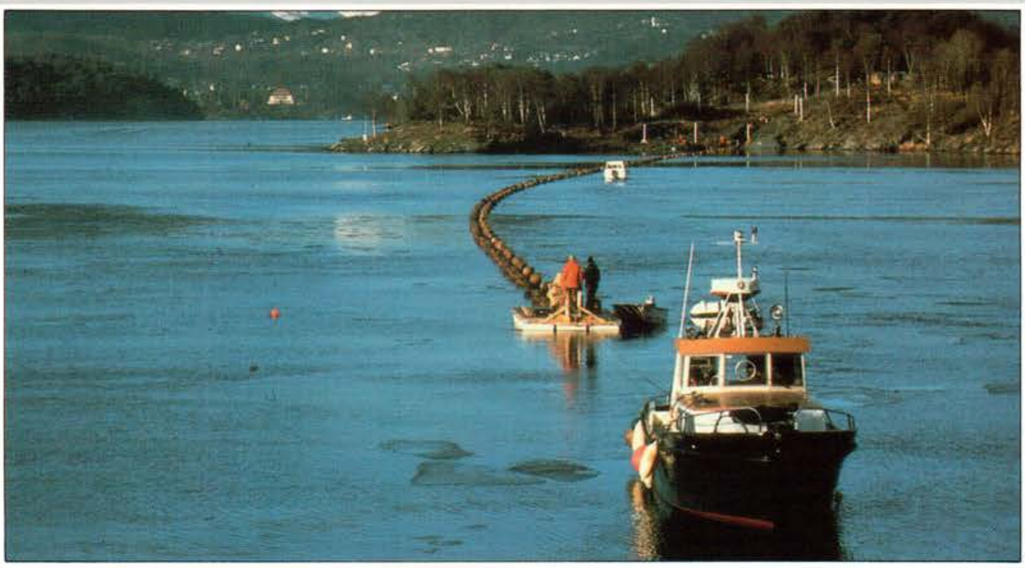
Transmission

A Choice of Options



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TRANSMISSION
A CHOICE OF OPTIONS

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PREFACE

With "Transmission: A Choice of Options", I have endeavoured to give a concise, understandable overview of the comprehensive domain of transmission, with the specific objective of showing that the major transmission media – optical fibre cable, microwave radio, and satellites / earth stations – are complementary rather than competitive.

The paper has been written to provide general information about transmission and to present the criteria for selecting the most cost-effective transmission media for particular applications. As such it will be useful for planning and purchasing officials of telecommunications operators as well as for Alcatel's marketing and sales staff dealing with transmission.

In writing this booklet, I have consulted various publications and technical papers within Alcatel as well as relevant information published by the ITU and other competent sources.

I would like to thank my colleagues who have supported me with various "facts and figures", especially:

Mr P. Samuel, for his comparative information
Mr Ph. Anache, for his support in the interest of an impartial balance between the presented applications
Mr G.Lupke, for his comprehensive support on various technical matters
Dr R.P. Harper, for his efforts to safeguard the "Queen's English".

Anton A Huurdeman
Alcatel Trade International
Paris, June 1991

Introduction

Principles
In the context of telecommunications, a transmission system transports information between the source of a signal and a recipient. Consequently it is the basis of all telecommunications systems.

In access and local networks, individual telecommunications users (originators and recipients) are connected either directly via single-pair cable in so-called *outside line plant networks*, or via a transmission system and one or more switches (the exchanges). In transport or trunk networks, on the other hand, transmission systems provide the links between different exchanges.

Figure 1 shows the principle of a telecommunications network, indicating the major transmission options for long-distance transmission between toll exchanges: cables, microwave radio and satellites.

For the normally short distances involved in urban transmission links between toll exchanges and local exchanges, between local exchanges, and between local exchanges and subscribers, cable is the standard transmission medium. However, under special circumstances it may prove cost-effective to use microwave radio or even satellite transmission.

Technology
Digital technology, the increasing scale of circuit integration offered by modern VLSI circuits and the expanding use of processor control have together led to a substantial decrease in the cost per channel. And in turn this has resulted in a tremendous increase in traffic. A variety of highly reliable transmission systems have been and are being developed to carry these large volumes of traffic between the exchanges of national and international networks.

Figure 2, based on a figure in the *ITU Telecommunication Journal*, volume X, 1990, shows how developments in the field of transmission equipment have contributed to achieving this reduction in the cost per channel. The curve shows that the major driving forces behind cost reductions were:

- coaxial cable from 1960 on
- microwave from 1970 on
- optical fibre from 1980 on.

As a result of recent developments in optical fibre, coaxial cable systems are no longer competitive, as clearly shown

Figure 1 : Major subsystems in a telecommunication network.

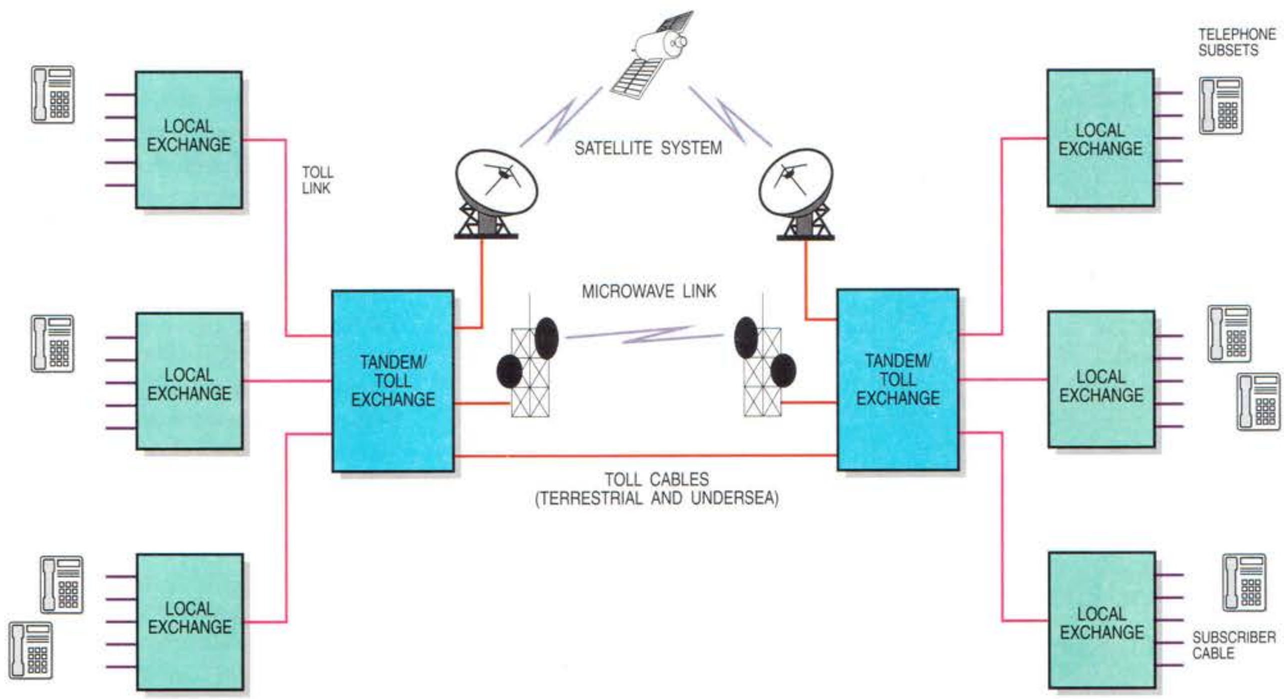


Figure 2 : Relative cost per transmission channel as a function of technology and year.

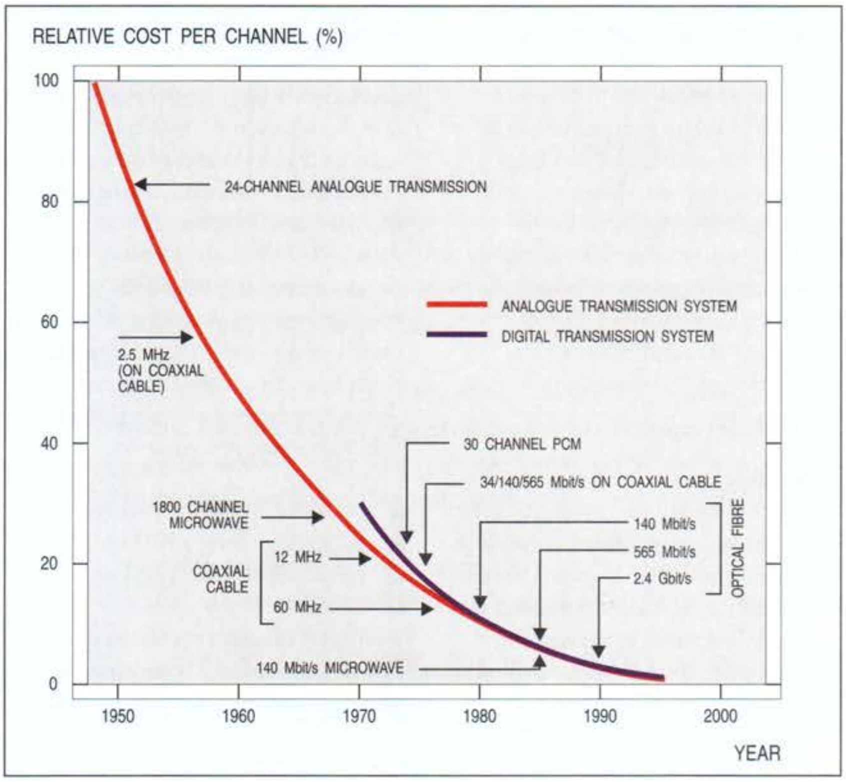
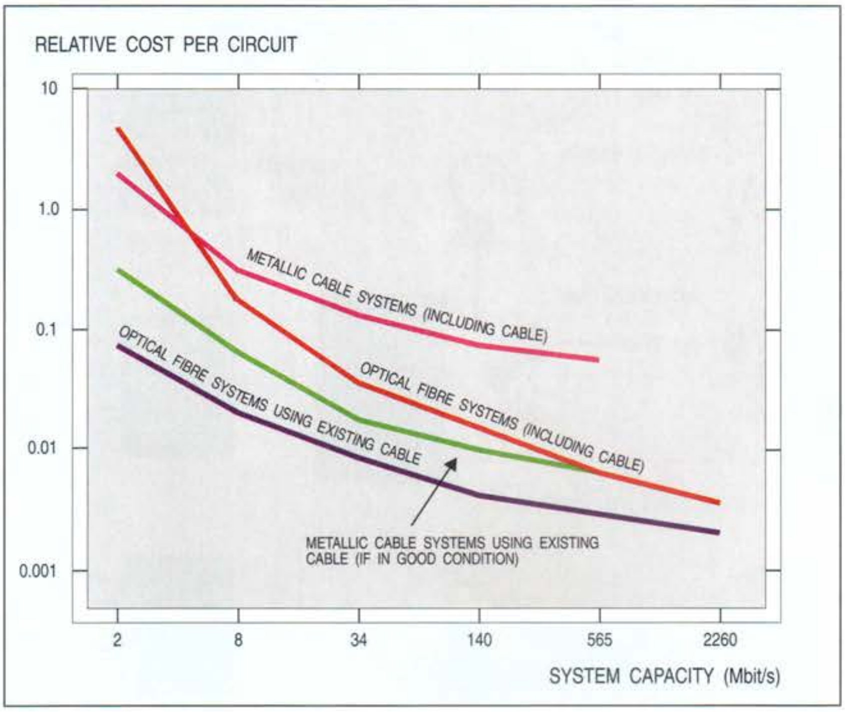


Figure 3 : Cost comparison between optical fibre and metallic cable.



in Figure 3. Whereas today about 60% of the installed long distance transmission cable is coaxial, by 1995 the ratio is expected to be 20% coaxial cable and 80% optical fibre.

However, in specific circumstances microwave radio and satellite transmission systems are still competitive with optical fibre transmission, so that basically the following three complementary transmission media are available:

- optical fibre cable
- microwave radio
- earth stations via satellites.

Which of these three media is chosen for a particular application will depend on the following considerations:

- required transmission capacity
- link distance
- terrain to be crossed
- quality and reliability criteria
- operational constraints, such as the urgency of implementation and flexibility of the network configuration.

This paper explains the merits and specific domains of application for these three transmission media. However, it should be understood that the transmission domain does not consist solely of the transmission media, but includes additional equipment for processing the subscribers' signals which are switched through exchanges before being transported over the transmission medium. This *multiplexing equipment* is common to all three transmission media and is therefore reviewed first.

Multiplex Equipment

General
The basic function of a transmission system is to provide cost-effective common links for a large number of voice frequency (VF) channels for telephony and data. To achieve this, specific numbers of VF channels are grouped together by multiplexing equipment (much like wagons in a train) before they are sent over the transmission medium (cable, microwave radio or satellite). For the sake of completeness and to make it easier to understand multiplexing, analogue multiplex equipment is described first. Although very little such equipment is manufactured today, it will remain in use for many years. Digital multiplexing is then described.

Analogue Multiplex Equipment
In analogue multiplexing, several VF channels coming from the exchange (or in the access network, direct from the subscriber) are connected in parallel to the multiplex equipment which first limits the bandwidth of each VF channel to 300–3400 Hz. Three VF channels are then grouped to form a *pregroup* by using each VF channel to modulate an HF carrier which is spaced 4 kHz from the next carrier in the same group. Four such pregroups are then modulated on four HF carriers, spaced 12 kHz apart, bringing twelve VF channels together in a so-called *basic group* (see Figure 4).

In this way the VF channels are frequency multiplexed in a multiplex group with 4 kHz separation between each VF channel. The multiplex groups are standardized by CCITT (International Telegraph and Telephone Consultative Committee) as shown in Table 1.

The multiplexing of basic groups to a *basic supergroup* is shown in Figure 5, to a *basic mastergroup* in

Table 1 – Standard CCITT multiplex groups

CCITT denomination	Number of VF channels	Frequency band (kHz)
Basic group	12	60 – 108
Basic supergroup	60	312 – 552
Basic mastergroup	300	812 – 2044
Basic supermastergroup	900	8516 – 12388

Table 2 – Main analogue transmission systems

System	Number of VF channels	Frequency band (kHz)	Transmission medium
Z 3F	3	4 – 16 / 18 – 31	Open wire lines
Z 12F	12	36 – 84 / 92 – 143	Open wire lines
Z 12	12	6 – 54 / 60 – 108	Symmetric cable pairs
VZ 12	12	6 – 54 / 60 – 108	Open wire, microwave
V 24	24	(6) 12 – 108	Microwave
V 60	60	12 – 252 60 – 300	Symmetric cable pairs Microwave
V 120	120	(12) 60 – 552	Symmetric cable pairs, microwave
V 300	300	60 – 1364	Coaxial cable, microwave
V 960	960	60 – 4287	Coaxial cable, microwave
V 1260	1260	60 – 5680	Coaxial cable, microwave
V 1800	1800	(312) 316 – 8204	Microwave
V 2700	2700	30 – 12435 (312) 316 – 12 388	Coaxial cable Microwave
V 10800	10800	4322 – 59684	Coaxial cable

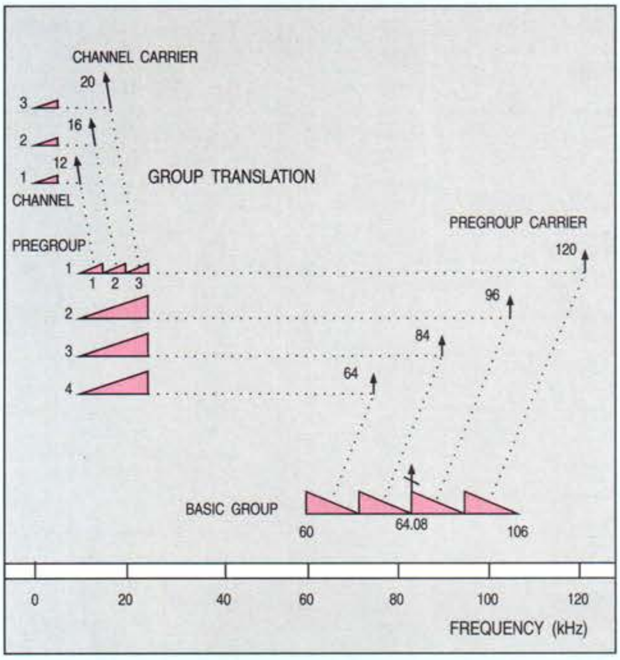


Figure 4 : Constitution of a basic group.

