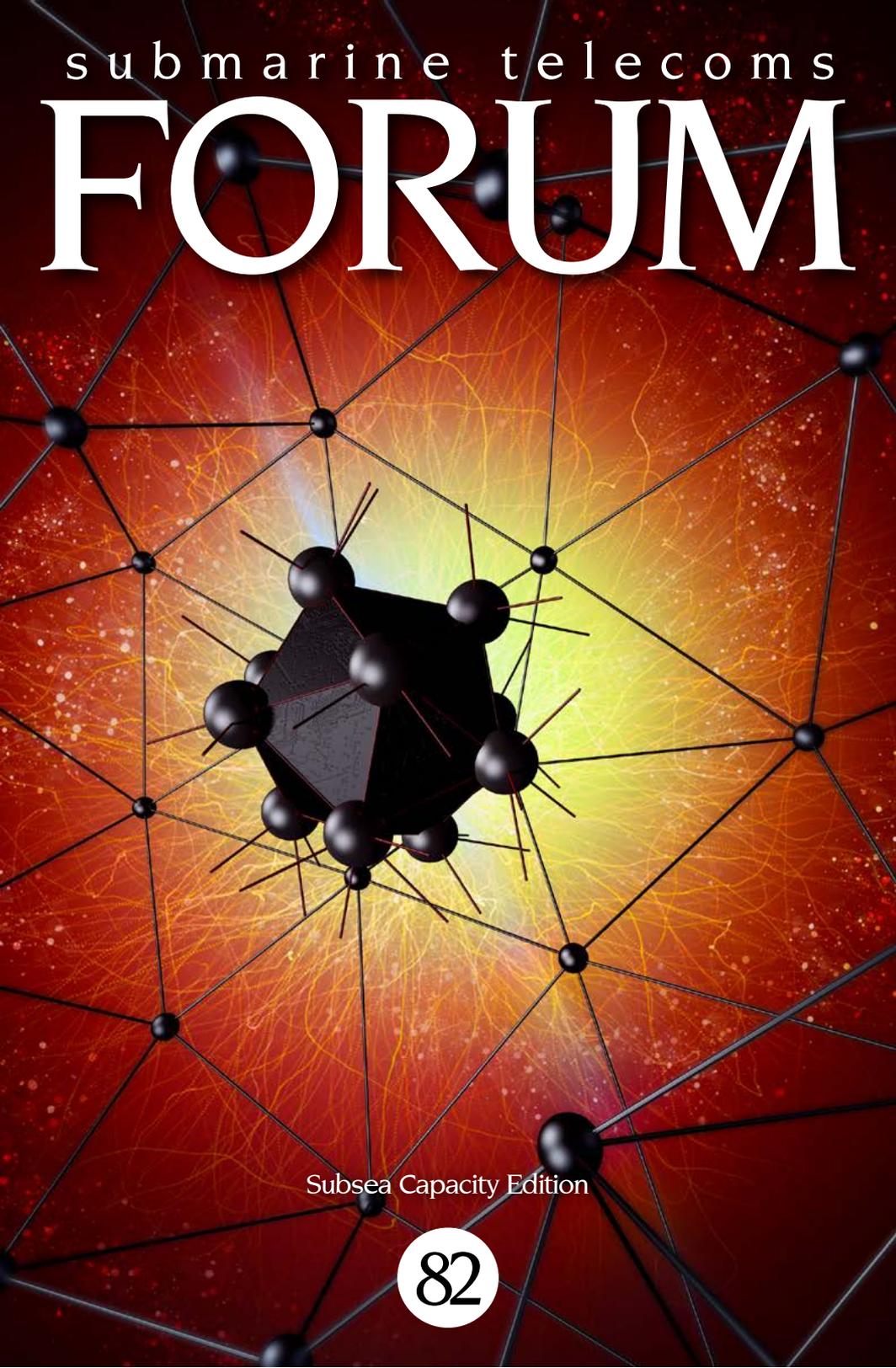


submarine telecoms

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Subsea Capacity Edition

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Latest Developments for Unrepeated Cable Systems

Bertrand Clesca

Definition of Unrepeated Cable Systems

The original definition of unrepeated – or repeaterless – cable systems referred to submarine links with nothing under water but the optical cable, with the Submarine Line Terminal Equipment (SLTE) being located in the cable landing stations. This first definition also implies that no electrical Power Feed Equipment (PFE) was used as there is no active submerged equipment to be remotely powered.

