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DIGITAL SYSTEMS AND NETWORKS

Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology

ITU-T G-series Recommendations – Supplement 42

ITU-T



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Supplement 42 to ITU-T G-series Recommendations

Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology

Summary

Supplement 42 to ITU-T G-series Recommendations contains a functional grouping of the ITU-T Recommendations on optical fibres and systems technology (e.g., optical fibres and cables, physical optical interfaces and optical fibre submarine cable systems).

An introduction to each category with more than one Recommendation outlines the subjects which are common to the category.

For each Recommendation, there is a short description of the purpose, content and, in many cases, the evolution of the content in the subsequent versions. There are also cross-references to the other Recommendations dealing with related issues.

The main purpose of this guide is to give to developing countries an improved capability in the application of standards, while the telecommunication industry, particularly manufacturers and operators, could benefit from the greater involvement of developing countries in the making and application of standards.

The guide could also have a wider use among manufacturers and operators who are not directly involved in the preparation of this group of Recommendations and they could find the guide to be a useful tool both for rapidly focusing on the Recommendation(s) of specific interest and for better understanding the meaning and the objectives of each Recommendation.

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FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this publication, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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Supplement 42 to ITU-T G-series Recommendations

Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology

1 Scope

WTSA-04 Resolution 44 (*Bridging the standardization gap between developing and developed countries*) requires the preparation of guiding documents to assist in the implementation of ITU-T Recommendations that could be used by developing countries in preparing national specific requirements for deploying new networks and services.

In this way, developing countries could benefit from an improved capability in the application of standards, while the telecommunication industry, particularly manufacturers and operators, could benefit from the greater involvement of developing countries in the making and application of standards.

The main objective of this *Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology* is to fulfil these requirements from the WTSA.

However, the guide could also have a wider use among manufacturers and operators who are not directly involved in the preparation of this group of Recommendations and they could find the guide to be a useful tool both for rapidly focusing on the Recommendation(s) of specific interest and for better understanding the meaning and the objectives of each Recommendation.

Recommendations related to the construction of optical cables, to the installation techniques (duct, tunnel, aerial, buried, mini-trench, micro-trench, etc.) and the associated hardware (closures, connectors, cabinets, poles, etc.) are outside the scope of this Guide because they are dealt with in [ITU-T L-Guide].

2 References

- [ITU-T G.707] Recommendation ITU-T G.707/Y.1322 (2007), *Network node interface for the synchronous digital hierarchy (SDH)*.
- [ITU-T G.709] Recommendation ITU-T G.709/Y.1331 (2009), *Interfaces for the optical transport network*.
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- [IEC 61292-4] IEC 61292-4 (2010), *Optical amplifiers – Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers*.
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- [IEEE 802.3ba] IEEE Std 802.3ba-2010, *IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 3: CSMA/CD Access Method and Physical Layer Specifications Amendment 4: Media Access Control Parameters, Physical Layers, and Management Parameters for 40 Gb/s and 100 Gb/s Operation*.
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NOTE – See Table 6-1 for a functional grouping of the ITU-T G-series Recommendations referred to in this Supplement.

3 Definitions

3.1 Terms defined elsewhere

All the terms used in this Supplement are defined in the described Recommendations.

3.2 Terms defined in this Supplement

There are no new terms defined in this Supplement.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

ADC	Adaptive Dispersion Compensators
ALS	Automatic Laser Shutdown
AON	All Optical Network
APR	Automatic Power Reduction
ASE	Amplified Spontaneous Emission
ATM	Alternative Test Method
BER	Bit Error Ratio
CWDM	Coarse Wavelength Division Multiplexing
DC	Dispersion Compensation
DGD	Differential Group Delay
DST	Dispersion Supported Transmission
DWDM	Dense Wavelength Division Multiplexing
FEC	Forward Error Correction
FSO	Free Space Optical
IaD	Intra-Domain
IrD	Inter-Domain

LWP	Low Water Peak
MD-ROADM	Multi-Degree Reconfigurable Optical Add-Drop Multiplexer
MFD	Mode Field Diameter
MPI	Multi-Path Interference
NRZ	Non-Return to Zero
OA	Optical Amplifier
OADM	Optical Add-Drop Multiplexer
OAN	Optical Access Network
OAT	Optically Amplified Transmitter
OAR	Optically Amplified Receiver
OD	Optical Demultiplexer
OM/OD	Optical Multiplexer and Demultiplexer
OEO	Optical-to-Electrical-to-Optical
OIF	Optical Internetworking Forum
OM	Optical Multiplexer
ONE	Optical Network Element
OSNR	Optical Signal-to-Noise Ratio
OTN	Optical Transport Network
OTUk	Completely standardized optical channel transport unit – k
PDC	Passive Dispersion Compensation
PDH	Plesiochronous Digital Hierarchy
PDL	Polarization Dependent Loss
PFE	Power Feeding Equipment
PLL	Physical and Link Layer
PLUG	Physical Layer User Working Group
PMD	Polarization Mode Dispersion
PMDC	PMD Compensators
PXC	Photonic Cross-Connect
Q-Factor	Quality-Factor
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RTM	Reference Test Method
SDH	Synchronous Digital Hierarchy
SLM	Single Longitudinal Mode
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module



TEE	Tail-End Equipment
TTE	Terminal Transmission Equipment
WDM	Wavelength Division Multiplexing
WWDM	Wide Wavelength Division Multiplexing

5 Evolution of optical technology and of the related ITU-T Recommendations

The invention of the laser and its demonstration is dated 1960. It was suggested in 1966 that optical fibres might be the best choice for using laser light for optical communications, as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was the high losses of optical fibres: fibres available during the 1960s had losses in excess of 1 000 dB/km. A breakthrough occurred in 1970 when the losses could be reduced to below 20 dB/km in the wavelength region near 1 000 nm. At about the same time, gallium arsenide (GaAs) semiconductor lasers, operating continuously at room temperature, were demonstrated. The simultaneous availability of compact sources and of low-loss optical fibres led to a worldwide effort for developing optical fibre communication systems.

