ELECTRICAL POWER, A POTENTIAL LIMIT TO CABLE CAPACITY

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Abstract: One of the factors limiting the potential capacity of a long submarine cable is the need to power the optical amplifiers which compensate for fibre loss. This paper shows how a number of routes to higher capacity all result in higher power requirements and uses the Shannon formula to assess upper limits on capacity. The results suggest that a promising, and practical, route to raising the limit would be to improve the powering of the optical amplifiers.

1. INTRODUCTION

The capacity demand for submarine systems has been increasing exponentially for over 10 years, with current estimates indicating that the rate of increase stands at over 50% per annum [1] and that this trend is set to continue. To provide the increases in capacity required to address this demand technology has provided us in recent years with optical amplifiers with higher power and larger bandwidths and increases in symbol rate, coherent detection and more bandwidth-efficient modulation formats.

The question we address here is whether there is any practical limit to the capacity that can be achieved? The simple answer is that recent advances will allow us to increase capacity by over ten times but that the electrical powering of the repeaters will reach a maximum threshold far earlier than optical transmission limitations.

2. MAXIMUM CAPACITY

If it were possible to overcome all transmission impairments except for noise, then Shannon's Law sets an upper bound to the capacity C of a system with a given Signal to Noise Ratio (SNR).

$$C \le B_o \log_2\left(1+S/N\right) \qquad (1)$$

$$S/N = \frac{P_o}{nB_o h\nu FG} \qquad (2)$$

Where:

P_o is the amplifier output power

n is the number of amplifiers

B_o is the optical bandwidth

h is Planck's constant

ν is the optical frequency

F is the amplifier noise figure

G is the amplifier gain

It is important to note, however, that Shannon's formula provides the channel capacity per transmission mode, so in the context of fibre optics, it may be augmented to give the total capacity C_T as

$$C_T = N_m N_c N_f C \qquad (3)$$

Where:

N_m is the number of fibre modes per core, including polarization modes

N_c is the number of fibre cores per fibre

N_f is the number of fibre pairs

From these equations, the most obvious candidates to increase the channel capacity are the bandwidth B_o and the total number of fibre cores or modes, since any change to the SNR yields only a logarithmic increase in capacity.

C band optical amplifiers can offer up to 40 nm of bandwidth, although typical submarine values are around 30-35 nm, with noise figures of the order of 4.5 dB. A larger bandwidth, and thus more capacity, could be achieved by a C+L band amplifier, or by using Raman pumping, to give bandwidths of 80-100 nm. Both require more, or higher power pumps.

As an alternative we could increase P_o or reduce the noise by increasing the number of amplifiers in the line, which improves the SNR by reducing the value of G. However, for any given system there is a limit to the number of amplifiers beyond which capacity reduces. The following figure shows the Shannon Limit capacity for a 10,000 km system with B_o = 35 nm, P_o = 17 dBm and F = 4.5 dB. These are "typical" figures chosen to illustrate behaviour, rather than those that might give the highest possible capacity in the future.

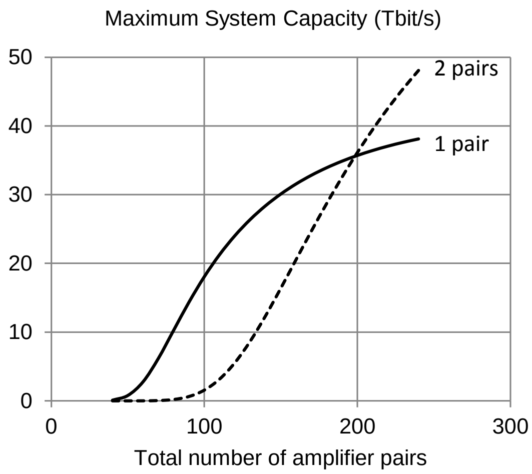


Figure 1: Capacity vs. number of amplifiers

As the gradient of the line for one fibre pair flattens there is a point, in this case around 200 amplifiers, beyond which it is better to spread the same number of amplifiers between two fibre pairs – this will vary from system to system.

Improving the SNR by increasing P_o is only possible to a limited extent. Non-linear optical effects in the fibre restrict the power levels that can be used and there are a number of papers [2,3,4] which consider how this affects the capacity that a single fibre can support. These each show that the increase in capacity starts to reduce as the optimum power is approached. The following figure shows the Shannon Limit capacity for a 10,000 km system with 150 amplifiers and B_o = 35 nm, P_o = 15 dBm and F = 4.5 dB.

