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OPTICAL FIBRE PLANNING GUIDE FOR POWER UTILITIES

Working Group 35.04

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1 INTRODUCTION

Power Utilities throughout the world are making increasing use of optical fibre technology for their telecommunication needs. In some cases optical telecommunications systems are required for business ventures outside of the needs of the utility itself. Whatever the application, optical telecommunications systems which make use of a power system infrastructure require special design and planning considerations. This guide sets out to provide all the information required for a Power Utility not skilled in the technology to plan and define such an optical telecommunications system.

The views expressed in this document are provided by leading experts in the field of optical fibre technology, representing Power Utilities and manufacturers, together with research and development organisations. The wealth of experience brought together by these major contributors represents views from across the world and therefore provides a definitive reference. However, optical fibre is a rapidly changing technology and there may be more recent developments beyond those explored here. These may be marketed with apparent financial benefits to secure new business, but the user must assess the risk to any project before accepting new ideas. Unexpected failure mechanisms may not materialise for many years after commissioning but may be catastrophic. The underlying theme for reliable performance is for manufactures and users to abide by internationally agreed standards.

2 STATE OF THE ART AND FUTURE TRENDS

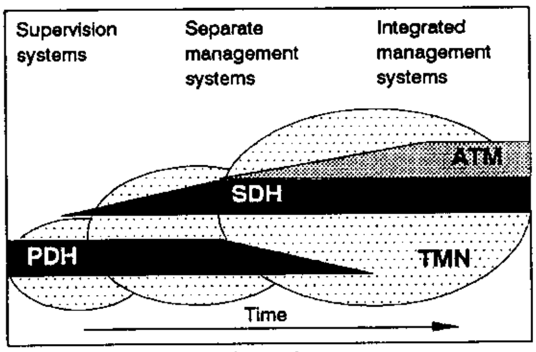
Optical transmission systems using glass fibre cables are already well established among Power Utilities on medium and long distance applications. In addition some local area networks are also in use. As a result of the adoption of newer technology by public telecommunication operators and new terminal equipment to support Integrated Services Digital Networks (ISDN), there is a rapid move towards higher data transmission rates. Some Power Utilities are exploiting the deregulation of communications in their countries by taking over functions previously performed by public communication facilities. This is leading to the introduction of broadband transmission systems. The Power Utilities are therefore found to be active in long-distance transmission, where optical cables are used for the private communications of the utility and additional fibres are provided for public communications use. Utilities are also active in the low-voltage distribution network where there is symbiosis between power distribution and TV distribution. It is in these two areas in particular that the Power Utilities are confronted by advanced communication systems.

2.1 New Concepts with Time Division Multiplexing [1]

The Plesiochronous Digital Hierarchy (PDH) and its associated CCITT [2] Recommendations were the basis for compatible transmission in telecommunication networks all over the world for many years. However, several drawbacks in PDH became evident:

- No line interface had been standardised
- No transmission above 140 Mbps had been standardised
- The world was split into regions employing different types of hierarchies
- Possibilities for operations, administration, and maintenance were limited.

The standardisation of the new Synchronous Digital Hierarchy (SDH) has overcome these drawbacks but, at the same time introduced into transmission systems a source of logical complexity that can only be handled by state-of-the-art microelectronics. SDH increases the performance of transmission networks in many respects, but it has one drawback; it does not offer unlimited flexibility in bandwidth allocation without any restriction in granularity. Asynchronous Transfer Mode (ATM) offers this feature and is therefore the next logical evolutionary step in transmission concepts after the introduction of SDH. ATM is already on the horizon, and will be available in a much shorter time span than the transition from PDH to SDH.



ATM asynchronous transfer mode
PDH plesiochronous digital hierarchy
SDH synchronous digital hierarchy
TMN telecommunication management network

Figure 1 Evolution Concepts for TDM

Although this is a fascinating technical prospect, it does create considerable economic problems due to shortened innovation cycles. **Figure 1** indicates the phased introduction of SDH and ATM in the public carrier market and the evolution of network management systems, starting with simple supervision systems and proceeding to integrated management systems.

An optical multiplexing and switching system will be required, particularly in the future broadband distribution network for Television (TV) and High Definition Television (HDTV). This technology is under particular pressure to find economical solutions to make this entertainment affordable to any subscriber. This requirement can only be met by employing optical or optoelectric integration. Some of the main technologies expected to help determine the future are described below.

2.2 Coherent Fibre Optic Transmission Systems

Today, only simple intensity modulated transmitters and receivers sensitive to optical power are in practical use. This direct detection demodulation is rather crude in comparison with modulation techniques used in radio or Power Line Carrier (PLC) links. The coherent optical system sets out to change this and begins to exploit the true potential of the optical spectrum. Light is treated as a carrier medium which can be amplitude, frequency, or phase modulated.

Three key requirements must be met to engineer a coherent optical fibre system. First, there must be a spectral line-width light source in which the natural emission spectrum without modulation is narrow compared with the data bandwidth. A second requirement is for singlemode fibre which does not distort the optical phase. The third and final requirement is an optical local oscillator laser which is locked to the incoming signal, as shown in **Figure 2**, so that the photodetector can be used either in heterodyne or homodyne mode. In the heterodyne mode, the optical local oscillator

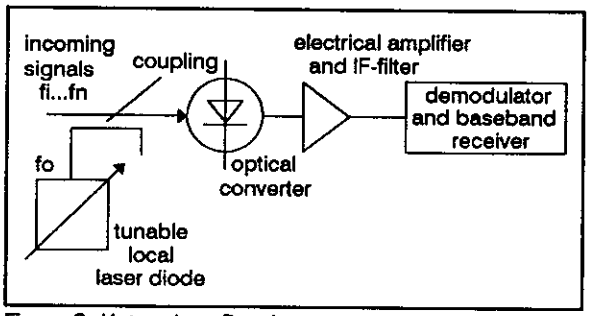


Figure 2 Heterodyne Receiver

wavelength is separated from the remote transmitter wavelength by an amount equal to the intermediate frequency in the receiver. In the homodyne mode the local oscillator must be phase-locked to the incoming carrier wave at the same optical wavelength.

Coherent systems have the prime advantage of higher optical sensitivity. This is why they were initially developed for long-distance systems. Owing to the use of fibre amplifiers, however, direct modulation now achieves virtually the same receiver sensitivity.

In the laboratory coherent transmission techniques have yielded impressively large bitrate-transmission distance products. The key component for the introduction of these types of transmission systems as economic production units in the field is the narrow linewidth, high reliability laser diode, but at the moment these are still expensive and available only in small quantities.

Coherent transmission technology is expected to become an important building block in future broadband distribution networks for television and broadcast radio. However, for the immediate future the conventional analogue methods used for TV signals, employing Vestigial Sideband Amplitude Modulation (VSB-AM) and Frequency-Division Multiplexing (FDM) will be used. In the longer term, digital transmission will no doubt also gain acceptance in the TV distribution networks.

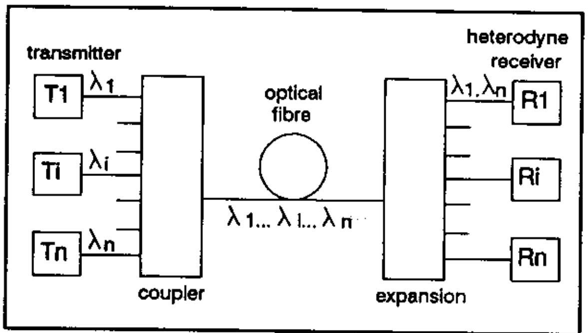


Figure 3 Coherent multicarrier system CMC

The most modern multiplexing principle, the optical frequency-division multiplex combined with optical heterodyne reception, as shown in **Figure 3**, will be used in coherent optical multicarrier (CMC) systems. CMC systems with tunable optical heterodyne receivers could be used for transmission and switching of broadband TV or HDTV signals. The transmitter of multichannel systems consists of several laser diodes and of a coupler, which collects the signals in a single fibre. The receiver selects the different channels with optical frequency-division multiplexers (OFDM) This could then provide 100 channels within a few nanometres of spectrum.

Each of these optical carriers can carry high bitrate time-division multiplex signals. This concept is in the research stage (RACE-CMC-Project) and can become competitive in the long term. The use of existing singlemode fibres is expected to be possible with only a small reduction in the transmission distance.

2.3 Integrated Optics

The optical integrated circuit (OIC) and the optoelectronic integrated circuit (OEIC) inherently have the same large characteristic bandwidth as the optical fibre because, in both cases, the carrier medium is a lightwave rather than an electrical current. In the OIC/OEIC a number of different optical devices such as sources, switches, amplifiers, modulators, and detectors are possible. There are two basic forms of optical integrated circuits. One of these is the hybrid, in which two or more substrate materials are bonded together to optimise performance of the different devices. The other is the monolithic OIC, in which a single substrate material is used for all devices.

Optical switching is one example which is widely regarded as a potentially important technology for the near future. One of the first applications will probably be optical space division switching with waveguide switches or optical amplifier switches. The optical solution requires only limited control electronics. The function is independent of bitrate transmission format and services.

3 INTERSTATION COMMUNICATIONS SYSTEMS

3.1 Functional and Economical Requirements

3.1.1 General system requirements

System types

Interstation communications systems presently used by Power Utilities are usually point-to-point links. A great variety of different system applications are required to coexist in the telecommunication network. Therefore, the demands placed on the communication media can vary case by case, and places different requirements for fibre type, optical window, cable structure, number of fibres, the types of cables and data rate.

Applications

The main applications are for the management of Power Utility electrical networks in the following areas:

- (A) Telecontrol
- (B) Teleprotection
- (C) Telephony

(A) The telecontrol and monitoring systems are based on a hierarchical structure of power system management linking National Control Centres (NCC) to the Area Control Centres (ACC) to the District Control Centres (DCC) and finally to the Remote Stations (RS). The essential requirements of the telecontrol systems are:

- System availability should meet the operational requirements.
- Transmission quality providing consistent system performance and system response time.
- Validity of information.
- Data rate application requirement support, dependent on the network, for example:
  - NCC-ACC, 64 kbps
  - ACC-DCC, 9600 bps
  - DCC-RS, 600 bps

(B) Most present teleprotection schemes are based on the transmission of commands over a telecommunication link between the two ends of a power line. Depending on the underlying protection concept typically one to four commands have to be transmitted. Networking is normally not needed, with the exception of the power system protection of 'tee'd' three or more ended lines. In this special application a command is still sent by only one location, but received and processed by all the other locations (two or more) in the system.

The command outputs of protection relays are not compatible with normal telecommunication interfaces, such as CCITT type data interfaces. Thus, for use on standard audio frequency analogue telephone channels, teleprotection signalling equipment is required to convert the relay signals into audio signals. On digital telecommunications systems, such as fibre optic systems, it is technically and economically desirable to convert the commands directly into a 64 kbps digital signal instead of using intermediate analogue to digital conversion interfaces. For this purpose digital teleprotection equipment with a 64 kbps interface can be used, or multiplexers with built in special teleprotection channel interfaces are also suitable.

The transmission time for teleprotection commands over digital systems should not normally exceed 2 - 6 ms, depending on the application. The coding of teleprotection commands should be such that under normal and worst case Bit Error Rate (BER) conditions on the link no unacceptable security and dependability values result. This is normally not a problem on fibre optic links. More critical error conditions are channel resynchronisations after sync errors, temporary slips resulting in mixing up of individual channels in a multiplexed system, sudden loss of receive signal, etc. In order to prevent maloperation of a protection system such conditions must be avoided, or at least fast detection of such conditions and immediate failsafe actions implemented.

Unlike distance protection with the transmission of commands, the longitudinal differential (or current differential) protection (LDP) scheme relies on the transmission a replica of the current waveforms, measured at the ends of the power line. Such a scheme allows better selectivity of the protection function in some special applications (e.g. cable protection, protection of short power lines, multi-terminal power line protection, intersystem faults between parallel systems on the same tower). The required transmission of power frequency waveforms between the ends of the line has been a difficult issue before fibre optic links have been used, because of heavy interference between the power system and the pilot wires used to transmit the protection signal, having the same frequency as the power system itself. Fibre optic systems used for this purpose can avoid these problems, but they have to provide interfaces that are able to transmit power frequency signals. As an alternative, new LDP relays have to be used which are already equipped with digital telecommunication interfaces (e.g. with CCITT G.703 64 kbps interfaces).

The availability of fibre optic links with high reliability and high transmission capacity will increasingly enable the use of advanced digital LDP concepts. Such new digital LDP relays typically need one to four 64 kbps transparent channels between the two or more terminals of a power line. Apart from the above mentioned LDP applications, LDP concepts with fibre optic transmission will also be used as backup protection schemes together with distance protection.

With this new protection scheme, some aspects of the telecommunications system have to be considered carefully. The transmission delay between terminals should be stable, especially in the case of re-routing. As for command transmission, critical error conditions are channel resynchronisation after sync errors, temporary slips resulting in mixing up of individual channels in a multiplexed system, sudden loss of receive signal, and others. Again, such conditions must be avoided with corresponding means, or at least detection of such conditions and immediate fail save actions are mandatory.

As an alternative to multiplexing digital teleprotection signals with other signals on fibre optic links, the use of a special pair of fibres directly between the protection relays may be considered, if such fibres are available. The definition of the signals and protocols to be used in this case is currently subject to investigations by different international bodies.

(C) It is essential for a Power Utility to have an efficient, reliable telephone system for the operational management. CIGRE SC35 Working Group 02 [3] has produced a design guide for Power Utility telecommunication networks.

For instance, a telephone link between the dispatching centre and substations has to be established very quickly, especially in emergency situations. The telephone system must provide facilities to give preference to important users. An interstation communication system needs not only a bi-directional link but also the greater availability and a very quick access.

On the other hand, administrative services (which do not concern the Power Utility operation and include teleprinting, facsimile, teleconference, other data communication) can use an interstation system. In such cases, the requirements regarding access, availability and reliability are less stringent.

Separate or shared equipment for different services

As it has been shown, the performance of the three main applications using a Power Utility network is affected by the quality of the interstation links. These three applications often use the same cable, the same fibre and for the same fibre the same terminal equipment.

Only separate channels distinguish these applications.

For the other services in which requirements are less restricting, there are three possibilities:

- The regulatory body does not allow any administrative communication on private links, in that case the Power Utility use the public network.
- The national policies of a regulatory body are more liberal but, requirements of transmission of administrative and of operational data being different, separate media are being used.
- The different services share the equipment, giving priority to the tasks vital for network security.

Facility sharing with other users

The Power Utilities have a lot of assets in case of deregulation in the telecommunications business:

- Long wayleaves for fibre optic cables.
- Technical expertise.
- Equipment and potential customers (industrial, residential or institutional).

Facility sharing with other users has been quite rare for the following obvious reasons:

- Today the national regulatory bodies are usually restrictive when giving necessary authorisation to the utility to own an independent network, so it is even more difficult to obtain it when sharing it with other users.
- The stations or power plants are scattered over the country often far from urbanised areas and potential users of the network.

However, there is mutual benefit in sharing optical fibre systems arising from the fact that the main component of cost is the cable and installation. The incremental cost of additional fibre is small. Also the potential transmission capacity of a single pair of fibres is 2.5 Gbit (using SDH) which is much higher than the needs of a Power Utility private network.

It may be that present and continuing deregulation in telecommunications will make it possible for utilities to hire out optical fibres or transmission capacity in the near future.

Moreover, this market is perpetually growing because of the increasing telecommunication needs of corporates such as insurance companies, banks, department stores, universities, hospitals and so on.

Distances

The attenuation budget is one of the major tasks of every system designer. Many factors influence the assessment resulting in a wide range of distances between regenerators.

Laser source is commonly used for interstation communications, except for very short distances where light emitting diodes (LED) can be used.

With an average singlemode fibre in the 1300 nm window, with an optical margin of 9 dB (depending on predicted degradation of system components), the typical lengths of span vary from:

65 km at 140 Mbps
to 90 km at 2 Mbps

Recent developments in both terminal equipment and fibre technologies allow these distances to be engineered. Some years ago a designer could expect only 40 km range, but technology is developing very fast and further extension to range will allow distances of up to 100 km without special engineering.

With such ranges, repeaters will only be necessary for quite long interstation distances, which will constitute a secondary point in optical system designing. As monitoring systems spread out to the market, several repeaters can be set up on the same line, so every distance can be covered with repeaters.

Future expansion requirements

Interstation communication links are often oversized for the operational tasks. Administrative needs or TV signals (in case of joint venture with cable TV operator) can use the free channels of the multiplexer.

Any future expansion consideration requires higher multiplexer levels, high quality fibre and better laser sources. This represents a higher initial cost than would be necessary for the initial identified need. However, the cost of upgrading can be very high and availability of existing services will be disrupted. The system designer should take into account all known future requirements when specifying system components to ensure an economic and high availability path to the final requirements. The

48 fibre cable construction is popular where leasing of services by the carrier is considered.

Motivation for the choice of fibre optics

Two of the main advantages to an Electricity Supply Utility are of electromagnetic compatibility within an electrically noisy environment, and the availability of the transmission path at times when power system protection operation is required.

The other secondary attribute is the potential of almost unlimited bandwidth. With telecommunications being an area of projected continuing growth, this unlimited bandwidth and freedom from the need to obtain radio transmission frequencies and licences from the PTT opens commercial possibilities for the exploitation of this resource either as a wholly owned and run venture, or in collaboration with the NationalTelecommunicationsNetworkOperator.

System cost

The total system cost changes with the type of cable and terminal equipment, etc.

A typical case is where an Optical Ground Wire (OPGW) with six fibres is compared with a normal ground wire. When a new ground wire is required anyway, the extra cost of providing fibres and associated work is about $US 10-15 per metre.

For new systems where the existing ground wire need not be changed, the main cost components are as follows:

- Fibre cable installation
  - fibre system planning
  - fibre material (cable)
  - installation material
  - installation work
  - jointing material
  - jointing work
  - commissioning

- Terminal equipment provision
  - planning
  - material
  - installation
  - commissioning

Table 1 compares the different costs of fibre cable systems. The costs are shown in $US/m. The total price of the system does not vary in direct proportion to the number of fibres in the conductor or cable. For example, the step change from 12 fibres to 18 fibres increases the cable system cost by 1.5 $US/m, or about 10% of the total installed cable cost. There are certain discreet steps in the cable price for a given number of fibres in the cable. The steps are not always comparable between the various cable technologies. Although it seems that the step from 18 fibres to 24 fibres is usually bigger than the step from 12 to 18 fibres, due to natural limitations in manufacturing and installation technologies.

	Type of Cable		
System Component	OPGW	Wrapped	ADSS
Planning	0.5	0.5	0.5
Fibre cable	9.0	9.0	7.0
Installation material	1.0	1.0	1.0
Additional tower structure	0	0	1.0
Installation work	4.0	2.5	4.0
Jointing	0.75	0.75	0.75
Commissioning	0.25	0.25	0.25
Total Cost ($US/m)	15.5	14.0	14.5

Table 1 Typical cost of different cable systems

The total cost of one item of optical line terminal equipment (item 6 or 7 in **Figure 4**) depends essentially on the capacity and technology needs. A 2 Mbps OLTE may cost between 1,500 and 4,000 $US. The cost of the technology does not essentially change from 2 Mbps to 34 Mbps. The cost of one 34 Mbps terminal depends mainly on the number of 2 Mbps access points required. At the other end of the range SDH terminals operating at 156 Mbps (providing 63 2 Mbps access points) may cost between 50,000 and 100,000 $US.

The total system cost depends on the length of the fibre cable route. The cost is dominated by the terminal equipment in the range of two kilometres or less. On the other hand, in the range of 40 to 50 kilometres, the high cost terminals do not essentially change the overall system cost.

There are a number of other factors determining cost, such as wavelength, range, network management, service facilities, and mechanical design.

Cost Comparison with other media

Other techniques for telecommunications systems will invariably involve either metallic cable systems, both coaxial and copper pairs, or radio systems such as terrestrial microwave.

The metallic solutions are both susceptible to electromagnetic incompatibility and are likely to decline in availability from manufacturers as fibre oriented systems become more competitive.

Economic cost comparisons are somewhat different for a Power Utility, when compared to a Post, Telephone and Telegraph (PTT) operator. For a PTT the full capacity of a fibre optic cable can be utilised and thus the cost per channel of this medium is the lowest when compared with alternatives. However, to achieve this cost advantage, PTTs have typically installed 16 fibre cables and use PDH transmission rates of 565 Mbps. The circuit capacity of such a fibre is far in excess of the requirements of a Power Utility. Power Utilities often require 8 or even 34 Mbps links and at these capacities fibre optic systems are generally more expensive than microwave radio systems, except for relatively short links.

The cost of Microwave links, if authorised, is independent of distance (within the range of the link) and the higher cost radio equipment does not normally change the cost balance.

Fibre optic systems can be selected between other cable solutions not only for its availability or reliability but on economic considerations. If the required capacity is high (more than some ten channels or so) the price advantage is normally in favour of fibre optics. Moreover, for distances between 30 to 80 km, one or more intermediary stations may be necessary in a coaxial cable system. In this case as soon as the coaxial link needs two repeaters, the use of fibre optics is generally economical.

In comparison with digital microwaves, capital costs of a fibre optic digital system are normally cheaper at distances less than around 30 km. Beyond this length the cable cost may make the fibre optic solution uncompetitive. Local terrain and other conditions may well influence microwave path lengths and where early repeater spacing is required fibre optic systems may prove more attractive. In addition, unproven availability of a radio system coupled with the licensing difficulties may well be a final influencing factor. See Section 3.3.1 *Construction of Fibre* for additional advantages of using fibre optic cables, and Section 3.4 *Cable Types* for other economic advantages.

3.1.2 Existing lines

Installing an optical facility on an existing line has usually one of the following options:

- Replacing old ground wire with new optical ground wire.
- Wrapping or attaching optical fibre cable on ground or phase wire.
- Installing self-supporting optical cable.
- Installing separate additional light weight optical ground wire.

Whenever any refurbishment that includes optical fibres is carried out, the following direct and indirect cost factors should be considered:

- Direct costs:
  - Fibre optics and cable
  - Cable splices and joint
  - Speed of installation
  - Machinery required, its availability and cost
  - Qualification of personnel
  - Accessibility to installation

- Indirect costs:
  - Expected remaining lifetime of an old ground wire
  - Maintenance (see Section 3.10 *Maintenance*)
  - Circuit outage time

When an optical cable is introduced on existing lines, there are different cost factors. Some of the costs are always present during the installation (direct costs).

Other costs may or may not apply during the installation. (circuit outage time, for example) or after installation (such as maintenance).

Circuit outage time will be a cost only in two cases:

- If the alternate transport lines fail, and no energy is supplied into an area
- If the transport energy cost is more expensive in the alternate line.

3.1.3 New lines

Constructing a new line with optical fibres usually has one of the following solutions:

- Optical ground wire.
- Wrapped or attached optical fibre cable.
- Self-supporting optical cable.

Whenever any new line including optical fibres is to be constructed, the following cost factors should be considered:

- Fibre optic cable
- Speed of installation.
- Qualification of personnel.
- Machinery required, it's availability and cost.
- Maintenance (see Section 3.10).
- Compatibility with the line constructing project.
- Considering future line extensions and modifications.
- Considering future customers in locating lines.
- The life time expectancy should be the same for optical fibre system as for other parts of the line.

The following things should be considered when planning the maintenance:

- Accessibility to fault location.
- Circuit outage time in different possible fault conditions.
- Personnel needed (available in-house?) for repair work in different fault cases (telecom people, power people), maintenance training program.
- Possibility of temporary repairs.
- Short return to service time of damaged parts of the system (cable, regenerator, terminal equipment etc.).
- The availability of spare parts.
- Service contracts.
- Duplication of certain parts of the system.
- Supervision of the system (separately or by the application).
- Automatic or manual changeover facilities (eg. spare fibres or alternate routes).

3.2 System Considerations

3.2.1 General system overview

The key features of a typical interstation communication system are shown schematically in **Figure 4** and are listed below.

1 Fibre Optic Cable System
2 Joint Boxes
3 Repeater (optional)
4 Optical Patching Frame (optional)
5 Optical Connectors
6 Optical Line Terminal
7 Optional Optical Line Terminal to connect to Other Station(s)
8 Protection Switching or Cross Connect Unit (optional)
9 Multiplexer
10 Interfaces for Power Utility Services
11 Power Utility Service (e.g. data terminal equipment, telephone switch, protection relay)

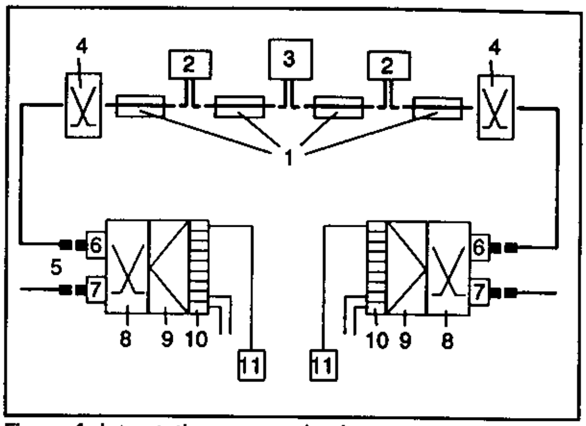


Figure 4 Interstation communication systems

3.2.2 Reliability and availability considerations

General requirements

The Consultative Committee for International Telephone and Telegraph (CCITT) makes a number of recommendations for the availability of telecommunications systems. However, in any communications system, it must be acknowledged that it is impossible to ensure an availability of 100%. For systems operating within the environment of a Power Utility both long and short term unavailability may be experienced.

The term 'availability' is generally accepted as being the ability to successfully pass information between two locations. The term reliability refers to the individual components comprising the system. The terms reliability and availability are mutual terms, i.e, if the reliability of the components of a simple system is poor, then the corresponding availability is likely to also be correspondingly poor. The term 'simple system' as used above refers to a basic communications link comprising of, say, two fibre optic terminals and an intervening fibre optic link without equipment redundancy.

The availability (A) of any equipment is defined as:

$$A = \frac{MTBF}{MTBF+MTTR} \times 100\%$$

where MTBF = Mean Time Between Failure
MTTR = Mean Time to Repair

Furthermore, the availability of the communications system is degraded from the above figure by transmitted information errors not attributable to equipment failure. An operational digital communications system is normally regarded as being 'available' when the information is being passed with a Bit Error Rate (BER) of less than one error in 10^6 bits. In practice, BERs of one error in 10^9 or 10^{10} are typical for optical transmission systems. The guarantee of low BERs is a function of system design to ensure that adequate signal to noise ratio margins exist between the transmitter and receiver. With such low typical BERs in optical systems, the main reasons of unavailability are cable failures, equipment failures, burst errors, and man made interruptions.

Although modern solid state equipment has inherently long MTBFs, failures still occur on a random basis. Also some semiconductor electronic components do have a defined ageing process with a finite life. The latter is most certainly true of optical interface components, in particular, laser diodes.

Likewise, the transmission medium also has its own reliability characteristics. In a microwave radio system, for example, the path unavailability would be almost exclusively attributable to atmospheric disturbances which, although they may occur with regular frequency, are likely to be very short term. Conversely, a fibre optic medium is likely to prove a very stable medium, but due to the fragile nature of the fibre, cable design and installation must be carefully considered if breakages, which may take some time before repair can be effected, are to be minimised.

When considering a system design, it is common practice to incorporate equipment redundancy into the design so that the system availability is increased and made relatively immune to individual component failures. Similarly, it is becoming common practice to incorporate alternative route diversity to overcome the effects of a fibre link failure.

Another critical factor in the determination of overall system availability is that of the time to repair the fault. This may be very variable depending on fault supervision, site access, personnel availability, etc. A MTTR of 15 minutes may be achievable in a main-station with continuous 24 hour manning by qualified technicians but for an unmanned repeater site located on a remote hill top cutoff during winter by snow drifts, a MTTR of 48 hours or longer may be more realistic.

Therefore, the system design should reflect such factors - unduplicated systems may be acceptable in the former case, whereas fully duplicated or even triplicated systems may be required in order to achieve the desired availability in the latter instance where an inaccessible location forms a critical communications node.

For most system availability calculations with normal access, a MTTR of four hours is generally regarded as acceptable for the electronic components. Repair of fibres or cables may take considerably longer.

There is a cost penalty for designing systems with very high availabilities, in general an availability of 99.995% which equates to a non-availability of some 25 minutes per year will be perfectly adequate for most telephony applications and should be achievable without undue duplication of equipment. Nowadays, a single fibre optic route with duplicated fibre paths should be capable of yielding availabilities in this order. However, to significantly improve upon this figure will require the implementation of route diversity which will more than double the capital investment in plant but may in practice only gain an extra ten minutes operating time per year. The design engineer therefore has to consider the criticality of the traffic which the link will carry and configure the system accordingly.

Finally, the design engineer must be aware of the probable failure modes and methods of repair of the system components. For instance, a faulty electronic module may be capable of being located and replaced within ten minutes once the technician has arrived on site, but a faulty section of a composite fibre optic earthwire could take well in excess of 48 hours to repair by the time a line access has been secured and the faulty section is replaced.

Cable stress, reliability and availability

Optical fibres by virtue of their nature are extremely fragile. Furthermore, it is known that their service life is adversely affected by strain, and that there is an inverse life versus strain characteristic. In general, the installed fibre strain must be kept below 20% of the proof strain to yield a reasonable fibre life (>25 years), and cable manufacturers incorporate a number of techniques to avoid excessive fibre strain during service life.

Such techniques usually involve manufacturing cables which contain a fibre length which is a fraction longer than the cable section length. This is achieved by overfeeding the fibre into the cable during manufacture. Such techniques usually incorporate the fibre in a plastic tube or open slot, and typically up to 24 fibres may be included within this space. The number of tubes per cable will be dependent upon the customers requirements, but fibre counts in excess of 100 are common-place for underground distribution service.

Other techniques for fibre strain relief include tight buffering the fibre. Here the fibre is coated with a high tensile plastic during manufacture so that this plastic absorbs the tension rather than the fibre.

Cable reliability is still a subject area where information is being gathered. Initial experiences have shown that, assuming that the cable has been correctly installed initially, service lives of 25 years should be achievable. Some of the early fibre optic composite earthwires exhibited slow attenuation increases attributed to an effect known as Hydrogen Degradation. The mechanisms which cause this hydrogen degradation are now fully understood (see Section 3.3.5 *Fibre buffering and protection* for detailed explanation) and the means for preventing or at least controlling the phenomena are now included in all cable designs.

There have been a number of instances when self-supporting fibre optic cables strung along the same routes as high-voltage power transmission lines (>150 kV) have failed due to sheath degradation.

Sheath degradation first manifested itself with the unexpected mechanical failure of a number of self-supporting fibre optic cables. Subsequent research and studies of the effects has enabled a full understanding of the mechanisms causing the problem, although the solutions to the problem are still being proven. The failure mechanism appears to be due to an effect known as 'dry-banding' which occurs when a weathered cable in mildly polluted atmosphere becomes 'wetted' as the result of a rain shower. As the cable dries, it does so unevenly, permitting dry-bands to form. As the cable is under the influence of an electric field, electrostatic voltages are induced in the semiconducting moisture film. As the areas of moisture film are separated by areas of insulating material (the sheath), the induced voltage can be sufficiently high to permit an arc or corona to form across the insulating barrier. The heat of the arc or corona is sufficient to erode the jacket material. The exposed tensile strength member then loses its strength because the resultant tracking reduces the cross sectional area to the point where mechanical failure occurs.

There are a number of approaches which may prove successful in overcoming this effect - firstly to develop a suitable sheathing material capable of withstanding the arcs or corona, or to use a semi-conducting plastic which will maintain a constant voltage gradient along the cable irrespective of the pollution during normal service life. A sheath having an electrical resistance of around ten megohms per metre has been proposed as being suitable. Furthermore the cable can mostly be installed at a position in the tower where the induced voltage is low or even zero. This reduces the 'dry banding' considerably and can even eliminate the effect.

Cable system availability is, in practice, usually dependent upon the cable remaining undisturbed whilst in service. Most fibre optic cable faults, excluding those attributable to mishandling or improper installation which are normally found at the time of commissioning, are solely due to external influences such as being unearthed by civil construction works or rodent attack in the case of underground cables, or in the case of aerial cables, mechanical wear, bird attack, shotgun blasts, etc.

Redundancy considerations on a link basis

A typical telecommunications service link will comprise two sets of terminal equipment and a transmission medium. In the case of a fibre optic system, the latter will be the fibres themselves. In most cases, the path will consist of a pair of fibres, one for the outward signal, and one for the return. As the system of this type cannot operate with only one fibre, the fibre pair is usually considered as a single entity.

However, for purposes of system planning, it is common practice to use two fibre-pairs for any given circuit within a single cable. This, with suitably duplicated terminal equipment, will permit instantaneous change-over from the primary to the secondary path should either of the primary OLTE (Optical Line Termination Equipment) or the individual fibre paths fail. Consideration should be given to the provision of spare fibres within the cable so that if a single fibre should develop a fault at any time, full system integrity can be re-established by simply abandoning that fibre, either on a temporary or permanent basis, until time permits a full fault investigation and replacement.

Similarly, consideration may be given to employing redundant multiplex equipment. At a remote site a critical network hub may require duplicated multiplex equipment, but at a manned station, unduplicated equipment may be satisfactory. The need for equipment redundancy will be influenced by a number of factors and will be one of the primary functions of the system designer. It must be remembered that equipment redundancy often multiplies the equipment count by a factor of three when the additional multiplex and equipment protection switching system is taken into account. There is little point in considering redundancy if the extra equipment yields a system of such complexity that the anticipated benefits are negated.

In general, a duplicated system should improve system reliability by orders of magnitude over an unprotected system, since the probability of the primary equipment failing at the same time as the standby equipment fails becomes extremely unlikely.

Unfortunately, the 'Achilles Heel' in a fibre optic system is the cable itself. An excavator from a construction site can most effectively render even the most carefully configured terminals useless by severing the primary and secondary fibre paths. In this instance, the use of route diversity is the only way to protect the system with two independently routed cables. This subject is discussed in greater depth in Section 6.3 *Reliability, Availability and Redundancy Considerations*.

Expected sources of errors, failures and characteristics

Apart from the effects of aging of certain components such as the laser, a system may experience random errors in the telecommunicated information due to external influences such as power system disturbances. Within a Power Utility context, such errors are most likely to be attributable to disturbances within the power transmission system itself as a result of opening circuit breakers or isolators, lightning strikes, etc.

The fibre itself is by nature free from these effects; the terminal equipment by virtue of being digital has a high degree of noise immunity but additional measures required, to reduce the chances of RFI pickup, include housing the terminal equipment in RFI proof cubicles and establishing good earthing practices.

Any susceptibility in the communications system will manifest itself as a burst of bit errors in the digital stream. The Bit Error Rate (BER) is generally accepted as recommended by CCITT as the universal method for rating the quality of a digital transmission system. A 'good' system should exhibit BERs in the region of one error in 10^{10} bits. By CCITT definition (Recommendation G.821), if the BER is between 1 error in 10^3 and 1 in 10^6 it is termed 'degraded' and for BER below 1 in 10^3 data is classed as 'severely errored'. However, the fibre optic terminal equipment may loose synchronisation when the BER of a 140 Mbps high order signal falls below 1 in 10^3. At this point a major system alarm is generated and the equipment shuts itself down. Thus a system will not normally be capable of operation with a BER of 1 in 10^3 or worse.

Terminating equipment reliability and availability

The terminating equipment in this context is taken to include the primary and higher orders of multiplex in addition to the Optical Line Termination Equipment (OLTE). Modern multiplex equipment has MTBFs quoted in the region of 30 years per module. The OLTE has a somewhat shorter life due to the ageing of the optical components, but even here MTBF of greater than ten years is now realistic. Thus, depending on exact configuration, a protected multiplex/OLTE combination should exhibit an availability of 99.999%. PSUs are generally the most unreliable system component and therefore use of duplicate PSUs should be considered.

3.2.3 Environmental considerations

The environment in general has to be taken into consideration in designing, or choosing the various components of a system; including terminal equipment, cables and regenerators etc. The environment considered here is the electrical, ambient, meteorological statistics and aggressive atmosphere.

In March 1988 CIGRE WG04 of SC35 sent out a questionnaire to all 24 CIGRE member countries to establish the needs of Power Utilities in optical fibre systems.

Results obtained in the survey that covered the main aspects of fibre optics for Power Utility communications were published by SC35 WG04 in August 1990 [4] and published in *Electra*.

The environmental issues covered revealed the following requirements. Terminal equipment is normally designed for a hostile electrical environment and is seen to be a requirement in a substantial number of cases (59%). The minimum temperature requirement was seen to be -20°C and the maximum 70°C. Taking into consideration the average values derived from the replies, a figure for low temperature is 0°C and for high temperature 46°C. Relative humidity ranges from 60% to 100% with an average value of 90%.

