Undersea Lightwave Systems

Peter K. Runge

Undersea lightwave systems have been in service since 1988 across the Atlantic Ocean, and since 1989 across the Pacific Ocean. These high-capacity, 280-Mb/s (megabit per second) digital communications systems have brought about a revolution in available system capacity and service quality compared to prior analog coaxial systems. In 1991, the technological progress continued as we began to install the higher capacity systems (i.e., 560 Mb/s) that use advances in laser and fiber technology. On the drawing board are systems targeted for service in 1995 that are based on revolutionary optical-amplifier technology with 5,000-Mb/s capacity. This paper will capture this unprecedented progress in undersea communications history. We start with the experience gained with today's undersea lightwave systems, then describe plans for the next-generation systems, and conclude with a look at the newest amplifier-based system technology.

Historic Perspectives and Trends

The providers of undersea communications systems can look back on a rich history of technological accomplishments. The first transatlantic telegraph cable was installed in 1858. In 1956, the first analog transatlantic telephone cable (i.e., TAT-1) began service with a capacity of 36 simultaneous voice-communications circuits (sometimes referred to as *channels*). Several families of analog coaxial systems followed with 140, 840, and 4200 channels per coaxial cable. The last of these systems, TAT-7, was ready for service in 1983.

All the analog cable systems used circuit multiplication techniques called TASI that effectively doubled the number of available telephone circuits. TASI, which stands for *time-assignment speech interpolation*, uses the natural pauses in conversations to carry other calls. (Panel 1 defines acronyms and terms.)

In 1988, the first transatlantic telephone system—i.e., TAT-8—was installed. It was based on the new digital lightwave transmission technology, and had a capacity of 8,000 digital voice circuits at 64 kb/s (kilobits per second). The quality of the digital service that this new lightwave technology provided was far superior to the quality of analog service. The technology supported digital service connectivity and the capability for new broadband digital services. In addition, enhancements in the digital technology permitted circuit multiplication of up to 5 to 1, which increased TAT-8's total potentially available capacity to 40,000 simultaneous voice-communications circuits.

This new lightwave technology reduced cable sizes and increased repeater spacings (the distance between repeaters), yet provided for greater capacity than the latest coaxial system. Clearly, it was the technology of choice. This first-generation system used the 1.3-μm (micrometer) transmission window. (This window is determined by a natural minimum that occurs in the fiber transmission loss around 1.3 μm.) Systems that operate in this window use multifrequency lasers and single-mode fibers with a 1.3-μm zero-dispersion wavelength.

International Network. With this first-generation lightwave system, digital optical communications systems have established themselves as the transmission medium of choice. This is confirmed by a look at Figure 1, a world map that shows installed and

Panel 1. Abbreviations, Acronyms, and Terms

AGC — automatic gain control

APC — undersea cable between Hong Kong and Singapore

APD — avalanche photodiode

ASE — amplified spontaneous emission

BER — bit-error rate

channels — simultaneous voice-communications circuits

EDFA — erbium-doped fiber amplifier

EMOS-1 — cable system that connects several countries on the Mediterranean Sea

G-P-T — cable system that connects Guam, the Philippines, and Taiwan

H-J-K — cable system that connects Hong Kong, Japan, and Korea

HAW-n — cable across the Pacific Ocean, extending from the continental United States to Hawaii

InGaAs — indium gallium arsenide

MAT-2 — cable system 2 in the western Mediterranean that connects Spain, Majorca, and Italy

NPC — undersea system across the northern Pacific

PTAT — cable system across the Atlantic Ocean that connects the United States to Bermuda and Ireland

SAW — surface acoustic wave

SDH — synchronous digital hierarchy

SEA-ME-WE-2 — undersea system 2 to connect southeast Asia, the Middle East, and western Europe

σ — standard deviation

Si — silicon

T/L — transposition and loopback

TASI — time-assignment speech interpolation

TAT-n — transatlantic telephone cable system

TCS1 — cable system that connects Florida, St. Thomas, and Columbia

TPC-n — transpacific cable system

UBM — undersea branching multiplexer

WDM — wavelength-division multiplexer

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planned undersea lightwave systems through 1996. The providers of international communications service are planning an extensive international communications network that connects major population centers in Europe, North America, and the Pacific Rim region. The network plan is based on three generations of undersea lightwave systems of consecutively higher capacities.

The *first-generation systems* operated at 280 Mb/s (megabits per second) per fiber pair. These systems cross the Atlantic Ocean as TAT-8, and the Pacific Ocean as TPC-3 (for *transpacific cable*) and Hawaii-4 (or HAW-4).

