DEEP WATER NETWORKING - A ROUTE TO RELIABLE CAPACITY ENHANCEMENT

Steve Desbruslais, Sumudu Edirisinghe (Open Systems Solutions)
Email: steve@opensystemssolutions.co.uk

Open Systems Solutions, London, UK.

Abstract: It is well known that the capacity of ultra-long haul submarine systems is limited by the power deliverable to the repeaters rather than by optical penalties. The limitation comes about due to the voltage rating of the cable and joints and is independent of the number of fibres in the cable. As a consequence, if, for example, it was required to increase the capacity of a long distance link by a factor of 4 then 4 separate cables would have to be installed, each with its own power feed equipment. It has been shown previously that a four-fold increase in capacity is also achievable by double end feeding a system. The well understood limitation of this approach is that, in the case of a shunt fault, which invariable occurs near one of the landing points, the far-end power feed equipment has to supply essentially all the system voltage, which in this case would cause the voltage to exceed the upper voltage limit of the cable. In this contribution, we explore reliable networking solutions which allow the system capacity to be increased by a factor of 4 without exceeding the voltage limit of the cable.

1. INTRODUCTION

Submarine Systems are unique in the telecommunications space in that the engineering required entails not only the traditional fibre optic design, low power electronics, mechanical rack designs etc., but also high pressure mechanical design of submersibles and high voltage cable and joint design. Furthermore, it is imperative that the designs are highly reliable. With all these disciplines involved we can't presume that optical impairments present the fundamental limit to the transmission capacity. In practice the limits are highly dependent on system length, and here we specifically address the regime of ultra-long systems, i.e., 6000km and above.

The identification of fundamental limits to transmission capacity has been a recurring theme in the literature. For some time it was thought that Polarisation Mode Dispersion (PMD) and nonlinearities set the limit [1-3]. With the advent of digital coherent communications however, this changed as the PMD could be equalised and the rapid changes in the State of Polarisation (SOP) tracked dynamically in the electrical domain. Although it is not possible to fully equalise Polarisation Dependent Loss (PDL) due to its non-unitary nature, it only presents a modest OSNR penalty. Also, the Polarisation Dependent Gain (PDG) which occurs in the EDFAs becomes insignificant when many channels are present [4]. The nonlinear penalty has been significantly reduced by performing all the chromatic dispersion equalisation at the terminals, again, a capability made possible by coherent communications [5]. Nonlinear penalties can be further reduced using digital backpropagation [6], especially in high baud rate systems. Systems built using coherent technology and soft decision Forward Error Correction (SD-FEC) can operate within a few dB of the Shannon limit. However, the total capacity of a system is not only determined by the channel capacity, it is also dependent on the number of channels. Attempting to more closely approach the Shannon limit is becoming more difficult but increasing the number of wavelength channels or using space division multiplexing (multiple fibres or multicore fibre) remains a practical way of increasing capacity.

Recently it has been shown that the fundamental limit to the capacity of long reach submarine systems is the voltage rating of the cable and joints [7, 8]. The analysis necessary to come to this conclusion was greatly simplified using the Gaussian Noise (GN) model [9] as the trends are easily understood without performing an impossibly large number of simulations over the parameter space. The voltage rating of the cables and joints is typically 12kV, including any earth fluctuations due to electromagnetic storms and magneto-hydrodynamic effects. To ensure satisfactory operation at these voltages, the cables and joints have to be proof tested at around ten times the rating to ensure that dielectric breakdown will not occur over the lifetime of the system. Using the GN model, it has been found that there is an optimum repeater spacing of around 50km for which the capacity is maximised [8]. The analysis also shows that the capacity increases with the square of the system voltage.

One way in which the system voltage can be increased is by double end feeding. With this scheme, the ends of the system are set at +/-12kv so that the 12kV rating is not exceeded with respect to earth potential and yet the potential difference across the system increases to 24kV. This doubling of the system voltage can increase the capacity of the system by a factor of 4. The drawback is that, in the event of a shunt fault, which invariably occurs near the shore, restoration of the system will require that the far end voltage be increased to 24kV, which is not permitted under the design rules. Here it is assumed that the shunt fault does not cause a break in the fibres so that communication is still possible by balancing the Power Feed Equipment (PFE) such that the inner conductor potential is the same as the sea potential at the fault location.

In this contribution, we show how it is possible to circumvent the shunt fault limitation so that the system can indeed be operated without exceeding the voltage limit thereby increasing the theoretical maximum capacity by a factor of 4 to over 1Pb/s. Furthermore, the reliability of the system is significantly increased.