For cables the environmental consideration in addition to the temperature and humidity, also needs to include wind speed, ice accretion and solar radiation. Temperature and relative humidity range from -20°C to +70°C and from 80% to 100% respectively. Wind speed ranges from 100 to 220 km/h and ice load, obviously in areas subject to ice formation, ranges from a minimum of 6 mm thickness to a maximum of 120 mm. The average value for solar radiation is equal to 1120 W/m^2.

Regenerators should cope with temperature ranges from -40°C to +80°C, and the relative humidity range is the same as for cables i.e., between 80 and 100%.

In addition a few utilities also stated maximum requirements for water, acid and salt corrosion. Special protection measures to be considered in accordance with specific or local problems may also include protection against vandalism, rodents, other animals (e.g. birds, termites) earthquakes, falling trees, vibrations, and lightning.

The above considerations together with additional specific problems to be taken into account when specifying system components, may be regarded as providing only a general guide. A careful analysis of the environment in which an optical system has been sited will be necessary in order to evaluate as accurately as possible the design parameters of the various components. Useful indications can also be obtained from relevant IEC and IEEE documents.

For meteorological considerations, a rational assessment of the relationship between the meteorological data (wind, temperature, ice) and the mechanical load to which optical overhead cables may be subject to can be deduced from IEC Report 826 *Loading and Strength of Overhead Transmission Lines*.

3.2.4 Services and interfaces

The services which are likely to be carried on interfaces between communication systems and application equipment by the Power Utility communications system will probably include:

- Telephony (analogue voice)
- Low Speed Data (<2 kbps)
- High Speed Data (>2 kbps, <2 Mbps)
- Very high Speed Data (>2 Mbps)
- Protection Services (N x 64 kbps, or single protection commands)
- Video (CCTV)

Different interfaces are required for each of these services; the exact nature of the interface will be dependent upon the bandwidth of the service. For instance, most telephony is analogue in nature and occupies a bandwidth of between 300 and 3400 Hz. Thus a standard VF interface would be appropriate. Low speed data, which is often asynchcronous, can be condensed into 64 kbps bitstreams by corresponding equipment or interface boards, or it can be transmitted via VF channels using modems.

As the data speed increases, interfacing technique will correspondingly vary. Typical practices will involve the use of some form of concentrator to combine a number of high speed signals into a single signal with a bit rate which will fall into one of the standardised levels, eg. 64 kbps, 256 kbps or 2 Mbps. Very High Speed Data such as inter-mainframe transfers in real time will demand their own 2 Mbps or higher circuits. These will simply connect via a suitable isolation interface to the appropriate digital multiplex port of the fibre optic terminal.

Protection Signals may be in either digital analogue or command formats. The protection equipment manufacturer will invariably design his equipment so that it interfaces with one of the common interfaces.

Real Time Video, by nature of its very high bandwidth (>5 MHz) is normally interfaced to the digital multiplex equipment at either the 34, or 140 Mbps levels, depending on the desired transmission quality and/or level of acceptable compression. The video signal itself is in an analogue format, and it is usual for the user to supply his own equipment for the analogue to digital conversions and vice-versa.

Video phone applications may be provided on an ISDN PTT network operating at 256 kbps.

Distributing different services within the station

In this context, the term 'station' is taken to be the area in which the telecommunications equipment is located. Ideally, the distribution practice should be that adopted by most Telecommunications Operators. All subscriber lines should be terminated at the Main Distribution Frame (MDF). There will probably be a Tie Cable between the MDF and an Intermediate Distribution Frame (IDF) located in the terminal equipment room. Between the IDF and the terminal Equipment it is common practise to insert jackfields for line and equipment test and monitoring and also attenuators or line amplifiers as required.

All VF lines should be balanced to minimise their susceptibility to induced interference. For higher bit-rate applications (>2 Mbps), the terminal equipment interfaces will invariably be coaxial. This poses two problems: firstly, it is more difficult to eliminate interference due to longitudinal current induction than it is for a twisted pair, and secondly, the attenuation of the coaxial cable may prohibit transmission over anything but a relatively short distance without the use of intermediate regenerators (or line extenders).

It is likely that there will be an increasing need to send high speed data across substation sites. In an Electricity Supply environment, there is likely to be significant rise of earth potentials across the site under system fault conditions. The effect of this can be negated by use of specially shielded cable but this is normally an expensive solution. All insulating fibre optic cable for cross site signal transfer is an obvious solution. Such applications to which this would be ideally suited would be where the telephone switch is remote from the telecomms apparatus room. A fibre optic cross site cable operating at 2 Mbps would in most cases provide the necessary trunks which would interface at the 2 Mbps level with the fibre optic terminal. The application can be extended to a small building with, say 12 telephones but no switch by equipping the remote primary multiplexer with two wire subscriber loop interfaces. Multimode technology would be appropriate for such cross site fibre systems and may result in savings over the singlemode counterpart.

3.3 Fibre - The Communications Medium

The glass fibre provides the heart of the communications medium. By its very nature it is extremely fragile when drawn into a hair-like strand. In order to operate as a reliable high quality component, the fibre must be pure and protected from mechanical stress. The development of technology to achieve this aim has been a major challenge for leading scientists around the world for many years.

3.3.1 Construction of fibre

Optical fibre is composed of the light guiding core and surrounded by cladding. Both are made of glass of high purity. The core can be germanium doped or pure silica. The core and cladding are then surrounded by one or two protecting plastic coatings. Acrylate is a common coating material. This coating affects the 'proof' or strength of the fibre.

Light propagates through the core by the principle of total internal reflection. The refractive index of the core is higher than that of cladding. The construction of fibre is shown in **Figure 5.**

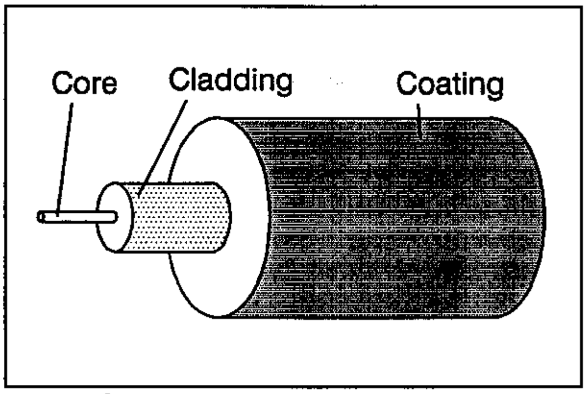


Figure 5 Structure of the optical fibre.

The light source converts electrical signals into light which in turn propagates in a fibre coupled to the source. At the other end of the link, the receiver end, signals are converted back to electrical pulses by a photo-detector.

Repeaters, which consist of receiver, amplifier and transmitter, are sometimes used in long links.

Some of the main reasons to use optical transmission in Power Utility applications are:

- It is not subject to electromagnetic interference (does not cause any interference itself either).
- Allows full electrical isolation of system components.
- Very small Bit Error Rate, high quality transmission media.
- Very long repeaterless transmission distances, up to about 80 km, compared with 1.5 km for coaxial copper cable.
- Very high transmission capacity which is mainly limited by the terminal equipment (up to 3 Gbps which allows more than 28,000 simultaneous telephone calls).
- Small size and light in weight.
- The cost does not depend very much on how much transmission capacity is needed.

The development of optical fibres has evolved in generations as follows:

1) First generation systems (1978-1982)

- 0.85 μm wavelength.
- Multimode graded-index fibre.
- GaAs LED or laser transmitter, silicon detector.

2) Second generation systems (1983>)

- 1.3 μm wavelength.
- Singlemode fibres.
- GaInAsP laser (or LED) transmitter, GaInAs detector.

3) Third generation systems (1989>)

- 1.55 μm wavelength.
- Singlemode fibres (also dispersion shifted fibres).
- GaInAsP laser transmitter, GaInAsP detector.

The wavelengths 0.85, 1.3 and 1.55 μm are often referred as first, second and third window.

3.3.2 Fibre types

Two main types of fibre exist: Singlemode and Multimode. When the fibre core is small enough, only one mode of light can travel through the core. This type of fibre is called singlemode fibre. In multimode fibre several modes can coexist and they have paths of different lengths.

Refractive index profiles for singlemode and multimode fibre types are shown in **Figure 6** and **Figure 7** respectively.

Singlemode fibres

Type of fibre	Refractive index profile	Mode field diameter	Applications
1.3 μm SM		9-10 μm	Standard telecom fibre
1.3 μm DC-SM (depressed cladding)		9-10 μm	Better bending performance
1.55 μm DS-SM (dispersion shifted)		7.5 μm	Optimised for 1.55μm -submarine -toll lines

Figure 6 Single mode fibre types

Multimode fibres - main types

Type of fibre	Refractive index profile	Size core/clad	Applications
Graded index		50/125 μm	LAN
Data fibre		62.5/125 μm	LAN

Figure 7 Multimode fibre types

Attenuation

The attenuation of the signal in singlemode fibre is significantly lower than in multimode fibre. This is the reason why singlemode fibre is preferred in Power Utility applications.

In Power Utilities the fibre optic systems are usually point to point links of length of one or more kilometres. Small attenuation means less repeaters and thus less cost. Repeater (regenerator) spacing with singlemode fibres can be more than 30 km, even 80 km. The typical attenuation of singlemode fibre at the 1.3 μm wavelength is less than 0.4 dB/km and at the 1.55 μm wavelength less than 0.3 dB/km, even lower values, less than 0.2 dB/km can be achieved.

Singlemode fibre also has higher data transmission capacity than multimode fibre. Multimode fibres are mainly used in local area networks, LANs, because the optical components for multimode fibres are cheaper than for singlemode fibres.

Transmission capacity depends on the speed of transmission. Since fibre has certain dispersion the light pulse is distorted in the fibre. Dispersion and attenuation deteriorate the form and power of the pulse thus limiting the link length. The higher the speed the shorter the link length.

Wavelengths

Singlemode fibres are designed for two wavelengths: 1300 nm or 1550 nm. Some fibres are specially designed for either of these wavelengths. 1300 nm is the most common wavelength used today in Power Utility point to point links. Fibre may be more easily disturbed by micro and macro bending if 1550 nm wavelength is used. However, today all fibre cables have double-window (1300 and 1550 nm) capability and are suitable for use on overhead lines.

Choosing the correct fibre type

When choosing the fibre for a certain application the following parameters should be considered:

- Singlemode or multimode fibre.
- Fibres and optical equipment already existing in network (compatibility).
- Attenuation of fibre, total attenuation budget of the link including splices, connectors, transmitter power and receiver sensitivity.
- Dispersion (data transmission capacity and speed, link length).
- The wavelength the fibre is designed for (equipment, existing fibres).
- Size of core (ie: mode field diameter) and concentricity (splicing with existing fibres).
- Practical colour coding for fibre recognition (for example IEC 304).
- The doping of the core material (splicing with existing fibres).
- Attenuation deviation due to temperature changes or fibre strain.

3.3.3 Number of fibres

The number of fibres varies in current Power Utility links from 2 to 24 and to even more in some cases.

With present technology only one direction of light signals carrying data flow is possible in one fibre. Data transmission is normally required to be bi-directional which means that two fibres are required. Some experimenting has been done for bi-directional data flow in one fibre but a practical solution is not yet available.

Power Utilities normally have the following data transmission requirements:

- Protection.
- Control.
- Measurement and supervision of the power network.
- Speech, administrative data transmission.

A Power Utility can reserve separate fibres for each of these tasks which means that at least eight fibres are needed. This will obviate the need for additional telecommunications (multiplexing) equipment by connecting the application directly to the fibres. However greater availability of service will be achieved by integrating the functions on a ring or link protected network.

Generally, four to eight fibres are used for the telecommunications needs of a Power Utility, but opportunities are being taken to move to higher fibre counts in the range 12 to 24. Usually a Power Utility itself does not need more than four or six fibres but in some countries it is already possible to hire fibres to other companies. These potential fibre leasees could be PTTs, other telecom corporates, banks, insurance companies, cable television or practically any big companies.

It is also a fact that the incremental cost of an extra fibre is minimal. Choosing the right number of fibres is a matter of optimising between the speed of equipment and number of fibres. When choosing the number of fibres for a new telecommunication link to be constructed the following things should be considered:

- Reserving selected fibres for critical tasks.
- Remember that bi-directional data flow is not yet available in one fibre in commercial products.
- The maximum amount of data to be transferred in the busy time unit. Restricted capacity will lead to loss of data.
- Spare fibres. If one fibre is damaged in the cable, it is probable that the other fibres will also be damaged, and may also fail in the immediate future. This is dependent on how the damage has occurred.
- Reserving fibres for leasing (or selling) if allowed or will be allowed by legislation in the future.

3.3.4 Fibre colouring

Different colouring methods have been used in Power Utility systems. Considering expandability and clearness of the system, standard and consistent colouring schemes should be used. Using too many colours can also be confusing since some colours can be very similar and thus may be confusing. In high fibre count cables (more than 12 fibres), grouping of fibres is recommended. For example IEC 304 colouring system using a maximum of 12 colours provides a good standardised method for fibre colouring.

Using IEC 304 also provides compatibility with PTT fibre which is useful when cooperating with such bodies.

3.3.5 Fibre buffering and protection

As the fibres are vulnerable they need mechanical protection. The construction of the cable has to be such that no damage will occur to fibres during any phase of installation or operation. The fibres themselves are not very sensitive to high or low temperatures but they are very sensitive to strain, radial or longitudinal pressure, bending and torsion. All these phenomena can result in fibre breaking and/or damage attenuation increase. Water can influence fibre in two ways. First there is the effect that the presence of moisture on the glass surface of the fibre enhances the growth of the always present flaws on the glass surface. Flaw growth velocity is determined by the mechanical stress in the glass surface and by the amount of water molecules present. The cable design must ensure that the stress on the fibre is considerably less than the fibre proof test, especially when there are no measures in the cable design that prevent moisture from moving to the glass surface of the fibre. Secondly water can react with the metals in the cable construction. The hydrogen can dissolve in the core-glass of the fibre where it is responsible for light absorption because of basic H_2 stretch vibrations at 2480 nm with first overtone at 1240 nm. The effect of the hydrogen can cause problems in the lower side of the 1300 nm transmission window and at 1550 nm. Problems with hydrogen in optical fibre cables can be prevented by not allowing hydrogen to be generated by coating the metal parts, or by allowing the generated hydrogen to escape. These phenomena are not a problem with fibres manufactured today because different doping techniques are now used. The reactions can be tested by spectral attenuation measurements.

The fibres can be packed into a cable either loosely so that they have space to move, or tightly. In loose buffered construction the cable can elongate a certain amount without any fibre elongation. The fibres have some extra length (bias) in the tube(s) and as they are stranded and have helical form, move towards the centre of the cable during strain. In loose buffered constructions normal primary coated fibres are used (outer diameter is about 0.25 mm). The loose buffered method is mostly preferred by the European manufacturers who claim that this method gives the fibres longer lifetime. However, the two most common OPGW constructions in America are tight buffered designs. Loose buffered constructions are common for underground fibre optic cables in Europe and America.

In tight buffered construction the fibres do not have any extra space. When the cable elongates the fibres elongate with it. This elongation is kept to a minimum but certain fibre strain exists and is allowed. Usually in these conductors all the strands are aluminium clad steel. Also the fibres have a higher proof stress. Manufacturers use either a thicker fibre coating with an outer diameter of about 0.4 mm or use normal primary coated fibres (outer diameter is about 0.25 mm) with the fibre unit buffered with a heavier coating to protect the fibres. The tight buffered method is used by the Japanese manufacturers and major American manufacturers. Using a 0.4 mm fibre is a common method in Japan. The major American manufacturers use standard 0.25 mm fibres with the fibre unit tight buffered as described. In either case, the higher proof-stress level is normally used.

3.4 Cable Types

Cable types can be divided into groups:

- Composite: A two function aerial conductor most commonly referred to as optical fibre ground wire (OPGW), or a post installed light weight additional metallic ground wire containing fibres.
- All dielectric self-supporting (ADSS) aerial cables (semi conducting or insulating).
- Attached aerial cables (wrapped or clipped onto existing ground or phase wire).
- Bundle sub-conductor.
- Ground or duct cable (metallic or non metallic).
- Submarine cables.

These conductors and cables have different constructions, environmental and electrical operating conditions and usage but they are all designed to work as a highly reliable telecommunications medium providing large bandwidth.

One aspect that requires careful consideration is that if all the parts of a system are constructed using the same type of cable and fibre and constructed in a relatively short period, a total collapse of the system is a possibility if there is some long term problem with fibre or cable construction. Consideration should therefore be given to diversifying cable design on any system, especially on a protected network.

3.4.1 Composite aerial conductors

Construction:

In composite conductors a fibre unit containing the optical fibres is integrated (or embedded) into a conductor. In voltages below 150 kV the composite conductor can also be a phase wire. Usually however, the fibre unit is inside a ground wire. This construction is called 'Optical Ground Wire' (OPGW).

OPGW can also be a light weight additional ground wire which is designed for existing lines and to coexist with conventional ground wire. The mechanical and electrical requirements are the same for OPGW as for corresponding conventional ground wire. The number of fibres in OPGW can be up to about 50 with today's constructions. These high fibre count constructions are popular where leasing or selling of capacity to a carrier is considered.

The fibre sensitivity and vulnerability described in Section 3.3.5 *Fibre buffering and protection*, has to be taken into consideration when designing OPGW. The operating conditions affecting OPGW design are described later in this chapter in more detail.

OPGW conductors can be categorised in a number of ways. Most common of those are: loose versus tight buffering; stranded over central element versus single tube; or fibres inside metallic tube versus fibres inside plastic tube (closed versus open construction). Refer to **Figure 8** and **Table 1**.

Metallic tubes are either welded or extruded. Plastic tubes are always extruded. In some constructions several tubes are stranded over a strength element, but sometimes just a single

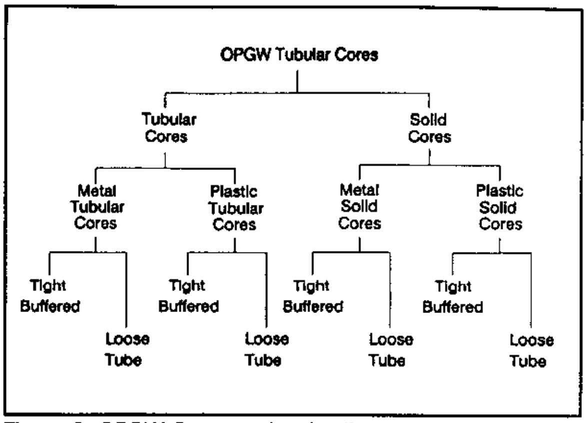


Figure 8 OPGW Construction family tree

tube is used. The fibres inside the tube are either loosely or tightly buffered. In OPGW, which is subjected to environmental as well as fault current induced stresses the fibre packing is an essential factor. The advantage of tight buffering is the construction of a small overall conductor diameter, while the advantage of loose buffering is that the fibres are not subjected to tensile stresses caused by conductor elongation.

Metallic tubes give hermetic protection against water and hydrogen penetration. But if there is hydrogen generation inside the tube it cannot come out. In plastic tube constructions the possible effects of water and hydrogen have to be taken care of by materials selection, filling compounds, and limiting fibre strain. In most cases the tubes are filled with compound material for water and vibration protection. In some constructions the fibres (or tubes) are

Construction type		Characteristic: Splicing	Crush resist	Strain relief
Tubular cores				
Aluminium	Tght buff	Diff	Med	Low
	Loose tb	Med	Med	Good
Plastic	Tght buff	Nt Cm	Nt Cm	Nt Cm
	Loose tb	Good	Lw md	Good
Solid cores				
Aluminium	Tght buff	Med	Good	Med
	Loose tb	Good	Good	Good
Plastic	Tght buff	Diff	Lw Md	Med
	Loose tb	Nt Cm	Nt Cm	Nt Cm

Nt Cm: not common; Diff: difficult; Lw-Md: low to medium; Med: Medium; Md-Gd: medium to good.

Table 2 Summary of cable characteristics

isolated from direct contact with metallic, current carrying parts. Plastic tube is faster and easier from the installation point of view (excluding stranded tube types) and it can be used as a cable itself inside buildings (if designed so).

The metallic wires have to give the OPGW conductivity to carry fault currents, and the strength to withstand mechanical stresses. Aluminium, aluminium alloy, galvanised steel, aluminium clad steel wires or a combination of them are used. Two armouring layers can be used to prevent the effects of torque. If the conductor has only one layer then, anti-rotation devices should be used during installation. Another important reason for two layers is a low temperature in the optical element in case of a fault by using steel wires in the first layer.

The following examples are generally available from manufacturers throughout Europe, USA, and Japan. This is not a complete list of available OPGW constructions but rather a collection of typical ones.

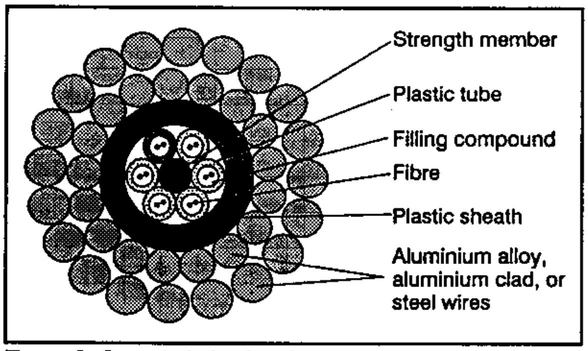


Figure 9 Stranded plastic tubes - plastic sheath

The OPGW in **Figure 9** represents the oldest type of plastic tube construction. Fibres are loosely housed and stranding gives controlled fibre overlength. Relatively sensitive to temperature changes. Crush resistance is low but in most cases possible deformation is reversible (recovers when load is removed). Only low number of fibres can be achieved (about 12). Splicing process is slow

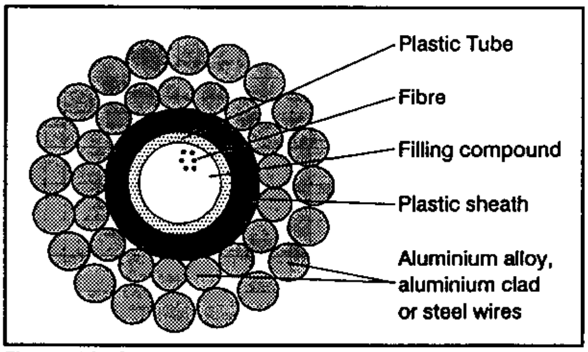


Figure 10 Straight plastic maxi tube - plastic sheath

Figure 10 illustrates a typical maxi tube design. Fibres are loosely housed. Fibre overlength is obtained only by biasing (feeding extra fibre into the tube) and thus cannot be controlled precisely. Needs very sticky compound (which may not be suitable for low temperatures) to avoid fibre and compound movement towards the lowest part of the catenary. Crush resistance is low but in most cases possible deformation is reversible. Average number of fibres can be achieved (about 24). Splicing process is fast.

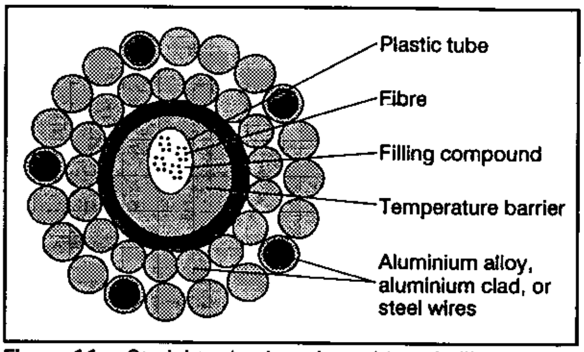


Figure 11 Straight plastic tube with spiralling hollow channel

In **Figure 11** a further evolution of straight plastic tube is illustrated. The hollow channel is in spiral form inside the tube to emulate stranding. Fibres are loosely housed and the oval shaped channel is filled with compound. Due to small size channel a filling compound for wide temperature range can be used. Controlled fibre overlength is obtained by biasing and stranding effect. Crush resistance is high and in most cases possible deformation is reversible. High fibre counts can be achieved (about 40). Splicing process is fast.

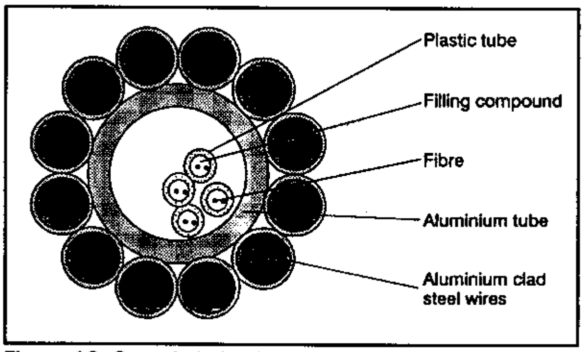


Figure 12 Stranded plastic tubes - aluminium tube

Figure 12 illustrates the original OPGW construction having stranded plastic tubes loosely housed inside an aluminium tube. Tubes can also be stranded on a central element and there can be plastic sheath on the tubes. Fibres are loosely housed in compound filled tubes. Fibre overlength is quite well controlled. Crush resistance is high but possible deformation is irreversible. Collapsing of the tube is possible if minimum bend radius is not observed. Typical fibre counts of up to 36 are achievable. Splicing process is slow. Aluminium tube can be very hot during a fault, typically hotter than the wires, which may require special tube material and fibre coatings.

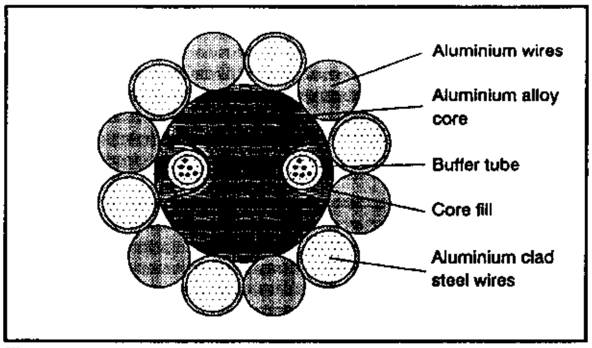


Figure 13 Slotted aluminium spacer - non metallic buffer tubes

The OPGW shown in **Figure 13** utilises a central helically grooved core of aluminium, into which is laid plastic compound filled buffer tubes containing primary coated fibres. A silicone heat resistant sealant seals the tubes into the core. Fibres have zero strain and achieve relief by radial movement of the fibre when the conductor is extended. This type of design has a very high crush resistance and is easy to splice. The aluminium core is relatively hot after a fault current but cools rapidly due to its bulk properties. Very high fibre counts are possible with cable designs of the same diameter of the displaced earth wire.

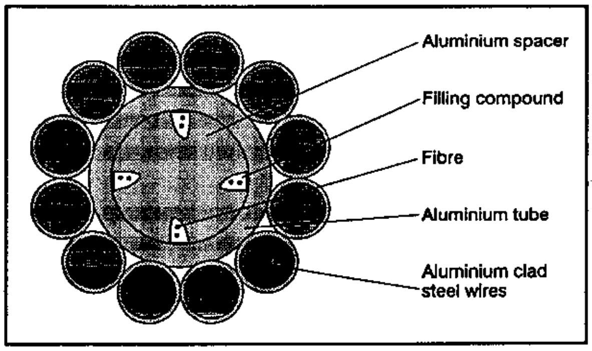


Figure 14 Grooved aluminium spacer - aluminium tube

The OPGW in **Figure 14** has a grooved or slotted aluminium spacer. Fibres are packed inside compound filled grooves. Typically fibres are packed tightly (no overlength). With low fibre counts loose packing is possible, providing controlled overlength. The aluminium tube is either extruded or welded on spacer. Crush resistance is very high but in case of collapse is irreversible. With tight buffering high fibre counts are achievable (about 48). Splicing process is slow. Aluminium tube and spacer can be very hot during a fault, typically hotter than the wires, which may require special fibre coatings.

Quite similar constructions with plastic slotted core also exist. In that construction fibres are loosely housed in slots. On the core there is either a plastic sheath or an aluminium tube.

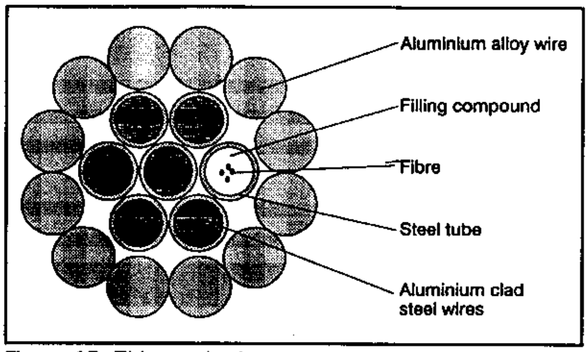


Figure 15 Thin steel tube

Figure 15 illustrates a new OPGW type. Fibres are loosely packed inside thin (same diameter as wire) compound filled steel tube. Steel tube is welded. Controlled fibre overlength is achieved by biasing and stranding. Crush resistance is quite good but possible deformation is irreversible. Splicing process is well developed and efficient. The use of aluminium alloy wires is important to prevent high temperature rise of the steel tube containing the fibres. If aluminium clad steel wires are used the steel tube may be very hot during a fault thus requiring special fibre coating.

Operating conditions:

OPGW conductors are normally at the top of the overhead line support structure and thus subjected to aeolian vibration, wind induced galloping, ice and wind loads, lightning strikes and possible ice induced galloping. OPGW may also have to carry ground fault currents.

It is essential that the Power Utility or constructor uses fittings, accessories and installation methods approved by the OPGW manufacturer. The usage of fittings to eliminate vibration or bending effects is discussed in more detail in Section 3.5 *Cable Fittings*. The effects of moisture and hydrogen are discussed earlier in this Section and also in Section 3.3.5 *Fibre buffering and protection*.

The fibre tubes should have a high crush resistance and minimal permanent or temporary deformation under mechanical pressure. The fittings should be designed to prevent or minimise these pressures. OPGW elongation under different stress situations likely during ice or wind loads or during ground faults has to be considered when designing wiring, tube or fibre overlengths.

OPGW has to be designed to operate continuously at ambient temperatures which can vary from -50 °C to +80 °C. All of the OPGW components have to withstand temporary high temperatures caused by ground fault currents and wiring, especially the outer layer, which has to withstand lightning strike induced heat. The fibre itself can tolerate very high temperatures but plastic tubes, fibre coatings and aluminium or aluminium coated steel wires can be sensitive to high temperatures. The conductor conductivity, outer layer wire diameter, and thickness of the aluminum layer over steel are important design points. In Europe the maximum temperature caused by ground faults is in most cases limited to below +200 °C, in some countries even to +130 °C. The main reason for this is to avoid reduced tensile strength of the armouring materials. The design basis should be the total duration of the fault current, consisting of the first current and currents caused by possible immediate and time based reconnections. When designing fault current carrying capacity the intermediate cooling times are not taken into account. Typically the relays de-energise the line in less than 0.5 seconds, thus the total duration is less than 1.5 seconds (in most cases 1 second is used). The line can be at a high temperature (over 100 °C) for several minutes after a fault. It is good practice to design the conductor conductivity to ensure that the highest temperature during a fault is as low as possible, preferably below +160 °C, so that there will be no permanent changes in aluminium parts (wires or cladding), or disturbances in telecommunications. For economic construction of an OPGW, it is necessary to know the maximum current through the cable (not the total short to ground current of the system) and the switch off time.

Protection against lightning strikes is taken care of by the outer layer, which in most cases should be at least 2.0 mm. The duration of the lightning strike (including all of its components) is in most cases less than 0.5 ms. The thermic effect is thus only in a small area at the conductor surface. In a high energy strike, aluminium or aluminium alloy wire is more liable to immediate breakage than aluminium clad steel wire, on the other hand, aluminium clad steel wire can loose its aluminium coating and thus corrode, resulting in breakage later. However, in most cases only a small crater results from a strike. A preformed rod can be used for recovering the lost strength. As most of the strikes happen at the poles, the preformed fittings are a good protection for OPGW. Damage resulting from lightning strikes is not considered to be a high risk. There is a lot of knowledge and statistical data about the phenomenon in conventional ground wires.

To protect against longitudinal water penetration, filling compound is used in many constructions. Filling compound is also a good protection against vibration (fibre movement) in tubes where fibres are loosely housed.

Installation and maintenance:

OPGW can be installed the same way as normal ground wire unless the manufacturer has stated otherwise. Scratching of the aluminium coated strands should be avoided in order to prevent corrosion.

The splicing of the fibres can be done either on the ground or at the top of the support structure. Some extra length is needed if the splicing is done at ground level but the splicing is easier to carry out. This extra length is not normally a problem from a system attenuation point of view. There is normally no safety problem exposing the fibres ready for splicing since OPGW is at ground potential. Handling requirements of the plastic tube and aluminium construction are quite different. Extreme care is required for dealing with the plastic and fibre components compared with the robust metallic elements. Single plastic tube is very easy to handle since it can be used as a cable as such and cutting one tube reveals all the fibres at once.

The lengths installed depend on the line route, maximum lengths the manufacturer can deliver and the maximum pulling force allowed. Today some manufacturers can deliver lengths of more than 10 km although shorter lengths are usually more reasonable. Long lengths are heavy and not very easy to handle. In most cases a three to five kilometre length is optimum. The longer the length the less splices and splice boxes are needed.

If OPGW is damaged (by lightning in very rare cases or by vandalism) the whole span should be replaced.

It may be good practice to monitor the attenuation of spare fibres from time to time (say, every 2-3 years). This will enable early detection of impending failure of a link before disruption to the service occurs.

Testing

The OPGW specific type tests contain pulling, torsion, bending, fault current and crush resistance tests to verify mechanical properties and to be sure that no damage to the fibres occur in any phase of installation or operation. Temperature cycles should be carried out and other mechanical tests if required. Every delivered length must be Optical Time Domain Reflectometer (OTDR) measured in different phases of manufacturing. No significant difference in attenuation shall occur between successive phases.

Economic considerations

OPGW is at its best when installed as new line or when old ground wire has to be changed. OPGW is also considered to be the most proven reliability fibre optic cable for Power Utility usage. When doing the cost comparison it has to be remembered that the existing ground wires and even support structures have to be changed anyway sooner or later.

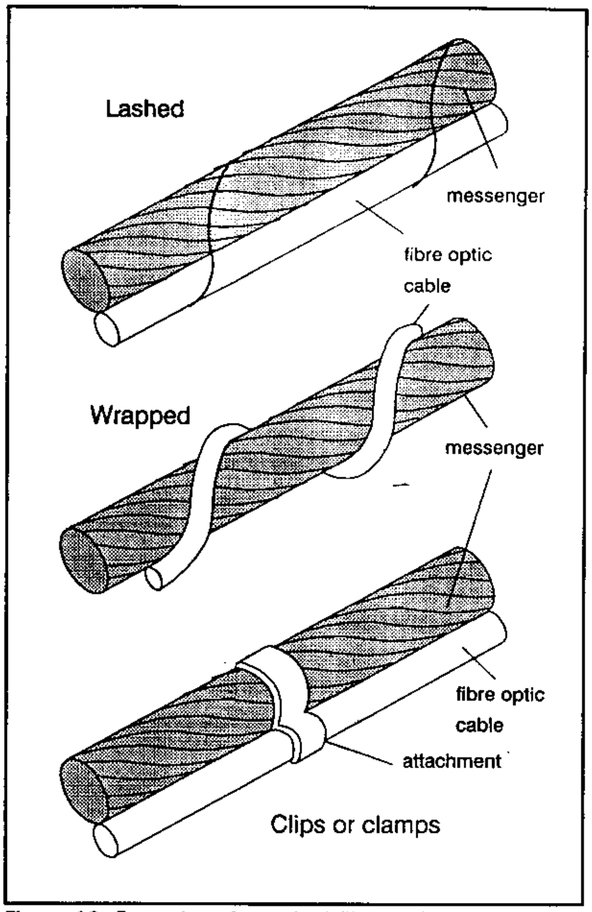


Figure 16 Examples of attached fibre optic cables

3.4.2 Attached aerial cables

Construction:

Attached cable can be fastened to or wrapped around the existing phase or ground wire, as illustrated in **Figure 16.** The wrapping type system is the only method available today. These cables are light in weight since they rely on strength of the wire supporting them. Typical cable diameter ranges from 4.5 mm for four fibres to about 7 mm for 24 fibres. The wrapping type cable should also be quite flexible. The number of fibres is normally in the range 2 to 24. Wind tunnel tests have shown that there are no aerodynamic instabilities, such as un-iced galloping, associated with the addition of these cables. Indeed, the helical wrap will tend to reduce the levels of aeolian vibration and the incidence of iced galloping, compared to those experienced by a normal ground wire. Diameters not greater than a third of the diameter of the supporting conductor are aimed at, so that significant increases in ice and wind loads are not experienced. Different kind of sheath materials are used to withstand bird attacks and electric fields induced by the phase conductors. The loose buffered tubes containing the fibres are jelly filled to protect the cable from water penetration.

