Strategies and Challenges in Designing Undersea Optical Links

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Abstract *We discuss trends and challenges in modern undersea optical fibre communications, which include power, space and cost efficiency. Progress in fibres and better subsystem engineering can address the problems in the near term. New technology discoveries are needed for efficient capacity scaling in the future. ©2022 The Author(s)*

Introduction

Recent innovations in optical fibre communications technology brought undersea systems to hundreds of terabit/s transmission capacities. As the single mode fibre capacity exhibited a saturation trend over the last several years, cable capacity kept increasing primarily due to increasing fibre count in cables. A reflection of this situation is clearly illustrated by Fig. 1, which shows highest fibre and cable capacity on recently installed or contracted systems. Further efficient capacity scaling presents several challenges due to a relative maturity of technology [1].

Why has fibre capacity saturated? Existing ways of improving fibre capacity approached either fundamental or important practical limits. Upcoming generation of transponders is capable of operating at nearly 2 dB away from the Shannon limit. Attenuation of single mode fibres is difficult to reduce: The last two record loss fibres were demonstrated 5-7 years ago [2][3]. Erbium amplifiers used for C- and L-bands [4] are unsurpassed in their power efficiency and noise performance. Any further improvement in either of the mentioned technologies is extremely challenging and would only lead to a single digit percentage of capacity gain. Using spectrum outside of C- and L-band is a possible but unattractive solution due to a combination of rising fibre attenuation and lack of efficient amplification.

Stagnation of fibre capacity is compromising the exponential cost per bit reduction that the industry enjoyed over decades. Further capacity scaling seems only possible through adding parallel space dimensions (known as SDM). This in turn, brings about challenges of power efficiency and space efficiency. The next three sections will discuss current ways of addressing these challenges.

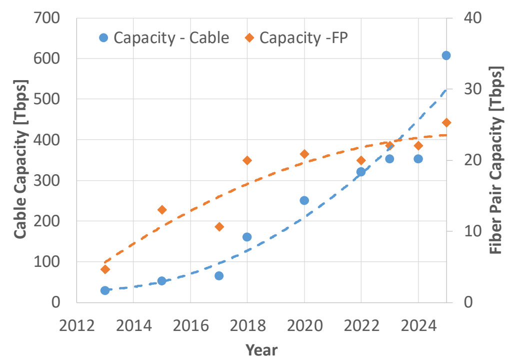

Fig. 1: Maximum estimated fiber and cable capacity on installed or contracted systems.

Power efficiency

Power efficiency is an issue specific to undersea systems because the electric power used to operate the repeaters is delivered from the shores. The amount of power carried by the conductor in the cable is limited by the mechanical and electrical properties of the cable. As a means to address the increasing capacity, the maximum operating voltage on the cable has been recently upgraded from 15 kV to 18 kV [5]. Further increase of the voltage or cable conductivity is practically difficult due to a combination of factors that include installation, mechanical and electrical requirements on the cable and subsystems.

Using increasing parallel spatial paths certainly raises powering requirements. On the other hand, it has been shown that using the number of space dimensions as a free variable can maximize power efficiency [6][7]. The underlying principle is splitting the existing power of the signal into several space dimensions. Adding power using space dimension leads to a linear capacity scaling as opposed to the logarithmic Shannon's law when using power to increase the signal to noise ratio (SNR) [6][7].

Splitting power between space dimensions implies lower SNR per dimension. The benefits of low power operation include lower nonlinear transmission penalty (less signal power is wasted on generation of nonlinear noise) and lower implementation penalty related to transponder's hardware [8]. Another useful technique to improve power efficiency is bandwidth and gain equalization management. Reduced bandwidth requires less aggressive gain equalization that carries smaller power loss. Bandwidth then could be traded off for the space dimensions. This principle has been demonstrated in [9]. Additionally, less frequent gain equalization has been useful in improving power efficiency [8]. Finally, efficiency of modulation formats (proximity to Shannon's limit) and lower loss fibre make a direct contribution to power efficiency. A combination of the described principles has led to a record power efficiency demonstration [8]. It is important to note that while these techniques lead to substantial power savings in limit cases, economic factors tend to offset the benefit. The best cost per bit configurations differ from the best power efficiency designs in practice [10].

