3. THE PROMISE OF ADVANCED TECHNOLOGY

"-- carrying human voice over copper wires is impossible and even if it is possible the thing would have no practical use"

Newspaper Editorial in 1870

The world has come a long way since commercial telephone service began shortly after the above quote appeared. The advances in telephony and related industries continue to emerge. Table 3-1, which is reproduced from Bonatti et al. (1989), depicts the evolution of telecommunications since the 1950's. Notably absent are newer technologies like personal communication systems and the asynchronous transfer mode.

Eight years ago Mayo (1985) described what he called three killer technologies: integrated circuits that killed the vacuum tube, fiber optic transmission that is replacing copper wires and cable, in some instances, and software that provides a new functionality and control. Today, all three continue to impact the industry, but new "killers" have been introduced. These include <u>intelligent networks</u>, controlled by artificial intelligence and expert systems, that are replacing many network management functions formally performed by humans, and ultimately could affect the entire infrastructure of telecommunication networks; <u>photonics</u>, that could push transmission and multiplexing speeds to the terabit per second region by the year 2000, and at the same time be used in switching arrays ending the need for electronic conversion; <u>wireless technologies</u>, that may free us all from the proverbial umbilical cord by providing universal services on a mobile-global basis; <u>broadband switching, multiplexing, and transmission</u> systems, that will replace today's narrowband world with new information age services like high definition television and multimedia desktop terminals; and finally, <u>high-speed global interconnectivity</u> using both hardware and software technologies that can provide significant increases in processing power, and networking capability to the user.

The following subsections describe these and other technologies that are expected to impact the telecommunications architecture. Section 7 then covers the specific networks that will use these advanced technologies and possibly others still on the drawing boards.

Table 3-1. Fifty Years of Telecommunications Network Evolution (from Bonatti et al., 1989)

	1950s	1960s	1970s	1980s	1990s
Switching	• X-BAR	• Stored Program Control (SPC)	• Digital Toll	• Local Digital Switching	• Wideband Switching
Transmission	• Analog Radio • Coax	• T-Carrier	• Digital Cross-Connect Systems • Digital Loop Pair Gain Systems • Digital Radio	• Fiber • Digital Circuit Multiplication Equipment	• Loop Fiber
Signaling	• In-Band SF and MF Signaling		• Out-of-Band Common Channel Toll Signaling	• Signaling-Based Service Utilizing Network Database	• Global End-to-End Signaling (CCS 7)
Customer Premises Equipment	• Private Branch Exchange (PBX) • Modems	• Automatic Call Distribution	• SPC PBX • Intelligent Terminals	• Digital PBX • LAN's • PC's • Facsimile	• Wideband Switch • Workstations
Data Communication Technology	• Modems		• Packet Switching • Circuit Switching	• Bandwidth Management Systems	• Asynchronous Transfer Mode • Wideband Packet Switch
Network Capabilities	• Automatic Alternate Routing		• Common Channel Signaling	• Dynamic Nonhierarchical Routing	• Worldwide Flexibility
Network Operations Systems	• Automatic Message Accounting	• Traffic Network Management	• Mechanized-Testing, Alarm Surveillance Traffic Admin	• Customer Control • Expert Systems	• Integrated Network Management • Automated International OPS
Public Switched Service	• Direct Distance Dialing (DDD)	• International DDD	• Free Calling Service ("800" Service)	• Long Distance and International Competition • Customer-Controlled "800" Service • ISDN	• Broadband ISDN
Private Network Service	• Tandem Tie Trunk Network • Private Lines	• Private Networks With Shared Switching	• Electronic Tandem Networks Switched Voiceband ($\leq$ 2.4 kbits/s)	• Software Defined Networks (SDN)	• International ISDN
Data Communication Service	• Voiceband Data Service	• Switched Voiceband Data ($\leq$ 1.2 kbits/s) • Nonswitched Voiceband ($\leq$ 9.6 kbits/s)	• Nonswitched Digital Data Services (56, 64 kbits/s) • Private Packet Switching • Public Packet Switching	• Switched Digital Service (56 kbit/s) • Nonswitched Data (2, 45 Mbits/s) • OSI	• Wideband Data-Switched (up to 150 Mbits/s) -Nonswitched (1.2 Gbits/s) • International Directory

3.1 Artificial Intelligence (AI) and Expert Systems

The potential for implementing AI technology into telecommunications, network management, operations, administration, and maintenance is almost unlimited but virtually untapped. According to Amarel (1991):

> "As a result of a series of advances in artificial intelligence, computer science, and microelectronics, we stand at the threshold of a new generation of computer technology having unprecedented capabilities. The United States stands to profit greatly both in national security and economic strength by its determination and ability to exploit this new technology."

AI technology offers advantages in software (e.g., languages such as LISP and programming advances) and at the same time reduces the costs of the hardware needed to support the software. AI machines could, for example, permit a single user to control large amounts of dedicated memory and processing resources to enhance overall processing power. The principal application of this new technology is expected to be network management and controls.

AI technology could also be used to plan and manage future telecommunications facilities, provide automatic advisory programs, and lead to a new generation of powerful computer-based design and manufacturing systems.

3.2 Photonics

Future computing and switching systems may use optical technologies for storage, processing, and switching as well as the transmission of information. This is a major research challenge today. The following subsections describe some of the applications of photonic technology beginning with the most current application--the transmission of signals over optical fiber.

3.2.1 Optical Fiber Transmission Systems

Until recently, the bulk of long-range communications was point-to-point microwave with some help from satellites. The development of inexpensive efficient optical fiber has revolutionized the transmission industry. Fiber is an almost ideal medium for transporting high bit-rate information because of its enormous capacity. At the same time, it occupies no radio spectrum, freeing the spectrum for other users.

The advantages of optical fiber are so great that it may even be used in some mobile radio systems and personal communications networks to provide the primary links between the fixed stations. Radio systems would only provide the short-range flexible link to mobile users. Since, the radio link is so short, very low-power portable transceivers become feasible for user convenience (Matheson, 1992, unpublished).

Optical fiber transmission systems have an enormous capacity for carrying information at low cost. Recent comparisons indicated typical capacities of 10^3 b/s for copper wire, 10^6 b/s for coaxial cable, and 10^9 b/s for fiber. The fiber capacity continues to increase each year due to technology improvements. Although fiber still only accounts for a small percentage of the mileage of copper, it has more than doubled copper networks' capacity.

In one decade, the AT&T optical fiber systems in service increased in capacity from almost 700 simultaneous calls to 48,000 calls over a single fiber pair. This corresponds to an increase in data rate from 45 Mb/s to 3 Gb/s (Ekas, 1991). According to Warr (1991), by the year 2000, Tb/s transmission speeds (10^{12} b/s) appear likely.

A typical coaxial cable weighs two hundred times as much as a fiber. In addition, fiber systems have low power requirements (10 mW is typical), are not disrupted by lightning, have no crosstalk problems, are relatively secure from interception, and are insensitive to many environmental effects.

Although fiber has been replacing copper wires and cable in many parts of the network, on the subscribers' side of the local telephone exchanges, (i.e., the local loops) copper still dominates. The replacement cost for the "last mile" (e.g., to the home or office building) is still excessively high because there is so much copper to be replaced. The current thrust for dealing with existing local loop cabling (plant) is to increase the copper's capacity by using compression techniques. The increase in capacity achieved by compression is limited and may not be sufficient for future video services.

Regarding the use of fiber in new introductions of cable, more and more fiber-to-the-home (FTTH), and fiber-to-the-curb (FTTC), is being installed. According to Shumate (1989), the cost of installing broadband FTTH in 1989 was between $5K and $10K; which was three to four times the cost of providing telephone and TV cable combined ($1.5K to $2.5K). These costs were expected to come down as demand for broadband services increase and the volume of fiber and components produced increases. The average installed costs of fiber and copper access lines as a function of time was given by Fahey (1991), who estimated that by 1995/1996 fiber will be competitive in case-by-case installations. The decreasing cost of fiber and increasing cost of copper is illustrated in Figure 3-1. This estimate may be conservative, however, if information presented at the October 1992 Newport Conference on Fiber Optics Markets is correct. It was indicated that in 1992 the circuit-mile cost of fiber was equal with that of copper. As more fiber cable is installed, the cost will decrease even further, and the cost of copper will increase due to the lower volume of copper cable used as seen in Figure 3-1. Five years ago this same conference reported that industry was reluctantly installing long-haul fiber optic cable. No one was sure that the broadband capability was necessary. Today this need is driving the installation of fiber cable. It was predicted that there will be at least ten more years of significant fiber cable installation. The 1997 volume of fiber cable is projected to be seven times that of 1992. Presently, undersea fiber cable for international service (to the former Eastern Block countries) is the most active fiber growth area. The next most active market is fiber-in-the-loop, also called fiber-to-the-home.

