Undersea Non-Repeatered Technologies, Challenges, and Products

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Non-repeatered undersea lightwave transmission links, whose signals don't require periodic amplification or regeneration, have historically been deployed:

- As part of larger, undersea networks that use repeaters, and
- In domestic non-repeatered systems installed either between islands or looping a shoreline.

With the world's transoceanic cable network rapidly expanding into a global undersea network—and transoceanic systems connected to regional systems, which are then connected to domestic systems—the market is moving towards an increased percentage of short-haul, non-repeatered systems. This paper discusses:

- The technologies and products AT&T Submarine Systems, Inc. (AT&T-SSI) is developing for this market,
- Future trends in non-repeatered technology and system design, and
- Actual and planned system deployment of undersea optical cable throughout the world.

Introduction

Advances in optical amplifier technology have paved the way for deploying increasingly long-length, high-capacity transmission systems without using the active optical-electric undersea components typically found in repeatered systems. The first commercial undersea non-repeatered lightwave system, which was installed in the Far East in the late-1980's, used state-of-the art technology to carry 417 Mbits/s of traffic over 104 kilometers (km). Laboratory demonstrations now have 5 Gbits/s signals traversing over 300 kilometers, or a bit-rate-distance product of more than 1,500 Gbits-km/s (5 Gbits/s x 300 km), and systems will soon be installed around the world with bit-rate-distance products approaching this level.

Customers of undersea systems see many advantages of non-repeatered systems over repeatered systems—particularly increased reliability, compatibility with terrestrial systems, upgradability, lower cost, and simpler maintenance. As a result, these systems are now competitive with other transmission systems, including domestic land-based networks, regional radio networks, satellite links, and undersea repeatered links. The developing technologies to support this rapidly evolving and competitive non-repeatered market provide new insights into optical transmission theory, and offer developers significant challenges to increase product performance, decrease cost, and improve delivery schedules.

Non-repeatered Design and Architecture

Non-repeatered systems have a few unique requirements, above and beyond the standard undersea system requirements for high performance, reliable transmission, and

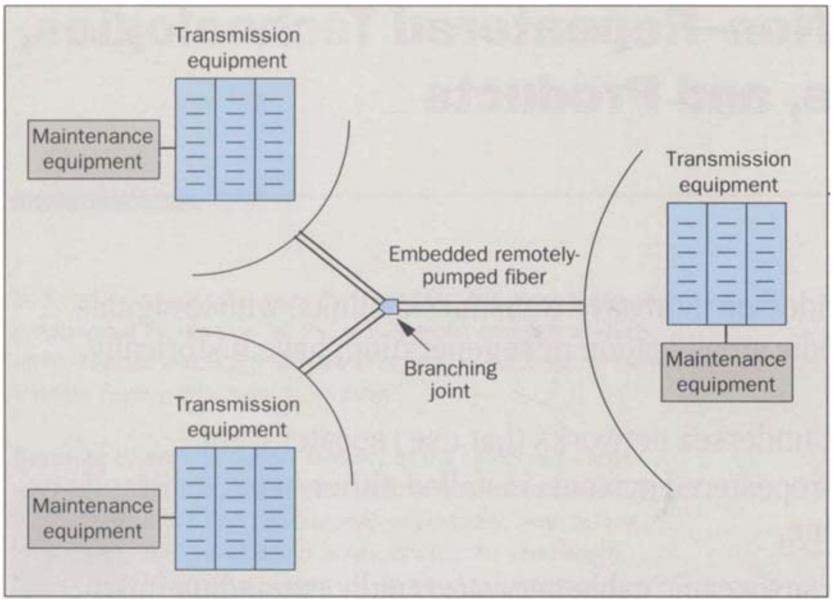


Figure 1. A non-repeatered undersea system basically consists of wet plant and dry plant equipment. The wet system includes the cable—with fiber and associated cable interconnection hardware, such as cable and passive branching joints—deployed between the system's landing points. The dry equipment, located in the land-based terminal station, consists of transmission and maintenance equipment.

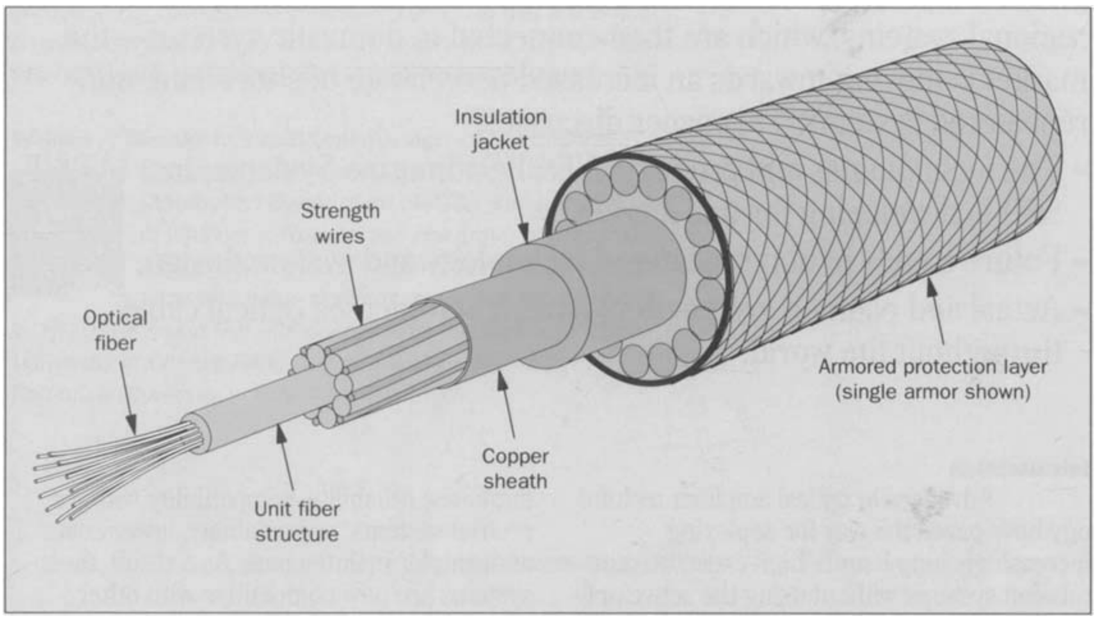


Figure 2. Typical elements of a cable design are the unit fiber structure (UFS), which contains optical fibers; strengthening wires, which provide stiffness and prevent fiber stretching during handling; copper sheath, sometimes used for power conduction during fault location; Insulation jackets for protection against water seepage and, finally, armored protection layers.

minimum maintenance.