In a second step, the unrepeated system category was extended to systems with submerged Remote Optically Pumped Amplifiers (ROPAs) jointed to the cable some distance away (typically 80 to 150 km) from the landing sites. The rationale for this definition extension is that ROPAs do not require electrical power – so no PFE needed in the cable landing station – and that there is no requirement for a copper-based power conductor in the cable. ROPAs need, however, some energy to provide local optical

gain when they are hit by the optical signals; this energy is remotely provided from the cable ends via optical pumping through the fiber(s). The optical pump modules housed in the cable landing stations can be seen as optical PFE with the significant benefit that the energy transport to ROPAs is achieved in the optical domain using an unrepeated cable structure.

Why Unrepeated Cable Systems?

By essence, unrepeated cable systems offer a limited reach, significantly shorter than what can be achieved by long-haul subsea cable systems equipped with optical repeaters (in-line amplifiers). Their applications are, however, multiple – provided that the distances between the cable landing stations is shorter (today) than 600 km. In the telecom world, the following applications can be listed:

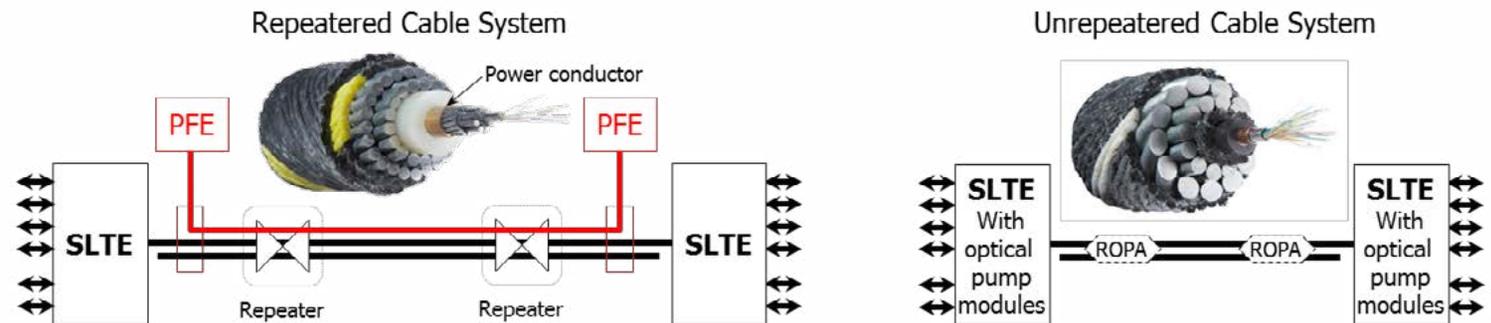
- Connecting two islands, or a group of islands, in a festoon, ring or meshed configuration;
- Connecting an island to the mainland;
- Connecting two sites separated by a sea straight;
- Building a coastal festoon in parts of the world where large populations live in a given number of sites on the seaside (very common configuration throughout the world);
- Connecting two cable landing stations in order to close a trans-oceanic ring for traffic restoration purpose;
- Complementing a long-haul repeated cable system to reach additional sites from the main landing sites and extend the capillarity of the long-haul system.

Unrepeated cable systems are useful in other market segments, like oil & gas, when there is a need to connect off-shore rigs to on-shore premises, or to connect different rigs throughout an off-shore field. Repeaterless optical systems are also found along power cables whose lengths are often compatible with unrepeated transmission reach.

Technologies for Unrepeated Cable Systems

Although the main goal of unrepeated systems has always been to achieve the longest reach, increasing traffic demands now require, however, both longer reach and higher transport capacity. To fulfill these needs, recent advances happened in the key enabling technologies such as line fibers, distributed Raman amplification, ROPA and coherent transmission with advanced modulation format. Even if digital data is transported,

Figure 1: Comparison between repeated and unrepeated cable systems (Cable photos courtesy of Nexans).



