Optical Fiber Technology **6**, 15–32 (2000)
doi:10.1006/ofte.1999.0308, available online at http://www.idealibrary.com on IDEAL®

Invited Paper

How Do Submarine Networks Web the World?

Jean-Marie Beaufils

Asia–Pacific Alcatel Submarine Networks, 6 Commonwealth Lane, #04-01/04 GMTI Building, Singapore 149547, Singapore
E-mail: jean-marie.beaufils@alcatel.com.sg

Received June 14, 1999

From late 1997 to mid-1999, major submarine cable projects have been launched and huge contracts have been signed for the implementation of transatlantic and transpacific submarine cable systems. The submarine cable industry has rarely seen so much interest in its history and the exponential growth of offered capacity on a single fiber pair has attracted all incumbent and new, national, and international, state-owned, and private operators. Will the capacity per fiber endlessly increase and the endless bandwidth needs continue to match or will limiting factors slow down the pace? It will be shown how this appetite has been made possible and what the required conditions are to keep the same pace. © 2000 Academic Press

BRIEF HISTORY OF THE SUBMARINE CABLE ADVENTURE

The history of communications by submarine cable can be seen to follow a series of evolutionary steps. This evolutionary process has been punctuated by a series of epochal events marking technological advances and, most recently, changes in the telecommunications regulatory environment.

The first stage in the evolutionary process is marked by the age of submarine communications by telegraph cable. This age dates back to 1850, when a telegraph cable was laid between England and France beneath the English Channel. Inter-continental communications by subsea telegraph cable began in 1866 when the first successful transoceanic telegraph cable was laid across the Atlantic between the United Kingdom and North America, while in Asia the Great Northern Telegraph

1068-5200/00 $35.00

Company opened the first Asian international submarine cable system between Japan and Russia in 1871.

The first hundred years of submarine communications saw the gradual and steady development of a worldwide network of submarine telegraph cables. Faster development in submarine communications was retarded by high construction and maintenance costs and the small number of circuits available in these systems. These factors translated into a high per circuit cost, restricted access, and high cost of submarine communications.

With the development of the first generation coaxial cables for submarine telecommunications applications in the early 1950s, the second age of submarine telecommunications was born. With this technology, submarine cable systems began to grow significantly in both size and importance.

The first transoceanic telephone cable system, Trans-Atlantic Telephone 1 (TAT-1), was laid in 1956 and had a capacity of just 36 circuits of which only 15 were actually sold. The first major cable to be laid in the Pacific Ocean was HAW-1, an analogue coaxial cable system with a capacity of 60 circuits, allowing 150 simultaneous conversations between Hawaii and California. ComPac, the first trans-Pacific (United States–Australia) cable system, became operational in 1962, with 80 circuits.

Trans-Pacific Cable 1 (TPC-1), which went into service in 1964, marked the introduction into the Asia-Pacific of the second-generation coaxial cable technology, with a capacity of 138 circuits. The third generation was introduced by HAW-3, with a capacity of 845 circuits. This was followed by Oluho, the fourth generation, with 1380 circuits allowing 3450 simultaneous conversations.

The explosive age in the development of submarine cable networks was triggered by the development of optical fiber digital technology in the 1980s. The first transoceanic fiber-optic submarine cable system TAT-8 came into service in 1988. It linked the United Kingdom, France, and the United States with more capacity in a single cable than the combined capacity of all the transatlantic cables existing up to that time, TPC-3 and HAW-4 rapidly followed TAT-8 in 1989 by providing submarine fiber-optic services across the Pacific between Japan, Guam, and the United States. Since these pioneering fiber-optic systems, the world has seen a proliferation in the development of a global submarine telecommunication infrastructure. The number of fiber-optic submarine cable systems distributed in the Asia-Pacific region in the last ten years already exceeds the number of analogue systems laid in the preceding 40 years. In 1998, the world investment in optical fiber submarine cable systems has exceeded US$18 billion, with more than half of this being spent in the Asia-Pacific region. By the end of 2003 forecasts show that worldwide investment in submarine telecommunication networks will more than double.

WHY SUBMARINE NETWORKS?

Submarine networks are commonly challenged by satellite communications systems. However, a comparison of the two technologies show that although satellite systems are the most efficient solution for TV broadcast, for access to remote locations, and essentially, for wireless access to the local loop and the network backbone, submarine networks are the best choice for transmission of high capacity traffic between countries, as long as they have a coastline, and between continents.

The main reasons are summarized as follows:

***Capacity*: Submarine systems offer very high capacity (today, systems are contracted for up to 2 Tbit/s per cable). This is far from the reach of any anticipated satellite system.

**Transmission quality*. Real time transmission along with very low bit error rate offered by submarine cables contrast with satellite communications which add delay to communications making interactive data transmission difficult and supply a quality of transmission subject to external factors.

**Confidentiality*. Submarine transmission offers undoubtedly the best confidentiality and security of transmission than any other means by its mere nature.

**Capacity upgrade*. To cater to increased traffic, it is relatively easy to increase the capacity of a submarine system during its lifetime by means of wavelength-division multiplexing technology. It is almost impossible to do the same with satellite systems.

**Lifetime*: Submarine systems are designed to last for 25 years whereas satellite systems have a much shorter lifetime.

**Maintenance*. Maintenance of submarine cables is possible in the event of a cable failure. Satellite failure cannot be repaired easily.

**Civil engineering works*. A submarine equipment station is usually a relatively small room in which the terrestrial electronics equipment (submarine line terminals, SDH equipment, network managers, etc.) is located. Earth stations require larger room space and installation efforts.

Hence, owing to their high capacity, high reliability, and high signal quality, submarine cable systems are well suited to trunk transport and backbone network infrastructure. On the other hand, satellite systems are more dedicated to video broadcasting and personal communication services such as mobile telephony (satellite constellations) or to access remote areas (geostationary satellites).

As a consequence, the share between cable and satellite communications over the oceans has drastically changed during the past years and will continue to favor submarine communications even more (see Table 1).

