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DIGITAL SECTIONS AND DIGITAL LINE SYSTEMS

DIGITAL LINE SYSTEMS BASED ON THE 1544 kbit/s AND THE 2048 kbit/s HIERARCHY ON OPTICAL FIBRE CABLES

ITU-T Recommendation G.955

(Previously “CCITT Recommendation”)

FOREWORD

The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of the International Telecommunication Union. The 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 Conference (WTSC), which meets every four years, established the topics for study by the ITU-T Study Groups which, in their turn, produce Recommendations on these topics.

ITU-T Recommendation G.955 was revised by the ITU-T Study Group XV (1988-1993) and was approved by the WTSC (Helsinki, March 1-12, 1993).

NOTES

1 As a consequence of a reform process within the International Telecommunication Union (ITU), the CCITT ceased to exist as of 28 February 1993. In its place, the ITU Telecommunication Standardization Sector (ITU-T) was created as of 1 March 1993. Similarly, in this reform process, the CCIR and the IFRB have been replaced by the Radiocommunication Sector.

In order not to delay publication of this Recommendation, no change has been made in the text to references containing the acronyms "CCITT, CCIR or IFRB" or their associated entities such as Plenary Assembly, Secretariat, etc. Future editions of this Recommendation will contain the proper terminology related to the new ITU structure.

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

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Recommendation G.955

DIGITAL LINE SYSTEMS BASED ON THE 1544 kbit/s AND THE 2048 kbit/s HIERARCHY ON OPTICAL FIBRE CABLES[1)]

(Melbourne, 1988; revised Helsinki 1993)

1 General

This Recommendation covers digital line systems for the transmission of signals based on both the 1544 kbit/s and the 2048 kbit/s hierarchy on optical fibre cables and includes systems conveying the following bit rates:

2 048 kbit/s	1 544 kbit/s
8 448 kbit/s	3 152 kbit/s
34 368 kbit/s	6 312 kbit/s
139 264 kbit/s	32 064 kbit/s
$4 \times 139\,264$ kbit/s	44 736 kbit/s
	$n \times 44\,736$ kbit/s
	97 728 kbit/s
	$4 \times 97\,728$ kbit/s

The requirements for overall performance and interfaces of the corresponding digital sections are given in G.900-Series Recommendations.

The aim of this Recommendation is to achieve longitudinal compatibility on elementary cable sections of different digital line systems, i.e. the possibility of installing digital line systems, produced by different manufacturers, on the same optical fibre cable.

For the purpose of this Recommendation, optical fibre digital line systems can be represented as in Figure 1. The system may have no intermediate regenerators as in diagram a) of Figure 1, one intermediate regenerator as in diagram b) of Figure 1 or a larger number depending on the system design and route length.

This Recommendation covers requirements for equipment intended to meet the relevant performance objectives of Recommendations G.821 and G.921 under all normally envisaged operating conditions. In any event, Recommendation G.821 remains the overriding performance objective of the network.

2 Type of transmission medium

Multimode optical fibres conforming to Recommendation G.651 or single-mode optical fibres conforming to Recommendations G.652, G.653 and G.654 are considered suitable for these systems. Operation may be in the region of either 850 nm, 1310 nm or 1550 nm or some other wavelength depending on the fibre and system type employed. The attenuation considered the most appropriate for operation at the various bit rates and wavelengths will be chosen by the Administrations in relation to the characteristics of the link to be realized and in accordance with this Recommendation. Similarly, splice losses, connector losses and the cable margin must be chosen together with the attenuation of the optical fibre in order to achieve the overall attenuation specified in 4.

3 System margin

For the purpose of this Recommendation, the total system margin [see diagram a) of Figure 1], or regenerator section margin [see diagram b) of Figure 1], is subdivided into two main contributions. The disposition of these margins is shown in Figure 2.