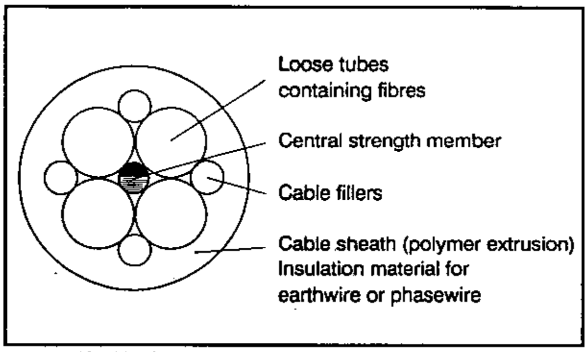


Figure 17 Typical attached aerial wrapping cable

Operating conditions:

The same environmental conditions apply to attached cables as OPGW. Where these are installed on phase conductors they also have to tolerate electric fields. Usually these cables are not installed onto phase conductors where the line voltage is more than 170 kV. This limitation is due to corona discharge caused by change to the electric field across the attached non metallic cable. There is no voltage limitation for attached earthwire installations.

These cables also have to be designed to withstand attacks from birds. Bird attacks were considered for some to be the worst problem for these cables, especially at times of migration.

Installation and maintenance:

The wrapping type cable is installed with a special machine. This machine travels along the cable either with a radio controlled motor or by pulling rope. Sometimes a helicopter can pull the wrapping machine. The problem of this method is the size and weight of the drum. This reduces the maximum length to about two kilometres for each drum but distances between joints may be up to four kilometres by double cassetting.

If the cable is attached to a phase wire it has to be isolated somehow in order to get it out from the wire, to be spliced. This problem caused by the potential of the phase wires increases the installation cost of this cable type. The splice box is usually placed at or near the top of the tower.

If the cable is damaged for some reason a midspan joint is possible in many cases. If this is not possible then the whole span should be replaced.

Testing:

The testing required is more or less the same as for OPGW but the mechanical strength requirement is much less. The sheath material should be tested to withstand birds and electric fields.

Economic considerations:

These attached cables are cost efficient when they are installed onto an existing line which is not very old. Installation equipment is small and typically provided by the supplier. No heavy equipment or vehicles are needed. Installation is quick and requires no gantries over roads, lines, etc as installation machines can be remotely operated via a radio controlled pulling unit. Attached cables are especially suited to existing lines where:

- Induced voltage gradients prevent the installation of self-supporting aerial cables, typically on systems 150 kv and above.
- Where ground clearances and/or loading prevent the installation of self-supporting aerial cables.
- Where difficult terrain and/or limited access prevents the installation of separate communication cables.

These cables have a failure mode which does not impair human safety, and a life expectancy in excess of 25 years.

3.4.3 All dielectric self supporting cables

Construction:

These cables must be designed with sufficient tensile strength to maintain clearance considerations and protect the optical fibres from external stresses and strains throughout the predicted service life. Consideration must be given to long term fatigue and creep. The support element is normally glass or aramid fibre or sometimes both. Metallic strength elements may also be used but are not recommended where a parallelism exists between the routes of the communications and power supply cables due to induction problems from the phase conductors. Due to the light weight and high strength to weight ratio very long spans (up to 1000 metres) may be achieved. The number of fibres is compatible with OPGW or wrapped cable designs, typically 24, but higher fibre counts are possible.

The fibres may be bundled, formed into ribbons or individually housed in loose buffer tubes or slots to provide adequate mechanical protection. The tubes or slots are grease filled to protect the fibres from water penetration.

Examples of all-dielectric self-supporting (ADSS) cables are illustrated in the following figures:

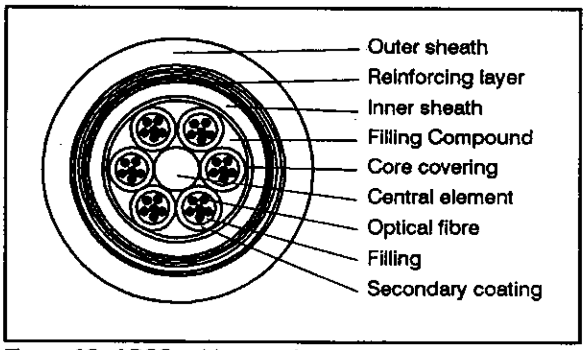


Figure 18 ADSS cable type A

Type A: Loose tube buffered fibres stranded around a Glass Fibre Reinforced Plastic (GFRP) core (inner sheath). Stranded (bundled) glass or aramid fibre yarns are applied beneath the outer sheath.

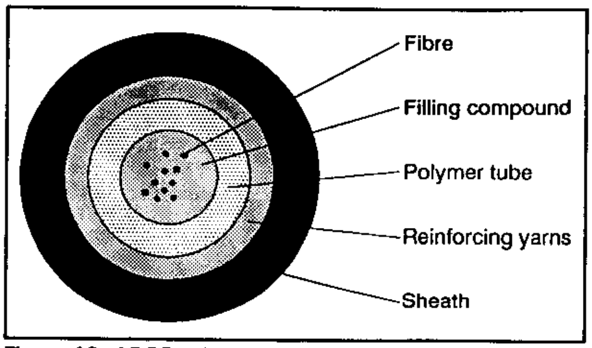


Figure 19 ADSS cable type B

Type B: This is a central maxi tube design with up to about 20 loosely housed fibres. By a special manufacturing process the fibres are incorporated with an overlength to avoid inadmissible fibre stress and thus stabilise attenuation under service conditions.

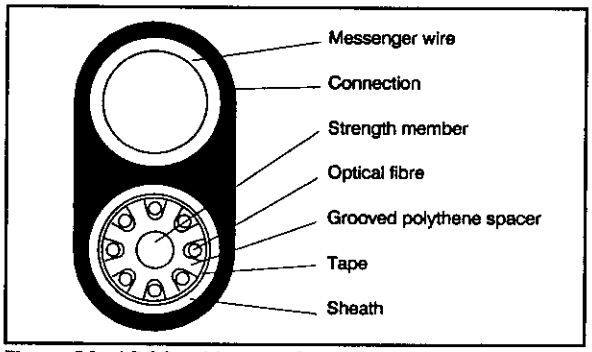


Figure 20 ADSS cable type C

Type C: GFRP, glass or aramid fibre messenger wire - optical bundle (loose tube or tight buffered) sheathed. Optical bundle clipped onto or stranded around messenger wire.

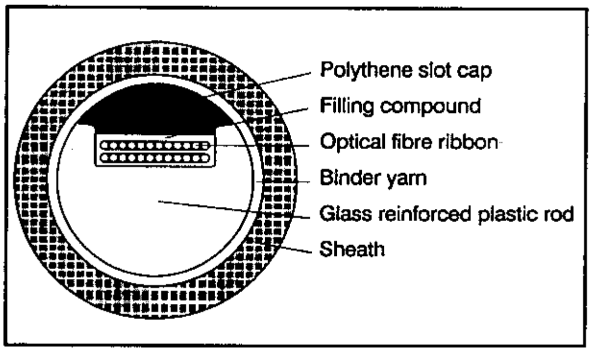


Figure 21 ADSS cable type D

Type D: Grooved or hollow GFRP rod with fibres inside outer sheath. This type of cable normally makes use of ribbon fibres and may contain up to three strips of ribbons.

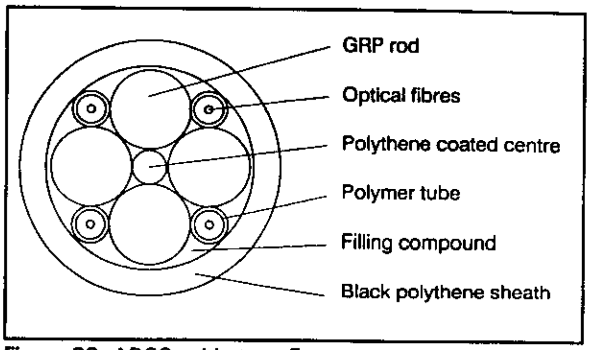


Figure 22 ADSS cable type E

Type E: GFRP rods and loose tube buffered optical fibre cable stranded together inside the outer sheath. This design offers a very flexible construction and is suitable for installations requiring small radius turns.

Operating conditions:

The operating conditions are almost the same as for attached cables. These cables also have to withstand aeolian vibration and possible galloping and touching the phase conductors. This cable and the attached cables are also quite vulnerable to vandalism and game shooting.

A particular phenomenon of an installed all dielectric self supporting cable is the 'dry banding effect'. This is due to the uneven drying of a dampened polluted cable where the electric stress is presented over the short distance of the dried part of the cable, causing local arcing and heating which may erode the cable sheath and strength member, leading to mechanical failure. See Section 3.10.3 *Maintenance of self-supporting cables* for ways to reduce this problem.

Installation and maintenance:

When selecting a suitable landing point on a support structure it is important to consider the following factors:

- Tower strength - In terms of bending and torque
- Clearance - Conductor/cable ground clearance taking into account ice loading where applicable. Clashing in high winds.
- Capacitively induced voltage.

All-dielectric cables, particularly when installed on lines in common with conductors carrying a supply voltage greater than 150 kV, are prone to sheath degradation. The extent of this degrading may be mitigated by the use of special sheathing compounds and by judicial placing of the cable between the phase conductors. It is recommended that the cable supplier or installer should provide data of the voltage stress applicable to the particular line in addition to providing evidence of the withstand performance of the cable.

During installation a prime concern must be to preserve the integrity of the cable sheath. It is therefore recommended that all dielectric cables are installed using the tension stringing method thus ensuring that the cable is not snagged or abraded along the ground. Adequate tension must be maintained at all times such that the pulling bond and cable are pulled through from support to support keeping them well clear of the conductors and other hazards along the route. As required scaffolding should be provided over obstacles such as low voltage lines, roads and railway lines.

The additional load on the supports may be as much as 25 kN dependent upon span length, sag limitations and worst predicted climatic conditions.

Installation and maintenance may be carried out, subject to correct safety procedures, without interference with the power system. In this respect self-supporting cables offer a minimal mean time to repair.

Splicing is normally carried out at ground level and the cable dressed up the support and housed at a height beyond the reach of the public. Alternatively the joint may be housed in an underground chamber.

In the event of cable damage the complete span must be replaced as mid-span joints are not practical or recommended.

Testing:

The cable and the associated fittings should be qualified for mechanical, electrical and environmental performance. These tests should include impact, abrasion, sheath tracking resistance, vibration, torsion stress and tensile performance. In addition it is particularly important that ultra-violet degradation performance is quantified as this may result in premature mechanical failure. Optical testing should be carried out on each drum length of cable supplied.

Economic considerations:

Self-supporting cables effectively separate the telecommunication and power supply systems, a particularly attractive feature when considering maintenance or repair to either system. With suitable planning, the cables can be installed without interference to the power supply. The life expectancy can be in excess of 25 years.

3.4.4 Bundle sub-conductors

Construction:

It is a new idea to place the optical cable inside a bundle conductor, as shown in **Figure 23**. The construction of the optical cable is the same as that for attached cables. Special spacers are required at regular intervals to maintain the position of the optical cable along the power line. This solution also requires the use of an optical insulator bushing similar to that show in **Figure 32** for the phase-to-ground termination of the cable.

The usage of this type of solution is not common today and only one experimental installation is in operation. Field tests have shown that there is no subspan oscillation of the cable due

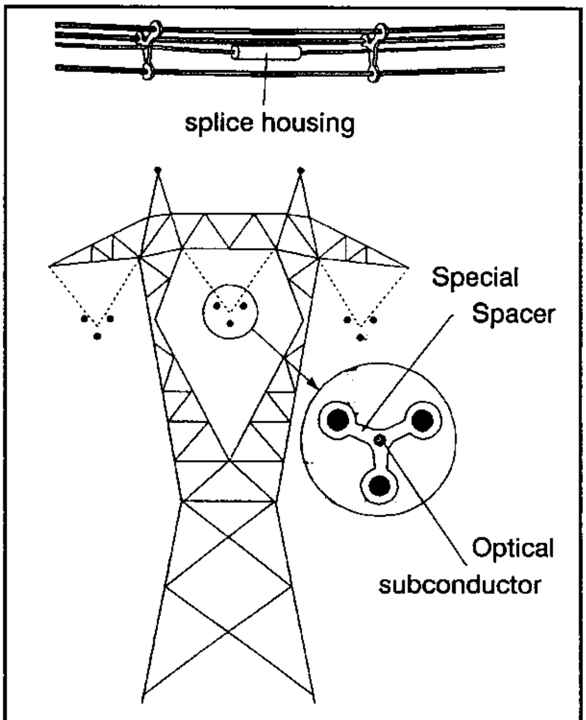


Figure 23 Example of optical cable inside a three-conductor bundle

to the wind and that the level of aeolian vibration is very low. Cable diameters of not greater than a third of the diameter of the bundle conductors are used and they cause no significant increase in the wind and ice loads on the towers. The cables must withstand the clash with a conductor of the bundle during short-circuit conditions; the dielectric cables are prone to sheath degradation, as are self-supporting dielectric cables.

Operating conditions:

Same as for attached cables.

Installation and maintenance:

Special spacer dampers are used every 60 m to keep the optical cable in the middle of the bundle. Midspan joints are used. If the cable is damaged the whole span should be replaced or mid-span repair joints used.

Testing:

As for attached cables.

Economical considerations:

This technique is suitable for existing lines. It is designed for bundle type conductors where wrapping type cables cannot be used and the cost of reinforcing (as in self supporting cable) the cable can be avoided.

3.4.5 Underground duct and direct buried cables

Construction:

In general, underground duct cables (a duct can be made of concrete, earthenware or high strength polymer) consist of an optical fibre bundle, either loose or tight buffered. A moisture barrier polymeric sheath is then applied overall. The moisture barrier sheath normally consists of an aluminium foil applied longitudinally with an overlap and bonded to an extruded polymeric sheath. Cables may be pulled or blown into ducts and must have sufficient tensile strength to allow installation without imposing undue strain on the optical fibres. Such tensile performance is provided by including strength members in the cable design. Strength members may be metallic or, where electrical considerations demand otherwise, non-metallic. The following types of strength members are common: steel wires, fibre (glass, aramid or others) reinforced plastic (FRP) rods, glass fibre yarns, aramid yarns, etc.

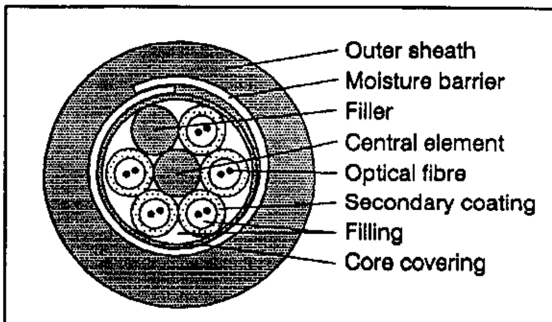


Figure 24 Underground duct cable

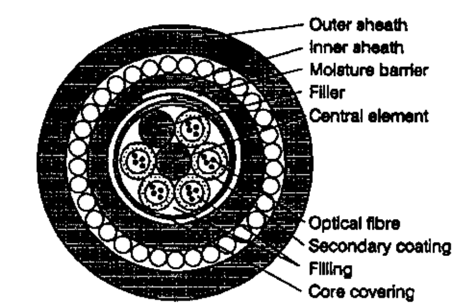


Figure 25 Underground direct buried cable

Direct buried underground cables are similar to duct cables with additional armouring or protection. The following methods are in use to provide the mechanical protection required:

- Helically wound steel wires
- Longitudinally applied (corrugated) steel tape
- Helically wound steel tapes

Underground cables must exhibit a high degree of resistance to the ingress of moisture. This moisture can be present in many forms ranging from the extremes of a flooded duct system to the less severe situation of a cable being located in a region with high atmospheric humidity. In either case, provision must be made to ensure that water cannot penetrate or permeate through the cable elements and reach the optical fibres where it could cause severe damage.

A high level of moisture protection is provided by the use of water blocking compounds such as petroleum jelly, thixotropic gel, grease or compounds that swell in the presence of moisture. It is also possible to stop the longitudinal ingress of water by waterblocks or by swelling tapes.

Operating conditions:

The operating conditions for underground cables are varied and the network operator must ensure that the cable supplier is fully aware of the local conditions. The following is a list of conditions but may not be exhaustive.

Temperature: Typically the operating range for underground cables is -30 °C to +70 °C.

Water: The presence of water or moisture in an optical fibre cable may cause severe deprecation in transmission performance or service life.

Lightning: In areas of known high lightning activity the cable core should be non-metallic. The sheath may incorporate steel tapes.

Electrical: Where there is a potential danger through fault or leakage currents the cable must be non-metallic or insulated.

Mechanical: For direct buried cables the crush and impact resistance is important.

Rodents: Steel or brass tapes are normally provided to prevent rodents gnawing through to the cable core.

Termites: In certain areas termite protection is required. A jacket of PA 12 extruded overall is the normal method adopted.

Hydrocarbons: Where cables are laid directly into polluted soil special sheathing compounds may be necessary.

Installation and maintenance:

Duct cables are pulled or blown into ducts. Blowing is only possible when the duct is a polymeric tube. Direct buried cables are generally laid in a trench to a specified depth and then back-filled with sand and other fine soil. They may alternatively be laid by mole-plough where the digging, laying and back-filling operations are carried out in a single mechanised process.

Testing:

The cables should be tested for optical performance, resistance to water penetration and mechanical performance including crush, impact and tension.

The water penetration tests are most important for these cables. Mechanically the crush test is also important and must be considered carefully, taking into account the type of terrain where the cable is to be used.

Economic considerations:

These cables are generally expensive to produce and therefore their use for an entire route length is uneconomic. In addition wayleave may be a problem. It is also important to carefully consider the degree of protection required from rodents and machinery, etc. Installation costs vary greatly dependent on ground conditions and are a major factor in determining overall project costs. It is for this reason that these cables are mainly used for substation approach routes where the lengths generally are very short.

3.4.6 Composite sub-marine cables

Construction:

These are otherwise normal sub-marine power cables, with fibre unit(s) integrated into their construction. In three-phase cables the obvious place is the space between phases. In one-phase cables (high voltage) the fibres can be embedded in a thin steel tube as a part of concentric wiring (usually copper strands).

Operating conditions:

The stable temperature and position of these cables once installed allows 1550 nm wavelength transmission. At this wavelength optical fibre cables are particularly sensitive to micro and macro bending and when planning any system this is a paramount consideration. Sub-marine cables must be sealed properly, eg. by lead sheath, to protect the fibres from moisture and hydrogen. It is important that the operating temperature be taken into account when specifying and designing the optical package.

Installation and maintenance:

The weight of the cable is a critical factor during the installation. The joints should be made at the factory and the condition of the fibres should be monitored during the installation. Otherwise the installation is similar to normal sub-marine power cable.

If the cable is damaged a certain length of the cable should be replaced. Lifting up the cable for repair is very expensive.

Testing:

The cable must be tested to ensure its withstand performance against the anticipated installation forces. Throughout these tests the fibres must be monitored for changes in attenuation. The cable must be tested for water penetration in addition to normal tests for submarine power cables.

Economic considerations:

Where a sub-marine power cable is contemplated in addition to the telecommunication cable, combining the two elements is a very economical solution. The power cable provides the required mechanical protection and the cost of dual installation, which is normally a significant part of the overall cost, is avoided.

Much of the manufacturing cost of an optical fibre cable is taken up by the expense of providing adequate mechanical protection for the optical fibres. In addition, the installation costs of a sub-marine system contribute a major proportion of the overall budget.

The power cable provides much of the required mechanical protection needed by the optical fibres when the optical package is included in the power cable. Additionally, the installation cost of a composite cable is only moderately greater than the installation cost of a dedicated power cable.

3.5 Cable fittings

3.5.1 Introduction

The principal requirements of optical cable compatible fittings are that the long term optical and mechanical integrity of the various cable types are maintained under service conditions.

Overall functional criteria for such fittings may be summarised as:

- Ease of installation with the possibility for error being minimised.
- Avoidance of concentrated clamping stresses to protect optical fibres.
- Accommodation of static and transient mechanical loads without damaging the cable or impairing optical performance (eg - wind and ice loading).
- Protection of metallic cables at support and tension points against lightning strikes.
- Mitigation of the damaging effects of wind induced cable vibration.
- Long term resistance to the degrading effects of environmental conditions and pollution. These effects in the presence of induced voltages may be particularly significant in the case of non metallic cables (ie: ADSS).

Design principles

For OPGW and ADSS cables, a number of solutions for the design of fittings are available based on experience gained with conventional conductors and cables. However, the paramount need to preserve optical as well as mechanical integrity has resulted in a number of important design changes to conventional fittings. Attached cables are not self supporting and rely on the host cable, therefore the fittings required must fulfil less onerous criteria than those for OPGW and ADSS cables and tend to be required predominantly for cable routings.

3.5.2 OPGW and ADSS cables

Termination

Tension grips made from factory preformed wire installed over preformed reinforcing rods offer a reliable grip without introducing concentrated clamping stresses and have been widely used on OPGW and ADSS cables with considerable success. In the case of OPGW cables, the use of preformed reinforcing rods is dependent on the number of layers of protective wires in the cable construction and the core design.

In the case of ADSS cables, the preformed solution is extensively used because ADSS is a very sensitive cable and maximum protection must be afforded to the polymeric sheathing and of course, the optical fibres.

Bolted clamps and helical preformed types, as shown in **Figure 26**, have been used on OPGW, and a combination of a conical 'dead-end' with preformed gripping rods has also been successfully used.

The use of bolted clamps on any cable carrying optical fibres must be approached with caution as any error during installation can lead to cable damage and functional impairment. Measures to prevent over-tightening such as shearhead bolts, slipping clutch torque wrenches and mechanical stops have been used with varying degrees of success.

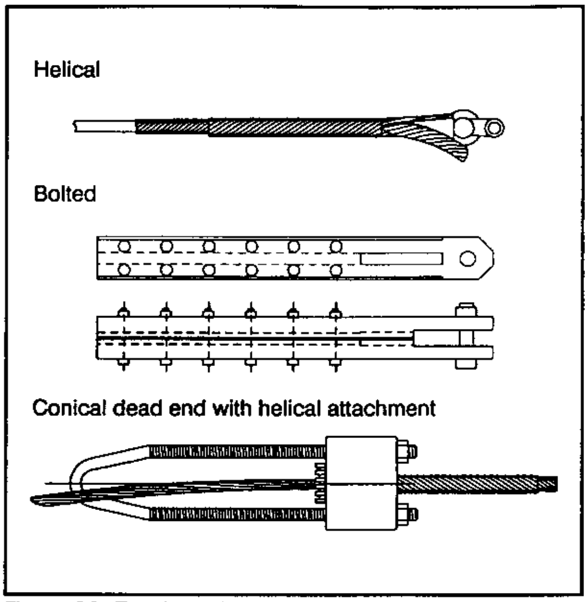


Figure 26 Tension grips

The installation of a mechanical fuse to relieve overloading of the cable has been considered as an additional safety measure.

Suspension

Conventional bolted clamps over preformed reinforcing rods (**Figure 27**) have been used on OPGW and ADSS. In the case of ADSS cable, an additional layer of preformed armour rods is used between the clamp and reinforcing rods to reduce bending and provide a 'controlled cable slip' characteristic in case of unbalanced loads if required. It should be noted that aging and weathering may change this characteristic over

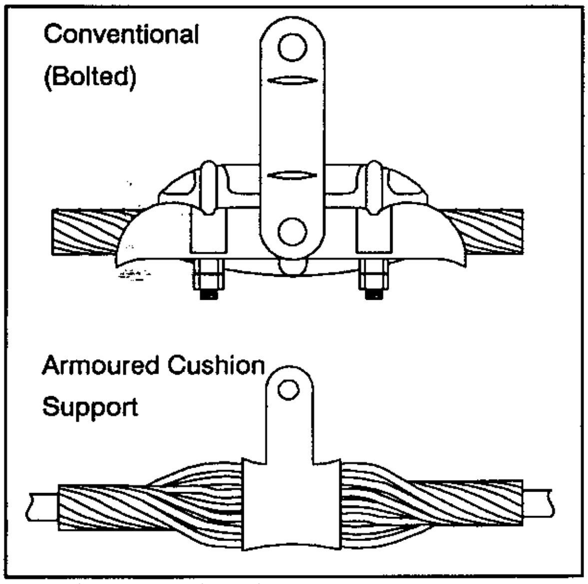


Figure 27 Suspension grips

time. Some Utilities, however, require the cable to be held under unbalanced load or broken conditions. The use of extended reinforcing rods also protects the cable against a lightning strike. The potential problems associated with bolted clamps and referred to above, should be noted.

The armoured cushion support (**Figure 27**) provides the maximum protection to both cable types. Reinforcing rods are applied directly on to the cable and carried in elastomer cushions. The whole assembly is secured by preformed armour rods and carried in aluminium housings and a strap. Concentrated clamping stresses are thus avoided and both static and vibration induced dynamic bending stresses are minimised. A controlled cable slip characteristic can also be provided if required by careful choice of the preformed rod characteristics.

Short spans

ADSS cable is sometimes strung on low voltage electrical distribution or telephone lines with short spans (usually defined as less than 200 m) and the resultant loadings are less than on longer spans. As a consequence, the associated fittings can be designed to a lower rating. The tension grips are often of the preformed type but may not necessarily be installed over reinforcing rods. The holding strength of the grips may be related to the maximum working tension of the cable with a safety factor rather than its breaking strength.

Suspension fittings may comprise metallic or composite dielectric material with elastomer inserts to cushion and protect the cable. Preformed reinforcing rods are not generally used, but a controlled slip characteristic can be achieved if required by careful design such that the closed diameter of the fitting is set by mating (machine tolerance) faces and is independent of clamping bolt tension. A typical short span suspension fitting is shown in **Figure 28.**

The cable may also be secured by preformed wires looped at the centre and suspended directly from the pole hardware via the loop.

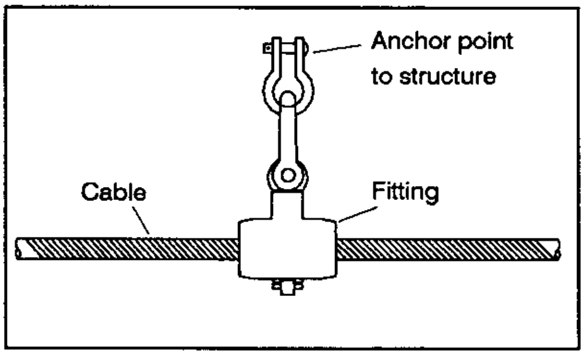


Figure 28 Typical short span suspension fitting

This fitting may not necessarily be installed over preformed reinforcing rods.

The application of vibration dampers to short spans is sometimes not considered to be as important as for long spans. They may be recommended for extra protection since high vibration levels have been reported in short spans. Appropriate damper types are discussed in *Vibration Damping* below.

Grounding connections

These are relevant for OPGW cables and are shown in **Figure 29**. A parallel groove clamp or wedgetap may be used but the design criteria must be such that a good grounding connection is not obtained at the expense of generating concentrated clamping stresses on the optical cable. The armour grip suspension clamp assembly can incorporate a grounding tap which is secured by the preformed rods. This grounding tap can also be used in other locations on the cable when special armour rods are

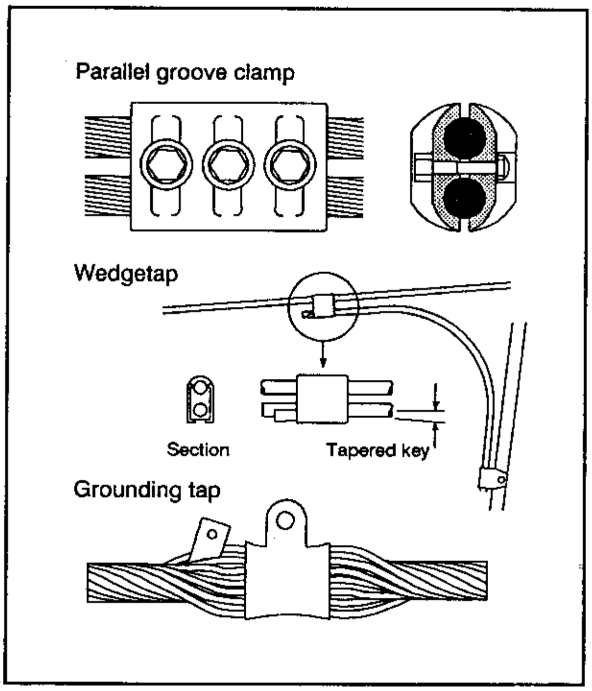


Figure 29 Grounding connections for OPGW

used to locate and fix it. Testing and operating experience has confirmed the efficiency of this technique.

Vibration damping

All overhead cables are subject to wind induced aeolian vibration which can cause damage to both cable and fittings as bending stress cycles are accumulated. The frequency of vibration is proportional to wind speed normal to the cable and inversely proportional to cable diameter. Therefore, for a given windspeed, smaller cables vibrate at higher frequencies.

The protection of optical cables and especially hardware fittings against vibration damage is of paramount importance and a number of methods have been used.

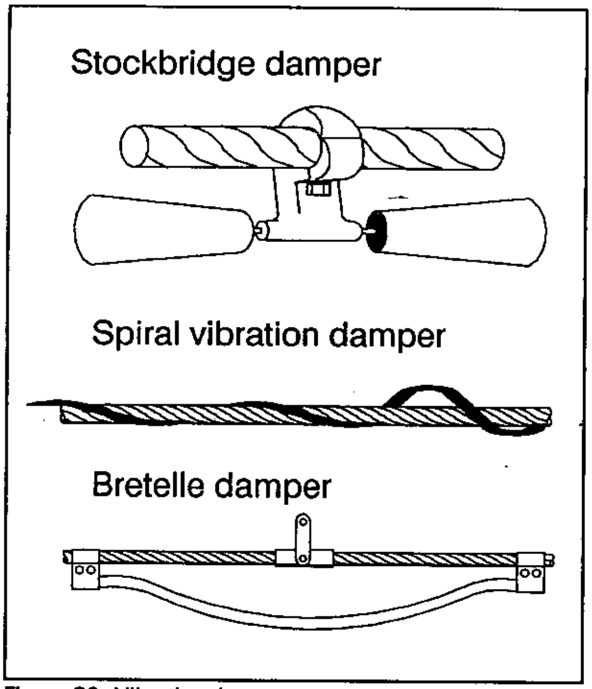


Figure 30 Vibration dampers

The stockbridge type damper and high performance multi-response variants (**Figure 30**) have been used on conventional conductors with success over many years. For efficient performance and maximum protection, damper dynamic characteristics must be carefully matched to those of the cable, which vary from design to design, and its positioning correctly selected. This is important in the case of optical fibre cables and particularly so for ADSS cable which vibrates at very high levels due to its low inherent self damping. This damper is normally applied over the preformed reinforcing rods of the termination and suspension fittings but has the inherent limitations of a bolted clamp fitting. The use of an elastomer lined clamp with preformed attachment rods has been proposed as an alternative means of attachment for this damper to sensitive optical fibre cable.

For cables up to about 18 mm in diameter, the Spiral Vibration Damper (SVD) (**Figure 30**) has been shown to be effective in controlling vibration particularly for ADSS cables. A polymeric rod is preformed such that a gripping section applied over the reinforcing rods of the tension and suspension fittings locates the

SVD, whilst a loose fitting helix extends over the cable and damps vibration by impacting. Experience and testing shows that the cable sheathing is not impaired or damaged by this action. The SVD is flexible in its application and does not have to be carefully matched to conductor or cable characteristics, nor is it location sensitive. The absence of bolted connections is a desirable feature, particularly for use on optical cables.

As previously indicated, in certain high voltage environments, generally above 150 kV, the level of induced voltage in the presence of pollutants can result in degradation of the SVD polymer. This, therefore, represents a present limitation in their use which may be overcome by the use of alternative, anti-tracking materials.

The bretelle damper (**Figure 30**) relies on the self damping of a bridge of untensioned cable across a suspension or tension point and has been successfully used on conventional cables for many years. In applying it to optical cables, care must be taken to avoid concentrated clamping stresses at the attachment points. Since the self damping of optical cables tends to be lower than conventional cables, particularly in the case of ADSS cables, lengths of conventional cable may need to be used for the bretelle bridge. Availability may be a problem since offcuts of cable during stringing are often used and this will not be possible in the case of optical cables.

It should be noted that instances have been reported whereby cable down leads within a tower have been damaged by vibration 'feedback' from the main span. This has been alleviated by clamping the free cable to the tower structure.

Galloping of overhead cables is a low frequency, high amplitude predominantly elliptical motion with the major axis vertical and is caused by aerodynamic forces generated by wind flow over unstable ice accretions on the cable. In extreme conditions, both cable, fittings and support structures can be damaged. Various devices are available which either change the dynamic characteristics of the cable or increase aerodynamic damping to reduce galloping and these have been used with varying degrees of success. However, concentrated dynamic stresses can be imparted to the cable via the attachment points which are undesirable in the case of optical fibre cables. These devices are usually fitted on line sections when galloping has occurred. An alternative is a preformed Air Flow Spoiler (**Figure 31**) which is overlaid on the cable and retained by preformed gripping sections. This has been effective on smaller conductors and jacketed cables, but is subject to the same high voltage limitations as the SVD. However, experience to date is limited but suggests that ice related galloping has not been a major problem on circular optical fibre cables, although 'figure 8' cables may prove to be more prone to galloping.

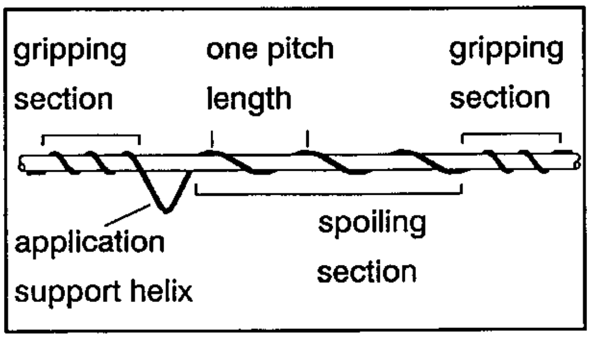


Figure 31 Air flow spoiler

Testing and installation

Testing of optical fibre cables should be carried out with the fittings to be used to ensure that both mechanical and optical integrity are maintained under specified design conditions. New standards are required since existing standards only deal with mechanical and electrical testing.

It is particularly important that every possible safeguard is introduced into the design and manufacture of fittings to ensure that the potential for cable damage during installation is minimised.

Preformed fittings should be correctly sized to the cable in question whilst bolted and wedge clamps should have smooth, correctly sized bores and safeguards should be introduced to prevent overtightening of bolts. All fittings should be free from sharp edges and corners which could inadvertently damage the cable.

3.5.3 Attached cables

All attached cables require fittings for cable routing and other purposes. The wrapped cable system (**Figure 16**) is the most commonly used type and has the advantage of minimising the number of fittings required since the cable is wrapped on the host cable.

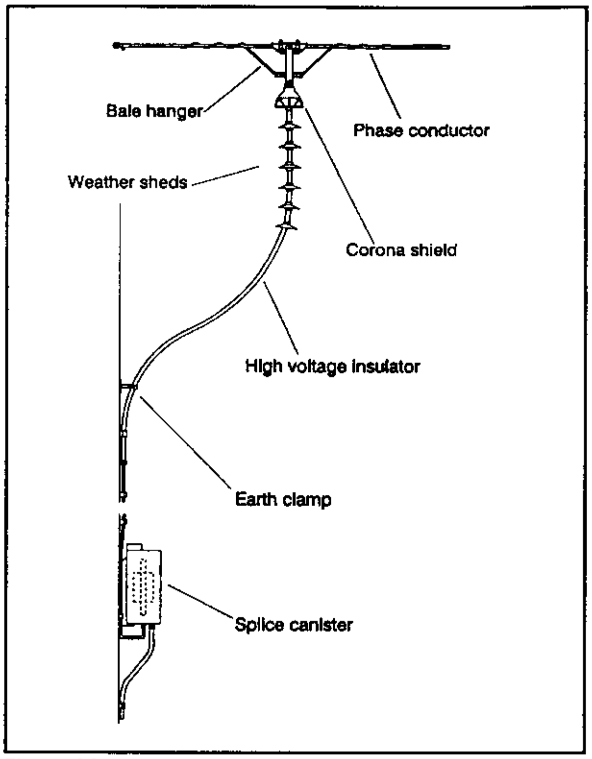


Figure 32 Phase to ground termination

The principal functions of the fittings are to:

- Route the cable around both pole and tower locations and obstructions such as vibration dampers as shown in **Figure 33** and **Figure 34**.
- Enable splices to be attached on the host conductor cable as shown in **Figure 34**.
- Provide phase-to-phase transitions (for example, to keep on the bottom phase of a phasewire installation when the cable is being routed across a transposition tower).
- Provide phase-to-ground transitions (for example, to route the cable to ground at the ends of a phasewire installation), shown in **Figure 32**.
- Provide ground-to-ground transitions (for example, to route the cable to ground at the ends of an earthwire installation).
- Enable splices to be housed at the base of a tower or pole (for example, at the ends of an installation).
- Enable the cable to be properly terminated in the terminal building.

A fitting often contains a number of items and therefore they are organised in kit form.

The protection of the cable is of paramount importance and the fittings must be designed to avoid abrasion and where possible, to accommodate the cable in a protective groove secured by a helical lash.

