Future Directions for Undersea Communications

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Technologies used in undersea systems have changed radically in the last five years, driven primarily by the emergence of the erbium-doped fiber amplifier (EDFA). EDFAs have enabled long, transoceanic systems to offer significantly higher capacities (5 gigabits per second [Gbits/s] per fiber pair) and much longer lengths in repeaterless systems. The opportunities offered by EDFAs, combined with other technological advances, extend far beyond those used in currently planned systems. This paper describes the new technologies that are expected to play a role in future undersea systems, and the opportunities for applying those technologies.

Introduction

The EDFA has revolutionized the business of undersea systems. Transoceanic systems using EDFAs are now being installed with capacities of 5 Gbits/s per fiber pair. This represents an increase of almost an order of magnitude relative to that of the previous generation, which carried 560 Mbits/s per fiber pair using regenerators.[1,2] The 5-Gbits/s capacity per fiber pair that EDFAs offer is significantly higher than the capacity that regenerated systems could provide, because of speed limitations of suitably reliable integrated circuits needed for undersea regenerators. The EDFA also supports significantly longer repeaterless system lengths, by using higher launched signal power into the transmission fiber and improved-sensitivity preamplified receivers, which can operate with lower received signal powers.[3]

These significant advances represent only the beginning of the opportunities EDFAs offer for undersea systems. This paper describes how some of the new technologies might be used in undersea systems. It also presents a series of key technologies, and shows how various combinations of these might be used in specific types of undersea applications.

Solitons

On a long system, regular placement of EDFAs can effectively compensate for the loss of signal power along the transmission fiber. Under these circumstances, first-order impairments—the amplified spontaneous emission (ASE) noise generated by the EDFAs, and the chromatic dispersion and nonlinearities in the transmission fiber—determine the maximum bit rate that can be transmitted over a given distance.

In long systems, the dominant nonlinearity is the Kerr effect, the intensity-dependent index of refraction. Here, the fiber's index of refraction, and therefore the propagation velocity, is a function of the instantaneous intensity of the light in the fiber. Interactions between chromatic dispersion and the Kerr effect nonlinearity limit the maximum bit rate that can be transmitted over long distances for the traditional non-return to zero (NRZ) pulse format. However, an alternative pulse format exists in which the specific shape and intensity of the pulses cause the impairment from the fiber nonlinearity to exactly cancel a specific amount of dispersion. Figure 1 compares these unique pulses, which are called solitons, with traditional NRZ signaling. For each of three signaling approaches shown, the presence or absence of a pulse in a given bit period represents a binary 1 or 0, respectively. In NRZ transmission, the pulse is the full width of the bit period, and, thus, a set of *n* contiguous binary 1's forms an effective pulse *n* bits long. As Figure 1 shows, solitons are a

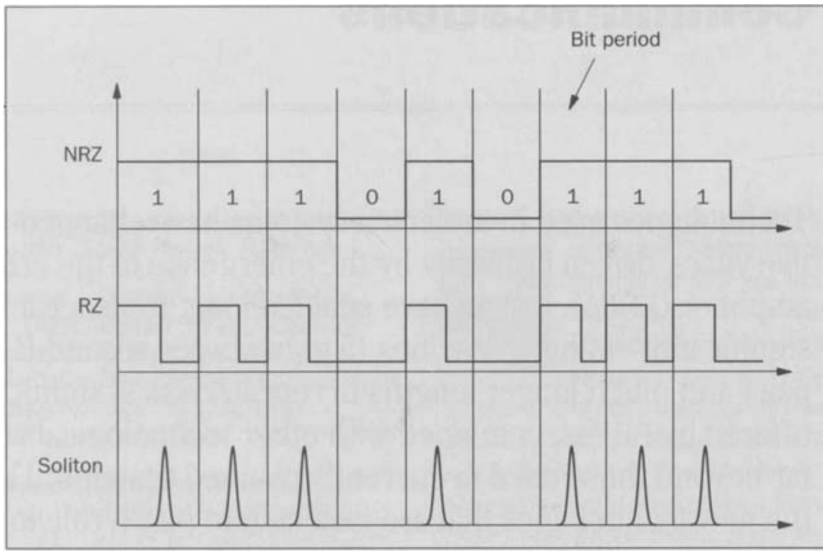

Figure 1. A comparison of the data waveforms of solitons with traditional NRZ and RZ signaling.

special case of the general class of return-to-zero (RZ) signaling, where no signal is present at the transition between bit periods.