Apart from the fact that many existing cables are now full or almost full, in particular across the Atlantic and Pacific oceans, other factors are pushing for the need for new capacity in the coming years:

*The Internet has surprised the telecommunications world with its sudden exponential growth. It is believed that the Internet demand will continue at a high rate during the next ten years. Growth forecasts are as optimistic as 10% per month to tripling every quarter (J.F. Mergen, GTE Internetworking). Voice is consequently being marginalized as it has been suggested that voice traffic will represent no more than 1% of the total traffic before 2004 (Ebbers, WorldCom, WSJ 9/9/97).

TABLE 1
Cable and Satellite Capacity 1986–2000

	Transatlantic voice paths		Transpacific voice paths	
Year	Cable	Satellite	Cable	Satellite
1986	22,000	78,000	2,000	39,000
1988	60,000	78,000	37,800	39,000
1990	145,000	283,000	37,800	39,000
1992	296,600	496,000	190,500	27,000
1994	664,000	620,800	264,000	234,000
1996	1,264,000	710,800	864,600	234,000
1997–2000	1,264,000	737,500	1,464,600	424,500

Source. TeleGeography, Inc.

This trend will be even more true with the advent of the second generation of the Internet. The Internet will not only carry e-mail, e-commerce, etc., but also voice, video, and HDTV. Table 2, which gives the actual and forecasted market for dial-up Internet in Asia and the Pacific between 1997 and 2006, confirms this trend in Asia.

*Liberalization of telecommunications in more and more countries will continue to lead to the advent of new operators who have little capacity and will seek new paths to compete with well-established traditional operators.

New telecom operators and Internet service providers are emerging and seek bandwidth with seamless connections from cities to cities. The classic club deal cable approach where capacity is brought from one side of the ocean to the other without the point of presence (POP) connection is not of interest to many of the newcomers who are seeking home-to-home connection capabilities. These newcomers are targeted by companies proposing worldwide end-to-end networks, providing to their customers one-stop shopping services.

TABLE 2
Market for Dial-up Internet

	1997 subscribers	2006 subscribers
Japan	8,500,000	25,711,000
Korea	325,000	7,125,000
Singapore	250,000	524,000
Malaysia	210,000	2,266,000
China	160,000	23,565,000

Source. IDC, Market Forecast for Internet Commerce, Oct. 1997.

*Globalization is also an important factor in the expected traffic growth. Big and small companies establish themselves in different parts of the world and need to link their different sites together with high-quality services at low cost. These companies are willing to exchange data—via the Intranet—on sales, finance, manufacturing processes, and R & D, in addition to ''traditional'' electronic mails.

*There are more and more demands for services: video-conferencing, real-time data transmission, and multimedia applications like the transmission of colored graphic images, video images, and high-fidelity sounds. E-mail, remote computing, and file transfer as well as conferencing and voice on the Internet are also possible and are becoming more and more popular. These services, and others to come, involve larger and larger amounts of traffic bandwidth.

All these factors, as well as the advent of new technologies that will provide higher capacities at much lower costs, will stimulate the market in return [1].

As a consequence, overall worldwide traffic will grow from approximately 40 billion minutes per year in 1997 to 210 billion minutes per year in 2009 according to ITU sources (see Fig. 1).

Furthermore, as an example, Fig. 2 shows the existing and forecasted transatlantic capacity for traditional circuit-switched traffic (PSTN) and other services like Internet or corporate networks. This figure shows that the available capacity has been filled since the end of 1998. By 2002 this capacity should (and will) be doubled to match the forecasted needs.

In 1998, data traffic in public networks has been more important in volume than voice traffic for the first time in history. Hence it is understandable that quality and high security are more and more in demand (more than is needed for voice traffic). Future networks will have to provide the users with error-free transmission and rapid restoration in the event of a catastrophic failure.

As a result, KMI forecasts that 616,634 km of cable will be installed worldwide during the next five years.

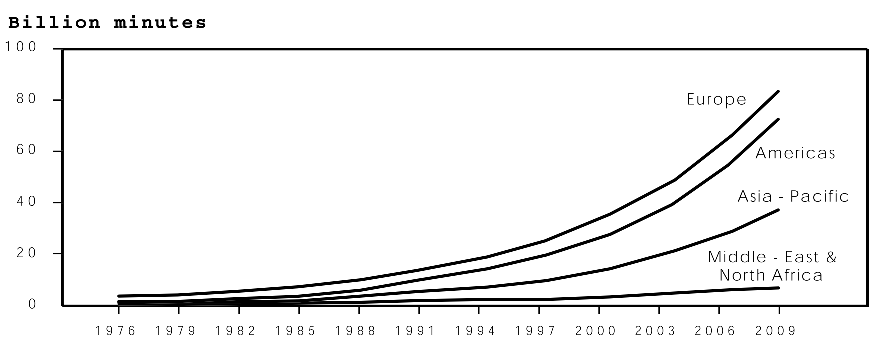


FIG. 1. International traffic growth.

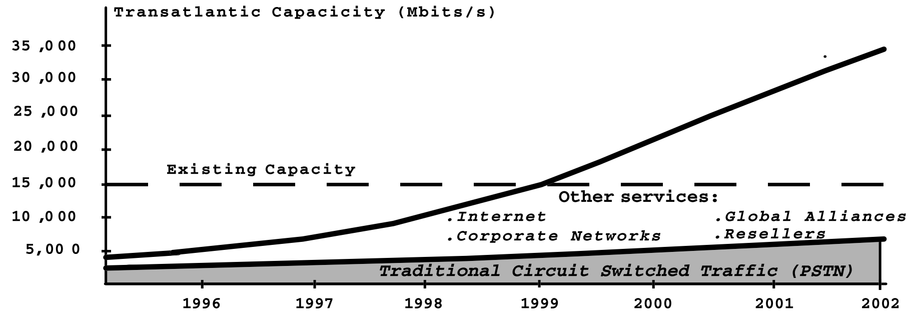


FIG. 2. Transatlantic utilized capacity (*Source*. ITU, FCC, CSMG).

