Design Requirements for the Current Generation of Undersea Cable Systems

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This article describes the design requirements of AT&T's third generation of optical submarine cable systems. Technology advances that have been incorporated in the design include erbium-doped fiber amplifiers, lithium niobate modulators, low-loss and low-polarization mode dispersion-shifted fiber, synchronous digital hierarchy terminals, and forward error correction. This paper discusses:

- Optical submarine cable systems,
- Customer requirements,
- New technologies used in system design,
- System building blocks,
- System performance, and
- System and component design rules to meet customer requirements.

Introduction

Developments in the undersea systems industry are spurred by three factors. The first is the customer's needs for new and expanded features and services. The second is new technologies that make it possible to increase system capacity and performance and reduce circuit costs. The third is the desire for shorter time intervals between order and delivery. This paper provides an overview of those factors and technologies that influence system design. It also offers a high-level description of the system designs developed by AT&T Submarine Systems, Inc. (AT&T-SSI), and the subsystems from which they are built. Many additional details of the designs and the operational characteristics of the major subsystems are presented in other papers in this journal. Finally, this paper explains how AT&T-SSI system designs use new technologies to meet the transmission performance, reliability, and operational features that customers want.

System Design and Customer Need

Principal factors influencing system design are customer needs, supplier needs, government regulation, and the available technologies. The primary customer needs relate to transmission capacity, quality, cost, reliability, performance, operation, and maintenance. Industry standards play a strong role in defining customer requirements and assuring compatibility between the undersea systems and the land-based telecommunications infrastructure. Customers for undersea systems, however, typically demand even better performance than that called for in the standards.

Suppliers, in turn, must consider the current and future capabilities of the underlying technologies, current manufacturing capabilities, and the match between immediate sales opportunities and long-range growth objectives for their product line.

Government regulations also affect system design, including safety and environmental standards for manufacturing, installing, and operating the systems. This article treats government concerns as part of the discussion on industry standards.

The major reason for using new technology in undersea cable systems is to reduce the cost per channel. A system's cost per channel is determined by the system capacity; the cost to procure the system elements; and the cost to install, operate, and maintain the system. System capacity has risen rapidly with each new generation of undersea system, while the price of a system of a given length has remained remarkably constant. Therefore, the cost per circuit has dropped dramatically over the past few years.

Transmission Performance. For more than a decade, transmission performance has been measured by the standards of the International Telecommunications Union (ITU, formerly CCITT). The network interfaces of greatest interest for undersea systems are the CEPT-4 140 Mbits/s electrical signal interface of the Conference of European Post and Telecommunications, and 155 Mbits/s optical and electrical signal interface of the synchronous digital hierarchy (SDH) synchronous transfer module. The relevant transmission performance standards, ITU-T Recommendations G.821 and G.826, define performance standards for national and international digital paths over any transport medium. ITU-T Recommendation G.826 is new, set in 1993, and imposes higher standards of performance than Recommendation G.821. It also reflects a shift in metrics toward error free blocks of data at the path bit rate, instead of error free seconds on 64-kbits/s channels, as in G.821. Table 1 shows the performance requirements from G.826 that apply to paths carried by digital line sections at the STM-1 rate.

Purchasers of undersea systems, as providers of telecommunications services, consistently demand system performance that is better than that specified in international standards, such as ITU-T Recommendation G.826, because they anticipate their customers' rising expectation of higher quality transmission to support new services. Also, with the recent growth in the number of international carriers and circuits, each carrier wants to be perceived as offering the best-in-class performance in order to attract prospective customers.

To give an historical perspective to performance objectives, compare the equivalent mean bit error ratio (BER) objectives for TAT-8 and the TAT-12/13 cable network. TAT-8 was the first optical trans-Atlantic undersea cable system, which began service in January 1989, and TAT-12/13 is the first trans-Atlantic cable network using the current generation, scheduled to start operation in September 1995. The equivalent mean BER requirement for TAT-8 is 6.8×10^{-12} per kilometer (km) of system

Panel 1. Acronyms and Terms Used in This Paper

ASE — Amplified spontaneous emissions
ATM — Asynchronous transfer mode
BBER — Background block errored ratio
BER — Bit error ratio
BOL — Beginning of life
CCITT — International Telegraph and Telephone Consultative Committee
CDRH — Center for Devices and Radiological Health
CEPT — Conference of European Posts and Telecommunications
DA — Double armored
dB — Decibels
DSF — Dispersion-shifted fiber
EDFA — Erbium-doped fiber amplifier
EOL — End of life
ESR — Errored second ratio
FDA — Federal Food and Drug Administration
FEC — Forward error correction
FIT — Number of failures in 10^9 component hours
HLLB — High loss loopback
IEC — International Electro-technical Commission
ISO — International Organization for Standardization
ITU-T — International Telecommunications Union - Telecommunication Standardization Sector
km — Kilometers
kpsi — Kilopounds per square inch
LWA — Light wire armored
nm — Nanometer
OSI — Open Systems Interconnect
PFE — Power feed equipment
PMD — Polarization mode dispersion, the pulse shape distortion due to a difference in the velocity of light with different polarization
ps — Picosecond
Q — The signal-to-noise ratio (SNR) measured at the decision point
S-R — System-to-receiver optical power
SA — Single armored
SDH — Synchronous digital hierarchy
STM — Synchronous transfer mode
SES — Severely errored second, worse than 10^{-6} error rate
SNR — Signal-to-noise ratio
SONET — Synchronous optical network
SPA — Special applications armor
SSI — Submarine Systems, Inc.
T-R — Transmitter-to-receiver optical power
TAT — Trans-Atlantic Telecommunications
TPC — Trans-Pacific Cable
WDM — Wave division multiplexing
Z-fiber — Pure silica fiber

Table I. Transmission performance objectives for an STM-1 digital line section derived from ITU-TSS Recommendation G.826

Parameter	Performance objective for a 27,500 km international digital path	Performance objective for 500 km portion of an international digital path
Error second ratio (ESR)	0.16	0.0016
Severely errored second ratio (SESR)	0.002	2×10^{-5}
Background block error ratio (BBER)	2×10^{-4}	2×10^{-6}

length, compared to a requirement for the TAT-12/13 cable network of 6.4×10^{-14}/km, a reduction in the allowed error ratio by a factor of 100.

The performance standards driving today's market originated in the needs of services carried on *pleisiochronous*, that is, almost synchronous, digital trunks, such as CEPT-4. Purchasers' requirements reflect the transition of the network toward the synchronous digital hierarchy, and they anticipate the need for asynchronous transfer mode (ATM). The impact of a bit or block error on a service using ATM is currently under study, and purchasers of undersea systems are reducing their risk of not yet being able to support such services by demanding higher levels of transmission performance than those specified from standards like ITU-T Recommendation G.826 alone.

System Availability. *Availability* is the percentage of time when a transmission system is able to carry customer traffic. It is the complement of *outage*, which is the unavailable time, defined as intervals of at least 10 seconds of transmission degradation—enough to cause severely errored seconds (SES), which are worse than a 10^{-6} error rate. For undersea systems, outage does not include unavailable time due to failures in the undersea portion of the system that require ship repairs—for which the *number of ship repairs* is the appropriate metric.