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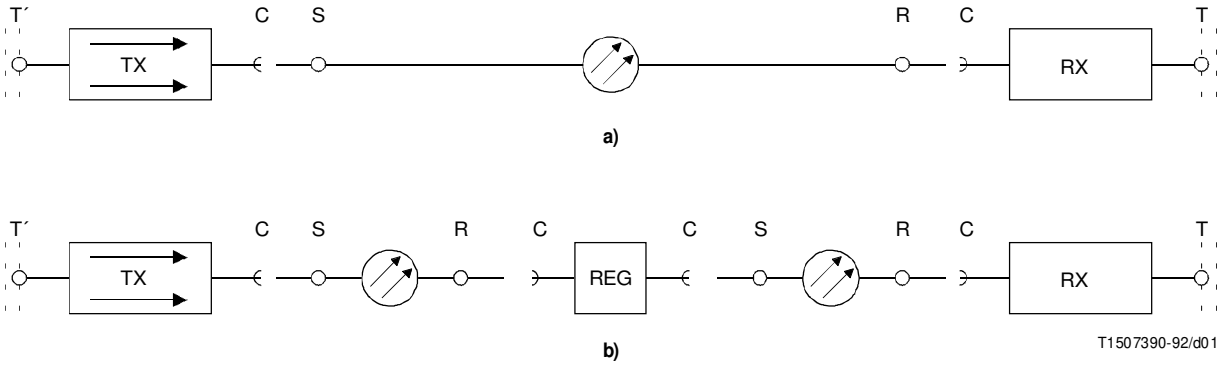
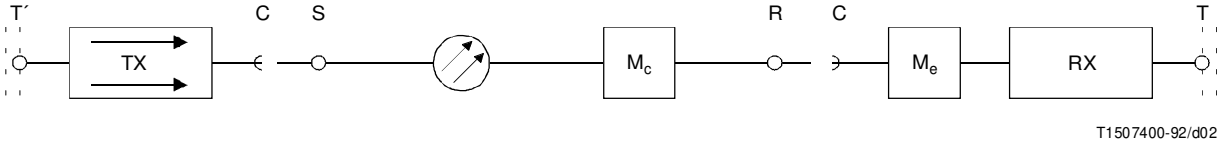
1) Recommendation G.955 totally replaces Recommendations G.955 and G.956 as contained in the *Blue Book*.



T, T´ Equipment interface in accordance with Recommendation G.703.
S Point on the optical fibre just after the transmitter (TX) or the regenerator (REG) optical connector (C).
R Point on the optical fibre just before the receiver (RX) or the regenerator (REG) optical connector (C).

NOTE – Additional connectors at a distribution frame (if used) are considered to be part of fibre link and to be located between points S and R.

FIGURE 1/G.955



NOTE – M_e represents the total combined equipment impairments from both transmitter and receiver.

FIGURE 2/G.955

3.1 Cable margin (M_c)

The cable margin, M_c, covers allowances for

i) future modifications to the cable configuration (additional splices, increased cable lengths, etc.);

ii) fibre cable performance variations due to environment factors; and

iii) degradation of any connector between points S and R when provided.

3.2 Equipment margin (M_e)

The equipment margin, (M_e), covers allowances for the effect of time and environmental factors on equipment performance (e.g. transmitter launched power, receiver sensitivity, equipment connector degradations).

NOTES

1 The design margin, which covers the allowance for the tolerances on the characteristics of the various components of the system, is not considered because worst case values for such characteristics are reflected in the specifications of 4.

2 The system margin is in relation to a BER threshold of 1×10^{-10} even though for practical reasons the measurements of receiver sensitivity may be carried out at other thresholds.

3 The approaches adopted in this Recommendation leave some additional margin in operating systems which can be considered as an unallocated margin.

4 System specifications

The optical link of a regenerator section can be represented as in Figure 2 from the point of the system specifications.

As a minimum requirement for maximum section length of typical commercially available systems, the transmitter and the receiver shall be designed so that the error performance requirements of 4.2 are obtained with an optical path as defined in 4.6 or 4.7.

4.1 Regenerator section lengths

The regenerator section length achievable with the systems specified in this Recommendation is related to the fibre characteristics and the specific capabilities of the transmitter/receiver equipment.

