

Undersea Optically Amplified Repeated Technology, Products, and Challenges

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Implementing the high performance and high reliability required in undersea transmission systems demands careful design, as well as the careful selection and management of technology. This paper explores the technology used in undersea systems that support optically amplified repeated applications at rates up to 5 Gbits/s. It provides a brief, high-level description of a typical undersea system and its subsystems, then examines each of the subsystems and associated new technologies in greater detail.

Introduction

After deploying two generations of regenerative repeaters for undersea optical fiber systems, AT&T is turning to optically amplified repeaters. Such systems are very attractive to the purchasers of lightwave transmission systems,¹ since the optically amplified repeaters:

- Are bit rate independent, which allows systems to be upgraded for higher frequency and additional capacity, without replacing repeaters;
- Are less complex than regenerators, using fewer numbers and types of components;
- Eliminate transmission path regenerative sections, along with the section termination hardware, firmware, and software appropriate for the data format, hierarchy, and standard being used; and
- Generally are less costly and more reliable.

On the other hand, optical amplified systems pose the design challenges of an optical analog transmission path, which include the proper handling of the transmission impairments stemming from polarization, dispersion, and non-linear effects. This article discusses AT&T's new undersea, optically amplified repeated system technology and product design.

The constituent parts of an undersea lightwave system are found in part under water, called the *wet plant*, and in part on land, the *dry plant* (see Figure 1).

Wet plant components consist of a cabled fiber transmission medium and

repeaters containing optical amplifiers that compensate for attenuation in the cabled fiber. The cable also contains a copper conductor to carry electrical power to the repeaters. Another component of some wet plants is a branching unit (BU), which provides for greater flexibility in undersea network architecture by allowing traffic to be split, or switched, to multiple landing points.

Dry plant components consist of terminal transmission equipment (TTES), line monitoring equipment (LMES), and power feed equipment (PFES). The TTES provide the interface between the "dry" inland communication network and the "wet" undersea transmission link. The LMES are part of a line monitoring system (LMS) that keeps watch over the health of the undersea link and locates faults, assisting wet plant maintenance. PFES energize the link, providing power to the repeaters.

Optically Amplified Transmission

SL2000 repeaters employ erbium-doped fibers (EDF) as optical amplifiers. Erbium-doped fiber amplifiers (EDFA) have become the dominant means for signal amplification in long-haul lightwave transmission systems, and are fast becoming a ubiquitous component in general optical transmission systems.

Compared to regenerative repeater technology—where the signal is converted from optical to electrical, reshaped, and con-

Panel 1. Acronyms and Definitions Used in This Paper

BeCu — Beryllium-copper

Birefringent — Exhibiting an anisotropic index of refraction.

BU — Branching unit

Compression — An operating regime of an amplifier in which changes in input power result in compensatory changes in amplifier gain.

COTDR — Coherent optical time domain reflectometer, a specialized "light radar" that uses reflected light to characterize a transmission path.

DA — Double armor

DC — Direct current

DW — Deep water

FEC — Forward error correction

GPa — GigaPascal, where Pascal is the metric unit of pressure equal to one Newton per square meter (N/m^2).

InGaAsP — Indium-gallium-arsenide-phosphide

ITU-TSS — International Telecommunication Union-Telecommunication Standardization Sector (formerly CCITT)

LCM — Loopback coupler module

LME — Line monitoring equipment

LMS — Line monitoring system

LTE — Line terminating equipment

LTU — Line terminating unit

LWA — Light wire armor

MPa — MegaPascal, where Pascal is the metric unit of pressure equal to one Newton per square meter (N/m^2).

msec — Millisecond

nm — Nanometer

Optically amplified repeater — Reshapes an incoming optical signal for re-transmission, without conversion to an electrical signal.

PFE — Power feed equipment

PMD — Polarization mode dispersion, which occurs when one polarization mode propagates at a different velocity than another.

psi — Pounds per square inch

Rayleigh scattering — Material property whereby there is a wavelength-dependent absorption and re-radiation of light.

Refractive index profile — The fiber core and cladding index of refraction design that, along with material properties of the glass, define the transmission properties of a fiber.

Regenerative repeater — Converts incoming optical signals to electrical signals for reshaping, before converting them to optical signals for retransmission.

SA — Single armor

SDH — Synchronous digital hierarchy

SL — Submarine lightwave cable

SPA — Special application

STM — Synchronous transfer mode

TPC — TransPacific Cable

TTE — Terminal transmission equipment

UPS — Unit fiber structure

WDM — Wave division multiplexer

ZDW — Zero-dispersion wavelength, the wavelength at which a fiber exhibits net zero dispersion.

verted back to optical—optical amplifiers have many advantages. Simplicity, high reliability, extremely wide bandwidths, relatively low cost, and insensitivity to transmission bit rates have made erbium-based optical amplifiers the undisputed technology of choice for undersea repeaters.

Optical amplifiers contain a length of erbium-doped fiber that provides a gain medium, an energy source that "pumps" the fiber to provide gain, and a means of coupling the pump energy into the doped fiber without interfering with the signal light being amplified.

Once an erbium amplifier is pumped into an excited state, it is capable of producing both optical gain through emission stimulated by a passing signal photon, and optical noise by radiative spontaneous decay. Much of the design effort of optically amplified systems centers on managing the ratio of stimulated photon emission (signal) to spontaneous photon emission (noise), called the signal-to-noise ratio (SNR).¹

In undersea systems, the repeater amplifiers must also operate in a state of compression. In compression, the amplifiers regulate the optical power of the