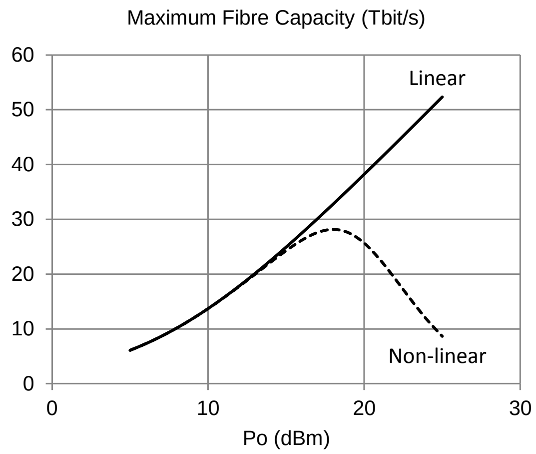


Figure 2: Capacity vs. power

In practice there are good reasons for operating at somewhat below the maximum value, since the capacity is only marginally smaller. The non-linear power limit, however, can be raised by increasing the fibre effective area, its chromatic dispersion or by reducing the attenuation coefficient. The latest system designs are mostly based on pure silica fibre with just these characteristics.

While non-linearity limits the capacity of a single fibre other routes to higher capacity could be to increase the number of spacial modes or to use multiple core fibres.

A little reflection shows that all routes to higher capacity require more power. Consider increasing the bandwidth while maintaining the same SNR: the noise $B_o hvFG$ increases in proportion to the bandwidth, which means that P_o must be increased by the same factor. Similarly, capacity will increase with the number of fibre pairs, but so too will the number of amplifiers. More amplifiers, or higher power amplifiers, both increase the overall power needed by the system amplifiers. It is evident that this is true of all the other routes to larger capacity. Noting that for several of these – e.g. increasing the number of fibres – it seems reasonable to suggest that at best the total amplifier power will increase approximately in proportion to the system capacity. In the case of higher amplifier bandwidth, the increase may be even faster.

On long systems the overall resistance of current cable designs and the voltages that can be applied to them set a limit to the current and thus to the power that can be delivered to the repeaters and later sections discuss how practical it would be to increase this.

It is our contention that the greatest obstacle to providing substantial increases in submarine system capacity is the delivery of electrical power to the repeaters.

3. POWERING

Submerged amplifiers are powered by current flowing through a conductive path in the cable, which needs to be insulated from the surrounding sea-water.

Submarine-grade polyethylene is one of the best materials for this purpose, as it offers excellent insulation while having mechanical properties suitable for a cable – higher voltage materials, such as glass or ceramics would clearly be too brittle.

Steel, which is used for most of the mechanical strength members, is chosen because it can provide good strength without being very expensive. However, its electrical resistivity is relatively high and some copper (which is one of the most conductive metals) is used to reduce the cable resistance. Copper, however, contributes little to the mechanical strength of a cable and lowering the cable resistance by increasing the amount of copper requires the steel content to be increased to support the extra weight. The extra metal makes for a bigger conductor and in turn needs more polyethylene to provide the same degree of insulation, making for a bigger cable, particularly when armour wires are added. Bigger cables are less flexible, take more space on a cable-ship and (most importantly) cost more. Most of the established suppliers propose submarine cables with a polyethylene diameter of around 17-18 mm diameter, with resistance around 1 ohm/km; cables with lower values exist, but these are often restricted to shallow (<3,000 m) depths. Power cables, of course achieve low resistance, but are also limited in depth.

There are a lot of practical and safety aspects of providing high voltage power feed equipment (PFE) and an accepted limit to the maximum voltage is around 12 kV.

One of the most common fault conditions, a "shunt fault" occurs when the cable insulation is damaged mechanically and the central conductor of the cable is exposed to the sea water making a connection to the sea, which is effectively at zero volts.

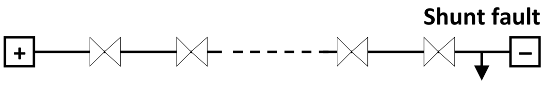


Figure 3: Shunt fault

The cable can still operate providing that the power feed voltages can be adjusted to make the cable voltage at the fault close to zero. Since such faults are nearly always in shallow water, this requires that one power feed must provide almost all the voltage. The ability to operate like this until a repair can be performed is clearly highly desirable.

4. AMPLIFIER EFFICIENCY

There are a number of stages in transforming the electrical power delivered to the repeater into light. A simplified schematic of an Erbium Doped Fibre

(EDF) amplifier is shown below. (Detailed implementation will obviously change from one supplier to another.)

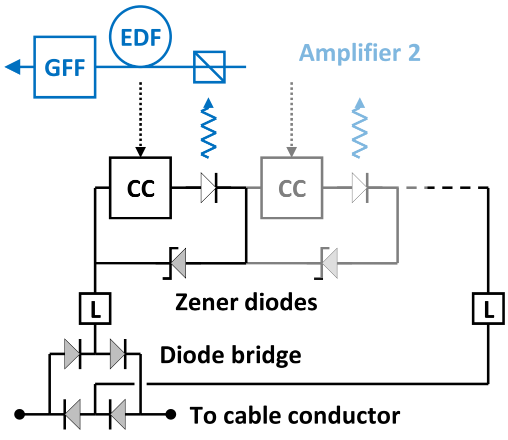


Figure 4: Schematic of EDF amplifier

Firstly, there is circuitry to suppress surges and control the pump current, usually a combination of Zener diodes (which also stabilise the voltage), some inductors and other devices. In most cases there is a diode bridge which allows for bi-directional powering, but is also useful in handling the surge currents which can result when a cable is cut. For reliability each bridge diode shown in the diagram is a parallel/serial combination of several individual components, so the voltage drop across the bridge is typically 3-4 volts.