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the almost 40-year period extending from 1975 can be grouped into several distinct phases. Over this time period the BL product (B is the bit rate and L is the repeater spacing, where the repeaters perform optical-to-electrical-to-optical (OEO) conversion) doubled every year. In every phase, BL increased initially but began to saturate as the technology matured. Each new phase brought a fundamental change.

5.1 The first phase

The first phase of lightwave systems operated near 850 nm and used GaAs semiconductor lasers with multimode fibres. After several field trials during the period 1977-79, such systems became available commercially in 1980. They operated at a bit rate of 34-45 Mbit/s and allowed repeater spacings of up to 10 km. The larger repeater spacing compared with 1 km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

This phase of lightwave systems was specified in two ITU-T Recommendations. The first one is Recommendation ITU-T G.651, where the characteristics of a multimode optical fibre operating at 850 nm are specified. The second one is Recommendation ITU-T G.956 (now Recommendation ITU-T G.955) where are specified the characteristics of the optical systems operating at 850 nm and suitable for the bit rates of the plesiochronous digital hierarchy (PDH).

5.2 The second phase

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave systems in the wavelength region near 1 300 nm, where fibre loss is below 1 dB/km. Furthermore, optical fibres exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating near 1 300 nm.

The second phase of fibre-optic communication systems, based on InGaAsP semiconductor lasers and detectors operating near 1 300 nm became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mbit/s because of dispersion in multimode fibres. This limitation was overcome by the use of single-mode fibres. A laboratory experiment in 1981 demonstrated transmission of 2 Gbit/s over 44 km of single-mode fibre. The introduction of commercial systems followed. By 1988, second-generation lightwave systems, operating at bit rates of up to 1.7 Gbit/s with a repeater spacing of about 50 km, were commercially available.

This second phase of lightwave systems was also specified in some ITU-T Recommendations. In particular, Recommendation ITU-T G.652 specifies the characteristics of a single-mode optical fibre operating at 1300 nm. Recommendation ITU-T G.957 specifies the characteristics of optical systems operating at 1300 nm and suitable for transmitting the bit rates of the synchronous digital hierarchy (SDH) up to synchronous transport module (STM)-16 (2.5 Gbit/s). Moreover, the text of Recommendation ITU-T G.956 (now Recommendation ITU-T G.955) was extended to also include PDH systems operating at 1300 nm.

5.3 The third phase

The repeater spacing of the second phase lightwave systems was limited by the fibre losses at the operating wavelength of 1300 nm (typically 0.5 dB/km). Losses of silica fibres become minimal near 1550 nm. Indeed, a 0.2 dB/km loss was realized in 1979 in this spectral region.

However, the introduction of third phase lightwave systems operating at 1550 nm over single-mode fibres was considerably delayed by the large fibre dispersion near 1550 nm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occurring as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using dispersion-shifted fibres designed to have minimum dispersion near 1550 nm or by limiting the laser spectrum to a single longitudinal mode (SLM). Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gbit/s over distances in excess of 100 km. Third generation lightwave systems operating at 2.5 Gbit/s became available commercially in 1992. Such systems were capable of operating at a bit rate of up to 10 Gbit/s. The best performance being achieved using dispersion-shifted fibres in combination with lasers oscillating in a SLM.

This phase of lightwave systems was also specified in some ITU-T Recommendations. Recommendation ITU-T G.653 specifies the characteristics of a dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.652, ITU-T G.955 (ex-ITU-T G.956) and ITU-T G.957 were revised/extended in order to include optical systems operating at 1550 nm. Recommendation ITU-T G.974 specified the characteristics of the optical systems to be used for submarine applications.

5.4 The fourth phase

A drawback of third phase 1550 nm systems is that the signal must be regenerated periodically by using electronic repeaters spaced apart typically by 70-80 km. This situation changed with the advent of fibre amplifiers in 1989.

The fourth phase of lightwave systems makes use of optical amplification for increasing the repeater spacing and makes use of wavelength division multiplexing (WDM) for increasing the aggregate bit rate. The advent of the WDM technique started a revolution that resulted in doubling the system capacity every 6 months. In most WDM systems, fibre losses are compensated periodically using erbium-doped fibre amplifiers typically spaced 70-80 km apart. Such amplifiers were developed after 1985 and became commercially available by 1990. A 1991 experiment showed the possibility of data transmission over 21 000 km at 2.5 Gbit/s and over 14 300 km at 5 Gbit/s, using a recirculating-loop configuration. This performance indicated that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11 600 km at a bit rate of 5 Gbit/s had been demonstrated by using actual submarine cables, but commercial transatlantic and transpacific cable systems also became available. Since then a large number of submarine lightwave systems have been deployed worldwide.