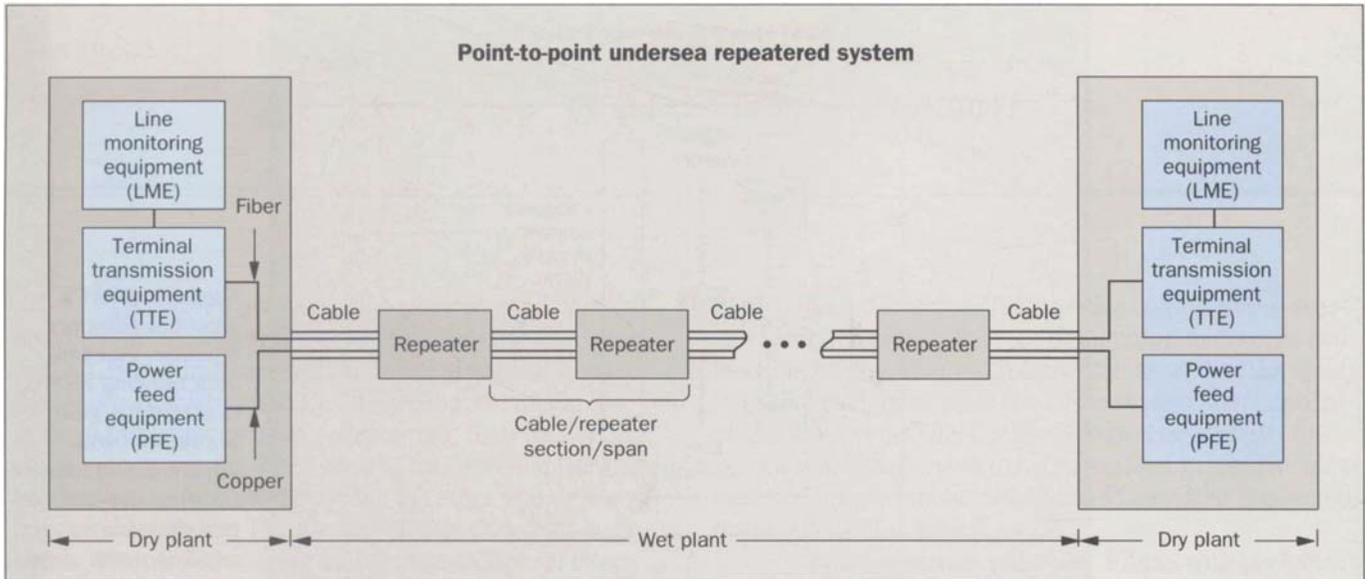


Figure 1. The constituent parts of an undersea lightwave optically amplified repeatered system are found in part under water, called the *wet plant*, and in part on land, the *dry plant*. The wet plant includes the cabling and repeaters, while the dry plant includes the terminal transmission equipment (TTE), line monitoring equipment (LME), and power feed equipment (PFE).

signals propagating through the undersea cable. A string of fiber/amplifier spans with amplifiers in compression compensates for system degradations through a process of automatic gain adjustment. The characteristics of optical amplifiers, in and out of compression, are shown in Figure 2. The figure shows the small signal gain, that is, the rate of change of the transfer function. For an operating point in the compression region, amplifier gain increases if the average amplifier input power decreases. Likewise, the gain decreases if the average amplifier input power increases. Thus, the gain of optical amplifiers operating in compression self-adjusts to variations in input power.

A properly designed optical amplifier achieves the optimum tradeoff between signal gain and noise production, while maintaining the output power and the compression specified for a transmission system.²

Undersea Repeaters. One of the main components of the undersea plant is the repeater. The AT&T repeater is a collection of optical and electrical components in a beryllium-copper (BeCu) housing identical to those used in previous generations of undersea systems. The housing can support up to four amplifier pairs, and can isolate electrical differences between the exterior BeCu, at sea ground, and the internal electronics of at least 7,500 volts without excess charge leakage or harmful corona effects.

Amplifier pairs are modular, independent building blocks that use the gain associated with erbium-doped fiber to support transmission on two-line paths simultaneously (see Figure 3).

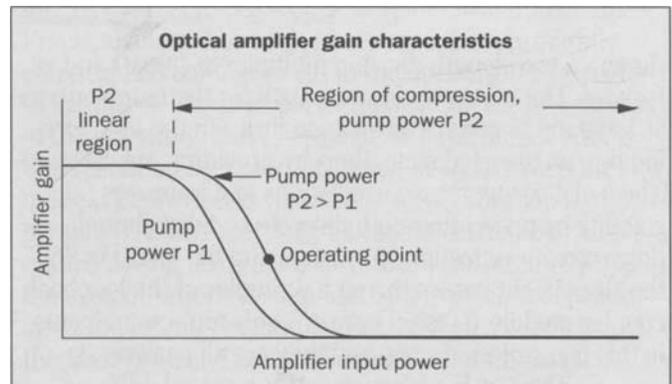


Figure 2. This illustration shows the characteristics of optical amplifiers, in and out of compression. The figure shows the small signal gain, that is, the rate of change of the transfer function. A reduction in pump power, as might arise from the failure of one of the redundant pumps, shifts the operating point to the P1 curve. Careful system designs can tolerate pump failures, with no significant degradation in system performance.

Amplifier pairs support the bi-directional communications associated with a single line-pair in an undersea system. There are three basic divisions in the architecture of the amplifier pair:

- Optics associated with transmission;
- Optics of the loopback coupler module, an element of the line monitoring system; and
- Opto-electronics and DC circuitry that provide and control pump energy—collectively called a pump unit.