The *second-generation systems* will operate at 560 Mb/s per fiber pair and will be installed across the Atlantic as TAT-9, TAT-10, and TAT-11, and across the Pacific as TPC-4. The technology advancements include a shift in the operating wavelength to 1.55 μm and the use of single-frequency lasers with high spectral priority.

Planning has now begun for the *third generation* of undersea lightwave systems. These systems will be based on a revolutionary optical-amplifier technology. They will operate at 5 Gb/s (gigabits per second) per fiber pair, and use fiber with a zero-dispersion wavelength at 1.55 μm. The systems will be installed as TAT-12 and TAT-13 across the Atlantic and as TPC-5 and TPC-6 across the Pacific, starting in 1995.
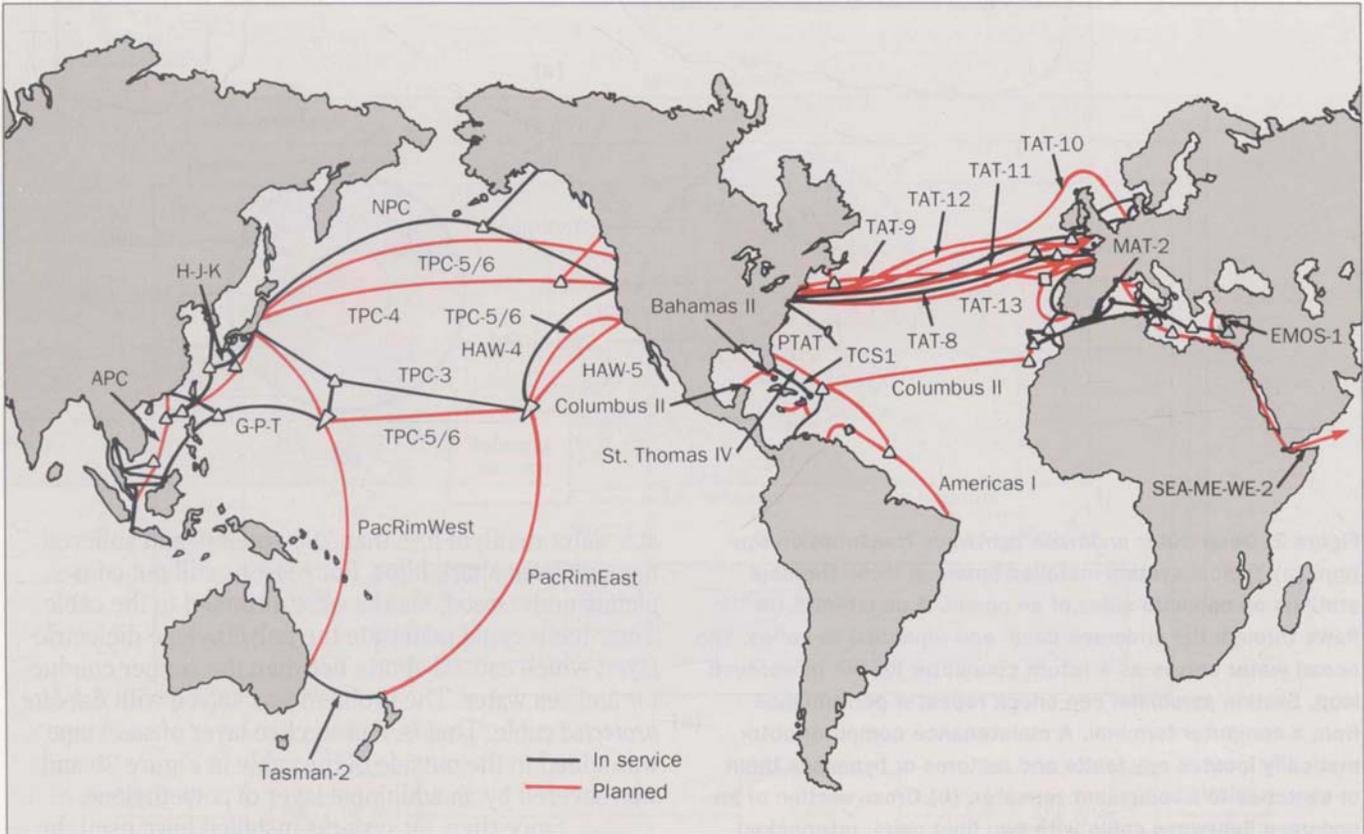
This paper discusses the:

- Three generations of undersea lightwave systems and their characteristics
- Technology improvements that led to this unprecedented growth in undersea lightwave systems
- Capabilities of a network based on undersea communications systems.