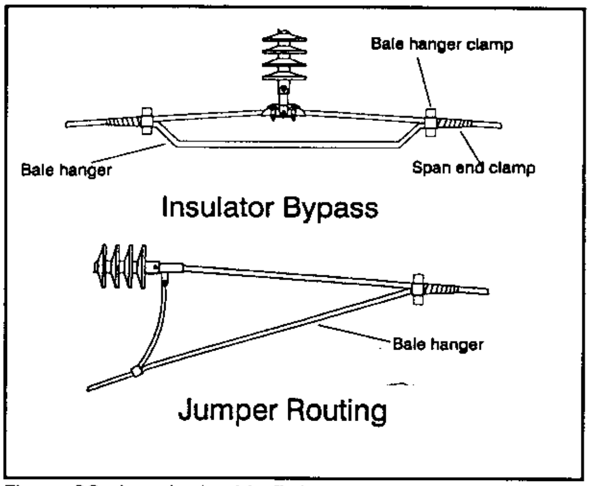


Figure 33 Attached cable fittings

Bypassing the tower top or other obstacles is achieved with the use of 'balehangers' as shown in **Figure 34**. These can be constructed from either plastic or metal dependent on their intended location (earth or phase).

Optical cables which are externally attached to overhead power line earth wires via spaced clips or a continuous lash are not common today but do utilise a similar method of by-passing tower tops and obstacles to that used by the wrapped cable systems.

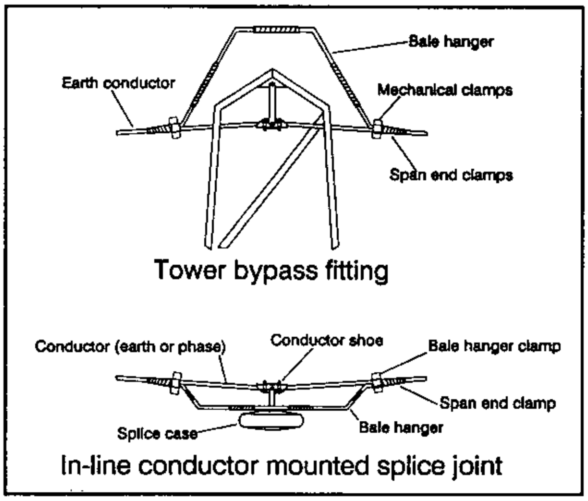


Figure 34 Attached cable fittings and splice housing

In the case of the lashed cable system, a small diameter metal wire is lashed helically over both the optical cable and earthwire. In the case of clipped externally attached systems, small 'C' type metallic clips or clamps are compressed onto the earthwire, supporting the optical cable, at 3-5 metre spacings.

3.6 Terminating Equipment

3.6.1 Fibre optic line terminals

For communication purposes, a multiplexer requires a line terminal suitable for the transmission medium (copper metallic, fibre optic) and for the transmission speed. In addition to the optical transmitter (Laser, LED) and the optical receiver (PIN, PINFET, APD), both dependent on the attenuation to be spanned, an optical line terminal comprises a line encoder suitable for the fibre optic transmission medium on the transmit side and a line decoder and regenerator on the receive side.

The optical line terminal equipment can be located separately from the multiplexer section. In this case, an additional line terminal for copper cable with HDB3 coding is required for transmission between the multiplexer and the optical line terminal. However, in units for Power Supply companies, the optical line terminal is usually mechanically integrated in the same slide-in unit, thereby eliminating the need for a special copper line terminal as, shown in **Figure 35.**

Optical semiconductor technology can still be regarded as a new and developing technology. Nevertheless, a whole range of standard components has already evolved, use of which can be recommended without reservations. However, in order to maintain good transmission performance it is vitally important that the receiver has a large signal dynamic range with a high saturation level. It goes without saying

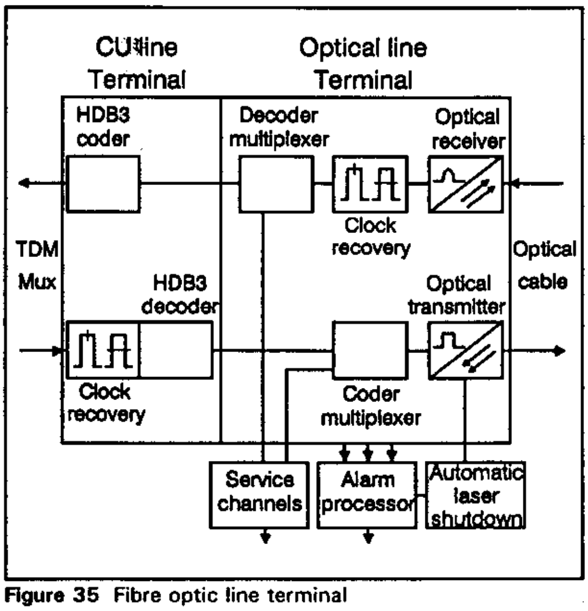


Figure 35 Fibre optic line terminal

that the receiver must be stable when operating near optical limits, but it is surprising how many examples fall short of this requirement.

In 'frontier' areas, eg., with very high optical output powers, they are still at the development stage. The question as to whether further developments of optical components, eg. integrated optical components, can be used economically by power supply companies depends to a very large degree on the use of such components by international telecom authorities. With their sometimes very large unit numbers, eg., for TV distribution, these authorities determine both prices and technology.

Optical line coding and supervision

The data signal from the time-division multiplexer, consisting of a random series of ones and zeros, is re-coded in the line coder of the transmitter section such that through a more frequent signal change the clock and data can be optimally recovered in the receiver even when the optical input powers are low. Apart from when a scrambler is employed for the NRZ code of the multiplexer, re-coding results in an increase in transmission speed. At the low bit rates up to 34 Mbps currently employed by the Power Utilities, a doubling of the modulation rate - as occurs with the frequently used RZ codes Manchester, CMI and similar - is generally tolerable. For higher bit rates, use is made of nB/mB codes (5B/6B, 7B/8B), in which a further bit is added to the n useful bits in accordance with a specified alphabet.

Supervising the output power of the optical transmitter and the input power of the optical receiver is helpful in localising a possible fault. The Bit Error Rate is monitored to allow better assessment of the quality of an optical transmission link. It is usual to have several thresholds for different Bit Error Rates. The violation of code rules is an indication of error accumulation, for instance.

Present designs of line equipment have auxiliary channels that can be modulated by means of phase shift keying, for instance, or subsequently multiplexed. They remain available even when the mainstream data signal performance has deteriorated. These auxiliary channels can be incorporated in supervision and service functions in various ways, eg. for service telephone signals, for in-house monitoring and for test loops. The functions can be controlled and read out via a telecommunication maintenance network. Auxiliary channels are also offered for customer applications where large additional capacity is required. With their help, services such as one or several protection channels can be transmitted with higher than average reliability.

Optical transmitters

In a light-emitting diode (LED), the light is generated by spontaneous emission. Surface emitters have gained importance for the first (850 nm) and second windows (1300 nm), while the edge emitter is mainly used for the second window. Refer to Figure 36.

In a surface emitter, light is emitted perpendicular to the pn transition and is uniformly distributed in the hemisphere. Approximately 10 μW output power with a spectral half-power width of 120 nm can be launched into a graded-index fibre (50 μm). Surface emitters can be used to form extremely economical transmitters which, combined with the similarly inexpensive PIN receivers, can only be used for short distances, ie. communication within substations. However, if more sensitive receivers (PINFET) are employed, line attenuations of up to approximately 30 dB can also be spanned at low bit rates (2 Mbps).

Edge emitters are more suitable for communication between stations. Their light emission is perpendicular to the layer structure as with lasers. Edge emitters feature a more concentrated beam. The spectral half-power width of 70 nm at 1300 nm is much narrower than in the case of the surface emitter. Edge emitters can launch up to 100 μW into graded-index fibres and up to 10 μW into singlemode fibres.

Both the bit rates and distances spanned can be increased if laser diodes (LD) are employed. For communication between substations, the LD is increasingly taking the place of LEDs, because they are suitable for all transmission rates and launch sufficient optical power into singlemode fibres for effective systems.

Bitrate (Mbps)	2	8	34	140/ 155	560/ 622
Transmit level (dBm)	-4	-4	-4	-4	0

Table 3 Laser diode launch powers verses transmission bit rates

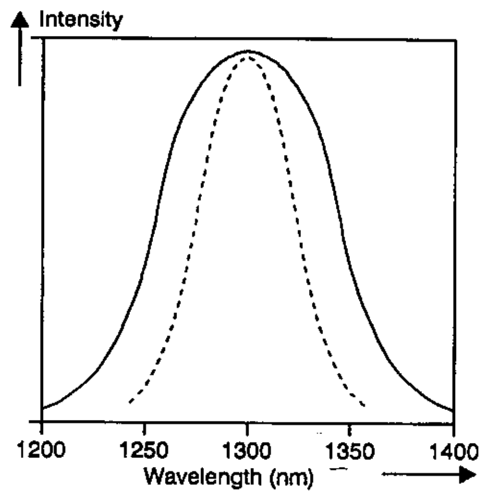


Figure 36 Spectra of light emitting diodes

Laser diodes

The laser diode is essentially a light-emitting diode (normally an edge emitter) with a wavelength-selective element - in the simplest case a Fabry-Perot cavity consisting primarily of two plane-parallel semitransparent mirrors. This cavity causes the intensity of light of identical wavelength and phase to become large even at low overall light intensity, so that stimulated emission begins at low injection current. Light Amplification by Stimulated Emission of Radiation (LASER) provides a higher light output power and improved collimation of the radiated light. The emitted spectrum is considerably narrower than that of the LED so that chromatic dispersion in the fibre is lower. The emitted spectrum of a customary Fabry-Perot laser diode is shown in **Figure 37**. These LDs are normally used for transmitters in Power Utilities (bit rates ≤140 Mbps and distances usually <100 km).

For high-bit-rate long-haul fibre optic systems LDs with distributed-feedback (DFB) are very important. Their major advantage in such applications, in comparison with Fabry-Perot LDs, is single-wavelength operation, resulting in lower bit-error rate at higher modulation frequencies. With these devices fibre dispersion is less of a performance limitation. DFB LDs are complicated to make. A feedback grating must be built into the semiconductor structure. These LDs lase in a single longitudinal mode over a wide range of currents. (See **Figure 38**)

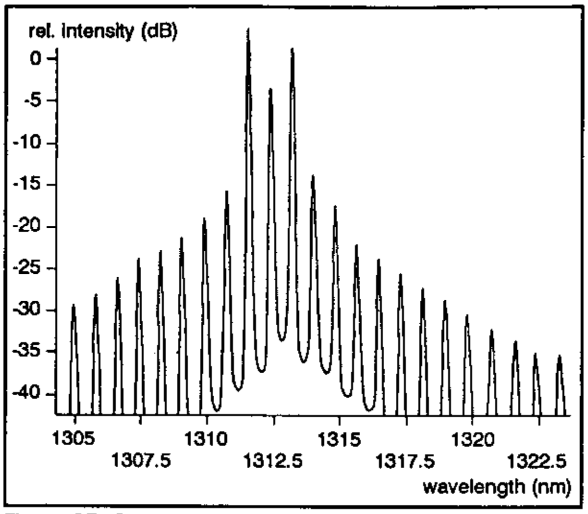


Figure 37 Spectra of Fabry-Perot laser diode

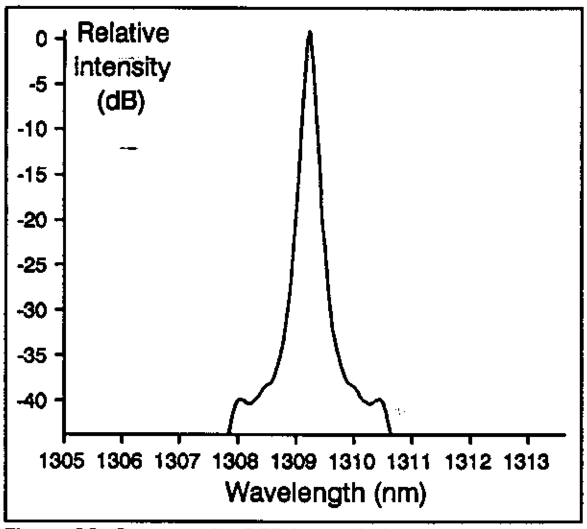


Figure 38 Spectra of a DFB laser diode

Non-linearities or 'kinks' in the light-current characteristics can severely limit the usefulness of LDs as sources in fibre communication systems because they are usually associated with higher order mode transitions and spectral broadening.

Line terminating units with LD transmitters should contain an automatic laser shutdown unit in order to prevent danger to personnel by emergent laser light (due to interruption at the optical cable terminal rack, or fibre breakage).

Optical receivers

Silicon PIN (Positive Intrinsic Negative Diode) photodiodes are used as optical receivers at wavelengths of 0.8 to 1 μm, while InGaAs has proven to be the most suitable material for the range from 1 to 1.6 μm.

Depending on the optical input sensitivity, the following receiver principles are employed:

PIN receiver

With the least complex receiver circuit, typical input sensitivity levels of approximately 34 dBm are obtained in the first and second windows with the bit rates of 2 to 34 (and in some cases 140) Mbps used by power supply companies. As already mentioned, this receiver is usually used together with a surface-emitter LED for local connections. In conjunction with a laser transmitter, this receiver circuit can also, however, be employed for interstation communication.

PINFET receiver

In this receiver for the second and third windows, the PIN photodiode is integrated in transimpedance or high-impedance circuits together with an amplifier with input FET or is designed in hybrid technology.

With the receiver principle employed for the above mentioned bit rates, typical input sensitivity levels of -53 dBm are obtained at net bit rates of 2 Mbps and -47 dBm at 34 Mbps.

APD receiver

With the more complex receiver incorporating an avalanche photodiode APD, the optical input sensitivity for wavelengths of 1300 and 1500 nm is increased in comparison with the PINFET receiver by approximately 3 dB.

Bitrate (Mbps)	2	8	34	140/ 155	560/ 622
Receive level (dBm)	-50	-45	-40	-38* -40+	-34* -36+

Table 4 Sensitivities versus transmission bit rate for PINFET and APD receivers

* = 1300 nm + = 1550 nm

3.6.2 Multiplexing

Overview

The basic function of multiplexing is to allow different signals to be transmitted over the same physical media at the same time. Three different methods of multiplexing electrical signals over an optical fibre can be considered:

- Wavelength division multiplexing (WDM).
- Time division multiplexing (TDM).
- Frequency division multiplexing (FDM).

In wavelength division multiplexing, several optical sources emitting at different wavelengths are coupled into the same fibre.

On the receive side, the combined signal is demultiplexed by wavelength sensitive devices, such as diffraction gratings, spectral filters, etc. This approach, however, relies on not yet fully field experienced technology and needs high performance and correspondingly expensive elements. Therefore it is not used to multiplex individual low capacity signals on interstation communication systems. Its application is justified when a high capacity TDM fibre optic system is still not sufficient, and when the inherently higher capacity of modern fibres has to be made available.

Frequency division multiplexing is related to analogue transmission systems. In the past, some analogue transmission systems using optical fibres have been realised. This may be justified by compatibility reasons in a completely analogue network. In such systems multiplexing is then done by analogue frequency division multiplexing.

In most applications, however, technically well established time division multiplexers are used. Such multiplexers are also economically optimum solutions thanks to highly integrated digital technology.

Interstation communications systems are often part of a communications network. In public telecommunication networks, the nodes are mostly realised by switching equipment, and the function of the multiplexers is then limited to multiplexing usually high channel numbers for transmission and to interfacing the switching equipment with the transmission equipment. In private networks, such as in power system communications, switching equipment in some nodes is provided for one or several different applications (telephone network, different data networks, etc.). Some nodes however are too small to justify switching equipment. The network node function has then to be implemented by the multiplexer. Thus, the multiplexer in a Power Utility private network has to cover the following different functions:

- Adaptation of user signals to digital network.
- Multiplexing of user signals for higher speed transmission.
- Dropping and inserting of signals as well as branching at intermediate locations.
- Cross-connection of signals in nodal points.
- Protection switching between alternative paths.

Digital networks with such nodes are dealt with in detail in the CIGRE document *Guide for Planning of Power Utility Digital Telecommunications Networks* (SC35 WG02) [3]. Often the multiplexer is considered part of the terminal equipment, and sometimes it is even mechanically integrated in the same piece of equipment as the fibre optic line terminal. It is therefore justifiable to include some aspects of digital multiplexers in this guide, in order to provide the reader with a complete view of the entire fibre optic communications system.

The principle of TDM

The high rate data stream on the transmission line is divided into frames of constant length. The information contained in a particular position relative to this frame structure is always allocated to the same channel or timeslot. In **Figure 39**, seven channels are multiplexed in a frame of eight timeslots. The remaining timeslot, S, is used to retrieve the frame structure at the receiving end of the link (frame synchronisation). Every channel is sampled once per frame and always transmitted in the same timeslot of the frame. Eg. channel four is always transmitted in the fifth timeslot of every frame.

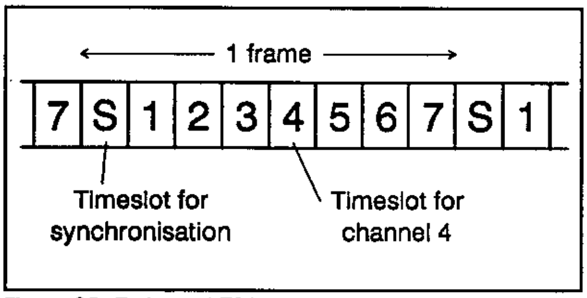


Figure 39 7 channel TDM multiplexing

The synchronisation overhead, ie. the capacity used for synchronisation and not available to the user, depends on the frame length and the required synchronisation performance. Short frames allow short synchronisation times, but need more synchronisation overhead. If the synchronisation process has to be improved, eg. in order to be safe against standing data patterns, additional means, such as CRC4-coding or special synchronisation patterns may be provided.

If a timeslot consists of one bit, then the method is called bit interleaving. If a timeslot consists of eight bits, then the method is called byte interleaving. As an example, standardised 2 to 8 Mbps multiplexers use bit interleaving, and standardised 30 channel 2 Mbps multiplexers use byte interleaving. This is convenient for PCM voice encoding, where eight bits are used to code one sample of the voice signal. The frame structure of the standardised 2 Mbps multiplexer is given in **Figure 40.** 16 consecutive frames form a multiframe, consisting of 512 bytes each.

In fast digital systems, it can be difficult to synchronise all multiplexed channels fully with the high bit rate line signal. Non fully synchronised systems are called plesiochronous. In order not to loose information in plesiochronous systems, spare bits can be inserted or deleted in case of a bit slip (positive or negative justification). Eg. standardised 2 to 8 Mbps multiplexers multiplex four plesiochronous bit streams of 2048 kbps nominal rate into one plesiochronous bit stream of 8448 kbps nominal rate.

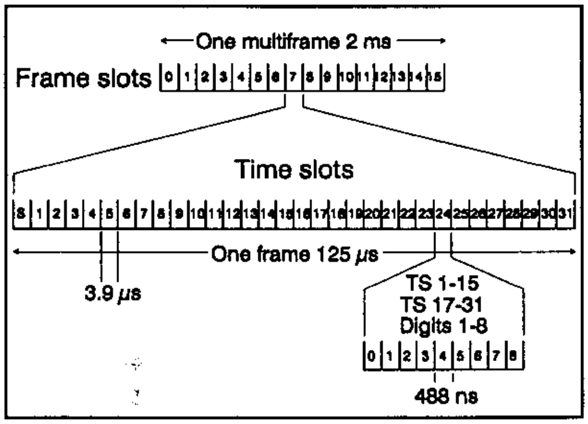


Figure 40 Frame structure of 2 Mbps multiplexer

If the allocation of channels to timeslots is fixed, a virtual transparent channel is available at all times for the connected application, irrespective of real data to be transmitted. The transmission delay of the channel due to the multiplexing process is a constant value and usually very small. In order to improve the use of the communication link, the allocation may be dynamic, offering more capacity to channels needing this capacity, while 'stealing' it from idle channels. Such dynamic multiplexers may be used for uncritical data transmission applications, but for real time applications in power system communications, such as teleprotection, a fixed allocation multiplexer is a must to ensure a defined constant delay.

3.6.3 The traditional multiplexing hierarchy

The traditional multiplexing hierarchy is based on plesiochronous interconnectivity. This allows each of the multiplexing levels to be asynchronous with each other where allowances are made for bit slipping to compensate for timing clock differences. However the level 1 multiplexer operates in synchronous mode.

In order to get a set of standardised hardware building blocks that can be used in different applications, the multiplexing of user signals to high rate transmission signals is done in hierarchical steps. This hierarchy is standardised in CCITT recommendation G.702 as shown in Table 5.

Hierarchical transmission bit rates (kbps)			
Level	Version 1	Version 2	Version 3
	64	64	64
1	1544	1544	2048
2	6312	6312	8448
3	32064	44736	34368
4	97728		139264

Table 5 Various standard transmission hierarchies

Version 1 is mainly used in Japan, version 2 in North America and version 3 in the other countries. On optical fibre links, even higher bit rates, such as 565 Mbps or 2.5 Gbps are used. For many applications in power system communications, line bit rates of 2 Mbps, 8 Mbps or 34 Mbps are the most popular ones and are fully sufficient. Up to hierarchy level 1 all bit streams are fully synchronised, the higher levels are plesiochronous. A typical realisation of hierarchical multiplexing is given in **Figure 41.** A 34 Mbps system is only partially used, the unused capacity (three 8 Mbps timeslots) is for

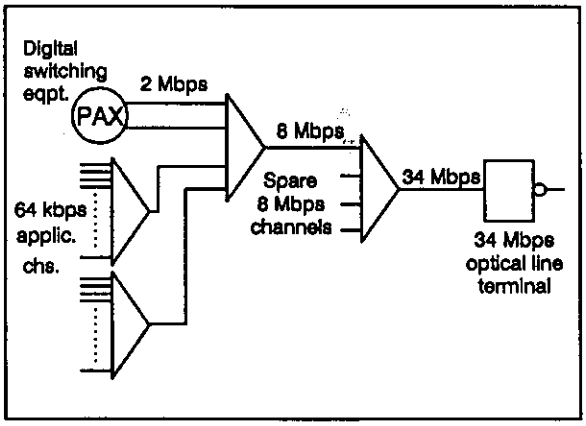


Figure 41 Typical 34 Mbps hierarchical system

future applications. Between every hierarchical level a specific multiplexer is used. In some applications it may be worthwhile to cover two hierarchical steps with one multiplexer, eg. with a 2 to 34 Mbps multiplexer. In the case where sharing a fibre with a third party is considered, high capacity line terminals of 140 Mbps or even higher may be appropriate, although only a small part is needed by the utility itself.

The lowest level of this hierarchy is 64 kbps. This serves well many applications, eg. transmission of the standard 4 kHz gross bandwidth analogue telephone channel. For other applications, such as slow data transmission for telecontrol, much lower data rates are satisfactory. It is then reasonable to sub-multiplex the 64 kbps channel into several slower data channels. This can be done according to appropriate CCITT-standards, eg. X.50, X.51, or using proprietary methods when sub-multiplexing is offered as an integral part of the multiplexer. Some applications have special requirements (eg. fully speed transparent asynchronous data channels, teleprotection commands), so that the multiplexing method has to be adapted to these requirements.

For special applications, eg. video encoding, intermediate bit rates, eg. 384 kbps, are used. This lower data rate video channel does not provide a broadcast quality service as described in Section 3.2.4 *Services and interfaces* but is suitable for confravision and surveillance applications. In future, the Synchronous Digital Hierarchy may be used, offering fully synchronous transmission for all data rates. A main advantage of these systems is the ease of extracting individual timeslots from high speed data streams, so avoiding long multiplexer chains. This new hierarchy can be easily interconnected with the plesiochronous hierarchy using the standard interfaces 2 Mbps, 8 Mbps, 34 Mbps, etc.

3.6.4 The Synchronous Digital Hierarchy (SDH)

For future high capacity digital communication systems, based on fibre optic technology, the new Synchronous Digital Hierarchy has been standardised by CCITT. This development is driven by the ever increasing capacity demands in public networks, mainly for the upcoming broadband services (broadband ISDN for videophone, high speed computer links, etc.).

In the SDH, the following hierarchical levels, so called synchronous transport modules (STMs), have been defined:

- STM-1 : 155 Mbps
- STM-4 : 622 Mbps
- STM-16: 2488 Mbps

A next level, STM-64 with four times the capacity of STM-16, is currently in the standardisation process.

Plesiochronous data signals of the traditional hierarchy can be packed in an STM-1 synchronous module in the following ways:

- 1 x 140 Mbps signal
- 3 x 45 Mbps signals
- 3 x 34 Mbps signals
- 16 x 8 Mbps signals
- 21 x 6 Mbps signals
- 63 x 2 Mbps signals
- 84 x 1.5 Mbps signals
- any combination of the above signals

The SDH presents the following main advantages as compared with the traditional multiplexing hierarchy:

- Drop, insert and direct branching supported on any level.
- Simplified hardware structure (no demultiplexing needed to access individual channels).
- Network management functions integrated in the system (sufficient overhead built in for network management data transmission in the frames).
- Existing plesiochronous data can be bound into SDH without a need to synchronise it.
- Standardised optical line interfaces for STM-1, STM-4, STM-16.

Different typical building blocks have been standardised, eg. an STM-1 terminal multiplexer with G.703 plesiochronous input signals, STM-1 drop/insert multiplexers, STM-1 cross connect node equipment and others. These building blocks allow use of the new architecture as an overlay high capacity network carrying the individual lower capacity plesiochronous channels (on a 140 Mbps, 34 Mbps or 2 Mbps level, etc.).

Synchronous operation is, as shown above, most advantageous for future high capacity transmission networks. From the point of view of the new broadband services (broadband ISDN) synchronous operation is not really required. It can be shown that for the switching equipment in the broadband ISDN an asynchronous, packet-like transmission mode is easier to handle and implement. Therefore, the

Asynchronous Transfer Mode (ATM) has been standardised by CCITT for broadband-ISDN services. ATM and SDH are the two main technological aspects in future public broadband networks. ATM cells can be integrated into SDH-modules as well as conventional plesiochronous channels.

ATM and SDH belong to a concept for very high capacity networks and are not yet fully developed and available. It is attractive for Power Utilities only, if the offered capacity is really needed. Low capacity networks are still based on the traditional multiplexing hierarchy. If in future SDH channels are implemented, the low capacity networks can without any problem be integrated in the new SDH network.

3.6.5 Multiplexers for public and private networks

Power Utilities evaluating multiplexers for fibre optic links have two basic options:

- Use of standard multiplexers built for public networks: This choice has the advantages of lowest cost and compactness (if just the multiplexer is considered). Other inherent benefits will occur when using identical equipment as PTT companies in the same country. These multiplexers are usually designed in slimline design practice.
- Use of multiplexers primarily designed for private or even power system communication networks: Such multiplexers are mostly covering the hierarchical level 1 (64 kbps to 2 Mbps-multiplexing), some even integrate higher multiplexing levels, eg. the 8 Mbps-level. These particular multiplexers have the advantages of more networking flexibility (they may serve as network node with drop/insert, branching and cross connect facilities. Signal cross connections are needed in all larger network nodes. Channels need to be rearranged between incoming and outgoing links. Traditionally this has been done by demultiplexing all the signals down to channel level and then cross connecting the signals in distribution frames. New possibilities for cross connections in digital networks are offered by digital cross connect systems, enabling cross connections without demultiplexing. Digital cross connect systems have 2 Mbps standard interfaces and they rearrange channels between 2 Mbps streams. Typically a small size digital cross connect system may have between 64 kbps and 2 Mbps interfaces. Systems with higher numbers of 2 Mbps ports are also available. Usually cross connections are done at 64 kbps level, but lower or higher bit rates are also possible. This cross connect function is usually software controlled, allowing dynamic allocation of capacity. Remote software control still increases the network flexibility, and allows better use of short transmission capacity, which, however, is normally not a problem in fibre optic systems.

Multiplexers particularly designed for private or even power system communication networks may have further advantages:

- Service specific interfaces integrated into the equipment.
- Individual channel interface cards.
- Submultiplexing cards offering still more flexibility.
- Protection switching in different schemes.
- Robustness against harsh environments.
- Choice of different supply voltages, with galvanic isolation.
- Integrated optical fibre terminals.

The higher cost relative to multiplexers for public networks may be justified and compensated by the mentioned advantages.

3.6.6 Adaptation of user signals

Taking into account the different applications for which telecommunications systems are in use today in power companies, it is a clear requirement for new systems to be able to adapt these signals to the standard bit rates and interface signals, eg. 64 kbps or 2 Mbps. This adaptation covers a lot of aspects:

- Adaptation of analogue signals to digital interfaces.
- Adaptation of electrical parameters (voltage, current, impedance, etc.).
- Adaptation of different timing schemes.
- Adaptation of isolation level and the EMC performance.
- Mechanical adaptation.
- Adaptation to redundancy and fail safe requirements.

This adaptation may be carried out by special equipment inserted between the digital multiplexer and the application circuits or by interface cards directly integrated in the multiplexer. In the latter case, savings may be realised due to less space being needed and the absence of additional power supplies, tiers, etc. Part of the adaptation function may also include specific multiplexing of several user signals into a standard 64 kbps or 2 Mbps data stream. This would be the case if several low speed asynchronous data signals had to be adapted to a synchronous 64 kbps data stream.

The following power system applications require such adaptations:

- Analogue telephone signals with different signalling criteria (eg. for PAX-PAX or for remote subscriber-application).
- Modem signals (eg. telefax), combined analogue 'data over voice' signals.
- Synchronous data for terminal computer links and RTUs, at standard CCITT V-series rates, eg. 9.6 kbps.
- Asynchronous data signals carrying telecontrol information from RTUs.
- Teleprotection commands.
- Analogue teleprotection signals (for phase comparison or longitudinal differential protection).
- Simple on/off state transfer signals.
- Analogue video signals.

3.6.7 Redundancy concepts

Redundancy is used to increase availability by switching from a main path to a standby one in case of a failure. This can be done either on the individual channel level (which needs one switch plus one control mechanism per channel - normally not a cost efficient solution) or on a higher hierarchical level, mostly the transmission level.

Redundancy can be applied as a point-to-point structure or as a more complex structure involving more than two stations. Point-to-point redundancy in power system communications is normally realised as a 1+1 protection switch with fully doubled transmission path between the two points. A more economical solution can be chosen if N transmission paths are already needed in normal operation between the two points. Then, just one additional path with corresponding switching mechanism is needed for an N+1 protection scheme. This scheme is often used in public networks.

More complex redundancy structures need less additional transmission paths than point-to-point redundancy. The following structures are in use:

- Ring structure. A self-healing ring can be realised with two fibres (one for each transmission direction). This ring is normally open at one defined location. In case of a failure of one link, the ring is rearranged so that the failure coincides with the location where the ring is open. This relatively simple structure needs a kind of alarm transmission in the ring to control the rearrangement in case of a failure. Other ring structures are also possible.
- Switching between predefined cross-connect-settings in cross-connect-multiplexers. According to the location of a failure in the network, the cross-connect-matrix in one node is automatically switched from a normal state to one out of a set of predefined standby states. In order to control the switching locally, again some kind of alarm information from the neighbouring nodes is required.
- In future, as part of a complete Network Management System (NMS), fully adaptive switching of the cross-connect-matrix can be provided. In case of a failure a centralised knowledge based system evaluates the optimal new network configuration and sends corresponding control signals to all the nodes. This structure needs special data channels for control purposes.

One important parameter of redundancy switching is the total switching time. This is the time elapsed from occurrence of the failure until full availability of the backup path (including resynchronisation). This parameter is influenced by the switching criteria (e.g. BER >1 in 10^3 on the transmission level, or any other alarm signal or combination of such signals), the evaluation algorithm, the frame structure and synchronisation, etc. As an example, switching on the 2 Mbps level can lead to a total switching time of 20 ms. During this time the data flow contains errors or is interrupted in a direct switching system. Error free switching systems use a corresponding delay of the transmitted signal and a memory on the receive side. However, this is undesirable in applications like protection.

Choosing switching times that are too short can lead to instabilities of the system and undesired interruptions in case of temporary faults. It must also be taken into account that if a network is split into isolated sub-networks by a failure, the network synchronisation must be rearranged, which may need a new synchronisation master.

Concluding, the switching characteristics must be carefully defined taking into account the real needs of the application.

3.6.8 Supervision and alarms

Supervision and alarms can be realised in different degrees of sophistication. Minimum requirements are the local supervision of some important parameters. Often needed in power system communications are common alarm and remote alarm facilities. The most sophisticated solutions are normally part of a complete Network Management System (NMS).

Important system parameters to be monitored are:

- Bit Error Rate (in optical line terminal as well as in multiplexer)
- Loss of incoming signal (in optical line terminal as well as in multiplexer)
- Increase of laser bias current (in optical line terminal)
- Loss of frame synchronisation (in multiplexer)
- Failures in checkbits (e.g. CRC4-code in multiplexers)
- Loss of clock signals (in optical line terminal as well as in multiplexer)
- Alarm from remote station or other equipment (AIS) (in optical line terminal as well as in multiplexer)

Some of the parameters will generate urgent alarms, others deferred alarms, depending on the severity of the disturbance and the possible consequences.

The settings of the alarm thresholds and the evaluation algorithms must be done taking into account the typical disturbance situation on fibre optic links:

- A slow degradation of the system parameters such as Bit Error Rate typically occurs in case of laser diode degradation. This effect can be detected by bias current supervision, generating a deferred alarm, as the time constant of degradation is very long
- A much more typical error situation is a sudden loss of the complete signal (fibre break, disconnection of connector by accident, etc.)

Consequently, in case of an alarm, an immediate blocking of vital functions (e.g. in teleprotection) is required in order to avoid false operation. Another consequence is that error correcting codes are not helpful - they may even worsen the situation.

Many aspects of supervision and alarms are covered in CCITT recommendations. Nevertheless, the implementations must take additional power system requirements into account.

3.7 Repeaters

3.7.1 The need for repeaters in long sections

Repeaters in telecommunications systems are needed, if the distance between neighbouring stations exceeds the maximum distance that can be overcome with available technology. This maximum unrepeated section length is calculated for given technology, equipment and other parameters using the optical power budget. The CCITT sets out recommendations (G.956) for calculation of these parameters and they are also outlined in Section 3.8. *System Planning*. The corresponding optical section is then subdivided into several subsections, each of which is shorter than the calculated maximum unrepeated section length. In practice, the repeater locations will be chosen at existing intermediate stations if possible. In certain cases, even some detours may be justified, if the repeater can be installed in existing stations. Such repeaters located in normal telecommunication rooms are called office repeaters. Office repeaters are normally built with ordinary terminal equipment connected back to back. In order to save money, a reduced configuration is sometimes sufficient (e.g. leaving out the multiplexing part), but in other cases provision for future local access channels is made, so that such repeater stations do not differ from ordinary intermediate stations in a line type network configuration.

Repeaters which cannot be located in existing intermediate stations, but have to be built outside power stations or existing buildings, are called field repeaters and have to be designed accordingly. The remaining sections of this chapter deal with field repeaters.

Special considerations are needed for given field site repeaters and the resulting cost and effect on system reliability make it worthwhile to try to avoid such repeater locations. This can sometimes be done by choosing corresponding system parameters to increase the maximum unrepeated section length, namely by:

- Increasing the allowed overall attenuation between sender and receiver.

- Reducing the applicable fibre attenuation per unit length by using better quality fibre.
- Lowering the optical bit rate to allow reduced receiver power without high BER.

The allowed attenuation can be increased by choosing higher transmit power (e.g. laser instead of LED), better receiver sensitivity (high sensitivity components) or by choosing lower transmission rates, if the system concept allows for (e.g. using 2 Mbps instead of 34 Mbps, which may result in 9 dB more allowed attenuation in a multimode fibre cable).

The applicable fibre attenuation may be reduced by choosing singlemode instead of multimode fibres or by choosing 1550 nm technology instead of 1300 nm.

Thus, using 1550 nm technology for a low data rate system at 2 Mbps may be justified for a Power Utility system if a repeater can be avoided, although under normal circumstances in public networks 1550 nm is used for very high capacity systems today. Using 1550 nm technology on OPGW however needs a very careful selection of the cable construction, because signal transmission at 1550 nm is much more subject to performance degradation caused by mechanical and temperature stresses (bending, elongation, pressing, short time currents) than at 1300 nm.

CIGRE Report N° 58 [4] showed that only 6% of the given system types use repeaters. This is related to the low average link length of fibre optic systems for Power Utilities (around 10 km for 2 Mbps systems and around 55 km for high speed systems), which results from the still high cost of optical cables. On long links other transmission media (e.g. radio) are still more economical than fibre optic systems. In the past years, the falling cost of optical cables has pushed up the crossover distance at which fibre optic systems are more economical than other systems, towards higher and higher values. But, at the same time, better technology has led to higher and higher unrepeated section lengths. So, the need for repeaters has been limited to a few links, and it can be expected that this situation will continue.