- First, capacity upgrades are common, even years after the initial system deployment. This requires very flexible equipment designs.
- Second, most non-repeatered systems are deployed in shallow water. Hence, the cable design can be geared towards lower strength and, thus, reduced cost.
- Finally, since non-repeatered systems are becoming more typical of the complex regional and domestic systems that connect many landing points, the system architectures are becoming more complex, from the standpoint of network protection, than those of the more traditional repeatered systems. Thus, non-repeatered systems require more sophisticated network management systems.

A non-repeatered undersea system basically consists of *wet plant* and *dry plant* equipment. The wet system consists of the cable—with fiber and associated cable interconnection hardware, such as cable and passive branching joints—deployed between the system's landing points (see Figure 1). The dry equipment, located in the land-based terminal station, consists of transmission and maintenance equipment. For both the wet and dry equipment, AT&T SSI has developed a platform of products that can be customized for specific customer applications.

A primary challenge of this market is to develop a platform that can provide cost-effective customer solutions. The cost and performance, such as bit rate, transmitter spectral quality, transmit terminal output power, etc., of terminal equipment must be balanced against the

Panel 1. Acronyms and Terms Used in This Paper

ADP — Avalanche photo diode
BER — Bit error rate
BU — Branching unit
CCITT — International Telegraph and Telephone Consultative Committee
dB — Decibel, optical power (relative)
dBm — Decibel, optical power (actual in milliwatts)
Dispersion — Optical signal velocity variation. A function of fiber physical characteristics and wavelength frequency. Leads to optical signal distortion.
DS — Dispersion shifted
FEC — Forward error correction
ITU-TSS — International Telecommunication Union - Telecommunication Standardization Sector
km — Kilometers
MQW — Multi-quantum well
MTBF — Mean time between failures
OTDR — Optical time domain reflectometer
Raman effects — Spontaneous amplification of the transmitted signal within the fiber at higher power levels.
SDH — Synchronous digital hierarchy
SONET — Synchronous optical network
SSI — Submarine Systems, Inc.
UFS — Unit fiber structure
WDM — Wavelength division multiplexing
Zero-dispersion wavelength — Frequency at which no dispersion occurs, determined by the physical characteristics of the optical fiber.

cost and performance of fiber, such as loss in decibels (dB) per km, dispersion characteristics, etc. For example, the lowest-loss fiber has a measurable dispersion penalty over the longest distances. This, therefore, requires better transmitters, especially at the higher bit rates, where dispersion is more of a factor. In response to this need, an expert system has been developed by SSI to define the optimal solution for any given application.

Engineering a customer's non-repeatered system to provide high-performance and virtually error-free transmission is a somewhat complicated task. The typical methodology for designing the span is to select various possible architectural options to meet specific span-length and capacity requirements. A loss budget is used to confirm adequate transmission. It simply adds up the cable dB losses, including margins and penalties, between the transmitting and receiving terminals and compares them to the available power and sensitivity of the terminal equipment.[1]

Some of the newer technologies being deployed in undersea non-repeatered systems, however, such as forward error correction (FEC) and remote pumping, which will be described later, preclude engineering a span simply by adding up the dB. Today, sophisticated modeling by computer simulation and laboratory experiments is required to develop the proper transmission budget.

Table I. Fiber type options

Transmission fiber type	Cabled loss (dB/km)	Dispersion (ps/nm-km) at 1,550 nm
Silica-core	< 0.180	20
Germanium-doped	< 0.199	18
Dispersion-shifted	< 0.210	–0.75

dB/km - Decibel/kilometer
nm - Nanometer
ps/nm-km - Pulses per second/nanometer-kilometer

The transmission technologies supporting state-of-the-art, non-repeatered, undersea lightwave systems include fiber, high-performance transmitters and receivers, forward error correction, dispersion compensators, tracking filters, and, most importantly, erbium-doped fiber amplifiers (EDFA) acting as post-amplifiers, pre-amplifiers, and remotely pumped amplifiers. Each of these technologies is discussed in two subsequent sections of this paper, "Transmission Terminals" and "Cables for Non-Repeatered Systems."

Supporting these transmission technologies are the marine technologies. Lightweight, transportable, high fiber count cable designs, which can be deployed and maintained with what are called local ships of opportunity, as opposed to highly specialized cable ships, are critical to reduce the costs of non-repeatered systems. Many potential owners of non-repeatered systems do not own cable ships, and would have to purchase these services to install and repair their systems. In other cases, the use of cable ships, even if available, is not an effective option. Instead, non-traditional vessels, such as small ships or barges, are a better choice for installing and repairing a system.[2]

Maintenance technologies for non-repeatered systems include network management systems, which monitor the alarms and error performance of the system,[3] plus wet-plant monitoring and fault location systems. The network management systems for non-repeatered applications should be compatible with terrestrial network management systems, since the undersea and terrestrial systems may be maintained by the customer as one integrated network.