In order to specify the characteristics of optical fibres and systems operating with optical amplifiers (OAs) and the WDM technique, many new Recommendations were developed in ITU-T. Recommendation ITU-T G.655 specifies a non-zero dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.694.1 and ITU-T G.694.2 specify the spectral grids for dense wavelength

division multiplexing (DWDM) and coarse wavelength division multiplexing (CWDM) applications. Some Recommendations specify the characteristics of optical systems devoted to particular DWDM applications: Recommendation ITU-T G.959.1 (inter-domain applications without line OA), Recommendation ITU-T G.698.1 (metro access applications without line OA), Recommendation ITU-T G.698.2 (metro core/regional applications with line OA), Recommendation ITU-T G.696.1 (backbone applications with line OA), Recommendation ITU-T G.973 (submarine applications without line OA) and Recommendation ITU-T G.977 (submarine applications with line OA). Recommendation ITU-T G.695 specifies CWDM systems for access/metro access applications.

5.5 The fifth phase

In the current development of lightwave systems, which we can consider as the fifth phase, there are several directions of evolution.

The first direction of evolution is towards increasing the capacity transmitted on an optical fibre:

- i) by transmitting more and more channels through the WDM technique in the C-band (1 530-1 565 nm), by reducing the channel spacing. Commercial terrestrial systems with a capacity of 1.6 Tbit/s (160 optical channels at 10 Gbit/s) are now available with a channel spacing of 25 GHz;
- ii) by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1 460-1 530 nm) and in the long wavelength L-band (1 565-1 625 nm). The Raman amplification technique could be used for signals in all three wavelength bands. Moreover, a new type of fibre, known as the dry or low water peak fibre has been developed with the property that fibre losses are small over the entire wavelength region extending from 1.3 to 1.65 μm . Availability of such fibres and new amplification schemes may lead to lightwave systems with a larger number of WDM channels on a single optical fibre;
- iii) by increasing the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gbit/s. Moreover, starting from 2006, some experiments demonstrated the feasibility of systems operating up to 100 Gbit/s per channel. Most of these new systems require an extremely careful management of their dispersion and new techniques to deal with polarization time variant effects (1st and 2nd order PMD, polarization dependent loss (PDL), etc.).

The second direction of evolution is the reduction of the number of expensive OEO conversions within the optical transport networks (OTNs). The two main reasons for the reduction in the number of OEO conversions are that DWDM systems are becoming capable of carrying light signals for thousands of kilometres without electrical regeneration and that photonic cross-connect (PXC) and reconfigurable optical add-drop multiplexers (ROADMs) are becoming available with the capacity, space requirements, power consumption, reliability and cost suitable for their use in the telecommunication networks. With this evolution it is possible to foresee that all optical networks (AONs) could extend to all potential routes of the backbone network of a medium size country with optical paths of up to around 2 000 km.

In the framework of these evolutions, several ITU-T Recommendations have already been prepared and the preparation of others is under way. Among those completed it is possible to quote Recommendation ITU-T G.656 for a fibre with non-zero dispersion for wideband optical transport, the extension of Recommendation ITU-T G.959.1 to also include 40 Gbit/s systems and 100 Gbit/s (striped across 4x25 Gbit/s lines) systems, Recommendation ITU-T G.672 with a description of relevant characteristics of multi-degree reconfigurable optical add-drop multiplexer (MD-ROADM) network elements and Recommendation ITU-T G.680 which allows operators to take optical add-drop multiplexers (OADM) and PXCs from different vendors and integrate them into an AON without having to add expensive OEO conversions.

5.6 Applications of optical fibres and systems technology in the telecommunication networks

Given that the first-generation systems had a capacity of 34-45 Mbit/s per fibre in 1980, the capacity of optical systems has jumped by a factor of more than 10 000 over a period of 30 years. Also over the same period the applications of optical technology progressively moved from short distance links (a few tens of kilometres) to the very long distance links of the backbone networks, completely substituting the traditional copper conductors. In recent years, optical fibres and systems technology have also started to be deployed in access networks.

6 Functional grouping of ITU-T Recommendations on optical technology

A possible functional grouping of ITU-T Recommendations on optical fibres and systems technology is shown in Table 6-1.

Table 6-1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
Optical fibres and cables: definitions and test methods	ITU-T G.650.1	Definition and test methods for linear, deterministic attributes of single-mode fibre and cable
	ITU-T G.650.2	Definition and test methods for statistical and non-linear related attributes of single-mode fibre and cable
	ITU-T G.650.3	Test methods for installed single-mode optical fibre cable links
Optical fibres and cables: multimode fibres	ITU-T G.651	Characteristics of a 50/125 μm multimode graded index optical fibre cable
	ITU-T G.651.1	Characteristics of a 50/125 μm multimode graded index optical fibre cable for the optical access network
Optical fibres and cables: single-mode fibres	ITU-T G.652	Characteristics of a single-mode optical fibre and cable
	ITU-T G.653	Characteristics of a dispersion-shifted single-mode optical fibre and cable
	ITU-T G.654	Characteristics of a cut-off shifted single-mode optical fibre and cable
	ITU-T G.655	Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable
	ITU-T G.656	Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport
	ITU-T G.657	Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network
Spectral grids	ITU-T G.694.1	Spectral grids for WDM applications: DWDM frequency grid
	ITU-T G.694.2	Spectral grids for WDM applications: CWDM wavelength grid
Physical optical interfaces	ITU-T G.691	Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers

Table 6-1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
	ITU-T G.692	Optical interfaces for multichannel systems with optical amplifiers
	ITU-T G.693	Optical interfaces for intra-office systems
	ITU-T G.695	Optical interfaces for CWDM applications
	ITU-T G.696.1	Longitudinally compatible intra-domain DWDM applications
	ITU-T G.698.1	Multichannel DWDM applications with single-channel optical interfaces
	ITU-T G.698.2	Amplified multichannel dense wavelength division multiplexing applications with single channel optical interfaces
	ITU-T G.698.3	Multichannel seeded DWDM applications with single-channel optical interfaces
	ITU-T G.957	Optical interfaces for equipments and systems relating to the synchronous digital hierarchy
	ITU-T G.959.1	Optical transport network physical layer interfaces
Free space optical systems	ITU-T G.640	Co-location longitudinally compatible interfaces for free space optical systems
All optical networks	ITU-T G.680	Physical transfer functions of optical network elements
Optical monitoring	ITU-T G.697	Optical monitoring for dense wavelength division multiplexing systems
Optical safety	ITU-T G.664	Optical safety procedures and requirements for optical transmission systems
Optical amplifiers, components and subsystems	ITU-T G.661	Definitions and test methods for the relevant generic parameters of optical amplifier devices and subsystems
	ITU-T G.662	Generic characteristics of optical amplifier devices and subsystems
	ITU-T G.663	Application-related aspects of optical amplifier devices and subsystems
	ITU-T G.665	Generic characteristics of Raman amplifiers and Raman amplified subsystems
	ITU-T G.666	Characteristics of polarization mode dispersion compensators and of receivers that compensate for polarization mode dispersion
	ITU-T G.667	Characteristics of adaptive chromatic dispersion compensators
	ITU-T G.671	Transmission characteristics of optical components and subsystems
	ITU-T G.672	Characteristics of multi-degree reconfigurable optical add/drop multiplexers
Optical fibre submarine cable systems	ITU-T G.971	General features of optical fibre submarine cable systems

Table 6-1 – ITU-T G-series Recommendations by subject matter

Category	Recommendations	Title
	ITU-T G.972	Definition of terms relevant to optical fibre submarine cable systems
	ITU-T G.973	Characteristics of repeaterless optical fibre submarine cable systems
	ITU-T G.973.1	Longitudinally compatible DWDM applications for repeaterless optical fibre submarine cable systems
	ITU-T G.974	Characteristics of regenerative optical fibre submarine cable systems
	ITU-T G.975	Forward error correction for submarine systems
	ITU-T G.975.1	Forward error correction for high bit-rate DWDM submarine systems
	ITU-T G.976	Test methods applicable to optical fibre submarine cable systems
	ITU-T G.977	Characteristics of optically amplified optical fibre submarine cable systems
	ITU-T G.978	Characteristics of optical fibre submarine cables
	ITU-T G.979	Characteristics of monitoring systems for optical submarine cable systems
Non-normative Supplements with informative content (also in the appendices of some Recommendations, e.g., Recommendations ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2, and ITU-T G.680)	ITU-T G- Sup.39	Optical system design and engineering considerations
	ITU-T G- Sup.40	Optical fibre and cable Recommendations and standards guideline
	ITU-T G- Sup.41	Design guidelines for optical fibre submarine cable systems
	ITU-T G- Sup.42	Guide on the use of the ITU-T Recommendations related to optical fibres and systems technology
	ITU-T G- Sup.47	General aspects of optical fibres and cables

7 Other standardization organizations working on optical technology

7.1 IEC Technical Committee 86 (TC 86)

IEC Technical Committee 86 (fibre optics) is responsible for the preparation of standards for fibre optic systems, modules, devices and components intended primarily for use with communications equipment. This activity covers terminology, characteristics, related tests, calibration and measurement methods, functional interfaces, optical, environmental and mechanical requirements to ensure reliable system performance. In particular, TC 86 is structured into three sub-committees.

Subcommittee (SC) 86A (fibres and cables) prepares international standards for optical fibres and optical cables embracing all types of communications applications. This activity covers terminology, generic characteristics, test and measurement methods and specifications for all types of single-mode and multimode optical fibres and all types of optical fibre indoor and outdoor cables to ensure reliable system performance and operation.

SC 86B (fibre optic interconnecting devices and passive components) prepares international standards for fibre optic interconnecting devices and passive components, embracing all types of communications applications. This activity covers terminology, characteristics, related test and measurement methods, as well as functional interfaces, including all mechanical, environmental and optical requirements to ensure interoperability and reliable performance of fibre optic interconnecting devices and passive components.

SC 86C (fibre optic systems and active devices) prepares international standards for fibre optic systems and active devices embracing all types of communications applications. This activity covers terminology, characteristics, test and measurement methods, as well as functional interfaces including all mechanical, environmental, optical and electrical requirements to ensure interoperability and reliable system performance.