3.7.2 Design of repeaters

The main functions of a repeater are:

- Reshaping of the incoming data.
- Signal-clock extraction.
- Regeneration of the data signal.
- Amplification of the signal for retransmission.

To perform these main functions no decoding and demultiplexing of the data signal is required. However, if some information has to be taken out from the signal or if some local information has to be inserted, decoding and demultiplexing down to a certain level is normally needed. This is practically always the case, as a bi-directional service channel is normally provided in repeated systems for supervision and fault location. As field repeaters are often located far from manned stations and working under severe climatic conditions, supervision of at least the following parameters is recommended:

- Bit Error Rate.
- Loss of incoming signal.
- Power supply.
- Battery charging.
- Temperature in repeater housing.
- Humidity inside repeater housing.
- Other equipment alarms.

Besides a service channel for bi-directional data transmission to and from the repeater, also a service telephone channel is often provided, enabling communication in case of maintenance work.

Basically the same kind of equipment can be used for repeaters and normal station terminals. It is often possible to use normal equipment (optical receiver and transmitter, multiplexer for the service channels) connected back to back. However the required operating temperature range for field repeaters is more severe than for normal station equipment. Also power consumption and volume of the equipment may be important, as these may influence size and cost of power supply and housing.

The design of field repeaters has to take into account the following particular aspects:

- Power supply.
- Housing construction.
- Climatic stresses.
- Reliability considerations.
- Vandalism.
- Rodents.

Unlike repeaters along public communication cables, repeaters in power system communications cannot normally be powered by separate copper wires in the same cable as the fibres. This would remove the high immunity to electromagnetic interference and the excellent electrical isolation of fibre optic systems - both very important properties for the Power Utility environment. Therefore local powering of repeaters is needed. Mostly solar power or mains (sometimes with diesel backup) is used as primary power source, connected with a battery system for buffering.

Designing solar powering needs careful consideration of the local climatic conditions (sunshine duration, dust, snow, wind etc.). The size of the array, the support structure and the battery system have to be chosen accordingly for a given power consumption of the repeater equipment.

When designing the battery system, its capacity, operating temperature range and sufficient ventilation to avoid dangerous gas concentration has to be considered.

Repeaters for OPGW systems can be located in a number of positions:

- At the bottom of towers mounted in small cabinets or boxes.
- Within the tower structure.
- Seperate shelters placed besides the tower.
- In underground manholes.
- Mounted in small cabinets or boxes in the middle or on top of the tower.

Small cabinets or boxes in exposed locations are vulnerable to wide temperature ranges and the repeater is subject to difficult access and influence of atmospheric overvoltages (lightning). Underground solutions are critical in respect to water condensation inside the container, air circulation and cost. In the case of underground containers the inside local climate (temperature, humidity) has to be investigated carefully, taking into account power dissipation, worst case outside mean temperature, thermal conductivity of the construction and relative humidity. In some cases it is recommendable to mount the repeater inside an airtight construction avoiding high humidity values.

As reliability of repeated systems is still a critical issue redundancy concepts are often applied. If just a small number of repeaters are needed in a link, the whole equipment can just be doubled forming two complete systems in parallel. For larger numbers of repeaters in a link, a cross connect facility in the repeater location may be provided, coping with multiple failures on the link. The switching in of the repeater locations must then be controlled by a special supervision or even a network management system.

Vandalism may be critical for repeaters, mainly if mounted above ground and for solar power systems. Corresponding protection must be provided.

3.7.3 Future trends for repeated fibre optic links

The technological progress is expected to increase the maximum possible unrepeated section length up to 200 km and more within the years to come. So, as it is today, repeaters will remain relatively rare. This is due on one side to new types of high power lasers under development, together with post-transmitter optical amplifiers, allowing the injection of much higher transmit powers into the fibre than in today's systems. On the other side new coherent modulation concepts allow much higher receiver sensitivities. These technologies are currently in a research stage, where distances over 300 km have been overcome without repeaters under laboratory conditions.

The concept of optical amplifiers may also be an interesting new approach to realise better repeaters. Two different technologies are under development:

- Solid state amplifiers. These devices are basically laser diodes with anti-reflection coatings at the end of the chip avoiding oscillation as in a laser diode.
- Fibre optical amplifiers. These devices consist of special types of optical fibres (normally erbium doped) in connection with a pumping power laser delivering the power for the signal amplification effect in the fibre.

Both technologies allow the amplification of light signals in both directions with high bandwidth. Thus, one advantage of these technologies is that repeaters become independent of the modulation method and signal data rate injected at the end of the link. A link equipped with such repeaters may therefore be upgraded for higher data rates in future without modifying the repeaters. This feature is of particular interest in sub-marine cables - for land based systems its advantage is probably less important.

Theoretically, such links are fully transparent and can also be used for OTDR fault location measurements. This reduces the need for special service channels accessible at the repeater locations for supervision purposes. However, reflections in such a bi-directionally amplified signal path may cause instabilities and result in parasitic oscillations in the system, so that optical isolators are normally required in practice. Then, the system becomes unidirectional again, OTDR measurements over the whole link are no longer possible and service channels to the repeaters cannot be avoided.

If service channels to the repeaters have to be provided, some kind of signal receiver and transmitter and possibly multiplexer is required at the repeater location. The basic advantage of the simple structure of a fully transparent optical amplifier, independent of modulation format and data rate of the passing signal, is then at least reduced.

The first operational repeated systems with optical amplifiers are now in evaluation for submarine cables for high speed public telecommunications systems.

However, the technology of optical repeaters is also promising for post-amplifiers inserted just after the transmitting laser diode, increasing the output power and correspondingly increasing the maximum unrepeated section length.

Although research in fibre optic telecommunication is primarily driven by the requirement of highest speed transmission applications in public networks, which is normally not the real need of power system communications, the new technologies under development will also help to increase the unrepeated section length for lower speed systems, which is a real need for many utilities.

3.8 System Planning

3.8.1 Channel numbers and capacity

Where possible, the multiplex channelling designations should follow national practice. Most schemes in use follow a plan where the highest multiplex order is the prefix, followed by the lower orders and finally the channel number of the primary multiplex unit in question. The reference number may therefore thus appear 1-4-2-27 which would indicate the circuit in question was:

Tributary #1 at the 34 Mbps level
Tributary #4 at the 8 Mbps level
Tributary #2 at the 2 Mbps level
Channel 27 of that primary multiplex

The required channel capacity and hence system bit rate of any system will depend upon traffic requirements. These should be determined during the feasibility study and initial planning stages.

3.8.2 Attenuation budget

The determination of system attenuation budget will be one of the first tasks for the system designer. There are four major factors which will need to be considered:

- The optical transmit power.
- The required optical receive power for the desired BER.
- The path attenuation.
- The optical margin.

The optical transmit power will be solely dependent upon the state of art for the LED or laser source. The average optical output of a laser diode is -3 dBm. Typical LED sources generate -20 dBm. Already higher power lasers are available in specialised production equipment.

The optical receive sensitivities are, for a given device, dependent upon system bit rates. As the bit rates are lowered, the receiver bandwidth may be effectively decreased which permits a higher power/bandwidth ratio and improved signal to noise ratio for a given optical power. Hence, for a desired BER, the signal level may be effectively reduced as the system bit rate becomes less. Today, all commercially available OLTEs employ direct photo-detection techniques. Typical receiver sensitivities are -38 dBm at 140 Mbps increasing to -51 dBm at 2 Mbps. It is possible that within the next few years, superheterodyne receivers will become available, using mixing techniques to generate an intermediate frequency (IF) where amplification will take place before detection. This will result in receivers having sensitivities possibly as low as -100 dBm, a dramatic improvement over the best receiver available today. Optical amplifiers can also be used in pre-receiver mode to amplify the signal before detection.

The optical margins will be design dependent and will be primarily based on the system designer's estimated degradation of system components over the system's intended operating life and this would be typically 7 dB, comprising of 3 dB for laser and photodetector ageing, 3 dB for fibre attenuation change, and 1 dB for miscellaneous component changes, eg connector wear. The terminal equipment is usually insensitive to temperature variations by virtue of being mostly digital circuitry, and it is known that under fault conditions, the fibres within a composite earthwire do show an incremental increase of attenuation although this is very small, in the region of 0.01 dB/km, and is self restoring to the nominal value after the power line fault is cleared.

The most critical component in the design is the fibre path attenuation. This not only has to include the fibre itself over the route length but also splices, connectors, flexible equipment connection tails, etc. The fibres themselves are continually improving, typical attenuations of 0.35 dB/km at 1300 nm and 0.25 dB/km at 1550 nm are achievable, and splice losses should be around 0.1 dB.

3.8.3 Repeaters

The system design will indicate if repeaters or regenerators are required. Generally, it is best to avoid them if possible as they are not only a potential source of noise (Bit Errors) but also are a maintenance burden and a financial burden on the capital cost of the project. If transmission distances are long and repeaters appear necessary then consideration should be given to changing to 1550 nm operation or even decreasing the system bit rate if possible.

If repeaters are unavoidable, it is preferable to place the equipment in existing suitable buildings where a secure environment and suitable power supplies are available. In these instances, the repeater may simply consist of a pair of back to back OLTEs. If circumstances dictate that there is no suitable existing building in the vicinity, then a decision will be required as to whether the repeater is to be tower or pole mounted, or buried. The former options are the cheapest, but leave the enclosures highly visible and potential targets for vandalism. The latter is much more costly, but by virtue of being underground is out of sight and in severe climates, the ground does help to thermally stabilise the electronics.

3.8.4 Location of splices

For aerial fibre optic systems, invariably the splice locations will be planned to coincide with tower or pole locations. As splices add losses to the fibre path, they should be minimised if at all possible by ensuring that the fibre optic cables are supplied and installed in the longest possible continuous lengths. The location for the splice on the tower or pole is likewise important. Although it is physically easier to splice at ground level than at a tower peak, the cable of course has to be brought to ground level in order to accomplish this. This could, for example, add 120 metres of cable to the system per splice location, which in a 50 km circuit may equate to another 3 km of cable and a loss of 1 dB from the optical margin.

3.8.5 Joint boxes and patching

The splices are extremely fragile and environmentally sensitive, particularly to moisture. After splicing, the splice should be protected with a proprietary sleeve. This should then be supported mechanically to avoid damage by movement, suitable plastic cassettes are available for this purpose. Afterwards, all these components should be mounted in a suitable hermitically sealed box mounted on the tower or pole. This box may be also proofed against ultra-violet degradation and impact from projectiles and sharp objects if the local conditions so demand.

It is recommended that fibre patching, if required, is only provided in environmentally controlled conditions such as equipment rooms. The fibre patch panels or Fibre Distribution Frames (FDFs) are sensitive to dust, dirt and moisture. They introduce additional transmission loss and have a finite number of times that patches may be changed. They are therefore best avoided if the system requirements allow.

3.8.6 Power requirements

In common with most telecommunications equipment, the fibre optic terminals are usually standardised on 48 volt d.c. positive ground power supplies. Other alternatives such as 24 volt d.c. inputs are frequently available. With the advent of switched mode power supplies, many items of equipment can accept inputs ranging from as low as 20 volt d.c. up to 70 volt d.c. without changing any internal components or strappings. Floating power supply inputs are becoming increasingly common so that the equipment may run from negative ground supplies.

The system power requirements will vary according to terminal size and complexity. Typical module loading of modern equipment will be in the region of between 10 and 20 Watts depending on function.

Powering of intermediate repeaters poses a number of problems. For conventional telecoms applications, it is common practice to construct the fibre optic cable with interstitial copper conductors for intermediate regenerator powering. In an electricity supply context, the proximity of the fibre optic cables to high voltage power lines will normally preclude the inclusion of these conductors due to the induction of high voltages from the power system.

Therefore, alternative arrangements have to be made to power remote regenerators. Typical arrangements may include:

- Solar Power
- Wind Turbine Generator
- Local Low Voltage a.c. Supply
- Thermoelectric Generators (TEGs)
- Diesel Generators

or any combination of the above depending upon local conditions.

3.8.7 Mechanical layout

The mechanical layout of the terminal equipment will be largely dependent upon building layout and positions of cable entry locations. For a small system, the equipment may be housed in one or more adjacent equipment racks of the user's preferred practice, eg. 19", TEP1E, ETSI, CEPT A or CEPT B.

Larger systems require a degree of care in their layouts as the quantity of equipment required has to be considered in conjunction with physical positioning between equipment so as to avoid excessive cable lengths yet be in a logical sequence so that faulty modules may be readily identified and located. A typical arrangement for a large terminal would be to place the OLTEs, regenerator power feed equipment (if applicable) and orderwire telephone in one area, but adjacent to the multiplexers arranged in descending order, and finally the primary multiplexers. Jackfields, etc, are normally located adjacent to any Intermediate Distribution Frame (IDF). The orderwire telephone handsets should be supplied with leads sufficiently long to permit movement to all equipment positions.

3.9 System Installation

3.9.1 General requirements

Before a system installation can take place certain information must be obtained. This includes:

- Route maps, including terrain and access points
- Tower types and associated drawings
- Site survey and questionnaire completion
- Special information such as required splice points
- Climatic conditions (especially important for OPGW and ADSS cables)

Once this information is available, exact material requirements can be calculated.

The manufacturing of the cable and accessories will be phased in to coincide with any planned power system outage.

Training would be provided for the installation crews including personnel provided by the Power Utility.

After installation, commissioning and testing of the system will be followed by the issue of a report containing optical details of the link.

Specific installation details will need to be provided for each installation to ensure that the expected optical performance is not compromised by the actions taken during installation.

Any optical cable should not be allowed to rotate during installation. If the cable rotates it means that stranding (metal layer or stranded plastic tubes) unwinds and gets looser. This in turn means that the cable elongates. In loose buffered cables some extra length of fibre is reserved for cable stress situations. This extra length disappears if cable elongates during installation and thus does not exist any more for the stress situations. Even worse is the case with tight buffered fibres where there is no extra fibre length reserved at all.

Two armouring layers (reasonably in balance considering strength) in OPGW or relatively rigid construction of OPGW or self-supporting cable can reduce this tendency to rotate.

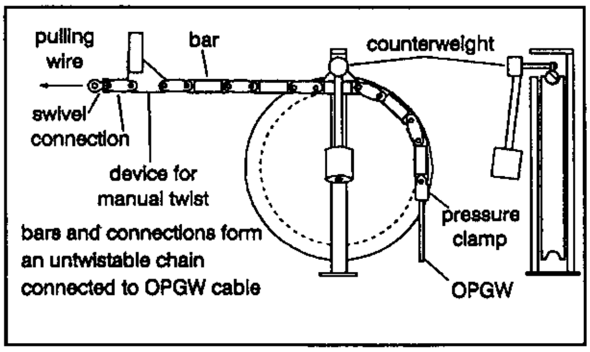


Figure 42 Anti-rotation techniques for OPGW

It is good practice to control the rotation of any cable type when it is being installed even though it may be of a reasonably balanced design. This can easily be carried out by placing rope hanging at the beginning of cable. It should be agreed with the cable manufacturer (and preferably tested) the number of rotations allowed per unit length.

In order to eliminate the rotation of the cable during installation, an anti-rotational device, as shown in **Figure 42**, is connected to the cable. This is especially important when installing single wire layer cables which are prone to rotate without the use of such devices.

3.9.2 OPGW installation

OPGW installation normally requires ground access along the power line route, even though tension stringing techniques are generally used. The planning activity will have identified where joint boxes are to be sited and from this, specific length cable drums will have been manufactured. A major factor in determining jointing positions is winching machinery access to the appropriate towers. Modern winching machinery is capable of handling drums up to 4½ tonnes gross weight, which represents approximately six kilometres of 20 mm diameter composite aluminium and steel reinforced conductor. This maximum cable length allows considerable freedom for choice of winching positions.

Suitable running blocks are then suspended from these attachment points. The type of running block to be used should be recommended by the cable manufacturer. A pilot rope is then manually installed through the running blocks between the first and last towers in the section. This overall distance can be up to approximately 6 km and it will therefore probably be necessary to have several individual lengths of pilot rope joined together by suitable connectors.

If ground obstructions prevent the rope from being 'walked' into place then alternative methods such as the use of a motorised tug travelling along the earth conductor may be used. Under extreme conditions the use of a helicopter might be considered.

The pulling winch and back tensioner are positioned at the first and last towers. These are now used to install the cable which is connected to the pilot rope, or alternatively can be used to first install an intermediate pulling bond which is then used to install the cable. In both cases the cable drum is located at the back tensioner and sufficient back tension is applied to keep the cable clear of the ground and other obstructions at all times.

The cable is drawn smoothly into position and fixed at the tower nearest the back tensioner by the application of a suitable clamp.

The tension in the cable is then adjusted until the sag of the cable conforms with the predetermined value, ensuring that the correct sag/tension parameters are achieved. The cable is then clamped off at the winch end of the first tension section and this sagging procedure is repeated for any other tension sections within the cable length.

Suspension clamps and vibration dampers are then fitted at all the intermediate tower positions and the cable is made ready for testing and subsequent jointing. Installation rates are about 6 km/week on 275/400 kV lines.

In recent years several electrical utilities, notably in Japan, have developed methods for changing earthwires on multiple circuit overhead power line routes, without the need to take adjacent circuits out of commission. Such schemes make use of cradle block stringing techniques and are of great interest and potential benefit.

In a typical scheme the new earthwire is pulled in, with a previously installed light rope pulling bond, at a very low tension. It is suspended at 10-20 metre intervals beneath the old earthwire, which maintains high quality earth continuity during the operation. When the new conductor has been pulled through, it is tensioned and bonded electrically to every tower, so the earth continuity is transferred to it. The dead ends are then cut from the old wire, which is coupled through, slackened, put into blocks and drawn out, in a fashion similar to that by which the new one had been pulled in.

The method provides an attractive option when earthwires are to be replaced independently of the phase conductors. The advantages are that there is no need for circuit outages, full fault current rated low resistance earth continuity is maintained throughout the operation and the need to protect roads, railways, low voltage lines and other obstructions is minimised. The procedure will free from system constraints decisions about routes along which earth wire can be changed. The freedom will thus be gained to change earth wires at will, either for their optical equivalent of for maintenance purposes, on routes other than those which are to be refurbished.

There are also considerable benefits which will accrue from improved safety. At present, earthwires are changed using tension stringing techniques with a single circuit outage. Historically, when doing this conductors have sometimes been dropped, giving rise to concern with regard to the risk of contact with the live circuit. The present practice is to use temporary earths on the dead circuit, to provide earth continuity while the work is done. These earths are not fully fault rated. The proposed procedure employs greatly reduced pulling tensions, the earthwire is supported at regular intervals, and the earth continuity is fully fault rated. Thus the risk, and consequences of failures is markedly reduced.

3.9.3 Attached cable installation

There are basically two types of attached cables available today:

- Fibre optic cables attached to the earth wire with 'clips' or 'lashing' wire.
- Fibre optic cables externally wrapped around the phase conductor or earth wire.

Lashed or clipped

These types of installations are not very common and only represent a fraction of the total installed fibre optic cables on overhead power lines.

Typically the optical cable is unwound from spools or reels positioned on the ground, normally moving ahead of the attaching system on a truck or ground wire trolley. The lashing system, which has largely been discontinued, utilises a lashing machine that runs on the earthwire behind the pay-off spool moving along the ground. A small wire, winding around the earthwire, attaches the cable. No known system exists for tension control of the cable but the lashing technique holds the cable firmly in position. Mechanical guides attached to the tower tops facilitate the passage of the fibre optic cable around these structures. Splices are mounted just above ground level on the tower. Mechanical clips attach the fibre optic cable to the tower legs at splice locations and terminal positions.

The clipping system which has been used more recently but again only on a very limited scale, uses similar accessories at towers and by-passes but the attachment of the fibre optic cable is achieved by using discreet clips or preforms. In some cases the clips are attached by hand from a conductor trolley or by an automatic machine running along the earth wire.

In both the lashing and clipping methods, dampers, aircraft warning balls and any other attachments need to be removed before installation. These can be replaced after cable attachment. Lashing and clipped installations can only be performed with the circuits dead.

Externally wrapped

In addition to the planning information set out in Section 3.9.1 *System Installation: General Requirements*, the installation of the externally wrapped cable requires the following additional information:

- Conductor size (earthwire or phase-wire)
- Position and type of dampers, aeroplane warning balls and conductor splices
- Condition of conductor (grease?)
- Details of road, river and powerline crossings if not already given in normal route maps.

The lengths of cable required are calculated during the planning stage which includes an allowance for wrap, sag and distance down towers or poles at splice points. The exact amount of cable is manufactured for each section and spin and splice points defined. The cable is cassetted onto two spools so that wrapping onto the conductor can start at a middle point along the route and progress in both directions without the need for an extra splice.

If the utility provides its own line crew, the supervisor from the cable company would use between one half and a full day to train them in all aspects of cable wrapping.

The cable cassette arrives at a designated wrapping start point where the spools are attached to wrapping machines which are then raised onto either the phase conductor or earthwire. If installation is to take place on the phase conductor, the circuit must be dead (adjacent circuits can be live). If installation is to take place on the earth wire, the circuits can remain live, but this is dependent normally on local working regulations. Aeroplane warning balls and dampers etc. must be removed prior to wrapping.

The wrapping machine is positioned on the conductor and safety locks, which prevent the machine leaving the conductor, engaged. The fibre optic cable, which has been especially designed for either earthwire or phase conductor application, is secured either side of the tower or pole before wrapping starts. This is done by using a cable clamp and a mechanical guide around the tower/pole top called a balehanger. The wrapping machine is then pulled along the conductor either by rope from the ground, or by a petrol driven tug that can be attached to the machine and remotely controlled via a radio from ground level. Helicopters have also been used to tow the machine in certain applications.

At the next tower top, the wrapping machine is transferred over the top of the tower or pole to the other side by a small 'jib' and hand winch. The tension on the installed cable is checked and adjusted as necessary. After tensioning, the cable is secured and guided over the tower in a balehanger, as shown in **Figure 34**. On the other side of the tower, the cable is secured, the counter balance arm and drag brake re-set for the next span. Wrapping can then proceed to the next tower.

When the wrapping machine reaches a designated splice point or terminal tower, the spool of cable is removed from the wrapping machine and the remaining cable unwound from the spool. The cable is then passed through either a conduit or composite insulator (depending on type of installation) which had previously been attached to the tower or pole. Splicing takes place at ground level and the splice case is positioned normally on the tower or pole. Alternatively, it is possible to have a splice case located on the conductor itself. In this case, splicing still takes place at ground level but the excess cable is wound up inside the splice case before suspending it from a conductor shoe on the conductor.

Aeroplane warning balls and dampers are replaced and attenuation of the system measured using an O.T.D.R. Traces of the system are recorded and a final installation report is issued.

Fittings and accessories are available for all types of tower constructions and conductor sizes.

3.9.4 Self supporting cable installation

The basic principles and techniques used in the installation of these cables are very similar to those used in the installation of the actual phase conductors. Conventional tension stringing techniques are adopted wherever possible utilising standard installation machinery and accessories although in some cases, specialist machinery may be needed. It is important therefore to follow the advice of the cable manufacturer in all aspects of the installation process.

The initial planning process involves a similar set of stages as outlined in Section 3.8. *System Planning*. Following the survey and project planning activities a decision will be made regarding the fixing point of the cable on each tower in the system. The actual point chosen will depend on a number of important considerations. Among these will be:

- The maintenance of ground clearance regulations.
- The proximity of adjacent conductors if installing under live conditions.
- The possibility of clashing with adjacent conductors under blow out conditions.
- The additional loading on the tower structure.
- The local induced voltage which may affect the cable sheath.
- The availability of a suitable fixing point in the desired location.

A significant factor in determining clashing conditions is the weight of the ADSS cable compound relative to the conductor. The ADSS cable is usually much lighter and will blow out further than the conductor. For lateral wind conditions, the blow out for the ADSS cable can be calculated. However, the situation is more complex for longitudinal wind conditions. Wind along the line route will tend to shift the cable sag close towards the leeward tower, and the effect will be greater for lighter ADSS cables. If the ADSS cable is above (or level with) a conductor (for example attached to the same tower cross arm) this effect makes it very difficult to avoid clashing close to the tower, especially on long spans. A possible solution is to attach the ADSS cable below the lowest conductor and to reduce the ADSS cable sag by increasing tension to maintain mid span clearance.

Various computer models exist to show the sag performance and relative movements of differ-

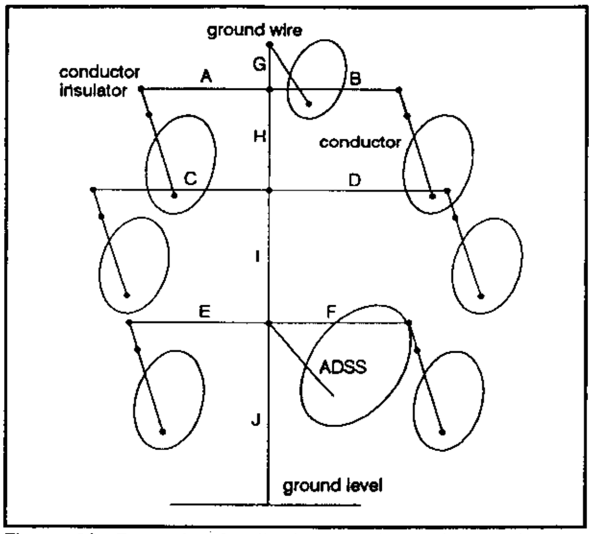


Figure 43 Example of galloping envelopes for conductors and ADSS cable

ent cables under a range of climatic conditions. As an example, the galloping windows of one installation involving earth, phase and ADSS cables is shown in **Figure 43**.

There are a also variety of computer models which illustrate the level of capacitively induced voltage on the surface of an ADSS cable. **Figure 44** and **Figure 45** show induced voltage effects for a double circuit line in which the phases are arranged vertically on cross arms either side of the tower. Note the voltage null point in **Figure 44**. Selecting a landing point in this region will ensure that, even under single circuit working, shown in **Figure 45**, the

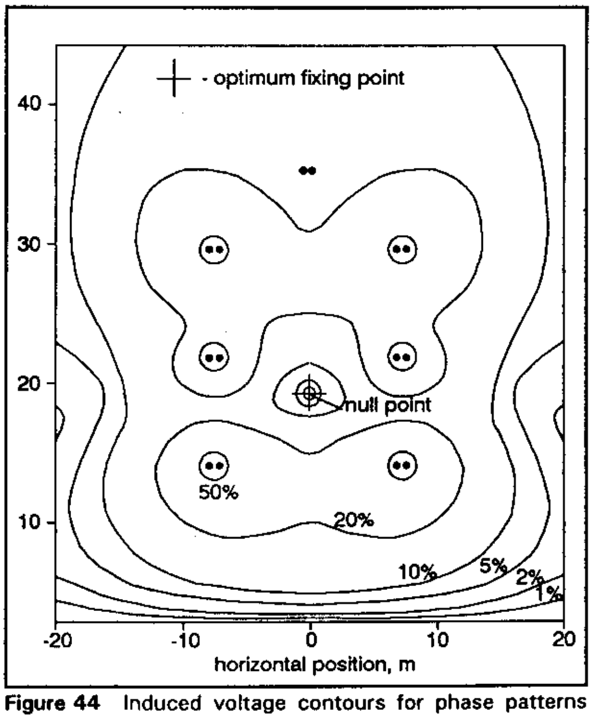


Figure 44 Induced voltage contours for phase patterns RYB/RBY

induced voltage need never exceed 10% of the maximum phase to earth voltage.

It is also recognised that a significant reduction of induced voltage exists at the bottom cross arm level with the more common RYB, BYR phasing arrangement. With this phasing the induced voltage at bottom cross arm level is less than 50% of that for the more onerous configuration in which the phases on the cross arm are common.

Other phase arrangements do not provide a null point. However, the computer models are able to indicate the most advantageous landing point for reduced induced voltage levels.

When the optimum fixing point has been chosen, installation begins with the fitting of the attachment points and any necessary reinforcing steelwork to each of the towers along the section. The drilling of steel towers is not recommended and should not be carried out unless absolutely necessary.

The installation procedure is identical to the OPGW installation method described in Section 3.9.2 *OPGW installation*, apart from cable lengths being normally restricted to 5 km or less. Installation tends to be faster than OPGW because of the lighter weights of both cable and stringing mechanisms.

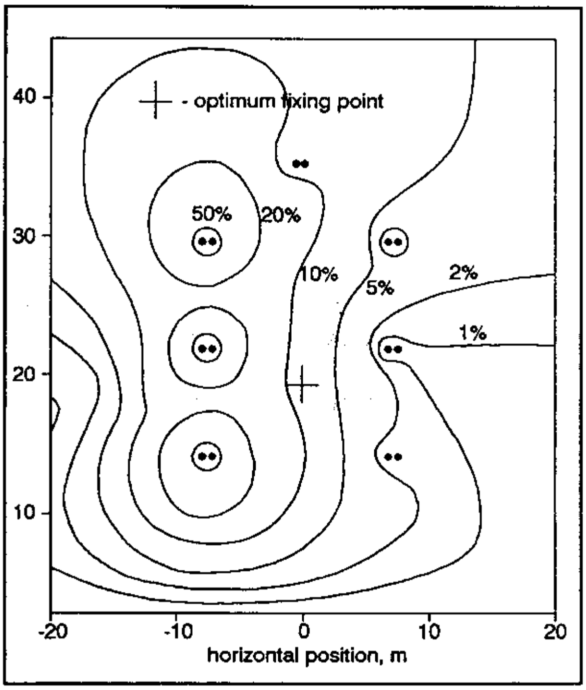


Figure 45 Induced voltage contours, with one circuit earthed

3.9.5 Splicing

Splicing operations on fibres of all standard lengths and of sub-station sections for the entire optical path is normally done by fusion. See Section 9.5 *Splices by Direct Contact.* for more detail. However, if only a limited number of splices are required a bonded splice may offer acceptable performance and be more economic (see Section 9.1.3 *Uses*)

To prepare the fibres for splicing the primary covering must be removed either mechanically or chemically. Although both methods yield good results, mechanical procedures are found to be more practical for operations in the field. The splicing operation in the strict sense is best performed with a splicer that automatically aligns the fibres and can run a check on the quality of the joint formed.

Protection for the splicing can be provided through one of the following ways:

- Reinforcing thermo-shrink tubes.
- Resins that reconstitute the acrylate and protection with flexible tubes.

Methods of protection used must give high priority to:

- Mechanical robustness.
- Lightness of the splice and the possibility of locating it, should the need arise, inside a joint box. Bearing this requirement in mind, a joint of limited length is preferable.

For the sake of convenience each spare fibre length of the joint should not be shorter than two metres.

Irrespective of the type of plant, splicing operations are generally carried out at ground level. The joint must be protected in special joint boxes. These can be suitably located on the plants structure according to the solution adopted, bearing in mind that since the joint can be regarded as being extremely reliable there is no need for access to the box for maintenance.

3.9.6 Joint boxes and cross connection

Joint boxes, in general are used to organise the spliced fibres and to give protection to the splices against the environment.

According to their different purposes the following types of joint boxes will be used, as indicated in **Figure 46**:

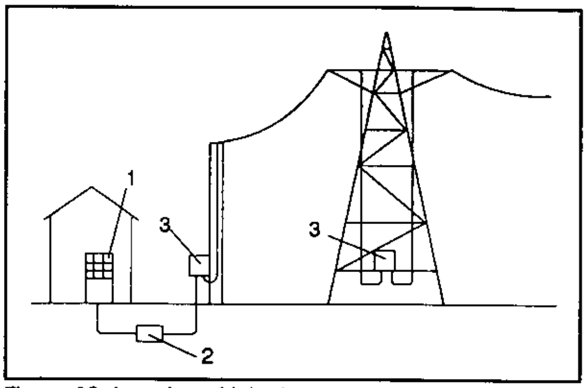


Figure 46 Location of joint boxes

- Type 1 termination boxes are used at the ends of the line as a housing for the splices and connectors. They are installed either in racks, cabinets, or on the wall.
- Type 2 thermoplastic joint closures are used for connecting, branching or distributing underground cables. The closures can be buried in the ground and give a highly reliable and secure protection for both fibres and splices taking on the function of the cable sheath.
- Type 3 metal hood closures for aerial cables are used to connect self supporting aerial cables as well as other types of aerial cables to underground cables.

For logistical reasons and easy handling the same fibre and splice organiser is used within all types of joint boxes described above.

3.9.7 Inline splicing methods and associated components

Splicing of the standard lengths of optical-fibre cables inserted in power-transmission lines should be carried out at the supports. The excess length that is to be spliced can be moored and the joint boxes can be supported and protected by normal support structures. Splicing operations should be performed at ground level at the support positions, so as not to interfere with normal stringing operations. Stringing operations may then proceed independently of the splicing. This is particularly important where different contractors may be employed with their respective skills.

This technique is not suited to splicing of dielectric or metal optical fibre cables associated with conductors carrying a live voltage. In this case splicing must be carried out in the span intervals between the supports (referred to hereafter as splicing 'between supports'). The following summary can be made with respect to various splicing arrangements:

- Dielectric cable wound along or suspended from the ground wire: the joint is formed at ground level and then raised to the height requested, the joint box being anchored to the tower.
- Dielectric cable wound on phase conductors. Splicing is carried out between supports, the potential of the joint box being brought into alignment with the conductor potential. It is not essential to position the joint at the tension tower, but if it is located here this makes it easy to support the joint box near to the insulators.
- Self-supporting cable splicing is carried out on cable lengths moored to the tower and brought down to ground level. The joint box and the relevant lengths of cable are raised up the tower to a height not easily accessible from the ground.
- Composite ground wire with optical fibres: splicing is carried out on the lengths moored to the tension tower and lowered to ground level. Once splicing is completed the joint box and the relevant cable lengths are raised up the tension tower to the proper height.
- Optical cable inside bundled conductor: the only kind of splicing possible is that between supports with the joint box operating at conductor potential. The joint box, anchored on one of the bundled conductor's spacers, must be able to withstand the mechanical pull of the sub-conductor.

In general, joint boxes for metal cables must be metal or, at least, they must have a metal covering. Those for dielectric cables, on the other hand, may be plastic. In all cases, and particularly so for plastic containers, it is essential that no metal part remains insulated from the power-transmission line element (ground wire or conductor) to which it is fitted - so avoiding the risk that it might assume random or floating potential, and therefore give rise to radio noise.

3.9.8 Substation access

As shown in the summary below various procedures may be adopted to bring the fibres down to sub-station level depending on the type of cable system used on the power line.

- Dielectric cable wound along or suspended from the ground wire: The fibres are brought down with the cable being supported on the terminal tower.
- Dielectric cable wound on phase conductor up to line voltages of 170 kV: To bring the fibres down necessitates the insertion of an optical insulator or, in any case, of a length of ribbed cable with similar insulation specifications to those of a voltage transformer for the same voltage level.
- Self-supporting dielectric cable: The fibres are brought down with the cable being supported on the terminal tower.

It is advisable that the configurations referred to above include an earthed metal protector mounted at the right height, to present a 'barrier' effect to any leakage currents caused by moisture on the dielectric cable. In the case of optical cables directly attached to phase conductors, there is a particular need for an earth-network 'barrier' element to handle any discharge currents that may damage the optical-terminal equipment.

- Composite overhead ground wires: for these the following types of installation are possible:

  - Overhead ground wire of power-transmission line connected to the substations earth network at the terminal tower: The wire, in its complete form, arrives at the joint box (at ground level on the terminal tower) and the optical path continues with the dielectric cable or any anti-rodent metal protected cable to the sub-station's earth network.
  - Overhead ground wire of power-transmission line insulated from the terminal tower, but connected to the sub-station's earth network. The ground wire is run down the terminal tower, in its entire form, and it enters the joint box. The box is mounted at a height which precludes it being reached by unauthorised persons. The wire and the joint box must conform to the required level of insulation between wire and terminal tower. The optical path continues from the joint box with a dielectric optical cable whose anti-rodent metal protection is connected to the sub-station's earth network. The joint box can only be accessed after it is connected to the earth network of the substation by means of a suitable selector switch. There should be an overhead spark gap between the ground wire and the earth network with a triggering voltage that is half the value of the insulating voltage between the ground wire and the earth network.

- Optical cable inside bundled conductors. The fibres can be brought down only by using an optical coupler that has similar insulation specifications to those of a voltage transformer for the same line voltage.

3.9.9 Commissioning measurements

Measurements for mounting and inspection operations on optical cables on power-transmission lines are best taken using reflectometers with the operational wave length. For certain operations, on singlemode fibres operating in the 1300 nm window listed among those below, the measurements should be repeated at 1550 nm. This is both to show up the presence of stresses of the fibre, which are not easily detected by measurements at 1300 nm, as well as to qualify the fibre for this wavelength which may be used in future.

The optical measurements referred to here are those that are performed in the field, acceptance tests being carried out at the manufacturers premises according to agreed specifications. It is important that records of measurement results are kept for future reference to allow monitoring of slow variations and changes which may lead to long term problems.