Table II. Cable type options

Cable type	Applications	Features and advantages
Deep water (LW)	• Benign, sandy bottom • Depths to 4,000 meters	• Core cable, light protection • Least expensive
Special applications (STP)	• Somewhat rocky bottom • Risk of fish gnawing • Depths to 3,000 meters	• Metallic tape, and second polyethylene outer jacket applied over core • Additional abrasion protection • Additional cost
Armored (SA, DA)	• Very rocky terrain • High risk of trawler damage • Depth to 1,000 meters • Burial regions	• Armor wire layer applied to core cable • Most protection • Most expensive

The wet plant maintenance systems for non-repeatered segments are a subset of those used on repeatered maintenance systems. The lack of any active undersea components simplifies fault location in a non-repeatered application.[4]

Cables for Non-repeatered Systems

AT&T SSI has developed a family of cable products to provide non-repeatered optical transmission in a variety of ocean environments over a 27-year system life. The key cable attributes for this market are fiber loss and dispersion; cable strength and protection; and fiber count, the number of fibers within the cable.

The three types of transmission fiber generally deployed within non-repeatered systems, silica-core, Germanium-doped, and dispersion-shifted, are summarized in Table 1. Small lengths of cabled erbium-doped fiber are deployed in a remotely pumped system. Although having somewhat different transmission characteristics than those of transmission fibers, they are equally reliable and can be cabled. AT&T SSI's cable strength and protection options are shown in Table 2. SSI cable designs can accommodate up to 24 fiber pairs.

Non-repeatered cables are structurally very similar to repeatered cables. They are, however, roughly 60 per cent smaller in diameter to provide the most cost-effective solution for their typically shallow water applications. Typical elements of a cable design are shown by the cable cross-section in Figure 2. These include:

- The unit fiber structure (UFS), which contains the optical fibers;
- Strengthening wires, which provide stiffness and prevent fiber stretching during handling;
- Copper sheaths, sometimes used for power conduction during fault location;
- Insulation jackets for protection against water seepage and, finally,
- Armored protection layers, which can be metallic tapes, combined with additional polyethylene layers and armor-wire layers.

The five major processing steps in manufacturing cable mirror the above description: (1) fiber manufacture, (2) unit fiber structure, (3) metallic structure, (4) insulation application, and (5) armor protection application. These manufacturing steps are more fully described in Mortenson et al.[4]

Figure 3 illustrates various types of non-repeatered cable designs.

Cable Interconnection Hardware. The capability for cable segments to be joined into various network architectures is provided by cable interconnection hardware. Cable joints allow two cable segments to be joined, while passive branching joints allow three cable segments to be joined.

Undersea Cable Joints. Cable joints provide optical, electrical, and mechanical continuity between contiguous cable sections. These joints are made either in the cable factory during system manufacture or on a ship during installation and repair work. The tensile strength of these joints are at least 90 per cent of the calculated minimum breaking strength of the cable. The joints are designed for operation in both deep and shallow water and on land.

Joints are designed to be handled by conventional cable machinery and to be buried without degrading their performance. Two types of cable joints have been designed: one for armorless cable, the other for armored cable. Armored joints combine deep-water jointing techniques and proven conventional technologies for armored coaxial cable.[4]

Passive Branching Joints. An increasingly common feature requested of non-repeatered system designs, especially those that have high fiber counts, is the ability to send optical signal paths from one cable landing point to many other points. This branching of the optical path is accomplished by using a passive splitter, also known as a passive branching joint, located in a branching unit (BU).

Table III. A comparison of single versus mass-fusion splicing of silica-core fibers

Splice type	Splice loss in dB	Estimated splice time
Single fiber	μ = 0.05 dB, or σ = 0.03 dB	10 minutes per single splice (120 minutes for 12 fibers)
Mass fusion (up to 12 fibers)	μ = 0.07 dB, or σ = 0.04 dB	25 minutes per mass splice (25 minutes for 12 fibers)

dB - Decibel

Table IV. Current key non-repeatered transmission terminal characteristics

Parameter	Typical options (all combinations of options not necessarily available)
Line rates	• 155 Mbits/s SDH/SONET • 565 Mbits/s PDH • 622 Mbits/s SDH/SONET • 2.5 Gbits/s SDH/SONET • 5 Gbits/s SDH/SONET
Tributary interfaces	• 2 Mbits/s via lower-order multiplexer • 55 Mbits/s for 155 Mbits/s SDH/SONET systems • 140 Mbits/s for 565 Mbits/s PDH systems • 140 Mbits/s or 155 Mbits/s for 622 Mbits/s, 2.5 Gbits/s, and 5 Gbits/s SDH/SONET
Terminal protection options	• Equipment • Line (0:1, 1+1, 1:*n*) • Ring (2- and 4-fiber)
Transmitter options	• Standard terrestrial (ITU compatible) • Selected narrow terrestrial • Externally modulated, dithered
Receiver options	• Standard terrestrial (ITU compatible) • Selected high-sensitivity
Amplified options	• Post-amp • Low-noise pre-amps with optional dispersion compensation • Remote pumps
Forward error correction	• Reed-Solomon code system with system gain of 4-5 dB

dB - Decibel
ITU - International Telecommunications Union
SONET - Synchronous optical network
SDH- Synchronous digital hierarchy
PDH - Pleisiochronous digital hierarchy

There are no active electrical or optical components in the joint. The unit's construction provides the same optical, mechanical, and electrical continuity as cable joints. In addition, passive-branching and cable joints share common hardware and jointing processes.

Cable Fiber Splicing. The joining of optical fibers is accomplished using electric arc fusion techniques. Fibers are spliced together one at a time or in groups of four to 12 fibers. Both single-fiber and mass-fusion splicing techniques are available. Each process begins with the removal of the fiber coating to expose the glass fiber. The fiber ends are then cleaved to make flat, mirror-finished ends. The ends are placed in splicing machines, where they are aligned and butted together and then welded by an electric arc to make a low-loss joint.