ITU-T is chiefly oriented to the needs of the public telecommunication networks and systems and gathers mostly experts from telecom operators and transmission equipment manufacturers. With regard to device/component product characteristics, ITU-T has generally focused on attribute definitions and their interaction with network functionality. In some cases, limits are recommended to ensure this functionality.

IEC is more oriented towards products with attention given to public networks but also to private, industrial, military, aerospace, transportation and automotive networks. IEC gathers experts mainly from device/component vendors and users. With regard to device/components, modules and subsystems product characteristics, IEC takes charge of all details associated with trade and commerce of the corresponding products. Such details can include items like terminology, measurement methods, environmental tests, configuration, interfaces, powering, reliability and environmental issues, etc.

7.2 OIF

The Optical Internetworking Forum (OIF) promotes the development and deployment of interoperable networking solutions and services through the creation of implementation agreements for optical networking products, network processing elements and component technologies. Implementation agreements are based on requirements developed cooperatively by end-users, service providers, equipment vendors and technology providers and are aligned with worldwide standards. The OIF perform worldwide interoperability testing, build market awareness and promote education for technologies, services and solutions. The OIF provides feedback to worldwide standards organizations to help achieve a set of implementable, interoperable solutions.

There are two OIF working groups mainly related to optical technology.

The OIF physical and link layer (PLL) Working Group develops implementation agreements related to physical and data link layer interfaces between optical internetworking elements and between their internal components, reusing existing standards when applicable.

The Physical Layer User Working Group (PLUG) guides with its requirements the PLL Working Group. The PLUG is open to all OIF members, but only network equipment/systems vendors have the right to vote.

7.3 IEEE 802

The IEEE Project 802 LMSC (LAN/MAN Standards Committee) develops LAN and MAN standards, mainly for the lowest 2 layers of the reference model for open systems interconnection (OSI).

In particular, IEEE Working Group 802.3 prepares the physical layer specifications for the Ethernet rates (e.g., 1 GbE, 10 GbE, 40 GbE, 100 GbE) defining the frame rate, the maximum frame size, the MAC data rate and the line coding of the various hierarchical levels.

Afterwards it is an ITU-T responsibility to define how to transport these client signals over the optical transport network.

8 Application of ITU-T Recommendations related to optical fibres and systems technology

8.1 Optical fibres and cables: definitions and test methods for single-mode optical fibres and cables

From the beginning of the ITU-T standardization activities on optical fibres, it was clear that it would not be possible to specify the values of the various attributes which characterize an optical fibre without having previously specified the definitions of the attributes and the test methods for measuring their values.

To start with, definitions and test methods were put in the same ITU-T Recommendation as the values of the parameters. Only in 1993 were definitions and test methods removed from single-mode fibre Recommendations and used to create a dedicated ITU-T Recommendation.

Test methods are classified into two categories: reference test methods (RTMs) and alternative test methods (ATMs).

A reference test method is a test method in which a characteristic of a specified class of optical fibres or optical fibre cables is measured strictly according to the definition of this characteristic. A reference test method gives results which are accurate, reproducible and relatable to practical use.

An alternative test method is a test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured in a manner consistent with the definition of this characteristic. An alternative test method gives results which are reproducible and relatable to the reference test method and to practical use.

Both the reference test method and alternative test methods are usually specified in Recommendations ITU-T G.650.1 and ITU-T G.650.2 for each parameter and it is the intention that both the RTM and the ATM(s) may be suitable for normal product acceptance purposes. However, when using an ATM, should any discrepancy arise, it is recommended that the RTM be employed as the technique for providing the definitive measurement results.

Recommendations ITU-T G.650.1 and ITU-T G.650.2 contain definitions and test methods suitable mainly for factory measurements, while Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical cable sections.

Definitions and test methods contained in these three ITU-T Recommendations are generally not appropriate for multimode fibre.

8.1.1 Recommendation ITU-T G.650.1 Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable

The purpose of Recommendation ITU-T G.650.1 is to provide definitions and test methods suitable mainly for factory measurements of the linear, deterministic attributes of the single-mode optical fibres and cables described in Recommendations ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656 and ITU-T G.657.

These definitions and test methods are generally not appropriate for multimode fibre, such as that described in Recommendations ITU-T G.651 and ITU-T G.651.1. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

Recommendation ITU-T G.650.2 (see clause 8.1.2) contains definitions and test methods for statistical and non-linear attributes of single-mode optical fibres and cables.

Recommendation ITU-T G.650.1 describes the following terms and definitions:

- i) general definitions (refractive index profile; RTM; ATM; cladding mode stripper; mode filter);
- ii) mechanical characteristics (primary coating; secondary coating; proof test level; stress corrosion parameter);
- iii) mode field characteristics (mode field; mode field diameter (MFD); mode field centre; mode field concentricity error; mode field non-circularity);
- iv) glass geometry characteristics (cladding; cladding centre; cladding diameter; cladding diameter deviation; cladding tolerance field; cladding non-circularity; core centre; core concentricity error);
- v) chromatic dispersion definitions (chromatic dispersion; group delay; chromatic dispersion coefficient; chromatic dispersion slope; zero-dispersion wavelength; zero-dispersion slope);
- vi) other characteristics (cut-off wavelength; cable cut-off wavelength; fibre cut-off wavelength; attenuation; macrobend loss).

