Cost/Bit Scaling Opportunities in Submarine Cables

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Abstract: The cost/bit of submarine networks has experienced enormous reductions in the past three decades. This decline starts to show signs of fatigue. This paper analyzes the causes and discusses opportunities to address this saturation.

1. Introduction

Submarine networks, which support the vast majority of international data traffic, have experienced a continuous and tremendous growth in capacity over the past three decades. To illustrate this, the first non-regenerated transpacific system (first with EDFAs), was the TPC-5 system built in 1996 and comprising 2 fiber pairs (FPs) with a capacity of 5 Gb/s each. Nowadays, technologies enable 24 FPs across the Pacific with capacities in the range of 15 to 20 Tb/s/FP. This is a 5 order of magnitude increase in capacity, which translates to a 6 order of magnitude reduction in cost-per-bit when costs are adjusted for inflation. This shows the remarkable innovation efforts in optical communications technologies, giving rise to the information society of nowadays. Figure 2 shows the evolution of cost/bit in a transpacific systems in the past 20 years, spanning 4 generations of fiber plants.

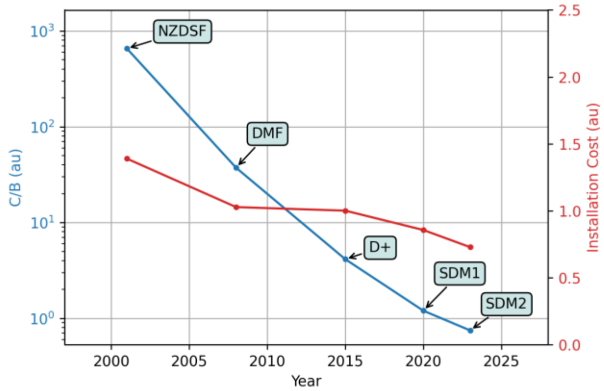

Fig.1. Evolution of cost/bit for transpacific system over the past 20 years. The cost exclude branches. Only equipment and marine installation is included. Cost data as of today, adjusted for inflation.

In recent times, cost/bit has become a fundamental metric when analyzing prospective technologies in submarine networks [1, 2]. We can define cost/bit as follows:

$$C/B = \frac{C_{OPTICS} + C_{HOUSING} + C_{INSTALLATION}}{B_T \times \log_2(1 + GSNR)} \quad (1)$$

Where B_T is the total system bandwidth carrying traffic, i.e. the number of fiber pairs times the EDFA bandwidth, typically 4.5THz for the C-band, times a spectrum occupancy ratio. The GSNR represents the average generalized SNR including a gap to the Shannon limit and SNR penalties of practical modems. The Cost can be separated into three contributions.

- Cost of optics: This is the cost of optical fiber and optical amplifiers. Amplifiers including EDF, optical pumps and other optical components. This grows linearly with the number of fibers in the system.
- Cost of housing: This is the material cost of submarine cable (excluding fiber) and repeater housing and sealing components. This also includes specific common circuits, such as surge protection circuits.
- Cost of installation: This represents the cost of installing the cable, i.e. loading the cable into a cable ship, transportation, mobilization, laying and burial operations.

In the past 20 years, the largest contribution to C/B reduction has been the tremendous increase of capacity of submarine cables. While keeping housing and installation cost almost constant, or with small variations over the years, the advent of digital coherent technology has brought a tremendous increase in fiber capacity that has drastically reduced the C/B. The development of powerful DSP enabled the use of SMF fiber with large chromatic dispersion. This simplified the wet plant design, reduced the cost of fiber dramatically and drastically reduced the effect of nonlinear effects which boosted the spectral efficiency with advanced modulation formats. Now that coherent communications have reached a great deal of maturity, the quest for further reducing the gap to the Shannon limit is no longer a practical approach to increase cable capacity. Mainly, due to the logarithmic growth of spectral efficiency with optical power, which burdens the remote powering characteristics of submarine systems. For that, Spatial-Division Multiplexing (SDM) was introduced to linearize the capacity growth by efficiently adding spatial channels [3, 4]. This is the current standard in designing submarine cables, which has enabled to continue to grow cable capacity to the Petabit level when this paper is written.

2. Cost distribution in modern submarine systems

Analyzing C/B scaling inevitably requires a few words about costs in submarine systems. However, it is difficult to stablish general trends as submarine systems are highly diverse. To illustrate this, the Figure 1 shows a typical breakdowns of cable for two different scenarios.