Splice losses are estimated by the arc fusion machine and the estimated splice loss is compared to previously obtained statistical performance data. The overall system loss is validated by optical time domain reflectometers (OTDR), which locate fiber faults. The long-term integrity of the fiber splice is ensured by testing the fibers, restoring the primary coating protection, and then protecting the splices with small metal splints.

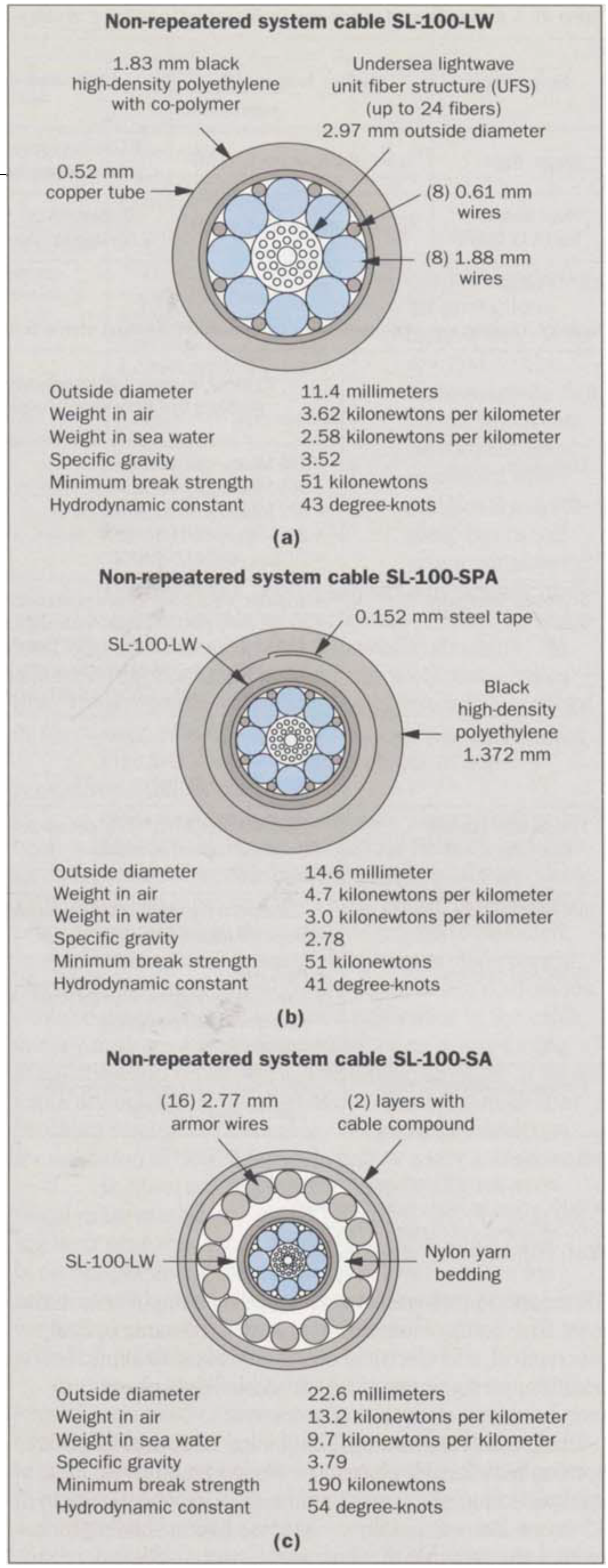
High fiber count cables make it essential to have a mass-fusion splicing capability for at-sea installation and repair. Mass-fusion splicing machines, which have the capability to splice up to 12 fibers at one time, reduce the splicing time, while adding only a slightly higher variation in splice loss. Minimizing the splicing time is critical to reducing the amount of time a ship is standing—with cable suspended overboard—during a splicing operation. Table 3 gives a comparison of the estimated versus the actual losses and times for both single and mass-fusion splices.

Transmission Terminals

Transmission terminal options for non-repeatered undersea systems are quite extensive, as shown in Table 4. These terminals are characterized by their ability to transmit over long distances. They use standard domestic multiplex equipment[4] that operates in conjunction with specialized optical line interfaces to provide transmission over the longer-length spans not typical of most terrestrial systems.

Beyond this transmission capability, the terminal has a wide variety of associated maintenance requirements—especially with respect to protection architectures. Transmission terminals can be provisioned for equipment redundancy, line redundancy, ring protection,

Figure 3. This illustration shows various types of non-repeatered cable designs, including AT&T's SL-100-LW, SL-100-SPA, and SL-100-SA.



and protection access.

A block diagram of an unprotected complete terminal is shown in Figure 4. Table 5 illustrates the various protection options available in an undersea non-repeatered transmission terminal.

As described earlier, many of the key transmission technologies of non-repeatered systems are deployed within the transmission terminal. These include amplifiers, high-performance transmitters and receivers, dispersion compensation, forward error correction, and wavelength-division multiplexing (WDM).

Terminal Post-Amplifiers. Post-amplifiers are positioned in the terminal immediately following the terminal's transmitter. They increase the transmitted output power to maximize the available power for the span. The most critical characteristic of this amplifier, therefore, is high output power. The post-amp amplifies a transmitter output signal, on the order of 0 dBm, to the level required by the system loss budget (up to +21 dBm). The two-stage amplifier is pumped bi-directionally by a 1,480-micron multi-quantum well (MQW) pump laser.

The system transmission penalties associated with these post-amplifiers are negligible when operating at low output powers. At higher output powers, the non-linear effects of the transmitted signal generate, for example, Broullian scattering, which is the result of energy in the fiber reflecting back towards the transmitter. This effect is minimized by broadening the transmission laser spectrum by using low-frequency amplitude modulation.

In addition, self-phase modulation can result from a too-close alignment of the dispersion-zero wavelength of the transmission fiber and the center wavelength of the transmitter. This effect must be carefully managed by the purposeful offset of the laser and fiber center wavelengths.