Undersea Transmission Optics. The transmission optics design philosophy is to minimize the number of components, and to use passive technologies. In an amplifier pair, incoming signal light at 1,558 nanometers (nm) is amplified by erbium-doped fiber before passing

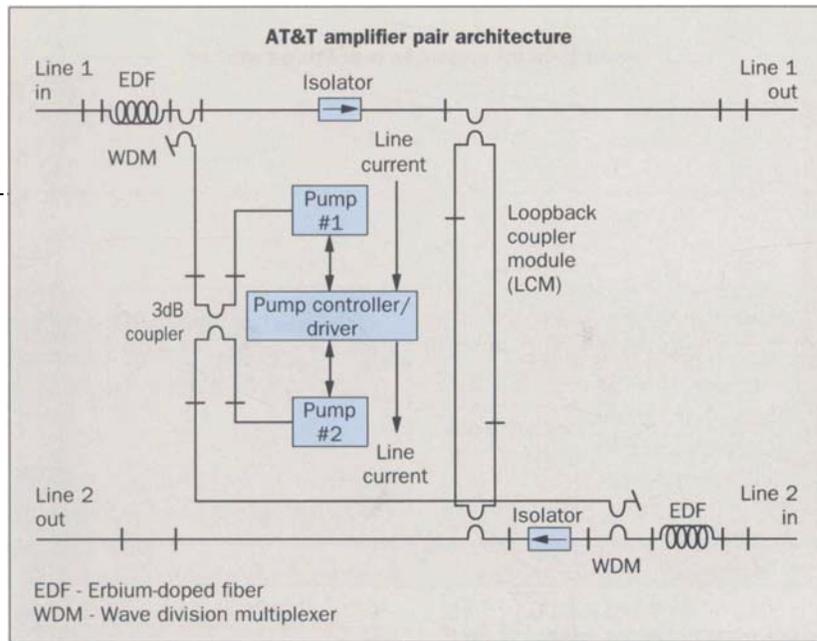


Figure 3. AT&T's amplifier pairs are modular, independent building blocks that use the gain associated with erbium-doped fiber (EDF) to support transmission on two-line paths simultaneously.

though a wavelength division multiplexer (WDM) and an isolator. The WDM provides the path for the pump energy at 1,480 nm to counter-propagate through the EDF, forcing it to an inverted state, thereby providing optical gain. The isolator suppresses oscillations and improves stability by preventing both discrete and distributed down-stream reflections from entering the EDF. Finally, the signal light passes through a coupler of the loopback coupler module (LCM). There are only four components in this transmission path, and they are all passive.

The EDF is a hermetic carbon-coated, high-strength, high-reliability device manufactured by AT&T. The isolator, also made by AT&T, takes advantage of magnetically-induced field rotation (called the Faraday effect) in bismuth-iron-garnet to achieve isolation in excess of 30 dB, while the WDM is all fiber and made using established coupled-wave device manufacturing technologies.³

Loopback Coupler Module. Part of the LMS, the LCM optics provide a facility for continuous monitoring of the undersea system's optical performance, and allow for the quick identification and location of system faults. A completely passive network of optical couplers, the LCM provides attenuated loopback signal paths between the outgoing and incoming transmission lines.

A loopback path couples a small amount of energy from the output of one amplifier to the output of the other amplifier in a pair (see Figure 3). This energy, when detected and processed by sensitive electronics in the dry plant, allows one to monitor the health of the system and to locate faults along its length.⁴

The symmetry of the LCM makes line monitoring capability available to both directions of transmission. The LCM also contains a path for coherent optical time-domain reflectometer (COTDR) equipment,⁵ which allows

an alternate means of assessing system health and locating faults. The LCM couplers are all-fiber coupled-wave structures that are manufactured using proven technologies.

Repeater Pump Unit. The pump unit provides the optical pump energy for both transmission directions of the amplifier pair. Its design efficiently combines the strengths of passive sparing, redundant pumping, and redundant electronics, without sacrificing cost or performance. In the pump unit, two pump lasers are powered and controlled by a single pump controller/driver circuit. This circuit derives power from a constant line current provided by the power feed equipment, and provides both surge current protection (from surges that can accompany a cable break) and bias currents for the pump lasers.

The pump lasers, AT&T InGaAsP capped mesa buried heterostructure devices, are passively cooled and are spliced to an optical coupler. The coupler combines the energy of the two filtered pumps and splits it equally for each half of the amplifier pair. This topology allows for passive sparing of the pumps and, with careful system design and power budgeting, redundant sparing of two transmission lines, using only two pumps.⁶

Repeater Mechanical Design. The BeCu housing is lined with a high-voltage insulator, into which aluminum sleeve segments are embedded. Four symmetric and identical delta-shaped chassis, each capable of supporting an amplifier pair, are mounted to an inner support and inserted into the housing/sleeve assembly to form the complete repeater. Springs between the inner support and the individual chassis force the chassis outwards against the aluminum sleeve. This configuration allows the internal structure to flex as the pressure vessel responds to external pressures ranging from 0 to 12,000 psi (0 to 83 megaPascals [MPa]).

The spring pressure also assures good contact between the chassis and sleeve. A broad chassis-to-sleeve contact area, combined with an integral contact between the sleeve, insulator, and BeCu housing, results in low thermal impedances from components, mounted on the chassis, to sea water. The result of this efficient thermal conduction path is low device temperature and, thus, improved reliability. The chassis also provides for large-radius, low-torsion routing and storage of optical fiber, which improves reliability.

Undersea Optical Cable

In this section, we will discuss the performance, design, assembly, jointing, and system assembly of optical undersea cable.

Optical Performance and Measurement of Cable.

Long-haul, amplifier-based undersea repeatered systems require:

- Cables that can withstand the rigors of the ocean environment, and
- Fibers that can meet the unique performance challenges of the high-capacity transmission path.⁷

Cables for SL2000 are based on standard AT&T undersea lightwave designs, which have been successfully used in first and second generation undersea optical systems.⁸

Various cable types afford different levels of protection, depending upon the conditions on the ocean bottom. Fibers for SL2000 systems have been optimized for four transmission parameters:

- Chromatic dispersion,
- Polarization mode dispersion (PMD),
- Non-linearity, and
- Attenuation.

Chromatic Dispersion. It is essential that the average zero-dispersion wavelength (ZDW) of each of the fiber transmission paths be precisely aligned with the narrow-band (1 to 2 nm) gain peak that results when hundreds of erbium-doped fiber amplifiers are cascaded in a chain that extends thousands of kilometers.