Current Lightwave Systems

By 1990, the first-generation undersea lightwave systems were providing digital connectivity between Europe, North America, and the western Pacific. In addition, systems had been installed between the United States and the Caribbean region, across the North Sea, and in the Mediterranean region. The first-generation undersea lightwave systems connect many countries in the world, giving them high-quality, digital service.

Figure 2a shows a typical undersea lightwave system, as it would be installed between three terminal stations on opposite sides of an ocean. (For example, this configuration was used for TAT-8, which provides service between the United States and Great Britain and France).

In the 280-Mb/s systems, each terminal station contains transmission equipment that multiplexes two incoming 140-Mb/s information streams to a 295.6-Mb/s line signal, and supplies optical pulses suitable for the optical, undersea communications medium. Power-feed equipment in the terminal stations can provide either positive or negative 7500V (volts) to power the submerged repeaters with a constant current of 1.6A (amperes) that flows through the undersea cable and all repeaters in series. The ocean water serves as a return conductor to close the power-feed loop.

Figure 1. A worldwide intelligent network is planned, based on three generations of undersea lightwave systems with increasing capacities. The first generation provides 280 Mb/s per fiber pair; the second generation will provide 560 Mb/s per fiber pair, while the third will provide 5 Gb/s per fiber pair. This map includes all major international systems.

In addition, the terminal station contains maintenance equipment. A computer terminal enables the station's craftspeople to interrogate the performance of submerged repeaters. If a fault occurs in the system, the maintenance computer can automatically locate the fault and execute restoration and bypass procedures, or switch to redundant transmitters in the undersea repeater, as needed.

The undersea plant consists of undersea cable and submerged repeaters. If needed, branching repeaters are included that allow some fiber pairs to branch off between two terminal stations. The undersea cable and repeaters are described in detail in the next two sections.

Undersea Lightwave Cable. Figure 2b shows a cross-sectional view of the deep-sea undersea cable, while Figure 2c depicts details of the core, i.e., the center of the cable.

The core consists of a center steel wire surrounded by an elastomer in which up to six communi-

cations fibers are embedded. (In the diagram, only four fibers are shown embedded in the elastomer, a rubber-like synthetic polymer.)