2. THE DUPLICATING BRANCHING UNIT

Although submarine systems are designed to achieve in the order of 1 ship repair over 25 years, this does not take into account the number of extrinsic faults due predominantly to cable damage. A system with an expected single ship repair in 25 years and a mean time to repair (MTTR) of 2 weeks is equivalent to an unavailability of 0.15%. However, if the system suffers from extrinsic failures at a rate of 1 failure per year (say) then the total unavailability increases to 3.9%, far exceeding the intrinsic unavailability.

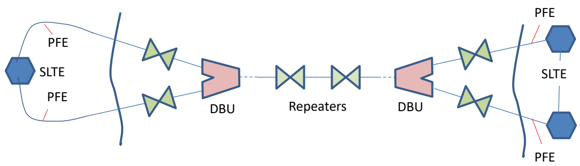


Figure 1: The Duplicating Branching Unit showing two backhaul options

One way to mitigate this problem is to duplicate the section of cable and repeaters near the shore ends as shown in Fig. 1. The signals in the shore direction are split into two paths within a Duplicating Branching Unit (DBU). Similarly, the identical signals traveling from the shore are switched at the DBU (in practice, the switching should be performed at the SLTEs to improve the DBU reliability). For the system to be robust to extrinsic faults, the DBU must be located sufficiently far from the shore that a cable hit from an anchor or trawler on one branch will not cause a hit on the second cable. Given that the stopping distance of a large tanker is around 10km, 25km separation should be sufficient. The advantage of this configuration is that an extrinsic failure does not cause the system to go down. We can assess the unavailability of the configurations with and without DBUs as follows. Let the intrinsic unavailability be $\bar{A}_I$ and the extrinsic unavailability at each end of the link be $\bar{A}_E$. The unavailability is defined as $\bar{A} = t_R/(t_F + t_R)$, where t_R is the mean time to repair (MTTR) and t_F is the mean time to failure (MTTF). For the intrinsic MTTF we use 25 years with an MTTR of 2 weeks. For the extrinsic MTTF we use 2 years at each end and the same 2 week MTTR. The total unavailability without the DBUs is then given to a good approximation by

$$\bar{A}_{tot} = \bar{A}_I + 2\bar{A}_E$$

With a DBU at each end of the link the total unavailability becomes

$$\bar{A}_{tot,DBU} = \bar{A}_I + 2\bar{A}_E^2$$

These relations give $\bar{A}_{tot} = 3.9\%$ and $\bar{A}_{tot,DBU} = 0.22\%$. The extrinsic unavailability is therefore reduced by a factor of 53 and the total unavailability with the DBUs in place is reduced by a factor of 17. The duplicated backhaul will also benefit from this redundancy. Note that this redundancy mitigates the effects of fibre breaks as well as shunt faults.

Fig.1 shows two possible backhaul configurations. To the left, both cables are routed to the same SLTE. On the right, two separate SLTEs are shown. Whilst this latter approach increases the resilience of the system, the single SLTE option has significant cost advantages.

The main optical elements of the DBU are shown in Fig. 2. For each fibre pair of the trunk, a separate fibre pair is employed for the branches, each with a 3dB loss. Since identical bi-directional signals are transmitted over the two branches, an optical switch at the SLTE selects one branch. The selected branch is powered with the PFE, but it is not necessary to power the spare branch.

An extrinsic cable failure is equally likely to affect the spare branch as the working branch, so it is just as important to detect a cable hit on the spare branch as it is on the working branch. A simple method of achieving this is by employing a low voltage continuity circuit which can be continually monitored. That way, the spare leg can be repaired at the convenience of the operator to restore the redundancy.

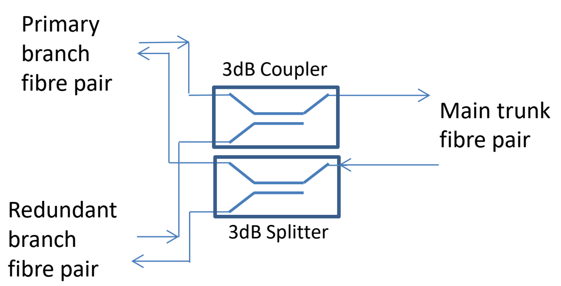


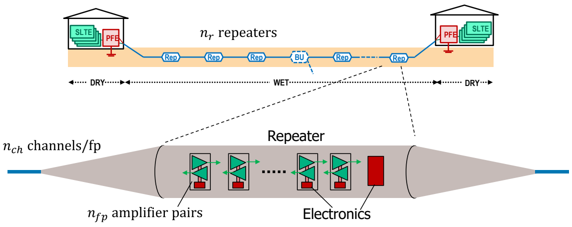
Figure 2: Key optical elements within the DBU

3. CAPACITY ENHANCEMENT USING DBUs

With the system availability now protected from shore end cable damage, we can justifiably use double end feeding. In [8] it was shown that the transmission capacity is maximised subject to the following criteria:

- The voltage drop across the cable is designed to be the same as the voltage drop across the repeaters.
- A power efficient modulation format such as PM-QPSK should be employed. Higher order formats result in an OSNR penalty which in turn limits capacity for a fixed PFE voltage.