The use of dispersion to cancel nonlinearity implies that soliton systems inherently require a transmission channel with non-zero chromatic dispersion, typically in the range of 0.5 to 2 picoseconds per nanometer per kilometer (ps/nm-km). This makes them incompatible with channels designed for NRZ operation, which require zero or near-zero cumulative chromatic dispersion to minimize pulse distortion.[2]

For soliton transmission, the dominant factors that affect the maximum capacity and distance are ASE noise (as in the NRZ case) and Gordon-Haus jitter.[4] Gordon-Haus jitter is caused by small deviations in the frequency of the solitons caused by interactions between ASE noise and the Kerr effect nonlinearity. Figure 2 shows experimentally measured performance for a soliton system using a recirculating loop. The entry labeled "no filters" reflects the performance of a simple soliton system.[5]

Recent research has identified several ways to reduce the magnitude of Gordon-Haus jitter and, therefore, to extend the maximum capacities and distances over which soliton systems can transmit signals. A sequence of bandpass optical filters[6,7] can reduce Gordon-Haus jitter by recentering the wavelengths of jittered pulses. Another method[8] uses a data rate clock to remodulate the pulses at intervals along the line, but this involves greater complexity. More recently, Mollenauer[9] proposed a sequence of bandpass filters whose center frequencies change gradually along the line. The interactions between these filters and the nonlinear soliton pulses enable the solitons to follow the gradual frequency shifts in this sequence of sliding-frequency, guiding filters

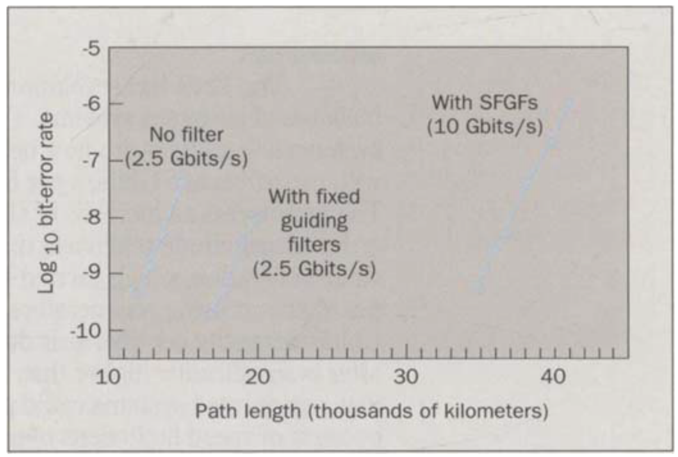

Figure 2. Results of experiments measuring the bit-error rate of soliton transmission without guiding filters, with guiding filters, and with sliding-frequency, guiding filters (SFGFs).

(SFGFs), but noise and other linearly behaving interferers cannot do this. Capacities of 20 Gbits/s (at a single wavelength) have been demonstrated using SFGFs in recirculating loop experiments over a distance of 8,000 km. Figure 2 also shows experimental performance with fixed filters and with SFGFs.

Solitons also offer significant benefits for systems using wavelength division multiplexing (WDM), as discussed more generally in the next section. In a WDM system, where the pulse streams travel at different velocities because of chromatic dispersion, if two solitions collide, the collision is elastic. The effect on each soliton as the pulses initially overlap is almost exactly counteracted by the inter-

Panel 1. Abbreviations, Acronyms, and Terms

ASE—amplified spontaneous emission
EDFA—erbium-doped fiber amplifier
NRZ—non-return to zero
RZ—return to zero
SFGF—sliding-frequency, guiding filter
SNR—signal to noise ratio
UV—ultraviolet
WDM—wavelength-division multiplexing

actions in the second half of the collision as they separate.