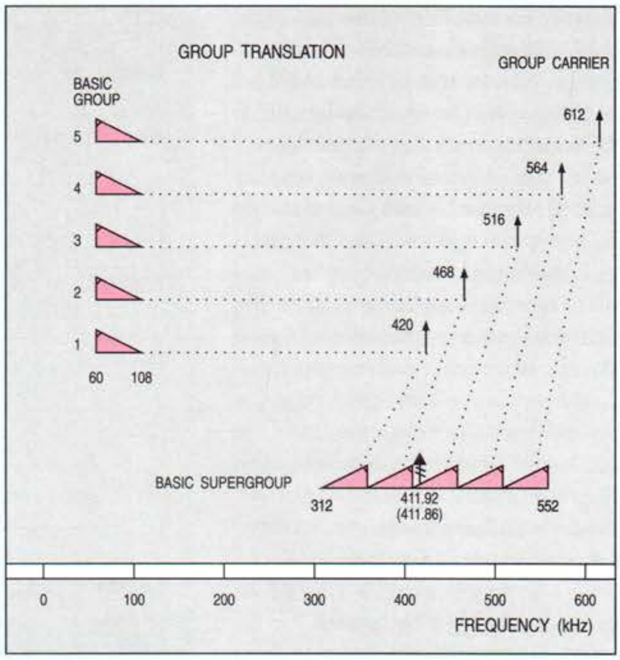


Figure 5 : Constitution of a basic supergroup.

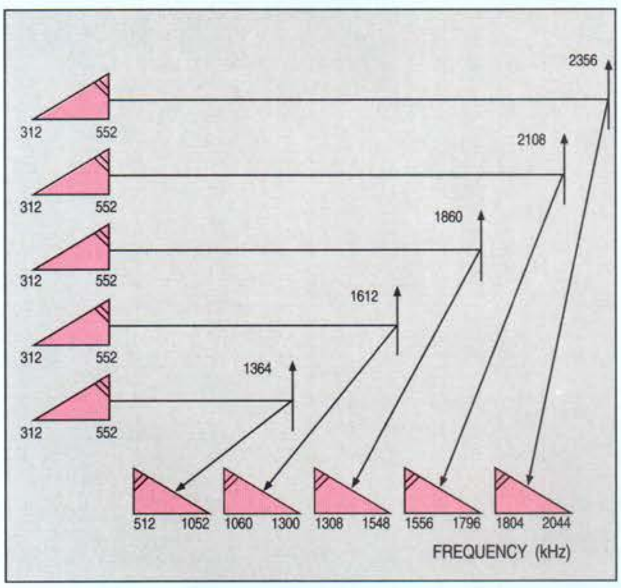


Figure 6 : Constitution of the basic mastergroup.

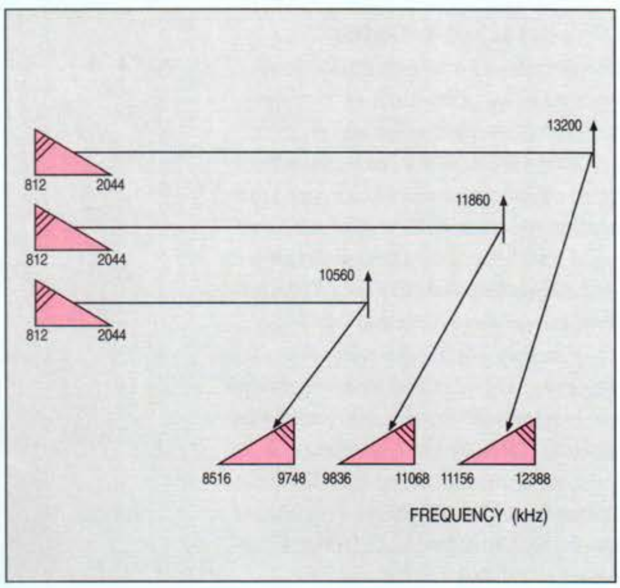


Figure 7 : Constitution of the basic supermastergroup.

Figure 6, and to a *basic supermastergroup* in Figure 7.

In order to transport these groups on the various transmission media, they are combined into analogue transmission systems as shown in Table 2.

Digital Multiplex Equipment

General

With analogue transmission systems, each time the signal is amplified at a repeater station or a back-to-back terminal, the inevitable signal distortions and unwanted (noise) signals generated in the cascaded repeater sections are amplified at the same time. Consequently the signal quality (signal-to-noise ratio) of analogue signals deteriorates as a function of distance.

Digital signals, however, essentially consist of coded *on* and *off* signals. As long as the repeater can recognize when an *on* signal has been received, it can then regenerate a new, undistorted signal and transmit this over the next section of the transmission link. Consequently, in contrast to analogue transmission, the quality of digital signals (measured by the bit error rate, or BER) is, up to a certain limit, practically independent of distance. Digital transmission thus offers substantially higher quality than analogue transmission. For technical and economic reasons, practically all new transmission equipment is now digital, in common with new telephone and data switching installations.

Plesiochronous Digital Multiplex Equipment

Transmission digitalization starts with the conversion of analogue telephone signals into digital format. An analogue signal can be converted into a digital signal of equal quality if the analogue signal is sampled at a rate which corresponds to at least twice the signal's maximum frequency. Analogue VF channels, which are limited to the 300 to 3400 Hz band, are sampled at an internationally agreed rate of 8 kHz. Each time the analogue signal is sampled, the result is then encoded using an 8-bit code, resulting in a transmission rate of 8 kHz × 8 bits, that is, 64 kbit/s, per VF channel.

Analogue-to-digital conversion is carried out by pulse code modulation (PCM) equipment which time multiplexes 30 VF channels (similar to analogue transmission where 12 VF channels are frequency-multiplexed to form a basic group) into a standard digital frame. The transmission speed of this frame must be sufficient to carry 30 VF channels + one channel for signalling + one channel for frame recognition, giving 32 channels × 64 kbit/s = 2048 kbit/s. This is usually referred to as the 2 Mbit/s primary level.

Although the sampling rate (fortunately, as we will later see under synchronous multiplex equipment) is accepted worldwide at 8 kHz, it has not proved possible to agree on a worldwide 2 Mbit/s primary level. Whereas this 2 Mbit/s primary level has been accepted in the CEPT (Conférence Européenne des Postes et Télécommunications) countries, in North America and in Japan a 1.5 Mbit/s primary level (corresponding to 24 VF channels, with each channel including its signalling in the 64 kbit/s frame) has been standardized.

Similar again to analogue transmission where large groups of VF channels are combined into basic, super and master groups, CEPT has defined a higher order hierarchy for digital plesiochronous transmission. Each higher level is set at "almost but not exactly" four times the bit rate for the previous order, as shown in Table 3.

Digital transmission systems are available for all five multiplexing levels (Figure 8). Only optical fibre transmission systems are at present available for the fifth level at 565 Mbit/s (not shown in Figure 8).

The higher level multiplexing hierarchy used in North America and

Table 3 – Digital multiplexing levels

Multiplex level	Bit rate (Mbit/s)	Bits per frame	Frame frequency (kHz)	Frame duration (μs)	Number of VF channels
1	2.048	256	8.0000	125.000	30
2	8.448	848	9.9622	100.3788	120
3	34.368	1536	22.3750	44.6927	480
4	139.264	2928	47.5628	21.0248	1920
5	564.992	2688	210.1904	4.7576	7680

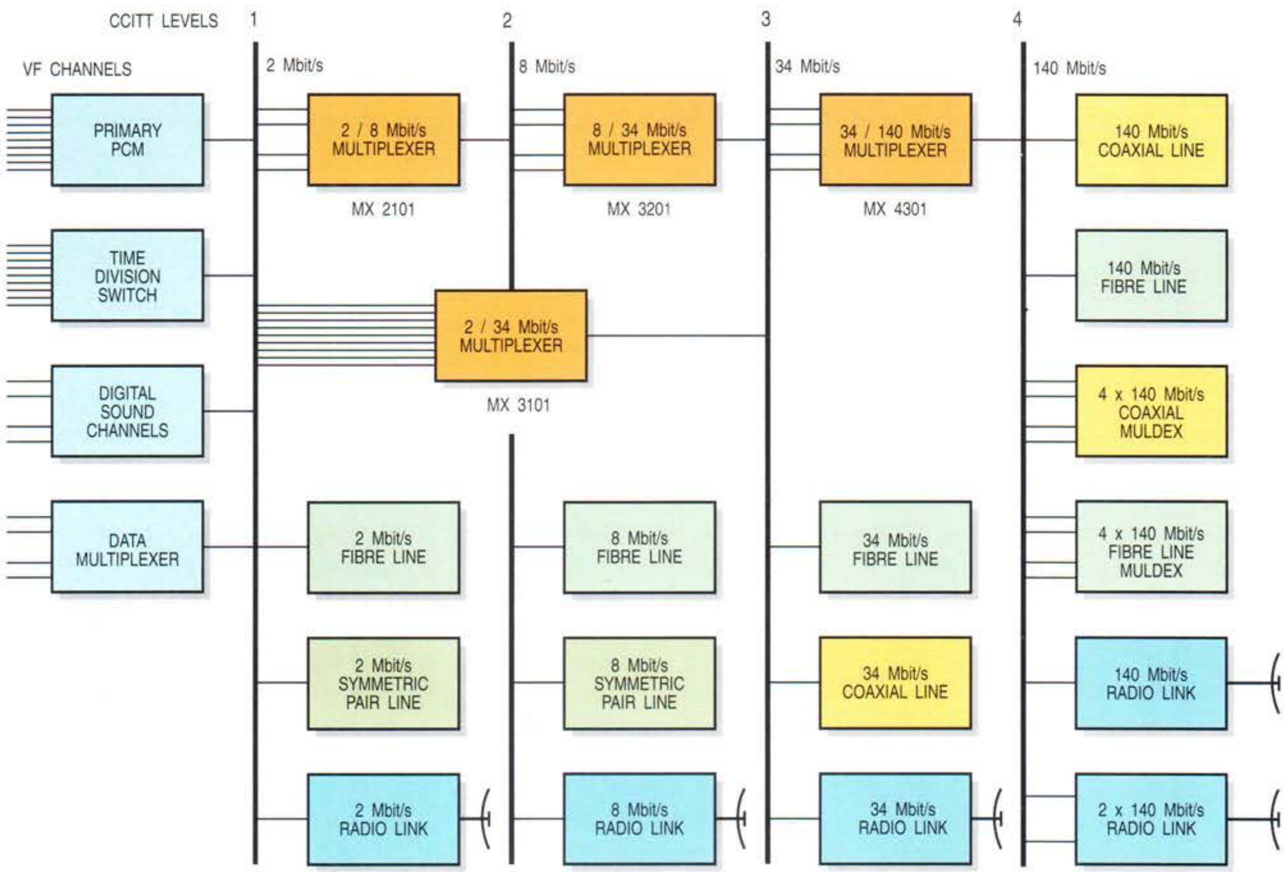


Figure 8 : High order multiplexer transmission environment.

Japan, based on their 24 VF channel system, is shown in Table 4.

Before going on to the next section, it is worth explaining the term *plesiochronous*. The prefix *plesio*, which is of Greek origin, means "almost equal but not exactly". As already indicated, each higher level in the CEPT hierarchy has been defined as "almost but not exactly" four times the bit rate of the previous level. For example, level 2 has a bit rate of 8.448 Mbit/s compared with the level 1 rate of 2.048 Mbit/s. However, $4 \times 2.048 =$ 8.192 Mbit/s, whereas $8.448 \div 4 =$ 2.112 Mbit/s. The difference of $2.112 - 2048 = 64$ kbit/s.

Table 4 – Higher order multiplex hierarchy in North America and Japan

Multiplex level	Bit rate (Mbit/s)	Number of VF channels
North America		
D1	1.544	24
D2	6.312	96
D3	44.736	672
D4	139.264	2016
D5	564.992	8064
Japan		
1	1.544	24
2	6.312	96
3	32.064	480
4	97.728	1440

The reason for this "little difference" of 64 kbit/s is partly because the so-called four tributaries which are combined to a common higher level can, in principle, come from different transmission stations which are "almost but not exactly" synchronous with one another. To compensate for this "*plesio*synchronousness" at each higher level, a number of bits are added to each tributary, depending upon the rate of plesio-synchronousness (i.e. divergence from the exact frame bit rate) of the tributary.

Level 2 tributaries are synchronized at 8.448 ÷ 4 = 2.112 Mbit/s. Thus a 2 Mbit/s tributary with a bit rate of 2.040 Mbit/s, say, instead of 2048 Mbit/s will get 2.112 – 2040 = 72 kbit/s added to its transmission rate, whereas a tributary coming from another station with a bit rate of 2050 Mbit/s, say, instead of 2048 Mbit/s will get 2112 – 2050 = 62 kbit/s added to its transmission speed. The bit rate of 2.112 Mbit/s has been chosen to be high enough to cater for the maximum expected plesiochronousness of a tributary.

Should this short explanation of a complex matter be only *plesio*understandable, it might be worthwhile reading it again!

Synchronous Multiplex Equipment
With increasing network digitalization, the inflexibility of plesiochronous multiplex equipment became increasingly obvious. In particular, interconnections via leased lines often required cross-connection and drop/insert functions. This is time consuming and costly because it is necessary to demultiplex to, and remultiplex from, the level to be accessed. In addition, rerouting may involve manual changing of cabling at distribution frames. To eliminate these problems, a synchronous hierarchy known as SONET (Synchronous Optical Network) was defined in the USA, with Alcatel involvement, in 1986. The SONET concept was then extended and adopted worldwide by CCITT under the name Synchronous Digital Hierarchy (SDH) at a CCITT Conference in Seoul in 1988.

The SDH concept is designed so that all digital signals at any synchronous multiplex level have a frame repetition frequency of exactly 8 kHz (125 µs) and the signals consist of 64 kbit/s (one VF channel) interleaved bytes.

It should be noted that the digital exchanges in an all-digital network must also be synchronized to this 8 kHz frame frequency to ensure that bit slips do not cause loss of information.

The SDH concept makes a clear distinction between multiplex functions and transport functions. It defines the Synchronous Transport Module (STM) as the only synchronous signal block which has to be transported from node to node in an SDH network. This STM signal has a frame structure which again has a frame frequency of exactly 8 kHz. The frame contains 9 × 270 = 2430 bytes, each of 64 kbit/s. The STM bit rate is thus 2430 × 64 kbit/s = 155 520 kbit/s. It is customary to show the STM frame graphically as a field of nine lines each with 270 bytes (columns), as shown in Figure 9.

The actual information being carried, which consists of 261 bytes (of 64 kbit/s) × 9 rows = 2349 VF channels, is defined as the payload. The integral section overhead (SOH) contains all operations and maintenance, order-wire, performance monitoring, framing, bit interleaved parity code data, etc, for centralized network management and remote control of section, line and path levels. Intelligent controllers at network nodes can use the SOH information to communicate and restructure the network quickly in response to fault conditions, traffic variations and specific customer requirements.

Administrative unit pointers (AU PTRs) are another key element in the SDH concept. In general, when a

Figure 9 : STM frame structure.