A matrix of interlocking steel wires surrounds the cable core and forms a cage around it. This cage inside the cable protects the fibers from ocean pressure and provides tensile strength to the cable. A tube of copper is compressed onto the steel wires, providing a hermetic seal to the core area. The copper tube also serves as the conductor path for power to the undersea repeaters. A layer of polyethylene insulating material surrounds the copper to provide dielectric insulation and protect the copper from mechanical abrasion.
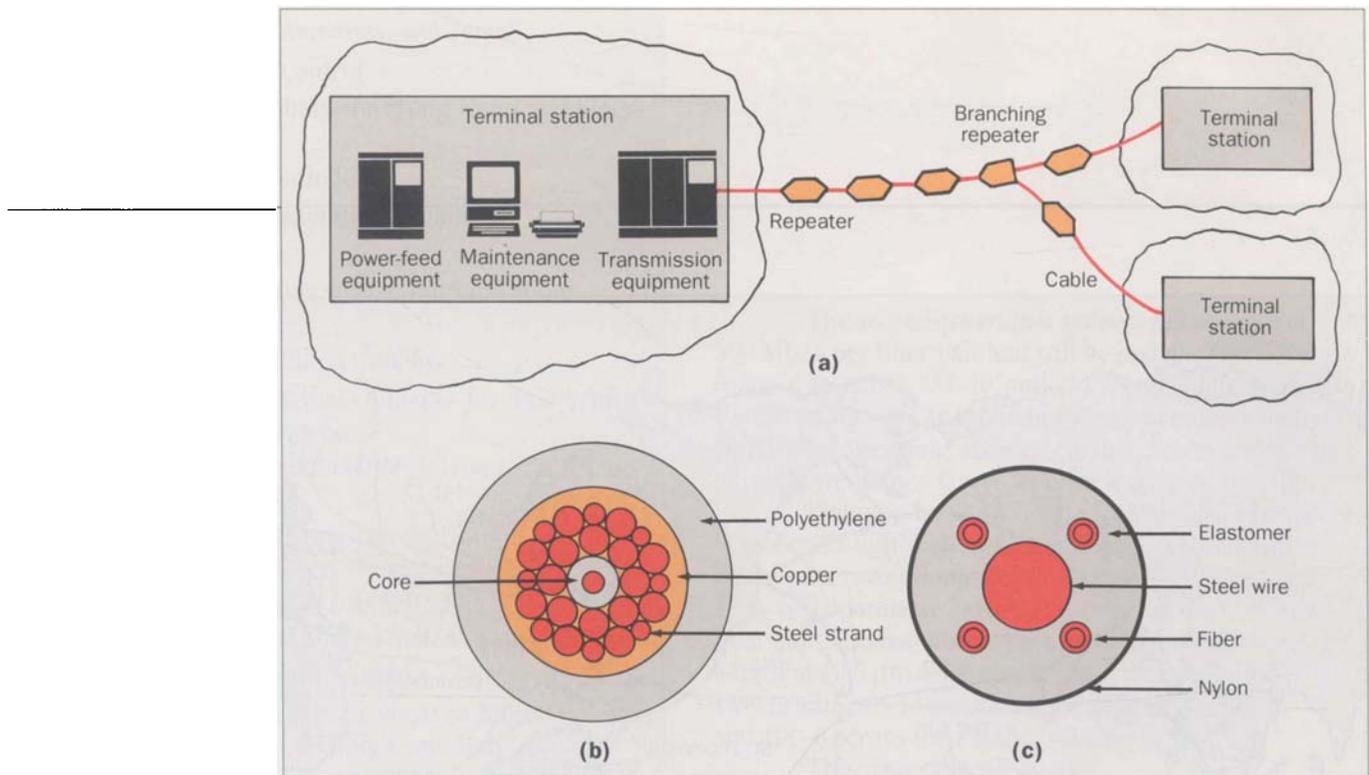
Figure 2. Deep-water undersea lightwave transmission system. (a) Typical system installed between three terminal stations on opposite sides of an ocean. A constant 1.6A flows through the undersea cable and repeaters in series. The ocean water serves as a return conductor for the power-feed loop. Station personnel can check repeater performance from a computer terminal. A maintenance computer automatically locates any faults and restores or bypasses them or switches to a redundant repeater. (b) Cross-section of an undersea lightwave cable with two fiber pairs. Interlocked steel wires surround the core to give the cable tensile strength and protect the fibers from ocean pressure. The copper jacket forms a hermetic seal for the core and conducts power to the undersea repeaters. (c) Up to six communications fibers may be embedded in the elastomer that surrounds the steel wire at the core's center.

Cables deployed in shallow water close to the shore run the greatest risk of damage from human intervention (for example, a ship's anchors or the activities of a fishing trawler) or natural causes (for example, undersea earth slides). To protect the cable, several layers of armored steel wires surround the basic cable structure that we show in Figure 2c. The armored cable is buried (to a depth of about 1 meter) in the ocean bottom near the shore ends of a cable system where fishing activities might otherwise snare and damage a cable that lies on the ocean floor.

In 1985, the first undersea lightwave system (Optican 1) was installed between Tenerife and Grand Canaria in the Canary Islands, and started to provide service in 1986. This system's deep-water cable was installed at a water depth of less than 2000 meters and suffered damage from shark bites. For reasons still not completely understood, sharks were attracted to the cable. Their teeth could penetrate the polyethylene dielectric layer, which caused shorts between the copper conductor and sea water. The problem was solved with *fish-bite protected* cable. That is, a protective layer of steel tape was added to the outside of the cable in Figure 2b and was covered by an additional layer of polyethylene.

Since then, all systems installed have used the fish-bite protected cable to a water depth of about 2000 meters. No further shark attacks have been recorded on any of these systems.

Undersea Repeaters. Undersea repeaters contain up to six optical regenerators to provide transmission for up to three fiber pairs. The repeaters also contain supervisory and power circuits. The major functional blocks in each regenerator (Figure 3a) include:
- The optical receiver
- An automatic gain control (AGC) amplifier
- A timing recovery circuit
- A decision circuit
- A transposition and loopback (T/L) circuit
- A transmitter and optical switch combination that provides two available transmitters per outgoing fiber.

All the electronic circuits were implemented with custom, Si (silicon) bipolar integrated circuits. The diagram shows the relationships among the regenerator building blocks and their connections to the supervisory monitoring circuits.