Fiber transmission systems provide the basic structure needed for B-ISDN which is intended to offer users a flexible, two-way medium and provide future broadband services such as switched video (see Section 7.3).

A fiber-based network known as the Fiber Distributed Data Interface (PDDI) has been standardized by ANSI. Applications for PDDI include its use (1) as a high-speed (100 Mb/s) backbone to interconnect low-speed LANs, (2) for connecting processors to other processors and I/O devices, and (3) for efficient access to wide area networks (WANs). The FDDI concept is discussed further in Section 7.2.

Installing fiber may not always be economically feasible, so compression techniques are used to reduce capacity requirements of conventional transmission media. The following examples demonstrate what can be achieved.

A T1 carrier operated at 1.544 Mb/s normally transports 24 two-way 64 kb/s voice circuits. Using 32 kb/s Adaptive Pulse Code Modulation (ADPCM), this same T1 carrier can transport 48 voice circuits. Today, a pair of optical fibers operating at 500 Mb/s is equivalent to over 300 T1 carriers and can therefore carry 14,000 voice circuits. In the near future, the potential number of voice circuits increases to approximately 5.6 million, if 16 kb/s digital voice

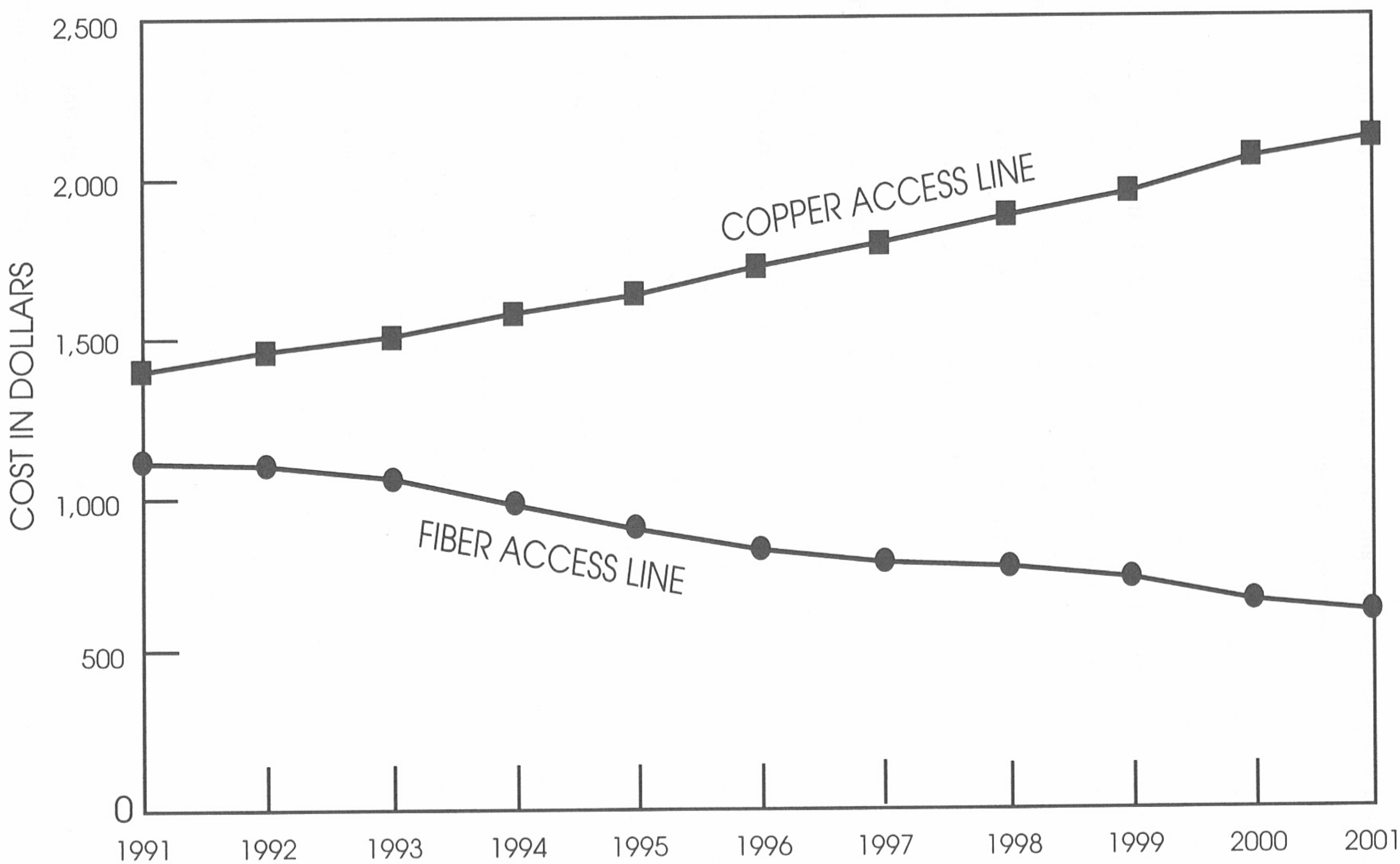


Figure 3-1. Average installed first cost of fiber and copper subscriber loops (Fahey, 1991).

processing is used along with time assignment speech interpolation (TASI), and 10 optical fiber pairs are used per cable, each operating at 5 Gb/s.

3.2.2 Other Photonic Applications

In addition to optical fiber transmission, there are a number of research efforts underway to increase the rate of processing and disseminating information. At the heart of this research is the development of optical-electronic integrated circuits (ICs), or all-optical ICs, that could ultimately replace many semiconductor ICs. AT&T has already announced a photonic switching system using lithium niobate devices. This system could be available in 1995 (Anonymous, 1991). Other research involves the development of ATM switching systems with 100 Gb/s to 1 Tb/s capacity (Warr, 1991).

Another research effort is directed toward developing optical amplifiers for increasing the capacity and regenerator spacing in fiber links. Typical transmission distance using optical electronic conversion amplifiers is currently about 50 km for a 565 Mb/s circuit (equivalent to 120,000 voice circuits). Using cascaded erbium-doped optical amplifiers, Millar (1991) predicts 2 Gb/s systems operating at 1,000 km (about 621 miles) can be achieved in the near future.

Digital-optical computing technologies are described by Medwinter and Taylor (1991). They note that "all opticallogic" with optical wiring is very difficult to achieve but that a hybrid optoelectronic processor architecture may be feasible.

Emerging integrated optical (IO) devices for use in communication satellite repeaters are discussed by Anunasso and Bennion (1990). Optical repeaters provide substantial savings and improvements in weight, volume, linearity, stability, and power consumption.

Integrated optical applications for amplitude modulators, phase modulators, demodulators, switching matrices, and beam forming networks are also possible.

Ultimately, the use of the physical properties of light to do the processing that is now done in the time-domain with microprocessors could revolutionize the whole network.

3.3 Wireless Networking

Wireless communications such as mobile radio and long-haul microwave links have been around for some time. Modern mobile communications based on cellular technology to alleviate spectrum congestion began in the early 1980's. Cellular systems rely on a network of cell sites and transceivers to provide the mobile service. According to Rappaport (1991), there were over 6.3 million cellular-telephone users as of September 1991. Due to price and size reductions, these mobile systems have grown approximately 50% per year, but are reaching saturation due to customer demand and channel capacity limitations. Two different digital technologies are under development to increase cellular systems' capacities, namely: time division multiple access (TDMA) and code division multiple access (CDMA). Both have certain advantages and disadvantages. However, CDMA appears to be able to expand system capacity by at least a factor of 10 over the analog cellular systems (Miska et al., 1992; Madrid et al., 1991; and Viterbi, 1991).

Cordless telephones (CT) used in the home are just wireless extensions of up to 1,000 feet to the existing telephone network. A year ago there were 30 million CTs in the United States.

Cordless networking for personal computers is under development. Miska et al. (1992) and Madrid et al. (1991) describe wireless business systems including cordless phones and cordless networking for personal computers. Radio packet networks are already in use for transmission of 2-way data messages. Personal communication systems (PCSs) for voice and data are on the horizon. The Federal Communications System has recently (1992) allocated frequencies in the 1.8 GHz to 2.2 GHz band for PCS, wireless PABXs and LANs. Figure 3-2 illustrates the cellular market trend in the U.S. as forecasted by Madrid et al. (1991). Wireless LANs and some PCS concepts are discussed in Section 7. The PCS is considered as a major emerging system for future applications in Section 8.

3.4 Broadband Switching and Transmission

In the field of telecommunications, the term "broadband" characterizes the capability of various products, systems, and services. One definition would characterize any network that is capable of supporting transmission bit rates above 1.5 Mb/s as broadband.