TECHNOLOGY BOOMING

By the end of 1998 there had been a 64-fold increase in available capacity since the first transoceanic fiber-optic system entered into service. This trend is expected to continue, with further increases in capacity (in excess of 1000 times greater than the first fiber-optic systems) being predicted within the next five years.

Optically amplified repeaters, the key elements in the system design, have seen their design dramatically changed from the previous regenerative era. Less than ten years ago, the optical signal had to be converted back to the electrical domain in each repeater. Then retiming, reshaping and regeneration (in fact, reamplification) were applied to the signal before converting it back to the optical domain. These repeaters were known as the ‘‘3R’’ repeaters. The newest generation systems are ‘‘all photonic’’ in that no electronics exists in their transmission path. This allows for simpler repeater construction using only low speed electronics and a bit rate free from modulation. The key components of a repeater are the pump lasers, which are protected on a 1 + 1 basis to cope with potential component failure. Technology has recently moved from the 1480 to the 980 nm technology, allowing longer repeater spans for a given bit rate.

System line performance can be monitored from the terminal station in a totally passive fashion. This is achieved by modulating a very low-level signal onto the carrier. At each repeater the signal is ‘‘looped back’’ through a special ‘‘high loss optical loop-back’’ coupler. The terminal can then determine the gain performance of each individual amplifier in the system by recovering this low-level signal as returned by each successive repeater and comparing the various levels.

Another feature of optically amplified (OA) systems is that they can be upgraded without replacement of the undersea plant as long as they have been engineered from the outset to provide for this capability. As a result, repeatered OA systems may be upgraded to higher bit-rates merely by changing the terminal equipment if the repeater spacing will support this. This capability results from the fact that optical amplifiers are bit-rate insensitive.

Forward error correction (FEC) is also used to provide virtually error-free performance of an increase in the system bit-rate. Application of FEC is a terminal function and has no impact on the submarine plant.

With the development of wavelength-division multiplexing (WDM) it is now possible to transmit more than one active signal on a fiber pair and particular wavelengths can be routed down spurs, or branches, to their intended destination, using wavelength filters (see Fig. 3). Using WDM techniques, an established route can be upgraded by adding more optical channels without additional fiber.

Wavelength-division multiplexing can provide not only higher capacity by multiplexing several wavelengths together, but also full mesh connection by wavelength, as well as easy wavelength allocation and reallocation adapted to the changing traffic (in association with SDH equipment such as add–drop multiplexers and digital cross-connects). It also facilitates the allocation of dedicated wavelengths between two particular nodes. Consequently, to protect sovereignty, as well as the merging of domestic and international traffic on the same fiber, different wavelengths are allocated to the two types of traffic.

WDM branching units (WDM-BUs) have the advantage that only traffic destined for a particular landing point need land at that point, and hence a high level of traffic security can be assured. On the other hand, WDM-BUs tend to be expensive and significantly more complex than simple passive branching units.

The repeatered undersea systems installed up to 1996 had a maximum capacity of 5 Gbit/s on a single wavelength per fiber pair with a maximum number of four fiber pairs per cable.

This led to a maximum capacity of 20 Gbit/s per cable. Current R & D programs allow commercial systems to be proposed with 10 Gbit/s per optical carrier (wavelength) for in-service dates during 2000.

Furthermore, the multiplexing of several wavelengths on the same fiber (WDM) now allows 16×2.5 Gbit/s = 40 Gbit/s of information to be implemented in the oceans. If four fiber pairs are included in a single cable, this means that 80 Gbit/s of information can be transmitted over that one cable—one fiber pair being required for 2-way traffic.

The next generation will push the capacity per fiber as high as 320 Gbit/s by multiplexing 32 wavelengths at 10 Gbit/s. With eight fiber pairs in a single cable, 2560 Gbit/s of capacity (more than 2 Tbit/s), representing more than 30 million simultaneous phone calls, will be available on a single cable by 2001.

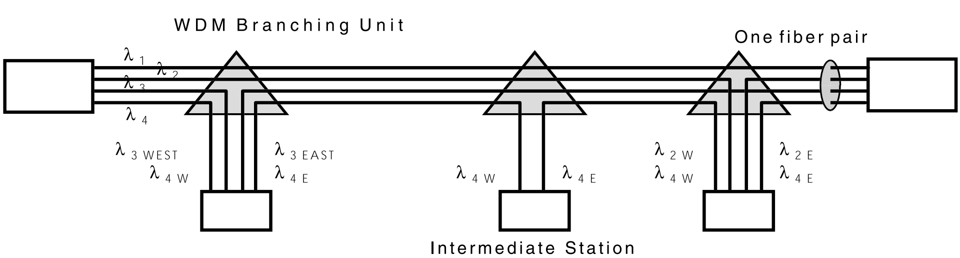


FIG. 3. WDM branching unit.

Even more ambitious systems for the future will allow 64 wavelengths at 10 Gbit/s per fiber. This leads to more than 5 Tbit/s in a single cable [2].

Figure 4 shows this steady and unexpected capacity growth in optical fibers over recent years. Looking further into the future, is it possible to forecast the bandwidth to be offered on a single fiber pair?

During the past few years, the submarine cable industry has been used to witness new performance leapfrogs every six months or so. Four and eight wavelengths at 2.5 Gbit/s were being offered with care in 1997. Since then, 16×2.5 Gbit/s products have been put on the market and these will be followed closely by 16×10 and 32×10 Gbit/s systems.

The next question is when long-haul 1 Tbit/s (1000 Gbit/s) transmission will be available on a single fiber. It may seem so easy that one expects it underwater soon.

However, to reach such capacity will mean dramatically changing characteristics of the current technology. What makes a high bit-rate system can be summarized in a few words: optical amplifiers, wavelength spacing, chromatic dispersion, basic bit-rate, and regeneration.

Only a good combination of these key features may allow future long-haul transmission at terabit speed. The current technologies on which all systems are based since the first announcement of the WDM technology cannot meet all the requirements for higher capacity.