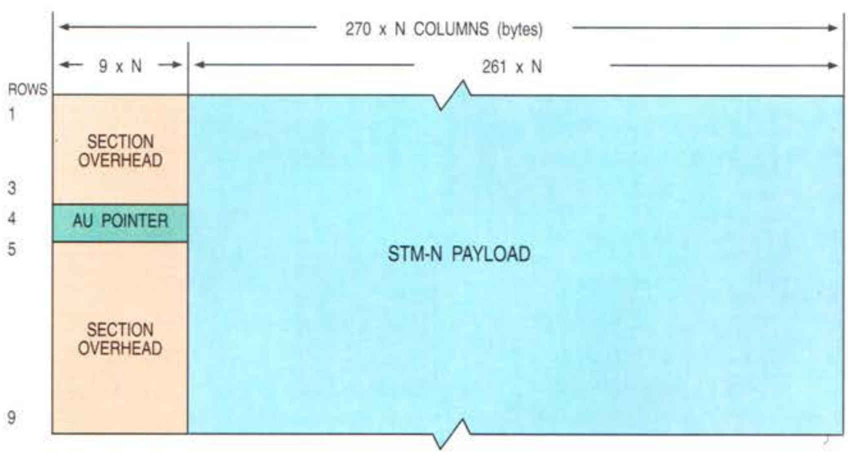


Table 5 – SDH virtual containers

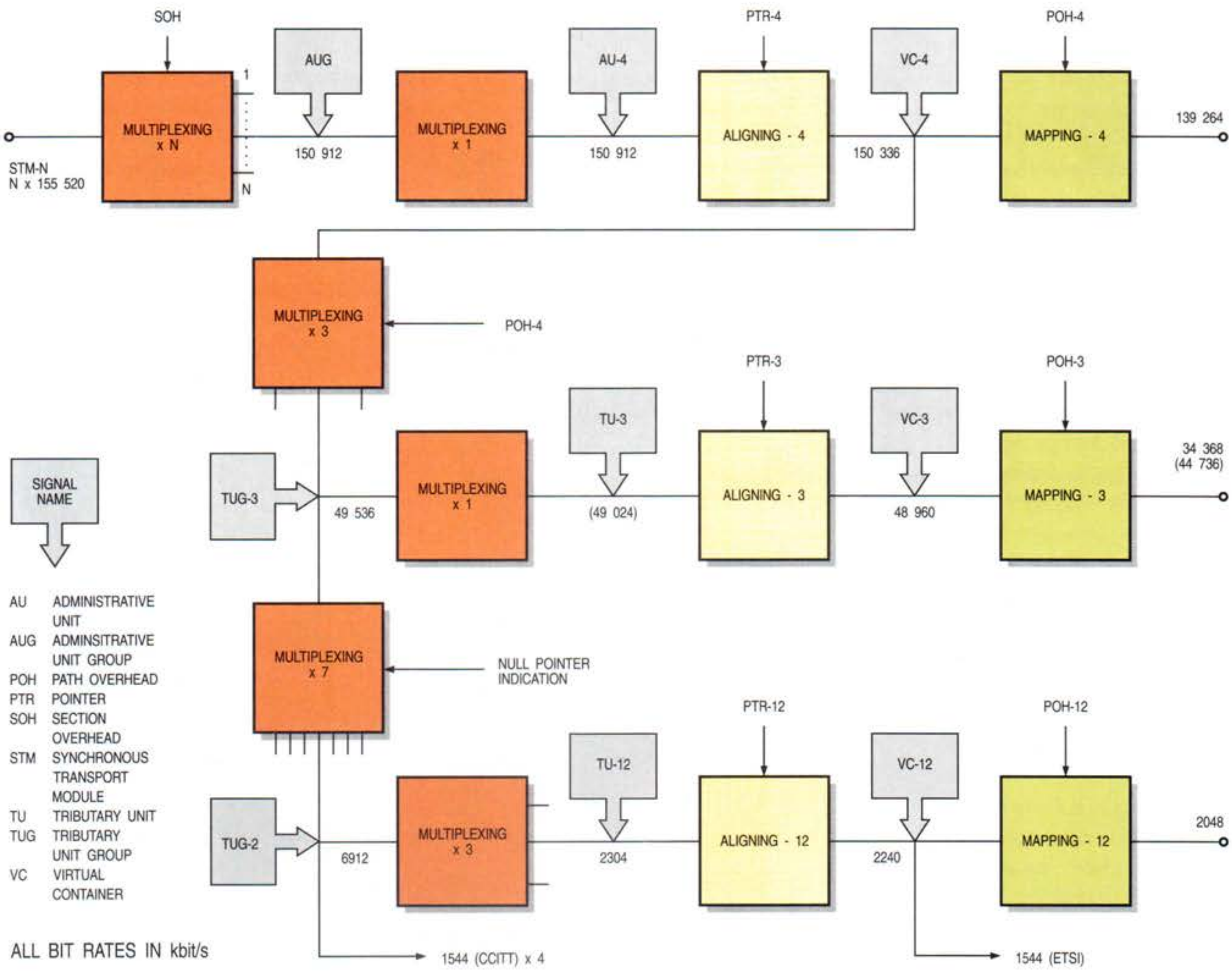
Hierarchy based on		Container designation
1544 kbit/s	2048 kbit/s	
1544		VC-11
	2048	VC-12
6312		VC-2
44 736	34 368	VC-3
	139 264	VC-4

tributary signal arrives at a network node its frame will not be in phase with the STM frame of that node. However, in the SDH concept it is not the phase of the signal which is aligned, but the phase relationship itself which is maintained and written into a pointer. The pointer provides information on where the first byte of the lower level signal starts within the higher level frame, making it possible to find any tributary signal in the STM frame.

A mandatory feature of the SDH concept is that it must be able to transport the plesiochronous bit rates of 34 and 140 Mbit/s as well as the 1.5, 6 and 45 Mbit/s rates of the American and Japanese standards. In addition, the 2 Mbit/s signal may be plesiochronous in relation to the SDH clock.

To meet this requirement, SDH uses the concept of *virtual containers.* These containers are wide enough to house the plesiochronous signal,

Figure 10 : Synchronous network multiplexing structure.



including bit rate justification signals. The containers are designated as listed in Table 5.

Figure 10 shows the complex multiplexing structure of SDH. This scheme is the most recent result of CCITT and ETSI (June 1990) standardization work. It is important to mention that the new standard uses only one VC-3, but this is wide enough for 34 Mbit/s as well as for 45 Mbit/s. The multiplexing of 2 Mbit/s signals is based on the rule $\times 3 \times 7 \times 3$, rather than on $\times 4 \times 4 \times 4$ as it was previously.

The synchronous frame structure and byte-interleaving multiplexing technique allow direct access to low bit rate channels without the need for multiplexers in a back-to-back configuration (see Figure 11). Individual channels can be added, dropped or rearranged without traffic interruption, local manual switching by operating staff or successive demultiplexing. This results in higher responsiveness to customer requests and significant savings in terms of hardware and human resources.

The synchronous digital hierarchy is again defined in steps of 4, but exactly 4 and not almost 4 as was the case for the plesiochronous hierarchy. Three SDH levels have been defined so far as *synchronous transport modules*:

- STM-1 155 520 kbit/s
- STM-2 622 080 kbit/s
- STM-16 2 488 320 kbit/s.

SDH optical fibre and microwave transmission systems are available or being developed for transporting these signals.

The comparison in Table 6 highlights the substantial advantages of SDH compared with the present plesiochronous hierarchy.

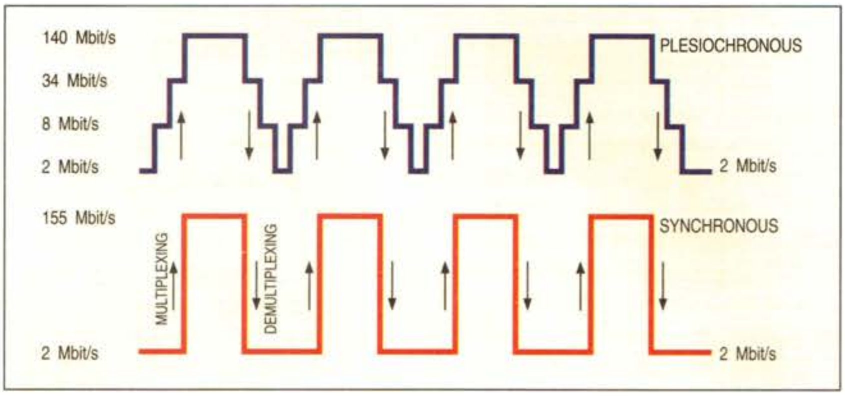


Figure 11 : PDH versus SDH 2 Mbit/s through connection.

Table 6 – Comparison between plesiochronous and synchronous digital hierarchies

Characteristic	Plesiochronous	Synchronous
Multiplexing	Bit interleaved	Byte interleaved
Frames of different levels	Uncorrelated	Fixed relationship
Frame duration	All different	125 µs for all levels
Drop and insert	With hierarchical demultiplexing/ remultiplexing	Direct access down to VF channel level
Extra capacity	None	Plenty for various applications
System structure	Gradually extended to higher bit rates as traffic increased and technology progressed	Top down design Few technological restrictions Complexity does not dictate costs because of use of VLSI
Technology	Hardware based	Software based
Cross-connection	Manual	Automatic
Network management	Possible	System incorporated; highly flexible, efficient and versatile

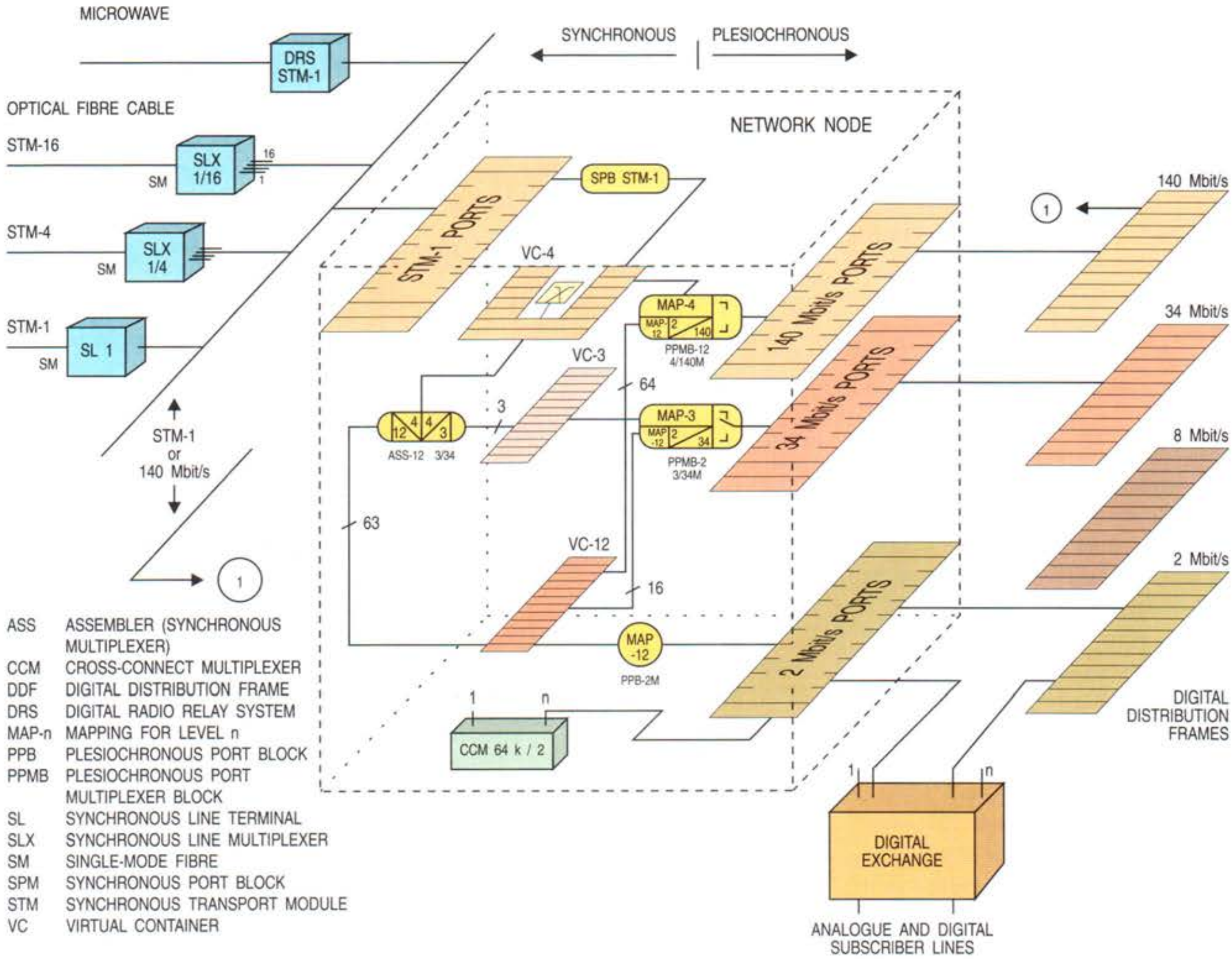


Figure 12 : Synchronous cross-connect network node with interface to PDH/SDH transmission and switching systems.

It should be noted that since SDH has been designed in such a way that plesiochronous systems can be incorporated at various interface levels, existing and planned investment in plesiochronous equipment is safeguarded. Plesiochronous equipment will remain cost-effective where traffic growth is slow and limited flexibility is needed. SDH will be complementary to plesiochronous systems for many years, providing a gateway between SDH and plesiochronous networks. It will be introduced progressively in high traffic networks that require greater flexibility. However, it will not make plesiochronous systems obsolete, at least not in this century!

Special SDH Applications

Cross-Connect Multiplexers

A cross-connect multiplexer is, in essence, an electronic line distribution frame incorporating multiplex equipment. In plesiochronous networks the rerouting of lines at transmission nodes (e.g. to change the allocation of leased lines) is currently done manually by changing colour-coded cable pairs at *main distribution frames.* As explained above, the SDH multiplexing structure with the help of the pointers and virtual containers allows any signal to be located within the STM frame. Consequently, any signal can be dropped directly from the STM signal. Inserting is also possible. Combining these possibilities enables traffic to be rerouted without demultiplexing.

Rerouting of tributary signals under computer control is the basis for the cross-connect concept. In addition to improving availability by allowing rapid rerouting in the event of equipment or link failures, cross-connect units can be used to handle time-of-day and seasonal traffic load variations, such as to carry cable TV programmes during the off-peak hours for telephone traffic.

Figure 12 shows the functions of such a cross-connect network node and its interconnection to the outside PDH/SDH transmission and switching environment. The node shown in Figure 12 can handle 140 Mbit/s or 34 Mbit/s plesiochronous signals as solid blocks for transportation only. Alternatively it can demultiplex them down to 2 Mbit/s for multiplexing according to the SDH rules. All VC-12, VC-3 and VC-4 signals can be routed separately, but all at the STM-1 (155 Mbit/s) level.

Besides the advantages of rapid, computer controlled operation of such cross-connect network nodes, the SDH structure enables the volume of the equipment, station cabling and power supplies to be greatly reduced compared with even the most modern plesiochronous solutions as it replaces higher order multiplex equipment and distribution frames in large or medium stations.

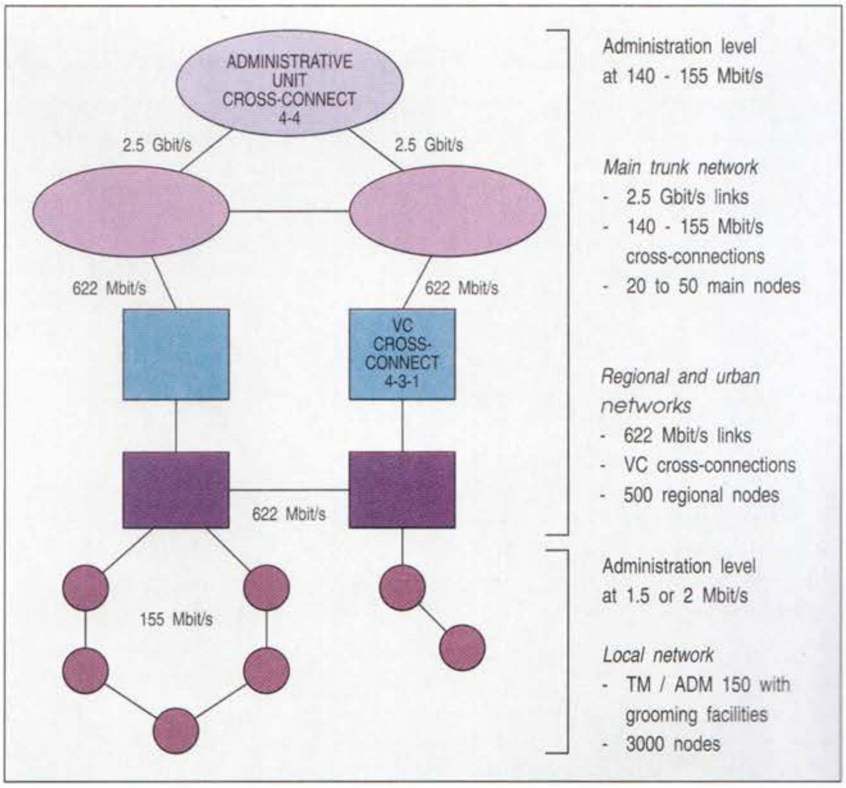
SDH Add/Drop Multiplexer
Cross-connect multiplexers provide a powerful means of interfacing synchronous and plesiochronous networks and of rerouting in high density traffic network nodes. However, for network nodes carrying low density traffic, *add/drop multiplexers* or *flexible multiplexers* provide a more cost-effective means of integrating plesiochronous signals into an SDH network. The add/drop multiplexer can insert into or drop from a 2(1.5) Mbit/s or a 34(45) Mbit/s signal of an STM-1 signal at repeater or back-to-back terminal stations. At terminal stations the add/drop multiplexer can be equipped with a simpler cross-connect enabling 2 Mbit/s (and/or 1.5 Mbit/s) tributaries to be rerouted.