Examples are given in Appendix I.

For multimode systems, the description of the baseband response with a single value (the –3 dB optical bandwidth) may not be sufficient to determine the suitability of the fibre for the specified system. In some cases, a more detailed description of this characteristic or the description of the impulse response may be necessary. Additionally, the overall –3 dB optical bandwidth is assumed to include modal and chromatic contributions.

For single-mode systems, a principle characteristic is that, for a given section length, they exhibit less pulse broadening than multimode systems, provided that the central wavelength of the laser is sufficiently close to the fibre's zero-dispersion wavelength.

In general, for single-mode fibre systems employing laser sources operating near or below a nominal bit rate of $6 \times 44\,736$ kbit/s, the regenerator section length is expected to be limited by loss and not by dispersion. At higher bit rates, the regenerator section length may be limited by dispersion. Therefore, it is desirable to check whether a regenerator section length is limited by loss or dispersion:

- *Loss-limited systems:* The loss-limited regenerator section length can be calculated taking into account the system gain, the loss introduced by the sum of connector and splice losses, fibre attenuation at the operating wavelength, cable margin, and the additional loss due to any dispersion penalty (including mode partition noise).

- *Dispersion-limited systems:* The dispersion-limited regenerator section length is dependent upon the receiver tolerance to pulse distortion (e.g. due to the transmitter source spectral characteristics, mode partition noise, and the fibre chromatic dispersion). The determination of section length should be consistent with Recommendation G.651 for multimode fibre systems, and with Recommendation G.957 for single-mode fibre systems.

4.2 Error performance

The transmitter and receiver shall be designed so that a BER not worse than 1×10^{-10} is obtained when operating over an optical path between points S and R corresponding to the relevant values given in Table 1 for multimode fibre systems and Table 2 for single-mode fibre systems.

TABLE 1/G.955

Recommended optical path allowances for digital line systems on multimode optical fibre conforming to Recommendation G.651 with a single optical transmission signal

Nominal bit rate (kbit/s)	Nominal wavelength (nm)	Source type	Allowances between S and R at 1×10^{-10} BER	
			Maximum attenuation (dB)	Minimum overall –3 dB optical bandwidth (MHz)
2048	850	Laser	51	10
		LED	a)	10
	1310	Laser	46	10
		LED	30	10
6312	850	Laser	47	17
		LED	34	17
	1310	Laser	34	17
		LED	21	17
8448	850	Laser	47	20
		LED	a)	a)
	1310	Laser	a)	a)
		LED	a)	a)
32 064	850	Laser	a)	a)
		LED	a)	a)
	1310	Laser	33	65
		LED	a)	a)
34 368	850	Laser	41	50
		LED	a)	a)
	1310	Laser	35	50
		LED	22 b)	50
44 736	850	Laser	42	62
		LED	29	62
	1310	Laser	33	62
		LED	21	62
$2 \times 44\,736$	850	Laser	42	90
		LED	a)	a)
	1310	Laser	30	81
		LED	a)	a)
97 728	850	Laser	a)	a)
		LED	a)	a)
	1310	Laser	31	100
		LED	a)	a)
$3 \times 44\,736$	850	Laser	a)	a)
		LED	a)	a)
	1310	Laser	28	120
		LED	a)	a)
139 264	850	Laser	35	100
		LED	a)	a)
	1310	Laser	27	100
		LED	18 b)	100

a) Values under study

b) Provisional value

NOTES

1 The description of the baseband response with a single value (the –3 dB optical bandwidth) may not be sufficient to determine the suitability of the fibre for the specified system. A quasi-Gaussian impulse response may be assumed for design purposes but a more detailed description of the fibre response may be necessary in some cases.

2 In the case of LED systems for the values given in the table the optical fibre is assumed to have a nominal numerical aperture of 0.20 to 0.21. Additionally, the overall –3 dB optical bandwidth (modal and chromatic) is assumed to be measured with an optical source having a maximum linewidth (FWHM) of 60 nm and 100 nm centred at 850 nm and 1310 nm respectively.