Light pulses in the incoming fiber (or lightguide) enter the receiver, where an InGaAs (indium
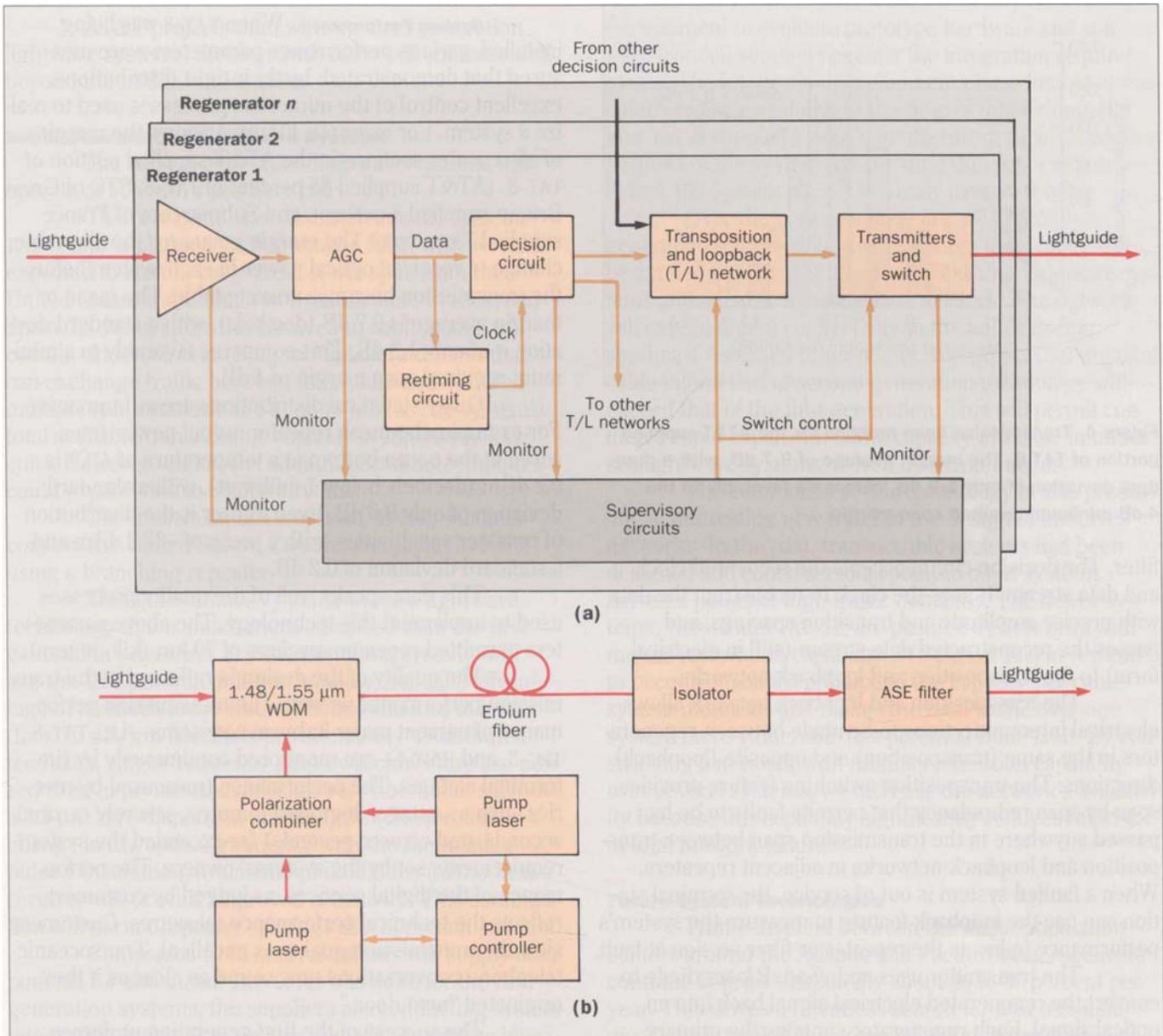
Figure 3. Repeater design. (a) Currently, each repeater has up to six optical regenerators that provide transmission for up to three fiber pairs. The regenerator's major functional blocks are connected to the supervisory monitoring circuits. (b) The new, one-way, optical-amplifier repeater operates at 2.5 and 5 Gb/s and does not require electronic circuits for detection, regeneration, and retransmission. Combining the output from two pump lasers provides robustness against the failure of one laser.