Again, the industry is moving toward ever higher expectations on performance. The outage allocated for a TAT-8 digital line section is 116 minutes per year, or 99.98% availability. The outage allocation for the TPC-5 cable network is 45 minutes per year, and recent requests for quotes for long undersea systems have specified maximum allowed outages that are less than five minutes per year.

As will be described later in this article and in other articles in this journal, AT&T-SSI systems manage outages through automatically switched redundancy in critical portions of the terminal equipment, passive redundancy in undersea amplifiers, and robust design practices for all system elements. With these approaches, transmission performance meets both the *present* and *anticipated* needs of system purchasers and their customers.

Traffic Interface Standards. An undersea system must interface with the domestic communications infrastructures of the countries connected by the system. Until recently, domestic networks were predominantly pleisiochronous, and differences between the coding and multiplexing hierarchies used in different regions of the world precluded simple digital interfaces. To overcome this problem and take advantage of the opportunity for high-capacity digital trunks offered by digital undersea systems, a specialized CEPT-4 "interworking" hierarchy was defined, which requires specialized terminal equipment.

With the advent of the synchronous network, as defined in SDH and the synchronous optical network (SONET) standards, the interface between the domestic networks and undersea systems is moving toward STM-1 (155.52 Mbits/s). This allows standardized equipment to be used within, and interfaced to, terrestrial/domestic networks and international networks. The flexibility of SDH also allows the cable system to efficiently transport traditional telecommunications traffic and new packet-switched data traffic using protocols, such as ATM.

Operations and Maintenance Standards. Previous generations of cable systems were primarily point-to-point systems, with dedicated and unique maintenance systems for the undersea plant and terminal equipment. Modern SDH cable systems are becoming more network-like, that is, architecturally more complex, and maintenance is evolving towards the goal of multi-vendor compatibility, based on the ITU-T Recommendation G.784. The heart of maintenance is the external "Q interface" connected to a flexible data communications network that allows surveillance and control to be performed from virtually anywhere in the world. The Q interface uses the Open Systems Interconnections (OSI) stack and pre-defined protocol suites (G.773) with many available registered SDH managed objects (G.774), that is, hardware and software system elements. It also is anticipated that the evolution of undersea cable systems will generate the need for new classes of managed objects in the future.

AT&T-SSI is defining its SDH cable system management offerings with the intent to leverage from terrestrial systems already in development. However, because most undersea cable system purchasers contractually define management systems in detail, the key to a successful product offering is flexibility and compliance with the relevant recommendations.

Quality Standards. ISO 9001, the "Model for Quality Assurance in Design/Development, Production, Installation, and Servicing," is an international standard for quality systems. This standard provides a model for defining quality system requirements suitable for use in all aspects of a systems supply process, and it is widely adopted in the undersea systems industry. With respect to design issues, ISO 9001 defines how to manage and control the design process and how to assure that the customer requirements are identified and met in the system design. The design, manufacture, installation, and maintenance processes of AT&T-SSI were initially certified to be in compliance with ISO 9001 in 1993, and recertified in 1994.

Environmental and Safety Standards. Customer requirements also cover the protection of personnel from optical, mechanical, chemical, and electrical hazards during the manufacture, installation, maintenance, and operation of a system throughout its life. For repeatered undersea systems, there has been a strong emphasis on electrical safety because of the high voltage levels—7,500 volts for a maximum-length system—required to power a repeatered line. All high-voltage equipment is equipped with key interlocks, which prevent access to hazardous voltages. Cable repairs are usually conducted on cables that are not energized. The exception is the case of branched systems, where special tools and techniques have been developed to repair a branch while the main trunk is still energized so that it can continue carrying traffic.

Aside from processes involving laser trimming and drilling, hazards arising from the exposure to high optical powers have not been an issue for optical transmission systems, due to the relatively low optical powers used and the wavelength of operation. With the advent of optical amplifiers and the higher optical power levels available, however, there has been an increased emphasis on optical safety. Current systems are designed to meet laser safety standards of the U.S. Food and Drug Administration (FDA) and the U.S. Center for Devices and Radiological Health (CDRH), as well as the International Electro-technical Commission (IEC) standards 825-1 and 825-2825-1 and 825-2

System Reliability Requirements. Repairs of the undersea portion of a submarine cable system are very expensive and require many days to complete. For these reasons, purchasers and operators of undersea systems require an extremely high level of reliability in the undersea plant. Traditionally, a 27-year-life transoceanic system should have no more than three ship-assisted repairs caused by spontaneous *component failures*, that is, failures not caused by external factors, and even lower levels are considered highly desirable. External factors include hazards to the undersea cable from trawlers, dredges, anchors, and cable abrasion.

Failures in *terminal equipment* can cause outages and severely errored seconds, as well as requiring the maintenance and replacement of failed components. However, typical terrestrial levels of component reliability, embedded in an adequately duplicated and protection-switched architecture, can limit traffic interruptions to acceptable levels.

External Damage and Power Surge Protection. Although not specifically included under the category of inherent reliability, the wet plant and land cables of an undersea system must be designed and installed to minimize the likelihood of damage by external forces. The differing conditions encountered in various ocean environments dictate that a range of armored cable designs should be available to match the anticipated hazards at any location. This, combined with careful route selection and burying the cable under the seabed in shallow areas, also minimizes failures caused by external aggression.

A cable break in a powered system can cause current surges greater than 200 amperes. Therefore, special circuits are incorporated in the power path of the repeaters to protect the components from being damaged by such a surge. In turn, the power feed equipment (PFE) must not aggravate the surges induced by cable breaks. Indeed, the PFE must protect itself from being damaged by the surge, as well as isolate the undersea plant from transients caused by lightening and power surges on the domestic power grid.

Networking. It is impossible to totally prevent component failures or damage caused by external aggression, and the consequent disruption of services, over an optical transmission path. By using multiple paths within a particular system and interconnecting multiple systems that span the same oceans, protection switching can maintain service for high-priority traffic in the event of a failure in a transmission path. In many cases, protection switching can be done without dropping any high priority calls. The implementation of this capability is discussed further in Zsakany et al. [1] and Liss and Kurek.[2]

Improved Cycle Time. For undersea systems designed using optical amplifiers, the interval between the initial feasibility demonstration and the first transoceanic system installation is less than four years. By contrast, the corresponding interval for the first generation of optical undersea systems was between seven and eight years. Due to the need for increased global capacity, the interval between contract and delivery has also fallen dramatically, from six years to less than one year in some cases. In recognition of these changing marketplace requirements, the development and manufacturing community has adopted concurrent engineering practices and continues to reduce both procurement and manufacturing intervals.