Figures 3a through 3e show a simulated sequence, in time, of snapshots of a pair of soliton pulses traveling in opposite directions as they collide. While they overlap, the pulses are significantly distorted, but, after the collision, the pulses are essentially unchanged from their former shape. This effect is only completely true when the transmission line characteristics—such as chromatic dispersion and signal power level—are uniform across the collision. Real-world designs of soliton WDM systems are possible with many wavelengths, and a high bit rate per wavelength, over transoceanic distances. SFGFs also improve the performance of soliton WDM systems by reducing the impact of small frequency offsets resulting from collisions that are not perfectly elastic. Periodic filter structures, such as Fabry-Perot filters, can filter each WDM channel separately. Analytical results predict capacities of 50 Gbits/s or more over distances of 10,000 km using soliton WDM with suitable choices of system parameters, including SFGF. Recirculating loop experiments at AT&T Bell Laboratories have demonstrated two wavelengths at 10 Gbits/s per wavelength over 13,000 km.[10]

As Reference 2 describes, polarization effects also represent a significant impairment for very long amplified systems. Soliton systems are expected to be less affected by both polarization-dependent loss and polarization mode dispersion, especially when SFGFs are used.[11]

An important supporting technology issue for soliton systems is the generation of a sequence of suitable pulses. Early experiments used laboratory lasers, which are unsuitable for practical applications. More practical alternatives have recently been identified, including mode-locked erbium ring lasers,[12] mode-locked semiconductor lasers using an external cavity formed with an ultraviolet (UV)-induced reflective grating,[13] and suitably shaped pulses directly carved from a stream of continuous-wave light using an external modulator.[14]

Higher-Bit-Rate Transmission Using NRZ

While solitons offer one opportunity to increase the capacity of each fiber significantly over long distances, it is also possible to increase the bit rate in single-carrier NRZ systems similar to those being installed today in the major transoceanic networks—TAT12/13 in the Atlantic Ocean and TPC-5 in the Pacific Ocean. System performance degrades with increasing bit rate, both from the increase in noise generated by the increased channel bandwidth required, and from the increased impact of pulse distortions caused by combinations of dispersion, fiber nonlinearity, and polarization effects on the shorter pulses required at higher bit rates.

A variety of techniques exist to mitigate these effects. Forward error correction[1] can reduce the channel signal-to-noise ratio (SNR) required for a given bit-error rate at the system interface. Adaptive equalization techniques at the receiver, such as nonlinear cancellation,[15] have shown promise in reducing pulse distortion. For new installations, polarization impairments can also be reduced by methods such as improving polarization-mode dispersion for the transmission fiber and reducing polarization-dependent loss in repeater components. Recirculating loop experiments in the laboratory have demonstrated NRZ transmission at 10 Gbits/s over a single wavelength for distances longer than 9,000 km, using transmission fiber and amplifiers representative of those being used in the TAT12/13 network.

Phase Conjugation

Single-wavelength NRZ transmission can carry as much as 10 Gbits/s on a channel similar to those being installed today. However, a technique called phase conjugation makes it possible to carry still higher capacities using single-wavelength NRZ transmission. Two important contributors to performance degradation in long NRZ systems are chromatic dispersion and the Kerr effect nonlinearity. For single-wavelength NRZ transmission, the dominant effect of these impairments is self-phase modulation, in which varying the intensity of the signal modulates its phase. This, in turn, produces significant spectral broadening, which, in combi-