Current to the pump laser needs to be controlled, in part to handle ageing of the laser, where the current required may rise by up to 50% by end-of-life. In the example shown it is clear that a significant amount of power will be dissipated by the Current Control (CC) circuitry which drive the pump diodes. Assuming a 2 V drop across the pump laser and 6 V zener diodes, gives an efficiency of 33.3%.

At start-of-life a good 980 nm pump laser can convert electrical power into light with around 20-22% efficiency, but some allowance needs to be made for ageing.

The Erbium Doped Fibre can convert around 50% of the 980 nm pump into output power, but a significant fraction is lost in the Gain Flattening Filter (GFF), the amount increasing rapidly as the bandwidth approaches around 40 nm. GFF losses are dependent on fabrication, but for a bandwidth of 35 nm around 50% of the power needs to be rejected by the filter to get good flatness: at 40 nm the figure is around 75%. Taking a figure of 50% for the GFF gives:

Driver	33.3%
Current for pump ageing	66.7%
Pump	21.0%
Doped fibre	50.0%
GFF	50.0%
Overall efficiency	1.2%

In addition, some power is dissipated in control and supervisory circuitry, making the overall efficiency <1%, a figure supported by a supplier's data sheet.

Before considering if, and how, the efficiency might be improved, it's instructive to consider the example of a 9,000 km system operating with amplifier output of 15 dBm – a value which should avoid non-linear effects. Taking an amplifier efficiency of 1.2% and 150 repeaters the following graph shows the voltage needed for 2-8 pairs.

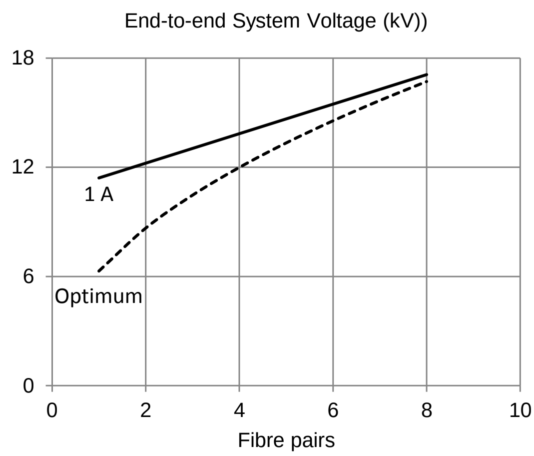
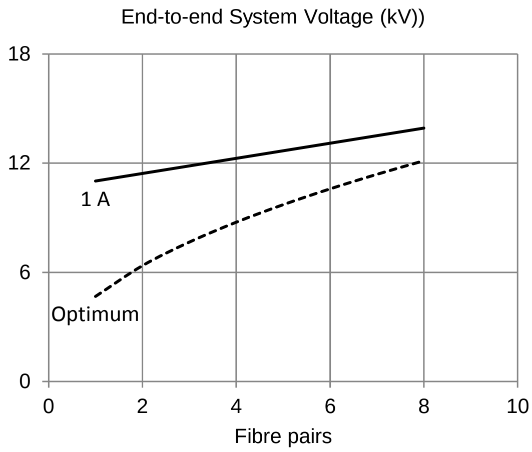


Figure 5: System voltage vs. number of pairs

Power feed current is 1 Amp (also a typical figure), but the dotted line shows the minimum voltage which could be achieved if the current were adjusted to minimise the total voltage.

To increase the number of pairs, most long systems do not aim for a single-end feed, instead using up to ±12kV, accepting that a shunt fault will disrupt the system.

When examining the detail of the electrical to optical conversion process it becomes clear that a significant inefficiency comes from driving a 2 V pump from a 6 V (or similar) supply via units which dissipate power. High-frequency DC-DC converters routinely achieve efficiencies of 75% and more. The following graph shows the effect of increasing the driver efficiency to just 65%.



The improvement is significant, making possible 8 pairs with single-end powering, since a good DC-DC converter has the flexibility to operate at the optimum current. In the example shown the optimum current would be ~0.6Amperes, which might require minor modification to the power feed units.

Applying the Shannon bound to this configuration we obtain a maximum total capacity of ~200 Tbit/s. In reality a smaller value will be achieved, but the computation shows both that significant capacity should be possible and that improving the powering efficiency is a useful route to it.

5. SUMMARY AND CONCLUSIONS

While transmission effects are clearly of immense significance to submarine system capacity, the issue of powering submerged amplifiers represents a significant constraint: by contrast, power is much less important in terrestrial systems.

A promising direction for improvement could be the use of better driving circuitry which could raise the electrical-to-optical efficiency of the submerged amplifiers.

6. REFERENCES

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