The bandwidth of optical amplifiers will have to be increased drastically to allow for the transmission of a large number of channels. It is likely that the current bandwidth would have to be doubled. To meet such a challenge, the structure of the amplifiers would have to be revised and new electro-optical components designed to get to the L-band (1570–1610 nm).

Fitting more wavelengths in a given amplifier bandwidth will require smaller channel spacing. A channel spacing of 0.4 nm (50 GHz at 1.5 μm wavelength) or less could be required, assuming, for example, a 48×20 Gbit/s scheme. As it is clear that current products are not capable of coping with such spacing, it is unclear if, with such spacing, limitation could be reached because of important

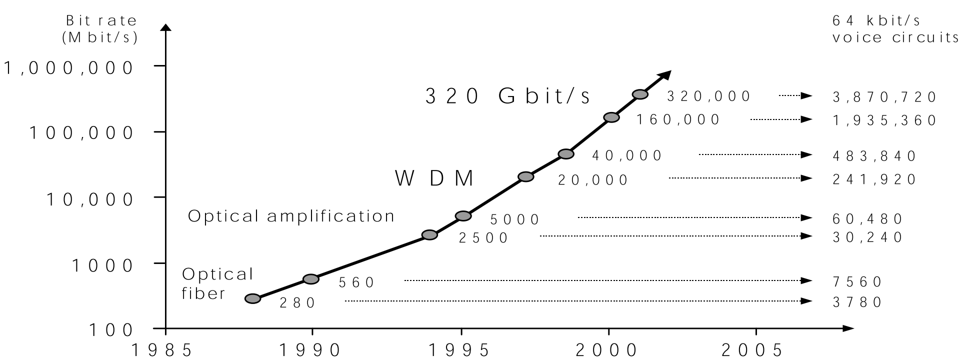


FIG. 4. Capacity increase over time.

interactivity between the channels themselves. In that case, even higher amplifier bandwidth would then be required.

Fiber is obviously another area of improvement. Large effective area fibers are now available for the future systems. However, for terabit applications, it is not clear which type of fiber will be most suitable. A new generation of fiber would probably be needed and its characteristics may also impact on the cable design itself.

Furthermore, the chromatic dispersion management, which is a key issue when designing long-haul systems, will have to be more and more complex. It may be necessary to install various types of fiber and mix them along the same cable.

Along with the fiber and the amplifiers, a new type of terminal equipment will have to be designed. In particular, the line code will have to move from the classical NRZ format to a more sophisticated format such as soliton, chirped-RZ, etc. A soliton pulse has the property of propagation without distortion, as long as an adequate relationship is preserved between the pulse power, the pulse width and repetition rate, and the fiber chromatic dispersion. Major limiting phenomena include signal-to-noise ratio degradation, soliton timing jitter, and polarization effects.

The move may even be more complex if regeneration is proven to be the only way toward long-haul terabit transmission. Two main areas of research still prevail: electronic regeneration and optical regeneration.

Going to electrical or optical regeneration would mean more power would need to be distributed on the line, to each repeater. This would probably affect the cable design itself as higher power would be needed through the cable for long-haul systems.

Since the introduction of WDM technology and probably into the beginning of the next century, WDM products, EDFAs, dispersion management, and line format have all been based on the same technical approach. Improvements are made step by step to fit more wavelengths and higher bit rates into the fiber. However, as seen previously, the long-haul terabit transmission will need drastic changes in the general philosophy of system and equipment design.

Obviously it is not possible to specify when all these future technologies will be ready for commercial systems. As shown in Fig. 5, all forecasts regarding the availability dates of new technologies that were made during the past ten years have been proved wrong and much too pessimistic. For example, in 1991, it was forecast that a capacity of 50 Gbit/s per fiber would not be available before year 2002. The reality is that the first 16×2.5 Gbit/s systems will be ready for service in 1999, three years before the data predicted in 1991. However, the amount of work to be done to:

—select and test the right technologies for each piece of the future terabit systems,

—get reliable opto-electronic components,

—design the commercial equipment/fiber/cable,

—manufacture the first systems

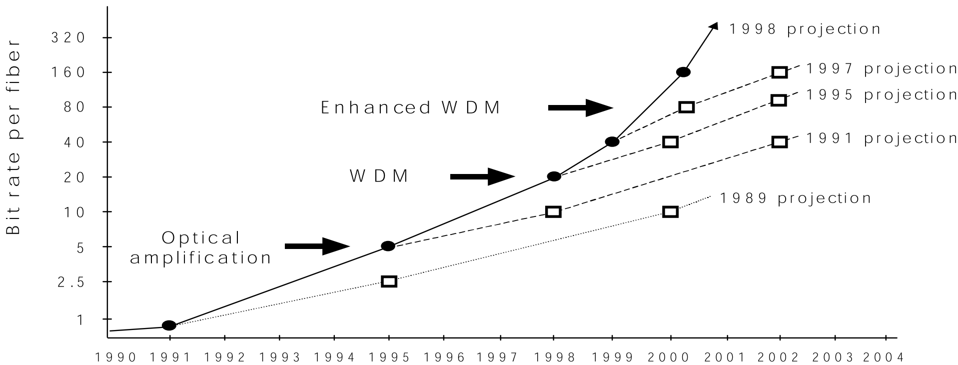


FIG. 5. Capacity blow-up.

is high and hard enough to agree that caution is required before making any forecast.

In turn, forecasting traffic is even more difficult. During recent years, the demand for capacity has outstripped supply owing to the explosion in Internet traffic and the development of broadband services.

The preliminary conclusion, if anyone could draw any conclusion at this stage, is that the offered capacity on a single fiber has grown exponentially during the recent past trying to catch up with the traffic demand. However, exponentially R & D efforts will be needed in the coming years to keep the same pace.

NETWORK SELF-RESTORATION

Parallel and technological advances in submarine cable technology have been changes in the philosophical approach of carriers to submarine telecommunications. Submarine systems were originally installed as point-to-point links, but these have now been superseded by a global integrated network approach, as operators have come to demand total solutions with unique network management for their terrestrial and submarine networks [3].