Component and system design, manufacturing process development, and even research may be carried on in parallel to shorten the time between conceptual design and product availability. Program risks are reduced by adopting rigorous change control and organizational structures that enhance communication among all involved. Also, in areas of high technical uncertainty, alternative technologies are developed in parallel to assure that at least one viable solution exists, without the schedule setbacks caused by planned implementations that cannot be made to work. Using these approaches, even fundamental changes in our understanding of the underlying technology can be accommodated during the development and introduction of the current generation of undersea systems.

Installability, Operability and Maintainability. In addition to the technical issues associated with system design, a well-integrated design also must take into account the cost and ease of installation, operation, and maintenance. Discussions associated with these aspects of system design are found in Kordahi et al. [3] and Liss and Kurek.[2]

Architectural Flexibility. As the benefits of undersea fiber optic systems expand, and more countries of the world recognize and act on their need to be tied into the international telecommunications grid, traffic volumes are increasing and patterns are shifting to include new areas of the world. For example, ten years ago, traffic flows warranted the use of undersea cable systems only in transoceanic trunks between major commercial centers and within large developed regions, such as the Mediterranean or China Seas.

Today, more attention is being given to regional and domestic applications in new markets, such as South America and India. In emerging markets, customers are interested in system designs that permit capacity upgrades after installation. On the supply side of this equation, the number of options for capacity and interconnection available through state-of-the-art undersea systems is expanding rapidly. System capacities have increased with the advent of multi-fiber cable/repeater designs, increases in the bit rate from 140 Mbits/s to 5 Gbits/s, and the use of wavelength division multiplexing (WDM) technology[1] to transmit several digital streams over the same optical path.

Undersea branching units (BUs) allow multiple landing sites for a given system, and increased routing functionality within branching units makes possible a diverse set of system architectures to address a wide range of traffic and restoration needs. These traffic pattern and technology shifts lead to a greater variety of customer choices and, therefore, place additional requirements on undersea systems for flexibility and upgrade options.

Tradeoffs. In the previous sections, the characteristics desired by purchasers, and the way these influence design, testing, and manufacture, have been touched upon. It is worth pointing out that, although listed as separate items, they all interact. Thus, new technology permits doing things that older techniques did not permit, such as providing redundancy and compensation for loss changes, without the addition of numerous and complex components. However, the lack of field experience with new types of components means that a given level of reliability is more difficult to demonstrate before the system is installed. One can compensate for this by requiring more qualification and certification testing

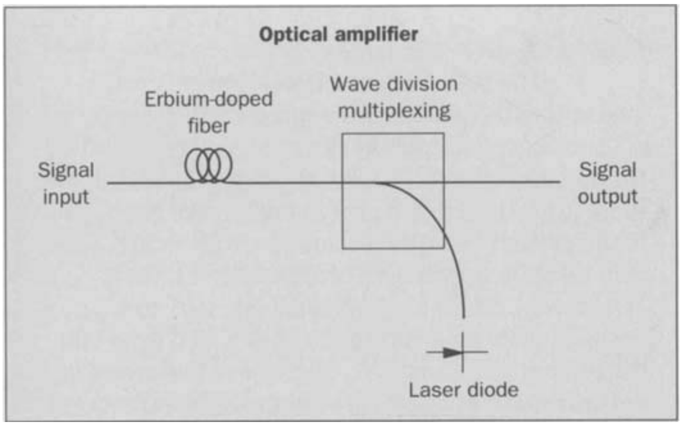

Figure 1. Typical optical amplifier components consist of erbium-doped fiber to provide optical amplification, a laser diode as the source of optical pump power, and a wave division multiplexer to couple the power into the amplifier.

(discussed later in this paper), larger margins for unknowns, and redundancy. On the other hand, if somewhat higher levels of outage are permissible, such as one or two hours per year versus a few minutes, system costs can be reduced by offering the purchaser a terminal with reduced redundancy.

Tradeoffs between transmission quality and reliability are possible by allowing greater or lesser signal-to-noise margins for the various possible impairments. More margins and higher transmission quality can be achieved by reduced repeater spacing or tighter component requirements—but this will, of course, drive up the cost of a system. The system architecture must allow some freedom in tailoring these attributes to the special needs of customers and their applications. In particular, customers need to be made aware of opportunities to reduce their cost by not paying for capabilities or performance levels that exceed their needs.

Developing Undersea Technologies

In parallel with evolving standards and customer requirements, and sometimes because of them, the undersea systems industry has taken advantage of important new developments in the technology. This section addresses some of the key changes in technology that have affected undersea system design. Additional details will be found in Mortenson et al.[4] and Stafford et al.[5]

Optical Amplification and Modulators. The most important of several key developments is the use of erbium-doped fiber amplifiers (EDFA) as high-power output amplifiers for optical transmitters, line amplifiers in undersea repeaters, and low-noise preamplifiers in optical receivers. In non-repeatered systems, the maximum transmission distance can be extended by many kilometers by using remotely pumped optical amplifiers. These amplifiers are a few meters of erbium-doped fiber (EDF) inserted into the transmission path, many kilometers from a terminal, and pumped with 1,480 nm light injected from the terminal. In repeatered systems, optical amplifiers replace the optical regenerators, making possible a repeater that has fewer components, is very reliable, and is bit-rate independent. Most fiber amplifiers in use today are variations on the basic amplifier topology shown in Figure 1.

There are several features of erbium-doped fiber amplifiers that recommend them for use in high-capacity transmission systems. First, they exhibit maximum gain at wavelengths near 1,558 nm, where the loss of optical fibers is near its minimum value. At optical pump powers less than 20 milliwatts (mW), they can be designed to have a wide range of gains and low noise, and their gain is very insensitive to the state of polarization of the signal. The gain medium is a doped-silica fiber, which is inherently stable and can be readily joined to transmission fibers via fusion splices.

Second, an EDFA can be operated so that gain increases with lower input optical power. This feature, called gain compression, is used to make undersea systems robust. Amplifier gain will increase to compensate for loss increases in components or fibers that reduce amplifier input power, thereby helping to stabilize optical signal levels near the design value over the life of the system. Because the physical processes responsible for gain compression are slow, with time constants on the order of one millisecond (ms), gain compression does not affect the optical pulse shape of the transmitted data. Two aspects of EDFA performance are discussed in Panel 2.

In addition to the availability of erbium-doped fiber, the fiber amplifier's success as a system element was made possible by advances in the performance and reliability of high-power injection lasers emitting at 1,480 nm. Packaged devices capable of delivering 10 to 25 milliwatts of optical power into the EDFA are widely available and have been shown to be highly reliable.

Passive components, such as optical couplers, optical filters, and isolators are used in the repeater for directing the signal and pump light to achieve gain, implement performance monitoring, and suppress reflections that degrade transmission. Important advances in these devices have been made in the areas of reduced loss, reduced polarization dependence, and increased reliability.