It has been demonstrated, however, that maintaining this zero dispersion along the length of the system results in large signal broadening, due to non-linearities in the fiber. It is essential in long systems, therefore, to intentionally accumulate negative dispersion, which is periodically equalized in order to reduce the accumulation

of non-linear distortion. This precise control of the average *in-situ* ZDW involves very demanding tolerances and tracking during fiber manufacturing, as well as the ability to periodically insert into the cable system short special-cabled fiber segments designed to precisely adjust the accumulated dispersion to its prescribed value. The measurement of chromatic dispersion in a system is covered elsewhere in this issue.⁹

Polarization Mode Dispersion. Fibers with perfect circular symmetry can propagate two orthogonal HE_{11} modes over a given distance with identical transit times. Practical fibers, however, have cores that are slightly elliptical and contain stress in the optical guiding region of the fibers. These imperfections break the degeneracy of the orthomodes,¹⁰ giving rise to birefringent effects that result in differences in group delay between the two modes. This effect is referred to as polarization mode dispersion. The fact that a signal can be carried by two modes having different transit times can seriously impair the system, where the amount of impairment depends upon the bit rate, system length, PMD characteristics of the fiber path, and interaction with other impairments, such as fiber non-linearity.

Practical fiber guiding systems are subject to distributed coupling between the propagating modes, causing an exchange of energy between them. This coupling, or exchange of energy between modes, is due to a combination of factors, some of which are intrinsic to the fiber as manufactured, and some of which are imposed by external factors, such as loading the cable on a bobbin, laying the cable, etc.

This coupling between modes can be beneficial, since the end-to-end dispersive effects are lessened in the presence of coupling. The beneficial effects of fiber paths with mode coupling, however, are difficult to characterize and portray, since they are statistical in nature.

Non-linearity. The refractive index profiles of silica-based fiber media are most often represented by simple numerical values corresponding to the core and cladding regions of the fiber. This representation is usually adequate for approximating propagation behavior, which comprises low signal-level transmission over propagation distances that are not too long.

However, in the case of amplifier-based systems that are thousands of kilometers in length, use of the simple index of refraction representation is not sufficient.

Table I. Typical cabled fiber optical parameters

Fiber type	Dispersion shifted
Mode field diameter (Petermann II)	8.4 microns
Effective area	> 50 μm^2
n_2	$2.6 \times 10^{-20} \text{ m}^2/\text{W}$
Polarization mode dispersion (PMD) in cable	< 0.1 ps/ $\sqrt{\text{km}}$
Proof test strength	200 kpsi
Loss in undersea cable environment	0.21 dB/km
Average λ_0	1,561 nm
Static fatigue n-factor	>18
Aging (all causes)	< 0.01 dB/km
Coating structure	Dual: high/low modulus 250 μm
Identification	Color coating

The refractive index of fiber in the long system is affected by the optical power level of the transmission signal. Although the change of refractive index is small, the cumulative effect over a long optical path can contribute to degradation in system performance, due to changes in the optical spectrum and the signal pulse shape.

Attenuation. The attenuation of dispersion-shifted fibers tends to be somewhat higher than that of conventional fibers, due to increased Rayleigh scattering resulting from higher levels of GeO₂ dopant incorporated in the fiber core. In the as-drawn and unspliced state, average losses are typically in the range of 0.200 dB/km. With cabling and associated splicing and jointing, installed losses of approximately 0.205 dB/km can be expected.

Cabled Fiber Performance Summary. Table I contains a summary of the typical optical performance values associated with cabled undersea dispersion-shifted fibers. As can be seen, all parameters have values consistent with demanding long-term system performance.

Fiber Design and Manufacture. In order to achieve very high levels of performance, careful attention is devoted to every stage of the fiber design and manufacture. This effort begins with synthetic quartz preforms, the glass tubes that eventually become the outer cladding of the fiber. The preforms are carefully processed for uniformity of thickness, concentricity, and minimum ovality. After the appropriate dopants, which will become the inner core of the fiber, are deposited inside the preform, the preform is heated and collapsed into a solid glass rod. This rod is heated again so the fiber can be drawn to long lengths at high strength—1.4 gigaPascals (GPa).

SL2000 fibers have been designed to have slightly higher mode field diameters than those found in other

dispersion-shifted fibers, while still meeting the requirement for low sensitivity to bending. This makes the “effective area” of the fiber core larger, which reduces the power density and minimizes the effects of non-linearity.

Fiber is selected for cabling using sophisticated routines that balance the distribution in ZDW, the PMD, and any differences in attenuation between fibers in a given group that are going to be assembled into a cable. The attenuations and ZDWs must be matched so that there is minimal variation in attenuation or dispersion between fibers in a group. “Running averages” are compiled and monitored to assure that the fiber sections will meet the final design requirements on attenuation and dispersion.

Cable Design, Processing, and Qualification. Cables are designed to isolate the fibers, insulate the electrical conductor from the ocean environment, and provide a range of levels of mechanical protection from known and unexpected hazards. The cable design and manufacture must reliably maintain the optical performance of the fibers at minimum cost.

Cables for SL2000 systems draw upon AT&T’s proven undersea design technology and manufacturing processes that have been demonstrated in earlier undersea lightwave systems. AT&T undersea lightwave cable consists of four major sub-units:

- Unit fiber structure (UFS),
- Composite power conductor,
- Polyethylene insulation, and
- Armor protection.

The modular nature of all SL2000 cable processes allows for flexibility in manufacturing cable. The degree to which cables must be protected varies with the depth of the water, since shallow continental shelves contain

Table II. SL2000 cable types and properties.

Property	DW	SPA	LWA	SA	DA
Outside diameter	21.0	31.7	38.0	42.2	51.0
UTS (kN)	107	107	181	223	434
NTTS (kN)	81	82	147	187	325
Cable modulus	22.4	19.8	7.5	8.3	8.4
Max. operating depth	6,000	4,500	1,500	1,300	400

more hazards than deep abyssal plains. Deep-water cables have no protection external to the electrical insulation, yet these cables are robust and cost effective for the majority of systems. Armor-protected cables consist of a "transmission core" and externally-applied armor (typically tapes or wires). Different levels of protection can be provided by varying the armor thickness and material, or using multiple layers of armor.

The degree of armor depends on the region in which the cable is to be deployed. Common AT&T undersea lightwave cables are described below and their properties are given in Table 2.