It has also become apparent to suppliers that demands for network protection are replacing requests for equipment protection and that network flexibility is high on the list of priorities for buyers in general. This flexibility includes easy network evolution and reconfiguration, as well as capacity upgradability. To fulfill these requirements, different types of basic network topologies are being offered which include:

—string/branched string and festoon;

—ring/collapsed ring;

—mesh/collapsed mesh; and

—integrated networks where the submarine system is planned as part of a network of mixed applications.

For point-to-point systems, protection via adjacent networks is mandatory. For transoceanic networks, the ring architecture is the most suitable way of providing efficient self-restoration.

Two types of self-healing rings are currently defined by ITU recommendations G.783 and G.841. The SNC-P (subnetwork connection protection) ring provides path protection. The MS-SPRing (multiplex section shared protection ring) provides section protection.

Furthermore, rings can be uni- or bi-directional, single or dual-ended. The MS-SPRing bidirectional dual-ended switching is suitable for networks where most of the traffic is exchanged between adjacent nodes. This is because the MS-SPRing allows the reuse of the bandwidth along the spans as traffic may be evenly dropped and added at each adjacent node. It is not optimized for hub networks where two main ‘‘hub’’ cities need to be interconnected.

It then requires sophisticated equipment: a complex protocol between nodes is necessary to allow for dual-ended switching (use of the K1/K2 bytes in the overhead of the STM-16 SDH frame). Hence the switching time over transoceanic distances is more significant. Furthermore, due to its mere nature, relooping at the section level following a catastrophic failure does not prevent a triple ocean crossing as shown in Fig. 6. The network protection equipment (NPE) can cope with this problem. This equipment needs to be installed in each station. It then allows the switching time to be lower than 300 ms. This equipment is part of the add−drop multiplexer (ADM), the main task of which is to allow any tributary from the incoming west and east aggregates to be dropped and, equally, any new tributary with equivalent capacity to be added to the west or east aggregates in place of the dropped tributary.

The SNC-P unidirectional ring with single-ended switching is a simpler ring type that also suits long transoceanic networks. SNC-P path protection implies that each virtual carrier VC-4 (or STM-1 in the SDH hierarchy) is broadcast over two separate routes. In the event of a cable cut or equipment failure, the end-node selects the best signal from the working and protected signals arriving via different routes. The switching time is very short (below 50 ms) as no particular protocol is needed between nodes to allow for restoration. Furthermore, no extra equipment is needed to restore the traffic with only one ocean crossing. Hence, no triple ocean crossing happens in the event of a failure.

A sophisticated extension to the ring architectures presented above, is drop and continue architecture. It is based on multiple interconnected rings. Figure 7 shows such an arrangement where three rings (two terrestrial and one submarine) are all interconnected. In this example, the interconnection is done at the landing station at the VC-4 level by means of ADMs.

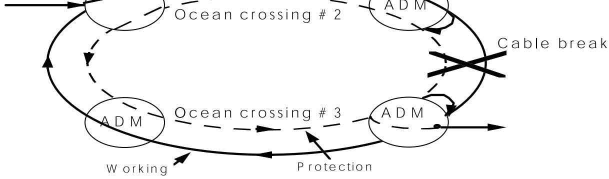


FIG. 6. MS-SPRing architecture; triple ocean crossing in the case of a cable failure.

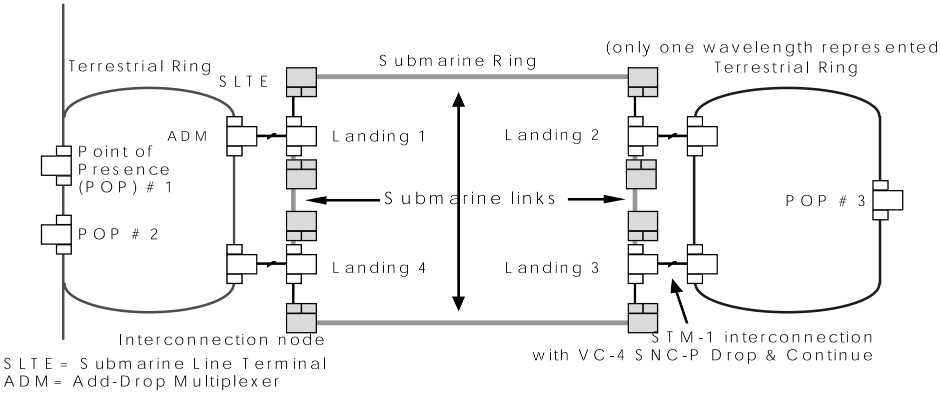


FIG. 7. Triple ring interconnection.

The ADMs are configured in the drop and continue mode. This means that a VC-4 is broadcasted in the ADMs from one incoming aggregate to the outgoing aggregate and at the same time toward the tributary interface. Then the outcoming STM-1 leaves the ADM of a ring and is connected to the adjacent ADM of the adjacent ring via the tributary interface.

The essential advantage of the drop and continue function is that it allows protection of simultaneous failures in each of the interconnected rings. Figure 8 shows an example of one failure in each of the three rings. In the submarine ring, it is imagined that a fishing net has cut the cable in the southern part of the ring. In one of the terrestrial rings, a cable cut has also occurred during digging work and in the other terrestrial ring, an equipment failure has occurred.

In that same figure one can see what happens to a particular VC-4 that leaves the POP at city #1 and is supposed to reach the POP at city #3. Due to the broadcasting of this VC-4 in the two directions of ring #1, it always reaches ring #2. Again, in ring #2, the broadcast along two possible routes allows the VC-4 to reach ring #3 even with a cable break in the southern segment, and so forth. This can be applied to every single VC-4.

Examples of the above architecture have been applied to the following transpacific contracted systems.