To get the best optical signal quality, the transmitters in the terminals use external modulation of a single-frequency laser. The source laser is tuned to the minimum loss wavelength of the optical path, which is controlled by the gain peak of the optical amplifier. Great progress has been seen in recent years in the design and manufacturing processes for external modulators, especially in lithium niobate and electro-absorptive modulators. Lithium niobate modulators also can be configured as optical phase shifters, which can be used as polarization modulators. This has become important in addressing transmission impairments caused by the variation of amplifier gain with changes in the signal state of polarization; using polarization modulators in the transmitter, the signal can be conditioned to prevent preferential gain of amplified spontaneous emission in long systems.

Panel 2. Noise in the EDFA

The gain of an EDFA results from erbium ions in the fiber excited into an energy state separated from a ground state by the energy corresponding to a photon in the 1558 nm wavelength band. When there are more erbium ions in the excited state than in the ground state, the erbium-doped fiber exhibits gain through the process of stimulated emission. Whenever there is an erbium-excited ion, however, it can also spontaneously emit a photon and drop into the ground state. Because spontaneous emission is not correlated to the transmission signal, it produces optical noise. This noise can be further aggravated by polarization hole burning, which can preferentially amplify the noise relative to the signal. This effect can be minimized by depolarizing the signal. The signal magnitude must exceed the noise accumulated from all the EDFAs in series by a sufficiently large ratio so that the bit error ratio requirement is not exceeded. How this is achieved is discussed in the section, "Loss and Performance Budgets."

Forward Error Correction (FEC). Forward error correction is a data coding technology that allows the reconstruction of an error-free data set from a coded data set with a low density of bit errors. Its use in the terminals adds an important dimension to the design process for transmission systems, allowing options for improving transmission performance, reducing system cost, and extending the range of possible applications for a given transmission technology. For randomly distributed, independent bit errors and some classes of burst errors, an FEC-coded data stream with a BER of less than 10^{-4} can be decoded into a customer data stream with a BER of less than 10^{-14}. The signal quality at a receiving regenerator required to achieve a BER below 10^{-4} is more than 5 dB less than that required to realize a BER of less than 10^{-14}. In a transmission systems using optical amplifiers, as opposed to systems using optical regeneration, the optical signal quality at the receiving terminal is affected by all components in the optical path. Therefore, these extra dB's represent a resource that can be used by the system designer to achieve better transmission performance, greater repeater spacing (fewer repeaters), greater system length, increased transmission capacity, and relaxed specifications on system components. Therefore, FEC is playing a prominent role in the design of amplified undersea transmission systems.

Fiber Technology. Long amplified systems operate in the 1,550 nm transmission window, using dispersion-shifted fiber (DSF) with a minimum dispersion wavelength close to the operating signal wavelength. Because of the high core index and small core size of DSF, it exhibits higher loss and higher levels of polarization mode dispersion (PMD) than either conventional single-mode fiber or silica-core fiber. Also, its smaller core size tends to exacerbate transmission problems associated with the non-linear optical properties of glass. However, recent advances in the design and manufacture of DSF have dramatically improved all three characteristics: the average cabled fiber loss for DSF is below 0.207 dB/km, PMD has been held below 0.15 ps/$\sqrt{}$km, and the effective area of the core is greater than 50 μm^2.

EDFAs require more splices, involving more types of fiber, than regenerative repeaters, making fiber splicing a critical technology for EDFA manufacture.

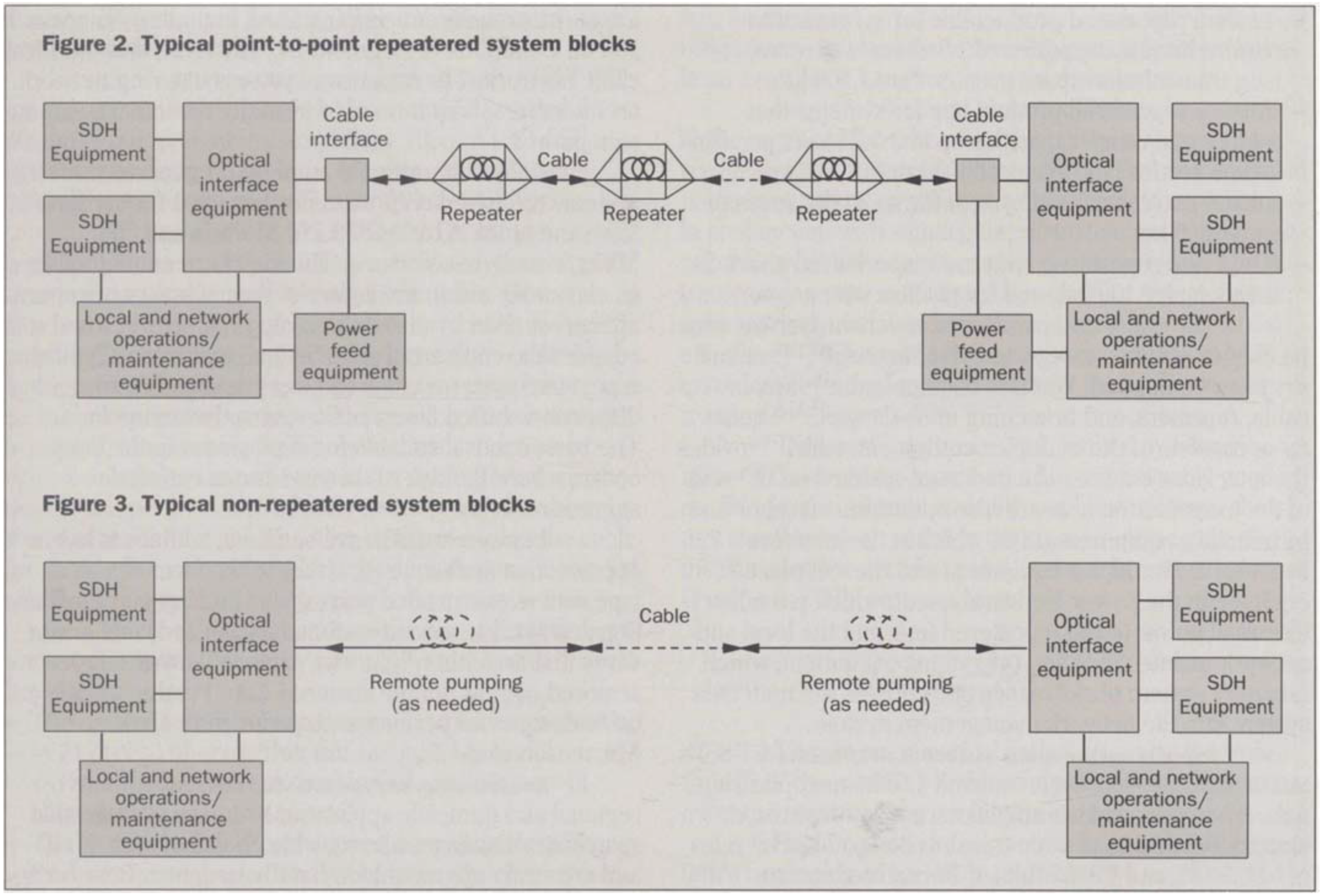

Figure 2. A typical repeatered undersea system consists of the dry plant transmission equipment, optical line equipment, and power feed equipment; and the wet plant undersea optical repeaters and cable.