For singlemode fibres, field measurements must be carried out on all the fibres of the cable using the following procedures:

- Measurements of attenuation of each maximum standard length in the coil; these should be performed at 1300 nm and at 1550 nm at one end only of the coil before unwinding.
- Attenuation measurements when splicing: these must be done at the operating wavelength from both ends of the installed cable in order to obtain average attenuation values for each joint.
- Attenuation measurements along the entire length; to be performed in the 2nd and 3rd window in both directions of connection.

For multimode fibres, the same method described above is used, but only at the one operating wavelength. Measurements that must be carried out for substation connections are taken during splicing, on completion of cable stringing.

If splicing is done with an automatic welding machine that can estimate the loss of the joint, then measuring operations during actual splicing can be reduced, provided that an acceptable correlation is obtained between estimated and actual measurements.

3.10 Maintenance

3.10.1 System supervision

Fibre optic system supervision is based on terminal equipment alarms at two levels. The major alarm detects unacceptable conditions of transmission, whilst the minor alarm indicates a lowering of the transmission quality.

3.10.2 Maintenance test and measurements

Transmission characteristics of the optical fibre and terminal equipment are measured.

The main measurements are:

- End to end power loss and consequently the optical margin.
- The characteristics of every optical fibre with an optical time domain reflectometer (OTDR) in the best window (in fact, sharpness can be better at 1.55 μm even if the fibre is used at 1.3 μm) monitoring the evolution of splices and connectors.
- The BER at several levels of the multiplexer and the digital quality according to the Recommendation G.821. Degraded minutes (DGMN), errored seconds (ESEC), severely errored seconds (SESC).

These measurements are wholly or partly made at a certain frequency during the fibre lifetime.

Moreover a continuous supervision can be carried out using unused VF channels to count the number of noise impulses or transmission interruptions.

3.10.3 Maintenance of self-supporting cables

All dielectric self-supporting (ADSS) cables require special safety precautions due to their possible semi-conducting nature which must be observed at all times when working under any live line conditions.

During installation of the self-supporting cable an all-insulating cable can be considered to be non-conducting and sometimes can be installed without disconnecting the line (if regulations allow). During service these cables become semi-conducting because of pollution on the surface and the hydrophillic nature of the jacket material. They may temporarily become significantly conducting because of humidity or moisture and thus have to be considered as conducting cable affected by electric fields. During maintenance this fact should be considered and at least in some countries these cables are considered as conducting cables under local safety regulations.

In some situations it is possible to carry out maintenance with power circuits live. However, maintenance teams working on ADSS cables should be made aware beforehand that it is possible to obtain current discharges due to capacitively coupled electrical currents flowing on the surface of polluted cables. These are not normally life-threatening, since the clamping units at each tower location act as earthing mechanisms. It may therefore not be necessary to remove power from lines during maintenance activities. During the installation of ADSS cables, such periodic earthing is maintained by the use of conductive running blocks connected to earthed structures.

Recent trials undertaken at Hunterston Power Station in Scotland [5] have shown that the build-up of pollutants on overhead cables is not as great as was once thought, the pollutants themselves having been stabilised by natural causes i.e. wind and rain. Without excessive pollutant build-up, the flow of surface current remains small. Together with the earthing effect at each tower, the chances of human safety being compromised during live-circuit maintenance is therefore low but local circuit configuration and proximity of ADSS cable to the conductor needs to be considered.

3.10.4 Test and maintenance aids

Test equipment required for maintenance is becoming well known to maintenance staff or system designers. Generally it is limited to the following equipment:

- Ratiometer (for optical power and budget)
- OTDR (for optical reference signature)
- Digital transmission analyser (for transmission quality)

The new generation of measurement equipment to carry out the above tests is now very easy to use by non-specialist staff. Moreover, terminal equipment present a lot of alarm displays on their front panel such as degraded laser, AIS fibre cut, card failure, and so on.

If the link has more than two ends or if there are no personnel at one of the substations, a supplementary monitoring channel is useful. This can be provided, for example, by an analogue amplitude modulator added and connected to the optical equipment thus providing the additional communication for monitoring dialogue.

3.10.5 Temporary solutions during cable failure

Ideally, an optical cable system is formed into a network which can be reconfigured if a fault occurs. This means that single cable or fibre breakage does not prevent access to any part of the network.

Temporary repair can be done with OPGW, or self-supporting cable which can be placed at any height to tower. The Power Utility should reserve some extra cable and joint boxes in different locations to allow for early repair. Additionally, wrap on cable may be applied as a repair if the integrity of the conductor allows.

To assist these temporary repairs some extra cable length can be reserved in a coil at the joint box tower. If breakage occurs this coil can be unwound in order to lower the cable to the ground where a new splice is made. This method creates a mid-span joint. Extra cable length can also be useful if the line route or tower heights must be changed at some later date.

Wrapped cable can with care be recovered and repaired. Utilities can keep a spare reel or cassette of cable for emergency repairs, but to effect early repairs wrapping and de-wrapping machinery is also required.

3.10.6 Procedures for cable repair

An Alarm Indication Signal (AIS) of a fibre break or change of light signature is required to identify a defect on each of the fibres. An interruption to the whole cable can then be readily determined by the number of simultaneous defective fibres alarmed.

For instance, so long as the number of undamaged fibres is above the number of used fibres, repair is planned but it is not necessary to carry it out immediately. The repair can be delayed until other maintenance operations are required. On the other hand if the communication system is making use of all fibres in a cable the repair must be done without delay.

If the defect is at a splice position, the repair is able to be done with the remaining part of the optical cable in service. If the defect is located along the power line, it must usually be taken out of service to allow for repair.

Mid span jointing has now been developed by some manufactures but it is not very common. Often when the cable length is manufactured it is customised to fit with the actual distance between a group of towers on the line. Without spare cable length this option is not possible. In any event mid span repairs require a lot of resource and probably a circuit outage. Under these circumstances it is usually more effective to replace a section of cable where splicing may be carried out at more conventional locations.

It may be preferable for new splices to be made by the cable manufacturer rather than the utility staff who may not be very familiar with the technology.

3.10.7 Maintenance organisation

As fibre optic technology is new and reliable, maintenance organisations have not yet achieved optimum efficiency. Maintenance principles are not universal across utilities. Some are satisfied with terminal equipment alarms, others recommend optical performance tests every three months for example.

However, a good knowledge of the optical fibre technology is necessary to secure continuation of service. Training courses on the technology, the equipment, maintenance, and cable repair are necessary. Techniques are required to ensure that there can be a rapid return to service after any failure. Spare parts are also required to limit the MTTR. A maintenance contract with the equipment manufacturer and/or cable supplier may also provide a cost effective alternative.

3.11 Existing Systems

The following is a small collection of short descriptions of typical existing systems

3.11.1 Operational experience of existing systems

- **OPGW (1):**

The National Grid Company in the UK developed a prototype system in 1978 between Nursling Substation and Fawley Power Station, a distance of 22 km. This has been the subject of an extended trial to gain operational experience of fibre optic systems under power system fault conditions. The system uses a composite fibre optic earthwire containing multimode fibres. System operation is at 34 Mbps at 1300 nm. There is an intermediate regenerator located approximately midway between Fawley and Nursling. The system currently carries a mixture of telephony and a trial digital protection circuit which operates at 64 kbps.

Today the NGC has about 300 km of OPGW and one 8.5 km wrapped cable telecommunication link operating at 140 Mbps. The longest distance between repeaters is 45 km. All systems use four fibres with automatic changeover in the event of fibre failure.

The NGC has not experienced any failure in its OPGW fibre optic system. A test was conducted on the Fawley-Nursling line to gain assurance of the fibre optic systems immunity to power line faults. It was arranged to drop a fuse wire from one of the 400 kV phase conductors to ground whilst monitoring the system for disturbances. During the test, no increases in BER were recorded.

It was also on the Fawley-Nursling line that the effects of what was later attributed to hydrogen degradation were first observed as an incremental increase in attenuation. Although this caused considerable concern initially as the rate of incremental increase was projected to render the fibres unusable long before their projected life of 35+ years had elapsed, the condition eventually stabilised within operational tolerances. In modern cables this effect is not present.

- **OPGW (2):**

In Germany the first optical fibre aerial cable was installed in 1978 on a 110 kV line. This aerial cable consisted of three star quads and two graded index fibres. Its 1.6 km length was installed in two pieces at the lower traverse of the towers. In further projects double-armoured OPGW with up to twelve singlemode fibres and no copper quads were installed on 20 kV lines.

Since 1986 nearly 7000 km of OPGW has been installed by the German Power Utilities.

- **WRAP-ON:**

China light and Power (CLP) supplies electricity to Kowloon and the New Territories, Hong Kong, where demand increases significantly every year. To meet this commitment, CLP relies not only on generation, and transmission capacity above peak demand level, but also upon faultless communications.

When upgrading its communication network with a fibre optic system linking its Hong Kong installations with those in China, CLP considered all cable options.

Due to the climate, terrain and inaccessibility of towers for heavy plant equipment, the installation of buried cables and earthwires containing integral fibres were ruled out. CLP decided to install a wrapped optical cable containing 12 singlemode fibres onto the earthwire of the 400 kV network.

Installation of the cable commenced in February 1990 and coincided with planned outages. The complete installation was fully commissioned with full communication and telemetry systems operational a year later.

- **ADSS (1):**

East Midlands Electricity, one of the Regional Electricity Companies (distribution) in the U.K., has installed a network of optical fibre cables as part of their EMNET telecommunications project. The central link between Nottingham and Corby, via Leicester, consists of an ADSS cable equipped with 16 singlemode optical fibres - the total route length is approximately 100 km. The optical circuits provide part of an integrated digital telecommunication services network operating at 140/34/2 Mbps for telephony, data, supervisory information, telecontrol and protection for the power network.

The performance of the ADSS system since its commissioning in August 1990 has been excellent particularly following the severe blizzard which hit the region on 8th December 1990. Mechanical loads of between 8 and 21 times the normal maximum ice and wind loads were experienced by the ADSS cable - subsequent tests revealed that at the second and third windows, the attenuation of all fibres were relatively the same as when commissioned.

- **ADSS (2):**

In Germany, all dielectric self-supporting aerial cables were installed at the beginning of the 1980s on 20 kV to 380 kV, but only in field trials.

- **ADSS (3):**

First trial ADSS cables were installed in Holland in 1981, followed in 1985 by a commercial route of 8 km. Presently there is about 40 km installed.

- **ADSS (4):**

In the USA installation of ADSS started in the mid 1980s. Nowadays there is more than 1000 km of ADSS installed in systems with voltages higher than 100 kV.

3.11.2 Overview of commercial and legal considerations

The capital cost of a fibre optic system is high when compared to other options such as microwave radio. The benefits of fibre optic systems do however include freedom from external influences such as Electro Magnetic Interference (EMI) both from internally induced factors (switching transients) and externally induced factors (interfering radio systems).

Furthermore, the fibre systems do possess inherently wide bandwidths which, in many instances, will preclude any possible use of radio systems.

In general the economic considerations taken into account when planning new fibre optic systems are:

- What is the return on capital invested and what additional maintenance costs are concerned with the installed fibre optic system?
- What is the competitiveness of other conventional telecomms systems against the proposed optical systems (i.e microwave radio)?

Other considerations need to be given to using groundwires, buried and overhead cable and their prices compared. Some consideration may also be given to security of communication.

It can be noted that some companies do not pay prime attention to economical consideration especially the Japanese who take technical considerations as the main criteria.

The other forms of telecommunications systems considered are mostly UHF/Microwave radio applications. However, some PLC and PTT services are also taken into account.

When carrying out economical surveys the main things considered by companies are:

- Existing power line routes
- Equipment and installation costs
- Capacity and terrain

Table 6 below shows the general trend for replacement of existing communications links being planned by those who responded to the CIGRE Report N° 58 [4] questionnaire.

Type of system	Date of replacement	System capacity	Number of systems
Microwave	1989	283 ch	31
PLC	1990	34 ch	4.5
PTT links	1990	88 ch	28

Table 6 General planning trend replacement of telecommunications links

It should be noted that the date of replacement, system capacity and the number of systems are all mean values, calculated from the results given by the companies who answered for each system type.

In general 35% of companies who replied indicated that they would consider joint ventures in fibre optic systems with a third party. Of these companies, 30% said they would opt for separate fibre in a common cable. The joint venture might be owned as a whole or by individual share holders.

20% of companies said they would create a new business by renting fibre optic services to external users. About half the companies involved said legal restrictions would play a part.

4 INTRASTATION COMMUNICATION SYSTEMS

4.1 Functional and Economic Requirements

4.1.1 Introduction

The following statements are preliminary. The detailed requirements are under consideration by CIGRE WG 34.03 and will be published in a later document.

4.1.2 Data Rate

The more fibre optic communication is used in intrastation applications the more will it be possible to use higher data rates than with present galvanic intrastation communication systems which are typically limited to 9.6 kbps.

In order to determine the required data rate the following considerations can be made:

- The most critical application is digital busbar-protection, which needs the transfer of a limited number of sampled analogue values, resulting in a data rate of about 1 Mbps. This is an example of a dedicated inter-bay unit level communication.
- On the bay unit control station level much more analogue values are needed for different purposes. However, for these applications the sampled waveform is not required, but only the RMS values are needed. This again results in a data rate of about 1 Mbps as a maximum.
- Normal inter-bay unit protection systems (e.g. blocking signals, breaker failure signals) need response times on the communication system of less than 10 ms - a data rate of 10 kbps is sufficient for this purpose.
- Although systems with 10 Mbps or more are available or are under discussion for future standards, it must be considered that these systems are usually based on buses with non-deterministic access mechanisms. If they have to be modified in order to have guaranteed maximum response times in all situations, the useable data rate under these circumstances is then reduced by up to two orders of magnitude.

A data rate of 1-2 Mbps seems to be able to cover all practical needs in modern substation control systems. It is therefore not required to ask for systems with significantly higher rates. In very large substations, where this rate might still be too small, it might also for other reasons like availability, be advisable to split the communication system into several subsystems linked together via gateways.

Independent from the basic requirements, higher data rates are at least today prohibited by economic reasons.

4.1.3 Response Time

For protection applications the response time of the inter-bay unit communication must be below 10 ms (guaranteed value in all circumstances). Where buses with non-deterministic access mechanisms are used, this requirement must be fulfilled with additional mechanisms in the protocol.

Response time is normally less critical in telecontrol applications.

4.1.4 Topologies and distances

Figure 47, as given by CIGRE WG 34.03, shows the different kinds of data flows relevant in a substation.

The following flows are part of the intrastation communication system under consideration in this chapter:

1. Intra-bay unit communication (between devices in one bay)
2. Inter-bay unit communication (between different bays/units)
3. Bay unit control station communication (between bay unit and control station)
4. Intra-control station communication (between devices in control station).

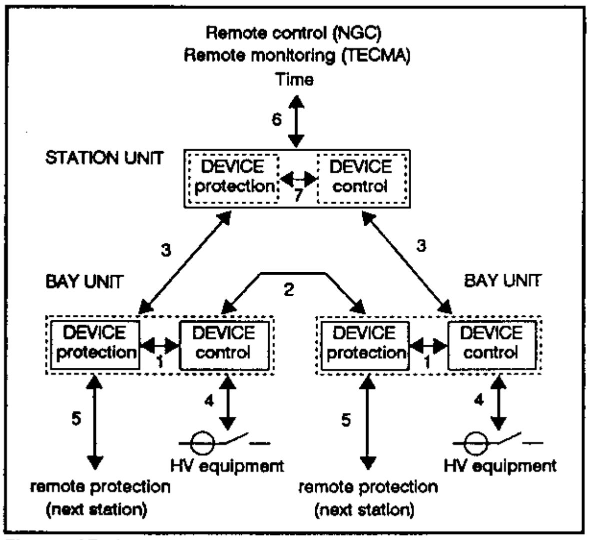


Figure 47 Data flows in the substation

A typical number is 20 bays/bus, although numbers of up to 100 bays/bus are discussed (which is however a rather theoretical figure).

From the reliability point of view optically tapped line structures with provision for alternate routing (through protection switching or ring structures) are preferable. The main problem involved with optical tapping is the power budget - however with today's technology sufficient numbers of taps are possible. If this is still the limiting factor, the communication system can be split into several subsystems with gateways.

Systems with centralised star couplers avoid the tapping problem, but they are normally sensitive to the availability of the active central star coupler with its multiple electro/optical conversion. Also, if the function of the star coupler is interrupted, the whole network is dead - in contrast to a failure in a node of a tapped line structure.

The transmission distances can be derived from typical station sizes. High voltage stations with conventional outdoor technology are typically 1000 m by 1000 m (maximum 2000 m). Stations with Gas Insulated Switchgear (GIS) technology are up to ten times more compact - however, in practical stations some GIS parts are often combined with conventional outdoor parts, so that the distances remain comparable with purely conventional stations.

Independent of the implementation, the intrastation communication must support the highly decentralised substation control and protection systems, and provide a graceful degradation in case of loss of single components/links.

4.1.5 Availability

One of the least reliable parts of a system is still the power supply. In order to get acceptable overall availability, it is required that the system must be immune against power supply failure in one single bay/unit (e.g. by passive optical tapping or by optical bypass relays).

4.1.6 Long term reliability

Although it is accepted that the lifetime of modern electronic systems is reduced as compared to old hardwired solutions, new systems must nevertheless be able to work for tens of years.

This requirement is a severe restriction for plastic fibres, the longterm performance of which is still not completely known. Also low cost snap-in connectors for plastic fibres have shown problems in applications where vibrations may occur.

Concluding, also for intrastation communication systems glass fibres with mechanically solid connectors (e.g. ST connectors) are recommended.

4.1.7 Environmental conditions

For intrastation communications, cables are normally laid into cable ducts. This eases future repair and extension works. The environmental requirements are therefore comparable to those for interstation communication systems using cables in ducts, eg. rodent protection and water resistance of the cable has to be considered.

4.1.8 Operational requirements

Although for the different data flows diverse technologies can be used to minimise the total investment amount, and overall cost consideration often asks for one single technology (spare part management, training cost, risk of faults, etc).

This is particularly true for the choice of the type of fibre. On some links, eg. within a GIS part, low cost plastic fibres could be used, whereas for longer links glass fibres are mandatory. However, if only glass fibres are used within the station (which could be the same type as for interstation communication, i.e. preferably singlemode fibres), considerable operational savings may result.

For the system cabling normally the same crews are used as for traditional systems. The handling of the cables should therefore differ little from traditional cable handling techniques (forces and radius' applied, etc).

4.1.9 Economic requirements

As a lower limit for the cost of a fibre optic intrastation communication system, the cost of a hardwired serial bus or of parallel hard wiring can be used in not too complex cases. A case by case study on purely economic grounds will hardly explore the additional benefits of using optical fibres.

As an upper limit for the cost of a fibre optic intrastation communication system a reasonable percentage of the total cost of the substation control system or the cost of marshalling and cabling of parallel wires in complex stations may be used. Today's substation control systems present a significant cost advantage as compared to traditional substations control with extensive and rather high current cabling. The communication system is an integral part of the whole substation control, so that only the whole system may be compared to the former situation.

4.2 Cable Types

Cables are available in a wide variety of designs to suit the particular application of substation site cabling under consideration. Intrastation cables can be subdivided into two main groups:

4.2.1 External Cables

All external cables, both duct and buried, must be designed to have a sufficiently wide temperature performance range. They must have a level of flexibility allowing easy installation and must be sheathed in materials which have good resistance to the effects of chemicals and ultra-violet radiation.

These cables are required to connect separate offices/buildings within an enclosed site and will be subjected to a range of environmental effects. A full description of cables suitable for this application is given in 3.4.5 *Underground duct and direct buried cables.*

4.2.2 Internal Cables

These cables are generally used to connect the external cable to the line terminal equipment and have specific requirements which distinguish them from external cables.

They are not generally subject to the same mechanical forces as are their external counterparts, nor do they have to contend with the problems of moisture ingress, rodent and termite attack. They do however have to be installed often in restricted spaces and therefore require a high degree of flexibility and handleability.

Taking all these factors into account, internal cables are generally non-metallic, strengthened by the inclusion of aramid yarn, unfilled and highly flexible. The fibres are individually sheathed to assist in handling and connecting activities.

One major consideration regarding internal cables is their performance in the event of a fire. Prime features of the materials used in these cables, particularly the sheathing materials, is that they exhibit minimum flame spread, low smoke emission and minimum toxic emission.

5 STANDARDS

Standards are required to assist both manufacturers and users in providing a common understanding of requirements for production which identifies an expected performance. Standards which are relevant to the subjects covered in the guide for both interstation and intrastation applications are set out below.

5.1 Standards for Optical Components

The IEC and related bodies have standards for Fibres, Cables, Connectors, Fibre Optic Couplers, Wavelength Division Multiplexers, Optical Switches, Relays etc.

5.1.1 Optical fibres and cables

At the international level the IEC committee TC86A is covering the development of recommendations for optical fibres and cables. The fibre optic interconnecting devices and passive components are covered by IEC TC 86B.

The IEC 793 publication establishes a set of uniform requirements for the geometrical, optical, transmission, mechanical and environmental properties of optical fibres for use in telecommunication equipment and in devices employing similar techniques.

Part 1 covers measurement methods for dimensions, mechanical characteristics, transmission and optical characteristics and environmental characteristics.

Part 1 has been revised to include additional information on issues like numerical aperture, attenuation measurement and definition, frequency response, impulse response. Insertion loss technique and cut-back technique are under consideration.

Part 2 provides a product specification for single and multimode fibres, defining four categories of multimode fibres and three categories of singlemode fibres according to, for example, the fibre dimensions and optical loss.

Part 2 has been revised to include additional information on different categories of fibres.

For short distances Central Office document 44 (May 88) describes type A2 fibres (step index up to 2 km), A3 (glass core, plastic cladding fibre, up to 1 km) and A4 (plastic fibre, up to 100 m).

The following CCITT recommendations for optical fibres are already in wide use and should be used as reference:

- G.651 50/125 μm multimode graded index optical fibre
- G.652 singlemode optical fibre
- G.653 Depressed clad fibre
- G.654 Dispersion shifted fibre

Cables

Publication IEC 794 covers fibre optic cables. Part 1 contains measurement methods for mechanical characteristics and environmental characteristics. Part 2 describes single-fibre cables for indoor use with applications such as transmission equipment, telephone equipment, data processing equipment and communication and transmission networks. It specifies construction, dimensions and packaging.

Attenuators

The publication IEC 869 describes optical attenuators. The optical, mechanical and environmental test and measurement methods are described. Attenuators are grouped into variable and fixed types. The variable types are further grouped in continuous, stepwise and continuous and stepwise types. Test and measurements methods are described together with the quality assessment procedures.

Connectors

The publication IEC 874 describes the requirements for optical demountable connectors.

Part 0 gives general recommendations for connectors, classification, mating faces and gauge information. Also the quality assessment procedures are covered.

Part 1 contains generic specifications for optical connectors. It covers terminology, classification, marking etc. The quality assessment procedures and measurement and test methods for dimensions, optical properties and mechanical tests are covered, as well as environmental test procedures.

Part 2 specifies the fibre optic connector type F-SMA which has the same mechanical mating dimensions. It is based on the electrical SMA connector. The standard covers the socket interface of all components but not quality assessment procedures. The specification prescribes interface dimensions for such connectors together with gauging requirements. Also prescribed are tests selected from IEC 874-1 applicable to all detail specifications. The dimensions ensure mechanical intermateability between connectors of this type. The tolerances required to produce a specific optical performance are given in the detail specification.

Branching Devices

Publication IEC 875 describes branching devices. These are subdivided in families to be treated in separate sectional specifications. The branching devices contain no opto-electronic or other transducing elements. They have three or more ports being optical or optical connectors exclusively.

The most useful component is covered in Part 2 and applies to transmission star couplers having an arbitrary number of input and output ports. In these devices the input light is shared by the output ports. The set of ports are reversible in that if one of the output ports is used for input then the input ports are output ports for this input light. Central Office document 44 further subdivides the devices in families:

- Transmissive star branching devices.
- Reflective star branching devices.
- Combined reflective/transmissive star branching devices.

Optical Wavelength Multiplexing is described in Section 2.2 *Coherent Fibre Optic Transmission Systems*. These devices have one channel on which signals can be transmitted multiplexed and N channels where the multiplexed signals can be transmitted demultiplexed.

Fibre Optic Switches

Fibre optic switches are covered by publication IEC 876-1. It contains quality assessment procedures, together with standard optical, mechanical and environmental tests and measurement methods.

Splices

In Central Office document 48-I&II a generic specification for fibre optic mechanical splices and accessories is given. Splice categories and interchangeability are described together with optical, mechanical and environmental performance test methods.

Further in 85B(Sec)135, fusion splices for optical fibres and cables are specified, while 86B(Sec)134 specifies the splice organisers and enclosures for optical fibres and cables.

5.1.2 Connectors

A range of connectors are being considered. Central Office documents 34, 33 and 28 describe connectors type OF-2, D and FC while Secretariat documents 129, 128 and 127 describe connectors OCCA-PC, OCCA-BU and ST respectively.

5.1.3 Standards for fibres, connectors and cables

The CCITT has recommended comprehensive specifications for both multimode (MM) and singlemode (SM) optical fibres (ref G.651 and G.652) and for depressed clad (ref G.653) and dispersion shifted singlemode optical fibres (ref G.654).

The specifications detail the preferred characteristics for multimode operation at 850 and 1300 nm, while the singlemode fibres are characterised for operation at 1300 and 1550 nm. It is not proposed to reproduce the entire specifications in this paper, but the fibre characteristics specified include core diameters, concentricity errors, non-circularity, and dispersion. Both recommendations also cover preferred methods of standardised testing. International Electrotechnic Committee (IEC) recapitulates CCITT recommendations and has complemented them with environmental tests in IEC 794.

Whereas the both multimode and singlemode fibre characteristics are well defined, there are a great variety of fibre optic connectors in use throughout the world. In the beginning of the 1980s, the FSMA connector was very often used but as it did not have good performance, many manufacturers developed other specific connectors. In Europe: Diamond HMS-10, to DIN 47256 or Radiall MFO, in USA, Biconic, in Japan FC, connectors. In 1985 AT&T developed the ST connector which is the connector most often used in multimode applications.

For singlemode use the FC is usually offered as the 'standard' by both terminal and test equipment manufacturers and enjoys a high degree of popularity. Now with the pending introduction of DFB (high power) semiconductor laser which are reflection sensitive, EC and SC connectors are normally specified because they have a high 60 dB return loss performance. As EC and SC are much less expensive than other connectors they are emerging as the future industry standard connector. See Section 9.3 *Types of Demountable Connectors* for a detailed description.

However, a Power Utility should set out to standardise on one particular connector for use throughout the company. If this is not done, the additional modules required for test equipment will be very expensive as there are no optical connector adapters.

5.2 The ISO Basic Reference Model for Open Systems Interconnection

5.2.1 General description

The basic reference model (ISO 7498) has seven layers. A detailed description of how they were chosen is as follows:

Layer 1: It is essential that the architecture permits usage of a realistic variety of physical media for interconnection with different control procedures (for example V.11, V.28, etc.). The Physical Layer is the lowest layer in the architecture.

Layer 2: Some physical communication media (for example telephone lines) require specific techniques to be used in order to transmit data between systems despite a relatively high error rate (i.e. an error rate not acceptable for the great majority of applications). These specific techniques are used in data-link control procedures which have been studied and standardised for a number of years. It must also be recognised that new physical communication media (for example fibre optics) may require different data-link control procedures. The Data Link Layer sits on top of the Physical Layer in the architecture.

Layer 3: In the open systems architecture, some open systems will act as the final destination of data. Some open systems may act only as intermediate nodes (forwarding data to other systems). The Network Layer sits on top of the Data Link Layer. Network oriented protocols such as routing, for example, will be grouped in this layer. Thus, the Network Layer will provide a connection path (network- connection between a pair of transport-entities; including the case where intermediate nodes are involved.

Layer 4: Control of data transportation from source end open system to destination end open system (which is not performed in intermediate nodes) is the last function to be performed in order to provide the totality of the transport service. Thus, the upper layer in the transport-service part of the architecture is the Transport Layer, on top of the Network Layer. This Transport Layer relieves higher layer entities from any concern with the transportation of data between them.

Layer 5: There is a need to organise and synchronise dialogue, and to manage the exchange of data. This function is carried out by the Session Layer which sits on top of the Transport Layer.

Layer 6: The remaining set of general interest functions are those related to representation and manipulation of structured data for the benefit of application programs. This function is carried out by the Presentation Layer which sits on top of the Session Layer.

Layer 7: Finally, there are applications consisting of application-processes which perform the information processing. The application processes and the protocols by which they communicate comprise the Application Layer as the highest layer of the architecture.

The resulting architecture with seven layers is illustrated in **Figure 48**.

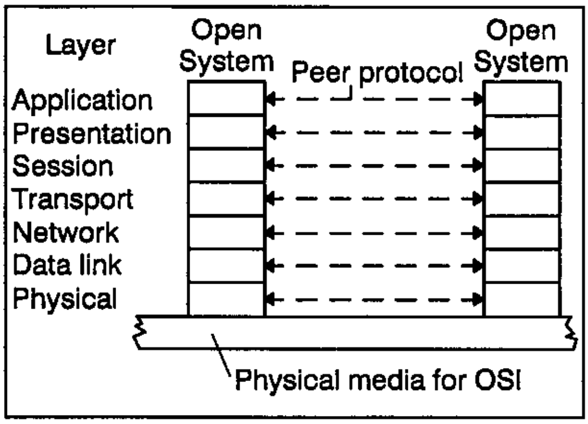


Figure 48 Open Systems Interconnection (OSI) stack

A few points concerning the model are highlighted in the following:

The open system is viewed as being logically composed of an ordered set of subsystems, represented as a vertical sequence. Subsystems of the same rank (N) collectively form the (N)-layer of the basic reference model. Layers are denoted relative to the (N)-layer. Eg. the layer above (N)-layer is denoted (N+1)-layer. Adjacent subsystems communicate through their common boundary.

Except for the highest layer, each (N)-layer provides (N+1)-entities in the (N+1)-layer with (N)-services. The highest layer is assumed to represent all possible uses of the services which are provided by the lower layers.

The services of an (N)-layer are provided to the (N+1)-layer, using the (N)-functions performed within the (N)-layer and as necessary the services available from the (N-1)-layer.

Several principles have been applied determining the seven layers in the reference model, and it is difficult to prove that any particular layering selected is the best possible. However, there are principles which can be applied to the question of the number of boundaries and of where a boundary should be placed. Mentioned for the definition can be:

- Create a boundary where the description of services can be small and the number of interactions across boundary are minimised.
- Create separate layers to handle functions that are manifestly different in the process performed or the technology involved.
- Collect similar functions in the same layer.
- Select boundaries at a point which past experience has demonstrated to be successful.
- Create a boundary where it may be useful at some point in time to have the corresponding interface standardised.
- Create a layer where there is a need for a different level of abstraction in the handling of data, for example morphology, syntax, semantics.

It is important to note that OSI per se does not require interfaces within open systems to be standardised. Moreover, whenever standards for such interfaces are defined, adherence to such internal interface standards can in no way be considered as a condition for openness.

5.2.2 Conformance testing

Recognising that the objective of OSI will not be achieved unless systems can be tested to establish whether they conform to the relevant standards, ISO has developed definitions of common test methodology, methods and procedures. These provide the framework for specific conformance test suites and the procedures to be followed during testing.

The purpose of conformance testing is to increase the probability that different implementations are able to interwork. However it should be borne in mind that the complexity of most protocols makes exhaustive testing impractical on both technical and economic grounds. Also testing cannot guarantee conformance to a specification since it detects errors rather than their absence. Thus conformance to a test suite only gives confidence that an implementation has the required capabilities and that its behaviour conforms consistently in representative instances of communication.

ISO 9646 is applicable to the different phases of testing including the specification of an abstract test suite, the realisation of executing specific test suites and the conformance assessment and test reporting by a test laboratory.

The standard consists of five parts:

1 General concepts including tutorial.
2 Abstract test suite specification.
3 The tree and tabular combined notation.
4 Test realisation.
5 Requirements on test laboratories and clients for the conformance assessment process.

Often certification is following a conformance test process. This is not covered by the standard.

Conformance testing of different implementations requires some experience with open systems. It is therefore not recommended to users who do not specialise in this field to interconnect different systems without clear interworking guarantees from the suppliers.

5.3 Standards for Interstation Communication Systems

5.3.1 Standards for terminating equipment

The CCITT has developed recommendations for standards of terminating equipment (G.700 series). Without exception, all 'mainline' telecommunications systems which employ fibre optic transmission media use digital multiplexed signals. However, throughout the world, there are effectively two digital standards in widespread use. The European Hierarchy based upon a 30 channel primary multiplex building block with an output bit rate of 2.048 Mbps, and higher rates of 8, 34, and 140. The North American Standard based upon a 24 channel primary multiplex building block with an output bit rate of 1.544 Mbps, and higher rates of 6.3, 45 and 98 Mbps.

The European PDH Hierarchy is almost universally adopted by every PTT administration outside North America and Japan, but for reasons of compatibility with national standards and interlinking a private network to the PTT, the national standard should be adopted.

5.3.2 Standards for equipment interfaces

There are a wide variety of different interfaces available for almost every conceivable variety of user interface.

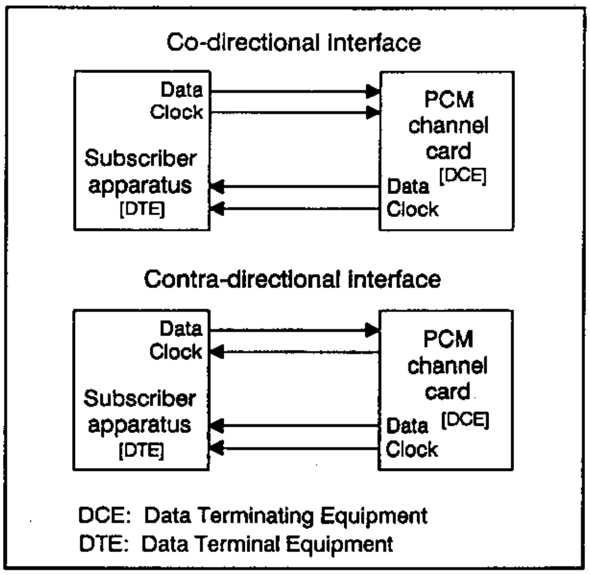


Figure 49 Co-directional and contra-directional interfaces

Commonly used interfaces for analogue connection include:

- 2 wire interface
- 2 wire interface with DC loop signalling
- 4 wire interface
- 4 wire interface with E & M signalling

However, there is no reason why user specific interfaces could not be manufactured or deployed.

As the digital frame structure is based upon a 64 kbps channel, direct interfaces will invariably be at this speed. Where lower speed data has to be carried, multiplexing of the slower signals into a 64 kbps stream may be done by using an external data concentrator or by submultiplexing boards in the multiplexer itself. Thus the digital connection at 64 kbps will probably be:

- 4 wire co-directional interface, and
- 2 wire contra-directional interface.

Typical arrangements using these types of interfaces are shown diagrammatically in **Figure 49.**

The co-directional interface will be found in single stand-alone links where it is permissible for the link to be synchronised to the subscriber's apparatus. Contra-directional interfaces are deployed where the path forms part of a larger network which itself is synchronised to a national standard or to the Power Utility network. In this case, the terminal sends a reference clock to the subscriber's apparatus for internal synchronisation of its output signal. The CCITT has developed a series of recommended interface signal levels for such services. For analogue signals, the multiplex interface cards will generally receive and transmit levels between +7 and -16 dBm (CCITT rec. G.101); most equipment manufacturers incorporate on-card user adjustable attenuators for level setting. The 64 kbps digital interface will invariably be to CCITT Rec. G.703 which accurately defines not only voltage levels but also bit masks.

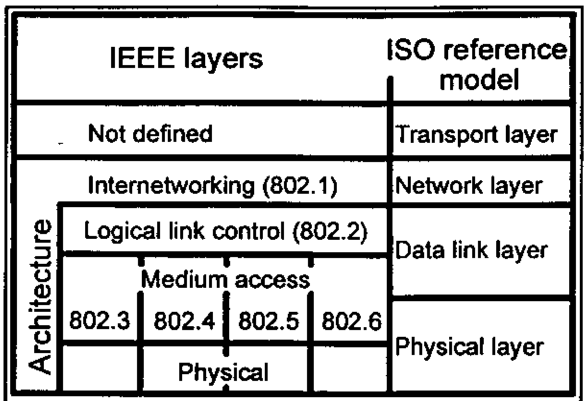
One of the main advantages of digital systems over their analogue counterparts is that of high noise immunity. This makes their deployment an attractive proposition within a Power Supply context. However, care must be taken in hardware selection to ensure that rises of ground potential does not create bursts of excessive BERs through inappropriate methods of marshalling signal grounds.

It is appropriate to mention that the manufacturers of protection systems have long realised the advantages of digital transmission in their applications, and now that the digital telecommunications systems are becoming a reality, they are introducing equipment which will interface to such digital systems.