3 Values given in this table are for source types other than *single longitudinal mode (SLM)* lasers.

4 Refer to 4.1, Regenerator section lengths, for other considerations.

TABLE 2/G.955

Recommended optical path allowances for digital line systems on single-mode optical fibre conforming to Recommendation G.652 with a single optical transmission signal

Nominal bit rate (kbit/s)	Nominal wavelength (nm)	Source type	Allowances between S and R at 1×10^{-10} BER	
			Maximum attenuation (dB)	Maximum dispersion ps/nm (Note 1)
2048	1310	Laser	46	N/A
	1550		a)	a)
8448	1310	Laser	40	N/A
	1550		a)	a)
34 368	1310	Laser	35	N/A (MLM)
	1550		a)	a)
44 736	1310	Laser	32	N/A (MLM)
	1550		a)	a)
97 728	1310	Laser	31	a)
	1550		a)	a)
3 × 44 736	1310	Laser	28	N/A (MLM)
	1550		a)	a)
139 264	1310	Laser	28	215 (MLM) (Note 4)
	1550		28	a)
4 × 44 736	1310	Laser	26	N/A (MLM)
	1550		a)	a)
6 × 44 736	1310	Laser	26	(Note 2)
	1550		a)	a)
4 × 97 728	1310	Laser	28	(Note 2)
	1550		a)	a)
9 × 44 736	1310	Laser	26	(Note 2)
	1550		a)	a)
12 × 44 736	1310	Laser	24	(Note 2)
	1550		a)	a)
4 × 139 264	1310	Laser	24	120 (MLM) (Note 3)
	1550		24 (Note 5)	a)
18 × 44 736	1310	Laser	24	(Note 2)
	1550		a)	a)
24 × 44 736	1310	Laser	24	(Note 2)
	1550		a)	a)
36 × 44 736	1310	Laser	23	(Note 2)
	1550		a)	a)

a) Values under study.
N/A Not applicable.

TABLE 2/G.955 *(cont.)*

NOTES

1 The reference to MLM- or SLM-lasers is related to a minimum condition for the indicated dispersion limit. In case of MLM-lasers, SLM-lasers should not be precluded.

2 Regenerator section lengths may be dispersion-limited. Specific values are dependent upon several factors and require further study. Refer to 4.1, Regenerator section lengths, for other considerations.

3 This value indicates the maximum permissible dispersion for 4 × 139 264 kbit/s systems at the limits of the operating wavelength range specified (1285 and 1330 m). The system supplier will need to determine any resultant design penalty considering the effect of mode partition noise, chromatic dispersion, etc. due to the spectral characteristics of the optical source. For reliable operation of systems it may be necessary to limit the maximum dispersion at the system operating wavelength to less than 100 ps/nm. This can be achieved by confining the system operating wavelength to a reduced wavelength range close to the fibre dispersion zero.

4 This value indicates the maximum permissible dispersion for 139 264 kbit/s system at the limit of the operating wavelength range specified (1280 to 1335 nm).

5 There are several network situations in which the need arises for increasing regenerator span length value of 4 × 140 Mbit/s systems at 1550 nm with respect to 4 × 140 Mbit/s systems at 1310 nm (already installed). In these cases an available attenuation higher than 24 dB between points S and R could be required. This requirement arises from the need to use existing network infrastructure (e.g. repeater cabinets built for existing 1310 nm 4 × 140 Mbit/s systems).

6 The maximum attenuation values my be increased in certain cases by future use of optical fibre amplifiers (OFAs). Details are for further study.

4.3 Receiver dynamic range

The optical receiver dynamic range should automatically accommodate a range of input levels to compensate for equipment production tolerances, cable attenuation ranges and tolerances, and the effects of temperatures and ageing.

It is desirable that the dynamic range of the receiver should also minimize the need for line building out attenuators.

4.4 Optical source

Multimode systems may employ either lasers or light-emitting diodes as sources. Single-mode systems generally employ lasers, although light-emitting diodes may have specific applications at certain bit rates. Single-mode systems using light-emitting diodes require further study.