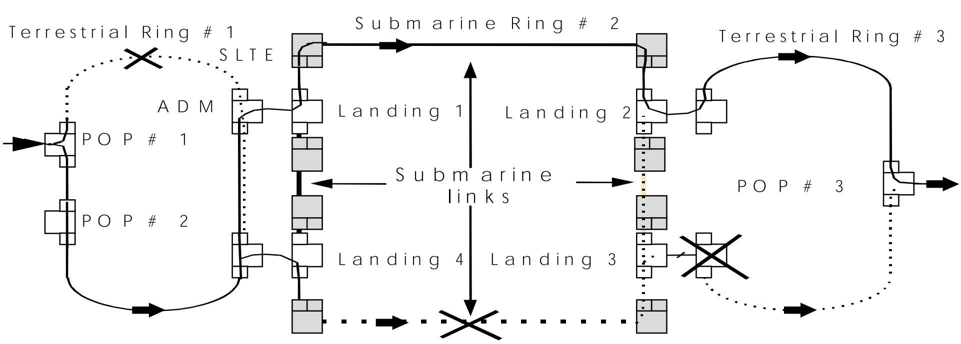


FIG. 8. Multiple failures in a triple interconnected ring topology.

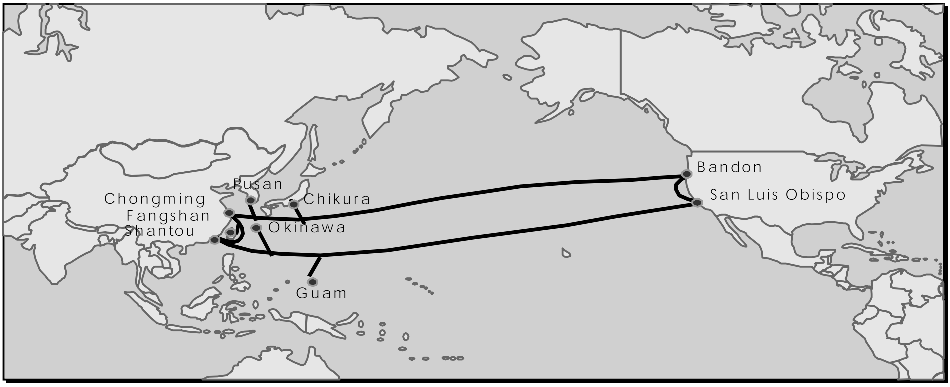


FIG. 9. China–United States.

1. *China–United States*

This system will link China, Japan, and Korea to the United States (Fig. 9). A branch toward Guam is also included. The ring comprises four fiber pairs at 8×2.5 Gbit/s and has the longest direct link ever: 12,500 km with no stop in between.

The contract for the system, valued at US$950 million, was awarded by an international group of 14 initial parties and is planned to be ready for service at the end of 1999.

2. *Japan–United States*

This system will link Japan to the United States with a stop in Hawaii (Fig. 10). It will also have a ring architecture and more than one landing in each country will be provided. Four fiber pairs will be installed, each carrying 40 Gbit/s (16×2.5 Gbit/s).

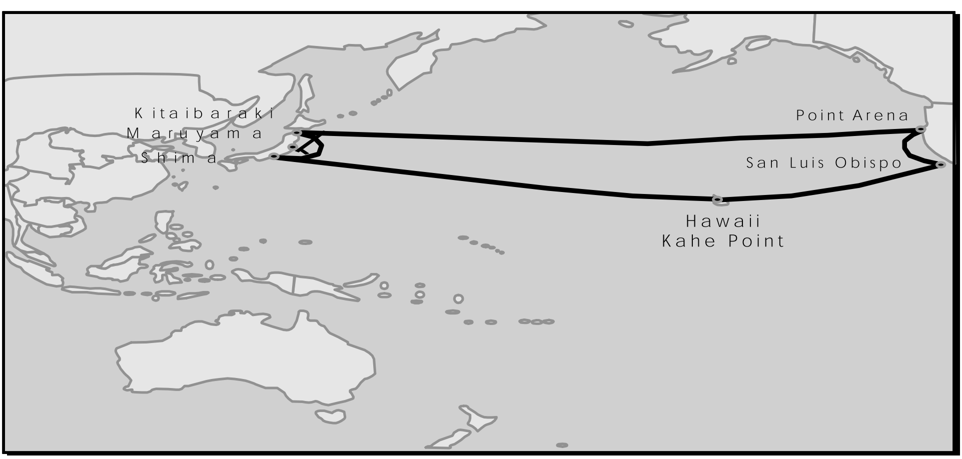


FIG. 10. Japan–United States.

The network, purchased by 12 companies, will be ready for service during the first half of the year 2000.

3. *Southern Cross*

A network of 29,000 km is planned between Australia, New Zealand, Fiji, Hawaii, and the United States (Fig. 11). Depending on the segment, three or four optical fiber pairs carrying 16×2.5 Gbit/s will be provided.

This network will involve various rings linking some or all of the landing points. They will be set up on a wavelength per wavelength basis according to the specific needs of each landing party. It is intended that the Southern Cross cable network will be owned and operated by a special purpose company called Southern Cross Cable Limited. Therefore, investment and ownership will be separated from usage rights.

The system will be installed in two phases. The first phase will be ready for service at the end of 1999, the second in August 2000.

4. *Pacific Crossing 1*

This system, valued at some US$1 billion, will connect the United States to Japan (Fig. 12). Some 21,000 km of cable will be laid between two landings in the United States and two landings in Japan using a ring architecture.

The first United States–Japan link is scheduled to be in service by March 2000 and the entire ring is scheduled for completion by July 2000. The principal owner of PC-1 is Global Crossing, a leading independent developer of fiber-optic undersea telecommunications cable systems. PC-1 will hence be one of the first noncarrier, privately owned and operated undersea cable networks to cross the Pacific Ocean.