Broadband switching and transmission systems are based on what is commonly called "fast packet" technology. Fast packet switching is a term that has been applied to a number of switching processes ranging from 1 or 2 Mb/s to 100's of Mb/s. Fast packet switching by this definition includes both frame relay and cell relay. Fast packet switching advantages include

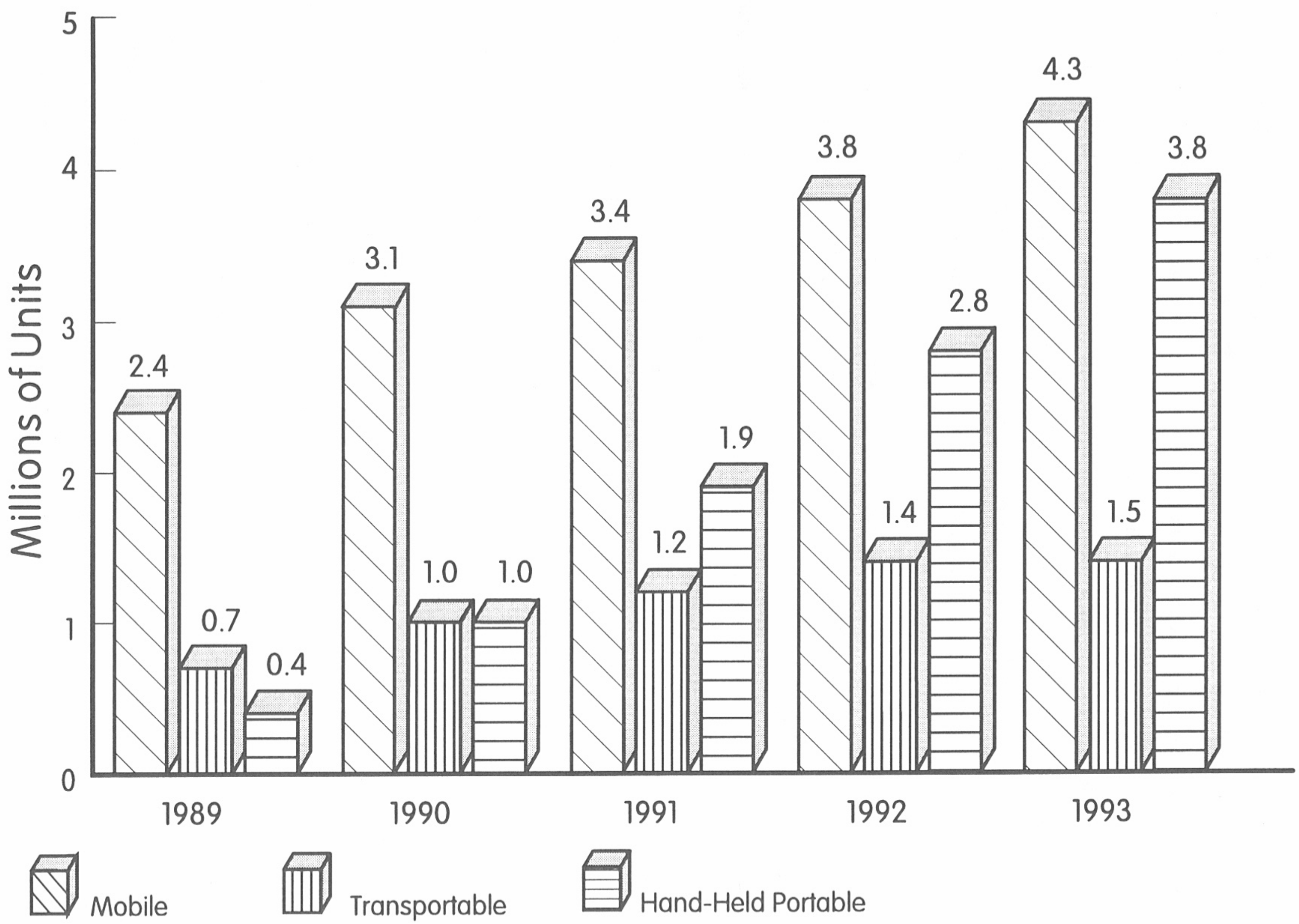


Figure 3-2. Cellular market trends in the United States (Madrid et al., 1991).

- flexible and efficient user access,
- variable bandwidth information rates,
- true integration of all information services for transmission and switching,
- rapid support for new services.

To achieve fast packet switching at video rates, switches need low delay (1 ms per node), high interface rates (e.g., 150 Mb/s) and large capacities (more than 10 million packets per second). By comparison, many packet switches used today in public data networks have node delays greater than 20 ms, interface rates of about 48 kbit/s and capacities less than 10,000 packets per second. This delay and capacity is unsuitable for most voice or video services.

Fast packet switches will be implemented with dedicated hardware using very large scale integrated (VLSI) circuits. One possible switch design, called the Banyon network is shown in Figure 3-3. It consists of 12 interconnected 2 x 2 switch elements in 3 stages. Each element can either switch straight through or exchange inputs. The elements are controlled by routing bits in the packet header which are set equal to the destination output port number. There is a single path between any input and any output which is determined by the output port number. Each bit of the routing field in the packet header indicates how the appropriate element of each stage should switch. A "one" indicates a switch of the input line to the upper output line, while a "zero" indicates a switch of the input line to the lower output line. The path through each element is held until the complete packet has been passed. The path selection is thus a simple step-by-step procedure based solely on the packet header. The switch can be implemented entirely in hardware and has many channels that can be processed in parallel. VLSI technology makes this concept feasible.

The following subsections describe some of the important switching, multiplexing, and transmission systems that are currently implemented or planned for the near future.

3.4.1 Frame Relay

Frame relay is a type of fast packet technology for transporting user data traffic over digital transmission links. Recommendation 1.233 of the CCITT defines frame relay as an ISDN bearer service, which is based on extensions to Recommendation Q.922 called the "core aspects."

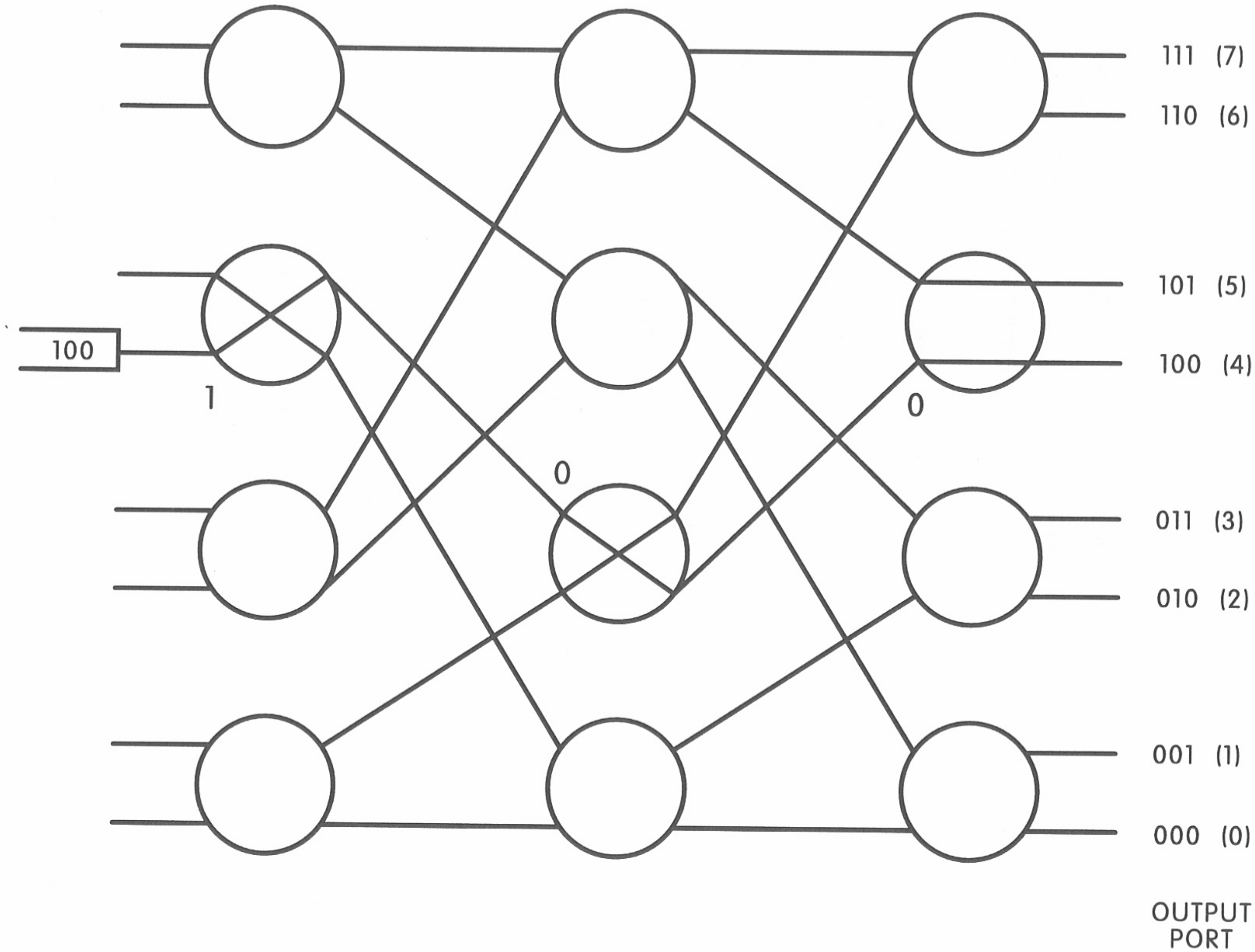


Figure 3-3. Fast packet switch, binary routing network.