Global Network Solutions
Alcatel provides a coherent family of products that will allow smooth evolution from today's plesiochronous networks to a more powerful SDH infrastructure. By incorporating SDH transport, cross-connect and network management systems within a network, it is possible to design a cost-effective, flexible network solution with end-to-end management that optimizes the specific network architecture.

Figure 13 illustrates a typical architecture for a synchronous network. The main trunk network along an STM-16 backbone link consists of 140/155 Mbit/s cross-connects and 2.5 Gbit/s optical line equipment. The regional and urban network typically consists of 622 Mbit/s optical line equipment and 155-to-2 Mbit/s cross-connects. The local network may be based on 155-to-2 Mbit/s add/drop multiplexers with cross-connect facilities for switches and large business customers.

The network infrastructure can evolve with the introduction of SDH; the number of main nodes can be

Figure 13 : Typical SDH network architecture.



reduced and the capacity of lines between nodes increased. Moreover, the network is built on only two administrative levels, 2 Mbit/s and 140(155) Mbit/s, thereby simplifying overall network management.

Digital Circuit Multiplication Equipment

Digital circuit multiplication (DCM) equipment increases the capacity of transmission systems by using digital speech interpolation (DSI) to eliminate the silent periods which occur naturally in speech. In addition it automatically adapts the digital coding to the traffic load by means of variable bit rate adaptive differential pulse code modulation (VBR-ADPCM). As a result it is possible to increase the transmission capacity by a factor of between 5 and 8 for speech, and between 2 and 3 for data, depending on the actual traffic.

DCM equipment can be used to increase the transmission capacity of satellite links as well as cable and microwave links. Deployment of the equipment can be planned from the time of initial commissioning of a transmission link to reduce the cost per channel, or as a retrofit to add extra capacity to keep pace with increasing traffic. Alcatel's DCM equipment is known by the trade name CELTIC.

Optical Fibre Transmission

The principle of guiding light through a transparent conductor was demonstrated as early as 1870 (Table 7). However it was the invention of the laser in 1959 which led Kao and Hockham to predict in 1966 that optical fibres drawn from extremely pure glass with very low transmission losses would be ideal support for the transmission of lightwaves. The subsequent discovery of windows of minimum attenuation and dispersion (see Figure 14) confirmed their prediction.

Types of Optical Fibres

Three types of optical fibre are currently available for use in optical transmission systems:

- step index
- graded index
- single mode

Figure 15 shows the basic characteristics of these three types.

Step- and graded-index fibres are also known as multimode fibres, since their relatively large diameter cores allow a number of light waves (or *modes*) to propagate in parallel.

Step-index Fibre

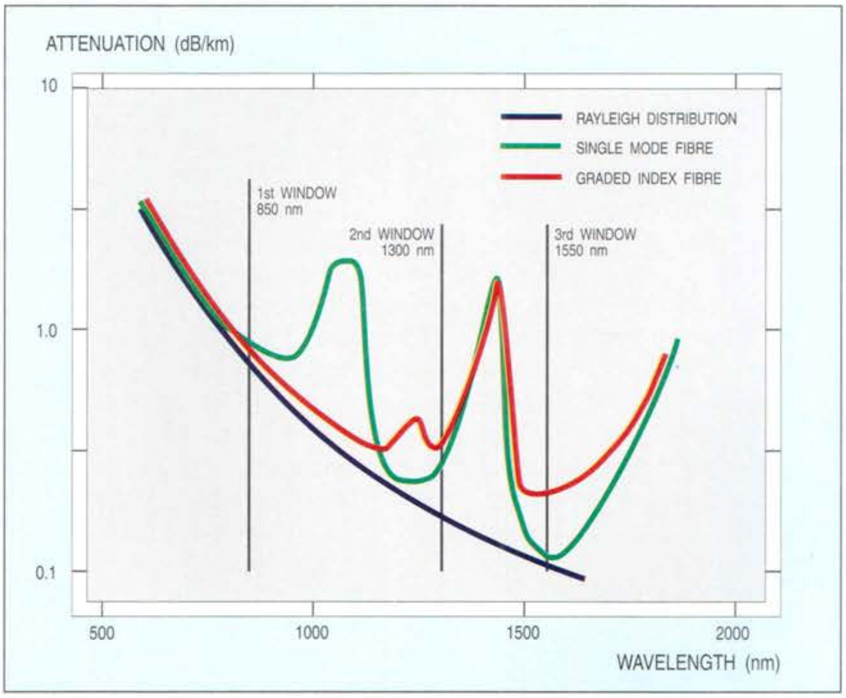
Step-index fibre has a uniform refractive index *n* in the core which is higher than that of the cladding; the refractive index transition at the boundary between the core and cladding is therefore shaped like a step.

Light waves are totally internally reflected at the boundary between the core and the cladding. If the wavelength of the light is short relative to the core diameter, the light can follow multiple paths which are different in length. Transit time differences therefore arise between individual light rays, resulting in time

Table 7 – Brief history of optical fibre transmission

1870	John Tyndal Society in the UK demonstrates that light follows beamed water streams
1959	Invention of laser
1966	Charles Kao and George Hockham in the UK discover the use of optical fibre for the transmission of modulated light
1972	Start of optical fibre development at Câble de Lyon
1980	First commercial link in France: 7.5 km in Paris operating at 34 Mbit/s using Alcatel equipment
1987	World's first commercial long distance optical undersea cable link: 390 km link to Corsica operating at 2 x 280 Mbit/s using Alcatel equipment
1989	World's first 2.24 Gbit/s trial systems in France and Germany, both using Alcatel equipment
1990	World market for optical fibre 5 500 000 km
1991	Alcatel provides Bell Communications Research with a 2.5 Gbit/s optical fibre trial system

Figure 14 : Attenuation windows for optical fibre transmission.



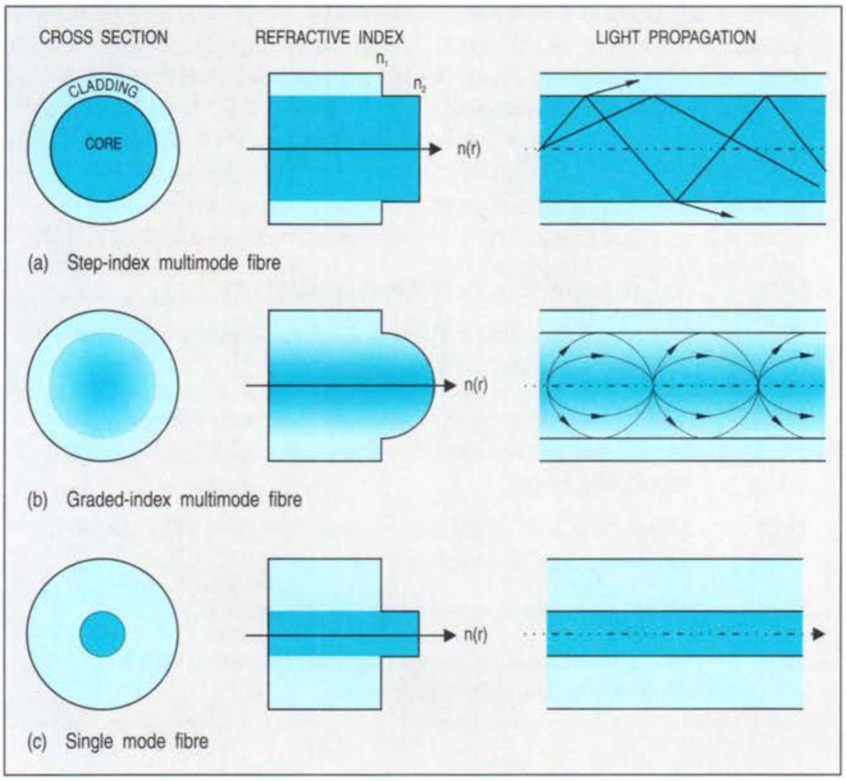
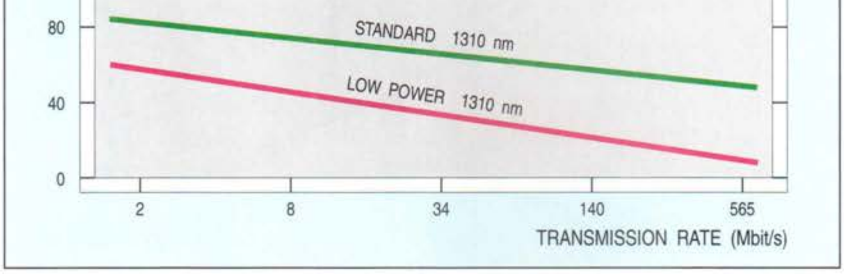


Figure 15 : Characteristics of different types of optical fibre.

Figure 16 : Variation of repeater spacing with transmission capacity for terrestrial optical fibre cable.



dispersion of the short input pulses. This pulse dispersion (or mode dispersion) limits the transmission bandwidth of an optical fibre cable to about 100 MHz × km.

Graded-index Fibre

Mode dispersion is significantly reduced by using graded-index fibre. In this configuration the profile of the core refractive index is parabolic, with the maximum value at the core centre, and reducing to the same value as that of the cladding at the cladding/core boundary. The relative refractive index difference between the core centre and the cladding is about one percent.

As a result of this parabolic index profile, the light rays now follow a sinusoidal or spatial helical path along the fibre axis, thereby reducing the spread of the transit times for different modes. With an optimum refractive index profile, pulse dispersion can be minimized and a transmission bandwidth of 1 GHz × km achieved.

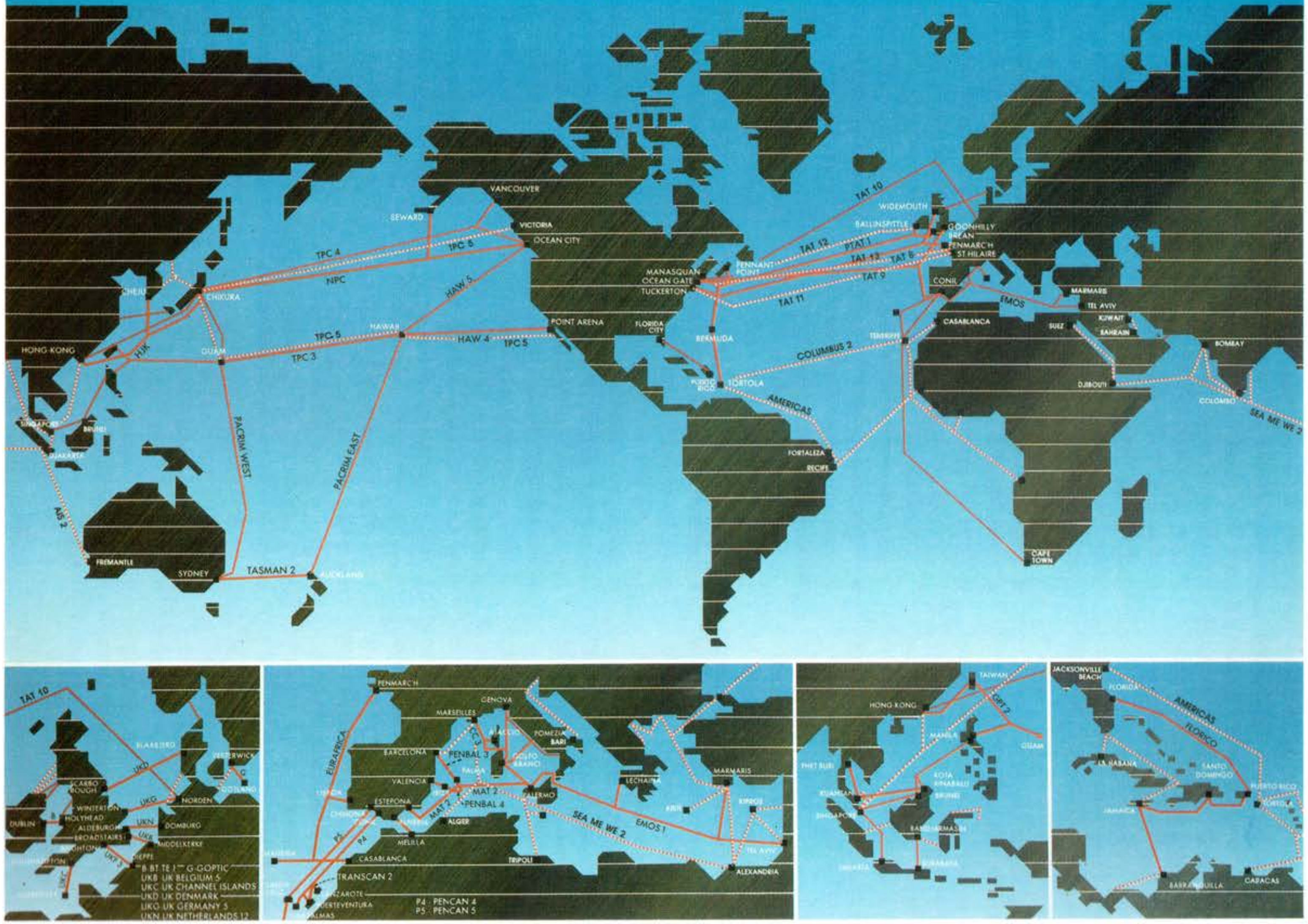
Single-mode Fibre

When the core diameter of a graded-index fibre is reduced sufficiently so that only a single mode can be propagated, the result is a single-mode fibre. In this case there is no longer any path-dependent transit time difference (mode dispersion) and the fibre has a very wide transmission bandwidth (10 GHz × km). As the fibre attenuation is very low, single-mode fibres are used when high bandwidths are required, principally in wideband, long distance systems.

Optical Fibre Transmission Systems

In 1987 the world's first commercial long distance submarine optical fibre cable went into service. This 390 km link consisted of two parallel systems,

Global Network of Optical Fibre Submarine Systems



Courtesy of Submarcom

each with a capacity of 280 Mbit/s. The cable and equipment was supplied by Alcatel. Since then, some 30 000 km of submarine optical fibre cable has been installed (see map on previous page) – over 6500 km by Alcatel.

A steady reduction in fibre attenuation (present state-of-the-art is already below 0.2 dB/km) has led to repeater sections of more than 100 km for terrestrial systems and close to 200 km for undersea systems (see Figure 16). Transmission quality is excellent, achieving a bit error rate (BER) as low as 10^{-10}.

The principal advantages of using optical fibre for transmission are:

- Low loss: enables terminals and repeaters to be widely spaced.
- High bandwidth: almost unlimited data transmission rates combined with extremely high quality (BER 10^{-10}).
- Light weight and small size: ideal for aircraft and car wiring applications.
- Electrical isolation: completely safe for high voltage, monitoring and control applications.
- Freedom from electromagnetic interference: no pick-up in electrically noisy environments and no crosstalk.
- No spark hazard: safe for operation even in explosive atmospheres.
- Security against tapping: fibres are difficult to locate and *tap*.
- Open circuit failure mode: no short-circuit fault damage to terminals.

With the transmission capacity on optical fibre systems presently increasing from 565 Mbit/s to 2.24 Gbit/s for plesiochronous and 2.5 Gbit/s for synchronous systems, and within the next five years to 10 and even 40 Gbit/s, transmission on optical fibre is becoming cheaper and cheaper on a per-channel basis. Consequently, broadband applications are becoming more and more affordable for transmission on optical fibre in domains such as:

- fibre in the loop (FITL)
- professional videocommunication
- terrestrial systems with transmission capacities from 2 Mbit/s to 2.5 Gbit/s and beyond
- submarine systems with transmission capacities from 140 to 560 Mbit/s and beyond (repeatered and unrepeatered).

Alcatel produces optical fibre line transmission systems with capacities of from 2 Mbit/s to 565 Mbit/s. Systems for $4 \times 155 = 622$ Mbit/s will soon be available.

At present, Alcatel is providing Bell Communications Research in the USA with a 2.5 Gbit/s optical fibre system operating according to the new SONET standard for use in their field trials. An SDH version of this new 2.5 Gbit/s system, which has a transmission capacity of $16 \times 2349 = 37\,584$ telephone channels on a single fibre pair, is scheduled to go into production at the end of 1991. Alcatel has already started an extensive research and development programme aimed at realizing optical fibre transmission systems with capacities of 5 and 10 Gbit/s. Indeed, Alcatel has already successfully completed the world's first trials of 20 Gbit/s transmission over a 115 km link and 25 Gbit/s over 40 km using optical amplifiers.

The low attenuation of optical fibre allows repeater sections exceeding 100 km in length compared with coaxial cable systems which required repeater sections every 1.5 to 10 km, depending on transmission capacity and type of coaxial cable. Consequently, in most cases repeaters can be located in telecommunications buildings instead of underground at fixed intervals along the route. In these cases it is no longer necessary to power feed the repeaters via the cable, so cables can be completely metal free.