5.4 Standards for LANs and Intrastation Communication Systems

5.4.1 IEEE Local Area Networks (LAN) [2]

Most of the standardisation work on LANs has taken place within the IEEE 802 committee. They have defined a family of standards (see **Figure 50**) for various ring and bus LANs. There is a separate standard for each type of access control which also covers aspects which are normally considered part of the physical layer. The logical-link sublayer is concerned with protocol issues such as error and flow control between a pair of stations and is independent of the type of medium access control. Note that the IEEE 802.1 standard covers both network architecture and inter-networking. **Figure 50** also shows the relationship of the IEEE sublayers to the ISO reference model. In this clause the medium-access mechanisms for rings is first covered and then those applicable to serial buses. Wide Area Networks (WANs) often use full duplex point-to-point channels, so



802.3 = Carrier sense multiple access bus with collision detection
802.4 = Token passing bus
802.5 = Token passing ring
802.6 = Metropolitan area network on a broadcast bus

Figure 50 IEEE LAN standards

no mechanism for sharing is needed. However, multidrop links are sometimes used to connect remote terminals to a central computer. The ISO standards have numbers like the IEEE preceded by 8, eg. IEEE 802.1 equals ISO 8802.1.

Token ring

Token passing rings are very popular in proprietary LANs, as they cater for variable-length messages and can be adapted to allow priority - based access. Prime and Apollo both market token passing rings as a basis for interconnecting their own machines. IBM appears committed to this type of ring for their long-term LAN technology. The following description is based on the IEEE 802.5 token ring. Token passing is also used in process control oriented systems.

A token circulates round the ring giving the stations permission to transmit. Only one station on the ring (the token holder) can be transmitting at any time. A station can only transmit a message when it receives a token marked 'free'. It changes the token to 'busy' and transmits its message immediately following the busy token.

When a station transmits a free token, the next station downstream has an opportunity to seize the token and transmit a message. Thus in heavy load conditions, access to the ring is scheduled 'round robin'. Knowing the maximum message length it is possible to calculate maximum delay for access to the ring.

The token contains a priority indicator. A station with a high-priority message to transmit can insert its priority level in a busy token.

One station is designated as an active monitor and it is responsible for detecting loss of the token or a continually circulating busy token.

The main disadvantage of the token ring is the complex token management required. Also a bypass mechanism is needed in the ring interface to cope with station power failure. The advantage of the token ring is that it caters for variable-length messages and has defined delays. Error reporting allows the isolation of faults to a particular station or link between stations.

Ethernet-CSMA/CD serial bus

Ethernet is a serial bus LAN developed by Xerox which is now being promoted by Digital, Intel and Xerox. It is the basis of the IEEE 802.3 LAN standard, which is being standardised by ISO. The Ethernet was aimed at office-automation and resource-sharing applications rather than industrial ones. It uses a coaxial cable with baseband signalling and a data rate of 10 Mbps. It can be used to interconnect up to 1024 stations over a maximum distance of 2.5 km. The service provided is a datagram. A cyclic redundancy check is used to detect errors and a message may be discarded, so higher layers (above the data-link layer) must be used to provide error recovery.

Although the Ethernet is essentially a broadcast bus, using coaxial cable as a transmission medium, it is possible to have branches off the bus. The connection to a branch is via a repeater which does not have any store and forward action. There must be only one path between any source and destination so that a signal does not arrive at a destination via paths of different length, as this would result in interference. Using coaxial cable it is possible to tap into the Ethernet at any convenient location. The Ethernet principles could be applied to other transmission media, eg. radio.

Control of access to the transmission medium is completely distributed amongst all stations and makes use of the following mechanisms.

A station, wishing to transmit a message, first listens for the carrier and defers transmission until the bus is quiet. It is possible that two or more stations will find the bus free and so start transmitting simultaneously, ie. a collision may occur. The station's transceiver receives the signal from the transmission medium while transmitting and compares the received data with that just transmitted. Thus if a collision has occurred the received data will be in error and so the transmission is aborted. After detecting interference the colliding stations stop transmitting and timeout for varying (random) periods before trying again. The randomness of the timeout intervals are calculated on the number of collisions thus as the Ethernet becomes heavily loaded and collisions occur more frequently the timeout intervals increase.

The ethernet is very efficient in that the utilisation can be between 80% and 95% of the channel capacity, depending on average message length. However, it should not be loaded above 50% as delays increase. Measurements have shown that channel capacity is equally shared by all stations but the probabilistic nature of the operation means that it is not possible to guarantee a finite delay on a particular message as can be done with rings and token buses, when errors are ignored. Errors make the performance of all communication systems probabilistic. When highly loaded, the probability of collisions becomes comparable to the probability of noise errors. Because the access control mechanism is very fast the probability of transferring data with a given delay is comparable with, if not better than, most other mechanisms.

Because the minimum message length is defined by the slot time, CSMA/CD is impractical for very high-speed buses (710 Mbps). The requirement to listen while transmitting makes the design of the transceiver rather critical and requires the use of expensive high-quality coaxial cable.

Token-passing serial bus

The IEEE adopted as the preferred media access method for General Motors' Manufacturing Automation Protocol (MAP). The token bus has the advantages of a passive bus but gives deterministic access times for real-time applications.

The stations connected to the bus form a logical ring. The station possessing the token controls access to the channel. The token is passed in an ordered sequence around the stations connected to the bus.

The token passing bus has very complex token management, and the performance is worse than CSMA/CD for light loads. However, it is superior in performance under heavy loads. If there are no errors, it is possible to put an upper bound on the delay for a particular message. The bus can be longer than that for CSMA/CD as there is no need to listen while transmitting, and so the electrical constraints are less severe. This allows the use of cheaper cables, and token passing can be used for very high-speed buses (>50 Mbps).

Broadband bus

Broadband LANs use radio frequency (eg. 5-300 MHz) modulation and so can use cable TV components. These allow splitting and joining operations so broadband topologies include both buses and trees. A number of manufacturers offer Broadband LANs, eg. IBM's PC-net, and Wang's network. Broadband is suitable for distances of tens of kilometres if amplifiers are used and so this is the basis of the IEEE 802.6 Metropolitan Network. A metropolitan network could connect tens of thousands of subscribers within a City.

The main advantage of the broadband network is its capability of mixing video, voice and data on a single cable and hence cutting the cost of laying separate cable networks. In addition the network can cover much greater distances than a baseband network. However, the cost of the physical interfaces is much greater, particularly if frequency-agile modems are needed.

Summary of 802 LANs

One of the design choices in a distributed system is whether it should use a bus or ring LAN topology. The former is a passive transmission medium if no signal regenerators are used, so is inherently more reliable. However, cable length is limited to about 1 km before signal regenerators are needed. Buses seldom use fibre optic transmission media, as tapping into these is very difficult. A ring regenerates the signal at each interface so can traverse longer distances. Because the station interfaces are active, the rings include mechanisms to cope with a station being switched off or failing, otherwise all communication over the ring will be prevented. It is easier to locate a fault on a ring as the station immediately 'downstream' will generate an error report. Locating a break in the transmission medium of a bus requires measuring the time it takes for reflections to be returned, so is more difficult. The choice of access mechanism often depends on whether guaranteed access times are required.

CSMA/CD (ie: Ethernet) is the simplest widely available access mechanism which gives the lowest average delays for a lightly loaded LAN. However, The access for a particular message is probabilistic and it does not include any priority mechanisms. Token passing over a ring or bus has a longer average delay but it is deterministic under heavy load conditions, so is favoured for real-time applications. Token passing can easily include priority. The token management needed for dealing with installation of new stations is very complex, making it more difficult to manufacture chips to support token passing. CSMA/CD is impractical for very high data rates (>10 Mbps) as the minimum message length (data rate x slot time) is too large.

Both slotted and buffer insertion rings have simpler reconfiguration management than token-passing ones, but slotted rings only cater for fixed-length messages, which is not really appropriate for distributed systems. Buffer insertion rings cope with variable-length messages, but the propagation delay can become quite large if many stations have their buffers inserted.

Broadband LANs are more suited to longer distances and can be used for mixed media (data, voice and vision) networks. However,the modems needed can be quite expensive, particularly if they handle multiple frequencies. A broadband bus has a single failure point: the head-end which can halt all communication.

5.4.2 Fibre Distributed Data Interface (FDDI)

As a result of the progress in fibre optic technology and the definition of a fibre optic based LAN, the fibre distributed data interface (FDDI) has been carried out in ISO. The standard ISO 9314 covers the physical layer and datalink layer. The protocol is designed to be effective at 100 Mbps using token ring architecture over a distance of several kilometres.

The main application areas of FDDI were defined to be:

- Data centre environments, characterised by rather few reliable stations (e.g. mainframes) placed rather close to each other giving fibre lengths not exceeding 400 m.
- Office/building environment with a larger number of units.
- Campus environment where optical links may go up to 2 km length, the FDDI typically being used for trunk lines.

The default values for FDDI were calculated on the basis of 1000 physical links and a total fibre length of 200 km (typically corresponding to 500 stations and 100 km of dual fibre cable).

The FDDI consists of a physical layer, a data link layer and a station management part. The physical layer is divided into a medium dependent (PMD) sublayer and a physical layer (PHY) protocol providing the connection between the PHY and the data link layer. The datalink layer is divided into a medium access layer and a logical link control.

The basic building block is a physical connection consisting of the physical layers of two stations which are connected over the transmission medium by a primary link and a secondary link. A primary link consists of a link connecting the output of station 1 to the input of station 2, and a secondary link connecting the input of station 1 to the output of station 2. Stations can be dual attached or single attached. The dual attachment is connected by two primary links using four fibres. Multiplexers offer attachment of more single attachments to dual stations.

The Media Interface Connector (MIC) for the FDDI connections has been submitted to the IEC/TC86B. The connector comes in four types:

- MIC A for primary in/secondary out.
- MIC B for secondary in/primary out.
- MIC M for attachment of a single attachment station to a concentrator at the concentrator side.
- MIC S for attachment of a single attachment station to a concentrator at the single attachment side.

The active input and output specifications contained in the standard are based on 62.5/125 µm fibre. Though other dimensions (e.g. 50/125 µm) could be used, the maximum distance achievable might be reduced. The wavelength is specified to be between 1270 nm and 1380 nm.

At present the chip developers have developed chip sets supporting the FDDI and the number of installations are growing.

5.4.3 Fieldbus

In distributed manufacturing or process control systems the concept of level of control is well established (see **Figure 51**). The LANs covered by the IEEE 802 series are mainly applicable to higher levels of control like plant wide redundant networks. At lower levels the LAN concepts are not that well developed.

The Fieldbus being developed by IEC TC65C/WG04 is intended to formulate a substitute for the 4-20 mA systems widely used at substations. Already several vendors are offering trial systems using a varying amount of concepts from the fieldbus standard working papers. Later a fibre optic physical standard will be developed as an addendum.

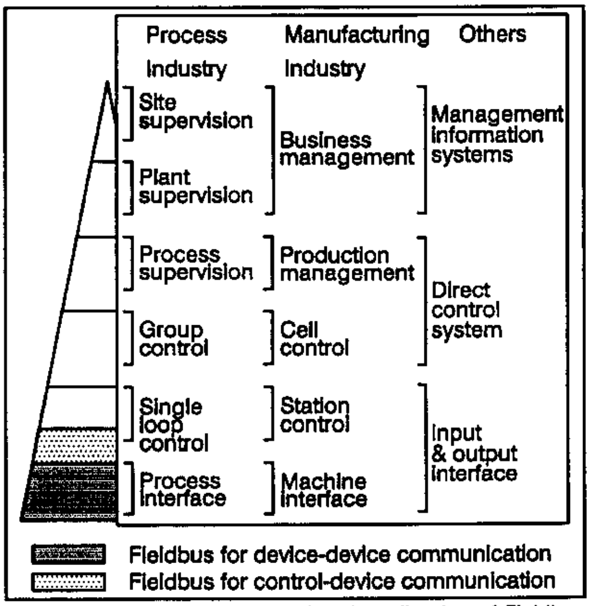


Figure 51 Hierarchy of control and application of Fieldbus

5.4.4 Standards for Communication in Substations

For interstation communication systems, the protocols to be used for telecontrol applications have been standardised by IEC (IEC 870). These standards are optimised for dedicated analogue communication channels. In order to be able to use modern packet switching networks also for telecontrol applications, new standards are under study by IEC TC57 WG07.

These standards are not directly applicable to intrastation communication systems. It is therefore necessary to have appropriate standards for the protocols within substations. The existing LAN-standard (refer to Section 5.4.1 *IEEE Local Area Networks*) often do not fully cover the requirements and, most important, do not standardise the application layer. Without that, the desired supplier-independent combination of substation equipment is not viable.

Therefore national bodies (e.g. VDEW in Germany) have started to develop the first minimum standards for numerical relays. Also IEC TC41 has initialised the work on such standards, and the CIGRE SC34 Working Group 03 deals with the same matter.

The complexity of the situation and experience with other standardisation work however leads to the conclusion that it will still take many years until a real standard exists. For the meantime, i.e. for the present and even the next generation of substation control systems, only proprietary or limited group standards (e.g. national) will be available. As a consequence of that and because systems may consist of old and new parts, a kind of interconnection possibility between parts with different proprietary protocols will be needed. For this purpose protocol converters will be available. For cost reasons, this kind of interconnection will however only be feasible on a high system level rather than on a bay level.

6 NETWORK COMMUNICATION SYSTEMS

6.1 Special Considerations for Fibre Optic Networks

Power Utility telecommunications is developing for both internal and external reasons. The basic trends are as follows:

- Digital telecommunications is replacing the analog systems. Integrated systems are feasible. The change of the technology has occurred and the power companies have to follow the changes. The technical alternatives and capacities exceed the existing needs.
- Utilities are developing administratively. Splitting of the utilities and privatisation are changing the organisations and operating methods. The needs for telecommunications are changing. Effective telecommunications is essential for any business. On the other hand, the cost of the privately owned telecommunications facility will be compared with the tariffs of the public network operators.
- Liberalisation in the telecommunications field is increasing the possibility to co-operate with other users and operators. Power Utilities will be one supplier of telecommunication services, either as bearer or even network operator.

A telecommunications network is an entity which consists of several components. The most important parts, of course, are the transmission systems. Traditionally, the telecommunications facility of the utility has developed stepwise, connection by connection. The change of the technology from power line carrier (PLC) or small-capacity radio links to digital microwave, and especially fibre systems, demands careful consideration regarding the total network concept. The preparation of a long range plan is recommended. There are a number of factors which should be taken into account. The structure of the power network, the geography, installation and renewing plan of the power lines, power plants and substations, other development plans of the utility/company, new protection schemes etc. Special consideration is required for the possibilities of co-operation with other companies, and the possibilities for entering into the telecommunications business are most important of all the other factors. Costs and risks against benefits must be evaluated. It is possible to forecast the near future but the risks increase in the long term expectations. The basic plan should be such that it can be modified dynamically should the business environment change.

Fibre optics is the one technology that has provided the most dramatic change in Power Utility telecommunications. Its telecommunication capacity is for practical purposes unlimited. Power lines provide an economic way to install new telecommunications capacity, especially in densely populated or geographically difficult areas. Administratively, fibre optics is the easiest system for Power Utilities. No frequency allocation, permission for access to external properties, etc. is needed. In addition, skills already acquired in working on power lines can be readily extended to install fibre optic technology. The only limitation deals with the licensing procedures which protect the local telecommunications utilities.

Power system control is the most important application to be supported on a telecommunications network. Operational telephone network has a similar topology, except that generally there are more connections into the main central office. The connections for teleprotection are mainly between two points on the network. Services may pass through several stations and therefore the network availability and performance will require consideration.

The power transmission network is normally connected in a series of loops of varying sizes. This is a very useful topography for high security protected fibre telecommunications systems. If all the power lines could be provided with fibres this would be a perfect solution. If some part of the loop is needed only for reserve use, the cost of the loop construction may be too high for the benefit obtained. In such cases where it is important to provide a back-up route, digital microwave can be applied to complete the loop. Due to the reduced transmission capacity of the microwave link the back-up facilities may be limited to the most important services.

The development of fibre network topology follows in many cases a natural development trend: separate lines equipped with fibres - local fibre networks - fibre backbone network. The time schedule to construct a utility-wide network may be a period between ten and twenty years due to limitations on cost effective financial investment.

Details of the fibre network are various. Highest voltage power lines are located in the areas outside the cities. The distances between substations may be very long in these lines, demanding repeater stations outside substations. These lines have normally a high availability. Although fibre system costs are proportional to distance, the fibre option may be still justifiable, because the fibre cost is often a small portion of the total project cost. The medium-voltage lines are located between cities and the distances between cities are fairly short. Extra repeaters are not normally needed.

CCITT has standardised the fibre connections into the following categories:

- Intra-office: distances less than 2 km
- Short-haul inter-office:approximately15 km
- Long-haul inter-office: approximately 40 km in the 1300 nm window and approximately 60 km in the 1550 nm window.

The capacity potential of the fibre systems has changed the standardisation of the telecommunications and led to new SDH-Standards. See Section 2.1 *New Concepts with Time Division Multiplexing*.

Broadband-ISDN standards are also developing and the principle is based on very high-speed switched services.

6.2 Integration Into Existing Systems

Nearly all fibre systems are digital. Their connection into analogue networks is made at the lowest level: either speech channel or data modem. This kind of connection is needed as long as any analogue part of the network exists. There are no major problems in the procedure.

Integration of fibre systems into the digital microwave environment is made by applying normal digital interfaces.

Fibre system terminals are located in the substation telecommunications room. The radio link station may be located outside the substation. The cabling between the radio station and substation is recommended to be based on fibres, because the interconnection is easier and risks of local earth potential difference problems due to lightning strike or power system fault are eliminated.

Protection switching between parallel systems is technically applicable for digital signals. 2 Mbps protection switching is standardised and may be located in a separate multiplex terminal, in the fibre optic terminal or in the radio link terminal.

Extra fibres within the cable are useful in providing economic growth during the development of a telecommunications network. Interconnections along the route may be organised in the way that the low-capacity connections are collected to the end of the line. Digital branching may be applied to minimise terminal equipment costs.

All equipment should be in accordance with CCITT standards, where applicable, to be able to interconnect by standard digital interfaces. Various systems are available. The special features for Power Utility applications deal mainly with teleprotection. Integrated fibre terminals for teleprotection, data and speech can be applied in separate substations which have fibre connection.

Separate 2 Mbps links to every substation is normally a waste of capacity in the existing environment where normal RTU data channel, operational telephones and command-type telecontrol connection is required to be supported. This is the usual case when a new telecommunications system is installed in the existing network. A normal practice is to connect several substations into a common 2 Mbps signal. Each substation will have a branched or drop-insert access to the connection.

When installing new high-voltage substations which have either efficient teleprotection needs or any other data needs than traditional RTU data channel, 2 Mbps connection is recommended. This does not demand a separate fibre because there are systems which branch one or several 2 Mbps signals from a higher rate signal.

Planning of the fibre system demands the allocation of splice joints with the associated joint boxes along the power line. It is worthwhile to try to locate the joints where the new branches and connections will most likely be needed in the future.

Consideration should be made to the upgradability of the network. For upgrading from one system level into a higher one when it is desired to maintain regenerator spacings for the original and upgraded system, the following options are available:

- The original system design may be based on the highest demand in future.
- If the original system operates in the 1310 nm region, then the upgraded system may be chosen to operate in the 1550 nm region to obtain lower cable attenuation, although with increased dispersion penalty which may limit the optical line rate.
- Relatively cheap high-loss components (e.g. connectors) may be replaced with more expensive lower-loss components for the upgraded system.

6.3 Reliability, Availability and Redundancy Considerations

Availability definitions and principles are explained in Section 3.2.2. *Reliability and availability considerations*.

The needs of the services are different. The basic services are listed as follows, in order of priority:

- Teleprotection
- Telecontrol
- Operational telephone
- Others

The needs of teleprotection vary but need to be established, based on proven protection principles. The needs are high for both availability and speed. In many cases, the teleprotection connections are duplicated in order to secure high availability.

Telecontrol also requires high availability which normally demands doubled routes in the network between control centres. Connections to outstation RTUs may also be doubled.

The structure of the telephone network is naturally such that alternative connections between exchanges are in existence. The subscriber lines are not normally doubled.

Network availability itself is difficult to specify generally and is dependent on the total concept of fault tolerance of the network. From the service point of view, unavailability is caused either by a fault in the system or by a deep fading in a microwave path. Short error bursts occur in every digital network. For most services they do not cause any harm, but for example telefax messages will partly be destroyed by errors. Therefore, the quality of service depends on availability and performance of the network. CCITT has made a general rule: all the failures lasting less than ten seconds are allocated into degraded performance category. Severe disturbances and breaks, lasting more than ten seconds, are unavailable time. This division is useful to apply in Power Utility networks, because the method of measuring with standard equipment assesses performance to the same criteria. The criteria is applicable for services other than telecontrol and protection which may need some additional study.

Availability of fibre systems is based on both power lines and fibre components. There is no fading or other statistical disturbance. In particular there is no loss of communication during a power system fault. If errors occur every now and then, there is probably some hidden fault which needs investigating before it manifests itself into a complete failure. In this respect, fibre systems have a better performance than any other transmission system. The fibre systems are dependent on the reliability of the power lines. The reliability can vary considerably, case by case. Most of the failures in power lines do not cause a failure of the fibre connection. If a cable failure does occur the time taken to repair may be long. Temporary jointing or jumpering methods may be needed. The design of the network needs to take into account the long time to repair when considering overall availability requirements.

Redundancy is applied with several methods:

- Network redundancy, alternate routes, loops
- Double routes with different techniques (fibre, microwave, PLC, public network)
- Several fibre cables (expensive)
- Several fibre pairs in use or easily put into use
- Protected terminal equipment

Redundancy can be activated either automatically or manually. Examples of the manual reconnections are the changing of the fibre pairs in the cable or changing of channels from fibre system into microwave.

Automatic redundancy is already present in data and telephone systems where there are several alternative routes in the network. Automatic redundancy between two points demands some active component. CCITT has standardised switchover terminals, applying 1+1 or N+1 principle. There is a mechanism to monitor the quality of 2 Mbps signal and switch it to the alternative path if required. 1+1 principle means that there is a spare connection available to one 2 Mbps signal. N+1 principle means that there is one spare 2 Mbps for several active connections.

The fibres in the power lines are dependent on the condition of the power lines. It means that the major failures of the power lines simultaneously interrupt the data traffic in the fibres. The biggest problem is caused to the teleprotection: if the line is severed no signal can be transported. Most other failures of the power network components do not cause any immediate degradation to a telecommunications data link.

6.4 Telecommunications Management Systems (TMS)

A network management system is a necessity for an integrated telecommunications network. The structure of the telecommunications management systems is based on hierarchies. The lowest level is always a separate item of equipment or unit of telecommunications system. This unit contains either traditional relay-based alarm interface or an active alarm/control sub-unit. Second level is the collection point of the alarms and controls. In small systems the second level may be located in the centralised management centre. A typical feature for the handling of the information at this level is that only experts who have a deep knowledge of the network and its facilities can operate the management system. It is possible that parallel terminals may be located into substations and distributed management centres. Third (highest) level of TMS is located into the centralised management centre. This system is not meant for any particular system or manufacturer but for the total telecommunications network management. The human interface is normally graphical, providing clear overview display that does not demand special knowledge of the details of any particular aspect of the telecommunications system.

There are available many TMS, either from the telecommunicationsequipmentsuppliersorfrom independent companies which specialise in TMS. The information transfer is normally more efficient if the TMS is from the same manufacturer who supplies the telecommunications system. In most Utilities, the system range is wide: from many suppliers and many generations of equipment. The interface to other suppliers' equipment is limited, normally only to the alarm relay contacts.

Collection of alarms is the first function of TMS. It is especially important for transmission systems which cover wide geographical distances. Development of technology and active alarm/control units have made control actions and remote measurements possible. In fibre systems control of switchover equipment and total network management can be carried out using TMS.

The SDH concept contains a standard comprehensive network management facility. Fibre terminals may be integrated into the SDH nodes and thus the fibre link performance and configuration information will be passed into the total system, thus providing very effective network management.

CCITT is developing a basic concept called Telecommunications Management Network (TMN). It is a very comprehensive concept, and the principles can be applied to both wide public andlimitedprivatetelecommunicationsnetwork. It is based on a layered model. It will essentially help the network operators to manage the total networks which contain systems from various suppliers. It is obvious that TMN concept will be developed simultaneously with SDH and ATM techniques for fibre transmission networks.

From the Power Utility point of view, standardisation itself is a recommended trend to make the interfacing and expansion problems easier. On the other hand, CCITT's recommendations may expand the simplest needs into a very expensive solution which is not justified for simple applications.

7 TESTING OPTICAL CABLES

The principal requirement is that the long term optical and mechanical integrity of optical cables is maintained under service conditions.

Testing must therefore take account of all predictable conditions likely to be experienced throughout the service life, together with any stresses during installation.

All the fittings recommended for use on optical cables should be subjected to rigorous laboratory evaluation in conjunction with the cables for which they are designed in order that the system performance is properly evaluated.

Testing of cables and fittings should be designed to demonstrate that the following functional criteria are satisfactorily achieved:

- Ease of installation with the possibility for error being minimised
- Avoidance of concentrated clamping stresses to protect optical fibres. In the cases of stringing cables on overhead lines and of pulling cables into ducts, cable damage immediately beneath the grip may be accepted, provided that it is demonstrated that no permanent damage is incurred on the remaining parts of the cable length not deemed to be sacrificial.
- Accommodation of static and transient mechanical loads without damaging the cable cladding and other components or impairing optical performance, except where the cable end is deemed to be sacrificial.
- Mitigation of the damaging effect of vibration. This will be particularly important for aerial installations or where the cable is attached to a structure such as a bridge.
- Long term resistance to degradation due to environmental conditions and pollution, particularly in the presence of induced voltages in the case of non-metallic cables.

Where internationally accepted standards are available these should be followed. Where no such standard exists it is the responsibility of the user to satisfy himself that the manufacturer has taken all reasonable steps to ensure the predicted service life of the cable is achievable.

7.1 Fibres

Fibres used in the manufacture of optical cables for Power Utility networks are normally standard telecom singlemode fibres conforming to CCITT Recommendation G.652. However, multimode or dispersion shifted singlemode fibres may be considered for specific applications. Where such fibres are used, CCITT Recommendations G.651 or G.653 are applicable.

The fibre manufacturer (which may be different from the cable manufacturer) ensures that the fibres meet internationally accepted fibre specifications (e.g. CCITT G.652), and attaches certificates of conformity to the despatch reels, along with the attenuation details. As a routine production test attenuation is checked at specified wavelengths.

Information provided includes the following test criteria:

7.1.1 Optical Characteristics

Attenuation
Details the loss per km in dBs, for varying wavelengths, temperatures, etc, in accordance with IEC 793-1-General. Of particular interest is the attenuation performance of the first and second windows.

Temperature cycling test
This test, in accordance with IEC 793-1-D1, determines the suitability of the fibre to temperature variations.

Microbending sensitivity
This test is required to define the resistance of the fibre to microbending. The IEC still have this subject under discussion but will be published as IEC 793-1-C3.

Frequency response
For multimode fibres it is normal to measure frequency response in accordance with IEC 793-1-C2B to establish usable bandwidth.

Additional information
Further details are normally provided for the following parameters, to the following specifications:

- Cut-off wave length — IEC 793-1-C7
- Mode field diameter — IEC 793-1-C9
- Fibre dispersion — IEC 793-1-C5
- Numerical aperture — IEC 793-1-C6
- Macrobending sensitivity — IEC 793-1-C11

7.1.2 Mechanical Characteristics

Typically the optical fibre proof test which establishes the durability of the fibre is the accepted reference information between manufacturers. This test is carried out strictly in accordance with IEC 793-1-B1.

Specifications for other parameters are under consideration and include:

- Bending — IEC 793-1-B3
- Abrasion — IEC 793-1-B4
- Visual Examination — IEC 793-1-B5
- Core concentricity — IEC 793-1-A3
- Strippability — IEC 793-1-B6

(These documents are awaiting IEC publication.)

Long term vibration can mechanically damage fibres. In loose tube constructions compound filling is the only way to be sure that no vibration damage will occur. In tight buffered cables, vibration can cause movement of fibre against other fibres and/or surrounding material. In this case friction can damage fibre.

7.2 Cables

This section covers general cable testing for cables applied to Power Utility overhead lines and covers the three main 'cable types' i.e. OPWG, ADSS and Externally Wrapped cables. Not all the various tests listed are relevant to each cable type. Cables intended for underground or subaqueous installation will not necessarily require the full range of tests listed, but in all cases the purchaser must be satisfied that the specific tests ensure that the cable is fit for the purpose and that it will withstand the rigours of the intended installation method.

The testing and product qualification of optical fibres is normally carried out over three phases:

- Qualification testing - tests carried out to verify design.
- Routine testing - tests carried out during manufacturing.
- Delivery testing - sites tests carried out on receipt of cable, after installation, or both.

7.2.1 Qualification testing

Qualification testing is by far the most complex of the three stages as this involves proving the 'design' for its intended use. Detailed specifications are readily available worldwide. This guide provides a basic listing of the various testing methods normally carried out by the manufacturers and does not attempt to provide a complete specification.

Mechanical Tests:

The qualification tests to be carried out will be dependent upon the perceived environmental conditions to be expected over the lifetime of the product. In addition, the anticipated method of installation will also define mechanical stresses on the cable, and must be verified by qualification testing. Individual requirements are normally specified in contract enquiry.

The IEC 794 series specification covers the test methods to be applied for many of the tests listed below.

Aeolian vibration test
The objective of the test is to assess the fatigue performance of the cable and the optical characteristics of the fibres under typical aeolian vibrations. This test is under review by IEC but will assess the effect of long term vibration on the cable.

Cold temperature flexure tests
As well as cyclic bending and flexibility tests carried out to IEC 794-1-E6, further tests may be carried out to ascertain the flexing of the cable at low temperatures, typically down to the minimum working temperature of the fibre elements.

Corrosion (salt fog) tests
The corrosion test is to assess mechanical degradation of metal components by accelerated life simulation using salt fog environment.

All metallic cables and fittings will suffer a degree of corrosion during their service life. This corrosion is normally mitigated by the choice of metal or protective coating, ie, zinc galvanising.

The test specification is still under consideration, but follows draft from IEC committee 36 (composite insulators).

Creep test
Minimum 1000 hours at 50% maximum working load. Elongation versus time to be monitored and recorded.

Crush resistance
This test may vary between cable types (OPGW, self supporting, etc) but should be carried out basically in accordance with IEC 794-1-E3.

Cut-through test
Specific test for polymer coated cables. Examines the ability to withstand damage due to pressure from sharp abrasive 'edges'.

Flexibility/cyclic bend testing
These tests are normally carried out in accordance with the procedures set out in IEC 794-1-E6 & E11, to determine bending radius and therefore general 'handling' characteristics. Usually carried out under normal atmospheric conditions.

Galloping test
At present under review by IEC as to exact specification for the task, but assesses the effect of galloping on the fibre optic cable. Galloping tests are particularly important for non-circular cables because of their inherent aerodynamic instability.

Impact test
Standard test in accordance with IEC 794-1-E4. Also varies between cable types (OPGW, wrap etc).

Sheave test
This is essentially an installation/bend test, the objective of which is to verify that stringing of the cable with the recommended sheave (running block) size and procedure will not damage or degrade the quality of the cable or fibres.

Stress/strain test
Carried out generally in accordance with IEC 794-1-E1 or equivalent. This test is used to obtain stress/strain curves. The procedure involves cyclic loading of the cable at varying levels of stress whilst monitoring the corresponding:

- Cable strain
- Fibre attenuation
- Fibre strain.

Temperature cycling test
Carried out generally in accordance with IEC 794-1-F1. This test is used to assess the suitability of cables over various temperature ranges. Attenuation measurements are taken at various stages during the test procedure.

Torsion test
The objective of this test is to assess the cable's susceptibility to torsion twist. Typically performed to IEC 794-1-E7.

Water blocking test
In accordance with IEC 794-1-F5 or equivalent. This test is designed to examine the water penetration effects of sheath damaged cable.

Weathering/heat-ageing test
Various tests exist for polymer coated cables including weatherometer equipment that duplicates 'weather' including 'light' from a xeron arc at an accelerated rate. Although test methods are well established from a variety of specifications including ASTM (American Society for Testing and Materials) G53 84, BS 2782 Part 5 and UK ESI (Electricity Supply Industry) Standard 09-13, there is no IEC publication yet published. Where a mutually acceptable standard exists, this may be used.

Electrical tests:

These are carried out to identify the mechanical robustness of cables when subject to stresses created by the electrical environment.

Fault current/lightning test
In accordance with local test procedures. Examines the effect of fault currents and lightning strikes on fibre optic cables.

Salt fog/erosion test
The objective of this test is to demonstrate the resistance of ADSS cables and its associated fittings to the effects of erosion and tracking, under combined electrical and mechanical stress in a worst case environment. The test is particularly important where all-dielectric cables are to be strung along power line routes with voltages of greater than 150 kV.

In the absence of a formally accepted international test, each manufacturer must satisfy itself and its customer that the test is as stringent and searching as necessary. One such test method, based upon IEC 87/27523 (now replaced by IEC 383) is described below:

Test arrangement
A length of cable shall be taken from a production run and sealed at each end against moisture ingress before being supported horizontally between two anchor points in a salt fog chamber. This will enable it to be tensioned mechanically to a level, agreed between supplier and customer, which is 90% of the maximum value during the service life of the cable. Typically this will be 15 kN. The earth termination shall be identical to that proposed by the supplier for use in service adjacent to a support tower, and may consist, for example, of spiral wrap gripping wires with suitable electrical or mechanical stress relieving accessories. The design of the high voltage termination shall be at the discretion of the supplier.

The gauge length between terminations must be long enough to avoid flash-overs from taking place during the salt fog test; a length of 25 mm/kV rms is usually adequate. The cable should be tensioned by a spring so that any creep of the cable materials during the test does not result in major reduction in tension. At suitable intervals during the test, say every 100 hours, the tension should be checked, and if it has changed by more than 10% of the initial value, it should be adjusted to fall within range again.

A conducting fog shall be produced within the chamber by the use of a suitable number of atomising nozzles, to the design shown in Figure 9 of IEC 60 Part 1. A useful guide is to have one nozzle for each 2.5 m^3 of chamber volume. The salt water to the nozzles shall be prepared from sodium chloride and tap water, with a droplet size of 5-20 microns. This generally requires an air pressure of 3.3 bar around the chamber, to give a homogeneous fog density, with no jet pointing directly at the cable. An aperture of no more than 80 cm^2 should be provided for the natural exhaust of air.

A power frequency test transformer shall be used, with a minimum continuous rating of 250 mA rms, and trip level set to 1 A rms. There shall be a clearance of at least 300 mm to earth in the vicinity of the cable.

Test procedure
After tensioning the cable it shall be wiped with a cloth or paper towel soaked in water, and then subjected to the salt fog. The test conditions shall be a follows:

Duration	1000 hours
Salt water flow rate	0.4±0.1 litre/hour for each cubic metre of chamber volume.
Droplet size	5-20 microns
Temperature	15-25°C
NaC1 content of water	10±0.5 kg/m^3
Test voltage	up to 60 kV As Agreed with customer

Acceptance
The cable shall have passed the test if there is no sign of tracking and if any sheath erosion is less than 50% of the original sheath thickness.

7.2.2 Routine production testing

Routine testing is carried out by the manufacturer at various stages throughout the production of the optical cable. The information obtained from routine testing identifies to the manufacturer the ongoing properties of the part built cable and prevents the complete manufacture of the cable where one or more properties may have been outside the required specification in an early process stage.

Routine testing is also a requirement of Quality Assurance system such as ISO 9001 or BS 5750 which calls for 'traceability' and tight controls for manufactured products. The exact tests carried out vary according to the type of cable manufactured. An example of routine tests is given below:

- Attenuation check on all fibres at various wavelengths.
- Cable jacket tensile test (polymeric sheathed cables only).
- Cable make up (correct number of fibres, colour codes, water blocking etc).
- Visual and dimensional check - diameter and quality finish of cable etc.
- Tensile test of cable produced (self supporting and OPGW types only).
- Resistance check (OPGW only).
- Fibre overfeed check on loose tube/loose buffered cables.

Resulting test reports should be held in the manufacturer's records for ten years and are often given to the end user for reference during operating lifetime.

Fibre overfeed tests
Routine checking of fibre overfeed is a simple visual check. A length of manufactured loose tube/loose buffered tube is cut from a production run (normally at the start and end of a production run), and its fibre withdrawn. The fibre is then laid alongside the buffer tube and the difference in length recorded. This then provides the percentage overfeed.

7.2.3 Delivery testing

Normally the customer accepts the product in the field with an attached factory test report. End users may require additional attenuation checks on the fibres (normally carried out using an Optical Time Domain Reflectometer (OTDR, see Section 8.2 *Field Measurements*) to verify optical cable performance before erection.