It is expected to eventually replace X.25 for comparable data communication applications. The X.25 protocol is designed to provide error-free delivery of user data over high error-rate links while frame relay relies on digital links that are essentially error free. The X.25 definition covers layers 1, 2, and 3 of the OSI model, while frame relay is defined for layers 1 and 2. Table 3-2 is a comparison of frame relay and cell relay technologies, which collectively define the concept of fast packet. Cell relay technology, which is used in the B-ISDN environment, is explained in Section 3.4.2. Korpi (1991 a and b) evaluates the frame relay concept in more detail.

Table 3-2. Frame Relay and Cell Relay Compared

Frame Relay	Cell Relay
A broadband technology	A broadband technology
Optimized for data	Optimized for multimedia (i.e., voice, data, video)
Based on variable-length message units (frames)	Based on fixed-length message units (cells)
Intended for speeds below 45 Mb/s	Intended for speeds above 45 Mb/s
Typically implemented in software	Typically implemented in hardware
Can interwork with cell relay systems	Can interwork with frame relay systems

Frame relay systems enclose user data into variable-size larger packets called frames, which typically may be 1,000 bytes or more in length. By contrast, in cell relay systems, user data is transported using fixed-size packets called cells. Every cell is identical in length although some may be full, some partly full or empty. Frame relay systems are more compatible with today’s data networks operating at 1.5 or 2.0 Mb/s, whereas cell relay systems support very high speeds (45 to 600 Mb/s) and serve multimedia applications efficiently.

Frame relay is designed to interface with ISDN’s primary rate interface at 1.5 Mb/s (North America) and 2 Mb/s (Europe) but could be enhanced to 45 Mb/s in the near future. Faster packet technologies using cell relay, such as Switched Multi-megabit Data Service (SMDS) and the Asychronous Transfer Mode (ATM), operate over optical fiber links and will be used for the higher speeds. These concepts are described in subsequent sections.

3.4.2 Cell Relay

Cell relay may ultimately replace frame relay. It is also referred to as cell switching (McQuillan, 1991). Cell relay uses fixed-size packets of data called cells. Each cell includes 48 bytes of user information and 5 bytes of overhead (4 for segmentation and reassembly and 1 for control). The Switched Multi-megabit Data Service (SMDS) and Asynchronous Transfer Mode (ATM) are also based on the cell relay concept, as is the IEEE 802.6 standard for public MANs which uses a distributed-queue-dual-bus (DQDB) architecture (Section 7.2). ATM may be used for WANs. Along with the synchronous optical network (SONET), ATM provides the standardized switching and transmission base for B-ISDN. Details of ATM and SONET are given in later sections. Their application in the B-ISDN infrastructure is covered in Section 7.3.

3.4.3 Switched Multi-megabit Data Service (SMDS)

The SMDS is a connectionless network-layer service (CLNS) provided by commercial carriers for data transport. It is a near-term, public, wide area network extension of existing and LAN and MAN services. It may be used to interconnect other high-speed networks (e.g., FDDI token ring LANs), at transport rates ranging from 1.5 to 100 Mb/s on a tariffed as-used basis. Presently, it is being implemented by local exchange carriers only for intra-LATA connectivity (mostly in major metropolitan areas). National service is anticipated in the 1996-1997 time frame.

The SMDS switch provides routing, sequencing, and billing functions. A SMDS router at the customer’s interface provides OSI link and network layer protocol functions plus packet segmentation and reassembly. Because SMDS is a switched service, it can reduce the number of access lines required when compared to using private leased lines.

SMDS and frame relay are competitive servers in some areas. Frame relay is used, either in public or private networks, for virtual private line services at DS-1 rates, whereas SMDS is a public, dynamically-switched service between SMDS subscribers at DS-1 and DS-3 rates.

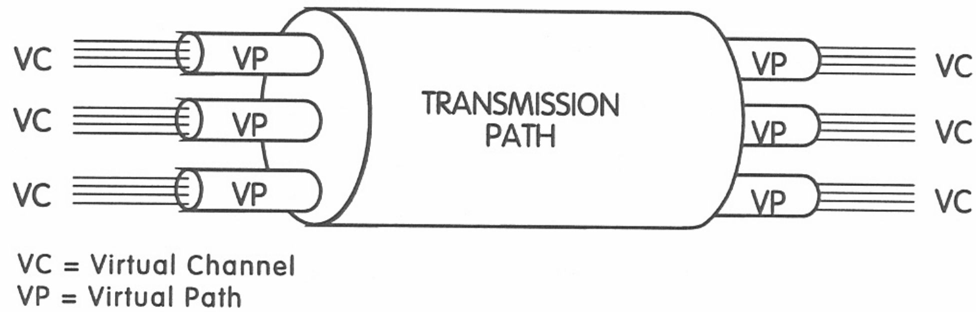
3.4.4 Asynchronous Transfer Mode (ATM)

The ATM is a standardized method of information transfer in which the information is multiplexed into fixed-length packets called "cells" and transmitted according to each user's instantaneous need. The short cell length of 53 octets (48 octets of information plus a 5-octet header) minimizes cell delay. A single 150 Mb/s fiber carries approximately 44 cells in a 125 µs frame, sufficient for high-quality video. At lower speeds (e.g., voice), users are multiplexed. An ATM switch differs from the conventional digital switch only at the functional level. The ATM switch uses a self-routing switching fabric as opposed to a software-controlled switching network. For a detailed description of some architectures for self-routing ATM cells see Daddis and Lorng (1989).

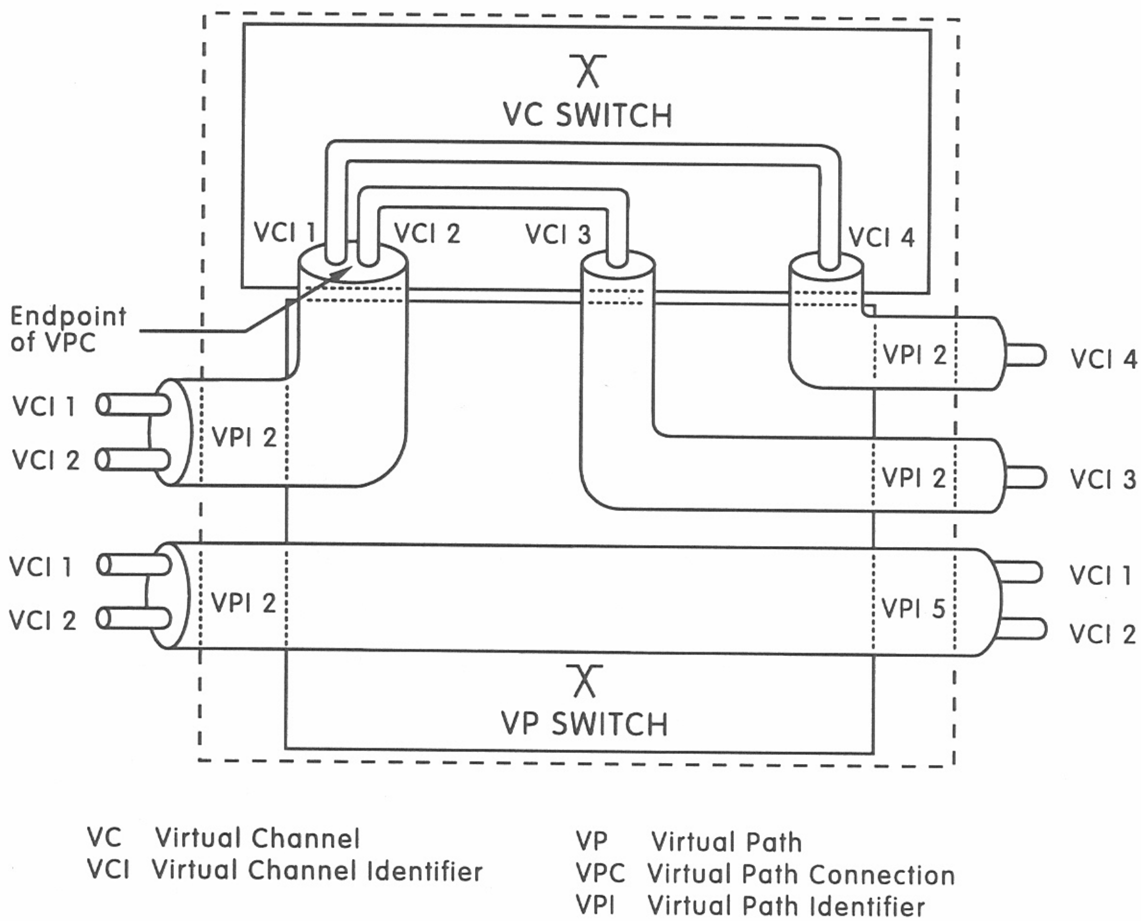
In summary, ATM

- provides a standard format for B-ISDN
- combines circuit and packet switching capabilities
- provides bandwidth-on-demand to meet any users applications
- supports multiuser architectures whereby many users can simultaneously share the network
- combines with SONET to provide transport of all B-ISDN services.