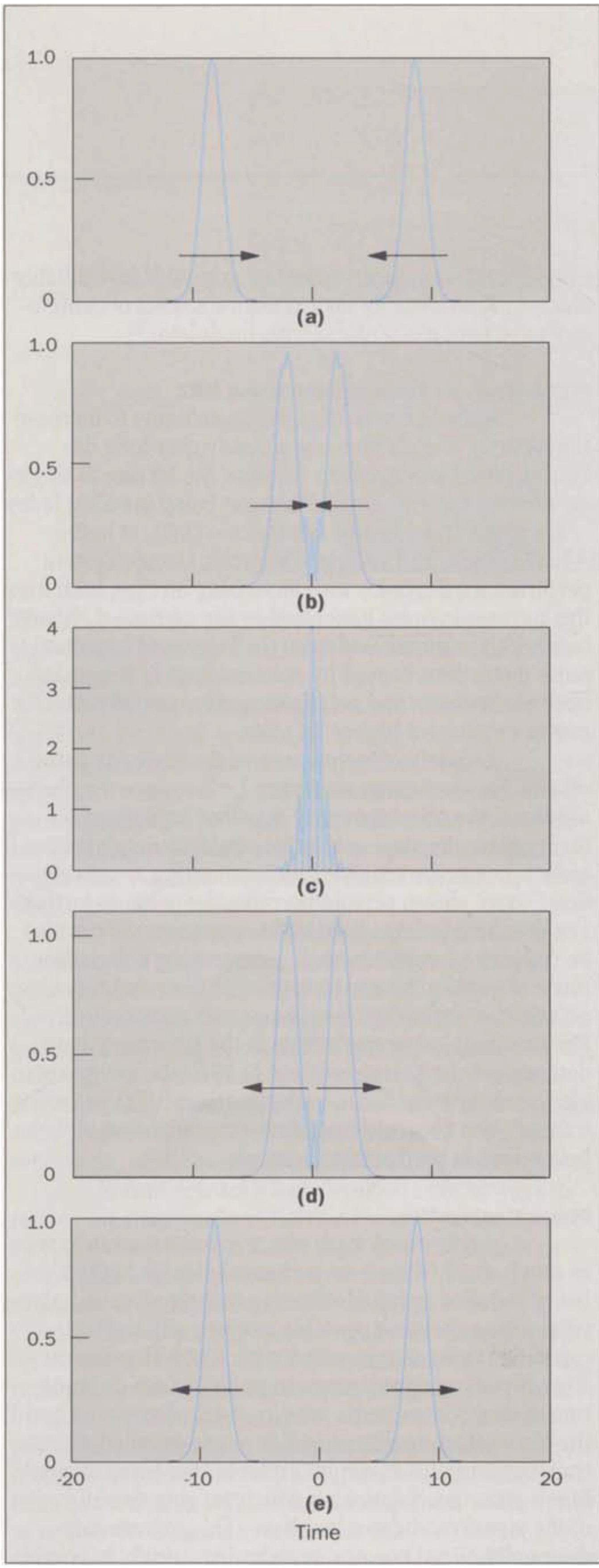

Figure 3. In a WDM system, the collision of two solitons is elastic in lossless fiber. The effects on each soliton as the pulses initially overlap are almost exactly counteracted by the interactions of the second half of the collision as they separate.

nation with dispersion, causes pulse distortion.

Soliton transmission represents one way of mitigating these effects. Another alternative is the continued use of NRZ transmission, in conjunction with optical phase conjugation.[16] In phase conjugation, the spectrum of the signal is inverted at the midpoint of the system, as shown in Figure 4. It can be shown analytically that optical phase conjugation can completely compensate for first-order chromatic dispersion in conjunction with fiber nonlinearity. Phase conjugation cannot completely compensate in practical systems, which have second- and third-order chromatic dispersion (i.e., the magnitude of the dispersion is a function of wavelength, and the slope of that dependence is a function of wavelength). Simulations[17] predict, however, that it would be feasible to transmit 20 Gbits/s over a distance of 9,000 km using NRZ transmission in the presence of realistic nonlinear and dispersive impairments.

Several techniques can invert the spectrum, including four-wave mixing in fiber[18] and semiconductor laser amplifiers.[19] In both cases, device nonlinearities are exploited to create an image of the original signal at a slightly different wavelength and with an inverted spectrum.

Wavelength Division Multiplexing

Figure 5 demonstrates that the EDFA provides suitable gain over a wide range of wavelengths. Figure 5a shows the gain versus wavelength of a typical unsaturated EDFA, and Figure 5b shows gain versus wavelength of an amplifier designed for single-wavelength applications, under saturated conditions. Depending on the amplifier design and the number of regularly spaced (i.e., cascaded) amplifiers, bandwidths of 5 to 50 nm can be achieved, corresponding to 600 to 6,000 gigahertz (GHz) at an approximate operating wavelength of 1,550 nm. Because a data stream can be transmitted using a bandwidth similar to its bit rate, this represents an enormous potential