4.5 Operating wavelength range

The nominal wavelengths of 850 nm and 1310 nm imply possible use anywhere in the range 820 to 910 nm and 1280 to 1335 nm respectively, for systems operating up to and including 140 Mbit/s. For systems at higher nominal bit rates the 1310 nm range is reduced to 1285 to 1330 nm. The range for the region around 1550 nm is under study.

It may be noted that operating wavelengths of 1310 nm and 1550 nm correspond to optical frequencies of about 229 THz and 193 THz, respectively.

NOTES

1 For single-mode systems operating in the 1310 nm range, the lower wavelength limit is determined from consideration of dispersion and cut-off wavelength effects, while the upper wavelength limit is due to consideration of dispersion and attenuation. In particular it should be noted that the range quoted in this Recommendation is restricted compared to the dispersion range of 1271 to 1360 nm quoted in Recommendation G.652 because of the possibility of OH peak related excess losses. To ensure satisfactory system operation, the cut-off wavelength of the shortest length of cabled fibre in a single-mode elementary cable section must not exceed the operating wavelength. The second order (LP_{11}) mode should be sufficiently attenuated along the fibre such that at the detector modal noise and bimodal dispersion effects are negligible.

2 The nominal wavelength ranges specified above are for LEDs and multilongitudinal mode (MLM) lasers. Single longitudinal mode (SLM) lasers require further study.

4.6 Optical path allowances for multimode fibre systems

The optical path allowances between points S and R are given in Table 1 for multimode fibre systems employing LEDs or MLM lasers. These allowances include the cable margin, M_c, and comprise the overall attenuation and 3 dB optical bandwidth.

These allowances represent the worst case parameter values derived from current practice within which a given system can be designed. Trade-offs among bandwidth, attenuation, dispersion, coding, etc. can vary these parameters.

The calculation of attenuation between points S and R should consider the variation of the optical fibre loss over the actual wavelength range of the optical source.

4.7 Optical path allowances for single-mode fibre systems

The optical path allowances between points S and R are given in Table 2 for single-mode fibre systems employing LED's or MLM lasers. These allowances include the cable margin M_c and comprise the overall attenuation and dispersion.

These allowances represent the worst case parameter values derived from current practice within which a given system can be designed. Trade-offs among attenuation, dispersion, coding, etc. can vary these parameters.

The calculation of attenuation between points S and R should consider the variation of the optical fibre loss over the actual wavelength range of the optical source.

4.8 Equipment margin (M_e)

The equipment margin as defined in 3.2 depends on the system characteristics, the environmental conditions and on the maintenance strategy. Administrations will need to choose a suitable value in cooperation with the system supplier for their applications.

A minimum margin of 3 dB is considered appropriate for systems using temperature stabilized lasers and PIN detectors, which operate in a typical station environment.

Greater margins may be necessary in systems using light emitting diodes or non-temperature stabilized lasers, or in systems operating in an outdoor environment.

4.9 Wavelength division multiplexing

The requirements for digital line systems employing wavelength division multiplexing techniques operating either within the same wavelength region or in separate wavelength regions are under study.

It may be noted that an optical wavelength interval of 1 nm corresponds to an optical frequency of about 175 GHz and 125 GHz at 1310 nm and 1550 nm, respectively.

5 Power feeding

The use of dependent regenerative repeaters is not generally required for optical fibre systems. It is not, therefore, necessary to recommend a specific remote power feeding system.

Where remote power feeding is required for specific applications, only constant current d.c. feeding should be used.

Where local power feeding is required a dc-voltage is sufficient.

Precautions must be taken to protect staff from any possible danger arising from the normal operating voltages and remote power feed currents as well as from induced voltages and currents. Appropriate safety measures should be adopted to ensure that under abnormal conditions the requirements of IEC Recommendation 479 are met.

Precautions are also needed for the protection of the equipment against induced voltages and currents.

NOTE – Precautions against induced voltages and currents require further study. The K-Series Recommendations may be relevant to this study.