ATM uses two distinct connections called virtual path and virtual channel. The relationship between virtual channel, virtual path, and transmission path is shown in Figure 3-4 (a). A transmission path may carry several virtual paths and each virtual path may carry several virtual channels. Virtual paths and virtual channels may be switched according to the virtual path identifier (VPI) and the virtual channel identifier (VCI) located in the header of each cell (Figure 3-4 (b)). The virtual channel provides the logical connection between users while the virtual path defines the route the cell takes between source and destination. This dual connection scheme reduces total overhead requirements and simplifies traffic flow control since this can be done at the virtual-path level. The 5-octet cell header format contains VPI, VCI, payload type, cell loss priority, error control, and flow control information. The 48-octet information field carriers the user's data. The B-ISDN standard specifies transmission rates of 155.52 and 622.08 Mb/s for ATM. All cells associated with an individual virtual channel and



a) Relationship between virtual channel, virtual path and transmission path.



b) Virtual channel/virtual path switching

Figure 3-4. The ATM transport network.

path connection are transported along the same route through the network. Cell sequence is preserved for all virtual channel connections. Figure 3-5 shows the OSI layered model for ATM. For a detailed description, see CCITT (1988b, d).

3.4.5 Synchronous Optical Network (SONET)

Some observers of the telecommunications evolution have made the analogy that SONET is to Broadband what T-1 Carrier was to Digital. SONET is the new family of optical transmission channels for speeds from 45 Mb/s to Gb/s. Just as T1 ports exist on customer premise equipment today, many telecommunications experts feel that SONET ports will be common features on equipment by 1997. The CCITT version of SONET is known as the Synchronous Digital Hierarchy (SOH). The relationship between SDH and SONET is shown in Table 3-3.

SONET defines standard interconnect line rates ranging from "STS-1" at 51.840 Mb/s to "STS-48" at 2.48832 Gb/s. When an STS-N signal is transmitted, the resulting optical signal is called an optical carrier OC-N. The number of 64 kb/s channels in each optical carrier is also indicated in Table 3-3.

The STS-1 frame format contains 810 octets and is transmitted over a 125 μs period. This results in the 51.84 Mb/s line rate for STS-1 as shown in Table 3-3. Multiples of STS-1 signals form STS-N signals by synchronously interleaving bytes from N STS-1 signals. Note that the lowest SDH level is STM-1 operating at 155.52 Mb/s. This corresponds to the SONET rate STS-3.

The STS-1 can be divided into subrates called virtual tributaries (e.g., VT 1.5 Mb/s) and used to carry the North American digital hierarchy up to and including level DS-3 as shown in Table 3-4. VTs come in four sizes: VT 1.5, VT2, VT3, and VT6.

A detailed description of the SONET concept is given by Ballart and Ching (1989). Its role leading to the development of B-ISDN is described by Stallings (1992) and the universal network node interface (NNI) for the SDH and SONET is described by Asatani et al. (1990). The SDH standard development was initiated by the CCITT Study Group XVIII in 1986 (CCITT, 1988a, c, and e). The IEEE (1992) special issue on gigabit networks provides a comprehensive set of papers concerning gigabit transmission systems and technologies including SONET and SDH.

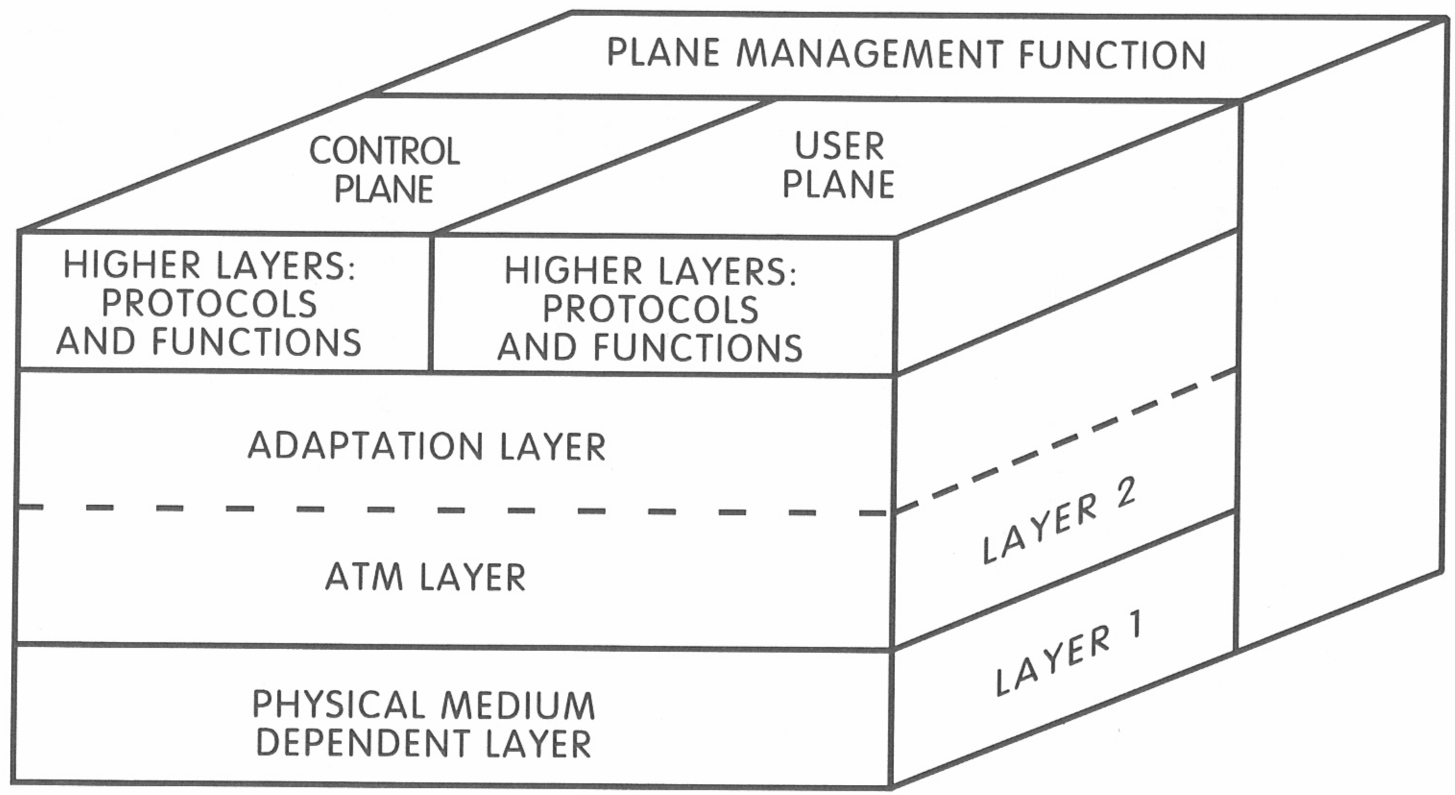


Figure 3-5. OSI layers for ATM.

Table 3-3. SONET Standard Digital Channels

SDH Designation	SONET Designation	Line Rate (Mb/s)	OC Level	64 kb/s Channels
------	STS-l	51.84	OC-l	672
STM-l	STS- 3	155.52	OC-3	2,016
STM-4	STS-12	622.08	OC-12	8,064
STM-8	STS- 24	1244.16	OC-24	16,128
STM-16	STS-48	2488.32	OC-48	32,256

Table 3-4. North American Digital Hierarchy

Digital Signal Levels	Transmission Rate	Number of T1 Equivalents	Digital Transmission Facilities
DS-4	274.176 Mb/s	168	T3M
DS-3	44.760 Mb/s	28	T3
DS-2	6.312 Mb/s	4	T2
----	3.152 Mb/s	2	T1C
DS-1	1.544 Mb/s	1	T1
DS-0	.064 Mb/s (64 kb/s)	1/24	---

As a high-capacity, fiber-based transmission system, SONET (or the SDH) may be expected to provide the future infrastructure for high-speed applications replacing the T-carrier technologies. The SDH will support B-ISDN using the asynchronous cell transmission of ATM.