The total capacity of the above projects exceeds 1.5 Tbit/s to be compared to the few Gbit/s of capacity which were available less than two years ago. This proves in turn that the first 1 Tbit/s system to be installed will have approximately as much capacity as all previously installed cables across the Pacific, making the

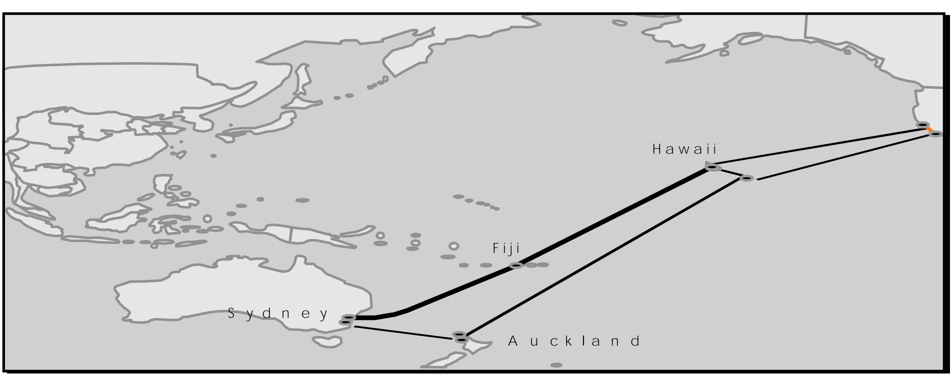


FIG. 11. Southern Cross cable network.

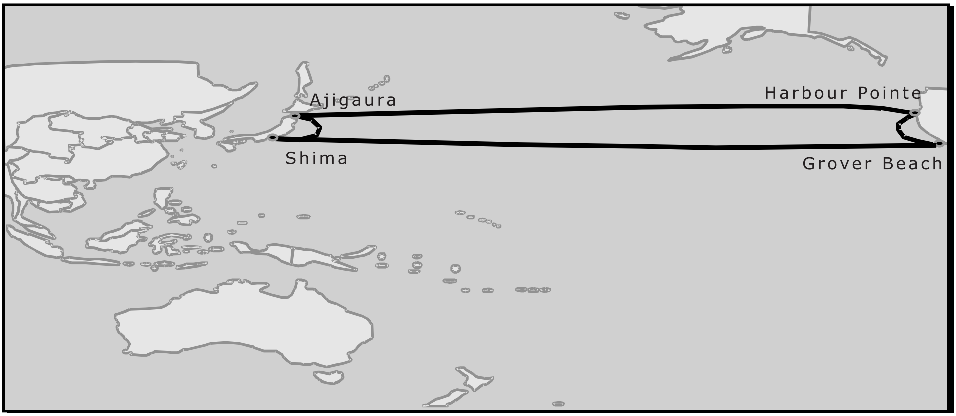


FIG. 12. Pacific Crossing 1 (PC-1).

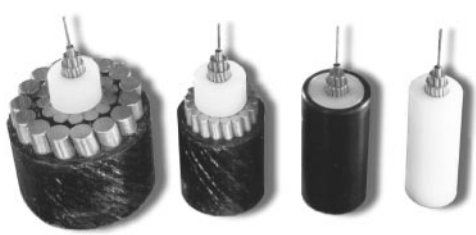
pressure on the technology even higher. It should be noted that an even higher pressure happens in the Atlantic where fierce competition pushes the technology to its limit. As an example, just a few weeks after the TAT-14 contract had been signed, Flag Atlantic Ltd. awarded a contract for twice the capacity of the TAT-14 in a single cable. Since then other major projects have been signed or announced.

CABLE TECHNOLOGY

It would be a pity if nothing was mentioned regarding the cable itself. Even if the bulk of the research and development is spent on opto-electronic and system design studies, it should not be forgotten that the optical fibers have to be laid on a seabed which can be rough, rocky, and down to 8000 m where the pressure is high, not to mention the negative effect of hydrogen on the fibers over time.

This is where the cable comes in. As shown in Picture 1 and Table 3, a cable does not need to have a large diameter to be strong and to comply with the 25-year design life of submarine systems. The 17 mm cable has a typical volume and weight of 3.5 km/m^3 and 2 km/ton.

The protection of the cable must be adapted to the seabed condition and the fishing activity of the area. A range of protections, from double armored to



PICTURE 1. Submarine cable (from left to right: double armored (DA), single armored (SA), lightweight protected (LWP), and lightweight (LW).

TABLE 3
17-m Cable Typical Characteristics

	LW	LWP	SA	DA
Cable diameter (mm)	17	22.6	31	46
Cable NTTS[a] (kN)	50	50	250	400
Cable breaking load (kN)	70	70	370	560
Max. deployment depth (m)	8000	7000	1500	500

[a] NTTS, Nominal transient tensile strength.

lightweight, allows application to a depth of 8000 m in various seabed conditions and areas of fishing activity.

Currently a submarine cable can accommodate four fiber pairs in its central tube. Ongoing development will soon allow cable to be manufactured with six to eight pairs. The limitation in the number of fiber pairs does not come from the cable itself but from the repeaters which have to house as many optical amplifiers as fibers in the cable.

MARINE INSTALLATION

The availability of network restoration is mandatory. Equally important, in order to avoid cable damage, is the standard of marine installation. The planning and implementation of marine operations is then critical to the success and long-term reliability of a submarine cable network.

External aggression to submarine cables result from human activities (commercial fishing, ships' anchors, seabed activities; these account for 90% of all faults) and natural factors (seabed current, marine life, hostile seabed terrain, earthquakes, underwater landslides, abrasion). Approximately 75% of the human aggression faults come from bottom fishing, most of the trawler related faults occurring in water depths of less than 500 m. Anchors are also a significant threat to submarine cables: they can penetrate the seabed up to 15 m in rare cases. This is why the marine route should avoid as much as possible areas where fishing activity is dense and risks of anchor drop high. If this is not possible, then ad-hoc cable burial needs to be carried out.

All this installation information is collected during a desktop survey followed by a marine survey. The desktop survey is based on environmental and oceanographic considerations, seabed topography and composition, shipping routes, fishing activity, military areas, and restricted zones. The result is in the identification of the most appropriate methods and equipment for the route survey itself. Once the desktop survey is completed, a cable route survey is launched. Geophysical and geotechnical investigation of the preselected route is done. It will determine the seabed topography and composition, identify and locate seabed hazards, and evaluate the seabed sediments, particularly if cable burial is necessary.

