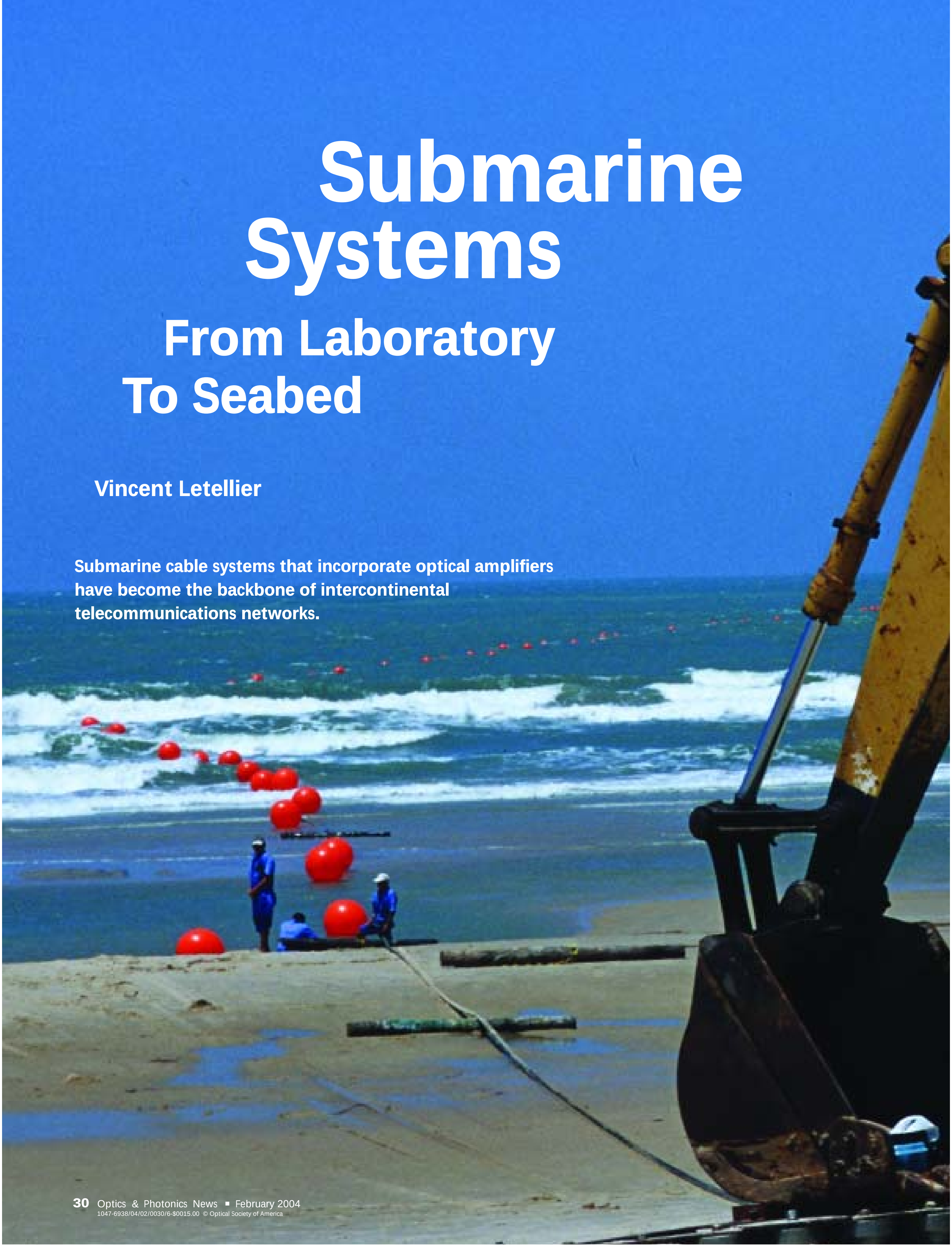

Submarine Systems

From Laboratory To Seabed

Vincent Letellier

Submarine cable systems that incorporate optical amplifiers have become the backbone of intercontinental telecommunications networks.