- Operate at the optimum span loss of ~8.5dB (50km spans for Pure Silica Core (PSC) fibres).
- Operate the system well below the optical nonlinear threshold.



$$P_r = \frac{2n_{fp}n_{ch}P_{ch}}{\eta_c} + P_0$$

P_r	Electrical power per repeater
P_0	Electrical power overhead per repeater
P_{ch}	Optical power per channel
η_c	Power Conversion Efficiency

Figure 3: Relation between the optical channel power and PFE power

Using these criteria, it was found that a transpacific link could support 250Tb/s for a PFE voltage of 12kV and 5% electrical to optical conversion efficiencies. The total bandwidth required was 700nm, which could be realised using 10 fibre pairs of 70nm each (i.e., C+L band). The relationship between the optical channel power and PFE power is illustrated in Fig. 3.

If we now use a DBU at each end of the system and double end feed to +/-12kV, then this capacity can be increased fourfold to 1Pb/s. The system parameters used are shown in Table.1.

In order to achieve this capacity in practice, a way must be found to support the required 2800nm of bandwidth. Using the C and L bands alone with a total bandwidth of 70nm would require 40 fibre pairs, which would be challenging mechanically. However, if multi-core fibres are used (6 cores, say) then we would need 7 multi-core fibre pairs, each core supporting 240 channels at 32.75Gbaud over a 67nm bandwidth.

Parameter	**Value**
Attenuation Coefficient (dB/km)	0.16
Affective Area (μm^2)	80
Dispersion Coeff. (ps/nm-km)	17
Span Length (km)	50
Noise Figure (dB)	4.5
FEC Threshold (dB)	10.8
FEC Overhead (%)	25
Link Length (km)	11000
System Margin (dB)	2.5
Cable resistance (Ω)	1.0
Bridge dissipation (W)	2
EO Power conversion efficiency	5
PFE Potential Difference (kV)	24

Table 1: Parameters used to determine the system capacity

4. CONCLUSIONS

A method has been proposed, using Duplicating Branching Units, which both mitigates extrinsic submarine system failures and quadruples the maximum capacity of ULH voltage limited systems. A maximum capacity of 1Pb/s is shown to be achievable over trans-pacific distances. Since high power efficiency modulation formats are necessary to make best use of the power available, the total bandwidth required is very large and would probably require multi-core fibre and physically small optical amplifiers to achieve it. The current limits to achieving the maximum capacities are therefore the mechanical design of the repeater, if many fibres are used, or else multi-core fibres and compatible amplifiers. Although the capacity advantages of the DBU have been emphasised, it would also benefit ULH systems of moderate capacity due to the resilience to cable damage and the resultant increase in system availability. Of course the cost per unit bandwidth will also be lower.

The authors would like to express their thanks to Xtera for supporting this research.

5. REFERENCES

[1] A. R. Chraplyvy and R. W. Tkach, 'What Is The Actual Capacity Of Single-Mode Fibers in Amplified Lightwave Systems?', *IEEE Phot. Tech. Lett*, **5**, pp 666-668, June 1993.

[2] C. D. Poole, R.W.Tkach, A R Chraplyvy and D. A. Fishman, 'Fading in Lightwave Systems Due to Polarization-Mode Dispersion', *IEEE Phot. Tech. Lett*, **3**, pp 68-70, June 1991.

[3] C D Poole and J A Nagel, 'Polarisation Effects in lightwave systems', in *Optical Fiber Telecommunications* IIIA, I.P. Kaminov and T. L. Koch, eds,, Academic Press, CA, pp114-161

[4] A. N. Pilipetskii and E. A. Golovchenko, 'Performance Fluctuations in Submarine WDM Systems', in *IEEE J. Light. Tech.*, **24**, pp. 4208-4214, Nov. 2006.

[5] S.J. Savory, G. Gavioli, R.I. Killey and P. Bayvel, "Electronic compensation of chromatic dispersion using a digital coherent receiver," *Opt. Exp.* **15**, pp2120-2126 (2007).

[6] X. Li, X. Chen, G. Goldfarb, E. Mateo, I. Kim, F. Yaman, and G. Li, "Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing," *Opt. Exp.* **16**, pp.880-888 (2008).

[7] T. Frisch and S. Desbruslais, "Electrical power, a potential limit to cable capacity," in SubOptic, 2013., paper Tu 1C 04

[8] S. Desbruslais "Maximizing the capacity of ultra-long haul submarine systems" *Proc of NOC'15* 2015.

[9] Poggiolini, P., "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," *IEEE J. Light. Tech.*, **30**, pp. 3857–3879, Dec 2012.