Specific Applications for Optical Fibre Transmission

Because of its many advantages, optical fibre transmission, although the newest of the three transmission media, has become the standard solution for the following applications:

- Undersea systems.
- High capacity terrestrial systems, except where adverse terrain, such as jungle, marshes and rocky areas, has to be crossed.
- Standard conditions with regard to project implementation schedule, security, distance and of rights of way.
- Easy extension to meet high traffic growth, and frequent drop and insert.
- Permanent location of the stations.
- Easy access to isolated stations and no existing infrastructure, such as towers and power plant (the converse could favour microwave).
- Low and medium capacity systems to replace open-wire lines.
- Application in areas with high electromagnetic radiation.

Satellite Transmission

Satellite telecommunications transmission systems are based on satellites located in a geostationary (synchronous with the earth's rotation) orbit some 36 000 km above the earth. Each satellite operates as a microwave relay station with a number of combined receiver/transmitters, called transponders. Signals are transmitted to and received from these satellites by earth stations, each of which is equipped with an antenna system pointed towards the corresponding satellite. Earth stations are also connected to the public (or a private) telephone network. Three such satellites are needed to ensure communications around the world. A brief history is given in Table 8.

Satellite transmission operates in the frequency bands listed in Table 9.

Intercontinental satellite transmission started in 1962 with the Telstar satellite which was linked to earth stations in the USA and to the Pleumeur-Bodou earth station* in Brittany, France, one of the most western parts of Europe. Alcatel participated in this first intercontinental satellite link. These early earth stations used a 20 m diameter horn antenna (see photograph on page 21).

INTELSAT

In 1964, Intelsat, the International Telecommunications by Satellite consortium, was set up, and in 1965 opened the first commercial international television and telephone transmission system between the United States and Europe via the Intelsat 1 satellite *Early Bird*.

* Pleumeur-Bodou is still an earth station site; in addition it is a museum dedicated to satellite telecommunications.

Table 8 – Brief history of satellite transmission

1962	First intercontinental satellite television transmission via Telstar between USA and France (Pleumeur-Bodou)
1964	Intelsat founded
1965	Intelsat I Early Bird; 240 telephone channels or one TV channel
1974	Symphony I; first European (French/German) satellite
1977	Eutelsat founded
1990	Over 3000 earth stations in operation worldwide (excluding VSATs)

Intelsat began with a charter membership of eleven nations. Its mission has been to provide worldwide satellite communications to all countries on a non-discriminatory basis. With its headquarters in Washington DC, Intelsat is now an international commercial (but non-profit making, by statute) cooperative of 118 member nations which own and operate the global communications satellite system. This network is used worldwide by countries for their international and, in many instances, domestic communications. Intelsat also offers, via its 14-satellite global system, such services as international TV transmission, teleconferencing, facsimile, data and telex.

Table 9 – Satellite frequency bands

Band	Earth station frequency (GHz) receive / transmit
C	4 / 6
Ku	11 / 14
	12 / 14
	12 / 18
Ka	20 / 30

The first Intelsat satellite, designed for an operating lifetime of 18 months, was capable of transmitting one TV signal and 240 telephone channels using analogue technology. Today's satellites have a lifetime well beyond 10 years and can simultaneously transmit three TV channels and 120 000 telephone channels.

INMARSAT

Satellite transmission has also proved to be an excellent method for communicating with ships. Until the last decade, ships crossing the oceans of the world had only one method of long-distance communications available – high frequency (HF) radio. Despite significant improvements since the days of Marconi, this technology is still far from reliable because of problems of propagation in the ionosphere, interference, crowded channels and areas where it is simply impossible to make any contact. Ships can be out of communications contact for hours, or even days.

The world's maritime nations, recognizing the advantages of satellite transmission, formed a cooperative called the International Maritime Satellite Organization (Inmarsat), which has its headquarters in London. At present 56 countries are members of the organization. Since 1982, Inmarsat has operated a system of satellites to provide telephone, telex, data and facsimile communications, as well as distress and safety communications services, to the shipping and offshore industries.

In 1985, Inmarsat introduced an aeronautical service, and today land mobile satellite communications is also available.

Inmarsat basically provides point-to-multipoint communications networks, but it is not a provider of carriers for international public telecommunications traffic. It is included here as an important satellite service provider, but in the sense of this book it will not be considered as a transmission media provider.

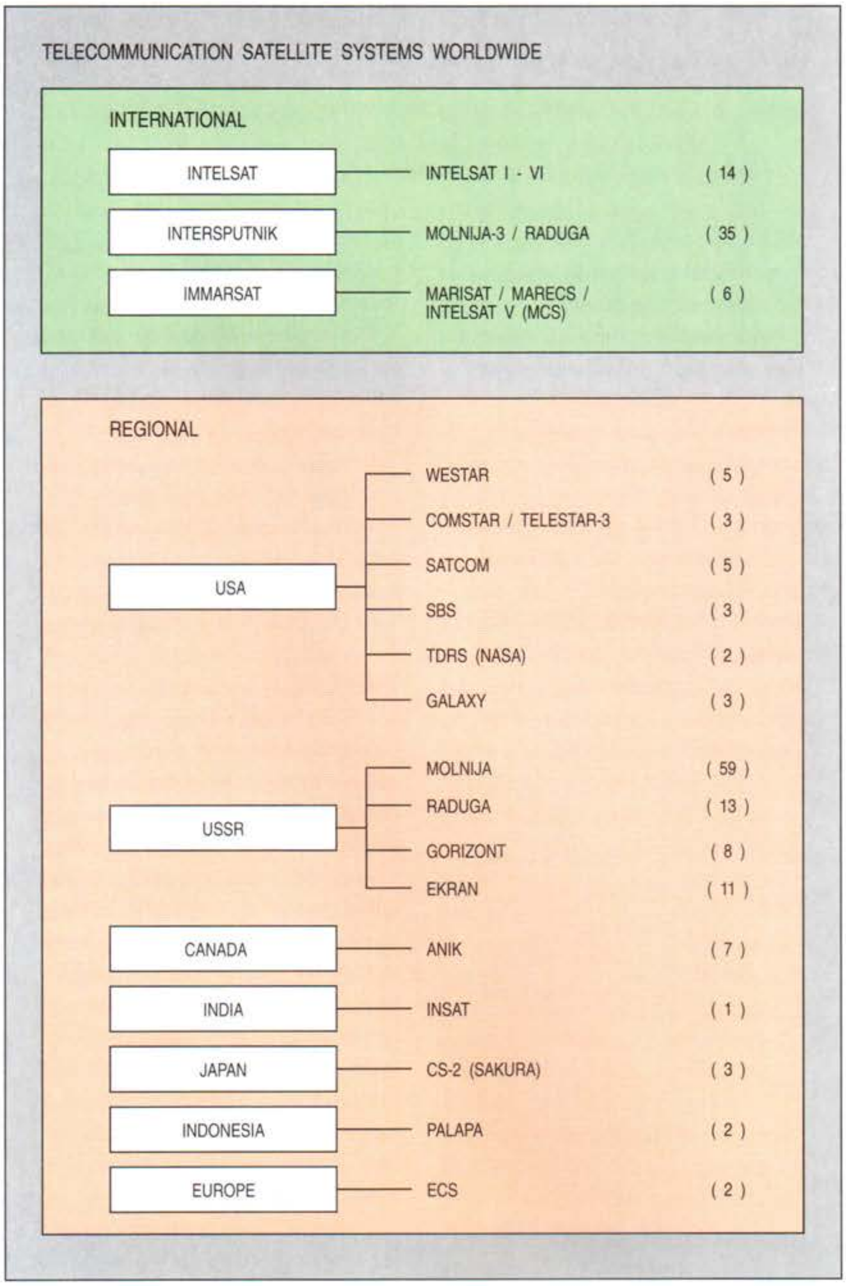


Figure 17 : Worldwide satellite networks.

Satellite Networks

Whereas Intelsat and Inmarsat provide worldwide coverage, regional organizations like Eutelsat, the Paris-based European satellite organization with 26 CEPT country members, provide continental coverage. National organizations like Brazilsat provide a national (domestic satellite or DOMSAT) satellite service. Figure 17 shows that some 182 commercial satellites are currently in operation.

Numerous organizations provide satellite services for private VSAT (very small aperture terminal) stations which are equipped with antennas with diameters as small as 1.2 m.

The development of small, low-cost unattended earth stations, such as Alcatel's FASTCOM station, offers an economical approach for providing national satellite transmission networks, for example, in countries with villages and small towns widely scattered in difficult terrain where there is an insufficient infrastructure of roads and electricity supplies.

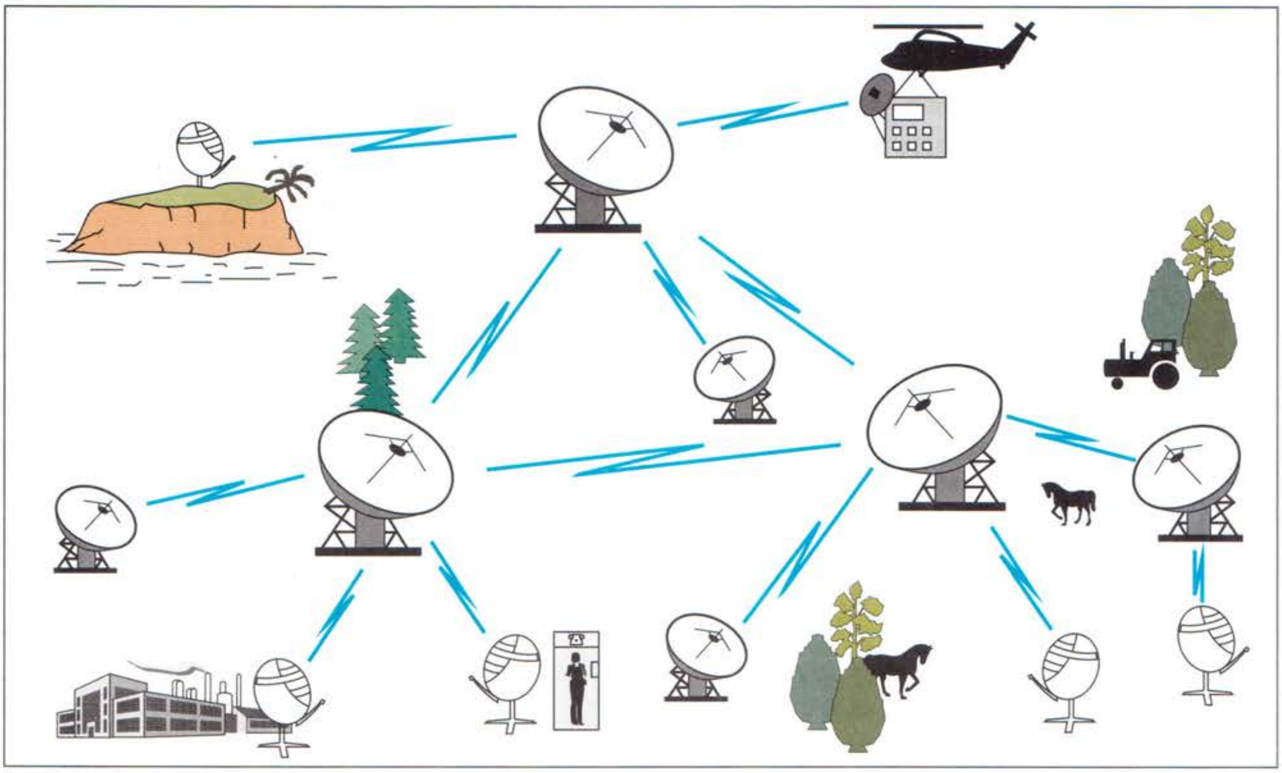


Figure 18 : Hybrid Domsat network.

Figure 18 illustrates a network based on a combination of FASTCOM and VSAT stations.

Once it has been established that satellite transmission can meet the communications requirements of a country, the next question is whether to purchase or lease Intelsat transponders or use a dedicated domestic satellite? The answer is not obvious, but in many cases a country can start by leasing several transponders from Intelsat (2 to 5) and use them for internal domestic needs (telephony, TV distribution). In parallel, plans can be developed for a domestic system that is tailored to the particular needs of the country. Although Intelsat satellites are versatile, they are not particularly matched to specific country needs.

Also the coverage area may not be optimum, resulting in the received power being too low and thus requiring more expensive earth stations. Changing the requirements can lead to a lengthy administrative process with Intelsat and it might be difficult to transmit secure communications through Intelsat transponders.

Therefore, when the operational constraints of using Intelsat transponders starts to adversely affect a country's communications needs, moving to a domestic satellite system is likely to be the right choice.

Alcatel has provided or is providing complete communications payloads (transponders and antennas) for the Telecom 1, Telecom 2, TDF 1 and 2, Tele-X, Eutelsat 2, and IOC satellites, among others. In other programmes, such as TV-SAT and Intelsat VII, Alcatel is delivering major subsystems as prime contractor for the payload.

In early 1991, Alcatel Espace teamed-up with Aerospatiale (France), ALENIA (Italy), Deutsche Aerospace (Germany) and LORAL (USA). As a result, Alcatel can now carry out complete turnkey satellite projects, including:

- satellite
- payload
- launcher (rocket)
- ground control station
- launch management
- civil engineering works
- insurance
- complete communications system.

Earth Stations

Earth stations communicate with one another, usually in a point-to-multipoint network, via a satellite transponder. Thus an earth station must be able to receive and amplify the weak signals received from the satellite and transmit strong signals to the satellite. The required bandwidth and transmit power of the transponder will determine whether large antennas (and low-noise amplifiers) will be required.

Table 10 – Summary of earth station categories

Category	Frequency band (GHz)	Antenna size (m)	Application	Alcatel trademark
Intelsat : standard				
A	4 / 6	15 – 17	International voice, data, TV	
B	4 / 6	10 – 13	International voice, data, TV	
C	11 / 14	11 – 13	International voice, data, TV	
D1	4 / 6	4.5 – 5.5	Domestic VISTA	Fastcom
D2	4 / 6	11 – 13	Domestic VISTA	Fastcom
E1	11 / 14 – 12 / 14	3.5 – 4.5	IBS	Fastar
E2	11 / 14 – 12 / 14	5.5 – 6.5	IBS	
E3	11 / 14 – 12 / 14	8 – 10	IBS	
F1	4 / 6	4.5 – 5	IBS	Fastar
F2	4 / 6	7 – 8	IBS	
F3	4 / 6	9 – 10	International voice, data, IBS	
Eutelsat				
Large	11 / 14	11 – 13	International voice, data, TV	
S1	11 / 14	6 – 7	International voice, data, TV	
S2	11 / 14	3.5 – 4.5	International voice, data, TV	Fastar
S3	11 / 14	2.5 – 3.5	International voice, data, TV	
General				
VSAT (1)	4 / 6	2.4 – 4.5	Corporate networks	Fastar
VSAT	11 / 14	1.8 – 2.5	Corporate networks	Fastar
TVRO	4	3.5 – 7.5	TV distribution	
TVRO	11 or 12	1.2 – 3.7	TV distribution	
SNG	11 or 12	1.2 – 3.7	Satellite news gathering	

(1) USAT for antennas 0.2 to 1.2 m.

Based on the various network applications, such as international (Intelsat, Eutelsat, Arabsat), Domsat, corporate networks and for professional video and sound transmission, earth stations are internationally classified as shown in Table 10. Alcatel can supply earth stations for all the categories shown in this table.

Satellite Transmission Technology
In terrestrial cable and microwave networks, a substantial amount of the installed transmission capacity is unused and available to meet future traffic increases. In contrast, for satellite transmission via expensive satellites with a still relatively short operating lifetime of some 10 years, the luxury of unused capacity cannot be afforded. On the contrary, the sharing of a satellite's transmission capacity by several users is the state-of-the-art. Basically this is achieved by multiple access (MA) techniques which enable each user to occupy a free channel of a satellite transponder only when it is needed. In the case of analogue transmission, frequency division multiple access (FDMA) is used. This operates in a similar way to analogue multiplex equipment: a number of channels are spaced from one another by set frequencies within a certain transmission band.

Transmission quality is further enhanced by using single channel per carrier (SCPC) modulation in which the carrier is switched-off during speech interruptions.

Time division multiple access (TDMA) is used for digital transmission; it enables each user to occupy a free time slot only during the period that it is needed. Digital transmission capacity can be further increased by using digital speech interpolation (DSI), which eliminates the silent periods in a signal.

To smooth the transition from analogue to digital operation, an intermediate data rate (IDR) modem has been standardized which enables digital signals to be transmitted via analogue satellite circuits at a variable bit rate of from 64 kbit/s to 44 Mbit/s.