Raman effects, or spontaneous amplification of the transmitted signal within the fiber at higher power levels, is not an issue with current post-amplifiers. At higher output powers, which are expected to be available in post-amplifier products in the relatively near future, Raman effects will be minimized by the use of larger core-area fibers in the cable sections closest to shore.

Terminal Pre-Amplifiers. Pre-amplifiers are posi-

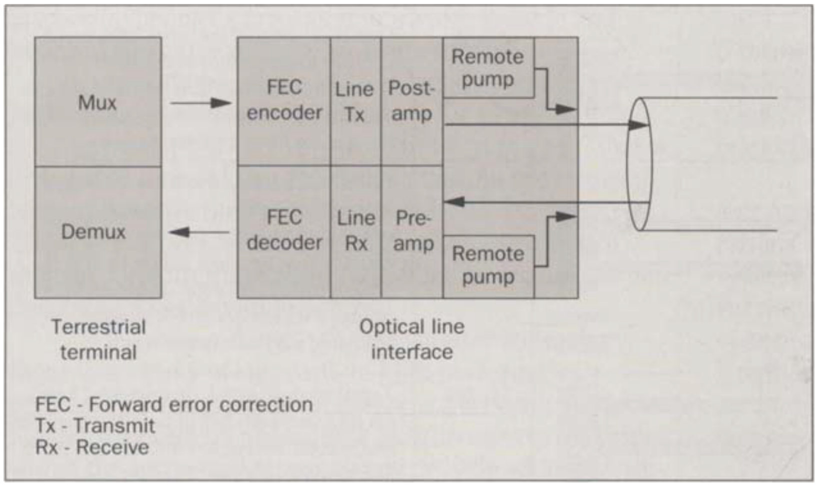


Figure 4: A block diagram of an unprotected complete terminal includes the multiplexing-demultiplexing equipment, forward error correction (FEC), encoders-decoders, line transmitters and receivers, pre-amplifiers and post-amplifiers, and remote pumps.

tioned just before the terminal receiver. They increase the terminal's effective receiver sensitivity, that is, error performance at various levels of received power. These pre-amps are characterized by low noise and high gain. Achieving this is one of the most challenging aspects of designing world-class pre-amplifiers. AT&T SSI products achieve a noise figure close to the theoretical limit of 3 dB by using a two-stage amplifier pumped by 980-micron pump lasers with appropriate isolation between the amplifier stages. Narrowband filter technology—typically less than 1 angstrom—also is critical to minimize this noise. SSI's preamplifiers have gain on the order of 35 dB.

Remotely Pumped Amplifiers. Remotely pumped amplifiers consist of both a short length of erbium-doped fiber (EDF) located within the cable span and pump lasers located at the terminal. The optical pump power is sent to the erbium-doped fiber via the transmission path. Upwards of 10 dB of gain can be achieved by deploying remotely pumped amplifiers at the receive end of a transmission span. Remote pumping also can be deployed close to the transmit end to achieve gains on the order of 5 dB.

One way of viewing a remotely pumped amplifier is as an undersea repeater without active components in the wet plant. As such, its wet portion is more reliable than an undersea repeater. Another means of viewing the remotely pumped amplifier is as an extended receiver. That is, it can be envisioned as the first stage of the pre-amplifier, and the terminal's pre-amplifier considered as a subsequent stage.

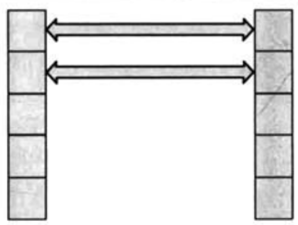
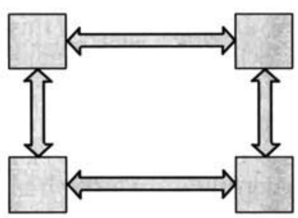
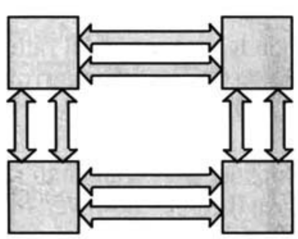
A key to the performance improvement of the remotely-pumped amplifier is getting as much pump energy to the remote erbium as possible. Therefore, the pump wavelength used is 1,480 nanometers (nm), the same as that used in the post-amplifier. This wavelength is sufficiently far enough away from the transmission wavelength of 1,550 nanometers not to interfere with the transmitted signal, yet the loss of the fiber at 1,480 nanometers is only approximately .02 dB/km greater than that at 1,550 nanometers. Therefore, with pump powers similar to those described for the post-amplifier, several milliwatts of power can reach the remote erbium-doped fiber, which has been optimized for maximum gain with low-levels of pump energy.

It is also noteworthy that the Raman gain of the transmission fiber between the erbium-doped fiber and the shore contributes to the overall performance improvement of this architecture. A few dB of the current improvement of over 10 dB is attributable to Raman gain, and not to the remote erbium itself.

Transmitters. For the shortest length spans of less than 100 kilometers—analogous to those used typically in a terrestrial system—the directly-modulated laser transmitters typically provided in standard terrestrial multiplexers can be used as sources for the undersea non-repeatered system. As the span lengths grow longer and bit rates get higher, however, these transmitters must have narrower spectral characteristics when using non-dispersion-shifted fiber. This requisite transmitter performance initially can be achieved simply by selecting transmitters within the terrestrial terminal. Eventually, however, the transmitter technology must shift from direct modulation to external modulation.