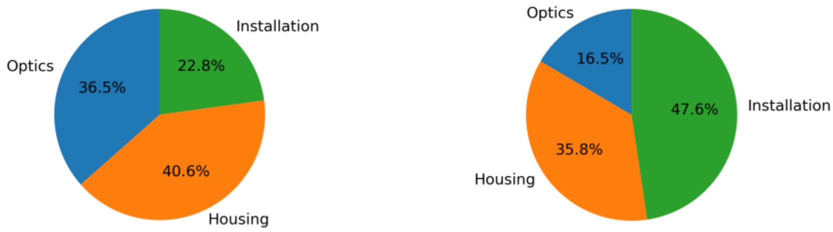

Fig.2. Typical breakdown of cost for two typical scenarios. Left, a 24FP point-to-point transpacific cable with single-end feeding. On the right, a 16FP intra-Asia fishbone system, with 10 branches.

Figure 1 shows the large disparity of cost distribution depending of the characteristics and geography of the system. For a high-capacity point to point transpacific system, the optics (i.e. amplifiers and fiber) bear a large portion of the cost, whereas the housing is dominated by the conductor cost to enable Single-end feeding. In case of an intra-Asia system with many branches, a typical system connecting Japan and South-East Asia, the cost is dominated by the marine installation. This due to the large amounts of armoring required in the shallow waters as well as the large amount of burial and shore-end operations. These approximate diagrams illustrate that submarine systems are diverse and different approaches could be optimum for different systems. In SDM systems, capacity has managed to grow while keeping powering under control. However, it is not obvious to expect a steady reduction on C/B by continuing to add spatial channels if the submerged plant housing must be expanded to accommodate large amounts of fiber and amplifiers. Also, marine installation costs will be increased due to larger volume and weight in the vessel tanks. Even less obvious are the implications in mass-production manufacturing and installation. Here, large investments must be made to adapt to larger bodies without compromising installation and loading speed. It seems clear that the path of SDM touches space limitations.

3. Cost/Bit scaling in next generation SDM systems

It appears that C/B reductions require two major efforts. One is to reduce the size and power consumption of optics and continue the path of capacity growth. For this to be effective, one must attempt to keep the housing and installation costs without increasing. Another effort is to reduce all the costs regardless of cable capacity. Using lower-cost *terrestrial* optics incurs in reliability penalties, which are not accepted by the industry, due to the large cost of repairs. Another approach is to explore the use of lower cost materials for housing. A good example of this is the use of aluminum conductor, instead of copper [5]. In this analysis we will focus on the first, approach, i.e. capacity increase, and we will differentiate into three vectors, namely: Optical performance, powering and density. The marine installation cost is estimated as a function of total weight of equipment. We will analyze a 9000km system with single-end voltage feeding.

3.1 Optical performance

SDM systems operate in the linear regime, therefore, improvements in fiber effective area or nonlinearity compensation are not effective in reducing C/B. Optical performance improvements are mainly correlated to power efficiency. Fiber attenuation, EDFA power conversion efficiency or gain flatness are the main vectors that contribute to C/B. Figure 3 shows example of how these items can improve C/B assuming that they are obtained at no additional cost. For these simulations, we unrealistically assume constant cable size and we assume that the repeater cost scales linearly the number of amplifiers. We ignore installation restrictions due to large equipment size. Figure 3 (top-left) shows C/B distribution as a function of capacity for various optical performance improvements ignoring space limitations in cables or repeaters.

3.2 Powering

Fig 3 (top-right) analyzes the effects of powering in C/B and same as before, we assume no space limitations. C/B plots are obtained when: (i) the pump sharing index is increased (which reduces significantly the repeater voltage drop); (ii) the cable DCR is reduced from 0.8 Ω/km to 0.6 Ω/km and (iii) when the PFE is increased from 18kV to 20kV. The elements provide a similar improvement in C/B being the sharing index the element that provides larger capacity, as expected in dense SDM systems.