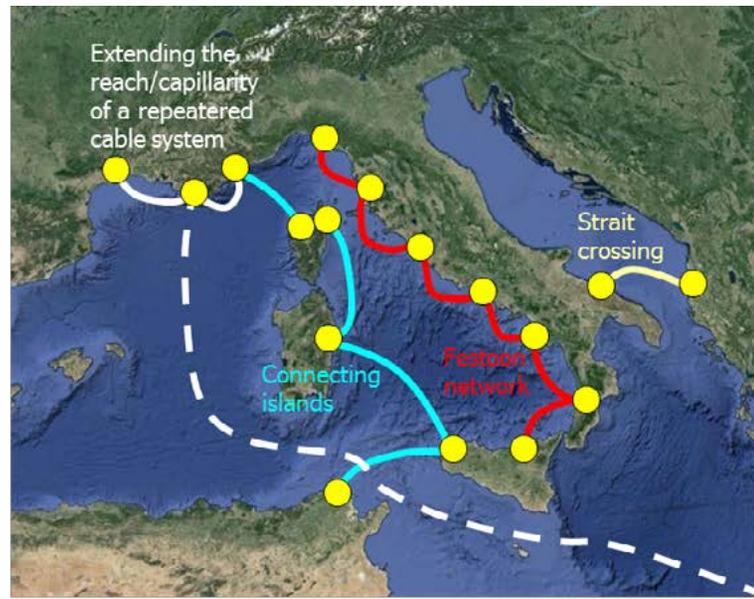
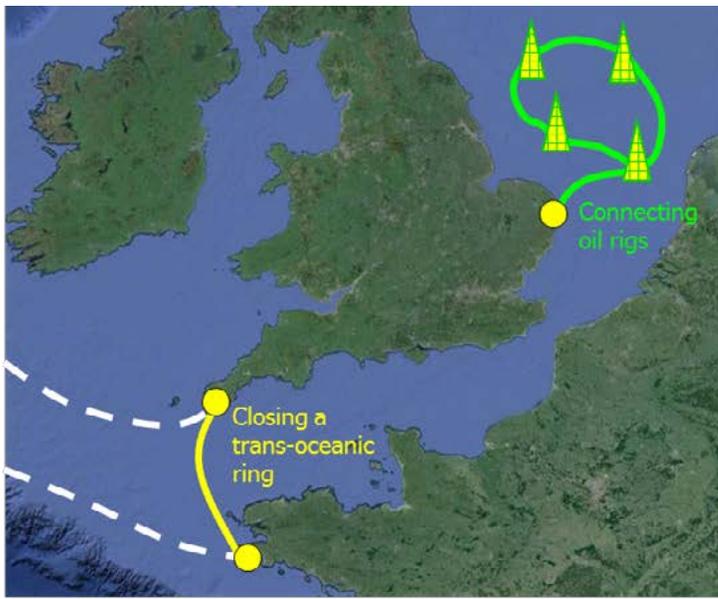


Figure 2: Applications of unrepeatered cable systems. The maps do not aim at being representative of actual cable systems.

attenuation is increasing.

Fiber effective area becomes a critical parameter when transmission distances are very long and high optical powers need to be launched into the fiber to compensate for signal attenuation. The effective area is a quantitative measure of the area that a fiber mode effectively covers in the transverse dimensions. The smaller the effective area, the more the optical field is confined within the fiber waveguide and the higher the optical intensity is, resulting in nonlinear effects that will adversely impact the signal quality. While regular G.652 fiber exhibits an effective area of about $80 \mu\text{m}^2$, unrepeatered transmission experiments with $112 \mu\text{m}^2$ [1] and higher effective core area fibers have demonstrated the benefit of a large core, allowing a significant

the propagation of the optical channels inside the line fiber is essentially an analog process with multiple interactions between the different factors that can potentially degrade signal integrity beyond what the receiver can recover.

Line Fiber

Chromatic dispersion is not an issue in unrepeatered cable systems because the modest fiber length results in a chromatic dispersion amount that can be easily compensated by dispersion compensation units when direct detection is used at the receive end, or by digital signal processing when coherent technology is implemented for 100G and 100G+ transmission.

Polarization Mode Dispersion (PMD) is neither an issue since it has been clearly identified and specified in the 90s, within the PMD tolerance of current detection options.