3.5 Satellites

Satellite networks have advantages over terrestrial networks because (1) they are accessible from any place, (2) cost is independent of user to user transmission distance or intervening terrain, (3) they are ideal for broadcasting transmissions over large coverage areas and for communications to mobile users, (4) they can be time shared, (5) they can transmit and switch high-speed digital data (10's of Mb/s) to many points economically, (6) they can be implemented and reallocated quickly because no rights-of-way or cable laying are required, and (7) additional receiving sites do not add to distribution costs. Important applications include communications for undeveloped countries and the ocean areas.

Traditionally satellites have been viewed as radio repeaters with a very long, 22,300 mile, microwave hop. Satellite earth stations interface with terrestrial networks. Recently, advanced-technology satellites have been proposed that incorporate antennas with multiple spot beams and on-board switching systems to interconnect the spot beams to dynamically alter circuit capacities between locations. Such systems operating over different frequency bands could support the growth of satellite communication services and alleviate congestion problems (Wright et al., 1990).

Modern satellite systems meet business requirements for high-rate (~ 100 Mb/s) data transmission as well as video and voice communications. Applications include reservation systems for airlines or hotels, credit card verification, video teleconferencing, and inventory management systems. Transmission rates ranging from 9.6 kb/s to 2 Mb/s can be allocated on demand depending on the application.

Very small aperture terminals (VSATs) appeared in the 1980's, and today are used increasingly by business to provide direct connections of user data, voice, and video terminals. They serve as an integrated Wide Area Network (WAN), bypassing traditional terrestrial networks including the local loop and the long-haul facilities. There are several advantages to VSAT networks over leased terrestrial facilities. These include service reliability, single point of contact (VSAT provider), customer control, configuration management, and lower cost. A typical VSAT network today usually includes many remote user terminals and a single central hub. Transmission rates to the hub are on the order of 128 kb/s using time-division multiple access (TDMA). The hub transmits to all VSATs in a broadcast mode using time division multiplexing (TDM). Such a system typically can support 31 in-bound TDMA streams per out-bound TDM stream. This TDMA/TDM technology provides interactive data exchange with fast response, data file transfer, and even digitized voice.

Other time sharing techniques including single-channel-per-carrier (SCPC) are used with Ku-band VSATs. A VSAT network may include several thousand VSATs. By joining networks, over 100,000 VSATs can be served.

VSATs can also be used to communicate with unmanned sites for supervisory control and data acquisition. They also perform load management functions for the electric utility industry (Jaske, 1991).

Satellite-based personal communications systems (PCS) have also been proposed. One such concept called Iridium would use a constellation of 77 low earth orbit (LEO) satellites to provide worldwide coverage. Iridium uses cell-forming antennas and radio relays located on the satellite rather than on the ground. Otherwise, the system is similar to terrestrial cellular systems. An overview of Iridium is given by Grubb (1991). Other mobile satellite systems are being discussed as listed below.

- Local Space and Qualcomm are proposing the Globalstar system, which has 48 satellites in LEO (orbiting at about 800 miles above the earth). Subscribers would receive direct satellite services through hand-held terminals. The Globalstar system, using spectrum in the L-band or S-band, would provide coverage over most of the earth’s land masses and major ocean areas, but not over the polar regions. Inter-satellite links are not used.

- TRW is proposing a system called Odyssey, consisting of 9 satellites at mid-earth orbit (MEO). These satellites would orbit approximately 6,000 miles above the earth. Plans call for the system to use the same satellite bands as the previous systems and may also include Ku-band.

- American Mobile Satellite Corporation (AMSC) and Telesat Mobile Inc. are proposing a geostationary system using Ku-band spectrum. The status of the proposed system is uncertain, pending action at the Federal Communications Commission (FCC).

- The European Satellite Agency is studying a proposed satellite system which uses highly elliptical orbits, from a perigee of about 100 miles to an apogee of about 700 miles. This system would provide coverage over Europe.

The World Administrative Radio Conference (WARC) meeting in Barcelona, Spain, allocated spectrum in the L-band (1.5 GHz) and S-band (2.5 GHz) for these satellite applications. Intersatellite links may operate in the Ku-band.

In 1987, there were over 200 satellites proposed or operating in the geostationary orbit according to Jansky and Jeruchim (1987). The investment in these systems is several billion dollars.

A satellite system in a synchronous orbit has several advantages as a very long (22,300 mile) radio repeater. Operating in the microwave band (4 and 6 or 12 and 14 GHz), the satellite can receive signals from properly oriented earth station antennas and relay them almost any place on earth in the coverage area. The transmission loss is therefore independent of the distance or intervening terrain between earth stations. Such satellites are ideal for broadcasting purposes since they can provide wide earth coverage, and propagation delay is not a factor in broadcast applications. Satellites can be time-shared on demand or prescheduled. They can carry tens of megabits per second and switch high-speed data to many points economically. Finally, satellite systems can be implemented quickly and reconfigured easily if desired.

Table 3-5, from Pelton (1988), compares the pertinent characteristics of satellites in synchronous orbit to an advanced fiber-optic cable system. Pelton also discussed the feasibility of using satellites in an ISDN environment and emphasized the potential cost savings and innovative services inherent in using both space and terrestrial communications.

Table 3-5. Satellite Versus Fiber-Optic Cable

	Advanced Satellite	Advanced Fiber-Optic Cable
System Availability	99.98%	99.98%
Bit Error Rate (BER)	10^{-7} to 10^{-11}	10^{-7} to 10^{-11}
Capacity (bits/sec)	1 gigabit to 3.2 gigabits	840 megabits to 2.5 gigabits
Transmission Delay	250 ms	Under 50 ms
Typical end-to-end transmission time	350 to 800 ms	200 to 700 ms

3.6 Hardware and Software Technologies

Much of this report is devoted to hardware technologies that interface with the traditional transmission media such as copper, optical fibers, and free space. Hardware components such as switches, multiplexers, transmission devices, and their associated computers are controlled and operated by software, however. Software technologies include languages of various types, operating systems, management systems, artificial intelligence, protocols, coding schemes, data base management systems, and the like. These software technologies are essential elements of any network. They make the hardware elements usable, permit the programming of control processors, manage the network's information base, and provide the interworking capabilities via protocols and expert systems. Protocols ensure the efficient transfer of information. Expert systems apply knowledge to manage and operate the network, monitor alarms, diagnose faults and automatically take corrective action to reconfigure topology, or switch in new components - all in essentially real time.

Software for controlling future networks such as B-ISDN must meet reliability, availability, and flexibility requirements far beyond those achievable today. Software modularity and reusability will provide a graceful evolution as new features and functions are added. See, for example, Vickers and Vilmansen (1987).

Digital networks today use hardware based on silicon technology for information processing, for performing switching functions, for storage elements, and for interfacing structures. Copper has been a major transmission medium but is being replaced by optical fiber. The capacity of a single-mode fiber has continued to increase year by year. By the year 2000 it could exceed 100 Gb/s as predicted by Bourne and Roth (1985). See also Section 3.2 on Photonics. Warr (1991) notes that semiconductor technology tends to follow certain laws and has for several decades. One example given is that memory and logic component density is expected to increase by a factor of 10 every five years through the end of this century. Magnetic storage density is increasing by a factor of four every five years and optical storage densities are increasing at a slightly slower rate. Finally, Warr notes that the cost/performance or size/performance of functions such as signal processing and database management will be improved by the year 2000 by factors of two or three orders of magnitude using parallel and distributed architectures. An example of the increase of bit and chip density is given in Figure 3-6. See also Mayers (1991).

3.7 Processors

The trends in processor speed [measured in Millions of Instructions Per Second (MIPS)] and fiber transmission rates, measured in Gigabits per second (Gb/s), are given by Fraser (1991) and illustrated in Figure 3-7. The increasing speed of these two technologies versus time is not very different except for the reduced instruction set computers (RISC) which are increasing at a faster rate. If this trend continues as indicated on the figure, one can expect microprocessing speeds on the order of 1 billion instructions per second (BIPS) and transmission rates around 300 Gb/s by the year 2000.

Most computers have a single processor that does the computational work such as addition, multiplication, and number comparisons. Human programmers divided the computational tasks into a sequence of steps which the processor executes one step at a time, an inherently slow process. By linking many processors together to form parallel computers, the processing speed is greatly increased.