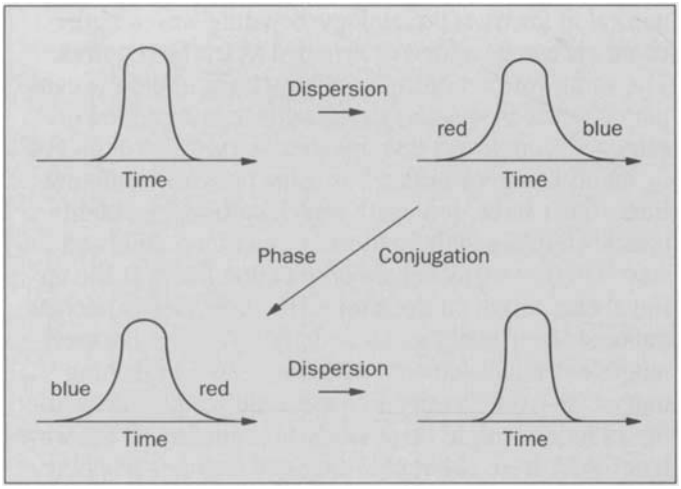

Figure 4. Phase conjugation inverts the spectrum of a signal at the midpoint of a system.

transmission capacity. One attractive way to use this capacity is to have multiple carriers at different wavelengths, each modulated separately with digital data.

Nonlinearities in the transmission fiber can degrade WDM system performance. The Kerr effect (intensity-dependent index of refraction) causes WDM carriers to interact in several ways. One way is cross-phase modulation, in which the intensity of one WDM carrier modulates the phase of other carriers. Another mechanism is four-wave mixing, in which additional frequency components are generated in the band of interest. For each pair of frequency components at frequencies A and B, respectively, additional frequency components are formed at frequencies 2A-B and 2B-A. If the wavelengths of the individual carriers are equally spaced, these mixing products land on wavelengths occupied by other carriers. Depending on the number of carriers and their spacing, this impairment can be minimized using unequal wavelength spacing.

In addition, the magnitude of the interactions from four-wave mixing is determined by the degree of phase matching between the WDM carriers involved. This is, in turn, determined by the magnitude of the chromatic dispersion. For NRZ transmission using WDM, it is desirable to have significant dispersion in any given segment of the system, while limiting the total overall dispersion to

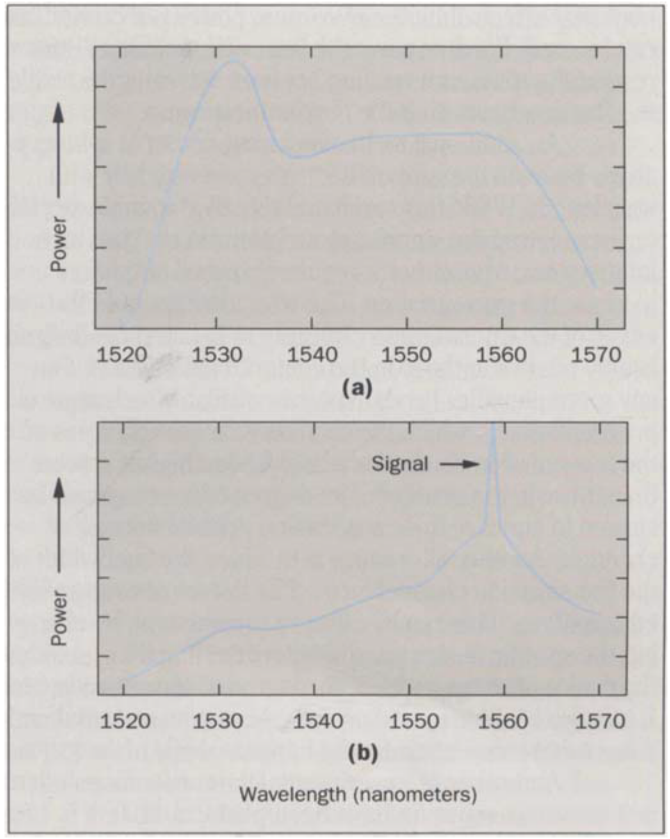

Figure 5. The gain versus wavelength of (a) a typical unsaturated EDFA, and (b) an amplifier designed for single-wavelength applications, under saturated conditions.