Attenuation is obviously a key factor as many unrepeatered cable systems are loss limited,

with a strong coupling between achievable capacity and end-to-end attenuation. For a given transmission technology at the interface card level (e.g. bit rate and modulation format), the number of wavelength-multiplexed optical channels that can be effectively transmitted is decreasing when the end-to-end

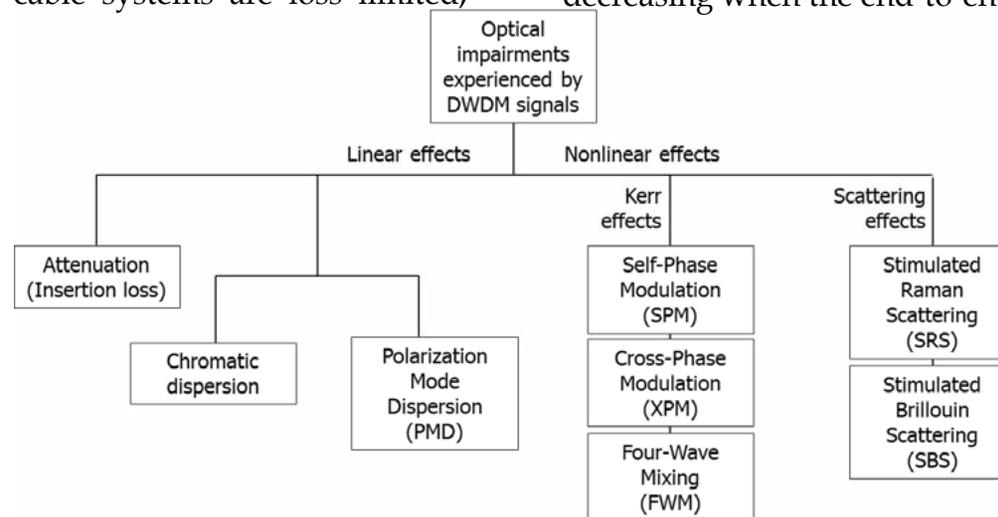


Figure 3: Optical impairments experienced by the optical carriers in multi-channel single-span transmission.

increase of the launched signal power with respect to standard fibers.

Optical Amplification

Since the length of unrepeated cable systems typically exceeds 200 km, up to 600 km, the optical signals experience a significant attenuation while propagating inside the line fiber. The physics of any detection solution (whatever direct or coherent detection) imposes minimum signal power and Optical Signal to Noise Ratio (OSNR) in order to guarantee a proper detection of the transmitted data. The first amplification solution that has been deployed for unrepeated cable systems is based on Erbium-Doped Fiber Amplifiers (EDFAs) delivering local amplification at the transmit and receive ends.

The longer the link, the higher the fiber attenuation, and the more optical gain is required to compensate for the loss in the power of the transmitted signals. However, optical gain, like electronic gain, is achieved at the expense of noise added to the signals. As a result, the OSNR of the optical carriers is degraded by fiber loss and

optical amplification as they propagate over long fiber distances. The optical noise imposes a lower limit on the per channel power along the optical fiber.

Parts of nonlinearities in silica optical fiber are caused by the Kerr effect. The Kerr effect describes the dependency of the refractive index of the optical waveguide on the instantaneous optical intensity. The higher the signal power, the higher the nonlinearities and the subsequent distortions that are experienced by the optical signals. Nonlinearities impose an upper limit on the per channel power that can be launched into the optical fiber.

Because of the upper limit for per channel power set by nonlinear effects and the lower limit imposed by minimal OSNR requirement, the per channel optical power profile must fit within some kind of "optical power tunnel" in order to guarantee data integrity along the optical fiber.

To extend unrepeated reach beyond 300 km, there is no other way than to use distributed optical amplification inside the line fiber; this distributed amplification is offered by