Figure 3. A typical non-repeatered undersea system, consisting of the dry plant and wet plant, uses neither power feed equipment nor undersea repeaters. For longer systems, an erbium-doped fiber can provide pumped amplification.

AT&T-SSI, working with manufacturers of arc-fusion splicing equipment, have overcome these challenges, while maintaining splice strengths that had formerly been available only from flame-fusion splicing techniques. They also have developed ways to estimate loss due to splicing, greatly facilitating the assembly processes.

Building Blocks and Components

Product Platforms. The goal of AT&T-SSI's design and development work is to deliver system designs that lead the industry in meeting the evolving needs of undersea cable customers. To achieve this, AT&T-SSI's products are structured as platforms, in which each platform represents a set of products targeted to a specific customer or market segment. An accompanying article[1] describes the undersea marketplace as being divided into four segments, or tiers. As implied by the characteristics of the market segments, product platforms addressing the market segments are distinguished by such features as system capacity, transmission distance, and interconnection capabilities. The AT&T-SSI products that address these markets are:

- SL2000, a repeatered product line for systems that require bit rate capacities of 2.5 Gbits/s or more, and long transmission spans greater than 1,500 km.
- SL1000, a repeatered product line for systems that require mid-range capacities up to 2.5 Gbits/s per digital line section, and spans of 300 km to 1,500 km.
- SL100, a non-repeatered system for short distances of under 500 km.
- SL50, a non-repeatered system for specialized short distances under 100 km, and for shallow water.

The major components of undersea systems can be divided into two categories: *Wet plant* equipment and *dry plant* equipment. Wet plant equipment consists of cable, repeaters, and branching units. Dry plant equipment consists of the multiplex equipment, which provides the interfaces between the undersea system and the rest of the transmission network; the optical interface, or line terminating equipment (LTE), which is the interface between the multiplex equipment and the wet plant equipment; the power feed equipment, which provides electrical power to the repeatered line; and the local and network maintenance and operations equipment, which monitors system performance and couples the undersea system into the network management system.

Repeatered Products: SL2000 & SL1000. AT&T-SSI's SL2000 and SL1000 products transmit 1,558.5 nm optical signals, erbium-doped fiber amplifiers, and low-loss dispersion-shifted fiber to provide transmission paths at bit rates of 622, 2,488, and 4,976 Mbits/s. Repeatered system lengths range from 300 to 9,000 km (See Figure 2). Details on how the wet plant and dry plant equipment function in repeatered systems can be found in Mortenson et al.[4]

With optical amplifier technology, regeneration occurs only at the terminals. Undersea repeaters provide only optical gain, which compensates for the attenuation of the transmitted signal as it propagates through the cabled fiber. This makes for a transparent transmission medium so that the capacity of these systems can be upgraded after system installation without repeater replacement, if adequate signal-to-noise margin is incorporated into the design of the undersea plant. The reduced number of devices, types of devices, and complexity of devices and subsystems in the current repeater supports more stringent objectives for system reliability than could be justified in regenerative undersea systems.

Several SL2000 systems have been installed or are in the process of being installed, including Americas 1 North, Columbus II (Segment B), TAT-12/13, and the TPC-5 cable network. The latter two systems use ring network architectures, which provide spatially diverse transmission paths.[1]

Cables for optically amplified regenerated systems are based on proven designs used for earlier SL280 and SL560, AT&T- SSI's 280 Mbits/s and 560 Mbits/s undersea systems. The fibers are embedded in an elastomer within the center of the cable structure, and are surrounded by ultra-high-strength steel wires and a copper tube encased in polyethylene insulation. Typical repeatered systems use a cable containing four to eight dispersion-shifted fibers as the transmission medium. The basic cable is suitable for deployment in the deep ocean, where the risk of damage due to external aggression is low.

In more hostile environments, additional layers of protection are required, either in the form of a steel tape with over-extruded polyethylene for special applications (SPA) cable, or conventional galvanized steel armor wires that are either light wire armored (LWA), single armored (SA), or double armored (DA). Further details on cable design and performance parameters are in Mortenson et al.[4]

Non-Repeatered Products: SL100 & SL50. Many regional and domestic applications require systems that span short distances, allow a wide choice of capacities, and are easily upgradable to handle larger traffic volumes as demand increases. Historically, non-repeatered systems have spanned distances from 100 to 150 km and operated at maximum bit rates of less than several hundred megabits per second, but offered customers the advantages of lower cost, higher reliability, and upgradability. To meet customer needs, AT&T has developed the SL100 and SL50 product lines to extend terrestrial transmission capabilities to non-repeatered undersea applications. SL100 systems being introduced in the future will be capable of spanning over 350 km for 622 Mbits/s systems, over 275 km for 2.5 Gbits/s systems, and over 250 km for 5 Gbits/s systems.

SL50 systems are designed for specialized applications that include span lengths under 100 km and at a bit rate of 155 Mbits/s, where the goal is modest performance at minimum cost. The basic offerings of SL100 and SL50 systems use standard terrestrial terminals and maintenance systems, and low-loss fiber in high-performance, low-cost undersea cable.

SL100 systems can be configured with AT&T-SSI's optical preamplifiers, power booster amplifiers, and remotely pumped optical amplifiers. All of AT&T-SSI's systems are design to operate for more than 25 years, virtually error- free, and with over 99% availability.

Figure 3 shows a block diagram of a non-repeatered system. As previously mentioned, the wet plant equipment typically consists only of the cable. However, SL100 systems can be configured with a remotely pumped amplifier, a short length of erbium-doped fiber embedded in the cable. The non-repeatered dry plant equipment, similar to the repeatered system with the exception that no PFE is needed, may contain high-powered optical pumps to drive a remotely pumped EDFA in the cable. Details on the design and performance of non-repeatered systems can be found in Stafford et al.[5] The fiber designs used in the cable for these systems can be selected, depending on line speed and length, to minimize dispersion or to minimize loss.

The basic cable structure for non-repeatered systems is similar to that of repeatered systems, with several key exceptions:

- The optical core has been designed to accommodate up to 24 optical fibers within the same dimensional space as the core for the SL2000 cable. Future designs will allow for the use of 48 fibers;
- The quantity of steel and copper, as well as the jacket thickness, and, hence, the cable strength, conductivity, and diameter have been reduced.

Non-repeatered cables are also offered with a variety of additional protective layers to accommodate various ocean-bottom environments.

Performance and Operation

System Performance. As discussed previously, AT&T-SSI's systems are designed to provide transmission performance to meet or exceed the requirements of the international telecommunications industry. Designs are *qualified* during development, and every component used in a system is individually *certified* to perform as required.

Performance degradations can be caused by the terminal equipment or the undersea equipment. For terminal equipment, including power feed equipment, the principal source of performance degradation is a component failure, which requires the substitution of a spare subsystem for the failed subsystem. For terminals with built-in redundancy and automatic switching, each failure results in an average of 1.1 severely errored seconds.