gallium arsenide) photodiode converts them into electrical pulses that a silicon bipolar preamplifier then amplifies. These electrical pulses go to the AGC amplifier, which provides most of the regenerator gain by electronic amplification. The AGC also adjusts the signal amplitude of the data stream to the optimum level for the decision circuit. From the electrical data stream, the retiming circuit extracts a clock signal that is phase coherent with the data. This circuit uses a surface-acoustic-wave (SAW)
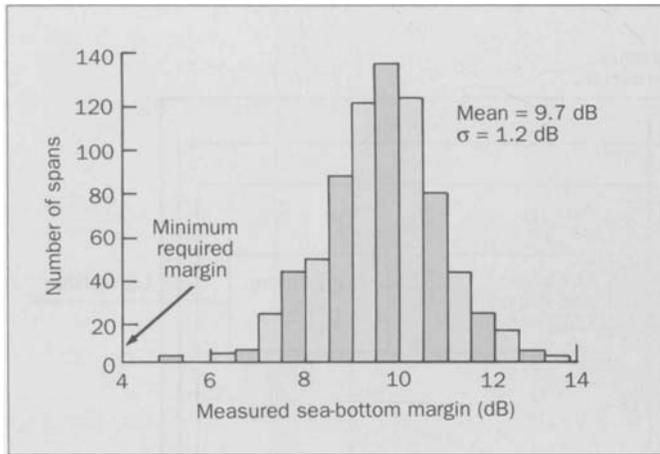
Figure 4. Transmission span margins for the AT&T-supplied portion of TAT-8. The margin average of 9.7 dB, with a standard deviation of only 1.2 dB, compares favorably to the 4-dB minimum required span margin.

filter. The decision circuit accepts the recovered clock and data stream. It uses the clock to reconstruct the data with precise amplitude and transition spacings, and passes the reconstructed data stream (still in electrical form) to the transposition and loopback networks.

The transposition and loopback network allows electrical interconnections to be made between regenerators in the same (transposition) and opposite (loopback) directions. The transposition switching feature provides span-by-span redundancy that permits faults to be bypassed anywhere in the transmission span between transposition and loopback networks in adjacent repeaters. When a faulted system is out of service, the terminal station can use the loopback feature to measure the system's performance to locate the repeater or fiber section at fault.

The transmitter uses an InGaAsP laser diode to convert the regenerated electrical signal back into an optical signal. Each regenerator contains the primary transmitter, along with an inactive transmitter that is on standby. Should the performance of the primary unit become marginal, the standby transmitter can be switched into service via the supervisory circuit. An optical relay that serves as a 2×1 optical switch connects the output fibers of both transmitters to the transmission fiber. The terminal station's supervisory unit switches the optical relays by remote control via the regenerator's supervisory control circuits.

System Performance. When TAT-8 was being installed, various performance parameters were measured that demonstrated, by their tight distributions, excellent control of the numerous processes used to realize a system. For example, Figure 4 shows the margins of all repeater sections in the AT&T-supplied portion of TAT-8. (AT&T supplied 85 percent of TAT-8, STC of Great Britain supplied 8 percent, and Submarcom of France supplied 7 percent.) The *margin* measures the allowable change in received optical power in each system before the transmission becomes unacceptable. The mean or margin average is 9.7 dB (decibels), with a standard deviation σ of only 1.2 dB. This compares favorably to a minimum required span margin of 4 dB.

Other statistical distributions are as impressive. For example, the mean repeater-output power (measured at the ocean bottom at a temperature of 4°C) is 0.2 dBm (decibels below 1 milliwatt), with a standard deviation of only 0.6 dB. Even tighter is the distribution of repeater sensitivities, with a mean of −37.2 dBm and a standard deviation of 0.2 dB.

This data speaks well of the quality processes used to implement this technology. The above parameters permitted repeater spacings of 70 km (kilometers).

The quality of the design is reflected in the transmission performance as well. The transmission performance of current major lightwave systems—i.e., TAT-8, TPC-3, and HAW-4—are monitored continuously by the terminal stations. The performance (measured by metrics such as outage, degraded minutes, severely errored seconds, and errored seconds) far exceeded the system requirements set by the systems' owners. The performance of the digital services, as judged by customers, reflects the technical performance measures. Customers view the transmission quality as excellent. Transoceanic telephone conversations now sound as clear as if they originated "next door."

The success of the first-generation undersea lightwave systems has been nothing less than spectacular. These systems have been installed at an average rate of about 18,000 km of cable per year, with more than 45,000 km of cable installed to date. The available circuit capacity for undersea systems is growing worldwide at a rate of about 200 million kilometers of voice circuits per year, as measured in 64-kb/s voice circuits. To date, more than 400 million kilometers of voice circuits have been placed into service.

AT&T projects that, with the next-generation lightwave systems, these growth rates will continue well beyond the middle of the 1990s.

Second-Generation Lightwave Systems

The second-generation lightwave systems will operate at 560 Mb/s per fiber pair.