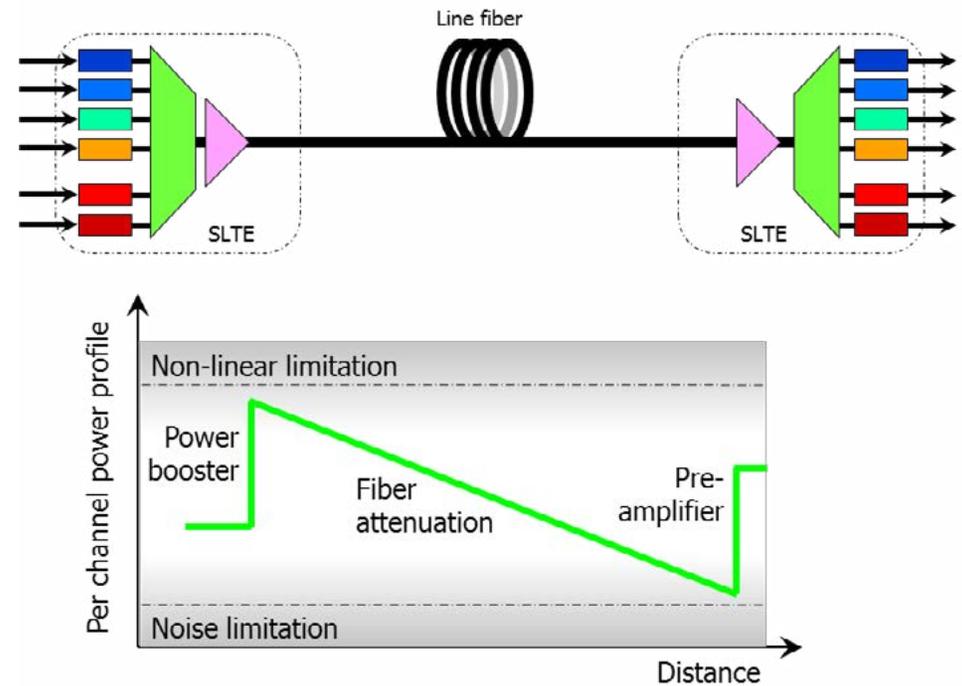


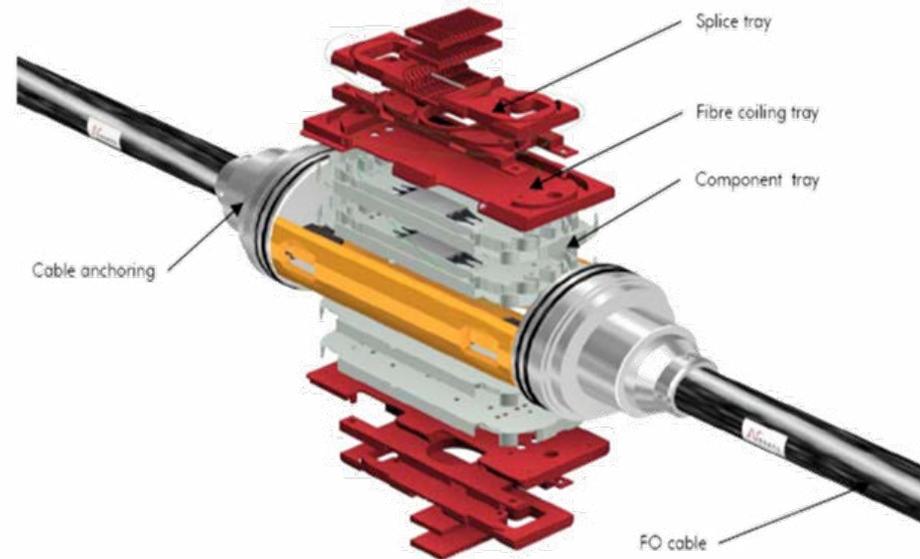
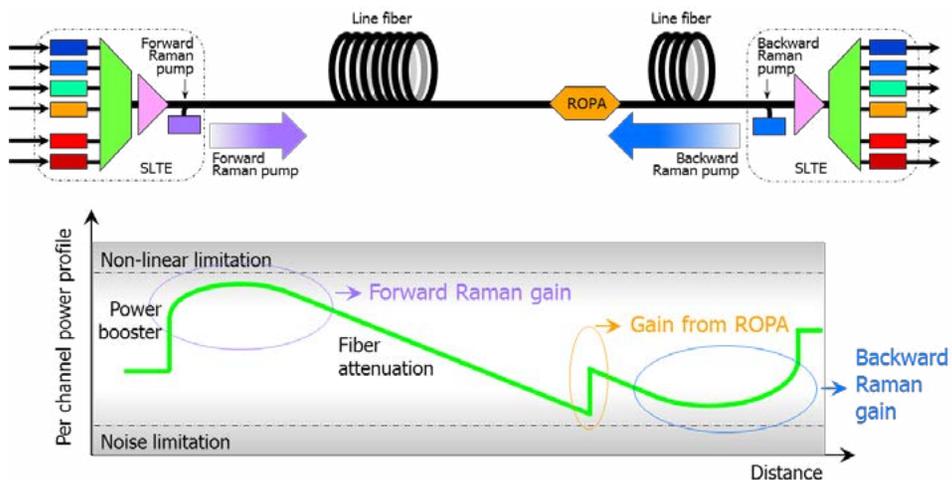
Figure 4: Per channel power profile as a function of the fiber propagation distance in a short unrepeated cable system with discrete EDFA-based optical amplification at transmit and receive ends.