Random bit errors are most likely to be generated in the regeneration process of the optical receiver, which terminates the undersea optical path. Optical and electrical noise from optical amplifiers and electronic components, in conjunction with signal pulse distortion, corrupt the signal delivered to the regenerator's decision circuit. The transmission path is designed by selecting repeater and cable characteristics to limit these degradations in a cost-effective way. The goal is to keep the probability of a bit error less than the limit derived from the system performance requirements.[4]

For a system where BER is limited by Gaussian noise at the decision circuit, which is a reasonably good model of well-designed optically amplified systems, the BER is related to Q, which is the signal-to-noise ratio (SNR) measured at the decision point. BER can be estimated from Q using the following equation:

$$BER \approx \frac{1}{Q\sqrt{2\pi}} \varepsilon^{\frac{-Q^2}{2}}$$

Margin on an optical path is given by the ratio (in dB) of the actual Q to the minimum Q required to meet the transmission performance requirements.[4]

Each system is designed to have a Q at the system's beginning of life (BOL) large enough to allow for system aging and repairs that degrade the optical path. Repeatered systems also have an allocation of 1 dB of margin at the system's end of life (EOL), which adds to the cost, but protects the purchaser from a significant error in performance modeling, or any unanticipated source or amount of degradation.

Robust System Design. The achievement of extremely high reliability in the undersea plant is greatly facilitated by a robust system architecture. AT&T-SSI's systems are tolerant to general aging, that is, small changes in many components, and are self healing, that is, they can absorb large transmission changes in a small number of components. As described previously, optical amplifier systems provide this kind of robustness by operating with the amplifiers in compression.

Redundancy in the undersea plant can avoid the need for a ship repair—even in the case of the total failure of a component. The likelihood of a ship repair equals the square of the probability of a failure in a component protected by redundancy. That is, if there is a 1% probability that a single pump will fail in 25 years, the probability that an amplifier pair will fail and require a ship repair is 0.01%. This is because amplifiers are driven by a pair of pump lasers. Optical amplifier technology permits redundancy protection of the pump laser, and the associated electronics, without requiring switches, supervisory command channels, or any other additional components beyond one optical coupler per amplifier pair in each repeater. The gain decrease associated with a single laser failure is compensated for by the action of subsequent amplifiers operating with gain compression, as described previously.

Compared to regenerative system technology, optical amplifier technology reduces the number, types, and complexity of components required in a repeater, helping achieve an extremely high level of system reliability for the customers.

High Reliability in Components. While a robust architecture helps achieve high system reliability, it does not eliminate the need for components with very low probabilities of failure. This is achieved by designing components with very large margins between the stresses that can cause failure and the stresses they will encounter in use. *Qualification* testing of designs verifies that the margins have been achieved, and looks for unanticipated failure modes so they can be eliminated. Accelerated testing at high temperatures, temperature cycling (typically between -40°C and + 85°C), vibration, shock, and operation at optical powers far exceeding those expected, are examples of stresses that can be used to verify high reliability.

During manufacturing, *certification* tests screen 100% of the product against performance requirements, by eliminating any individual units or batches of units that do not meet the design due to some abnormality in materials or fabrication.

An important element in achieving high system reliability is minimizing the likelihood of fatigue failure in optical fibers within the cable and repeaters. This is achieved by using fibers and splices that have been tested to 200 kilopounds per square inch (kpsi) and by cable designs and installation procedures that minimize the occurrence and magnitude of residual stresses in the optical fiber.

For all components, qualification testing using optical powers, temperatures, temperature cycling, and mechanical shock and vibration at levels far exceeding worst case use demonstrated the components' ability to meet the requirements with margins for variations and uncertainty. During certification testing, similar tests at somewhat lower stresses are applied to all units that are candidates for undersea use. The various types of components are discussed individually in the following paragraph.

For the pump laser, the most important failure modes that must be controlled to acceptable levels are:

- Snapping, a catastrophic thermal runaway mechanism originating at dark spots in the active region of the laser;
- Chip aging, decreasing efficiency in generating light; and
- Package aging, changes in the efficiency with which light is coupled into the fiber pigtail.

Three concerns associated with the erbium-doped fiber amplifier are darkening, or reduced gain, as a result of high optical power densities; ionizing radiation from the sea bottom; and diffusion of hydrogen into the fiber. Again, by using overstresses that far exceed operating levels, adequate stability can be demonstrated. In the case of hydrogen-induced darkening, a desired enhancement of the margin is achieved by carbon coating the fiber—which greatly decreases the hydrogen diffusion rate. As with all fiber, static fatigue is a concern for EDFAs. This is controlled by proof testing to verify minimum strength, using packaging hardware that protects against residual stress, and using carefully controlled assembly procedures to protect against handling damage.

With the other optical components (couplers, isolators, and filters) dimensional stability, achieving high strength and low residual stress, and carefully controlled handling during assembly, lead to high reliability. For these components, temperature cycling and, to a lesser degree, mechanical vibration appear to be the most effective accelerant tests, and these were used for qualification and certification testing.

Reliability Budget. The design, qualification test results, and robust system architecture in which the components are embedded, are compatible with the assignment of very low failure rates to the components. Table 2

Table II. FIT allocation to SL2000 wet plant subsystem

Subsystem	Unit	Number of units per subsystem	Average[1] FITs per unit	Average[1] FITs per amplifier pair	Average[1] FITs per repeater section	Ship repair per repeater section
Erbium-doped fiber amplifier (EDFA) module	Erbium-doped fiber module	1	0.1	0.2		
	Wave division multiplexing	1	0.1	0.2		
	Isolator	1	0.1	0.2		
	Splices[2]	5	0.05	0.5		
Pump unit	3 dB coupler	1	0.1	0.1		
	Pump filter module	2	0.1			
	Pump laser module	2	46			
	Splices[2]	4	0.05	0.51[6]		
	Integrated circuits[4]	2	1.0			
	Capacitors[4]	32	0.05			
	Power transistors[4]	2	0.1			
	Film resistors[4]	80	0.01			
	Power resistors (film)	2	0.01	0.02		
	Circuit board/solder joints	1	0.1	0.1		
	Zener diode[5]	1	0.1	0.1		
Loopback coupler module (LCM)	Loopback line coupler	2	0.1	0.2		
	Loopback path coupler	2	0.1	0.2		
	Splices[2]	5	0.05	0.25		
Other repeater elements	Other splices[2] (per amplifier pair)	4	0.05	0.2		
	Mechanical integrity and moisture exclusion	1			1.5	
Cable and couplings	Fiber path, including splices[3]			0.2	0.8	
	Power path				2.5	
Subtotals				2.98	4.8	
Total, for 1 pair					7.78	0.0017
Total, for 2 pairs					10.76	0.0024
Total, for 3 pairs					13.74	0.0030
Total, for 4 pairs					16.72	0.0037

1 Averaged over the 25 years service life of the system.

2 Fiber splice plus fiber length to adjoining components.

3 The per-amplifier pair allocation is for cable-to-repeater coupling fiber splices and associated fiber length (4 x 0.05 FITs = 0.2 FITs). The per-repeater allocation is additional for risk of delayed fiber fracture in cable kinks.