Parallel computer architectures operating with a distributed operating system that runs on multiple, independent, central processing units transparent to the user will play an important role in the future. According to Kleinrock (1985) distributed systems can provide the processing

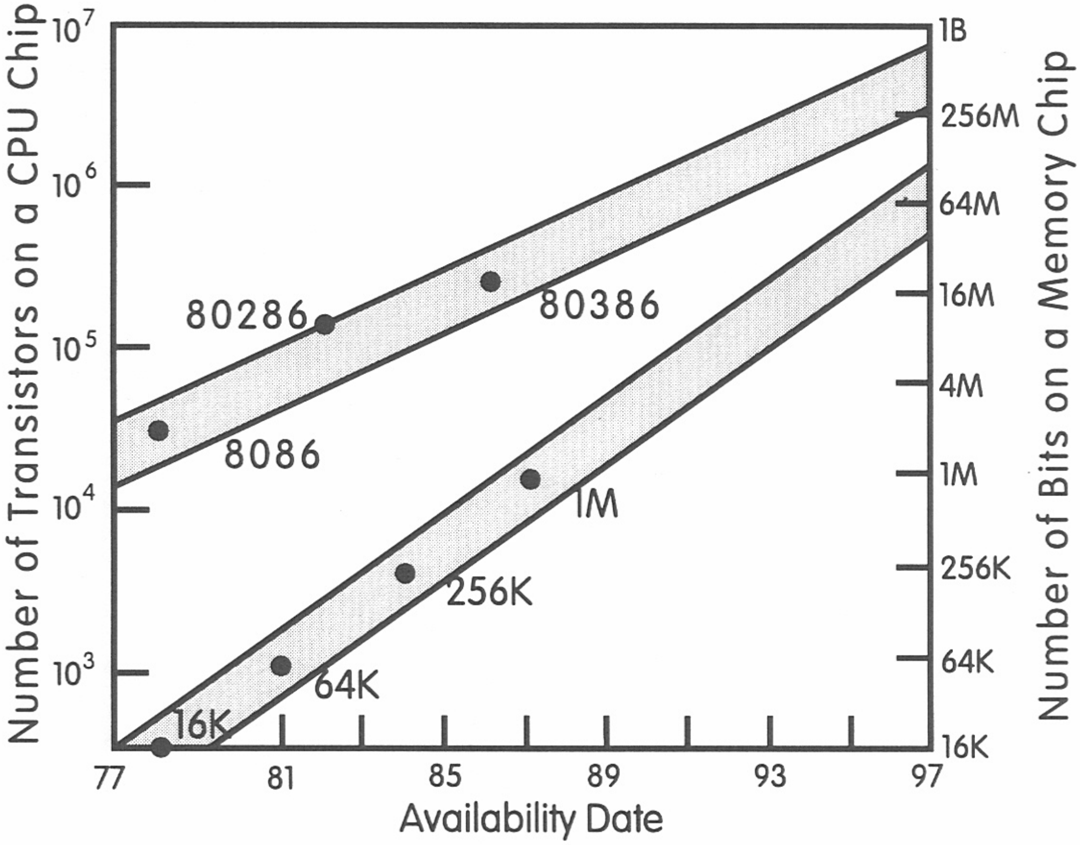


Figure 3-6. Increases in bit and chip density (Gould et al., 1991).

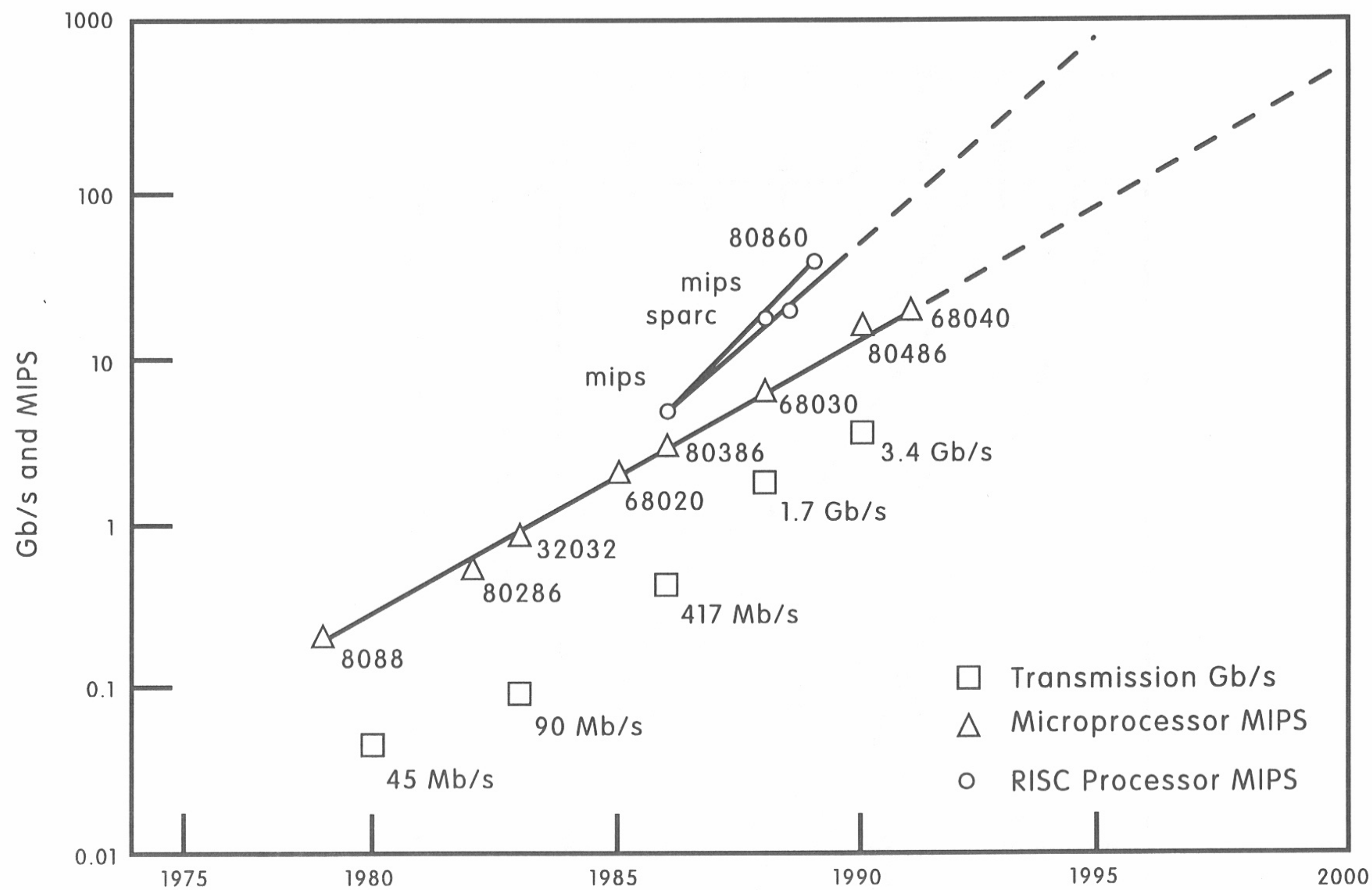


Figure 3-7. Processor and fiber transmission speeds (Fraser, 1991).

power needed to meet future user demands. Distributed data bases, distributed processing and distributed communication networks give rise to some complex architectures including parallel processing systems.

Sequential computing used in the past is being replaced by parallel computing due to advances in VLSI, parallel software, and communication technologies. Networked workstations connected by optical fiber links and optical switching may soon provide the potential for parallel computing with a great deal of processing power (Chandy and Kesselman, 1991). Massively parallel computers (MPC) imply a large number (~ 1,000 or more) processors implemented with single instruction multiple data stream. These concepts are described by several papers in a special issue of the IEEE Proceedings in April 1992. Since the number of processing elements is high and parallelism is exploited at a very fine grain, the interconnecting network plays an important role for MPCs.

3.8 Evolutionary Trends

Figure 3-7 showed a curve portraying the history and projection of computer processing unit speeds. This curve is repeated in Figure 3-8 and compared with the trend in transmission speeds for data communications over LANs and WANs.

Increasing the transmission rate of modem networks into the gigabit range introduces a new level of complexity because the delays are dominated by propagation delay. Communications techniques and protocols used for networks operating at Mb/s may be inefficient or even ineffective for networks operating at Gb/s. This latency-versus-bandwidth tradeoff is discussed in detail by Kleinrock (1992). Kleinrock concludes that due to the finite speed of light in Gb/s networks, the propagation delay for long links is much larger than the time required to transmit blocks or packets of data into the link. This introduces entirely different issues concerning flow control, buffering, error correction, and congestion control that are still unknown. Fraser (1991) notes that the ratio of backbone speed to local area network speed is expected to be 50:1 by 1997 and continue to increase.

