Technology Evolution and Capacity Growth in Undersea Cables

A. N. Pilipetskii and G. Mohs
SubCom, 250 Industrial Way West, Eatontown, NJ, 07724, USA
apilipetskii@subcom.com

Abstract: We examine the technology evolution that fueled exponential cable capacity growth over the last decades. We are at a critical point when transmission technology is mature and approaching fundamental limits. What is the path forward?

1. Introduction.

Undersea fiber optic cables are an integral part of the worldwide communications infrastructure carrying more than 99% of international data traffic between continents. In a bit more than 25 years, transmission technology experienced explosive growth resulting in more than 5 orders of magnitude increase in fiber pair capacity. Cable cost stayed roughly the same resulting in a corresponding reduction of the cost per information bit. Despite this progress or maybe because of it, the demand for communication capacity is far from saturation with a current annual growth rate of at least 30% [1]. We are reaching a point in history when transmission technology is mature and has approached fundamental limits [2]. The natural questions to review are what directions the technology will choose, and will it be able to provide continuing support to meet the capacity demand? This paper examines the evolution of transmission concepts that changed multiple times in the last 25 years, the next immediate steps in technology evolution, further challenges facing continuing capacity growth, and the need for new disruptive technologies.

2. Technology Evolution Over the Last 25 Years.

Evolution of single mode fiber (SMF) capacity in record experiments over time is presented in Fig.1. Fiber capacity grew from less than 1Gb/s to more than 70 Tb/ resulting is similar cable capacity increase (Fig. 2). More than 4 orders of magnitude of increase in cable capacity was achieved utilizing optical Erbium Doped Fiber (EDF) amplification technology. The critical contributors for the growth in fiber and cable capacity were: improvement in amplifier NF, increase in amplification bandwidth to full C and C+L bands, improvements in fiber loss and effective area, DSP including coherent receivers and advanced FEC leading to ~ 15, 2, 10 and 20 dB of capacity gain, respectively. Coherent detection also allowed for efficient bandwidth utilization using dense WDM and variable spectral efficiency. The latest capacity numbers in both fiber and cable were achieved by using dispersion uncompensated large effective area low loss fiber transmission [3,4] with digital compensation in coherent receiver DSP.

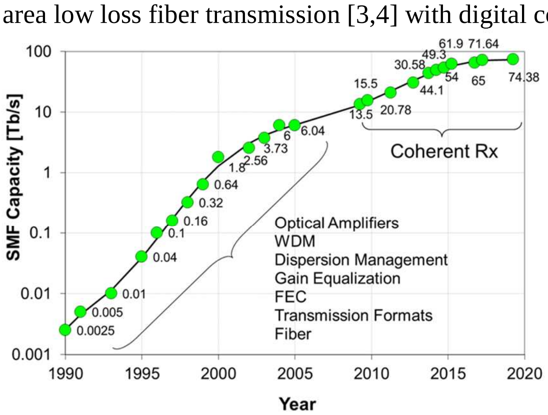

Fig. 1. Record SMF capacity over time

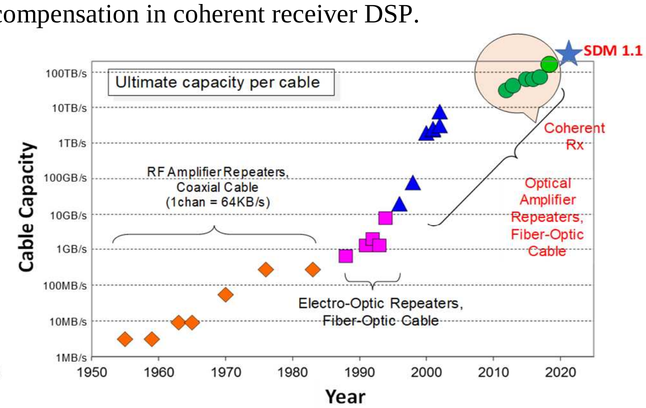

Fig. 2. Evolution of cable capacity

It is important to note that cost per information bit had also exponentially declined over this period since the basic cable technologies and optical amplifier components were not changing significantly while capacity was exponentially increasing Other observations can be made: deployed cable/fiber capacity was tracking in time the results of record experiments with some offset accounting for actual product manufacturing processes; the philosophy in growing both fiber and cable capacity was maximizing optical performance of a single mode fiber. This growth path was practically over when SMF capacity reached saturation point around 2017. Modern cable systems utilize full C-band and the first C+L Transpacific system was deployed as well [5]. Growing transmission bandwidth in SMF beyond C+L is problematic due increased fiber loss beyond C+L window and lack of efficient amplification. It can be also seen from the Fig. 1 that only little room remains to grow fiber and system capacity through the increase of spectral efficiency in C or C+L bandwidths. The reasons are: diminishing returns from improvements in SMF technology, limited ability to mitigate fiber nonlinearity, modulation and decoding schemes already ensure performance only ~ 2dB away from Shannon limit [6], and most importantly logarithmic dependence of achievable spectral efficiency versus SNR according to Shannon law.