4 One integrated circuit, 1 power transistor, 11 film resistors, and 4 capacitors per pump unit (there is one pump unit per amplifier pair) are left out of the table and neglected for reliability analysis because they perform filtering for the electroding function, which is used only for near-shore fault location. A failure in the electroding filter circuit could cause a small signal-to-noise degradation of the main signal, but that would only occur at the time of electroding.

5 Failure rate specified is for open and short circuit failure. All the risk is assumed to be for shorts that cause a system failure. Open circuit failure is less severe since it causes a loss of surge protection, which is a problem only when a cable break (which dictates a ship repair event) occurs near the repeater (estimated vulnerability region is within 10 repeater sections) with the open zener.

6 Considering redundancy. This value is obtained by summing all FITs associated with the redundant components (97 FITs), dividing by 2 (48.5 FITs), converting to probability of failure by multiplying the number of hours in 25 years (0.0106), squaring (0.000112), and converting the resulting number back to FITs by dividing by the number of hours in 25 years (0.51 FITs)

Table III. Example of TAT 12/13 interlink loss budget

Item	Loss/gain	Nominal	Units
1	Cabled fiber loss plus splices and connectors	44.5	dB
2	Transmitter output power	17.0	dBm
3	Receiver sensitivity	-35.9	dBm
4	Transmitter-to-receiver (T-R) power (item 2 – item 3)	51.9	dB
5	Terminal margins (dispersion, etc.)	0.5	dB
6	System-to-receiver (S-R) power (item 4 – item 5)	51.4	dB
7	Beginning-of-life (BOL) margin (item 6 – item 1)	6.9	dB
8	Repair margin	3.6	dB
9	Equipment and cable aging	2.3	dB
10	End-of-life (EOL) margin [item 7 – (item 8 + item 5)]	1.0	dB

summarizes the failure rates, expressed in FITs = number of failures in 10^9 component hours, allocated to each component type. The allocations are combined to obtain the ship repairs in 25 years per repeater, which is given in the lower right-hand corner of Table 2. The allocations are combined, taking into account the impact of redundancy and the numbers of components in a repeater section. (Redundancy reduces the 97 FITs in the pump units for a span pair to an effective FIT rate of 0.51. Obviously, the numbers of components in a repeater section depend on the number of fiber pairs in the system—from one to four.) Thus, a maximum-length system with 270 repeaters and two transmission pairs would give 270 *x* .0024 = 0.65 expected ship repairs. This falls well below the normal limit of 3 repairs, to provide a very high likelihood that the number of ship repairs caused by component failure will, indeed, fall below the specified upper bound, even in early installations of the new technology.

As manufacturing and installation experience accumulates, improvements will be introduced where necessary, and the likelihood of achieving *no* ship repairs in the 25-year life of the system will be within grasp. This is because an expected value of 0.65 ship repairs corresponds to a probability of 0.5 that no ship repair will be required, and a 0.86 probability that no more than one ship repair will be needed.

Terminal Protection. As mentioned previously, a primary metric for the customer is the availability of transmission paths. In general, the multiplex, transmitting, and receiving terminals are fully duplicated and protection switched, so that a failure does not result in an outage.

For repeatered systems, terminals also must provide the power required to operate the lasers in the undersea repeaters. The PFE typically delivers a constant current of .92 amperes down the power conductor of the cable, powering the repeaters in series. Allowing for earth potential, a maximum length system can require +7,500 volts at one terminal and -7,500 volts at another. Such systems use fully redundant PFE at each end. Shorter systems capable of being powered at one end—without exceeding the maximum voltage capability of a PFE—still are normally powered from both ends, but usually without PFE redundancy within a terminal. Redundancy is provided by the fact that if one PFE fails, the other takes over the entire load.

Double-ended powering also permits balancing out the voltage at the location of a shunt fault (an insulation breakdown between the power path and the ocean) to give approximately 0 volts relative to the ocean. This enables the fault to be accurately located and allows the system to continue carrying traffic during the days the repair is planned and the ship is sailing to the fault site.

Loss and Performance Budgets

The central tool for designing an undersea system is the performance budget, which lists the principal degradation mechanisms and shows the impact of each mechanism on margin.

Non-Repeatered Systems. In non-repeatered systems, degradation mechanisms can be identified with optical losses or equivalent losses, and the standard format for the performance budget is an optical loss budget. SL100 systems are designed to operate for more than 25 years without degradation of the optical signal and to meet the CCITT's recommended system performance requirements. The result is an optical signal performance, throughout the system life, which is better than 10^{-11} bit errors per second.

To achieve this, a detailed optical power budget is prepared before the system is installed. It assures that the proper equipment is selected to meet this 25-year requirement. This represents the budgeted "requirements" for the

Table IV. SL100 terminal equipment maximum outside plant losses

Equipment	622 Mbits/s	2.5 Gbits/s	5 Gbits/s
Standard terminal equipment	Up to 64 dB	Up to 57 dB	Up to 54 dB
Standard plus forward error correction (FEC)	Up to 68 dB	Up to 61 dB	Up to 58 dB
Standard plus FEC and remote pumping	Up to 78 dB	Up to 71 dB	Up to 68 dB

manufacture, assembly, and installation of the system.

As the equipment is manufactured and before it is installed, therefore, each subsystem (terminal equipment and cable) is measured to verify and certify that the system meets the budgeted requirements. Table 3 gives a representative loss budget for a non-repeatered system, in this case a 5 Gbits/s system, 170 km in length.

To prepare the power budget, the following steps are taken:

- First, the customers' requirements are identified for system span length, bit rate, terminal and cable installation environments, as well as for number of repairs.
- Second, based on the span length and bit rate, a fiber type and its associated attenuation/loss (this parameter includes fiber production splices, but not installation splices) and dispersion parameters are selected. For example, SL100 supports low-loss (less than 0.19 dB/km at 1550 nm) silica-core fibers, germanium-doped fibers (greater than 0.21 dB/km at 1550 nm), and dispersion-shifted fibers (less than 1 picosecond [ps x nm/km]). The product of the span distance and the selected fiber loss yields the budgeted loss associated with the total length of the supplied cable. After manufacture, each of the cable section losses are measured and compared to this budgeted loss to assure that the cable can be assembled and installed.
- Third, the number of splices, both undersea and land, and connectors, that is, optical distribution panels, terminal connectors, etc., are identified and associated losses are added to the cable loss. The resultant number yields the budgeted losses associated with the "outside" plant.
- Fourth, based on the budgeted outside plant losses, terminal equipment is selected to handle these losses. Depending on the bit rate and equipment used (see Table 4), SL100 terminal equipment provides a range of transmit-to-receiver (T-R) powers to accommodate various amounts of outside plant losses. Terminal equipment allocated margins, such as dispersion penalty, temperature variation penalties, etc., are subtracted from the T-R to yield the system-to-receiver (S-R) power, the maximum outside plant losses the terminal can handle. The actual manufactured terminal data is collected and compared to the budgeted terminal S-R to assure that the terminal equipment has been manufactured properly.
- Fifth, the difference between the terminal S-R and the outside plant loss yields the budgeted beginning-of-life margin. Obviously, the BOL margin must be greater than zero for the system to operate properly over its life, accounting for the expected aging margin. The BOL margin for the actual installed system is measured and compared to the budgeted BOL margin to certify that the system has been assembled and installed properly.
- Next, the allocated margin is calculated for the customer's repair requirements. This is based on the extra cable and splices needed to make repairs within the various water depths of the system. For non-repeatered systems employing FEC and remote pumping, margin allocations for repairs cannot be determined by adding the losses of the extra cable and splices; sophisticated computer simulations and laboratory experiments are required to develop effective loss budgets.
- Finally, the allocated margin is calculated for the aging of the cable and equipment (from the manufacturer's specifications). The allocated margins for repair and aging is then subtracted from the BOL margin to yield an end-of-life margin, which must be greater than zero for the system to reliably perform satisfactorily.