Once the route is known, route clearance operations may be necessary. The objective is to clear out-of-service cables prior to the commencement of ploughing operations. Prior to the main lay/ploughing, a prelay grapnel run is carried out along the proposed cable route. The intention is to attempt clearance of any seabed debris (wires, fishing equipment, etc.) which may have been deposited over time along the route.

Suitable vessels then perform the main lay and the cable burial if this is required. Depending on the conditions, surface lay can be performed at a speed between 150 to 250 km a day. If ploughing is required, the speed would reduce to 10 to 40 km a day. In general, for water depths greater than 1500 m, cable burial is not necessary; in that case the cable is surface laid onto the seabed with suitable slack to ensure that it conforms with the seabed as much as practical.

Shore end installation can be done by the same layer or is carried out as a separate operation. The vessel will anchor/lie as close as possible to the landing location. A rope is first established between the shore and the ship. This will then be attached to the cable end and the cable will be hauled ashore using mechanical aids as necessary. The cable is normally floated using pillow floats. Once the cable is ashore and secured on the beach, the floats will be cut off and the cable will sink to the seabed. Once the cable has been tested and inspected by divers, the cable vessel will commence laying away from the shore. The cable will be joined to the land cable either prior to or subsequent to the vessel commencing the lay, depending upon circumstances.

Postlay activities may then be necessary. For example, cable postlay burial may need to be performed or cable pinning may be required in shallow areas of rocky seabed. Other ancillary works may also be required to make the overall operation a success and the cable safe for years.

SUBMARINE NETWORKS: FROM CONCEPT TO IMPLEMENTATION

It is not only technology which has been evolving; 1998 saw the submarine telecommunication industry going through further evolutionary changes. These changes have been brought about by a combination of deregulation and new ways of financing telecommunications development. Deregulation in telecommunications has allowed a growing number of nontraditional carriers to enter the business

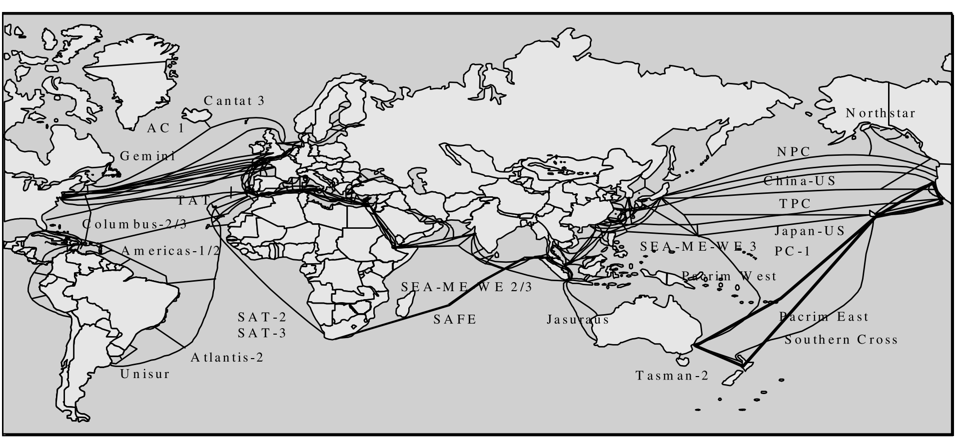


FIG. 13. World's fiber-optic submarine systems.

whereas the financing of submarine cable projects is also evolving more toward sponsorship.

Traditionally, operators signed a construction and maintenance agreement (C & MA) under which they agreed to contract, commission, operate, maintain, and own the system. However, in the sponsors' approach, private sponsors undertake the construction of the cable and bear all the related risks. The capacity is sold to operators, either through presales or after final acceptance, and is set at the market price. Operators can buy circuits as and when they are needed, according to their short-term needs. The capacity is bought from a special purpose company that serves as the interface between the operators, the suppliers, and the banks. This company has responsibility for the cost and completion of the project, as well as for the associated risks.

The sponsors' approach was initiated with the fiber-optic link around the globe (FLAG) system which came into service in November 1997, followed by projects like Southern Cross (Australia–New Zealand–United States) and this trend is likely to move forward with other future projects.

These new approaches will in turn allow for more projects to happen and push the technology to its limits as competition among all types of carriers is more fierce (Fig. 13). The internet being behind this battle is and will be one of the main components of the future development of telecom infrastructures as well as economies. John Chambers, president of Cisco Systems, Inc., says "if you don't invest in this new technology (Internet), you will get left further and further behind.... Those countries who know how to deploy it, will have the higher standard of living and the others will be left behind".

Then the challenge for system suppliers will be to bring the right technology to the market at the right time. As very high capacities will be mandatory from cities to cities, countries to countries, and continents to continents, there is no other alternative than feeding submarine fiber-optic cables with higher and higher bit-rates per wavelength and increasing the number of wavelengths across longer and longer distances.

However, increasing the capacity on a single fiber will become more and more difficult as the terabit target approaches for long-haul systems. It will mean higher and higher R & D efforts to match the potential market demand. And this is what suppliers are aiming at.

Consequently, the future of the submarine cable industry has never appeared as bright, as full of surprises, and as promising as now. It is the task of this community to bring innovative solutions to mesh the world at the speed of light.

REFERENCES

[1] P. M. Gabla, "The place for submarine systems in global networking," in *Telecom'97 Conference*, 24–26 March 97, South Africa, Midrand.

[2] J. Chesnoy, O. Gautheron, L. Le Gourrierec, and V. Lemaire, "Evolution of WDM submarine systems towards terabit/s integrated networks," *Alcatel Telecommun. Rev*. 3rd Quarter (1998).

[3] C. Mathieu, "State-of-the-art design and configuration of submarine networks," in *Submarine Communications*, 26–28 October 1998, London, England.