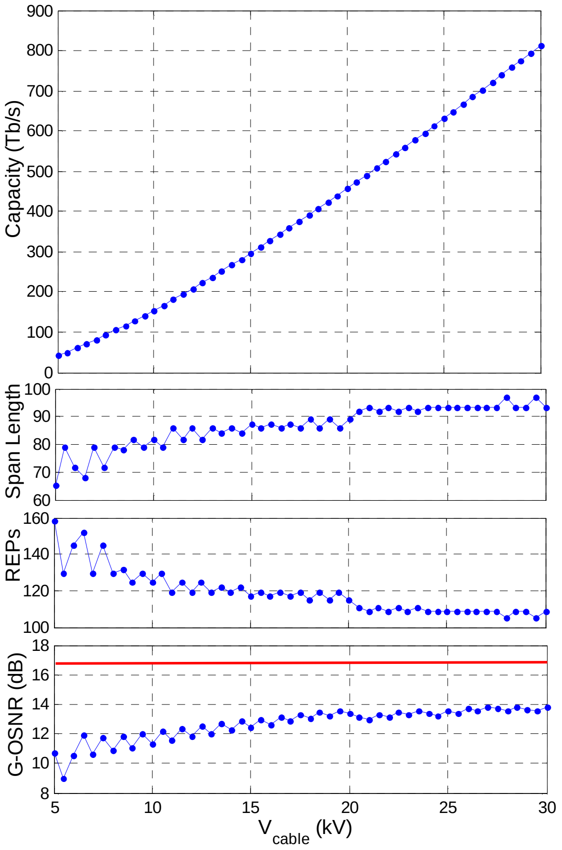

Figure 5: Submarine Shannon Capacity as a function of cable voltage (on top). On the bottom, the ROP span length and G-OSNR are shown. The plots show the results for the following loss/A_{eff} parameters (0.155dB/km, 150 μm^2). The Red line represents the maximum achievable G-OSNR, 16.7dB, at 45km span with ROP=17.2dBm.

If the system is allowed to be double-fed, then the maximum capacity becomes 800Tb/s approximately with a maximum of 29 fiber pairs.

As the allowable voltage is increased, the system tends to optimize the voltage drop along the cable by finding the best compromise between the number of repeaters, number of fiber pairs and the spectral efficiency (or G-OSNR). Figure 6 shows the EDFA and Repeater efficiency and the product of both as a function of the available end-to-end Voltage.

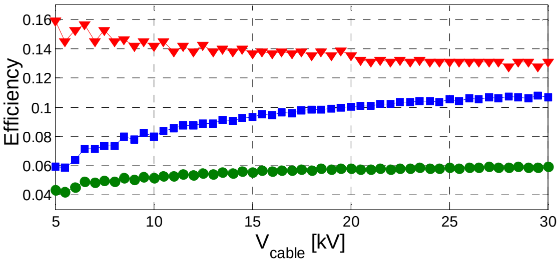

Figure 6: EDFA Efficiency (Red triangles); Electrical-to-Optical efficiency (Blue squares); Product divided by the sum (Green circles).

For lower voltage values, the maximum capacity is achieved at lower G-OSNR, which favors the addition of fiber pairs at the expense of spectral efficiency. As the allowable voltage is increased, the G-OSNR grows until an optimum value is reached, where the maximum product of EDFA and repeater efficiency is achieved. After this, the capacity grows linearly with the addition of fiber pairs.

In Figure 7, the maximum capacity under fiber pair count restrictions is shown.

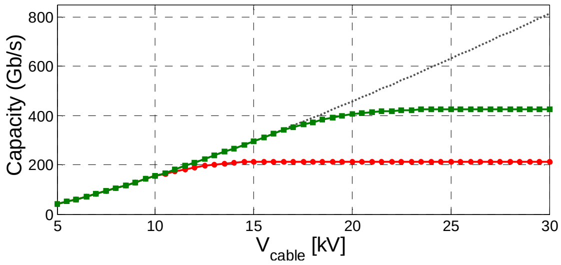

Figure 7: Maximum cable capacity and fiber pair limitation. 12 FPs maximum (green bullets); 6 FPs maximum (red squares).

Results are shown for the case of 6 FPs and 12 FPs, when the maximum number of fiber pairs could be limited, for example, due to cable diameter restrictions. As the maximum allowable voltage increases, the capacity increases to the maximum achievable G-OSNR, providing the maximum spectral efficiency at the Shannon limit. Figure 7 also shows the voltage level required to achieve the maximum capacity, reached at 12kV and 20kV respectively for 6 and 12 fiber pairs.

The results shown in this paper assume typical electro-optical parameters for the repeater. These parameters depend of the electrical design of the repeater and they can differ depending of items such as pumping scheme, electrical configuration, control circuitry, redundancy, etc.

In order to further increase the capacity of submarine cables, a number of possible directions could be explored both from the optical and electrical perspective.

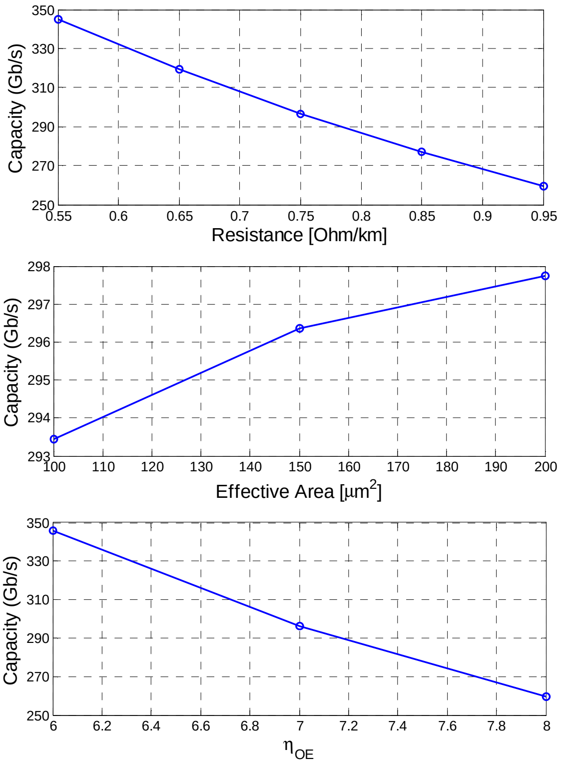

Figure 8: Capacity as a function of cable resistance (up), fiber effective area (middle) and voltage drop of the repeater (bottom). Results are obtained for a voltage drop of 15kV.

Figure 8 how the maximum capacity changes as function of several critical parameters. A 26% reduction of the cable resistance provides a 16% capacity increase. A 14% reduction of the repeater voltage drop, which results in a 17% increase of the optoelectronic efficiency, provides a capacity increase of a 17%. Finally a 33% increase of the fiber effective area provides a very small improvement in capacity (less than 1%) when the G-OSNR is optimized. Obviously, the impact of the effective area becomes more significant in the case where the number of fiber pairs is restricted.

Clearly, it is the efficiency in the way we convert electrical power into optical power the item that provides a more promising path towards increasing the maximum capacity of submarine cables as a function of the allowable end-to-end voltage.

6. CONCLUSION

This paper presents a simulation and calculation model to obtain the maximum achievable capacity (at the Shannon limit) in submarine cables as a function of the available end-to-end voltage.

7. REFERENCES

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