- Deep water (DW) - Basic AT&T undersea lightwave cable, suitable for deployment in the deep ocean, contains the unit fiber structure, composite power conductor, and polyethylene insulation.
- Special applications (SPA) - This configuration consists of the DW cable protected with a longitudinal metallic barrier and covered with a high-density polyethylene protective layer. It is suitable for deployment in areas where fish gnaw, where there is a chance of natural abrasion, and at all planned cable joints.
- Light wire armor (LWA) - This configuration consists of the DW cable, protected by a single layer of medium-strength armor wires, suitable for ocean burial.
- Single armor (SA) - Similar to LWA cable, this cable has a single layer of steel protection wires that provide greater strength for cable in unburied applications.
- Double armor (DA) - Two layers of protective steel are placed over the DW cable for areas near the shore, where abrasion damage is greatest.

Section Assembly. Section assembly is the process of configuring the inventory of manufactured cable sub-

sections to meet the requirements for each cable repeater section, and the ensemble of repeater sections that comprise the entire system. Optical amplifier technology requires a more stringent process than that required for regenerative systems.

During the construction of the sections, consideration must be given to the losses of individual section fiber paths, as well as the loss of each fiber path over the system length. Given the possibility of loss variation between paths, the section assembly process must periodically make adjustments to the loss of one or more fiber paths to achieve requirements over the system length. The adjustments are made through the insertion of planned high-loss splices.

After cables have been selected for repeater sections, they are joined together using cable-to-cable joints. SL2000 systems use the same 11-Type joints proven in past undersea system generations for all jointing, with the exception of the beach joint and spare cable termination.

Jointing Techniques. Cable jointing provides the ability to:

- Splice sub-sections of cables together to form sections,
- Join cables to repeaters during system assembly,
- Terminate the ends of cables for later conversion to cable-to-cable joints during system installation, and
- Join undersea cable to land cable at the beach joint.

All undersea hardware is designed to provide reliable interconnections during the rigors of ship loading, deployment, recovery, repair, and redeployment at depths of up to 7,500 meters. Appropriate hardware designs are available to meet the various requirements of armored undersea cable.

The primary structural members of an 11-Type

joint are the two cable sockets, the splice shelf, and the pressure housing. The cable strength members are terminated with a plug-in-socket design, whose breaking strength exceeds 90 per cent of the cable's required minimum breaking strength. This connection also terminates the electrical conductor in the cable and provides electrical continuity across the joint. Bend-limiting boots assure a gradual transition in bending stiffness across the joint, and are designed to pass through the cable-handling machinery on board cable ships.

System Assembly. System assembly is the integration of assembled cable sections with repeaters to form a continuous system segment. Chromatic dispersion management, which started during the manufacture of the fiber, continues through the system assembly to ensure the needed dispersion configuration, or "map," in the finished system. To accomplish the needed map, periodic adjustments are made to bring the cumulative chromatic dispersion to the specified requirement. As previously noted, these adjustments involve the periodic insertion of cabled non-dispersion-shifted (low zero-dispersion wavelength) fiber into selected repeater spans.⁹

Branching Units

The contemporary undersea system market demands system topologies that are more complex than simple point-to-point interconnects, as shown in Figure 1.¹ Meeting this demand requires a method of splitting traffic undersea to allow multiple landing points. Branching units with the capability to join three cables, each with up to four fiber pairs, address this need.

In optically amplified systems, branching units perform three basic functions. They provide the:

- Facility for managing the optical fiber interconnect between three cables,
- Facility for managing power and traffic flow between three cables, and
- Mechanical strength needed to accommodate laying and recovering three joined cables.¹¹

There are three application-specific branching units: *passive*, *power-switched*, and *fiber-switched*.

Passive Branching Units. As its name implies, a passive BU contains no electronics. It is a three-port pressure vessel that provides the facility for splicing optical fibers and system power conductors. Passive BUs are used primarily in repeaterless systems.

Power-Switched Branching Units. Power-switched BUs provide for the shore management of power flow between three cables. Power switching allows system managers to route power around system faults, assuring that two of three legs in a branched system remain powered in the event of a fault on one leg. In a branched application, there are four operating states: normal, branch number one fault, branch number two fault, and trunk fault. A power-switched BU can be configured in any of these four states by the appropriate power-up sequencing of the three legs of a branch. Power-switched BUs do not permit active optical traffic routing.

Fiber-Switched Branching Units. Fiber-switched BUs provide for the management of both power flow and optical traffic flow through a branch. A fiber-switched BU has the same four operating states as a power-switched BU, and each of these states has an associated optical fiber path configuration. The fiber-switched BU also configures through a power-up sequence, avoiding the costs and reliability risks associated with an active command channel.

Branching Unit Technology. Branching units have been proven in past undersea systems. The Be-Cu pressure vessel has successfully managed the high voltages, high pressures, and mechanical stresses placed upon it. The optical relays and high-voltage electrical relays have been used in past generations of undersea systems. All other active electronic technology is qualified for and used in standard SL2000 repeaters.

Terminal Transmission Equipment

Dry plant components consist of terminal transmission equipment, line monitoring equipment, and power feed equipment. The fundamental terminal transmission equipment elements are the synchronous digital hierarchy (SDH) multiplex/demultiplex equipment, line terminating equipment, order wire equipment, switches and bridges, and monitoring and control circuitry.

SDH Multiplex/Demultiplex Equipment. SL2000 SDH equipment is an implementation of the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-TSS) synchronous digital hierarchy standard. Use of a standard simplifies the interconnection of networks owned by different entities with equipment purchased from a multitude of vendors. Use of an international standard is essential for global interconnection.

The SDH standard provides a framework to

develop digital telecommunications transport over a worldwide fiber-optic network. This multiplex/demultiplex equipment can be procured from a number of suppliers and a number of architecture and networking options are available. Examples are Americas 1 North/Columbus TTE, which deployed 1 x 0 point-to-point equipment, and TAT 12/13 and TPC-5, which are using add/drop line-switched ring-protected equipment.