Recommendation ITU-T G.650.1 contains the RTM and ATMs for several parameters of the optical fibres: MFD, cladding diameter, core concentricity error, cladding non-circularity, cut-off wavelength, attenuation, chromatic dispersion, proof testing and coherent multi-path interference (MPI) in short optical fibre cables (jumpers).

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

8.1.2 Recommendation ITU-T G.650.2 *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*

The purpose of Recommendation ITU-T G.650.2 is to provide definitions and test methods suitable mainly for factory measurements of the statistical and non-linear attributes of the single-mode optical fibres and cables described in Recommendations ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656 and ITU-T G.657.

These definitions and test methods are generally not appropriate for multimode fibre, such as that described in Recommendation ITU-T G.651.1. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

Recommendation ITU-T G.650.1 contains definitions and test methods for linear deterministic attributes.

Methods how to compensate impairments caused by polarization mode dispersion (PMD) can be found in Recommendation ITU-T G.666.

Recommendation ITU-T G.650.2 describes the following terms and definitions related to PMD:

- i) the phenomenon of PMD;
- ii) principle states of polarization (PSP);
- iii) differential group delay (DGD);
- iv) PMD value;
- v) PMD coefficient.

The mathematical definitions of PMD are also given.

Recommendation ITU-T G.650.2 contains the RTM and ATMs for the PMD.

Test methods for non-linear attributes are currently empty because these test methods are still under study. However, Appendix II of Recommendation ITU-T G.650.2 gives some information on effective area (A_{eff}), non-linear coefficient (n_2/a_{eff}) and stimulated Brillouin scattering.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

8.1.3 Recommendation ITU-T G.650.3 *Test methods for installed single-mode optical fibre cable links*

Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical fibre cable links. It includes a collection of references to the main measurement methods and gives an indication of which are most suitable for installed cable sections, depending on the required inspection level needed.

Recommendation ITU-T G.650.3 contains test methods which are particularly suited to the characterization of single-mode optical fibre cable links. The methods are not intended for application to links that contain optical network elements (ONEs), amplifiers, dispersion compensators, or passive splitters/combiners.

Recommendation ITU-T G.650.3 uses a tiered approach. The first level indicates measurements that may normally be done as part of installation. The second level indicates measurements that are normally done on exception, such as to satisfy service level agreements or to verify attributes of older links that may be used at high bit rates.

Test methods for characteristics of optical fibre cable links specified in Recommendation ITU-T G.650.3 include attenuation, splice loss, fibre uniformity, PMD and chromatic dispersion.

Recommendation ITU-T G.650.3 contains some non-normative appendices.

Appendix I of Recommendation ITU-T G.650.3 gives the analysis of OTDR traces.

Appendix II of Recommendation ITU-T G.650.3 lists ITU-T Recommendations on optical transmission systems where there are the requirements for the fibre parameters dealt with in Recommendation ITU-T G.650.3.

Appendix III describes a method for differentiating splice loss and macrobending loss in installed links when large loss is observed at a fusion splice point.

8.2 Optical fibres and cables: multimode fibres

8.2.1 Withdrawn Recommendation ITU-T G.651 *Characteristics of a 50/125 μm multimode graded index optical fibre cable (withdrawn in 2008)*

Former Recommendation ITU-T G.651, originally published in 1984, covered the geometrical and transmission properties of multimode fibres having a 50 μm nominal core diameter and a 125 μm nominal cladding diameter. This Recommendation was developed during the infancy of optical fibre solutions for public switched networks. At that time (pre-1984), these fibres were considered as the only practical solution for transmission distances in the 10's of kilometres and bit rates of up to 40 Mbit/s. Single-mode G.652 fibres, which became available shortly after the publication of Recommendation ITU-T G.651 have almost completely replaced multimode fibres in public switched networks.

Today, multimode fibres continue to be widely used in datacom applications like premises and data centres cabling supporting Ethernet and fibre channel systems standards over maximum distances ranging from 100 m up to 2000 m, depending on bit rate. With a change in the applications, the multimode fibre definitions, requirements and measurements evolved away from the original Recommendation ITU-T G.651 and were maintained or improved in others. For this reason

Recommendation ITU-T G.651 was agreed to be withdrawn at the February 2008 meeting of Study Group 15.

The transmission characteristics from Recommendation ITU-T G.651 have been upgraded to the current more modern multimode optical fibre Recommendation ITU-T G.651.1 (see clause 8.2.2). A complete documentation for the modern requirements is in IEC 60793-2-10. It was agreed in 2008 to summarize the main parts of the former Recommendation ITU-T G.651 in a new appendix to Recommendation ITU-T G.651.1.

8.2.2 Recommendation ITU-T G.651.1 *Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network*

The purpose of Recommendation ITU-T G.651.1 is to provide specifications for a 50/125 µm multimode graded index optical fibre cable applied for the optical access network (OAN) in specific environments. These environments are multi-tenant building sub-networks in which broadband services have to be delivered to individual apartments.

The recommended multimode fibre supports the cost-effective use of 1 Gbit/s Ethernet systems over link lengths of up to 550 m, usually based upon the use of 850 nm transceivers.

Worldwide, various technologies for broadband access networks are advancing rapidly to provide the high capacity needed for the increasing customer demands with respect to new services. Apart from the technologies, network structures and customer densities also vary considerably.