Newer transmission terminals, which are being developed for the terrestrial markets with WDM, will use externally modulated lasers and, thus, eventually may partially negate the need for a special transmitter for the high bit-rate non-repeatered systems using non-dispersion-shifted fiber. When using dispersion-shifted fiber, the

Table V Transmission terminal protection options

Protection type	Architecture block diagram	ITU reference	Protection features and advantages
Unprotected (0:1)		G. 782	Terminal failure may result in system failure.
Equipment protection		N/A	Totally duplicated terminal equipment (1 for 1) independent of the line. Probability minimal that terminal failure results in system failure. No protection of wet system failure via terminal
1+1 line protection	 Bridge Tx end / Switch Rx end	G.783	Terminal duplicated via duo-feeding of redundant fiber path at transmit end and switching at receive end. Probability minimal that terminal failure results in system failure. A single undersea fiber failure, if it ever occurred, would be protected via the terminal.
n:1 line protection	 Switch Rx end / Switch Tx end	G.783	Terminal duplicated, on an *n*-for-1 basis, via transmit switches at both the transmit and receive end of redundant fiber paths. Switch time is slower than for 1+1. Probability minimal that terminal failure results in system failure. A single undersea fiber failure, if it ever occurred, would be protected via the terminal.
Protection access	N/A	N/A	Provides capability of utilizing redundant equipment for service on a preemptable basis.
2-fiber ring		Pending draft G.7HR-1	Provides redundant terminal via fiber-path/line switching around a two-fiber (single-pair) ring. Protects most of terminal and protects against single cable breaks, if system is engineered for twice the capacity.
4-fiber ring		Pending draft G.7HR-1	Provides redundant terminal via fiber-path/line switching around a four-fiber (2-pair) ring. Protects most of terminal and protects against single cable breaks, or single fiber faults if system is engineered for twice the capacity.

ITU - International Telecommunications Union
Tx - Transmit
Rx - Receive

dispersion penalties are much more manageable and, hence, transmitter requirements are relaxed.

In addition, at the longest lengths, using very high output-power post-amplifiers, the spectral width of the transmitter may actually need to be "dithered," that is, broadened to avoid non-linear penalties. As the transmitter performance improves, additional costs are incurred. Therefore, it is essential that good cost/performance models, for both transmitters and fiber, be available when designing a system architecture.

Receivers. As with the transmitter technology, there is a variety of standard- to high-performance receiver options available in non-repeatered applications. Standard avalanche photodiode (APD) receivers available within the terrestrial terminal may provide adequate sensitivity for the shorter spans, but selecting a receiver by its sensitivity may be required for somewhat longer spans. Once world-class receiver performance is required, the preamplifier, as well as fixed or tracking narrowband filter technologies described in this paper, must be used.

Dispersion Compensating Fiber. At the longer distances and higher bit rates, dispersion may accumulate within the transmission path to a level at which it can not be managed solely by a standard receiver. This is especially true when sections of silica-core fiber are used within the wet plant, either for minimum loss over distance or to minimize the effects of Raman scattering. In such cases, dispersion compensating fiber, or negative dispersion fiber, must be used within the pre-amplifier. Typically, it is used after the second stage of the pre-amplifier, and is followed by an additional stage, or stages, of amplification. The additional stage is necessary because the tens of kilometers of dispersion-compensating fiber, which is required to negate the hundreds of kilometer's worth of dispersion in the wet plant, has significant amounts of loss itself—10's of dBs.

Forward Error Correction. FEC encodes the transmit signal with overhead bytes that are used, on the receive end, to detect and correct errors that were introduced in the transmission path. Current FEC technology allows performance budget improvements of between 4 and 5 dB.

Wavelength Division Multiplexing. This is a means of increasing the capacity of the fiber path by transmitting additional carriers at different wavelengths over the same fiber path. The transmission terminal in a WDM system must, therefore, have the ability to be provisioned with transmitters with very specific characteristics. In addition, the appropriate wavelength combiners and splitters must be provisioned at the transmit and receive ends, respectively.

In summary, the transmission terminal technologies and architectures for undersea nonrepeatered applications have much in common with terrestrial lightwave systems and repeatered systems. They also have some very unique features, however, which enable different system architectures to meet specific reliability, span length, and capacity requirements.

Non-repeatered Maintenance Equipment

As there are no active components in the transmission path of the non-repeatered undersea plant, the probability of failure or degradation of the wet plant is less than in a repeatered system. Hence, wet plant monitoring and fault location systems for non-repeatered systems use less complex, less expensive equipment than those in repeatered systems.

The wet plant can be adequately monitored while in-service by end-to-end transmission performance measures, such as bit error rate, block error rate, etc. These measurements are monitored at the transmission terminals by the network management systems. Should a wet plant fault occur, it would be located out-of-service with the combination of an optical time domain reflectometer, which locates fiber faults, and a cable continuity/electroding test set, which provides a low-level tone to the metallic path of the cable to detect and isolate faults.

The cable electroding testing capability is a traditional fault isolation technology for repeatered systems. It has been made available on newer non-repeatered systems, as customers have become more interested in these systems. Since complete electrical isolation of the cable's metallic path to sea earth potential is not critical to the performance of a non-repeatered system, however, the most important fault isolation tool is the OTDR.

Performance & Reliability Results. There are two key performance parameters typically prescribed by customers of non-repeatered systems. The first is error performance, as measured typically by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-TSS) or the International Telegraph and Telephone Consultative Committee (CCITT) G.821 or G.826