The transmission rate for LANs and WANs may continue to rise as shown in Figure 3-8 and could approach 1 to 10 Gb/s by the year 2000. An overview of Gb/s LANs from a systems perspective is given by Kung (1992). Important applications for these high-speed networks include three-dimensional imaging and computing. More important than the immediate

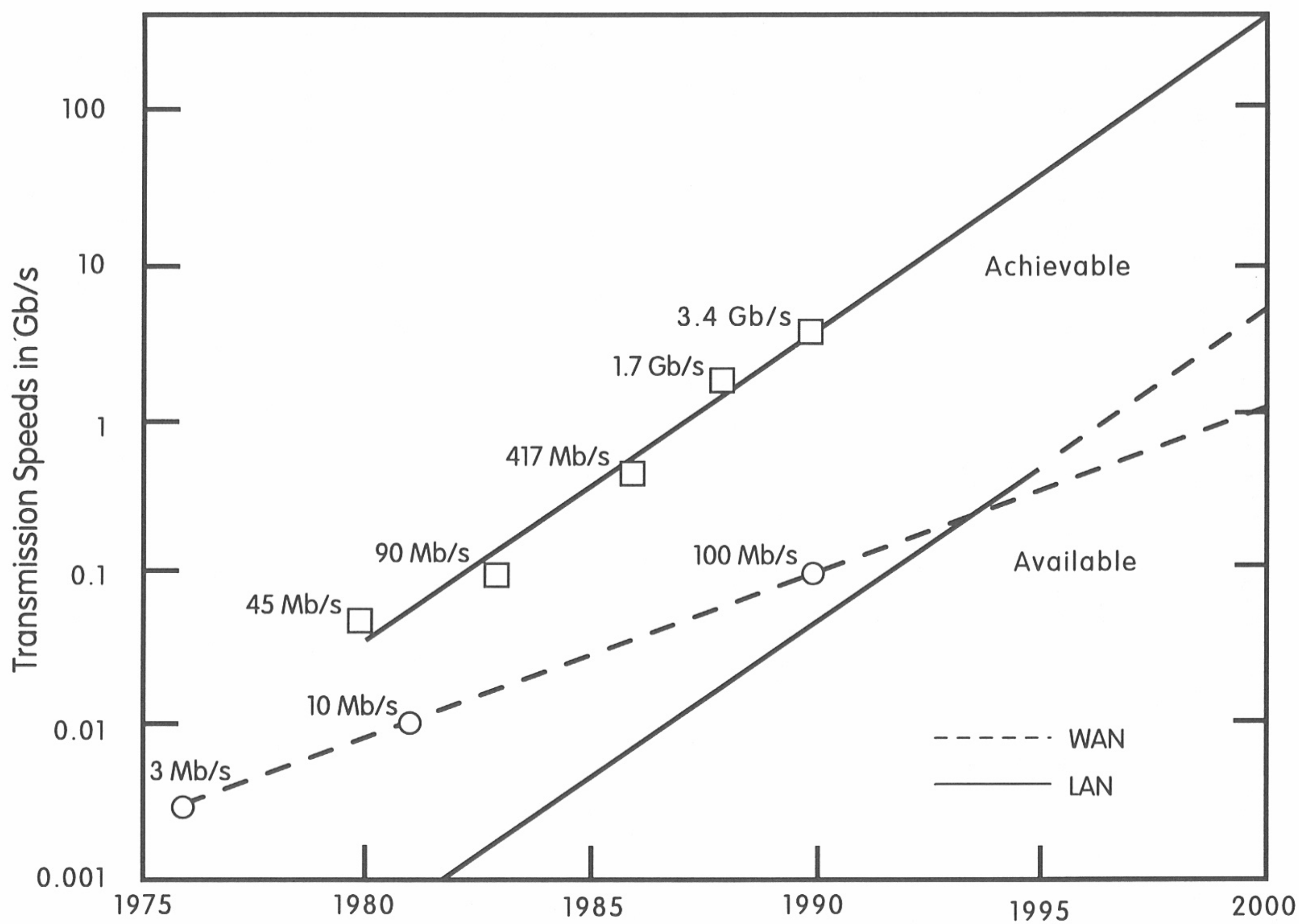


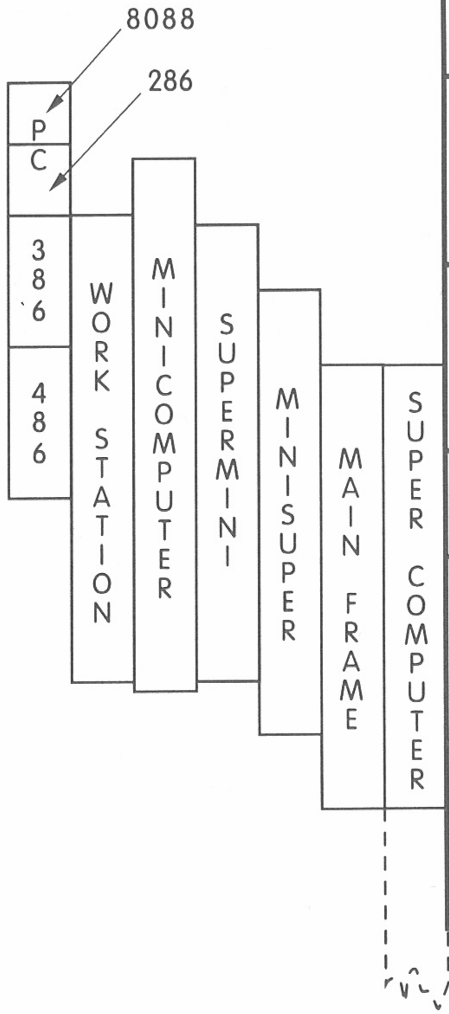
Figure 3-8. Transmission speeds for data communication (Fraser, 1991).

application is that these gigabit networks can change computing and communications in fundamental ways that have yet to be explored.

Table 3-6 summarizes the evolution of switching and multiplexing technologies beginning with conventional systems, from analog to digital, through packet and fast packet switching, and culminating in broadband ultrafast packet switching based on cell relay concepts. Figure 3-9 illustrates, in another way, the progress that has been achieved in processing and transmission technologies since 1985. The figure includes projections beyond the year 2000 when transmission speeds at terabits per second (10^{12} b/s) are potentially feasible.

Table 3-6. Evolution of Switching/Multiplexing Technologies

	Conventional					Fast Packet					Ultrafast Packet	
Type Service	Analog Voice/Data	Analog Voice/Data	Digital Voice/Data	Low-Speed Data	Video	High-Speed Data		High-Speed Trunking	High-Speed Switch Access	High-Speed Data	Digital Broadband	Digital Broadband
Switch Technologies	Mechanical Circuit Switch	Electronic Circuit Switch	Circuit Switch	Packet	Channel	Frame Relay		Cell Relay	Cell Relay	Cell Relay	Cell Relay	Photonics
Control Technologies	Manual and Mechnical	Software	Software	Software	Software	Software		Software	Software	Software	Software	Software
Switching and Multiplexing Rate	1.2 kb/s to 9.6 kb/s	9.6 kb/s	64 kb/s to 1.5 Mb/s	56 kb/s	1.5 Mb/s to 45 Mb/s	Below 1.5 Mb/s	Below 45 Mb/s	Below 45 Mb/s	Below 45 Mb/s	Below 150 Mb/s	Below 600 Mb/s	Above 1 Gb/s
Transmission Rate	4 kHz Voice Channel	4 kHz Voice Channel	DS-0 (64 kb/s)	DS-0	DS-1 and DS-3	DS-1 (1.5 Mb/s)	DS-3 (45 Mb/s)	DS-3	DS-3	OC-3	OC-12	OC-3 and Higher
Interface	Data Modem	Data Modem	Voice Codec	Voice Codec	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Optical
Physical Transmission	Copper, Radio	Copper, Radio	Copper, Radio	Copper, Radio	Copper, Fiber, Radio	Copper, Fiber, Radio		Copper, Fiber, Radio	Fiber	Fiber	Fiber	Fiber
Application	Pt-Pt Voice and Low-Speed Data	Pt-Pt Voice and Low-Speed Data	Pt-Pt Voice/Data	Pt-Pt	Broadcast and Pt-Pt	MANs	MANs	LANs and MANs	MANs and WANs	WANs	WANs	WANs
Examples	PSTN Dial-up Data	PSTN Dial-up Data	PSTN Dial-up Data	PDN and PLN	Conferencing TV	LAN Interconnect		Internet B-ISDN	SMDS	ATM/SONET B-ISDN	HDTV	Future Multimedia, Video
Availability	Disappearing Fast < 5% Today	Today 50%	Today 50%	Today	Today	Today	~ 1994	Today	~ 1993	~ 1995	~ 1995	~ 2000 +



DATA RATE	ERROR RATE	INTERCONNECT POSSIBILITY	TRANSPORT MEDIUM	CHRONOLOGY
1 Mb/s to 10 Mb/s	Standard Performance	Ethernet Token Bus Token Ring Packet Switching ISDN	TP, C, C TP, C TP TP	1985 to 1990
16 Mb/s	Mid Performance	Token Ring FDDI ISDN Frame Relay MAN/SMDS	TP, C F TP TP TP, F	1990 to 1995
100 Mb/s	High Performance	FDDI MAN/SMDS ATM	F	
100 Mb/s	Super Performance	FDDI FDDI II 802.6 MAN/SMDS ATM/Cell	F	1995 to 2000
1 Gb/s and Beyond	Ultrahigh Performance	ATM/Cell Self-routing Switching	F and Photonic Amplification	Beyond 2000

TP = Twisted Pair C = Coax F = Fiber Optic Cable

Figure 3-9. Processing and transport mechanisms.