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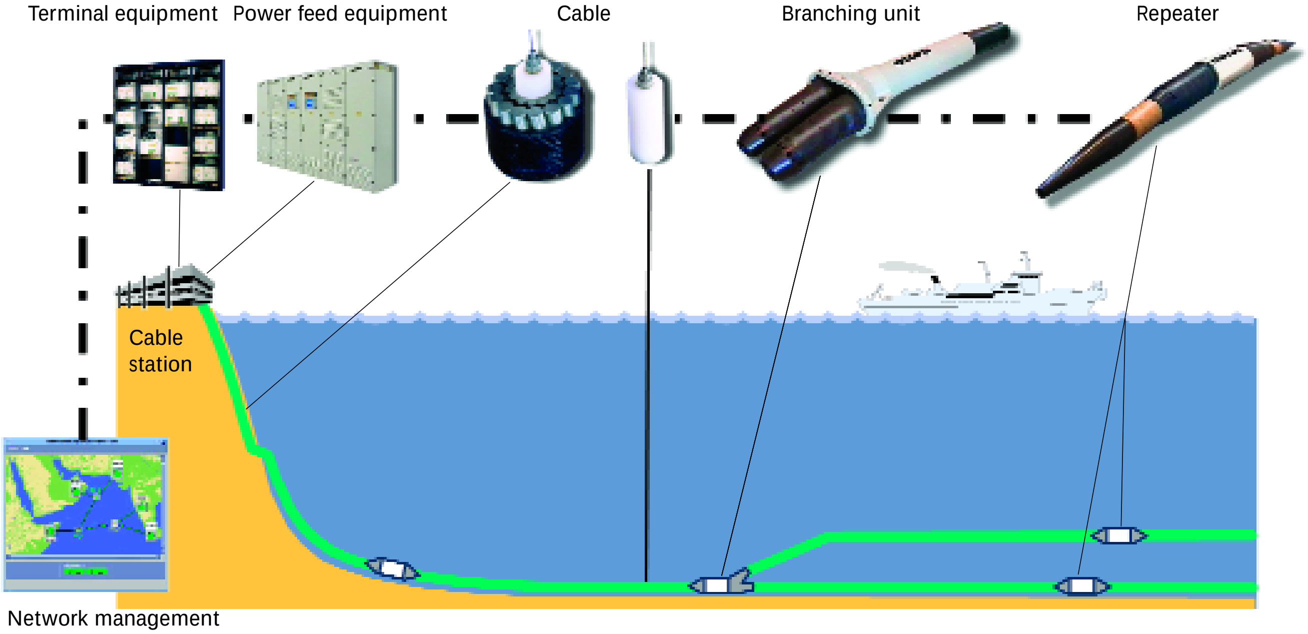
The history of transoceanic submarine cables began nearly 150 years ago, when the first attempt was made to lay a telegraph cable across the North Atlantic ocean in 1857. The first transatlantic telephone cable was installed a century later, in 1956; it offered 48 voice circuits by means of coaxial cable and bidirectional regenerators. The same technique was used until the late 1980s; thanks to improvements in cable characteristics and repeater electronics, by that time capacity over the Atlantic ocean had been expanded to as many as 4,000 voice circuits.

The first fiber optic based system, TAT-8, was installed in 1988. It operated at 280 Mbits/s and offered 35,000 voice circuits over two optical fiber pairs. This state-of-the-art solution was effectively a hybrid optical system: the repeaters, which were required at intervals of 100 km, received incoming optical signals and converted them into electrical ones, allowing for regeneration and transmission of optical signals. The advent of optical amplifiers allowed high-speed electronics to be removed from the submerged repeaters, making it possible to create an end-to-end optical channel. The first fully optical system was the TAT12/13 network, which was laid across the North Atlantic ocean in 1995 and 1996. Since each fiber carried 5 Gbits/s—then a huge capacity—two cables were deployed in a ring configuration, allowing for self-restoration of traffic in case the cable was cut.



