SDM and Parallelism in Submarine Cable Systems

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Abstract: We review the most recent achievements in undersea transmission with high optical power efficiency and the associated enabling technologies and discuss the economics of SDM and the corresponding reduction in cost per bit for submarine cable systems.

1. Introduction

Since the advent of digital coherent technology, laboratory demonstrations of single-fiber capacity have increased from 10 Tb/s to 74 Tb/s (Fig. 1). These achievements are enabled by several technology improvements including broadband optical amplification, ultra-low-loss fiber with, large effective area, advanced modulation formats with constellation shaping, nonlinearity compensation, variable spectral efficiency, forward error correction (FEC) codes etc. [1-3]. Recently, space division multiplexing (SDM) concepts have increased single-fiber capacity to 520 Tb/s over 8,830 km using 12 core MCF [4]. Simultaneously, the capacity of deployed systems (Fig 2) has also increased significantly from a few Tb/s up to 200 Tb/s (MAREA Cable) [5]. Most recently, the first deployed cable embracing the SDM concept (Dunant, 300 Tb/s) was commissioned [6], and more cables using the SDM concept are on the way, for example 2Africa [7], SMW6 [8].

Modern undersea cable systems use high-voltage power feed equipment at the shore to supply a constant current and a maximum voltage of order of 15 kV. Ref [9] shows ~1% overall efficiency in optical power to the undersea repeaters. It's challenging to supply enough electrical power to the undersea repeaters in the cables with aggregate capacity in excess of hundreds of Tb/s. SDM offers improvement in total system capacity and optical power efficiency (OPE) by enabling transmission at lower spectral efficiency (SE) per SDM path without an increase in total power requirements. Multiple results [10-26] have been demonstrated in power efficient transmission since 2015. This paper examines power efficient transmission and its interplay with increase in practical cable capacity

2. Technologies to Improve Optical Power efficiency

2.1. Power efficient EDFA gain shape management

In general, EDFA efficiency becomes lower (~20%) when operating at low output powers (<10 dBm) compared to an EDFA with >15 dBm output (~40%). EDFA efficiency can be improved by optimizing the width and location of the operating bandwidth [10]. By reducing the BW to ~20 nm the gain excursion can be reduced to ~0.4 dB. Ref [10] demonstrated the first power efficient transmission using 20 nm of optical bandwidth and a single gain equalization filter after nine EDFAs. Ref [24] used skip-GFF implementation to improve the OPE by ~0.4 dB.

2.2. Ultra-low-loss Optical Fibers

Ultra-low-loss optical fiber (<0.15 dB/km) [27] is a key enabler of all recent high OPE demonstrations.

2.3. Advanced Modulation Formats & Variable Spectral Efficiency

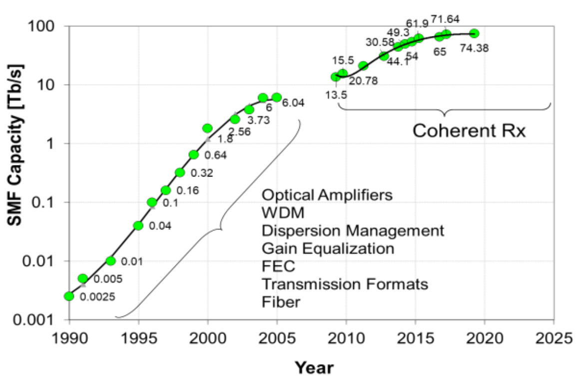

Fig.1 Record SMF capacity over time.

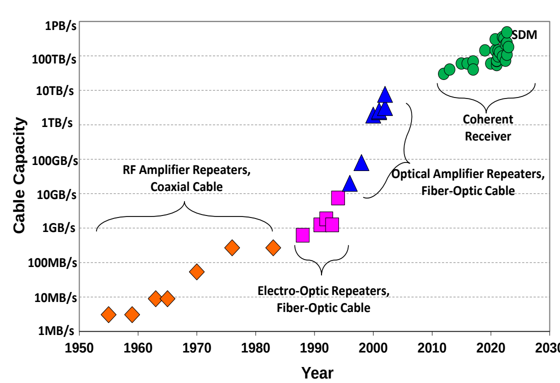

Fig.2 Evolution of cable capacity.