Space efficiency

There are two components to be addressed in undersea systems for better utilization of space: Cable and repeaters. The cable space can be readily improved with smaller diameter fibres. Currently, the undersea industry uses 250 µm outer diameter fibres. Reduced coating fibres with the outer diameter of 200 µm exist in terrestrial markets and can increase the space utilization by up to 50%. Further improvements could be gained by using multicore or multimode fibres. Four uncoupled cores and seven coupled core fibres have been demonstrated in standard 125 µm cladding diameter with relatively low loss [11]. Larger number of cores has been demonstrated in larger size fibres [12]. However, the significance of adhering to the standard cladding diameter originates from the industry's standards related to practical characteristics of the fibre such as splicing, handling, bending and reliability. Multimode fibres offer the best space utilization but come with significant challenges associated with mode dependent gain/loss and transponder complexity. As an intermediate solution to space efficiency, C+L band transmission can be utilized, which almost halves

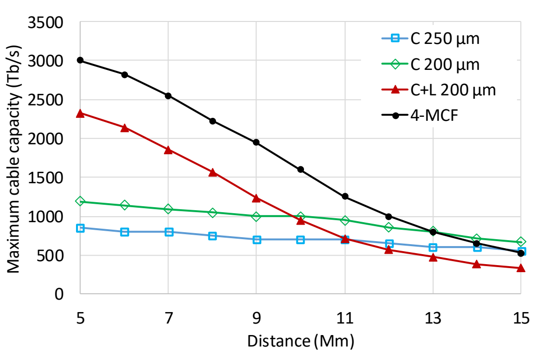

Fig. 2: Achievable capacities with various technologies: C-band with 250 and 200 µm fibres, C+L with 200 µm fibres and C-band based 4-core MCF systems

the cable space usage.

The repeater space efficiency can be addressed in the near term through more efficient mechanical designs. Longer term would require hybrid or highly integrated component architectures. If multicore or multimode fibres become a reality in undersea systems, it would likely be necessary at some point to develop a fully integrated multicore or multimode amplifier. There are some demonstrations of the principle [13] but practical realization requires weighting power efficiency, noise performance and mode dependent gain in case of MMF (or coupled-core MCF) against the economic benefits.

MCF technology is currently considered as the next step in capacity scaling by some industry players. While it is extremely space efficient, it presents some technological and economic challenges. From a technology perspective, additional optical components will be required, such as fan-in and fan-out (FIFO) devices, which add both optical losses and cost to the system solution. From an economic perspective, there should be sufficient cost savings so that the developmental and manufacturing expenses for both the fibre and the cable manufacturers to make the approach viable [14][15].

Achievable capacities with various technologies are shown in Fig. 2. In this example we assumed 0.015 dB/km higher loss for the MCF relative to the 250 µm SMF and 0.005 dB/km higher loss of 200 µm SMF. FIFOs were assumed to have 0.4 dB loss each. Increased capacities are expected for the MCF for all but the longest distances. Similar effect is observed for the C+L technology. Both are affected by the power limitations due to higher attenuation of the fibre and FIFO losses for the MCF and reduced amplification efficiency for the C+L transmission. This illustrates a technological path toward multi-petabit cables in sight. Hypothetical improvements in powering and cable solutions can enable further progress.

Cost efficiency

One important concept of SDM is the availability of an additional degree of freedom for system optimization. Traditional system design philosophy has been to maximize *fibre* capacity. In contrast, with the SDM approach, one can aim to optimize the *cable* capacity. An illustration of the benefits of such principle is demonstrated in Fig. 3 as simulated in [10]. We calculate costs for two systems, each optimized for minimum cost per bit: One system design is forced to operate at the maximum fibre capacity, and the other

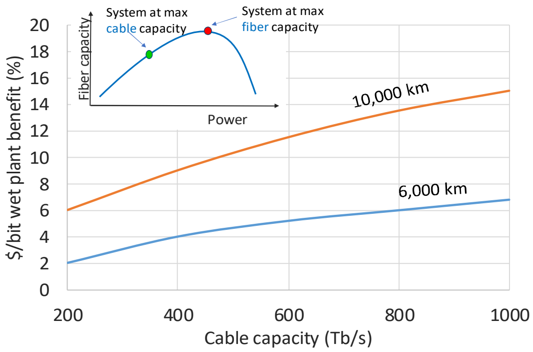

Fig. 3: Benefit of per cable design philosophy.

