High-Capacity Submarine Cables – Past, Present and Future

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Abstract: This tutorial discusses high-capacity submarine cables, tracking their evolution from the recent DWDM past, through their transition to Space Division Multiplexing to the current state-of-the-art systems, and considers available technology choices for the industry's future.

1. Introduction

For more than 30 years, the submarine industry increased cable capacity by focusing on fiber pair capacity and improving spectral efficiency. Technologies to achieve this improvement included erbium doped fiber amplifiers (EDFAs), Forward Error Correction (FEC), dense wavelength division multiplexing (DWDM) and, more recently, coherent transmission. The fiber pair capacity improved over five orders of magnitude during this time, from 280 Mb/s on TAT-8 in 1988 [1] to 26.2 Tb/s on a system deployed in 2018 [2].

After this era of such rapid growth, the fiber transmission capacity approached the maximum capacity of a noisy channel as determined by physics [3], and the additional spectral efficiency improvement opportunities for each fiber pair became limited. This period marked a transition for the industry towards Space Division Multiplexing (SDM), a general philosophy to focus on optimization of the total cable capacity, rather than on the capacity per fiber pair.

In the initial implementation of SDM, the available optical pump power in the subsea optical amplifiers, referred to as "repeaters", was distributed over multiple fiber pairs to save hardware and thus support more fiber pairs. This approach was first implemented on a trans-Atlantic route on a system in 2020 [4]. This version of SDM is the starting point for this Tutorial. From there, we will consider SDM technology options that exist today with the capability to provide at least another order-of-magnitude increase in cable capacity, the challenges, and tradeoffs inherent with each option, and their corresponding engineering solutions.

The topology of high-capacity subsea cables has also evolved significantly in recent years, from simple point-to-point connections to complex networks with many landing points and traffic routing capabilities [5]. This tutorial will discuss these new topologies and the submerged network elements that enable this progress.

2. Increasing Cable Capacity

In 2020, the first trans-Atlantic cable employing SDM technology was installed and commissioned for service [4]. Previous subsea cables on high-capacity routes were mostly focused on maximizing spectral efficiency to maximize transmission capacity on a limited number of fiber pairs. This was possible because the system designs were still many dBs away from fundamental physical limitations. In the early 2000s, a state-of-the-art subsea cable would use 10 Gb/s channels with on/off keying (OOK) amplitude modulation, with 50 GHz channel spacing across a 28 nm optical gain bandwidth, on each of 4 fiber pairs, corresponding to 64 channels or 0.64 Tb/s per fiber pair and 2.56 Tb/s total cable capacity [6], with a spectral efficiency of approximately 0.2 b/s/Hz. The direct detection modulation formats required sophisticated dispersion management for all routes, with alternating cable sections of positive and negative cable dispersion.

Today, using modern coherent transmission, spectral efficiency near 6 b/s/Hz is possible on a trans-Atlantic route [2], a 30-fold growth in 20 years. The range for further improvement is limited because the spectral efficiency in modern coherent transmission is approaching the Shannon Limit. Claude Shannon first described the maximum transmission capacity over a noisy channel in 1948 [3]. Equation (1) shows the famous Shannon Limit:

$$SE = 2\log_2\left(1 + {}^{S}/_{N}\right) \qquad (1),$$

Where SE is the spectral efficiency, S is the signal power and N is the noise power in the signal bandwidth. The factor of 2 in front of the logarithm comes from the two degenerate polarization modes in single mode fiber. The maximum signal power level is limited due to nonlinear effects in the fiber [7]. The noise power is present in the channel due to the distributed chain of optical amplifiers that are needed to maintain optimum signal power [8].

The initial version of SDM in subsea systems takes advantage of the fact that spectral efficiency only depends logarithmically on signal power, while the total capacity is the product of spectral efficiency and bandwidth. It is therefore advantageous to distribute the available signal power over more bandwidth. This reduces nonlinear effects, while slightly reducing spectral efficiency, and thus increases total cable transmission capacity for the same amount of optical pump power. In practice, this is done by splitting and distributing available optical pump power over multiple fiber pairs, and then increasing the number of fiber pairs of the cable to increase cable capacity.

How do we increase cable capacity by at least another order of magnitude from here? Several technology options exist to make use of the SDM concept.

The first and most straightforward is to continue to add fiber pairs to the cable: the first SDM cable features 12 fiber pairs followed by another cable that went into service in 2022 with 16 fiber pairs [9]; a trans-Atlantic cable with 24 fiber pairs has been announced [10]. Increasing the size of the cable to add more fiber pairs is a straightforward engineering problem, but one that impacts system manufacturing and deployment, and may not be the most cost-effective option for increasing cable capacity.

Reducing fiber diameter allows the cable to support more fiber pairs while maintaining cable size. Subsea fiber typically has a glass diameter of 125 um and a coating diameter of 250 um. Fiber with the same glass diameter but a reduced coating diameter of 200 um is in use in terrestrial applications. The application of this technology to subsea cables might be the next logical step to improve cable capacity. Even further reduction in fiber diameter may be possible by further reducing coating diameter, and in addition glass diameter [11]. In these approaches with reduced coating diameter, the micro-bend sensitivity and mechanical reliability must be carefully balanced with achievable cable capacity to optimize performance.