In addition to SDH multiplexing, the SL2000 TTE can perform one additional higher level of multiplexing. Specifically, two STM-16 signals at 2.48832 Gbits/s (approximately 2.5 Gbits/s) can be bit interleaved to form a single 4.97664 Gbits/s (approximately 5 Gbits/s) signal. The bit interleaving circuitry is physically associated with the line terminating equipment.

Line Terminating Equipment. The line terminating equipment, or line terminating unit (LTU), is an adapter that connects standard terrestrial multiplex/demultiplex equipment to the undersea cable. On the terrestrial side, the LTU provides SDH standard interfaces to multiplexing equipment. On the undersea cable side, it provides an interface compatible with the special needs of long-distance undersea transmission.

5 Gbits/s LTU Architecture. The LTU comprises two basic and independent functions: an LTU transmitter and an LTU receiver. The LTU transmitter combines two optical SDH STM-16 data streams and produces a single 5 Gbits/s optical data stream that is compatible with the undersea cable. Conversely, the LTU receiver detects a 5 Gbits/s optical data stream from the undersea cable and divides it into two STM-16 optical data streams. Both the LTU transmitter and LTU receiver have special features that optimize the performance of the overall transmission system, and both incorporate leading-edge technologies. These features are discussed below.

5 Gbits/s LTU Transmitter. At the head end of an undersea system, the 5 Gbits/s LTU transmitter provides two STM-16 optical interfaces to the multiplexing equipment in the terminal transmission equipment. These optical data streams are detected by SDH receivers that convert them into electrical data streams. The electrical data streams are encoded on systems employing forward error correction (FEC), and are elastically stored to provide stable, phase-aligned 2.5 Gbits/s data to a multiplexer. The multiplexer bit-interleaves the two 2.5 Gbits/s data streams to produce a single 5 Gbits/s electrical data stream.

The 5 Gbits/s electrical data drives a transmitter, which converts the data back into an optical signal. This optical signal then passes through a polarization management device and on to an optical boost amplifier. The amplifier provides the power levels needed by the undersea cable.

Features of the 5 Gbits/s LTU transmitter include:

- Optional forward error correction that can add 5 dB or more to the system transmission margin, with only a seven per cent increase in transmission bit rate;
- World-class optical rise/fall times (~50 ps);
- Ultra-stable transmitter wavelength with annual drift of less than 0.12 nm per year;
- Options for both data-synchronous and asynchronous polarization scrambling; and
- STM-16 compatible optical interfaces to the TTE.

5 Gbits/s LTU Receiver. The LTU receiver terminates an undersea transmission path, providing a 5 Gbits/s receiver for the undersea side and two STM-16 optical outputs to demultiplexing equipment in the TTE. The optical data from the undersea system is amplified through an optical preamplifier, filtered, and detected by a receiver, which converts and de-interleaves the optical signal into two 2.5 Gbits/s electrical data streams. These two streams are decoded (in systems with FEC) and converted back into STM-16 optical data streams by SDH transmitters.

Features of the 5 Gbits/s LTU receiver include:

- Large input dynamic range using optical automatic gain control,
- Front-panel access to a high-quality linear receive channel to accommodate field measurements,
- Optional FEC, and
- STM-16 compatible optical interfaces to the TTE.

Order Wire Equipment. Order wire channels are voice and data channels used by system engineering, installation, and maintenance personnel for telemetry or conversation between different network stations and operation control centers. These circuits are used for, among other things, system coordination, control (action relative to activation, deactivation, configuration change, signal rerouting, maintenance, etc.), and reporting. Order wire channels are carried between points in the overhead section of either the SDH frame structure or the forward error correction frame. As with the SDH multi-