3. SDM 1.1 as a Current Technology.

Currently the only way to increase cable capacity is to utilize the space dimension through increasing the number of optical paths (fibers) in a cable. Undersea systems have also a unique powering problem where electrical power delivery to optical amplifiers is from the shores through a conductor in a cable [7]. It means that the available power needs to be managed effectively in the cables especially when increasing the number of fibers in the cable. It was shown in [8-10] that utilizing space division multiplexing and splitting the optical power between space dimensions can result in significant overall cable capacity increase while keeping power requirements the same. Fundamentally it also means that the previous approach of maximizing transmission performance in an individual fiber is no longer the best approach. The subsequent question was whether this is an economic way forward since it requires utilizing more single mode fibers and more components in a cable. Techno-economic models of the "SDM 1.1" scenarios [11-12] showed that it is possible to reach hundreds of Tb/s of cable capacity and still achieve a reduction of the cost per bit at the same time. The first cable based on the new SDM design principles was announced recently [13]. It was also shown that for fiber pair counts more than ~ 16 (32 fibers) SMF based SDM approach using current cable structure and component base starts to bring diminishing returns in terms of cost per bit [11]. This represents a significant "cost per bit crunch" challenge going forward since an exponential reduction in cost per bit may be needed to support the projected exponential growth in capacity demand.

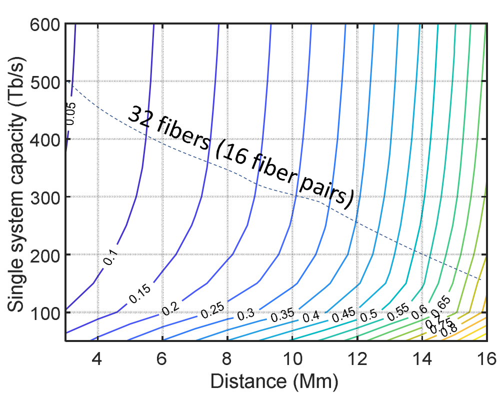

Fig. 3. Normalized cost per capacity for optimized SDM SMF based wet plant

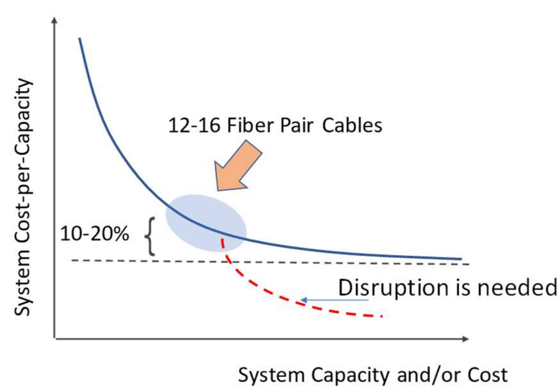

Fig. 4. Saturation in cost per bit improvement for SDM SMF based wet plant

4. Integration as a potential path forward.

It is not clear yet how to overcome the "cost per bit crunch" problem. There is still room for improving product efficiencies and making evolutionary steps in existing technologies. Next logical steps are a combination of the SDM approach with C+L transmission and smaller coating diameter fibers. On the other hand, scaling up existing technologies indefinitely is difficult and eventually would face space limitations in the cable, repeaters and the need to deal with thousands of passive components per repeater. A technology disruption is needed beyond the first generation of SDM systems based on SMF. As an example, this might happen through integration using such technologies as multicore or multimode fibers [14-16], micro components in the optical amplifier assemblies [17], and semiconductor optical amplifiers [18].

It is unlikely that the optical performance of the new technologies will be better that that of SMF based system with discrete optical components. An important principle must be followed: to be able to successfully adopt new technologies: any associated performance penalties need to be significantly overcompensated by potential cost savings.

5. Conclusions

Optical transmission technology advances have led to exponential growth of undersea cable capacity and a corresponding reduction of the cost per transported bit. Even though fiber pair capacity is approaching fundamental limits, the first generation of SDN systems based on SMF technology allows to extend this trend. Further technology disruptions are needed to continue the growth path.

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