Specific Applications for Satellite Transmission
Satellite transmission is the only possible choice where worldwide coverage is required. However, it can also be economical for domestic and regional operation in the following circumstances:

- Scattered population in a large number of widely dispersed towns and villages (less than about 5000 inhabitants) where the terrain is hostile or difficult (e.g. deserts, mountains, islands).
- National and/or regional TV distribution.
- Rapid implementation of national networks.
- Flexible network configuration.
- Temporary use in, for example, the event of a natural disaster or war, or to support major exhibitions and sports events of international interest.
- Corporate networks.

First generation earth station with 20 m horn antenna at Pleumeur-Bodou.

Microwave Radio Transmission

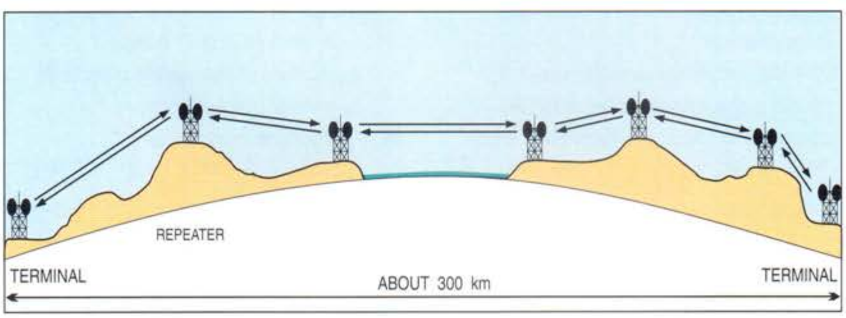
Table 11 – Brief history of microwave radio transmission

1888	Heinrich Hertz in Germany demonstrated that electromagnetic waves can be directed and received at distant points
1896	Marconi in Italy transmitted radio signals over a few kilometres
1930	André Clavier in France demonstrated transmission of radio signals at 1.7 GHz
1934	World's first commercial microwave link between UK and France (included Alcatel equipment)
1953	Eurovision transmission of the coronation of Queen Elizabeth II in the UK via microwave radio network connecting seven European countries
1990	Total annual world market about 50 000 transmitters/receivers
1991	First trial link of 622 Mbit/s, 4 GHz SDH microwave radio

Microwave radio transmission systems operate at carrier frequencies above 300 MHz. High gain antennas concentrate the transmitter power in the preferred direction. The distance between adjacent stations is normally restricted to the line of sight (they are often referred to as LOS systems), except in the case of over-the-horizon (troposcatter) systems. Longer distances can be spanned by setting up intermediate repeater or relay stations, which is why microwave transmission is also called radio relay transmission.

Figure 19 illustrates the principle of a microwave radio link. Although the principle of microwave transmission was discovered by Heinrich Hertz as early as 1888 (see Table 11), it was only in 1934 that the world's first commercial microwave link went into operation. The 56 km link crossed the channel between Dover in the United Kingdom and Calais in France. The French station even then used Alcatel equipment. This link operated at 1.7 GHz and successfully transmitted air traffic control, telephone and telex signals until the beginning of World War 2.

Figure 19 : Principle of a microwave radio link.



During the war, microwave radio proved its effectiveness in networks covering up to 5000 km in Europe and North Africa.

Soon after the war, microwave radio developed into a flexible and reliable means of providing low, medium and high capacity transmission. It is especially effective for the national and regional distribution of TV programmes, and for high capacity backbone systems with small and medium capacity access routes for public telecommunications networks. Another important application is in "linear" networks alongside oil and gas pipelines, electricity supply lines, railways, roads and so on.

Microwave Radio Technology

The distance which can be covered between two microwave stations along the line-of-sight (hop-length) depends on the frequency.

Figure 20 shows the principle of microwave link planning. A basic condition for optimum microwave transmission is that the path between adjacent stations along the link should be completely free from obstructions, not only along the direct line of sight but also within the ellipsoid defined by the first Fresnel zone of the standing wave relation between the two stations. The radius (r) of this ellipsoid at any point is defined by the formula:

$$r = \frac{(d_1 \times d_2 \times Y)^{0.5}}{(d_1 + d_2)}$$

where Y is the wavelength. This formula makes it clear that the longer the wavelength (i.e. the lower the microwave frequency), the larger r is

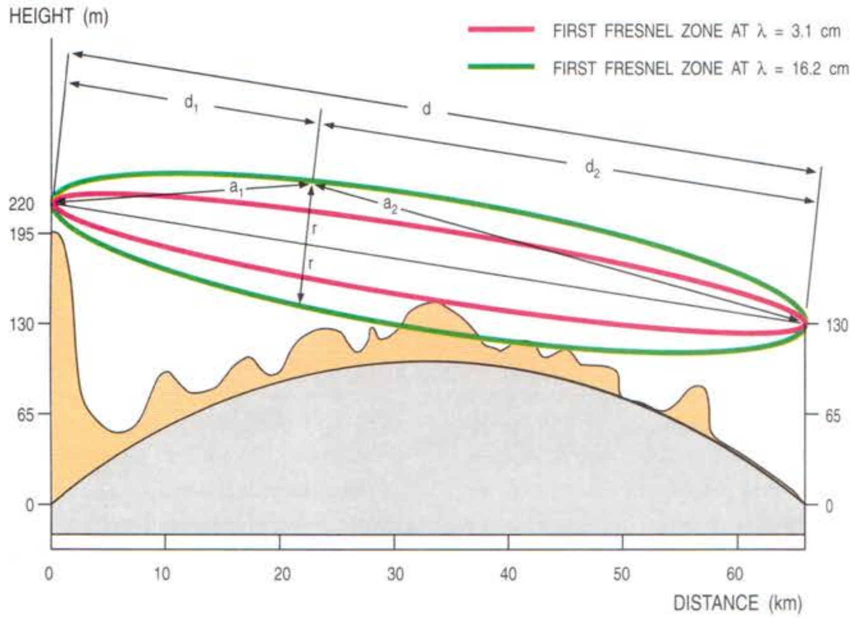


Figure 20 : Free space propagation as a function of wavelength.

Table 12 – Typical hop lengths

Frequency band (GHz)	Typical hop length (km)
2	60
4	50
5	50
6	50
7	45
11	35
13	25
15	20
18	10
30	5

and therefore, for a given link, the higher the antenna towers must be. Consequently, the use of the higher frequency bands would seem advantageous to reduce tower costs. On the other hand, signal attenuation on the link increases substantially with frequency. The frequency bands between 4 and 7 GHz are therefore preferred for long distance routes (backbone systems), with the frequency bands below 4 GHz tending to be reserved for rural and cellular mobile radio applications. Frequency bands beyond 10 GHz (thus with shorter hop lengths) are mainly used for urban systems and backbone access systems.

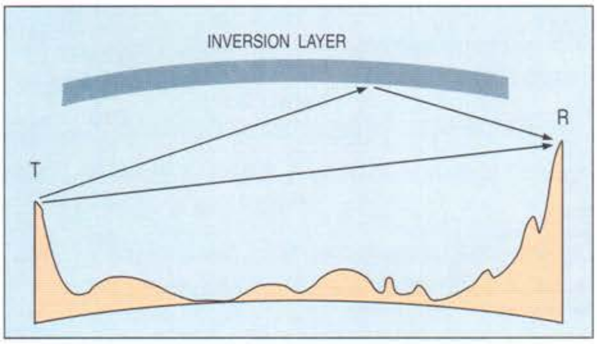
The frequency bands around 20 GHz (with very short hop lengths) are particularly useful for microwave radio access links from public to cellular networks and for interconnecting the base stations of cellular radio cells. Because of the high attenuation at these high frequencies, the same frequency (RF channel) can be reused on more than one hop within the same area without the signals interfering with one another.

Typical hop lengths for the various frequency bands are given in Table 12.

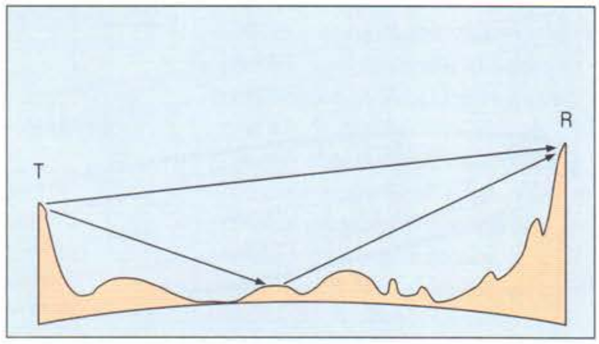
In many applications, depending on the geographical conditions, much longer individual hops are needed. In special cases, hop lengths of more than 200 km, and exceptionally beyond 300 km, can be required. In such cases, large diameter antennas (up to about 5 m instead of the normal 3 m) are used to compensate for the higher link attenuation.

A basic constraint of microwave transmission is that the microwaves themselves are propagated through the atmosphere which is, by its nature, non-homogeneous. As a result of this non-homogeneity, the signal

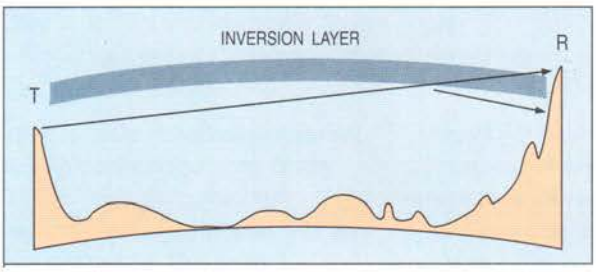
Terminal station of a 330 km hop between Majorca and the Spanish mainland.



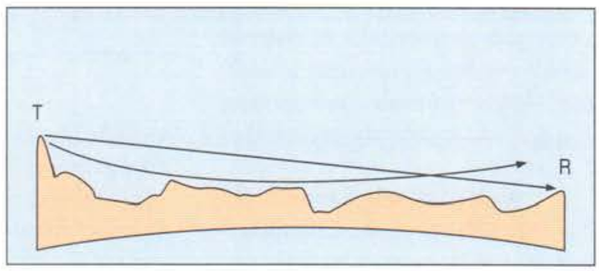
Multipath propagation caused by reflection from an inversion layer.



Multipath propagation caused by reflection from ground or water.



Deviation of part of the radiated waves from their initial path by partial reflection at an inversion layer (long-term fading).



Abnormal diffraction.

Figure 21 : Causes of fading.

received at each end of a microwave hop is normally not constant but *fades* around a nominal value. The causes of fading are shown in Figure 21.

Overcoming these constraints to achieve a transmission quality comparable with that offered by cable systems is standard microwave engineering practice. In addition to automatic gain control (AGC), which is standard in a microwave receiver to achieve a constant output signal from an input signal that is fading over a wide range, a number of corrective devices may optionally be used:

- *Space diversity receiver:* combines the signals received by two antennas which are vertically separated by up to 15 m. It provides a low correlation coefficient between the distortion resulting from the propagation conditions that affect the two subchannels. Combining these signals optimizes the received power and minimizes the distortion of the resulting signal.

- *Adaptive time domain equalizer:* minimizes intersymbol distortion. It is built into the intermediate frequency (IF) equipment by means of transversal filters. Distortion is analyzed in the baseband of the demodulated signals.

- *Adaptive frequency domain equalizer:* corrects the spectrum of the received signal. Part of the IF equipment, it corrects linear distortion introduced by propagation.

- *Forward error correction codec:* used to correct errors that remain after the equalizing and combining methods have been used. Limited to the correction of isolated errors, the improvement that it contributes is better the lower the error rate before correction.

The time domain and frequency domain equalizers process the signal that is obtained by combining the signals in a space diversity receiver. Their coefficients are calculated continuously, making it possible to achieve real-time distortion compensation.

Microwave radio backbone routes (similar to cable routes which have a number of pairs in a cable) normally operate on a number of RF channels, each with the same transmission capacity, which work in parallel within a specified frequency band in a so-called $N + 1$ configuration. (The "1" refers to the standby channel.) The number of channels N depends on the required total transmission capacity; the maximum value of N depends on the chosen frequency band. An initial 2 + 1 system operating in the 11 GHz band could, for example, be extended to 11 + 1 to cope with growth in the required transmission capacity without interrupting the installed system.

Table 13 summarizes the major frequency bands used for high capacity digital microwave transmission. Note that co-channel operation is possible for the new 155 Mbit/s SDH systems (i.e. one Tx/Rx path using horizontal polarization and one Tx/Rx path using vertical polarization operating on the same RF channel), thereby doubling the capacity of the band.

Modulation of the 140 or 155 Mbit/s signal on the microwave frequency is a complex matter which cannot be fully described within this book. However, in order to understand at least the terms quadrature amplitude modulation (QAM) and trellis code modulation (TCM), a much simplified explanation is given in Table 14.

Microwave Radio for SDH Transmission

The new synchronous digital hierarchy initially introduced for transmission on optical fibre cable systems, presents a number of challenges to microwave engineers in terms of increased bit rates, synchronization and system supervision. Microwave systems are faced with constraints, such as compatibility with existing systems, and economic requirements such as the need to optimize the reuse of the existing infrastructure and equipment.

In view of the following technological constraints:

- limited spectrum available for line-of-sight microwave transmission
- existing RF channel plans and compatibility with existing systems
- bandwidth-dependent sensitivity to multipath propagation

Table 13 – High capacity microwave radio systems

Frequency band / *frequency range* (GHz)	**Channel spacing (MHz)**	**Number of RF channels**	**Type of modulation**	**Capacity per RF channel (Mbit/s)**
3.9	40	9	16 QAM	140
3.4 – 4.2			32 TCM	155
4	29	6	64 QAM	140
3.6 – 4.2			128 TCM	155
5	28	10	64 QAM	140
4.4 – 5.0			128 TCM	155
6.2 or lower 6	29.65	8	64 QAM	140
5.9 – 6.4			128 TCM	155
6.7 or upper 6	40	8	16 QAM	140
6.4 – 7.1			32 TCM	155
8	29.65	8	64 QAM	140
7.7 – 8.3			128 TCM	155
11	40	12	16 QAM	140
10.7 – 11.7			32 TCM	155
13	28	8	16 QAM	140
12.7 – 13.2			32 TCM	155

Table 14 – Types of modulation

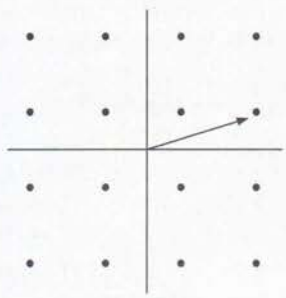
n QAM

n = 16, 64, 256, etc. Number of signal points equally distributed over four quadratic fields

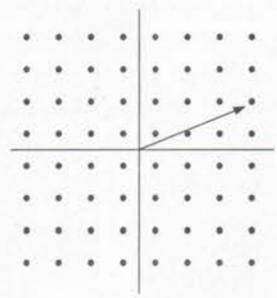
Q = Quadrature; determines the signal phase

A = Amplitude; determines the signal amplitude

M = Modulation.



16 QAM



64 QAM

n TCM

n = 32, 128, 512, etc. Number of signal points distributed equally over four quadratic fields

T = Trellis; sloped grid for the likely convolutional position of signal points

C = Code; coding of related groups of signal points

M = Modulation

The convolutional positioning of the signal points is compared with a choice of possible predetermined positions (positioned on a sloped grid, hence Trellis coding), whereby:

- In the modulator, signal points coinciding with the expected trellis position are not coded, thus reducing the required transmission bandwidth
- In the demodulator, distorted signal points are replaced by the most likely Trellis position, thus improving the bit error rate (BER)

TCM is an improved QAM including error correction.

special efforts are necessary for the development of SDH microwave equipment. Systems for transmitting the 155 Mbit/s STM-1 data stream, using a single carrier as for plesiochronous transmission (i.e. 155 Mbit/s modulated on one RF carrier), will be available soon. Multicarrier systems may have economic advantages for the transmission of higher hierarchical levels. In this case, a number of 155 Mbit/s modulated carriers are transmitted on one RF channel. For STM-4 transmission, the following solutions are being considered:

- *Single carrier transmission:* the STM-4 signal is transmitted as four separate parallel 155 Mbit/s data streams, each on a single standard RF channel, with one transmitter/receiver per channel. Thus four transmitter/receivers are required in parallel.
- *2 × 2 carrier transmission:* one transmitter/receiver carries two separate RF carriers, each modulated with a single 155 Mbit/s data stream. Two transmitter/receiver pairs are needed using the same or different antenna polarizations.
- *4-carrier transmission:* only one transmitter/receiver is used for the transmission of four separate RF carriers, each modulated with a single 155 Mbit/s data stream.