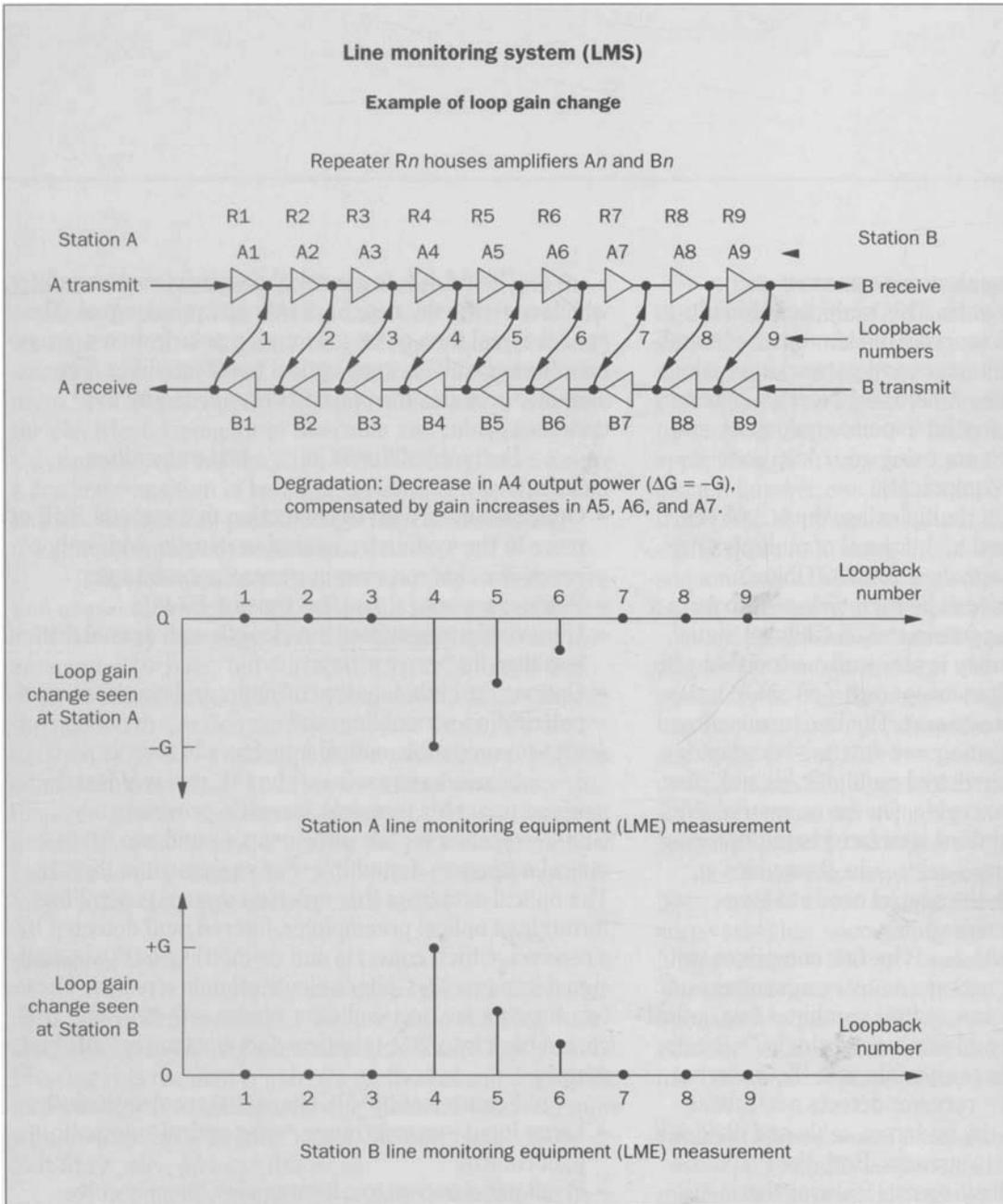


Figure 4. This figure shows the changes that appear in a system with a decrease of output power (gain) from a single repeater amplifier. The loop gain plots provide a signature, which characterizes the cause and location of the degradation. The loopback path couples a small amount of energy from the output of one amplifier to the output of the other amplifier in a pair. This energy, when detected and processed by sensitive electronics in the land plant, allows one to monitor the health of the system along its length and to locate faults.

plex/demultiplex units, undersea lightwave order wire units are standard, off-the-shelf, purchased equipment.

Switches and Bridges-Redundancy.¹ Equipment redundancy, which leads to a very high level of system reliability, is an important attribute of undersea lightwave equipment. With the dual-path architecture of an undersea lightwave redundant terminal, signals passing through the equipment in either the tributary-to-line (multiplex) or line-to-tributary (demultiplex) direction pass through duplicated equipment paths.

Input signals are split/bridged and flow continuously through both paths, while outputs are switched and

the signal from either one path or the other is transmitted on a tributary or undersea cable. Such an architecture is commonly referred to as "1 + 1" equipment protection.

Some system architectures call for multiple cable paths between stations to realize increased system reliability and the capability to restore traffic. One such architecture makes use of a ring structure with add-drop SDH multiplex equipment outside of the SL2000 terminal equipment.

Specifically, in the ring structure, the tributary inputs are STM optical signals. As indicated previously, in a 5.0 Gbits/s system, there are two STM-16 tributary

inputs that are bit interleaved to form the 5.0 Gbits/s line signal transmitted on the undersea cable.

Monitoring and Control Circuitry. The monitoring and control circuitry in an SL2000 TTE receives messages from the SDH and line terminating equipment, determines the health of each terminal signal path, and maintains the position of the output switches. The result is a fully functional path that drives tributary and undersea cables at all times. In addition, the circuitry directs order wire signals to the appropriate path and distributes trouble indicators to station alarm systems.

Line Monitoring Equipment ^{2,4}

The line monitoring equipment is used in the monitoring and maintenance of the undersea cable, or wet plant. Specifically, the LME performs routine in-service monitoring of the cable and repeaters, and can report wet plant changes, should they occur. Additionally, the equipment provides an out-of-service fault location capability. The LME is part of a line monitoring system that uses the passive elements in the repeater string to perform the monitoring function.

Under normal, fault-free conditions, systems are designed so that repeater amplifiers operate in gain compression. Each amplifier operating point is such that its gain compensates for the loss of the cable preceding it. As long as the signal level at the input to each amplifier remains constant, the gain of each amplifier remains constant, and the system is in equilibrium. If the signal level at the input of an amplifier decreases due to a degrading or failed pump in the previous amplifier, a degrading splice, a repair, or some other cause, the gain of that amplifier will increase (see Figure 4).

If the increase in gain is not sufficient to totally compensate for the degradation, the input power level at the subsequent amplifier in the system also will be lower than it had been prior to the system change, and the gain of that amplifier also will increase. Gain increase will continue in as many amplifiers as is needed to restore the input signal, at subsequent repeater amplifiers, to the original equilibrium level.

Similarly, if the signal power level at the input of an amplifier is higher than the equilibrium level, the gain of that amplifier will be compressed, as will the gain of as many following amplifiers as are needed to restore the signal to its original equilibrium level.

System measurements indicate that, if subsequent amplifier/cable spans are operating properly, the input signal power at a given amplifier may be increased or decreased from its nominal value in excess of 6 dB, without noticeable impact on system performance. In such a situation, signal levels return to a normal operating level within two or three cable-amplifier spans, and end-to-end transmission performance is largely unaffected.

As indicated above, the LMS uses repeater loopback couplers to make wet plant loop gain measurements, looking for changes over time. Figure 4 shows the changes that appear in a system with a decrease of output power (gain) from a single repeater amplifier. The loop gain plots provide a signature, which characterizes the cause and location of the degradation.

Loopback gain measurements are made by the LME. The equipment modulates the optical intensity of the line signal emitted by the terminal LTU. The modulating signal is a 2-MHz square wave which, itself, is modulated by a pseudo-random bit pattern.

The loopback path in each repeater returns a low-level version of the transmitted monitoring signal to the LME with a unique round-trip delay. Using digital signal processing techniques to correlate each returned signal with a delayed version of the pseudo-random signal transmitted, the gain of each loopback path can be measured (all loopbacks can be measured simultaneously). For in-service monitoring, a modulation index in the range of two to ten per cent is used. For out-of-service measurements, 100 per cent modulation can be used, which allows for a shorter measurement interval.