The first installation is a transatlantic system, TAT-9, and is planned for September 1991, with service expected to start in early 1992. It will span from the United States and Canada to Great Britain, France, and Spain. In this system, the connecting cable nodes will contain undersea branching multiplexers (UBMs) that can exchange traffic between fiber pairs and between multiple cable stations at 140 or 45 Mb/s. The system's total available transoceanic capacity is 16,000 voice circuits. However, digital-circuit multiplication techniques could expand this to 80,000 circuits.

The first transpacific system, TPC-4, will interconnect the United States, Canada, and Japan in 1992, using a branching repeater.

This generation's systems will use lightwave technology that is much more advanced than the first generation's systems. For the first time, systems will use the 1.55-μm transmission window, and take advantage of its much lower fiber-transmission loss of less than 0.2 dB/km (decibels per kilometer). Distributed-feedback, single-frequency lasers with low chirp are now required to permit transmission over fibers that still have a 1.3-μm zero-dispersion wavelength. (*Chirp* refers to a change in the optical frequency with the modulating pulse.) In addition, avalanche photodiodes (APDs) in the receiver will provide improved sensitivity. This combination will permit repeater spacings that approach 150 km.

Companies from several nations will supply components for and install TAT-9. As was done for the first-generation systems, the suppliers are conducting system-integration activities to ensure that all subsystems interwork successfully. The integration methodology consists of the development of detailed interface specifications for the underwater transmission plant to allow interconnections between hardware from different suppliers. Furthermore, interworking specifications were developed for the shore equipment: transmission terminals, special UBM terminal equipment, and power-plant equipment.

During the development phase of the project, the suppliers ran test programs in a simulated environment to evaluate prototype hardware and software from all suppliers against the integration requirements. The integration development phase for TAT-9 was completed successfully. At the time of this writing, the four TAT-9 suppliers were manufacturing their respective portions of the system. By the time this paper is published, the system should be ready to start service.

Over the next several years, this second-generation undersea lightwave system technology will be applied to augment the already existing lightwave systems and expand the worldwide network. The network will extend digital connectivity to the South Pacific, southeast Asia, and other points. We expect that the total cable kilometers of second-generation technology will exceed that of the first generation. This will permit continued rapid expansion of the capacity available in undersea lightwave systems, driven by market needs.

The economics of this technology is also producing an interesting new trend in the design of undersea networks. In the past, transoceanic systems had been designed and constructed as point-to-point systems between points of high-traffic demands. The newer systems, TAT-10 and TAT-11, are planned as networks with mutual restoration capability. We expect this new trend to become standard practice as the capacity per cable system increases and makes the total traffic over one system more vulnerable to a potential cable fault. By constructing a network with mutual restoration capability over several systems, we increase the network's availability because this capability significantly reduces the risk of total network failure.

Future-System Technologies

Traffic demand between the major population centers around the Atlantic and Pacific oceans seems to continue to grow unabatedly about 20 to 30 percent per year. This drives a relentless search for new technologies to help exploit the potential of lightwave communications. For undersea systems, several choices were available as candidates for next-generation systems.

Extending the current regenerative technologies into the multi-gigabit range ranked high on the list. Development of terrestrial systems has begun for 2.5-Gb/s transmission systems based on the synchronous digital hierarchy (SDH). Next-generation undersea systems could have been built on that expertise and could have provided a fourfold increase in transmission capacity.
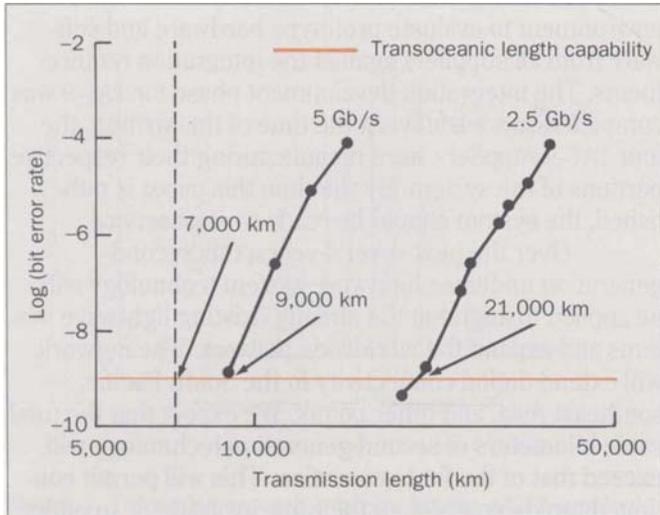
Figure 5. Logarithm of measured bit-error rate (BER) as a function of transmission length through the loop. These results demonstrate transoceanic length (9000-km) capability for both 2.5 Gb/s and 5 Gb/s.