The total bandwidth required depends on the modulation method and will be matched to the internationally agreed frequency plans.

For the transmission of a complete STM-16 signal, four times the configuration used for STM-4 transmission might be installed.

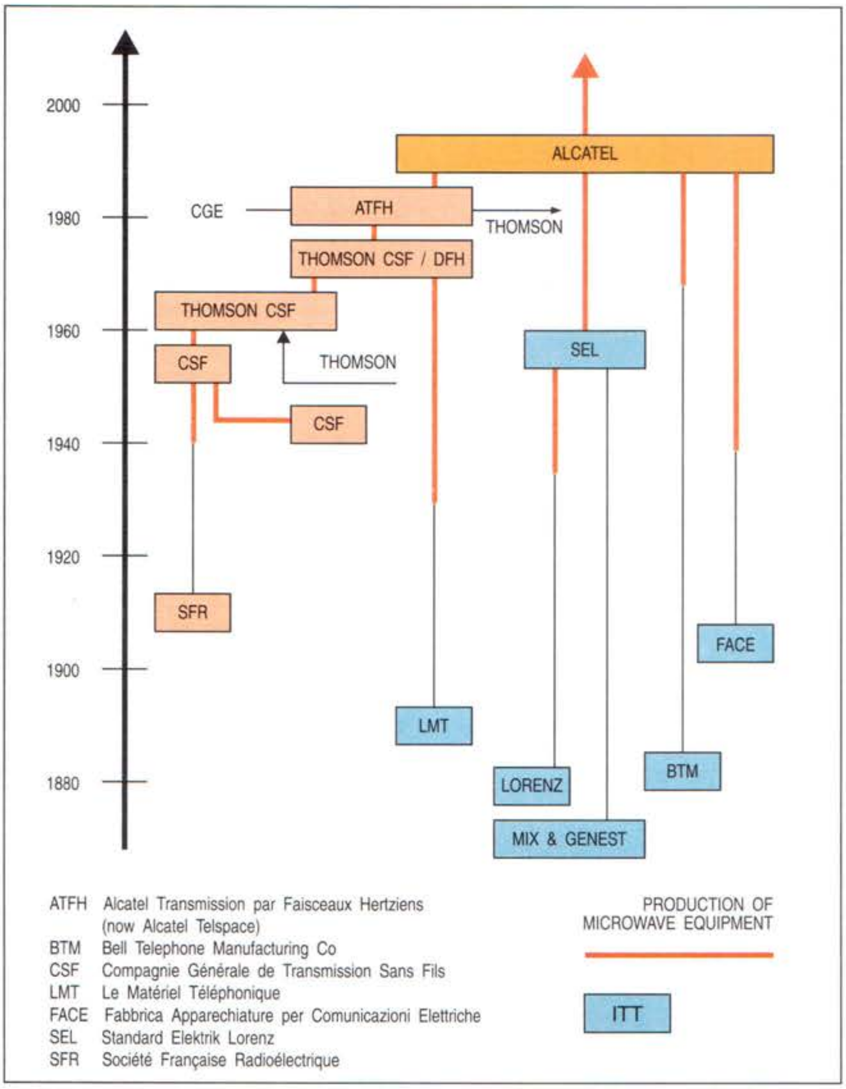


Figure 22 – History of microwave radio within Alcatel.

SDH transmission will not, therefore, remain an exclusive domain for optical fibre transmission. Microwave radio equipment will be available in 1991 for STM-1 transmission and is expected to be available later for STM-4 and even STM-16 transmission.

The two main areas for SDH microwave transmission are expected to be:

- Local and regional networks where microwave transmission is of interest because of special geographical conditions or where it offers economic advantages over fibre optic transmission because only limited capacity is required.
- Trunk networks where microwave transmission can be useful for backing up line transmission systems.

The second case particularly, is economically necessary in order to re-use as much as possible of the infrastructure for existing analogue systems or digital plesiochronous systems. This will lead to a migration from plesiochronous to synchronous microwave networks.

Scope of Microwave Equipment

Microwave radio equipment operates on a specific frequency which can be selected within a frequency band, and has a specific transmission capacity which cannot normally be changed. Depending on the application, therefore, an extensive range of microwave radio equipment exists with different transmission capacities for application in long distance backbones and short haul access to backbones, as well as urban and private networks.

Alcatel has extensive experience in microwave technology (Figure 22). Today Alcatel manufactures a full range of microwave radio systems with transmission capacities ranging from 0.7 to 155 Mbit/s operating in frequency bands from 0.4 to 22 GHz, as shown in Figure 23.

Point-to-Multipoint Microwave Radio Systems

Following the digitalization of microwave equipment and the implementation of time sharing using demand-assigned time division multiple access (TDMA), the latest microwave equipment for point-to-multipoint operation can now provide telephone, telex and data services to subscribers in rural areas with a cost and quality similar to that for urban subscribers. Alcatel's RURTEL equipment can provide telecommunications services to 320 subscribers located up to 500 km from a telephone exchange, with up to 48 subscribers sharing the same remote radio station. Figure 24 shows a typical RURTEL network configuration.

Point-to-multipoint microwave radio equipment is likewise used for the distribution of TV and audio broadcast programmes from a central point to feed a number of remote cable TV networks. Alcatel produces suitable equipment, operating in the 12 GHz band, which can carry up to 23 TV channels and 20 stereo or 40 mono audio broadcast programmes.

Future of Microwave Radio Transmission

It is difficult to make a reliable prognosis as to the future of radio relay transmission. Over the past 20 years it has been claimed from time to time that radio relay transmission has no future! When satellite transmission systems first went into commercial operation it was believed that it would soon replace both submarine cable and radio relay transmission, but both remain in a very healthy state.

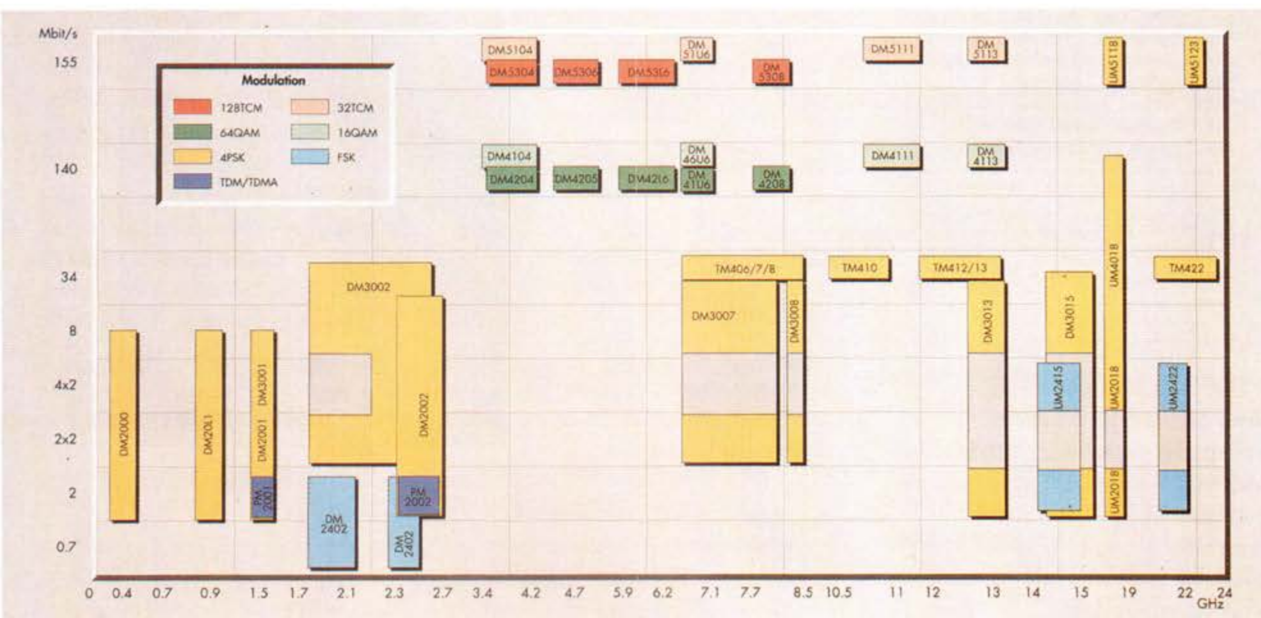
Less than 100 years after Heinrich Hertz proved the feasibility of radio relay transmission, many skilled engineers have made it the most reliable and cost-effective means of transmission for capacities of up to some thousand telephone channels and over distances up to several thousand kilometres. Depending on geographical conditions and actual transmission requirements, today 20 to 50% of the transmission capacity of public telecommunications networks is provided by radio relay systems.

Over the past 10 years, a more or less constant annual quantity of about 50 000 microwave transmitter/receivers has been produced worldwide. Similar numbers of transmitter/receivers will certainly be required over the next 10 years, mainly for wideband short-haul urban systems and narrowband rural systems, as well as for wideband long-haul systems, for regional networks and for less industrialized and geographically difficult countries.

Specific Applications for Microwave Radio Transmission

Microwave radio transmission is the best solution for applications where the

Figure 23 : Alcatel's range of microwave systems.



terrain or other conditions limit the use of optical fibre, as well as in situations where traffic is too dense and the distance not long enough to justify the use of satellite transmission. The major applications are:

- Dual-routed national networks in parallel with or meshed with optical fibre cable.
- Urban access routes.
- Backbone routes in countries with difficult terrain.
- Digital backbone routes in countries where an analogue microwave infrastructure already exists.
- Emergency situations where it enables the station locations to be changed at short notice.
- Short term project implementation following a national disaster or in the event of war.
- Moderate density, distance and growth rates.
- Semi-stationary operation in which the location may need to be changed from time to time.
- Links for pipelines, electricity and water distribution networks, railways, security networks and other non-public users, especially where a network is also needed during the construction phase.
- Access links from public to cellular radio networks and interconnection of cells.

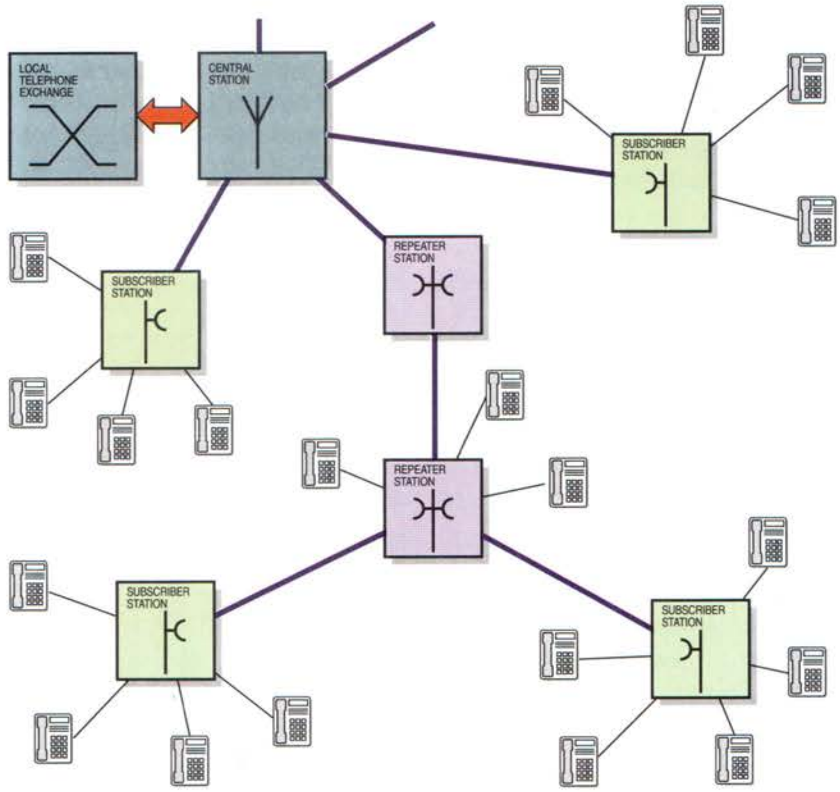


Figure 24: Typical RURTEL network.

- Point-to-multipoint operation for:
  - rural areas
  - TV distribution
  - data collection and distribution in urban areas.

Comparison of Options

The three transmission media – optical fibre, satellite and microwave – are basically complementary and the choice between them depends primarily on the application. As a rough cost guide, the *lines of equal cost* charts published by the ITU in *Telecommunication Journal*, volume 11, 1987, indicate whether to select optical fibre versus satellite (Figure 25) or microwave versus satellite (Figure 26), depending on distance and system capacity. However, recent advances in fibre optic technology and the introduction of SDH have undoubtedly changed these lines of equal cost in favour of optical fibre and microwave radio transmission.

Figure 25 : Line of equal cost for satellite and optical fibre transmission.

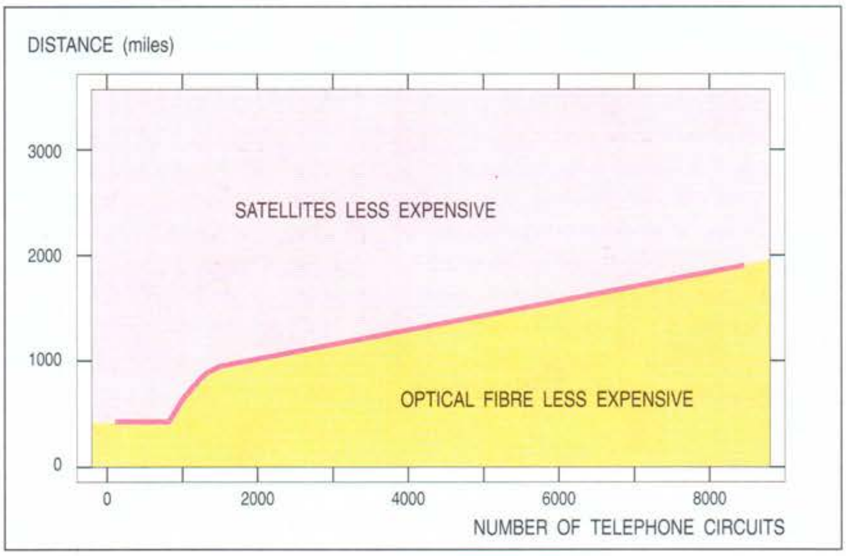
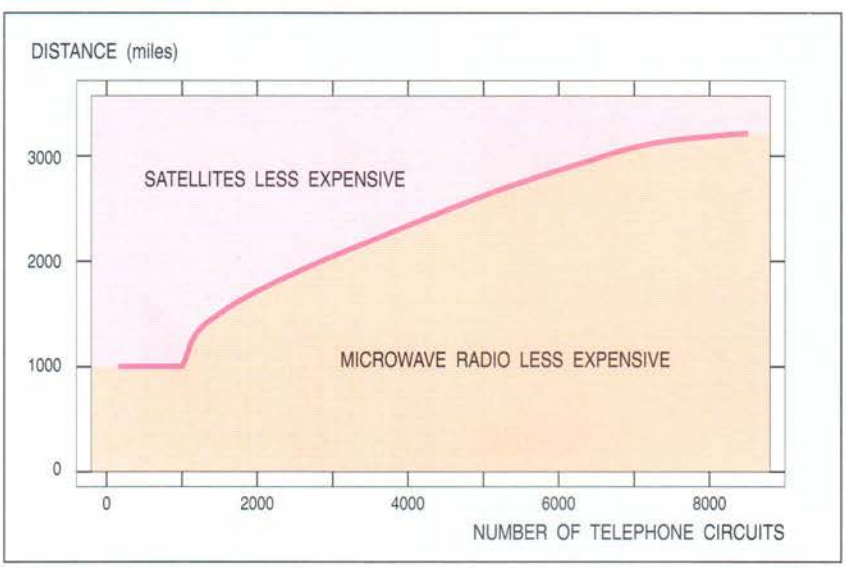


Figure 26: Line of equal cost for satellite and microwave transmission.



General Comparison of the Transmission Media

A study conducted by Comsat Laboratories and published by Communications Systems Worldwide in November 1989, concerning satellite versus optical fibre transmission, showed that over the investigated period of 1995 to 2005 satellite transmission will remain competitive with optical fibre transmission within the Atlantic region and even more so in the Pacific because of longer distances involved. Whereas intercontinental traffic is expected to grow at about 9.5% annually over the period, satellite transmission is estimated to grow at "only" 7.5% annually, so the satellite share of total intercontinental traffic, which is about 53% today, will drop slightly to around 44% by the year 2005 (see Figure 27).

A study by Frost and Sullivan in early 1990 even speaks of a renaissance for satellite transmission, predicting a doubling of the earth station market over the next five years, especially in the Asia-Pacific region and in South America.