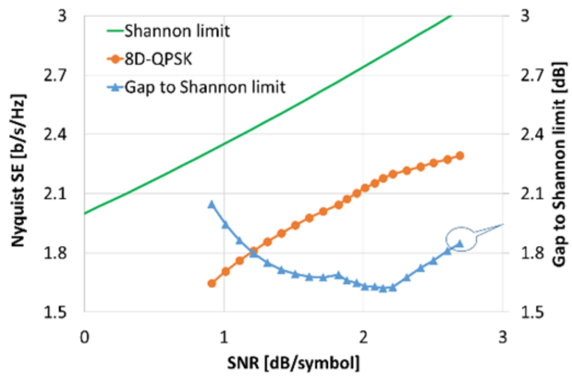

Fig.3 Lab measured 8D-QPSK SE (circle) & gap to Shannon limit (triangle) vs. SNR [24].

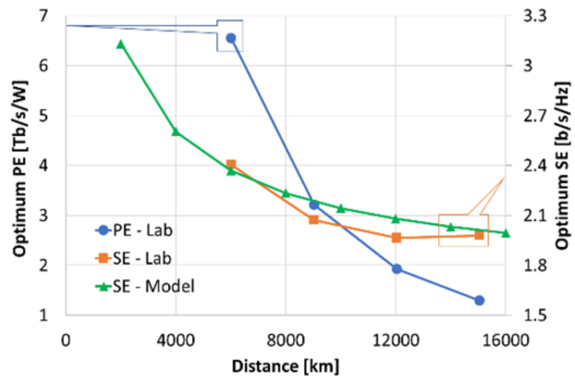

Fig.4 Optimum power efficiency and the corresponding SE vs distance (green from theoretical calculation) [24].

Using modulation formats that are closer to the Shannon limit is another key enabling technique in improving OPE. One example is the 8D-APSK coded modulation format with spectral efficiency equivalent to QPSK but with ~0.8 dB better receiver sensitivity [10]. Another example is the 8D-QPSK modulation format, which offers ~1.6 dB gap to Shannon at SE=2 b/s/Hz [Fig. 3]. System capacity can be maximized by pairing channel OSNRs at different levels [24] with different modulation formats or variable spectral efficiency.

2.4. Optimum SNR and Spectral Efficiency to Achieve Maximum Power Efficiency

Due to signal droop and noise saturation, there is an optimum SE / OSNR combination that maximizes OPE. A recent publication [22] showed an optimal SNR of 0 dB with corresponding optimum spectral efficiency of 2.0 b/s/Hz. The expected OSNR at 2 b/s/Hz in experimental work is about 1.5-2 dB due to the gap to Shannon for a modulation format with implementable FEC and hardware implantation penalty. Recently, we transmitted 9 Tb/s over 15,050 km using only 29 mW optical pump power per EDFA with a record OPE 1.24 Tb/s/W (Fig 4). The optimum SE is 2 b/s/Hz and the corresponding OSNR is 1.8 dB. This record was achieved by designing the experiment at the optimum SNR and SE, using power efficient 8D-QPSK format with variable overhead FEC, ultra-low loss fiber (0.145 dB/km) and power efficient EDFA gain shape management (skip-GFF).

3. Technologies to Improve System Aggregate Capacity

With maximized power efficiency, the largest system aggregate capacity can be achieved using WDM (C+L band) or SDM technology. In commercial subsea systems, we also need to take the economical aspect into account, to achieve a high capacity, low cost-per-unit-capacity system. Techno-economic model [21] which combines physical and economic aspects of the submarine links and considers the relationship between power efficiency and cost-per-unit-capacity optimizations for submarine links. The modeling results of cost optimization are shown in Fig. 5 where for each pair of transmission distance and cable capacity a cost optimized solution was found [21]. The optimization parameters are number of fibers, spectral efficiency, EDFA output power and so-called SDM index (number of fibers per pump unit). Capacities are calculated using 4.5-5.5 dB distance from Shannon limit (depending on the system SNR) to emulate performance of a typical transponder plus system margin. Each curve in Fig. 5 out of the family of curves represents constant cost per bit after the cost optimization. Larger capacity for the fixed transmission distance means that more SMFs and larger scaled up cables are assumed [20]. The model results suggest that 32-fiber SDM systems are a practical spot for near-future systems close to the cost-per-unit-capacity limit of the wet-plant.