avoid pulse distortion. Meeting these constraints requires various cyclic sequences of different dispersion fibers, typically called dispersion maps.[2] The overall concept, although not the specific values of constituent fiber dispersion or intervals, is similar to that used in single-wavelength systems.[2]

The Raman effect[20] is an additional nonlinearity in the fiber. It potentially degrades system performance, by transferring energy from lower to higher wavelength carriers. For the relatively close wavelength spacing used in these systems, this effect becomes larger as the wavelength spacing increases. For WDM systems using NRZ transmission, both of these nonlinear effects limit the maximum power per carrier that can be used. Furthermore, the Kerr effect nonlinearities restrict the minimum spacing between wavelengths, while the Raman effects limit the maximum spacing.

An additional technology issue for WDM systems arises because the gain of the EDFA varies slightly with wavelength. While this variation is small in a single amplifier, it can introduce significant variations in net gain on a long system, whose many, regularly spaced amplifiers increase the gain variation. The WDM carriers near the edges of the transmission channel can be attenuated significantly relative to those in the center of the channel. For any given amplifier bandshape, one available technique is pre-emphasis, in which the carriers near the extremes of the transmission channel are launched at higher powers than those in the center.[21] The degree of pre-emphasis is chosen to equalize the transmission performance of all channels. Another alternative is to widen the bandwidth of the transmission channel formed by the set of concatenated amplifiers. This can be done, to some extent, by changing the specific design parameters of the amplifier, such as the choice of pump wavelength, degree of compression, etc. It can also be done by adding optical components with bandshapes that compensate for the intrinsic shape of the EDFA.

A number of experimental demonstrations of NRZ WDM transmission have been performed. In a straight-line experiment,[22] sixteen 2.5 Gbits/s channels were transmitted over a distance of 1,420 km. High-dispersion fiber was used to minimize four-wave mixing, and channels were set at equal spacing of 0.8 nm. The amplifiers, whose spacings ranged from 95 to 122 km, were designed for high output power and high bandwidth using 980-nm pumping. In a separate experiment, a recirculating loop transmitted four 2.5 Gbits/s channels over a distance of 9,000 km.[23] Although it was not the optimum for WDM applications, this experiment used the same dispersion map (and the same amplifier design and 45-km spacing) as the TAT12/13 single-wavelength system currently nearing installation. Unequal wavelength spacings were used to minimize the impact of four-wave mixing, in part because of the non-optimum dispersion map used.

Branching Technologies

Undersea networks that contain many points along a cable where traffic is added or removed are a natural fit for WDM technology. Separate wavelength channels can be added or dropped as traffic requires. These networks require branching units along the cable, points at which specific wavelengths can be added or removed from fibers that are also carrying through traffic on other wavelengths. For some network configurations, this can be done with wavelength-independent optical couplers in the undersea branching units and wavelength-selective channel selection filters at the terminal equipment on the shore. However, issues such as national sovereignty and wavelength reuse make wavelength-selective elements in the undersea branching units a virtual necessity. For some simple network configurations, it might be possible to predefine all the wavelengths of these channel-adding and channel-dropping filters when the system is manufactured. In effect, this predefines the connectivity between the various landing points in the undersea system. Larger, more realistic networks, however, are likely to need some level of configurability of traffic capacities after the system is installed. This, in turn, requires that some or all of the channel-dropping and channel-adding filters be able to select the channel(s) to be dropped or added.

A number of technologies allow dropping and adding selected channels from a WDM stream on a fiber. Alternatives that drop or add fixed wavelengths include waveguide routers,[24] interference filters, and various grating filters. Some of these, particularly the waveguide router, are well suited to implementation on planar waveguide technology.[25] An alternative for selectable channel add/drop is one or more fixed selectors combined with optical switches. Other options include $LiNbO_3$ tunable filters, acousto-optic filters, or magneto-optic filters.

New Installation Techniques

New technology not only improves products, but can also reduce system costs during installation. Investigations are under way to explore increasing the speed at which deep-water cable is laid under favorable conditions, from current maximum speeds of about 7.5 knots[26] to speeds in the range of 10 knots. A significant amount of time could also be saved by automating the process of joining sections of systems aboard ship. In addition, adding armoring aboard ship only to those sections of cable that are likely to encounter adverse conditions would significantly reduce both the cost and cable storage space on the ship.