Power Feed Equipment

To power the undersea electronics, power feed equipment converts 48-volt battery power to a constant current of 0.92 amps at up to 7,500 volts. The basic purpose of the PFE is to safely provide a constant current, at the required system voltage, with high availability.

As shown in Figure 5, PFES at opposite ends of a cable can supply power to each of several hundred undersea repeaters spanning up to 9,000 kilometers. Judicious use of redundancy within the PFE is used to achieve availability. The features required in undersea cable power feed equipment are:

- Low-drift, current-regulated output to enable PFES connected in series to share the total system voltage;

- Automatic mode change-over from current to voltage regulation in order to control, or clamp, the maximum voltage imposed on a system;
- Stable output current and voltage regulators capable of working with a resistive load during testing, an inductive load during cable laying, and a capacitive load in normal cable powering;
- A multiplicity of alarms and protective shutdowns;
- A slow ramp up, or ramp down, with a means of pausing at preselected output voltage levels;
- A means of modulating the output at low-frequency (electroding signal) to enable remote detection equipment to locate submerged and buried cable;¹²
- A simple means for reversing the output polarity for system reconfiguration;
- An embedded test load to enable full-power testing of the PFE during maintenance activities; and
- A provision for historical data recording and an interface to system monitoring equipment.

In addition, the PFES must enable personnel to safely take portions of the equipment out of service for maintenance, while continuing to feed the system.

The system configuration depicted in Figure 5 represents a point-to-point system. This is the simplest of configurations and forms the operational basis for more complex arrangements.¹³ In the point-to-point arrangement, the PFES at each end of the cable are balanced to share the system load.

System Voltage. The required system voltage is proportional to system length and consists of several components: repeater and branching unit losses; the voltage drop associated with the cable conductor; and an allowance for an opposing earth potential. The earth potential allowance component of the system load is a direct consequence of using a single conductor cable with an ocean ground return. It accounts for geomagnetically induced differences in voltage of the ocean ground beds at landing points on opposite ends of a cable system.

For SL2000 cable systems, repeater and branching unit voltage accounts for 53 per cent of the system load, and cable losses account for an additional 40 per cent. Thus, slightly over half of the power delivered by the PFE directly supports transmission, while the remainder is allocated to support power delivery to the repeaters.

PFE Architecture. The PFE can be provided with one to three identical converters, each containing one to

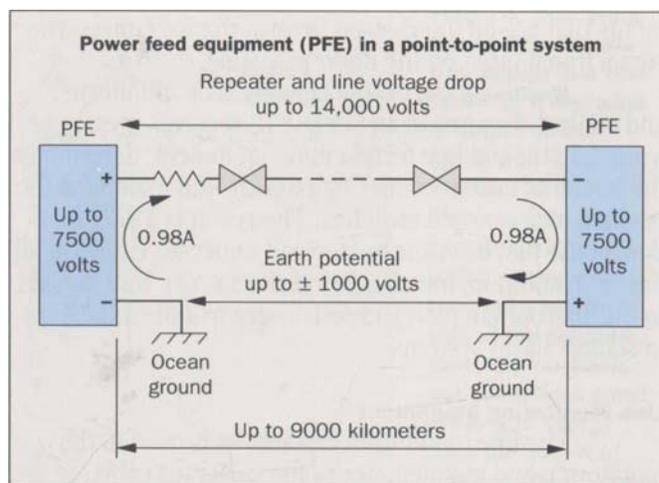


Figure 5. Power feed equipment (PFE) at opposite ends of a cable can supply power to each of several hundred undersea repeaters spanning up to 9,000 kilometers. Judicious use of redundancy within the PFE is used to achieve availability.

five serially connected power conversion units (power stages). Each of the power stages provides up to 1,600 volts of output at 0.92 amps (approximately 1,500 watts maximum). For a given application, the converters are each equipped with enough power stages to meet the cable system voltage requirement, which is proportional to the length of the cable.

Three converters are configured in two plants, a *regular plant* and a *standby plant*. The regular plant has two converters connected in series, each sharing half of the cable load. In this manner, the failure of one converter will result in the remaining converter assuming the entire load in less than 50 milliseconds (msec). The standby plant is normally connected to a variable test load (zero to 10,700 volts at 0.92 amps) for testing and verification. A manual transfer switch is provided so that the standby plant can be placed on cable and the regular plant on the test load. A "hitless" transfer can be accomplished when the standby plant and test load are preadjusted to match both the output voltage and the current at which the regular plant is operating on the cable.

This architecture is flexible, in that it allows for the capacity of a PFE to be matched to the system voltage requirement by specifying the appropriate number of power stages, from one (1,525 volts) to five (7,500 volts).

Further, the architecture allows the converter redundancy to be matched to the application. For example, for systems having required voltages of less than 7,500 volts, the standard practice is to provide each PFE with the capacity to single-end feed the entire system, enabling continuous powering in the event of a shunt fault anywhere along the cable route.

As a consequence, the opposite end PFE can serve as the "standby" during maintenance activities, obviating the need for a standby plant at both ends. Additionally, for very short systems, the series converter in the regular plant may not be required. For example, for a cable system 1,000 km in length, approximately 300 msec is required to redistribute the cable voltage to its "single end feed" distribution. This compares to 50 msec for the series converter in the regular plant to assume the full load.

Summary

Customers for new generation undersea lightwave cable systems want increased reliability and easier, less expensive upgrades—with that same high-level transmission performance obtained from past generations of equipment. Optically amplified systems accomplish just this. High reliability is achieved due to the simplicity of optical amplifier repeater design—with few total components and even fewer complex components.

In addition, the bit rate independent characteristic of the repeaters can lead to easy, inexpensive system upgrades. This is because submerged hardware does not have to be replaced in order to expand system capacity by increasing the data rates. Finally, there is nothing inherent in the technology that prevents a properly designed, optically amplified repeatered system from providing performance surpassing that of previous generations of undersea technology.

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