6 Systems for short haul applications

The allowances for digital line systems found in Tables 1 and 2 are aimed at specifying minimum requirements for transmission systems with maximized section lengths. However, for applications not requiring maximized section lengths, more economical equipment can be used. Parameters for such equipment may differ from those in Tables 1 and 2 by allowing trade-offs to be made.

Furthermore, remote power feeding and remote supervision of intermediate regenerators may not be necessary.

7 Working conditions

See Recommendation G.950.

8 Overall design features

Three possible approaches for the design of the elementary cable section are a worst-case design, a statistical design, and a semi-statistical design.

The worst-case approach gives an absolute confidence that the required performances between points S and R will be met, at the expenses of a more conservative regenerator section length.

The statistical approach is based on designing an enhanced regenerator section, but admits a predetermined possibility of insufficient optical path allowances between point S and R. In this way a cost saving can be achieved in long-haul, high-bit-rate optical systems through the reduction of the number of repeaters.

When using the statistical approach, the sub-system parameters can be expressed in terms of their statistical distributions, which need to be available from the manufacturers. Such distributions can be handled either numerically (e.g. by Montecarlo or mapping methods) or analytically (e.g. Gaussian averages and standard deviations).

Examples of parameters which can be considered statistical in nature are the following:

- cable attenuation;
- cable chromatic dispersion (zero-dispersion wavelength and zero-dispersion slope);
- splice and connector losses;
- transmitter spectral characteristics (central wavelength, spectral width, etc.);
- available system gain between points S and R (e.g. optical power available at point S and receiver sensitivity at point R. These parameters may need to be considered separately for transverse compatibility considerations).

According to design practices, each of the above parameters can be considered either statistical or worst-case.

In a semi-statistical approach, those parameters assumed deterministic may be given a zero-width distribution around the worst-case value (see Appendix I).

In general, the statistical consideration of the cable attenuation coefficient, dispersion coefficient and splice loss is particularly significant for the advantages taken from statistical and semi-statistical design approach. The choice of deterministic or statistical parameters is based on the experience of the particular administration/operator.

9 Maintenance strategy

9.1 Type of supervision and fault location

In-service monitoring or out-of-service fault location can be used. For bit rates equal to or above 139 264 kbit/s, in-service monitoring is recommended. In the absence of suitable metallic conductors in the optical cable the supervision of the intermediate regenerator, where appropriate, should be provided by the same two optical fibres used for the line systems.

9.2 Fault conditions and consequent actions

The following fault conditions should be detected in addition to those specified in Recommendation G.821 for the relevant digital sections, and the associated consequent actions should be taken:

a) *failure of remote power feeding* (if applicable)

- a prompt maintenance alarm should be generated, if practicable;

b) *low error ratio threshold exceeded*

- this threshold is 1×10^{-5} for systems up to 8448 kbit/s and 1×10^{-6} for systems at higher bit rates.

A deferred maintenance alarm should be generated to signify that performance is deteriorating.

Furthermore, for systems with a laser, means to detect laser deterioration are considered advisable. For this fault condition, a deferred maintenance alarm indication is considered adequate.

10 Safety considerations

The Recommendations for guidance for the safe use, maintenance and service of line systems on optical fibre cables with operating wavelengths between 400 nm and 10 000 nm are currently under study by the IEC. This includes the operating wavelength ranges defined in 4.5 and will be considered in this Recommendation when completed.

IEC Standard 825 or appropriate national standards on laser safety may be used for guidance in this area.

Automatic laser shutdown may also be employed to achieve necessary standards for safety.

Appendix I

Calculation of regenerator section length

(This appendix does not form an integral part of this Recommendation)

I.1 Approaches

In general, three possible approaches can be defined in multi-mode and single-mode optical fibre system design:

- worst-case approach (purely deterministic);
- statistical approach (all parameters are statistically defined);
- Semi-statistical approach (only some parameters are statistically defined).