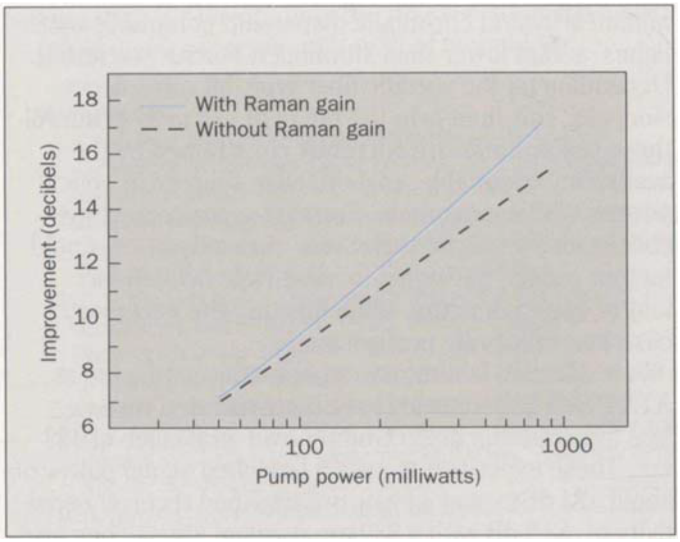

Figure 6. The improvement in overall loss that can be tolerated in a repeaterless system, shown as a function of the pump power launched toward a remote EDFA.

Applications to Transoceanic Systems

Transoceanic systems such as TAT12/13, TPC-5, and their anticipated successors, whose transmission paths range in length from 6,000 to 9,000 km, need the highest possible capacity at the lowest cost per bit. The capacity of first-generation optical amplifier systems currently being installed might be upgradable. The dispersion maps of these systems are optimized for NRZ transmission, with near-zero cumulative chromatic dispersion, and are therefore unsuitable for soliton transmission. Opportunities do exist, however, to expand the capacity using NRZ.

Recirculating loop experiments on equipment similar to that in TAT12/13 have been performed over a distance of 9,000 km using both single-wavelength 10 Gbits/s and 4x2.5 Gbits/s WDM NRZ transmission. While neither of these experiments demonstrated the degree of margin necessary for an actual system application, they helped define how much margin would be needed. One possible technique for providing this margin is forward error correction.

Another possible opportunity for upgrading an existing transoceanic system is to add a phase conjugator in the middle of the system. This would require a deep-water "repair" and the development of sophisticated optics with the prerequisite undersea reliability, but it might offer capacities in the 20-Gbits/s range as upgrades to existing systems.

For new systems installed in transoceanic applications, any of these alternatives could be used. In addition, an NRZ system that incorporates a dispersion map and an amplifier design more suited to WDM transmission might support more than four WDM carriers or multiple carriers at higher bit rates. For new system installations, soliton transmission also becomes a viable alternative, either as a single high-bit-rate soliton stream of perhaps 20 Gbits/s, or as a set of WDM channels from about 5 to 10 Gbits/s each. Simulations predict that soliton WDM systems could eventually offer more than 50 Gbits/s per fiber pair.

Multipoint Networks

Many emerging applications in the undersea cable system call for multiple points where traffic can be added or dropped. In TAT-9, an early application, undersea branching multiplexes first convert 591.2 megabit per second (Mbit/s) optical streams into electrical format, demultiplex and cross-connect constituent channels at 45 and 139 Mbits/s, and then reassemble an outgoing 591.2 Mbits/s stream for conversion back to optics. Future applications of multipoint networks, such as Africa ONE, call for significantly more complex network topologies, as well as much higher overall capacities at lower equivalent costs. WDM technology fits these applications exceptionally well. Individual wavelengths representing the traffic to and from a particular node on the network can be easily combined with the traffic from other sites, using simple, passive, optical components. Depending on such parameters as the overall length, the channel-bit rate, and the underlying technology choices (e.g., NRZ or solitons), many WDM channels can be carried on a single fiber pair, making complex network topologies possible. To create still larger networks, multiple fiber pairs, each carrying a spectrum of WDM carriers, can be used.