Raman nonlinear effect that turns the line fiber into an optical gain medium when strong optical pump waves, with the appropriate optical frequencies, are launched into the line fiber [2]. Depending on the fiber attenuation and long-term capacity requirements, backward Raman pumping is first implemented when the length of the unrepeated

system lies between 300 and 450 km; when the length exceeds 450 km, then forward Raman pumping is added.

Remote Optically Pumped Amplifier (ROPA)

A ROPA is a very simple sub-system that is typically placed 80 to 150 km ahead of the receive end. This sub-system is based on a few passive optical components that are placed inside an enclosure jointed to the cable. By nature, the ROPA is a fully passive sub-system that requires no remote electrical power feeding from the cable end.



The energy necessary for creating optical amplification is brought to the ROPA by optical pump waves launched into the line fiber from the terminal equipment. Actually, this is the residual pump power that has not been consumed to build Raman distributed gain inside the line fiber that is used to pump the ROPA. As we are in a small-signal regime, 5 to 10 mW of pump power is enough to create sufficient optical gain (in the range of 20 dB) at the ROPA level. When the fiber length exceeds 500 km, a second ROPA can be inserted in the optical path, 50 to 80 km after the transmit end.

For extreme applications (for transmission distance longer than 550 km), extra fibers, parallel to the line fibers within the same cable structure, can be

Figure 5: Per channel power profile as a function of the fiber propagation distance in a long unrepeated cable system with discrete optical amplification at transmit and receive ends, distributed optical amplification inside the line fiber, and Remote Optically Pumped Amplifier (ROPA).

dedicated to the sole purpose of optical pump transport from terminal end to ROPA.

Interface Cards

In the past few years, we have seen a tremendous surge in terrestrial fiber capacity enabled by 100G optical channels built upon PM-QPSK (Polarization Multiplexing Quadrature Phase Shift Keying) modulation format, coherent detection

Figure 6: ROPA enclosure for subsea applications (Courtesy of Nexans).

and powerful Digital Signal Processing (DSP). These innovations were introduced in a second step into both unrepeated and repeated subsea cable systems.

To address the insatiable capacity needs of the near-future, more sophisticated modulation formats (like 16QAM - 16-state Quadrature Amplitude Modulation) have been developed to supersede the current 100G technology with the objective of increasing spectral efficiency (equal to the bit rate divided by channel spacing, expressed in bit/s/

Hz). 16QAM modulation is the key technology for high-capacity optical networking as it is the basic foundation for 200G carriers, with optical channels at 400G or higher rates (e.g. 1 Tbit/s) being based on the combination of two or more tightly spaced 200G optical.

From a transmission reach performance perspective, this strategy suffers from a fundamental limitation; the higher the spectral efficiency, the higher the OSNR requirement at the output end of the optical path. The OSNR figure could theoretically be enhanced by increasing the signal power but, unfortunately, fiber nonlinearities impose an upper limit upon the per channel

power that can be launched into the fiber span.

While the ultimate reach performance is similar between 10G and 100G channel rates (632 and 607 km, respectively, in the work described in [3]), the longest unrepeated transmission distance reported so far for 200G channels based on 16QAM modulation format is 363 km [4].

Evolution and Conclusion

Today, unrepeated cable systems can offer 100G transmission distance in excess of 600 km [3] and a cross-sectional capacity of 15 Tbit/s over 410 km [5]. These industry's leading results were obtained with a 0.16 dB/km fiber offering a 112 μm^2 effective area. Improved fibers with lower attenuation and larger effective area [6] are likely to further improve these reach and capacity figures. On the terminal side, Reconfigurable Optical Add Drop Multiplexers (ROADMs), implemented inside cable landing stations, in addition to the associated control plane, are becoming crucial equipment to build a global network with high resiliency against multiple faults.

Moving to network design, longer reach enables all-optical connectivity between points of presence or between datacenters with the wet unrepeated piece in the middle, instead of the traditional connectivity between beach manholes with expensive interfacing between subsea link and terrestrial networks inside the cable landing stations.

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