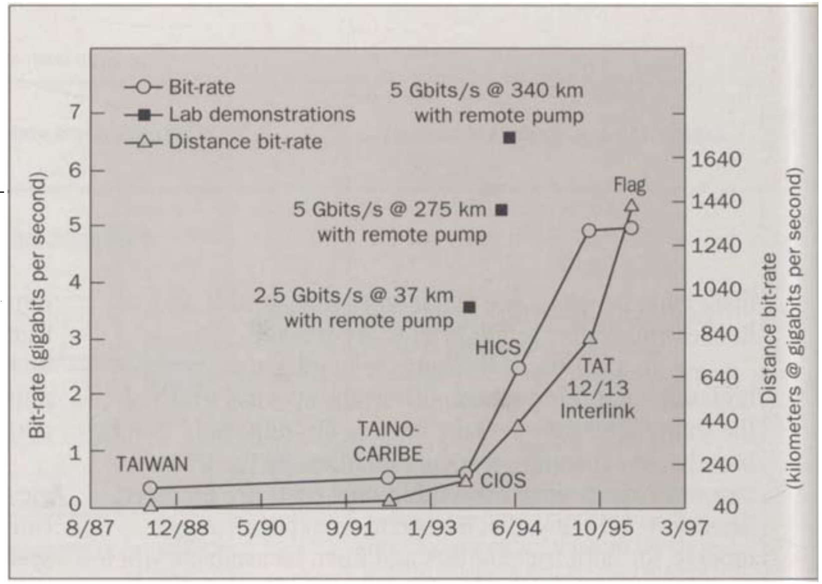


Figure 5. The bit-rate-distance product of AT&T non-repeatered systems over time, together with the recent AT&T Bell Laboratories experiments outlined in Table 6, clearly show the rapid growth in capacity and distance over the last few years. This figure also shows systems that will be installed in 1995.

standards. The second is reliability, as measured by the number of ship repairs.[1] Note that the customer's definition of a ship repair includes only those faults that are attributable to the failure of wet plant components. The definition does not include faults caused by external factors (called external aggression), such as damage by ship anchors or fishing-trawler nets, since such factors are not typically under the control of the undersea system supplier.

External causes do have the potential to significantly impact the overall availability of the system. Therefore, protection against such causes is typically taken into account by customers in their prescribed architectures, which provide for network protection and restoration, and in their engineering guidelines, which specify cable types and cable protection guidelines.

The required system error performance is achieved by the appropriate design of the system loss budget mentioned earlier. This loss budget includes an ample margin for unknown effects, predictable aging, future repairs should they be required, etc. Undersea systems installed by AT&T over the last decade typically are performing virtually error-free, which is better than what their customers require.

FEC will correct errors until the line has aged to the point of a complete failure condition, which, in principle, should never happen. That is, an FEC system will either be operating error free—exclusive of highly-improbable error bursts—or it will fail. If so, it will operate at an excessive bit error rate (BER) outage, or at extended periods of high BER (10 seconds or more), both normally associated with a complete failure in a transmission system. However, since there are no active undersea components to fail, and since redundant terminals are normally equipped with switching times within a fraction of a second, outages are extremely rare in a non-repeatered system.

A terminal protection switch will result in an errored block or an errored second. Therefore, the terminal design must have a mean time between failure (MTBF) that is well within the system error performance requirements.

In many cases, the owners of a system will separately specify the MTBF of the terminal equipment. The terminal MTBF is almost always determined by the transmission terminal optics, especially for the longer-length systems using amplifiers. The effect of the higher MTBF of these subsystems is minimized not only by using redundant subsystems, but also by using redundant components, such as pump lasers. Good design practices result in significantly superior performance than that which would be determined solely by the customer-prescribed error-performance requirements.

The reliability of the system, in terms of the number of ship repairs, is achieved by the use of high-strength, reliable fiber and cable. All fiber product are tested in the factory to assure they meet reliability requirements, and each cable design is carefully qualified through a combination of experiments simulating ocean conditions and actual sea trials.

The probability of a fiber failure in a system is virtually zero over the typical 27-year life of a cable system. Fiber faults that are not due to a cable fault, but which appear within a system, are typically not the result of design or manufacturing flaws, but rather of fiber stress due to cable kinks—induced, perhaps, by varying cable tensions during difficult cable laying conditions. Therefore, as described in Kordahi et al.[2], it is imperative that undersea systems be installed and maintained very carefully to help preclude such situations.

Beyond fiber faults, non-repeatered undersea

Table VI. Results of AT&T Bell Laboratories non-repeatered system experiments

Date	Distance (km)	Bit rate (Gbits/s)	Fiber type	Post-amp (dBm)	Receiver sensitivity w/pre-amp)	Remote pump improvement (dB)	FEC gain (dB)	Margin (dB)	Bit rate distance (Gbits-km/s)
1Q94	273	5	DSF	21.5	–38.2	N/A	0	1.5	1,365
1Q94	374	2.5	Hybrid silica-core and DSF	21.2	–42.6	11 (Rx end)	0	1	935
2Q94	339	5	DSF	24.0	–38.2	13.5 (Rx end)	0	5	1,695
3Q94	423	2.5	Silica-core and DSF	+25.0	–42.5	15 (Rx and Tx ends, combined)	0	2	1,057

dBm - Decibel referred to one milliwatt
DSF - Dispersion-shifted fiber
FEC - Forward error control
Rx - Receive
Tx - Transmit

system customers worry about cable breaks due to external damage. As described earlier, these types of faults are not only minimized by the use of cable with appropriate levels of protection, including both armoring or metallic wrap, but also by burial in the ocean bottom.

Trends in Non-repeatered Systems

Future trends in non-repeatered system design will focus on expanding the market for these products via design improvements. These improvements will increase the:

- Maximum span distance;
- Cost-competitiveness of non-repeatered systems;
- Network design options;
- Reliability of the installed network; and
- Capability of using local resources in manufacturing, installing, testing, and maintenance operations.

One of the challenges of non-repeatered products will be to increase the span length, while still remaining cost competitive to repeatered systems. It soon may be that repeatered systems spanning multi-hundred kilometer lengths will approach costs equivalent to non-repeatered systems, in which case the customers must weigh each product's relative advantages of reliability, upgradability, flexibility, and maintenance.

The technologies that will enable this increased distance for non-repeatered systems include:

- Higher-power pump lasers,
- Associated passive components to increase their ability to energize an amplifier with limited power,
- Improved error correcting codes, and
- Lower-loss fiber and large core area fiber.