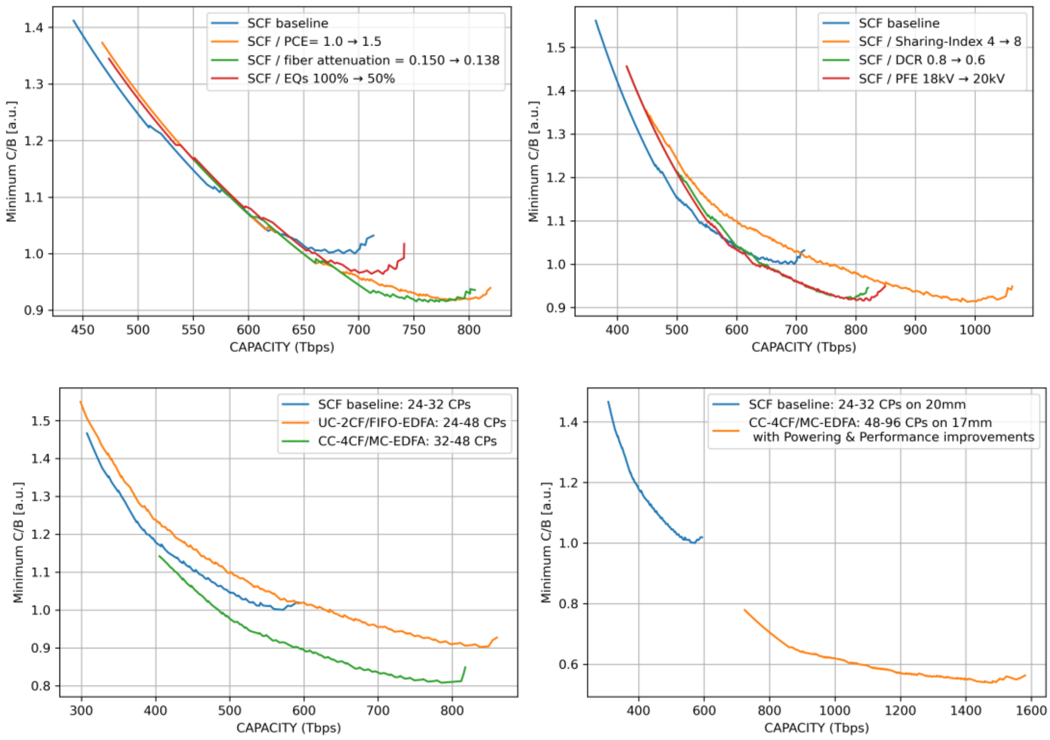

Fig.3. Technoeconomics of submarine systems under various scenarios.

3.3 Density: Multicore systems

Here, we quantify the C/B effects in terms of density. In particular, we restrict this analysis to multicore components. Larger bandwidth systems, such as C+L, are equivalent solutions to increase cable density. Unlike the previous cases, we assume now realistic space limitations of 20 and 17mm cable and state-of-the-art repeaters. As necessary, we assume interleaved repeater solutions to double the capacity of EDFAs. Fig.3 (bottom-left) shows a comparison between 3 systems. A baseline with SCF and large diameter cable. A UC-2CF system with FIFO-EDFA and a CC-4CF with MC-EDFA. For fiber cost, 2CF assumes the same cost/core than SCF. For 4CF, we assume a cost/core factor or 0.5 and a size reduction of 50%. We do not assume any capacity penalty from MIMO DSP. In case of MCF-EDFA, we assume a reduction of 15% of PCE penalty compared to SC-EDFA. Figure 3(B) shows the C/B for these 3 scenarios. As for Cross-Talk, -55dB/100km is assumed for uncoupled fiber. Finally, a plot comparing a baseline 24FP SCF system with all the elements working together is shown, i.e. fiber attenuation, flatness, PCE, DCR and Voltage, showing that MC technologies (together with other improvements) are promising candidates to further achieve C/B reductions.

4. Conclusions

C/B of submarine systems has continued to drop with the introduction of SDM submarine systems. However, adding more spatial channels encounters not only powering limits but also space barriers that prevents further C/B reduction. This paper quantitatively analyzed scaling opportunities to continue to reduce C/B by exploring the Technoeconomics of optical, powering and density improvements.

5. References

[1] J. D. Downie, et al, "Modeling the Techno-Economics of Multicore Optical Fibers in Subsea Transmission Systems," in Journal of Lightwave Technology, vol. 40, no. 6, pp. 1569-1578, 15 March15, 2022
[2] R. Dar et al., "Cost-Optimized Submarine Cables Using Massive Spatial Parallelism," in Journal of Lightwave Technology, vol. 36, no. 18, pp. 3855-3865, 15 Sept.15, 2018
[3] A. Pilipetskii, “High capacity submarine transmission systems,” in Proc. Opt. Fiber Commun. Conf. Exhib., Los Angeles, CA, USA, 2015, Tutorial W3G.5.
[4] E. Mateo, et al., “Capacity limits of submarine cables,” in Proc. SubOptic, Dubai, UAE, 2016, Paper TH1A.1.
[5] H. Fevrier, S. Grubb, N. Harrington, A. Palmer-Felgate, E. Rivera-Hartling and T. Stuch, "Facebook Perspective on Submarine Wet Plant Evolution," 2019 Optical Fiber Communications Conference and Exhibition (OFC), 2019, pp. 1-3.