The maximum number of parallel SDM paths are limited by the diameter of optical cable and optical fiber. In commercial submarine systems, typical lightweight (LW) cable outer diameters range from ~17 mm to 21 mm. Without changing the optical cable significantly, smaller cladding diameter (200 µm) are being developed to increase system aggregate capacity. Ref [29] demonstrated an uncoupled 4-core fiber which has the potential to quadruple undersea system aggregate capacity. Fig. 6 shows maximum cable capacities [30] with standard undersea cable for C- and C+L-band transmission with 250 µm and 200 µm outer diameter SMFs and the uncoupled 4-core MCF. 200 µm fiber provides a noticeable increase in maximum cable capacity; however its advantage is reduced at longer distances due to a combination of its slightly higher attenuation and system power limitations. Single mode C+L solution offers a significant gain in capacity, but this advantage goes away with increasing distance due to the lower power efficiency. Increased capacities are expected for the 4-core MCF for all but the very longest system distances, which are affected

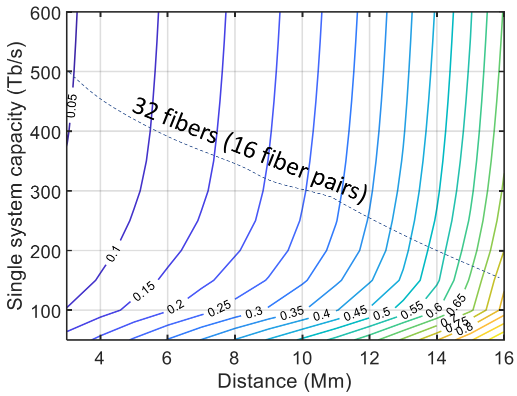

Fig.5 Normalized cost per capacity for optimized SDM-SMF based wet plant [21].

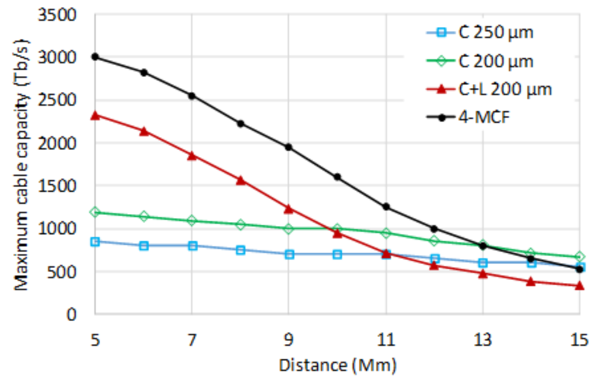

Fig.6 Achievable capacities with various technologies: C-band with 250 and 200 µm fibres, C+L with 200 µm fibers and C-band based 4-core MCF systems. [30].

by the higher fiber loss, FIFO losses, and limitations of system power. With advanced power delivery, the capacity gains could be extended for longer distances in both C+L and MCF solutions.

A further increase in the number of fibers in a cable has diminishing returns for current technologies and cost structure. This represents a significant "cost per bit crunch" challenge going forward since an exponential reduction in cost per bit is needed to support the projected exponential growth in capacity demand as illustrated in Fig. 2. To overcome the "cost per bit crunch", disruptive technologies are needed beyond the first generation of SDM systems. Recent works on hollow-core fiber, semiconductor fiber amplifiers, integration of repeater components, and advanced power delivery (such as floating power buoy) are going to keep pushing the aggregate capacity of undersea transmission systems to beyond a few Tb/s

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