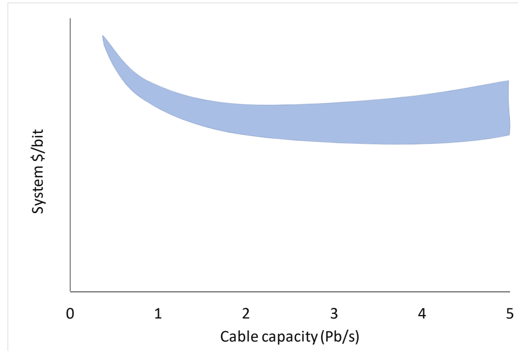

Fig. 4: Cost per bit: End of exponential reduction in sight.

does not have this constraint. We then plot the benefit percentage of the fully optimized design. As clearly seen from this illustration, there is a substantial cost advantage of per *cable* design philosophy versus per *fibre* design. This has become an important paradigm shift for the industry. The first undersea cable to adopt this concept, Dunant, has been ready for service in January 2021 [16].

As we mentioned earlier, exponential cost per bit reduction has slowed down due to the fibre capacity saturation. Fig. 4 shows the schematic projections of the near future cost per bit trends for the currently understood technology such as C+L and 4-core MCF. In this hypothetical example, we assumed that 4 core fibres would be available at some point as well as improved powering solutions. The spread is related to the uncertainty in future component and fibre pricing. Even in the more optimistic scenario (to the best knowledge currently), the exponential cost per bit trend appears to stop. Current cable capacities approached 350 Tb/s and will cross 0.5 Pb/s mark in about two years. We will probably see >1 Tb/s demand in 4-5 years. Thus, there are a few years ahead when better engineering and incremental cost saving initiatives will allow us to stay on the cost per bit reduction curve. After that, some technological breakthrough or conceptual shift in cable capacity utilization would be necessary.

Future outlook

Near term capacity scaling and cost per bit reduction could be enabled by using compact fibres [17], C+L technology [4] and integration of amplifier components [18]. As a next step, MCF technology is a widely discussed option, however, currently there is no industry agreement on standards such as the number of cores, dimensions, amplifier, etc. and the economic benefits are yet unclear [14].

There is a number of research directions that might enable future capacity scaling. Multimode fibre transmission is a potentially attractive solution if it comes with large mode count fibres and integrated multimode amplifiers. Amplifier integration appears to be an important area as well [11][13],[19][20][21]. Higher attenuation and mode-dependent gain/loss would significantly impact the performance and power efficiency. However, large number of modes could potentially overweight the penalties. Additional complexity is associated with the transponders that would require mode demultiplexing. The development effort would depend on what the industry would agree as a standard type of fibres and mode numbers or otherwise create a universal set of algorithms.

Semiconductor optical amplifiers (SOAs) have attracted recent interest [22][23][24]. Despite the known problems with nonlinearities, polarization properties and reliability, the renewed interest is fuelled by potential cost benefits.

Rapid progress in hollow-core fibres [25] opens space for considering such fibres for future transmission systems with extra low loss. The transparency window could potentially be matched with novel amplification media such as >115 nm Bismuth-doped fibres [26] to make use of a wider bandwidth.

Finally, capacity scaling has to fit into the increasing complexity of the future submarine ecosystem. New functionality recently includes reconfigurable add/drop multiplexing, fibre switching and interconnects [27]. Technologies for capacity growth that we discussed here need to be compatible with such networking functionality.

There is a line of sight, not without challenges, of achieving multi-Pb/s undersea cables. And while the industry adopts relatively straightforward near-term solutions, it is likely that some disruptive ideas will appear in the future.

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