Repeatered Systems. In repeatered systems using optical amplifiers, the performance budget cannot be expressed as a simple optical loss budget. Unlike systems using regenerative repeaters, the optical path accumulates degradations over its entire length. Optical noise is added in each repeater, and optical non-linearities in the transmission fiber can distort pulses and cause mixing between the signal and noise. The result is a very complicated relationship between the system component characteristics and the SNR or Q at the input to the receiving regenerator's decision circuit.

Table V. Nominal beginning-of-life (BOL) design parameters for the 5.0 Gbits/s optical transmission paths of 4,500 km system without forward error correction (FEC)

Parameter	Symbol	Units	Nominal	Range
Operating wavelength	λ_s	nm	1558.5	+/– 0.25 nm
Gain peak wavelength	λ_{pk}	nm	1558.5	+/– 0.50 nm
Zero dispersion wavelength	λ_o	nm	1558.5	+/– 0.40 nm
Repeater output power	P_{out}	dBm	3.5	+/– 0.50 dB
Repeater spacing	L_s	km	50.0	+/– 5.0 km
Cabled fiber loss	L_f	dB	10.3	+/– 1.0 dB
Repeater input power	P_{in}	dBm	–6.9	+/– 1.5 dB
Repeater noise figure	NF	dB	6.0	+/– 0.5 dB
Receiver optical filter bandwidth	B_o	nm	2.0	+/– 0.25 nm
Number of repeaters	N	#	89.0	+/– 3

The starting point in the design of the optical path is the estimate of the optical signal-to-noise ratio, SNR_0, at the detector for an optical section (path). SNR_0 is given by the following equation:

$$SNR_0 = \frac{P_{in}}{NF h\nu B_0 N}$$

where P_{in} and NF are the average input optical power and noise figures, respectively, of the repeaters; $h\nu$ is the energy of a photon at the signal wavelength (1.28×10^{-19} Joules for wavelength = 1558.5 nm); and B_0 is the optical bandwidth, in Hertz (Hz). Humblet and Azizoglu[6] derived the following relationship between SNR_0 and Q:

$$Q(dB) = 20\log \frac{2SNRo\sqrt{\frac{Bo}{Be}}}{1+\sqrt{1+4SNRo}}$$

The ideal Q, derived from system design parameters using these two equations, does not account for many degrading factors, including signal/noise mixing through non-linear effects in the fiber, interference from optical power leaked between fiber paths through the high-loss loop back (HLLB) paths in the repeater, reflections, and imperfect transmitter and receiver characteristics. An effective design methodology to account for these effects is to allocate degradations (expressed in dB of Q) to each mechanism, subtract these allocations from the ideal Q described above, and compare the results to a minimum acceptable Q derived from a BER objective. The BER objective, in turn, is derived from the customer's requirements on errored seconds ratio (ESR) or background block error ratio (BBER). The summary of allocated degradations is called an impairment budget. Tables 5 and 6 illustrate the design parameters for a system and the associated performance budget. Here is the scope of some of the impairments listed in the performance budget table.

Line 2: Interactive impairments include all penalties to average performance present in a laboratory experiment, namely: nonlinearities in the transmission fiber, noise caused by reflections at the inputs and outputs of the erbium-doped fiber amplifiers, finite extinction ratio, receiver timing offset, receiver baseline wander, receiver noise (excluding preamplifier noise), and intersymbol interference.

This impairment is a combination of several important effects which, together with ASE noise (see Panel 2), dominate system performance. The impairment is calculated using a modeling tool that has been validated using data accumulated on various test bed experiments.

Line 7: Transmitter/receiver design margins include potential system performance degradations from pattern-dependent transmitter/receiver performance, offsets between the receiver decision threshold and the optimum decision threshold, and noise generated by the receiver optical preamplifiers.

Table VI. Performance budget for the 5.0 Gbits/s optical transmission path

	Parameter	Value or penalty (dB)
1	Ideal Q (dB)	30.51
2	Interactive impairments	–7.87
3	Fluctuation impairment	–0.84
4	Worst case non-impaired Q (sum of items 1, 2, 3)	21.80
5	Beginning-of-life (BOL) impairments	
6	Line design margin	–1.00
7	Transmitter/receiver design margin	–0.88
8	Wavelength range impairment	–0.10
9	Loopback path impairment	–1.29
10	Supervisory modulation impairment	–0.20
11	Expected BOL performance (sum of items 4 – 10)	18.33
12	Unallocated margin	–0.54
13	Minimum BOL performance (item 11 + 12)	17.79
14	End-of-life (BOL) impairments	
15	Line aging	–0.24
16	Transmitter/receiver aging	–0.42
17	Repairs	–0.01
18	Minimum EOL performance (sum of items 13 – 17)	17.12
19	Q performance objective for BER = 8.2×10^{-11}	16.12
20	Minimum BOL margin (item 13 – item 19)	1.67
21	Minimum EOL margin (item 18 – item 19)	1.00

Line 9: Loopback path impairment is the system performance degradation that results from the presence of loopback paths in all repeaters.

Line 15: Line aging is the sum of system performance penalties associated with systematic and random changes in repeater gains and cabled fiber span losses. The dominant contributors to this impairment are loss increase in the cable fiber with time, failure of one pump in one or more pump units, and localized increases in loss of several dB in a small percentage of passive optical components.

Line 17: Repair margin is included to allow for added cable and splices along the transmission path, in accordance with the required repair allowances. The required repair allowance is derived from the customer's requirements on the number and type of repairs that must be covered in the system design.

Conclusions

The new generation of undersea systems is implemented by optical amplifier technology, which offers a wide range of capacities, unprecedented levels of transmission quality and reliability, and the possibility of upgrading, that is, increasing transmission capacity by means of changing terminal equipment only. In applications ranging from short, non-repeatered connections to transoceanic networks, this technology provides a versatile and cost-effective platform for constructing the world's communication network.

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