Submarine system equipment family.

Only a few years later, the use of dense wavelength division multiplexing (DWDM) and wideband erbium-doped fiber amplifiers (EDFAs) made it possible to increase capacity per fiber to approximately 1 Tbit/s. In 2002, Alcatel Submarine Networks installed the i2iCN cable, composed of eight fiber pairs, which links Singapore to India. Designed to carry up to 8.4 Tbits/s by use of 10-Gbits/s DWDM technology, it is currently the highest capacity system operating in the world.

The modern submarine network

Today's submarine systems are composed of: a cable that contains as many as eight optical fiber pairs; submarine repeaters that provide gain to compensate for fiber loss; a branching unit that allows for undersea fiber connections; submarine line terminal equipment (SLTE) that interfaces terrestrial traffic to the submarine transmission line; and power feed equipment (PFE) to "fuel" the submerged plant. All the equipment is monitored and controlled by a submarine management system (SMS).

Because systems with a life expectancy of 25 years are laid in the water to depths of up to 8,000 meters, the key parameter for a submerged plant is the reliability of the cable and the repeaters.

The cable

The cable design is based on a welded steel tube to ensure the fibers a long lifetime in a stress-free environment. At the heart of the cable is the fiber unit structure; here, optical fibers in the steel tube are protected by a special gel from water penetration in case of a cable cut. The composite conductor is insulated with high-density polyethylene. The insulation also provides abrasion resistance. This structure, used for deep-sea deployment, is Alcatel's lightweight cable type. In shallow water, armored cables provide additional protection from hazards such as ship anchors, fishing and abrasion from rocks.

The repeaters

The repeaters use erbium-doped fiber amplifiers (EDFAs) with 980 nm optical pumping to amplify incoming signals in the C band (1530-1565 nm). Depending on the length and capacity of the system, amplifier gain can range from 10 to 22 dB, which corresponds to amplifier spans of 50 to 110 km. Submerged equipment, designed on a fiber-pair basis to support bidirectional transmission, can contain as many as eight amplifier pairs.

The industry standard for submerged plant reliability is that there be no more than a single ship repair over the 25-year life of a transoceanic system. To meet this requirement, highly reliable components and self-healing architecture are essential. For example, the 980-nm pump laser diode (LD) power is shared between two EDFAs of an amplifier pair so that if one LD fails the other is still operational.

The power feed equipment

The repeaters are fed in series with an approximately 1 A direct current which is supplied by PFE in the terminal stations that can generate up to 10 kV. The current flows through the copper conductor in the cable and is returned through the ground. The high range of power, reliability and control that is needed can be achieved through the duplication of strategic circuits. To minimize repair time, the design must also be characterized by low component complexity and modular construction. Two units (each capable of producing on its own the total output current needed) are initially set up to supply only half the necessary power. In the event of a failure in one unit, the second is designed to automatically increase the current it produces and thus support the entire load.

The submarine line terminal equipment

To obtain pulse shapes compatible with transoceanic propagation without the need for regeneration, the SLTE is fitted with a high performance line transmitter. To ensure the highest possible level of performance, the receiving equipment includes chromatic dispersion compensation units as well as optical preamplifiers. In a WDM SLTE set-up, more than 100 channels at 10 Gbits/s—with channel spacing as low as 33 GHz—are multiplexed and demultiplexed. Such a high level of spectral efficiency requires stable laser sources on the transmitter side and very selective optical filters on the receiver side.