A specific segment, which is in the main scope of Recommendation ITU-T G.651.1, is the network in a multi-tenant building. Quite a large percentage of all customers in the world are living in these buildings. Due to the high connection density and the short distribution cable lengths, cost-effective high capacity optical networks can be designed and installed by making use of 50/125 µm graded index multimode fibres.

The effective use of this network type has been shown by its extended and experienced use for datacom systems in enterprise buildings with system bit rates ranging from 10 Mbit/s up to 10 Gbit/s. This use is supported by a large series of IEEE system standards and IEC fibre and cable standards which are used as the main references in Recommendation ITU-T G.651.1.

The recommended fibre type is an improved version of the well-known 50/125 µm multimode graded-index fibre formerly recommended in Recommendation ITU-T G.651, which has been withdrawn as of February 2008 (see clause 8.2.1).

The 50/125 µm graded-index multimode optical fibre cable described in Recommendation ITU-T G.651.1 is suitable for use in the 850 nm region or in the 1 300 nm region, or alternatively may be used in both wavelength regions simultaneously.

The geometrical, optical, transmission and mechanical parameters are described in the following two categories of attributes:

- i) fibre attributes are those attributes that are retained throughout cabling and installation;
- ii) cable attributes that are recommended for cables as they are delivered.

Recommendation ITU-T G.651.1 is intended to support the following related system standard:

- IEEE Standard for Information Technology 802.3TM-2008.

Recommendation ITU-T G.651.1 contains since 2008 an appendix summarizing the main parts of the withdrawn Recommendation ITU-T G.651.

8.3 Optical fibres and cables: single-mode fibres

These ITU-T Recommendations describe the geometrical, optical, transmission and mechanical attributes of various types of single-mode optical fibres and cables.

The meaning of the terms used and the guidelines to be followed in the measurements to verify the various characteristics are given in Recommendations ITU-T G.650.1, ITU-T G.650.2 and ITU-T G.650.3.

There are three categories of attributes which describe the geometrical, optical, transmission and mechanical parameters: fibre attributes, cable attributes and link attributes.

Fibre attributes are those that are retained throughout the cabling and installation. Among the fibre attributes, only those providing a minimum essential design framework for fibre manufacture are recommended (e.g., MFD, cladding diameter, cut-off wavelength, macrobending loss). Chromatic dispersion coefficient is also included in these attributes. There are two methods for specifying the limits of the chromatic dispersion, the original method, which is a box-like specification and a newer method in which the dispersion coefficient values are bound by a pair of curves.

Cable attributes are recommended for cables as they are delivered. The attenuation coefficient and the PMD coefficient are included among the cable attributes since they are barely affected by the cabling process.

The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1 310 nm and 1 550 nm regions.

The PMD is not specified in all tables. When required, cabled fibre PMD is specified on a statistical basis, not on an individual fibre basis. The manufacturer shall supply a PMD link design value, PMD_Q , that serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M cable sections. The upper bound is defined in terms of a small probability level, Q , which is the probability that a concatenated PMD coefficient value exceeds PMD_Q . Measurements and specifications on uncabled fibre are necessary, but not sufficient to ensure the cabled fibre specification. The maximum link design value specified on uncabled fibre shall be less than or equal to that specified for the cabled fibre. The ratio of PMD values for uncabled fibre to cabled fibre depends on the details of the cable construction and processing as well as on the mode coupling condition of the uncabled fibre.

Link attributes are characteristic of concatenated cables. A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs are to be obtained.

Link attributes are affected by factors other than optical fibre cables such as splices, connectors and installation.

The attenuation (in dB/km) can be calculated from the attenuation coefficients of the factory lengths, assuming a linear dependence on length. Loss of splices and line connectors should be added together with a suitable margin for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.).

The chromatic dispersion (in ps/nm) can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length.

The DGD is the difference in arrival times of the two polarization modes at a particular wavelength and time. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength.

Values for the link attributes are not indicated for the fibre specified in Recommendation ITU-T G.657 because its characteristics are specified for deployment in the access network.

8.3.1 Recommendation ITU-T G.652 *Characteristics of a single-mode optical fibre and cable*

This was the first ITU-T Recommendation for single-mode fibre and cable and for this reason, the ITU-T G.652 fibres are often called "standard single-mode fibres". These fibres were the first to be widely deployed in the public network and they represent the majority of fibres that have been installed. The agreements that led to the first publication of Supplement 41 to the ITU-T G-series formed a key foundation to the modern optical networks that are the basis of all modern telecommunications.

Supplement 41 to the ITU-T G-series describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has zero-dispersion wavelength around 1 310 nm. This fibre was originally optimized for use in the 1 310 nm wavelength region, but can also be used in the 1 550 nm region. This is the latest version of an ITU-T Recommendation that was first created in 1984. These revisions have been intended to maintain the continuing commercial success of this fibre in the evolving world of high-performance optical transmission systems.

Over the years, parameters have been added to Recommendation ITU-T G.652 and the requirements have been made more stringent to meet the changes in market and technological demands and in manufacturing capability. An example is the addition of a requirement for attenuation at 1 550 nm in 1988. In that year, the chromatic dispersion parameters and requirements were also defined.

Some other examples include the addition of low water peak (LWP) fibres with negligible sensitivity to hydrogen exposure and the addition of requirements for PMD. However at the advent of these new capabilities and perceived needs, there was a consensus that some applications would need these attributes for advanced technologies, bit rates and transmission distances, but there were also applications that would not need these capabilities so that some options had to be maintained.