After installation an attenuation measurement is made at the appropriate wavelength again using an OTDR. If demountable connectors are included in the cable supply an attenuation power-meter check can also be made.

8 MEASURING OPTICAL COMPONENTS

The principal requirements of an optical link is that the long term optical and mechanical integrity of optical components (fibres, cables, joints etc.) are maintained under service conditions.

The quality of the optical components is normally identified by measuring attenuation. Two types of attenuation measurements can be made to quantify quality:

- Measure the new components - normally done in the laboratory.
- Measure the installed link - normally done in the field.

8.1 Laboratory measurements [6]

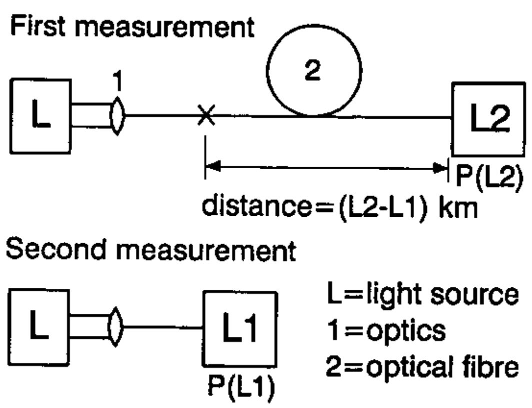
Measurements made in the laboratory are used to characterise and qualify the design of components.

To qualify the design of fibre a cut-back method is used, and for a joint or connector qualification an insertion loss method is normally used.

8.1.1 Fibres

The reference method to measure attenuation of fibre is the cut-back method.

The cut-back method requires measurement of optical power at two points L1 and L2 in an optical fibre. Usually L2 is at the far end of the fibre and L1 very near the beginning (usually about two metres). In the measuring process the light power P is first measured at the end L2 (in db) and then at L1. This involves cutting the fibre at L1 without changing the launch conditions between the light source (transmitter) and the fibre.



The attenuation coefficient α (in dB/km) of the fibre is then calculated by

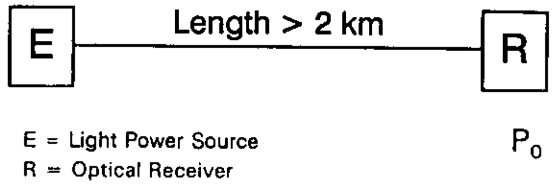
$$\alpha = \frac{10}{L2 - L1} \log \frac{P\ (L1)}{P\ (L2)}\ db/Km$$

8.1.2 Joints

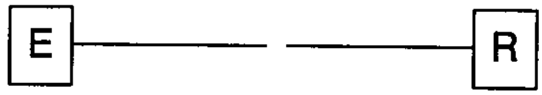
The reference method to determine the power loss through a connector is done as an insertion loss measurement. Measurements of joint insertion loss are intended to give a value for the decrease of useful power expressed in decibels, resulting from mated connectors within a length of optical fibre. However, it is possible to launch into a fibre, optical power which has a broader or narrower distribution of modes than equilibrium distribution which would be attained after transmission through a long length of fibre. Also, power may be launched into, and guided by, the cladding of some fibre types. The test results do not necessarily represent the losses that occur in a long or short line length system. Furthermore, deviations in fibre geometry and optical characteristics (eg. core elipticity, core eccentricity errors, numerical aperture changes, etc.) may lead to variations of insertion loss which cannot be attributed to defects in the connector quality.

The reference method to determine losses of a connector is may be carried out as follows:

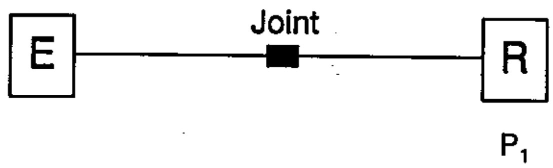
Step 1 - The light power P_0 is measured first at the far end of the fibre.



Step 2 - The optical fibre is cut in the middle.



Step 3 - The joint under test is inserted and light power P_1 is measured at the receiver.



The insertion loss of the joint is given by the relation:

$$Attenuation = 10 \log \left[\frac{P_o}{P_1}\right] dB$$

For multimode measurements of a joint, it is important to take care that the launch conditions are the same for the two measurements because change in optical impedance may change the launch power.

8.1.3 Connectors

Tests which can be practised on optical connectors are described in IEC 874-1 specification. Tests which are prescribed depend on the application.

Optical tests which characterise optic connector performances:

- Insertion loss is a measurement of joint insertion loss and is intended to give a value for the decrease of useful power (normally expressed in decibels) resulting from the insertion of a joint within a length of optical fibre cable.
- Spectral loss - is a measure of wavelength dependence of joint (expressed in decibels) resulting from the presence of a joint within a length of optical fibre cable.
- Return loss - is the measure of the fraction of input power that is returned along the input path by an optical component such as connector. The return loss or reflected

power is produced by a difference in the index of refraction. Return loss disturbs DFB laser behaviour.

- Susceptibility to ambient light coupling measurement of connector is intended to give value of amount of optical power which can be coupled into the optical fibre at mated connector from external light sources.

Mechanical tests which characterise the optical performance of a system or component:

- Strength of cable retention test: the object of this test is to determine whether the device for fixing or clamping the cable is effective when tensile, bending and/or torque is applied to the attached cable relative to the connector.
- Shearing test - can determine the suitability of fixed joint for use in positions where it may be subjected to shearing forces.
- Vibration, Bump, Acceleration. The purpose of these tests is to determine the optical degradation effect as a result of physical loads and to verify the quality of the mating points.
- Crush resistance test - is to simulate the effects of loads applied to a joint such as might occur when the joint is in a vulnerable position such as on the ground or floor surface.
- Axial compression test - is to determine the optical and mechanical effects on an applied force tending to thrust the optical fibre cable into the connector shell or housing. It is intended to simulate the effect of rough handling of a free or panel-mounted connector set.
- Impact test - is intended to determine the ability of optical fibre connector to withstand a localised impact or a series of impacts with hard objects.
- Drop test - is intended to assess the ability of optical fibre connector to withstand impacts it could receive when dropped onto a hard surface.
- Mechanical endurance test - is intended to verify the number of operations of connector separation that is obtained without degradation of optical performance.

Climatic and environmental tests are performed to verify the influence of temperature and humidity on optical performance of joints. They include climatic influences of Cold, Dry heat, Damp heat, Climatic sequence and Condensation.

Climatic testing is required to be supplemented with tests that verify the influence of pollution on optical performance. They include Corrosive tests, salt mist, industrial atmosphere, Condensation, Dust, Sealing, Resistance to solvents and contaminating fluids.

Additional tests are required to verify the compatibility of different materials used in optical system components. They include rapid change of temperature and the effects of corrosion and mechanical degradation due to solar radiation.

8.2 Field Measurements

During installation of a link, it is not practical to use laboratory reference methods because the necessary cut-backs for accurate results are destructive. Insertion loss by substitution and reflective backscattering technique is normally used, providing rapid results with acceptable accuracy.

8.2.1 Insertion loss method

This measurement method requires that the light power at the far end of the fibre under test is measured and compared with the light power end of short piece of optical cable connected temporarily connected to the light source. This piece of cable is used as reference. As the test is being carried out, it is important to take care that the launch conditions for the reference measurement is as similar as possible to those for the loss measurement. Due to these limitations, accuracy and reproducibility of insertion loss technique are less favourable than with the cut-back method.

8.2.2 Backscattering method

In the backscattering technique light is launched into as well as received at one end of the fibre and provides details of the variation of attenuation along its length.

Rayleigh scattering provides the basis for this technique and an Optical Time Domain Reflectometer (OTDR) measuring instrument has been developed for the purpose. The principles are illustrated in **Figure 52.**

A laser diode monitored by an electrical generator emits a series of light pulses which are injected into the fibre to be tested by means of a directional coupler. During propagation, the light power carried by the pulse is partly absorbed and scattered. The detector placed

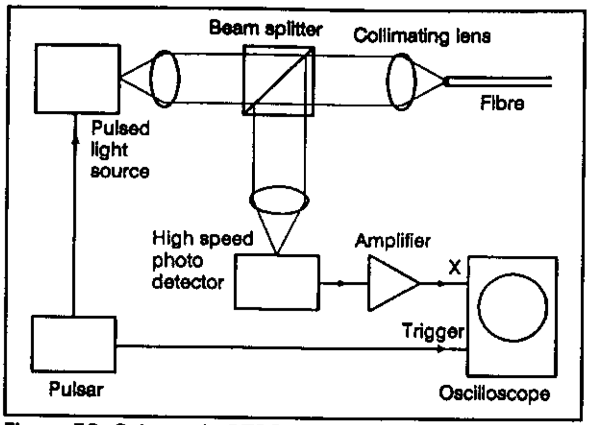


Figure 52 Schematic OTDR principle

onto one arm of the directional coupler receives part of the reflected scattered light which comes back in the opposite direction towards the near end of the fibre and is measured.

This reflected power is also attenuated as it propagates back through the fibre. From this backscattered light power and the propagation delay in the optical fibre it is possible to derive the attenuation coefficient over the entire length of the fibre. The variation of backscattered signal with distance can easily be observed on an oscilloscope.

Presentation of the reflectometer

A typical backscattering curve is shown in **Figure 53**. If the attenuation coefficient and the backscattering factor remain constant over the

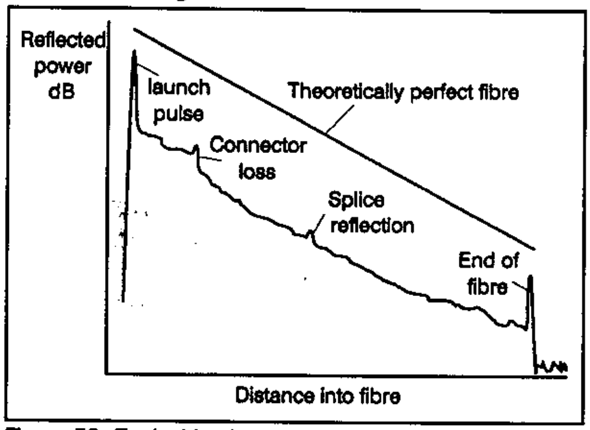


Figure 53 Typical backscatter curve

fibre length, then the curve falls linearly (in dBs) from the beginning of the optical fibre. Due to the jump in refractive index at the glass/air interfaces and at the beginning and end of the fibre a relatively large portion of the light power is backscattered, which causes the large peaks at the beginning and end of the curve.

If it is not certain that the backscattering factor, the numerical aperture, and the core diameter remain unchanged over the length of the optical fibre, then two measurements should be made, one from each end, and the results averaged. Because the backscattered power is relatively low, greater demands are placed on the sensitivity of the receiver. In order to improve the received signal, the individually measured values are averaged many thousands of times. In addition to the fibre attenuation measurement, attenuation due to connector or splice joints can be readily identified. See **Figure 54**.

The linear parts AB and CD between peaks characterise the losses caused by the different segments of the fibre length (Rayleigh scattering). Thus the scattering curve can be regarded

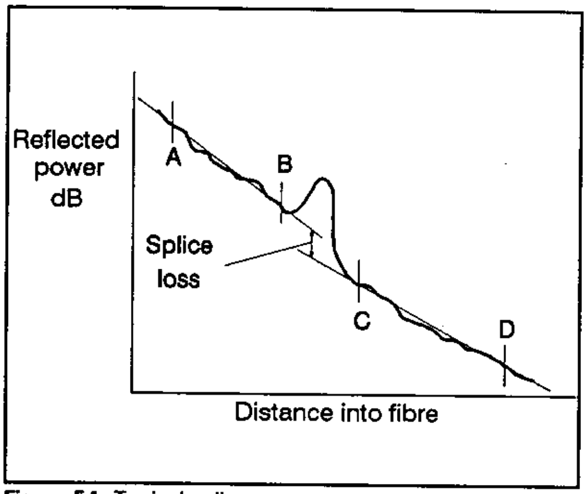


Figure 54 Typical splice trace

as the result of the signal reflected by the discontinuities (Fresnel reflection) and of the signals backscattered by the fluctuations of density at the microscopic scale.

8.3 Measurement of optical fibre attenuation

During forward propagation, the pulse experiences an accumulated attenuation which can differ from that of the reflected signal. This occurs for non-symmetrical, non-uniform fibres.

In the simple case of uniform symmetrical fibre, the linear attenuation α, expressed in dB/km, is given by the absolute value of the slope expressed in dB/km. Refer to **Figure 54**.

If however, the fibre is not uniform, the linear attenuation of the optical fibre must be measured from each end, α_1 (A to D), and α_2 (D to A). The linear attenuation is given by: $\alpha = \frac{1}{2}(\alpha_1 + \alpha_2)$ dB/km.

8.4 Measurements of connector and splice losses

If the optical fibre is of the same type both sides of the connection or splice, the insertion loss corresponds to the difference between lines AB and CD, as shown in **Figure 54** by the annotation *splice loss*.

If different optical fibre types are used either side of the join, the insertion loss must be found by making measurements from each side. The actual insertion loss of the joint is given by half the sum of the insertion loss each way.

9 JOINING OPTICAL CABLES

A number of technologies are available for joining, protecting, and installing optical fibres. The choice of technology depends on the following parameters:

- Cladding of fibre
- Connection of cable
- Environmental conditions.
- The intended use of the fibre

Some requirements are the same for all joints: jackets must correctly retain the optical fibre and protect the joint against tensile strain and bending.

There are two sorts of joints, as defined by terminology set out in IEC 86B - Central Office 48-1:

- Permanent joint
- Separable joint

Fibre splice: A fibre splice is a permanent or separable joint between two fibres. It generally provides protection from damage which might result from normal handling of the fibre.

Cable splice: A cable splice is a protective splice of two or more cables containing one or more optical fibres. The cable splice consist of optical fibre splice, organisers and closures.

Permanent splice: A splice which cannot be separated without destroying the joint.

Separable joint: A splice which can be separated yet is intended for permanent engagement, as opposed to a connector which is intended for multiple engagements and separations.

9.1 Permanent Joints

Permanent joints are used during the installation of the link and permit a very good non-demountable connection.

9.1.1 Fusion splices

Fusion splices generally require advanced equipment which is expensive and requires a skilled worker to produce consistent high quality splices. The technology used makes use of torches or electric arcs with automatic or manual positioning of the fibre for end alignment and verification of transmitted optical power. High quality splice losses are low (<0.2 dB) but vary according to fibres and the equipment used. With singlemode fibre, there is no reflection loss.

The splice must be protected against mechanical risk, (tensile, twisting, bending strength...) and environmental risk (duty, humidity...). One solution to this problem is to use a thermoretractable jacket strengthened with metallic protection.

9.1.2 Bonded splices

The bonding of two fibres is made with resin which polymerises with ultra-violet rays. The equipment used is simple and cheap. The performance is good, in the majority of cases less than 0.3 dB loss is achievable. With singlemode fibre, a system to adjust fibre optic alignment is required to ensure low loss. Under these circumstances return losses of 35 dB are possible.

9.1.3 Uses

Fusion and bonded splices are used in line to join two optical fibres. If there are a lot of splices to make (more than 500 a year), then it is economic to make use of a fusion splicer. In the other cases, the use of glued splices may provide a more economic and satisfactory solution.

9.2 Separable Joints

There are two sorts of separable joints:

- Mechanical splices
- Demountable connectors

All components which can join optical fibre by means of a mechanical device are called mechanical splices. They align the two optical fibres and hold them together rigidly with precise alignment.

9.2.1 Mechanical splices

There are two types of mechanical splices:

- Bare fibre splices where the optical fibre is directly manipulated to provide the light connection.
- Mechanical splices where the optical fibre is held rigid with plugs (see Section 9.4 *Mechanical Splices* for a detailed description).

With bare fibre splices only a few connections/disconnections (about ten) are possible. Insertion losses are low (0.5 dB for multimode fibre), their use is easy and does not require advanced equipment or qualified personnel for repeatable high quality connections.

Mechanical splices are used in cupboards to mix and occasionally change optical links. Their main application is in local area networks, where attenuation of joints is not so critical.

9.2.2 Demountable Connectors

These devices are generally used at the extremity of links. They provide the function of repeated connection and disconnection for cross connection purposes or access to terminal equipment. The number of connection and disconnection operations can be several hundred.

The performances of connectors is very different between models of connectors. The best connectors have insertion losses of less than 0.3 dB, the worst have insertion losses greater than 1 dB.

9.3 Types of Demountable Connectors

9.3.1 FSMA (Fibre Sub Miniature Type A)

In the mid-seventies, when suitable fibre optic connectors were not commercially available, Amphenol modified its existing sub miniature type A (SMA) design of radio frequency connector for use with fibre optics. Because of the familiarity of designers with the SMA mechanical features in coaxial cable connections, the fibre optic SMA connector has become a defacto standard.

It was small, and manufacturers of SMA coaxial connectors could make it very quickly, but not necessarily to the required very high quality. FSMA connectors were used for non demanding

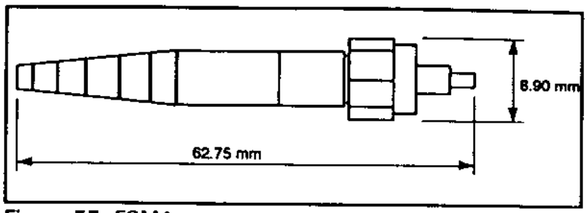


Figure 55 FSMA type connector

optical links. This connector is adopted in IEC 874. For long distance and high data speed connectors which are required to have better performance and reliability the Biconic (see Section 9.3.3 *BICONIC*) in USA and FC (see Section 9.3.4 *FC and PC*) in Europe have a much wider application.

Performance

- Typical insertion loss: 0.4 dB
- Temperature Range: -20°C; +70°C
- Durability: 1000 mating cycles
- Cable retention: 100 N

9.3.2 ST (Standard Telephone)

In 1985 AT&T developed ST connectors for use with the fibre widely used in telephone applications: having core/cladding of 62.5/125/0.28 mm. It is also usable with 50/125/0.20 and 85/125/0.26 fibres. Some manufacturers also offer it with an opening suitable for use with 100/140/0.30 fibres.

Relative to the FSMA connector, it has a number of benefits and only one disadvantage. The main benefits are key mating (cannot be rotated) and bayonet coupling (cannot be

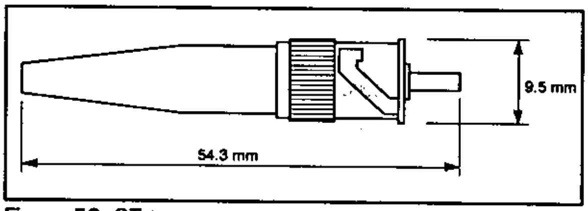


Figure 56 ST type connector

loosened by vibration). Less obvious benefits are the 2.5 mm ferrule (a size having international popularity) and ease to assembly (some versions of FSMA match this). The only slight disadvantage is that it is not a pull-proof connector.

Originally, the ST connector was designed with a ceramic ferrule for precision in mating, but for lower cost applications a plastic-ferrule ST connector is available.

The size of the ST connector is comparable to the FSMA, that is 8.5 to 9.1 mm diameter coupling ring and the length from coupling ring to where cable bending can start is also the same.

Performance:

- Typical insertion loss: 0.3 dB
- Return loss: >30 dB
- Temperature Range: -20°C; +70°C
- Durability: 1000 mating cycles
- Cable retention: 200 N

9.3.3 BICONIC

This term is applied generically to connectors following an AT&T design in 1980s. In this design each fibre terminates in a conical housing. To form a complete connection, the two

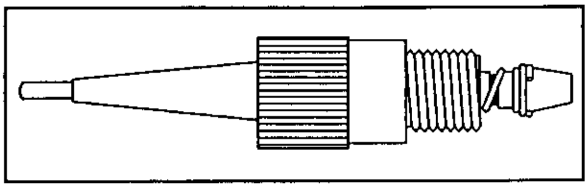


Figure 57 Biconic type connector

fibre terminations are each mated in female assembly. The advantage of the biconical design is that the cones form a set reference surface that provides accurate fibre-to-fibre alignment. This factor is essential in obtaining low loss performance in singlemode fibres and accounts for the success of this design in telecommunication applications.

9.3.4 FC (Fully Compatible) and PC (Physical Contact)

The FC connector is a screw-on design. It came into widespread use in the early 1980s by Nippon Telegraph and Telephone Corporation. It is used in the United States by long distance telephone companies, the TV industry and some data communications companies. The FC is also the connector widely used by the European and Japanese Post, Telephone and Telegraph (PTT) organisations.

The ferrule material is typically ceramic. It is precision-ground and is mated in a steel sleeve.

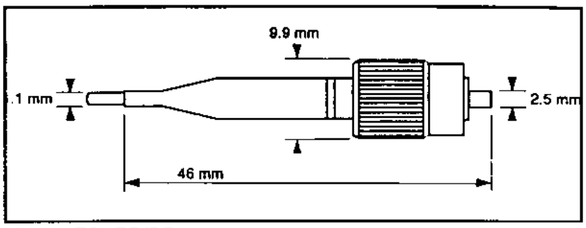


Figure 58 FC/PC type connector

An important evolution of the FC connector is the PC (Physical Contact or Polishing Convex) connector which lessens the requirement of extensive polishing of the end face by fabricating the ends with a convex profile. The physical contact is used with singlemode connectors to improve the suppression of light reflection and decrease insertion losses. When the PC polishing technique is applied to a typical singlemode connector, an average return loss of -30 dB is achieved, which is a reflection improvement of approximately 16 dB including the Fresnel reflection. Insertion loss is decreased to 0.2 dB from the previous value of 0.5 dB.

The original PC connector design consisted of two rectangular surfaces brought into contact to form a cross when mated. As the speed and capacity requirements of optical communications systems have expanded, the need to decrease optical connector reflection has grown. High levels of reflection create problems in sophisticated fibre optic systems, and interference and optical feedback dramatically effects the optical power budget and signal-to-noise ratio. Analyses have revealed that light reflected from the connector end surface is affected by even the least minute residual layer at the optical fibre surface end face. When the optical fibre surface is not sufficiently cleaned and polished for bonding the process to occur uniformly, external pressure must be applied to force the surface to bond around the defects. In a PC connector, a gentle convex surface formed at the tip of the field connectable ferrule is incorporated. It has a precise symmetrical configuration with a curvature symmetry and mechanical axis. A spherical convex version of the PC known as the SPC, (Super Physical

Contact) connector has been developed to provide even higher return loss performance.

Performance:

- Typical insertion loss: 0.27 dB
- Return loss: PC>30 dB
  SPC>40 dB
- Temperature Range: -40°C; +80°C
- Durability: 1000 mating cycles
- Cable retention: 200 N

9.3.5 EC (European Connector)

The EC connector has been designed in the frame of the 'Research for in Advanced Communication Technologies in Europe' (RACE) program to be cost effective in the subscriber loop application. Due to its high return loss performance it is a suitable demountable interconnection component for any transmission line using DFB lasers. It also provides a good connector for high bit rate as well as coherent transmissions applications.

Its construction features a precise metal drilled ferrule for cone to sphere alignment. Oblique

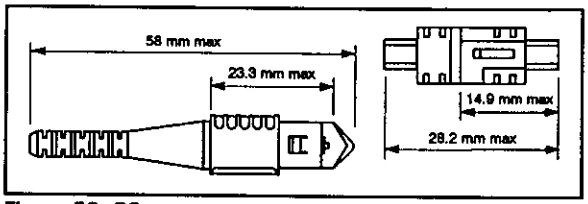


Figure 59 EC type connector

polishing of fibre end face and silicone based index matching membrane ensures a high performance.

Very low return loss reflection (<-60 dB) has been obtained. The connector has a push-pull coupling with plastic housing. It can be easily mounted onto fibre ends in the field with simple tools.

Performance:

- Typical insertion loss: 0.25 dB
- Return loss: >60 dB
- Temperature Range: -40°C; +85°C
- Durability: 500 mating cycles
- Cable retention: 100 N

9.3.6 SC (Super Connector)

The SC is a push-pull connector used in the early 1990s by NTT. It is a recent connector and is replacing the FC for new construction in Japan and the USA. It has the same optical performance as a PC connector. The advantages of SC connectors are that they provide duplex, triplex and other configuration multiple connections. The first ceramic used was

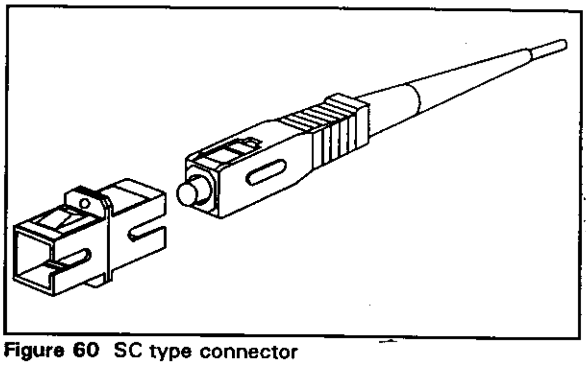


Figure 60 SC type connector

alumina which is a very hard, inelastic material that will hold the tight tolerances required for hole diameter and concentricity as well as outside ferrules dimensions. In addition, its thermal coefficient of expansion is similar to glass, so it performs well over large temperature ranges. However, because of alumina's hardness, it is brittle. As a result, it sometimes breaks under excess stress in the field and is perceived as being less rugged than other materials when exposed to extreme conditions. Zirconia ceramic has been introduced to the connector industry. Like alumina, Zirconia is a hard material; but being a slightly softer material than alumina, is more elastic and therefore more resistant to impact damage.

Performance:

- Typical insertion loss: 0.3 dB
- Return loss: >60 dB
- Temperature Range: -20°C; +70°C
- Durability: 500 mating cycles
- Cable retention: 100 N

9.4 Mechanical Splices

Mechanical splices have been developed after an important demand for low cost and easy field termination product for video communication networks. This technique is now widely used in Local Area Network applications. It is an intermediate component between the demountable connector and fixed permanent splice

Connection is made by the use of an adaptor, which allows optical links to be changed quickly. Mechanical splice allows execution of manual commutation.

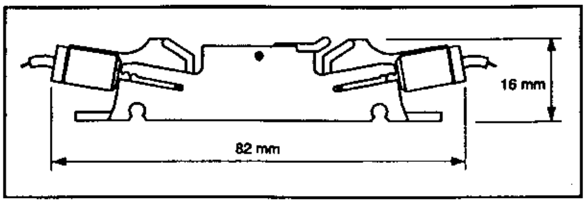


Figure 61 Mechanical splice

Mechanical splice systems are generally composed of two plugs that permit fibre and cable retention by means of a crimping ferrule. The plugs also provide protection of optical fibre when they are disconnected. A common adaptor permits plug retention and secures direct alignment of fibre with the aid of a liquid index fill material.

Mechanical splices are not very often used in the electricity supply industry due to problems that may be associated with vibration, and in any case optical performance is somewhat inferior to fusion splices or high precision demountable connectors.

9.5 Splices by Direct Contact

9.5.1 Glued splices

Glued splices offer good performance and provide economical permanent joints where only low quantities are required, since it is not necessary to employ expensive fusion joining machinery.

Optical fibres are aligned in a centering device (generally a groove). Fibre ends are uncoated, cleaned and cleaved, then inserted into the groove. After insertion, adhesive is applied and cured by means of an ultra-violet lamp. The polymerisation normally takes about one minute at normal temperatures.

Insertion loss Performance: 0.15 dB

9.5.2 Fusion splices

The main benefits of optical fibre fusion splicing are the low splice loss and the high tensile strength of spliced joints. To achieve this splicing quality, the splicing method using electrical discharge as a heat source for melting glass is adopted in most splicers. Very precise core alignment is necessary especially in singlemode fibre splicing, and is normally carried out automatically by light power measurement or by physical alignment.

The core aligning techniques are classified into the following three methods.

Power monitoring method

Optical power is injected into the fibre at the light source side, the power is transmitted through the splicing point and this power is monitored at the other end. Core aligning is done by maximising the monitored power level. The aligning sequence can be automated by feeding back power to the splicing point via pair wires in fibre cables using the data communication technique.

This method is called the 'three point method' because the splicing work is done at the centre power injecting and monitoring points. The advantage of the method is that the splicing loss can be accurately measured. However, this method has the following disadvantages:

- Operators are needed at three working sites.
- It takes a long time to get ready to start work due to the additional equipment such as the light source, power meters and data transmission apparatus which have to be deployed to the working sites.
- A data signalling path (normally a pair of copper wires) is needed to send the monitoring level signal to the splicing point.

Local monitoring methods

There are two local monitoring methods for assessing the quality of a fusion splice. They are the Local Detection System (LDS) method and the Local Injection and Detection system (LIDS) method.

LDS Method:

This injects light power into the fibre core at a position farthest from the splice point and detects the leaked power from the core just after the splice point by bending the fibre in a small radius.

LIDS Method:

This injects and detects light power into or from the fibre core each side and adjacent to the splice point by bending each of the fibres in a small radius.

At present LIDS method is generally adopted in most countries to eliminate extra working time and operators. However, the LIDS method also has the following problems:

- It is difficult to apply LIDS method to Nylon Jacketed fibres.
- The alignment precision of the LIDS method is reduced with coloured fibre coated UV acrylic or silicon resin.
- Bending the fibre in a radius of about 10 mm for injection and detection of light may cause degradation of the tensile strength of the fibre by propagating minute surface imperfections (cracks).

Direct Core Observation Method

This method aligns the fibre core physically by observing the core axes. Detection of core position is by processing the white and black image made by illuminating white light to the fibre and taking advantage of fibre lens effect due to refractive index difference.

A cross sectional image of the fibre is visualised by simple white light illumination and a small TV camera installed in the splicer. The image data is analysed by the image processor to detect and align cores automatically. This technique is called PAS (Profile Alignment System), because it uses a cross-sectional image profile.

This PAS method has the following advantages over the power monitoring method and the local monitoring method.

- does not need any additional equipment such as light sources or power meters.
- can align fibre cores without fibre bending and thus maintain fibre integrity.
- is not influenced by fibre coatings, composition and refractive index distribution of fibre cores.
- makes it possible to splice fibres at arbitrary splicing points simultaneously over the whole transmission length.

Overall the PAS method achieves the most ideal splicing system.

Performance of equipment:

- Insertion loss: <0.05 dB
- Temperature: 0 to 40°C

9.5.3 Mechanical permanent splices

Mechanical Permanent splicing is a new technique on the market. It is very easy and quick to make a permanent splice and is very useful to make repairs.

9.6 Examples of Joining

9.6.1 Long distance cable

It is generally accepted that fusion splices are used to joint long distance cable because they normally form part of a long distance telecommunications system and the highest possible reliability is required since repair will be extremely costly.

At the extremities, optical singlemode connectors are used, generally FC connectors. By using demountable connectors, it is possible to check the optical link if there is a problem, by making OTDR measurements to verify the attenuation of the optical fibre route.

9.6.2 Local area networks

In local area networks (LANs) multimode (62.5/125μm) optical fibre is generally used. There are normally no long distance links so it is not normally required to joint two different types of fibre cables at the local equipment ends. Generally ST type multimode connectors are used.

It may be necessary to have a maintenance policy which may be implemented by monitoring transmit and receive powers to check changes in optical fibre attenuation before data performance is affected. The monitoring may be automatic or carried out manually on a regular (six month/one year) basis.

9.6.3 Evolution

Singlemode fibre optic cable will be more widely used in the future as costs reduce and the higher performance advantage over multimode fibre finds application in the electricity supply industry.

In-line fusion splices already have a wide application, but for the future there will be a general trend towards PAS splicing techniques to avoid unnecessary stress on the fibre and therefore secure the longest possible service. Most suitable splicers are Fujikura, Sumitomo, and Furukawa from Japan, and Siemens, Ericsson and BICC from Europe.

At the extremity of line, demountable, optical connectors are used to connect the equipment. In new installations, EC or SC Connectors are emerging standards for singlemode links, and perhaps ST connectors in multimode links. For high performance links only the EC or SC connectors are suitable.

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11 GLOSSARY AND DEFINITION OF TERMS

ACC Area Control Centres.

ADSS All Dielectric Self Supporting aerial cable containing no metal components.

AIS Alarm Indication Signal.

APD Avalanche Photo diode - inherently high gain photo detector having a higher effective response than a PIN diode.

ATM Asynchronous Transfer Mode.

BER Bit Error Rate.

CCIR International Radio Consultative Committee.

CCITT The International Telegraph and Telephone Consultative Committee. Part of the International Telecommunications Union, which sets standards for manufacturers and users.

CMC Coherent Optical Multicarrier.

CCTC Closed Circuit Television.

dB Decibel is the relative logarithmic ratio of two electrical or optical powers.

dBm Absolute level of power relative to 1 mW expressed in decibels.

DCE Data Circuit Equipment (e.g. a modem).

DFB Distributed Feedback.

DGMN Degraded Minutes.

DIN German national standard - 'Deutsche Industrie-Norm'.

DTE Data Terminating Equipment (e.g. a computer).

EC European Connector.

EMI Electro Magnetic Interference.

ESEC Errored Seconds.

FDDI Fibre Distributed Data Interface.

FDF Fibre Distribution Frame.

FDM Frequency division Multiplexing.

FRP Fibre Reinforced Plastic.

GFRP Glass Fibre Reinforced Plastic.

GIS Gas Insulated Switchgear.

HDTV High Definition Television.

IDF Intermediate Distribution Frame.

IEC International Electrotechnical Commission.

IEEE Institute of Electrical and Electronic Engineers.

IF Intermediate Frequency.

ISDN Integrated Services Digital Networks.

LAN Local Area Network.

LASER Light Amplification by the Stimulated Emission of Radiation - Spontaneous emission occurs as a result of recombination of excited electrons and holes. In a laser diode photons are predominantly generated by stimulated emission. The stimulated photons are coherent with the generating photons and have the same wavelength and phase. The result is a narrow spectrum unlike LEDs which have a wide spectrum.

LD Laser Diode.

LDP Longitudinal Differential Protection.

LDS Local Detection System.

LED Light Emitting Diode - A device for generating light by recombination of electrons and holes inside a p-n junction. Each recombination releases a photon.

LIDS Local Injection Detection System.

MAP Manufacturing Automation Protocol.

MDF Main Distribution Frame.

MIC Media Interface Connector.

MM Fibre Multimode fibre includes both step-index and graded index types. In the case of step-index fibre the light is guided by total reflection at the core/cladding boundary. The core diameter is typically 100 μm allowing a significant range of internal reflection angles. Low bandwidth is a significant disadvantage of step-index fibres due to the wide range of propagation delays. Fibre is limited to 850 nm systems with a bandwidth of 20 Mhz.km. Graded index fibre achieves a higher bandwidth by providing the core with a bell shaped index profile across its diameter which bends the light rays towards the line of the fibre thus reducing the number of propagation modes. Typical core diameter 50 μm and 62.5 μm with bandwidth 1 GHz.km.

MTBF Mean Time Between Failures - normally expressed as the average number of hours an item or system is expected to run without breakdown.

MTTR Mean Tine to Repair - average time taken to return to service the faulty item or system. Both MTBF and MTTR have a direct bearing on system availability.

NCC National Control Centres.

NMS Network Management System.

OEIC Optoelectronic Integrated Circuit.

OFDM Optical Frequency Division Multiplexers.

OIC Optical Integrated Circuit.

OLTE Optical Line Termination Equipment.

OPGW Optical Ground Wire - an alterative description for a composite conductor where fibres are embedded within the power conductor.

OTDR Optical Time Domain Reflectometer - an instrument for measuring the characterisation of fibre attenuation, uniformity, splice loss, breaks and length.

PAS Profile Alignment System.

PAX Private Automatic Exchange.

PC Physical Contact or Polishing Convex.

PDH Plesiochronous Digital Hierarchy.

PIN-Diode Positive Intrinsic Negative Diode.

PIN Generic term for a Photon energy absorbing detector. The material of the device is chosen according to the maximum efficiency at the operating wavelength eg. Silicon for 850 nm. InGaAs for 1300 nm.

PLC Power Line Carrier - Carrier frequency equipment operating in the 30-500 kHz frequency range for conveying telecommunication signals over power lines.

PMD Medium Dependent Sublayer Protocol.

PTT Post, Telephone and Telegraph.

RACE Research for Advanced Communications in Europe.

REC Regional Electricity Company.

RS Remote Stations.

SDH Synchronous Digital Hierarchy.

SESC Severely Errored Seconds.

SM Fibre Singlemode (also termed monomode) fibre - a fibre with a small core diameter of 5-10 μm which forces the light propagation into one mode only. This fundamental mode travels in a straight line without being reflected at the boundary between the core and the cladding. Bandwidth 100 GHz.km.

STM Synchronous Transport Module.

SVD Spiral Vibration Damper.

TDM Time Division Multiplexing.

TEG Thermoelectric Generator.

TMN Telecommunications Management Network.

TMS Telecommunications Management System.

TV Television.

VSB-AM Vestigial Sideband Amplitude Modulation.

WAN Wide Area Network.

WDM Wavelength Division Multiplexing.

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