I.1.1 Worst-case approach

This approach consists of considering the worst possible values for all design parameters of the repeater span. This approach penalizes the achievable span length with respect to statistical or semi-statistical combination of design parameters, but guarantees in 100% of cases, over the lifetime of the system, an attenuation and a dispersion between points S and R lower than the specified system values.

In this approach the regenerator section length can be calculated considering that for a specified application at the end of the optical path between points S and R (see Figure 2) the overall attenuation should not exceed the specified value.

The optical path attenuation between points S and R is evaluated according to:

$$P_T - A_{tot} - P_D - M_e - P_R \geq 0$$

The optical path attenuation satisfies also:

$$A_{tot} = (\alpha_c + \alpha_m) \cdot L + (N-1) \cdot l_s + N_c \cdot l_c$$

where:

P_T is the transmitted power at point S (dBm);

A_{tot} is the total attenuation allowable between points S and R (dB);

P_D is the dispersion power penalty (dB);

M_e is the equipment margin (dB);

P_R is the received power at point R (dBm);

α_c is the cable attenuation coefficient (dB/km);

α_m is the cable margin coefficient (dB/km);

L is the total length of fibre cable (km);

N is the number of cable factory length in the repeater section;

l_s is the splice loss (dB);

N_c is the number of connectors between points S and R;

l_c is the connector loss (dB).

The optical total length of cable satisfies:

$$L \leq \frac{P_T - P_R - P_D - M_e - (N-1) \cdot l_s - N_c \cdot l_c}{\alpha_c + \alpha_m}$$

Concerning chromatic dispersion of single-mode fibre in order to obtain the regenerator section length defined by the power budget and to respect the overall limit defined in Tables 1 and 2 one defines the dispersion power penalty.

This penalty (P_D) contains effects of intersymbol interference (ISI), mode partition noise (for MLM lasers) and wavelength chirping (for SLM lasers).

For additional information on the calculation of elementary cable section lengths, refer to Recommendation G.651.

Concerning the bandwidth for multi-mode fibre, in order to obtain the regenerator section length defined by the power budget and to respect the overall limit defined in Tables 1 and 2 the following condition has to be satisfied (see 3/G.651).

$$B_T = \left[B_{\text{MODAL}}{}^{-2} + B_{\text{CHROMATIC}}{}^{-2} \right]^{-1/2}$$

For additional information on the calculation of bandwidth for elementary cable section, refer to Recommendation G.651.

I.1.2 Statistical approach

In this approach the statistic distributions of each parameters design, which influence the attenuation and dispersion of regenerator section length, are considered.

In general, the parameters which can be considered statistical in nature are the following:

- cable attenuation;
- splice loss;
- connector loss;
- zero-dispersion wavelength;
- zero-dispersion slope;
- operating wavelength;
- optical power available at the transmitter;
- receiver sensitivity;
- equipment improvements.

With this approach the design, starting from the characteristics of statistical distribution, consists in defining a statistical confidence level (e.g. 99%) by which it is possible to satisfy the attenuation and dispersion limits imposed in the regeneration section length.

When using the statistical approach, the sub-system parameters are expressed in terms of statistical distributions, which are assumed to be available from the manufacturers or from data obtained from equipment production facilities. Such distributions can be handled either analytically (e.g. convolution functions or Gaussian averages and standard deviations) or numerically (e.g. by Montecarlo method or mapping methods). Applying convolution functions, the probability distribution functions (PDF) of all design parameters existing between the optical transmitter and the optical receiver have to be known.

The design of optical transmission path involves the convolution of the PDFs of all the relevant parameters. This method requires more computation effort than the analytical one but will provide a more accurate estimation of the performance of real systems.

If all parameters have Gaussian statistical distributions, a simple design process may be used considering for each one mean value (μ) and standard deviation (σ).

The formulae to be implemented for this approach need further study.