The subsea community has also been investigating multiple core fiber types. The technology that seems closest to initial application in this industry provides multiple independent cores, where the cores are optimized to suppress crosstalk sufficiently for long haul transmission. Versions of MCF with two cores and four cores while maintaining the standard glass diameter have been demonstrated [12]. At this point, the cores must be amplified separately in single-core amplifiers because practical multi-core amplifiers [13] are not yet available, requiring fan-in and fan-out (FIFO) devices to couple between the MCF cores and the amplifiers. These FIFO devices add cost, take up space in the limited undersea repeater housing, and add to the span attenuation, all impacts that must be considered when comparing to competing solutions. Introduction of an amplification approach that can meet subsea performance standards while not requiring FIFOs will shift the analysis significantly.

MCF fiber technology with “coupled cores,” where crosstalk is part of the fiber design, can relieve the severe crosstalk requirements on independent cores, and is an active area of research in the industry [14]. When this fiber type is used, the modes of all coupled cores must then be demultiplexed after transmission with higher-order MIMO (multiple in / multiple out) processing, in a fashion similar to polarization demultiplexing in coherent transmission. This feature requires a terminal modem that has access to all cores and is not yet available in current generation digital signal processing.

Excellent work has also been done recently with Multi-mode Fiber (MMF) [15]. A significantly higher number of modes are available for transmission in each fiber, which makes this technology attractive for increasing cable capacity, yet with even more difficult multiplexing and demultiplexing challenges than with coupled-core MCF. Mode dispersion must also be managed on subsea transmission routes, like management of chromatic dispersion prior to coherent transmission.

An interesting additional option to increasing the number of modes-per-core, cores-per-fiber and fiber pairs-per-cable is to increase the bandwidth per fiber pair. L-band amplification is in widespread use on high-capacity terrestrial routes and has also been deployed on a trans-Pacific cable [16]. Other bands like S-band are also being investigated for increasing bandwidth and transmission capacity. These enhanced bandwidth solutions can be combined with any of the above approaches to provide more transmission cores or modes.

One other alternative to increasing transmission capacity on a given route is the option of building and deploying more cables more quickly. While it will be difficult to achieve a 10-fold increase in cable manufacturing and deployment capacity over a short period of time to accommodate the exponential demand growth, optimization and standardization of manufacturing processes have proven effective in other industries, affecting not only manufacturing volume but also product cost.

3. Power Efficiency

One important aspect to consider is the amount of electrical power required to optimize transmission capacity. To date, power can only be supplied to the undersea cable from shore and is a limited resource in the system. The SDM concept can be applied to significantly increase cable capacity up to an optimum spectral efficiency for a constant power applied to the cable [17]. After this optimum spectral efficiency, more power must be applied to the system to further increase the cable capacity, typically by applying higher voltage to the system. The maximum voltage capability of power feed equipment for subsea systems has therefore increased recently, and a cable with 20% higher voltage has been announced [[18]].

Not all power applied to the cable is converted to useful optical power, because a significant portion is dissipated as heat. Lower direct current resistance (DCR) designs will reduce the ohmic loss of the cable and are beneficial. In traditional cable designs, reducing the DCR requires more copper, the most expensive material in cable production. An attractive alternative conductor material is aluminum. While aluminum has a higher resistivity than copper, the significantly lower commodity price may potentially provide a lower resistance at similar material cost. That benefit may be offset by aluminum being more difficult to process than copper, potentially affecting production efficiency. Cable with aluminum power conductor is now commercially available in subsea systems [[19]], but cable with a lower resistance than the copper-based counterpart is still pending.

4. Subsea Network Topology

Subsea cables used to be simple point-to-point connections. Branching units allowed the routing of fiber pairs between landing points, and different electrical powering configurations. Traffic can now be dynamically steered between landing sites with wavelength granularity enabled by submerged reconfigurable optical add/drop multiplexing (ROADM) technology. And entire fiber pairs can be dynamically re-routed based on traffic demand and fault recovery requirements with smart branching units (eBU). Branches with subtended branches can be included in the submerged network topology, where needed [[5]].

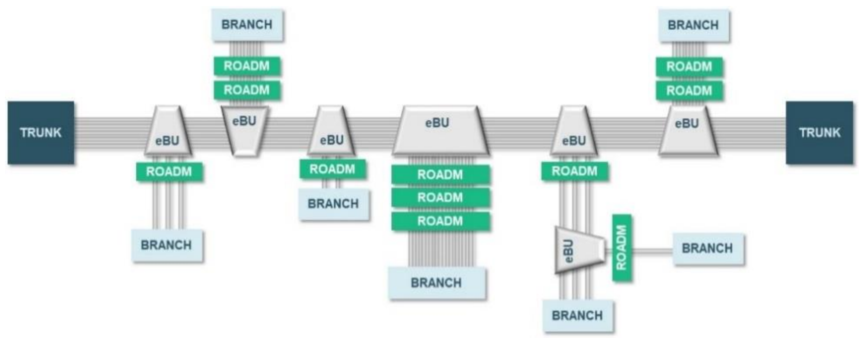

Figure 1: Example of a modern subsea network topology

4. Conclusion

Subsea cables have increased capacity by 5 orders of magnitude over the last 30 years, now reaching fundamental limits on spectral efficiency. Space Division Multiplexing technology approaches can enable at least another order-of-magnitude of cable capacity growth. At the same time, subsea cables have evolved from point-to-point connections to complex networks with dynamic traffic routing capabilities.

3. References

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