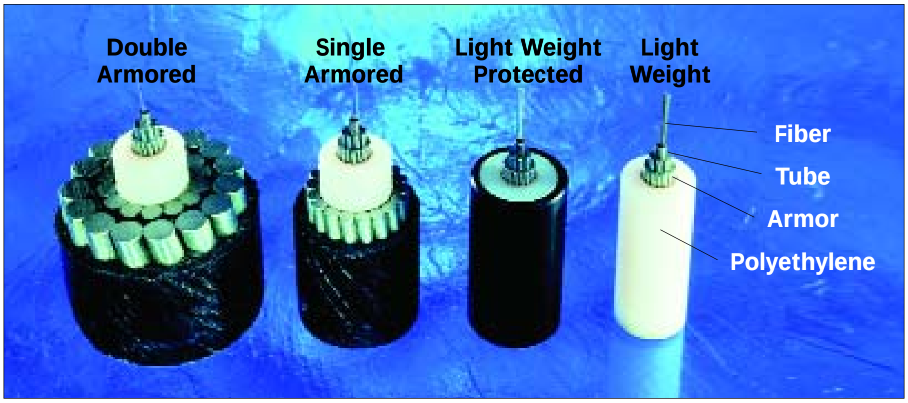
The use of forward error correction (FEC) enables longer repeater spans and performance higher than that stipulated by ITU-T G.826, which specifies a bit-error ratio (BER) below 1×10^{-13}. FEC also provides a convenient method of assessing the evolution of transmission performance by indicating the number of corrected errors.

To monitor submerged repeater parameters such as input power, output power and pump LD bias, the SLTE is equipped with in-service line supervisory signal generation and detection by means of low-frequency overmodulation of the optical carrier. The comprehensive supervisory information is passed to the submarine management system, a dedicated network that oversees the entire submarine line equipment family, including SLTE, PFE and repeaters.

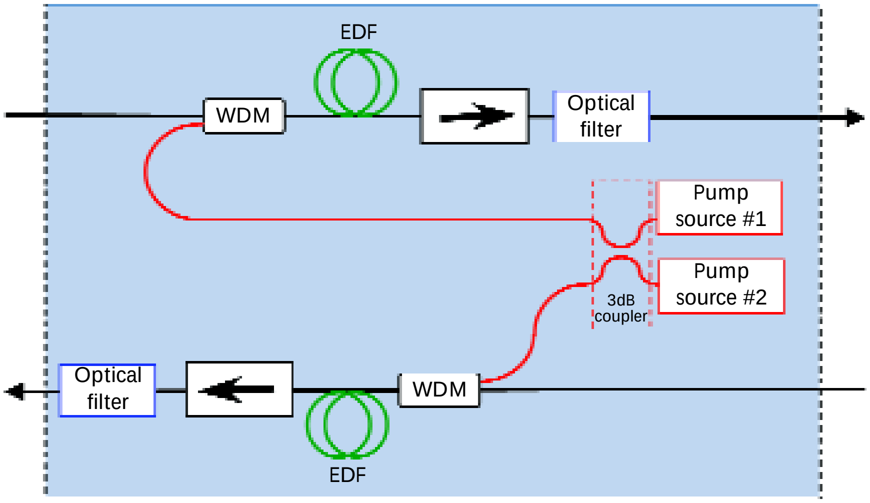
Eighteen months to implementation

Continuous improvements in fiber communication technology have led to a reduction in time to market. Today's submarine systems are usually manufactured, laid, installed and commissioned in an 18-month period starting from when the contract is signed.

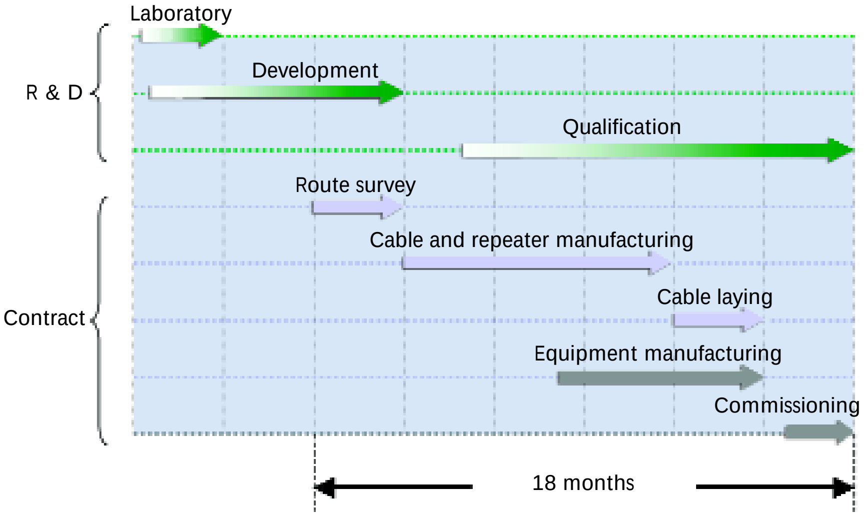
Benchmark analysis shows that laboratory experiments reported at industry conferences such as the Optical Fiber Communication Conference and Exhibit (OFC), SubOptic and the European Conference on Optical Communication are typically 24 months ahead of actual system installation.