For this reason, it was agreed to create different categories of ITU-T G.652. At the present time there are four categories, A, B, C and D, that are distinguished on the PMD_Q link design value specification and whether the fibre is LWP or not, i.e., water peak is specified (LWP) or it is not specified (WPNS), as shown in the following table.

Category	Maximum PMD_Q (ps/km ^{1/2})	Water peak
A	0.5	WPNS
B	0.2	WPNS
C	0.5	LWP
D	0.2	LWP

A non-normative appendix gives representative values of attenuation and chromatic dispersion which can be taken as basis for the design of concatenated optical fibre links in accordance with the guidelines outlined in Supplement 39 to the ITU-T G-series (see clause 8.12.1). The same appendix gives an indication of the maximum link length at various channel bit rates allowed by different values of polarization mode dispersion (PMD_Q).

Other documents related to Recommendation ITU-T G.652 include the IEC specification for uncabled fibre, IEC 60793-2-50, and Recommendation ITU-T G.657. The IEC specification is aligned with all the ITU-T fibre and cable Recommendations but does specify some additional attributes such as coating dimensions and environmental tests. Sub-categories A1 and A2 of Recommendation ITU-T G.657 (see clause 8.3.6) are aligned with all the ITU-T G.652.D values but have more stringent bend loss requirements.

8.3.2 Recommendation ITU-T G.653 *Characteristics of a dispersion-shifted single-mode optical fibre and cable*

Recommendation ITU-T G.653 describes a dispersion-shifted single-mode optical fibre and cable which has a nominal zero-dispersion wavelength close to 1 550 nm, and a dispersion coefficient which increases monotonically with wavelength. This fibre was initially developed for use in single-channel high bit rate and long distance transmission in the 1 550 nm region (where the attenuation coefficient is smallest) by shifting the zero-dispersion wavelength of the ITU-T G.652 fibre to around 1 550 nm. This fibre is optimized for use in the 1 550 nm region, but may also be used at around 1 310 nm subject to the constraints outlined in Recommendation ITU-T G.653. Some provisions are made to support transmission at higher wavelengths up to 1 625 nm and lower wavelengths down to 1 460 nm.

This was the second ITU-T Recommendation for single-mode fibre and cable and was first created in 1988. The current version contains two categories, A and B, that are distinguished on the PMD_Q link design value specification, the description of the chromatic dispersion coefficient, the geometrical parameters and the macrobending loss specifications.

ITU-T G.653.A fibre is the base category for a dispersion-shifted single-mode optical fibre and cable and retains the original "box-type" specification for the dispersion coefficient. The zero-dispersion wavelength is within the operating wavelength range from 1 525 nm to 1 575 nm, so that it performs very well for single-channel systems (e.g., ITU-T G.957, ITU-T G.691, ITU-T G.693 systems), but non-linear effects are deleterious in DWDM systems with an equal channel spacing in the 1 550 nm wavelength region. However, this category is also suitable for multichannel systems (e.g., ITU-T G.692, ITU-T G.977 systems) with an unequal channel spacing in the 1 550 nm wavelength region (for more detail on unequal channel spacing see Appendix IV of Recommendation ITU-T G.692). The ITU-T G.653.A fibre is used for multichannel systems with equal channel spacing within the operating wavelength range from 1 565 nm to 1 625 nm where the chromatic dispersion has non-zero values (e.g., ITU-T G.698.1, ITU-T G.698.2 systems).

Many submarine applications can utilize this category. For some submarine applications, full optimization can lead to the selection of limits other than those that are found here. For example cable cut-off wavelength limits could be allowed to values as high as 1 500 nm.

ITU-T G.653.B fibre attributes are similar to those of ITU-T G.653.A, but the more stringent PMD requirement allows STM-64 systems to use lengths greater than 400 km and ITU-T G.959.1 non-return to zero (NRZ) 40G applications. This category defines the chromatic dispersion coefficient requirements as a pair of bounding curves vs wavelength for wavelengths from 1 460 nm to 1 625 nm. This category may support CWDM applications which do not have significant non-linear impairments.

8.3.3 Recommendation ITU-T G.654 *Characteristics of a cut-off shifted single-mode optical fibre and cable*

Recommendation ITU-T G.654 describes the geometrical, mechanical and transmission attributes of a single-mode optical fibre and cable which has its zero-dispersion wavelength around 1 300 nm and which is loss-minimized and cut-off wavelength shifted at around the 1 550 nm wavelength region.

At first, Recommendation ITU-T G.654 was created as *Characteristics of a 1550 nm wavelength loss-minimized single-mode optical fibre cable* in 1988, for the purpose of submarine cable system use. In 1997, the name of this Recommendation was changed to *Characteristics of a cut-off shifted single-mode optical fibre cable*, in order to make clearer the features of this fibre.

The main features of the fibre described by Recommendation ITU-T G.654 are its longer cut-off wavelength and lower attenuation coefficient at 1 550 nm compared to other single-mode optical fibres. The longer cut-off wavelength can allow lower macrobending loss fibre design, hence it is advantageous to submarine cables which require lower attenuation. The lowest values of attenuation coefficient depend on the fabrication process, fibre composition and design and cable design. Values