On the other hand, systems based on optical amplifiers seemed farther away from reality. However, optical-amplifier systems had the promise of upgradability to even higher capacities per fiber pair than conventional regenerative systems.

AT&T has achieved experimental results that confirm the transoceanic distance capability of erbium-doped fiber-amplifier systems.[1] For these experiments, we used a recirculating loop that consisted of an amplifier chain with three 40-km spans of optical fiber, four optical amplifiers, and the requisite optical components for the loop.

By loading the loop with optical pulses and closing it back on itself, one can observe the optical pulses as they propagate over many thousand kilometers, together with the degrading optical noise. Figure 5 shows a plot of the measured transmission bit-error rate (BER) as a function of the transmission length. (In reality, we show the logarithm of the bit-error rate.) The measured BER results for 2.5 Gb/s and 5 Gb/s demonstrate transoceanic length capability (i.e., 9000 km) for both.

Figure 3b is a schematic diagram of a one-way optical-amplifier repeater that can operate at either 2.5 Gb/s or 5 Gb/s. Noteworthy is the basic simplicity of such a design (compared to the regenerative repeater

of Figure 3a) because no detection, regeneration, or retransmission is required. Therefore, the undersea plant needs neither high-speed electronic circuits, nor high-speed optical receivers, nor optical transmitters.

The optical transmission path consists only of passive optical components:
- A wavelength-division multiplexer (WDM)
- The erbium-doped fiber amplifier
- An isolator
- A filter to reduce noise from amplified spontaneous emission (ASE).

To provide active gain, we "pump" the erbium-doped fiber with optical power from 1.48-μm pump lasers through the WDM. Light from the pump laser excites the erbium atoms in the doped fiber, so that they are able to provide optical gain for the 1.55-μm signal.

Also noteworthy is the simple sparing scheme for pump lasers. To provide robustness for the amplifier against the failure of one pump laser, we combine the output power from two pump lasers (using a polarization combiner).

Current plans are for optical-amplifier-based systems to be available for transoceanic service in early 1995. Such systems can be operated initially as 2.4-Gb/s SDH-compatible systems to meet the needs of the evolving international network. As the communications traffic increases, these systems (unlike the regenerator-based systems) can be upgraded to 4.8 Gb/s just by changes in the terminal stations. Thus, the system can give the network's customers double the initial capacity for minimal additional cost.

AT&T and its partners have announced plans to expand their international networks in the Atlantic and Pacific regions in 1995 and 1996 by using undersea systems with this new amplifier.

Should the traffic demand continue to increase as it has in the past, can the system technology respond and provide an even larger transoceanic capacity per fiber pair than 5 Gb/s? The answer is a resounding *yes*. Already, some experimental results using optical solitons in an amplifier-based system have demonstrated the feasibility of 5-Gb/s capacity.[2]

Solitons are high-speed pulses that use the nonlinearity of the refraction of the optical-fiber core material to compensate for the effects of fiber dispersion. Consequently, the envelope of the soliton pulses and the pulse spectrum suffer little change, if any, over

extremely long transmission distances. Because the spectrum does not change, multiple soliton channels at different transmission wavelengths could be sent simultaneously over the same fiber. Mollenauer predicts[2] theoretical capabilities of five simultaneous 5-Gb/s channels over a 9000-km transmission distance, for a total of 25 Gb/s per fiber pair.

Solitons are also highly polarized. In principle, we could use polarization multiplexing for a further doubling of the available capacity. It seems, the technology will be able and available to continue to meet the ever-increasing service demands.

Conclusion

Lightwave undersea transmission systems have had a major impact on international communications. We are witnessing an interplay between increased service demand that drives improvements in optical communication capabilities, and optical system capability that allows improved service capabilities.

We see the evolution of a global telecommunications network that relies on high-quality, undersea lightwave transmission systems. This network will provide worldwide, highly reliable, digital connectivity.

AT&T has provided technology and leadership to bring to market undersea lightwave systems that have revolutionized, and are likely to continue to revolutionize, international communications.

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Peter K. Runge *is head of the Undersea Lightwave System Implementation Department with AT&T Bell Laboratories in Holmdel, New Jersey. He is responsible for implementing undersea systems, including system test, installation, and maintenance support for current systems; integration of multi-supplier systems; and forward-looking work for future systems. Mr. Runge joined the company in 1967 and has both an M.S. and Ph.D. in electrical engineering from the Technical University of Braunschweig, Germany.*