The technology chosen for the signal sources and the channel-selecting devices associated with each receiver may make some of these types of WDM networks highly reconfigurable. Other individual applications of these technologies, such as wavelength shifters,[27] may eventually play a role in such reconfigurable networks.

Repeaterless Systems

Interconnecting nearby islands, or implementing a domestic network using a series of undersea festoons, requires undersea systems without any repeaters.[28] As Reference 3 describes, repeaterless products currently planned by AT&T Submarine Systems, Inc. use remote pumping, in which 1,480-nm pump power is sent in the reverse direction on the transmission fiber, from the receiver to a piece of erbium-doped fiber several tens of kilometers offshore. Figure 6 shows the degree of improvement, as a function of pump power launched into the transmission fiber, that can be achieved in the overall loss (which is proportional to the length of the fiber) with remote pumping. This is compared with a system that has a near-optimum optical preamplifier but no remote pumping. Particularly at higher pump powers, Raman gain from the nominally 1,480-nm pump is a significant factor. Forward error correction, which allows the receiver to operate at a higher bit-error rate and a lower incoming signal power, while meeting customer error-rate requirements, is also part of current product plans.

Extending the maximum repeaterless span at a given bit rate beyond that achievable with the technologies described here is limited by several things. One fundamental limit is fiber loss. Current silica core fibers, with losses of less than 0.18 dB/km, are already quite close to the fundamental limits of 0.155 dB/km for silica-based fiber. Fibers based on materials such as fluorides could theoretically offer much lower loss, but research in these areas has not been promising.

Another limit is the power that can be launched into the transmission fiber, including signal power limits at the transmitter, and pump power limits at the receiver and, perhaps, the transmitter. Stimulated Raman scattering[20] offers a fundamental limit on launched power for a given transmission fiber design, and may also define the practical limit for pump power launched for remote pumping purposes. This limit is in the 1- to 2-watt range (+30 to 33 decibels referred to one milliwatt [dBm]) for typical current fiber designs. For launched signal power, however, the interaction between the Kerr effect nonlinearity and chromatic dispersion potentially establishes a limit lower than stimulated Raman scattering. Depending on the specific fiber type, bit rate, dispersion, etc., this limit is in the range of +22 to 27 dBm. All these power limits are currently constrained by the availability of suitable, cost-effective sources of optical powers of this magnitude. Forward-error-correcting codes more powerful than those currently in use could further reduce the signal-to-noise ratio needed for longer system lengths, while meeting the necessary customer error-rate performance.

Recent laboratory experiments conducted at AT&T Bell Laboratories have demonstrated repeaterless transmission of 2.5 Gbits/s over a distance of 423 km. These experiments used a launched signal power of about +24 dBm, and a basic preamplified receiver sensitivity of -42.6 dB with a 980-nm pumped EDFA. They also used a remotely pumped "offshore" EDFA, pumped at 1,480 nm with about +27 dBm of launched pump power from the receiver, to provide about 15 dB of loss budget improvement. A similar remote pumped post-amplifier at the transmitter, also pumped by about +27 dBm, provided 3 dB of loss budget improvement. Experiments to be performed late in 1994—with still higher pump power, forward error correction, and silica core fiber with separate dispersion compensation—are expected to transmit signals at a speed of 2.5 Gbits/s over a distance of 500 km.

Conclusions

New undersea lightwave systems now being installed have just begun to tap the enormous potential offered by the EDFA. A variety of new technologies will offer undersea systems with not only vastly greater capacities, but also with the ability to implement complex networks. A key technology for these advancements is WDM, which enables the same EDFA to amplify digital signals at numerous different wavelengths. This set of many digital signals supports both significantly higher total capacity and flexible traffic routing. Where higher capacity is the focus, higher-bit-rate systems operating at a single wavelength are also feasible. Both WDM operation and higher-rate single-wavelength systems are possible with the NRZ signaling used in the current generation of undersea optical amplifier systems. Soliton transmission is expected to increase the number of wavelengths available, as well as the capacity per wavelength. Overall, only the first few steps have been taken down a long, fruitful path of technology.

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