Submarine cable types for repeater systems.



Optical scheme for an amplifier pair.



The phases of research and development, and a contract implementation work plan.

The lightweight cable is coiled in tanks aboard ship.

Laboratory experiments

Over the course of the past 20 years, large-scale research and development (R&D) efforts have made it possible to increase cable capacity and robustness in accordance with market needs, at the same time that submarine systems have become the backbone of intercontinental telecommunication. The most significant innovations in this respect were the erbium-doped fiber amplifier, developed by Payne and Poole at Southampton University in the 1980s, and the out-of-band FEC, which was pioneered by Alcatel in the 1990s.

Prior to subsea installation, all technical innovations undergo intensive laboratory testing. To monitor optical transmission performance, in most of the experiments a circulating loop set-up is employed. The advantage of this configuration is twofold: the cost is low since it requires only a few hundred kilometers of fiber and a limited number of amplifiers; the set-up is easy to reconfigure. To simulate long-haul transmission, the optical signal is circulated through a short amplified link. The loop, which is usually 500 kilometers long and employs representative components, is also used to conduct parametric investigations aimed at establishing equipment specifications.

Whatever the system length and target capacity, the standard performance requirement for a submarine system is a BER below 10^{-13} at end of life. The use of third-generation FEC allows the BER requirement to be reduced to 4×10^{-3} before error correction. Taking into account margin allowances for system repair, aging and manufacturing, the laboratory experiment to validate the design of a system corresponds to a BER of 5×10^{-5} before error correction. Such a circulating loop experiment was carried out 100 times at 10-Gbits/s transmission over 6,000 km. In this particular transoceanic experiment, the 100 channels were spread over a 32-nm amplifier chain bandwidth that corresponded to channel spacing of 0.32 nm or 40 GHz. The measured BER of each channel was better than 5×10^{-6}, or 10 times better than the 5×10^{-5} BER requirement. The experiment thus validates the design of terabit/s transmission per fiber over transatlantic distances.

To optimize the cost structure, repeater spacing is planned on the basis of the specific length and capacity of each system so as to minimize repeater count.

The cable route survey

There are two ways to improve reliability: the cable can be armored to increase robustness or buried to protect it from damage. Because both techniques increase the cost of the system, choices regarding armor and burial are important ones. Choice of route and choice of protection go hand in hand; the optimal route avoids both manmade aggressors, such as ship anchors, and natural hazards. Definition of the route is a three-step process which consists of a desktop cable survey, an electronic route survey (ERS) and an electronic burial assessment survey (EBAS). The first step allows for predefinition of the best route and an estimate of armoring and burial needs on the basis of known seabed profile and human activity. The ERS and the EBAS allow for further refinement; they entail generation of a geophysical profile of the seabed along with examination of discrete samples of sediment. This three-part technique allows for the determination early on in the process of the types of armored cable that will be necessary, their lengths and the specifications of burial depth and tools.