Pump lasers using newer technologies will deliver over a watt of output power. Higher-power amplifiers using these pumps, either as post-amplifiers or remote amplifiers, will require a more careful management of dispersion and non-linearities through fiber concatenation. Table 6 shows various AT&T Bell Laboratories' lab-top experiments, which have been published within the past year. These tests reflect the increasing trend towards longer distances with ever higher bit rates.

Accomplishing the second goal of increasing the cost competitiveness of non-repeatered systems must be achieved through a combination of product and service design changes. Lower-cost terminals and cabled fiber may be achieved with some of the technology improvements mentioned above, as well as by manufacturing improvements. In order to make the complete system increasingly cost competitive, the products also must be inexpensive to install and maintain. This implies:

- Product changes to allow low-cost transport, especially for the cable;
- Use of local supply vessels;
- Simplified terminal equipment installation;
- Simplified cable installation, particularly jointing, to minimize expensive ship time; and
- Prefab modular terminal stations and marine tools, etc.

Increases in the reliability of non-repeatered systems will come predominantly through improved network designs and better cable protection techniques. Network design changes most likely will be founded upon a combination of re-used and re-engineered terrestrial network architectures, such as rings; off-the-shelf terrestrial transmission terminals; and undersea technologies, such as branching units combined with WDM, etc. One possibility, for example, is compressed rings with multiple WDM channels operating on a common,

Table VII. Key characteristics of sample AT&T non-repeatered undersea systems

System and location	Date	Maximum span length (km)	Bit rate (Gbits/s)	T-R (dB)	BOL margin (dB)	System architecture	Key information	Bit rate distance (Gbits-km)
Commando Fox, Okinawa	4/85	150	0.0015 PDH (dipulse coding)	57	10	Off-shore platform	• Single-mode fiber • Select terrestrial transmit and receive	0.225
Taiwan	6/88	104	0.417 PDH	42	18	Domestic island hop	• Single-mode fiber • Select terrestrial transmit and receive	43
Taino Carib, Puerto Rico-Virgin Islands	9/92	135	0.565 PDH	37	8	Branched regional island hop	• Germanium-doped fiber • Select terrestrial transmit and receive	31
CIOS, Cyprus-Israel	9/93	268	0.622 SDH	58.7	5.1	Regional island hop	• Silica-core fiber • +16 dBm post-amp • Select terrestrial receive	167
HICS, Hawaii Inter-Island	7/94	195 and 165	0.622 SDH and 2.5 SDH	56 and 46	12 and 10	Domestic inter-island hop	• Dispersion-shifted fiber • +16 dBm post-amp • Select terrestrial receive	121 412
CADMOS, Lebanon-Cyprus	8/95	234	0.622 SDH	59	7	Branched mainland-island hoop	• Silica-core fiber • +15 dBm post-amp • Select terrestrial receive	145
TAT 12/13	8/95	162	5 SDH	48	6	International non-rapid segment of repeatered system	• Dispersion-shifted fiber • +16 dBm post-amp w/dithered ext/mod. transmit • -34 dBm receive with pre-amp	7,776
FLAG, Egypt	12/96	277	5 SDH	68	8	International non-rapid segment of repeatered system	• Silica-core fiber • +19 dBm post-amp • –35 dBm receiver with pre-amp • 10 dB remote pump • 4 dB forward error correction (FEC) • Dispersion compensation	1,385

dB - Decibel
dBm - Decibel referred to one milliwatt
PDH - Plesiochronous digital hierarchy
SDH - Synchronous digital hierarchy
TAT - Trans-Atlantic Telecommunications
T-R - Transmit-receive

well-protected, deep water trunk, with channel separation at wavelength-splitting branching units.

Achieving improved cable protection for the predominantly shallow non-repeatered market will require improved installation and burial techniques.

A key to market success in the regional and domestic areas is the use of local resources to build, install, and maintain non-repeatered undersea systems. Regional production facilities, such as cable manufacture, also can minimize expensive cable transport. Local construction support, such as ships, shipboard personnel, land-cable and shore-end construction, and cable station construction, also may be necessary in the future.

Non-repeatered System Applications

The technologies described herein have been deployed by AT&T and its competitors worldwide, dating back to the mid-80's. Table 7 lists systems that AT&T has installed. In addition, a graphical depiction of the bit-rate-distance product of these systems over time, together with the recent AT&T Bell Laboratories experiments outlined in Table 6, are plotted in Figure 5. This chart clearly shows the rapid growth in capacity and distance over the last few years. The figure also shows systems that will be installed in 1995.

Summary

The global non-repeatered undersea lightwave market is continually evolving in ways that challenge developers on all fronts. While pushing the edge of leading lightwave technology to achieve longer and longer span distances, the products must continue to be cost-effective and flexible to meet a wide spectrum of customer needs. As non-repeatered undersea system technology continues to develop, it is becoming increasingly competitive to alternative, more traditional telecommunications options, including radio, terrestrial lightwave, satellite, and undersea repeatered systems.

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References

1. Joel Schesser, Stuart M. Abbott, Robert L. Easton, and Marcha Spaulding Stix, "Design Requirements for the Current Generation of Undersea Cable Systems," *AT&T Technical Journal*, January/February 1995, Vol. 74, No. 1, pp. 16-32.
2. Maurice E. Kordahi, Robert F. Gleason, and Ta-Mu Chien, "Installation and Maintenance Technology for Undersea Cable Systems," *AT&T Technical Journal*, January/February 1995, Vol. 74, No. 1, pp. 60-74.
3. Jonathan M. Liss and Kathleen A. Kurek, "Network Planning, Operation, and Maintenance Practices for Undersea Communication Systems," *AT&T Technical Journal*, January/February 1995, Vol. 74, No. 1, pp. 75-82.
4. Robert L. Mortenson, B. Scott Jackson, Seymour Shapiro, and William F. Sirocky, "Undersea Optically Amplified Repeatered Technology, Products, and Challenges," *AT&T Technical Journal*, January/February 1995, Vol. 74, No. 1, pp. 33-46.

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