During the time of analogue transmission, in view of the vulnerability of cable routes and to ensure uninterrupted availability of transmission routes, many telecommunications administrations adopted the approach of dual routing on cable and microwave, either in parallel or even better in a meshed network. Now with the widespread introduction of digital transmission, dual routing is even more important

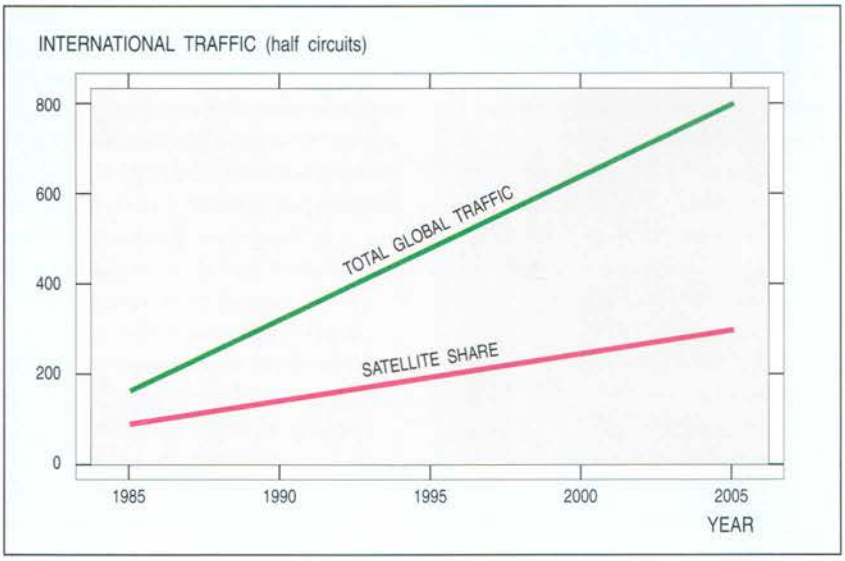


Figure 27 : Satellite share of intercontinental traffic.

to guarantee uninterrupted transmission of data, for example, between computer centres.

In the same way as microwave networks are used as back-up for fibre optic transmission systems, satellites will remain necessary as a back-up for undersea cable and, under special conditions, for terrestrial microwave and cable links. The importance of dual routing is demonstrated by the example in Table 15 which is based on transatlantic traffic between the USA and Europe.

Optical fibre line transmission equipment is already available with transmission capacities of 565 Mbit/s. Microwave transmission equipment is keeping pace with capacities of 140 Mbit/s, 155 Mbit/s, 310 Mbit/s, 622 Mbit/s and very soon 1 Gbit/s. Even a system operating at more than 2 Gbit/s is reported to be under development. At first sight this still does not seem to match the 2.5 to 20 Gbit/s mentioned earlier for fibre optic systems. Nevertheless, the transmission capacities quoted for microwave are per RF channel, and on high density microwave routes some 20 RF channels can easily operate in parallel. This would provide a total transmission capacity of 20×155 Mbit/s = 3.1 Gbit/s with today's, and 20×622 Mbit/s = 12.5 Gbit/s with tomorrow's microwave technology.

Consequently, microwave will remain complementary to and competitive with optical fibre and satellite transmission, each comfortably keeping its market share.

Table 15 – Link availability for different transmission media

System	Availability (%)	Equivalent annual traffic interruption (hours)
Submarine	99.6	35
Submarine with satellite as standby	99.8	17.5
As previous, but terrestrial cable between submarine cable, earth station and exchange double routed (parallel cable or cable / microwave)	99.98	1.75

Comparison within a Network

The unification of East and West Germany has provided a unique opportunity for comparing different means of transmission and analyzing the cost structure of the fully digital telecommunications network which is being planned for what was the German Democratic Republic. Over a seven-year period, a total of ECU 27.5 billion is planned to be invested in this new network as shown in Table 16.

Even in this new network, which can be constructed using the most modern equipment available and with few constraints with regard to existing systems, but where early implementation is important, transmission is almost equally divided between optical fibre and microwave systems.

Table 16 – Cost structure of digital network for the former East Germany

Investment	%
Total investment structure	
Outside line plant	40
Switching	25
Transmission	10
Cable	9
Sites and buildings	9
Terminal equipment	7
Total investment	**100**
Structure of 10% investment on transmission	
Multiplexing	54.5
Optical fibre transmission	18.5
Microwave radio	15
2 Mbit/s copper systems	6
Earth stations	4
Cross-connects	2
Total transmission	**100**
Stucture for transmission media alone	
Optical fibre transmission	49.5
Microwave radio	40
Earth stations	10.5
Total transmission media	**100**

Market Comparison

Finally, when comparing the three transmission options it is useful to evaluate the Transmission World Market forecast as included in the 1991 issue of the Telecommunications Market Analysis (TMA) published by Alcatel Strategic Planning (Table 17). These figures show a total market growth over 10 years of:

- optical fibre transmission 66%
- microwave 52%
- earth stations 42%
- total transmission media 55%.

From these figures it can be concluded that although optical fibre transmission gradually increases its market share, both microwave links and earth stations will remain important transmission media well beyond the beginning of the next century.

Table 17 – Transmission world market forecast

Transmission options/year	1990		1995		2000	
	BECU	%	BECU	%	BECU	%
Total line system market	12.5		17.3		23.2	
Of which Line equipment market	2.1		2.6		3.4	
Submarine equipment	0.3		0.5		0.6	
Total optical fibre transmission market	**2.4**	36	**3.1**	37	**4.0**	39
Microwave systems market	**2.3**	35	**2.9**	34	**3.5**	34
Earth station market	**1.9**	29	**2.4**	29	**2.7**	27
Total transmission media	**6.6**	100	**8.4**	100	**10.2**	100

Conclusions

The three major transmission options – optical fibre, microwave and satellites with earth stations – are complementary and will remain so at least for the next 10 years. Each option will have its own domain of maximum cost effectiveness. This complementary nature is clearly demonstrated by Figure 28 from the Alcatel Radio Space and Defence product group.

This figure has been simplified to emphasize its message. Especially in the overlapping areas, careful consideration has still to be given to the rate of increase in traffic, geographical conditions and operational requirements of each application. Moreover, the introduction of metropolitan area networks, fibre in the loop (FITL) and unrepeatered undersea optical fibre cables, together with the future use of Erbium-doped fibre as natural signal boosters in submarine cable, will substantially extend the overlap between optical fibre and both microwave and earth stations. Consequently, for many applications in these overlapping areas, a detailed evaluation will be required to determine the most cost-effective solution. The Appendix will be found useful in making such a detailed evaluation.

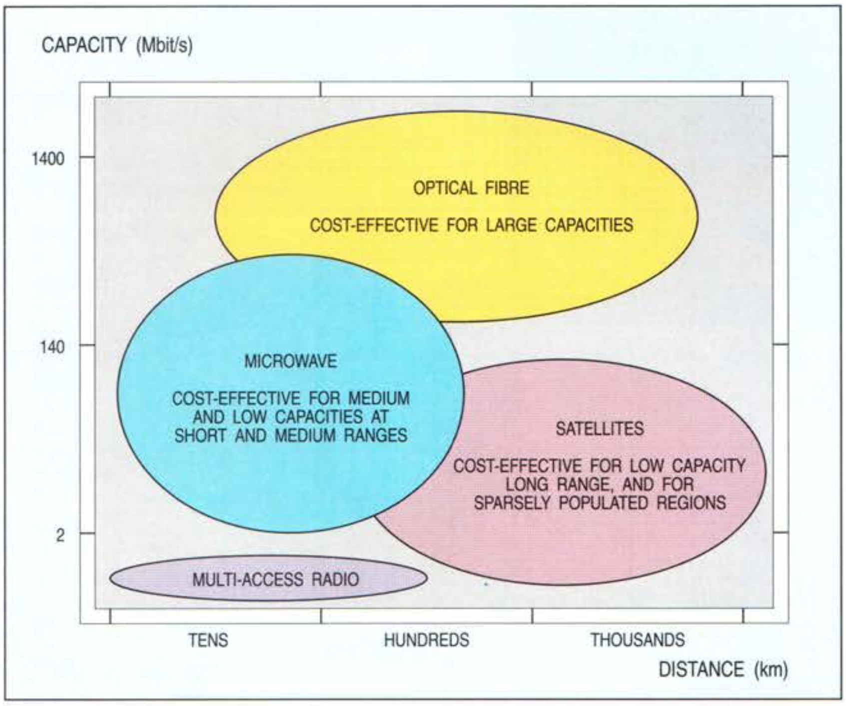


Figure 28 : Complementary nature of the major transmission options.

Finally, Figure 29, recently published by the Alcatel Research Group, clearly indicates that even future broadband networks will make extensive use of all three transmission media.

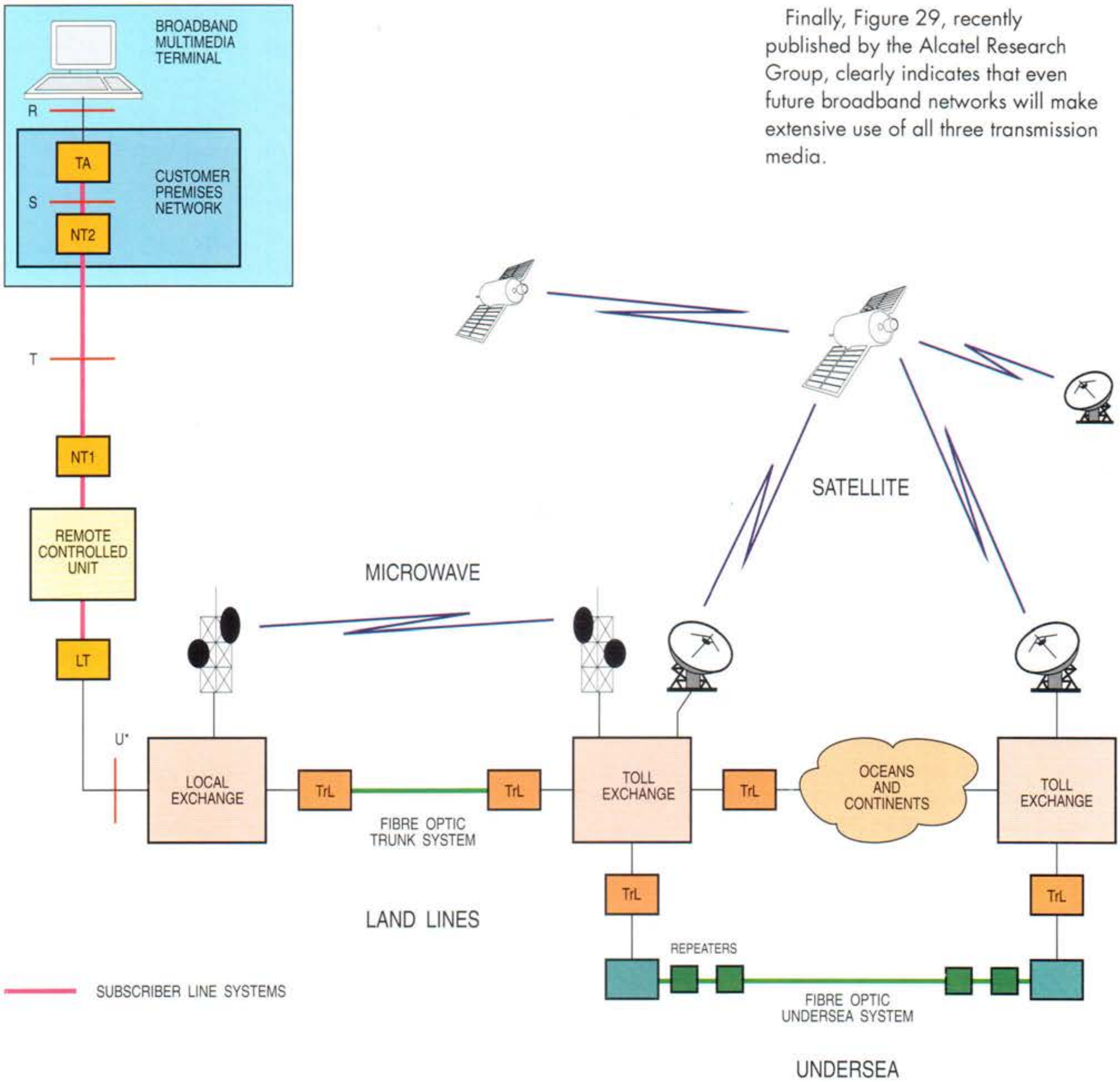


Figure 29 : Future broadband transmission network based on optical fibre, microwave and satellite systems.

LT – line termination	*NT – network termination*	*TA – terminal adapter*
TrL – trunk line	*R, S, T, U – broadband interfaces.*	

Appendix : Main Criteria for Selecting Specific Transmission Options

Criteria for selecting transmission options

Criteria	Best solution		
	Optical fibre	**Microwave**	**Earth stations**
Transmission capacity			
Low and medium		◆	◆
High	◆	◆	
Very high	◆		
Distance			
Short	◆	◆	
Medium	◆	◆	
Long	◆		◆
Very long			◆
Geology			
Flat area, soft soil	◆		
Mountainous		◆	◆
Jungle		◆	◆
Marshy and lakes			◆
Population density			
Low, scattered			◆
Medium	◆	◆	
High	◆	◆	
Infrastructure			
Electricity and roads			
Good	◆		
Bad		◆	
Nonexistent			◆
Existing cable ducts	◆		
Existing microwave buildings and towers		◆	
Right of way			
Easy to obtain	◆		
Difficult to obtain		◆	◆

Criteria for selecting transmission options (cont)

Criteria	Best solution		
	Optical fibre	**Microwave**	**Earth stations**
Project implementation			
Standard	◆		
Short time		◆	
Very short time			◆
Environment			
Electromagnetic radiation	◆		
Earthquake zone		◆	◆
Private customers			
Banks and other companies with various sites			
In urban areas	◆	◆	
In isolated areas		◆	◆
Pipelines, highways			
New	◆		
Existing		◆	
Communication required during construction		◆	
Special circumstances			
Emergency use after natural disaster		◆	◆
International events (sport, festivals, etc)		◆	◆
Reconstruction after war or occupation		◆	◆
Flexible TV studio access		◆	
Network			
Stations on flexible sites			◆
Stations at short distances with frequent drop and insert	◆		
Lower capacity spurs in high capacity networks	◆	◆	
Access from public to cellular networks and interconnection of cells		◆	

Criteria for selecting transmission options (cont)

Criteria	Best solution		
	Optical fibre	**Microwave**	**Earth stations**
Operation			
Mobile		◆	
Dual routing			
Terrestrial	◆	◆	
Intercontinental	◆		◆
Geography			
Industrialized area	◆		
Urban	◆	◆	
Rural		◆	◆

Abbreviations

ADM	Add/drop multiplexer
AGC	Automatic gain control
Arabsat	Arabian Satellite Organization
AU	Administrative unit
BER	Bit error rate
CCIR	Comité Consultatif International de Radio
CCITT	Comité Consultatif International Téléphonique et Télégraphique
CEPT	Conférence Européene des Postes et Télécommunications
CdL	Les Câbles de Lyon
DCM	Digital circuit multiplication
Domsat	Domestic satellite
DSI	Digital.speech interpolation
ETSI	European Telecommunications Standards Institute
Eutelsat	European Telecommunications Satellite Organization
FDMA	Frequency division multiple access
FITL	Fibre in the Loop
HF	High frequency
IBS	Intelsat business service
IDR	Intermediate data rate
IF	Intermediate frequency
Inmarsat	International Maritime Satellite Organization
Intelsat	International Telecommunications by Satellite Consortium
ITU	International Telecommunication Union
LAN	Local area network
LT	Line terminal
MA	Multi-access
M/W	Microwave radio
NT	Network termination
OF	Optical fibre
PCM	Pulse code modulation
PDH	Plesiochronous digital hierarchy
PTR	Pointer
QAM	Quadrature amplitude modulation
REP	Repeater
RF	Radio frequency
RSD	Radio Space Defense
SCPC	Single channel per carrier
SDH	Synchronous digital hierarchy
S/N	Signal to noise ratio
SNG	Satellite news gathering
SONET	Synchronous optical network
STM	Synchronous transport module
TA	Terminal adapter
TCM	Trellis code modulation
TDMA	Time division multiple access
TMA	Telecommunication market analysis
TrL	Transmission line
TVRO	Television receive only
USAT	Ultra small aperture terminal
VBR-ADPCM	Variable bit rate – adaptive differential pulse code modulation
VC	Virtual container
VSAT	Very small aperture terminal

Designed by PubTec, Barnston, England. Printed by FM Litho, England.

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