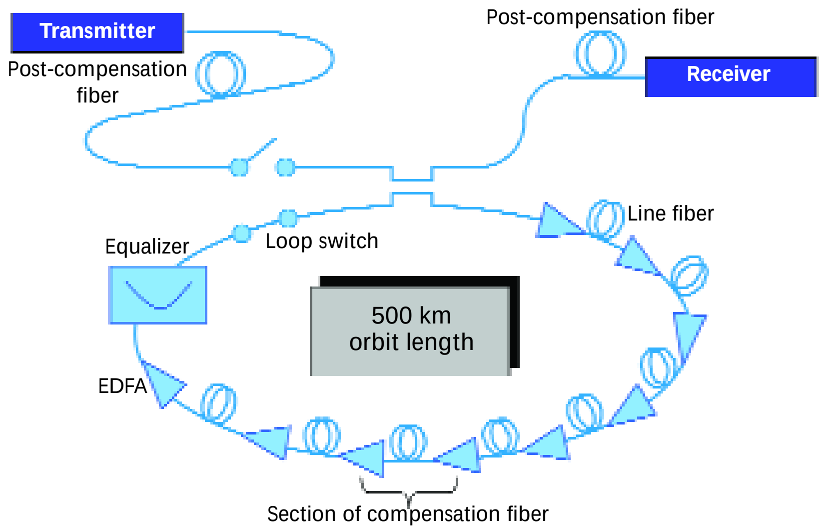
The assembly of the submerged plant

After the repeaters and cable have been manufactured, the system is assembled in sections and a number of tests are performed. Electrical and optical tests—of insulation, conduction and current-voltage characteristics—are carried out on the assembled sections. The optical tests measure gain flatness and chromatic dispersion. The test results allow for adjustments to be made and are also used as a source of reference data during loading and laying of the cable. The cable system—often in more than one piece—is then loaded onto the cable ship where it is carefully coiled in storage tanks.

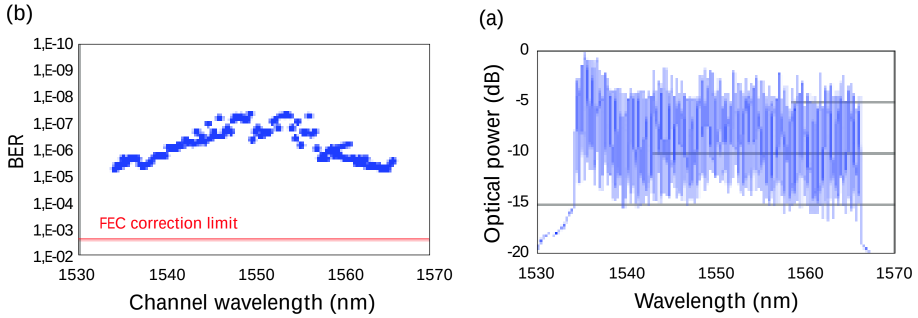
Laying cable

Actual marine operation begins with the cable being floated ashore from the cable ship to the landing position. The cable is floated ashore to prevent damage to the seabed as well as to the cable itself. After the cable end is ashore and secure, the floatation bags are removed and the cable settles to the seabed. The cable ship then follows the predetermined route; the cable is buried or surface laid as required.

The cable is usually buried in areas at which water depth is below 1,000 meters or, in some cases, below 1,500 meters.



The circulating loop set-up.



(a) Received optical spectrum and
(b) recorded BER of each of the 100 channels after 6,000 km.

Cable can be simultaneously laid and buried by use of either a plow that can bury it at depths of between 1.5 and 3 meters or a remotely operated vehicle equipped with jetting tools. Such complex operations are conducted at reduced speed of between 50 and 1,500 meters per hour, depending on the seabed profile and the sediment. When laying and burial cannot be performed simultaneously because of the seabed profile or hardness or because a plow is unavailable, post-lay burial is performed by use of jetting or trenching tools. On long systems, however, most of the cable is laid in open sea, where a ship that contains as much as 4,000 kilometers of lightweight cable can lay it at speeds of 10 kilometers per hour.

System commissioning

In parallel with marine operations, SLTE and PFE are installed in the cable stations. When this equipment is connected to the submerged plant, the commissioning period can begin. Commissioning tests verify cable powering, submerged equipment and transmission performance to evaluate the actual margins of the system. When all the results have been reviewed and accepted by the purchasers, the system is ready for service and integrated into the global network.

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