Some of the design parameters cannot be assumed to have Gaussian distributions (e.g. splice attenuation). However, in this case, we can consider the following hypotheses:

1) the mean values and standard deviations are representative of the parameters over time and sample sizes are sufficient to warrant the use of Gaussian statistical theory;
2) the parameter distributions are reasonably Gaussian in shape;
3) all connector and splice losses are uncorrelated with fibre losses;
4) the loss allowance associated with transmitter wavelength drift is correlated in different reels;
5) cable losses, except those associated with transmitter wavelength variation, are correlated over the mean reel length but are uncorrelated from reel to reel;
6) all cables are represented by the same statistics.

Assuming that mean values plus two sigma (standard deviation) are less than the worst-case values, it is possible to invoke a valid statistical method, with a simple analytic method, in 97.7% of cases.

Nevertheless, in a very small percentage of cases, it is possible that attenuation or dispersion between points S and R is larger than specified system values. In these cases it will be necessary to sacrifice part of the system margin or selecting source and receiver to overcome power budget and/or dispersion limit problems. However, the remedies produce several problems of logistic and operating nature.

I.1.3 Semi-statistical approach

Considering the previous statistical approach the parameters relating to fibres and passive devices can confidently be considered statistical; on the other hand, parameters such as optical transmitter power and receiver sensitivity should not be considered on a statistical basis, because deterministic values of these parameters are set in the factory and because

this Recommendation specifications are recommended in terms of allowable attenuation and dispersion between points S and R. However, statistical data could be generated from production measurements.

In this situation, the semi-statistical approach considers some parameters in a deterministic way (worst-case), as, for example, operating wavelength, optical power available at the transmitter and receiver sensitivity. For other parameters (as fibre attenuation coefficient, splice loss, etc.), statistical distributions are considered, with suitable statistical parameters (e.g. mean value, standard deviation, skewness).

For example a semi-statistical method can use a set of values distributed according to Gaussian distribution generated through a Montecarlo algorithm starting from the factory statistical values (e.g. mean value, standard deviation, skewness). This set of values is used to evaluate the total dispersion and the total attenuation over the repeater section. The calculation is iterated a number N of times. A number of iterations equal to 100 gives a statistical confidence level better than 99% relating to the largest regenerator section length at which the allowable attenuation and dispersion limits between points S and R are not exceeded. A three-term Sellmeier equation is used to calculate the total dispersion, at the wavelength of interest, over the regenerator section.

As regards total attenuation the power budget is calculated taking into account the relationship reported in the worst-case approach (see I.1.1).

I.2 Statistical data form

One form is shown in Table I.1 which may be used to record statistical data. In this form, besides the parameters mean values and standard deviations, the distribution type is required where possible for further information.

TABLE I.1/G.955

Statistical data form

Parameter	Unit	Worst-case approach	Statistical approach		
			μ	σ	Distribution type
P_T	dBm				
P_R	dBm				
P_D	dBm				
λ	nm				
$\Delta\lambda$	nm				
l_c	dB				
a_c	dB				
l_s	dB				
λ_0	nm				
s_0	ps/(nm^2 · km)				

P_T	Transmitted power at point S – Transmitted power can be controlled to be within the specified limits throughout its working life. Margin is accounted for in the standard deviation.
P_R	Input optical power at point R that is necessary to achieve a specified bit-error ratio.
λ	Source operating central wavelength.
P_D	Dispersion power penalty (dB) due to inter-symbol interference, mode partition noise and chirping.
$\Delta\lambda$	Source spectral width.
l_c	Connector loss.
a_c	Cable loss (at ambient temperature) at the end of cable lifetime and at the transmitter's nominal central wavelength.
l_s	Splice loss at ambient temperature.
λ_0	Zero-dispersion wavelength of the fibre.
s_0	Zero-dispersion slope of the fibre.

I.3 Examples

For further study.

I.4 An example of a statistical optical power budget

This clause gives an example of an optical power budget for a hypothetical rather than any particular system. Statistical convolution is applied to the equipment components only, the outside plant between points S and R is not included in the analysis. Rather than manipulating mean and standard deviation values of the individual budget components, all parameters are represented as frequency – histograms based on a common 0.1 dB magnitude increment. The overall result is then obtained by direct convolution of these components.

Two typical distributions are shown in Figure I.1.

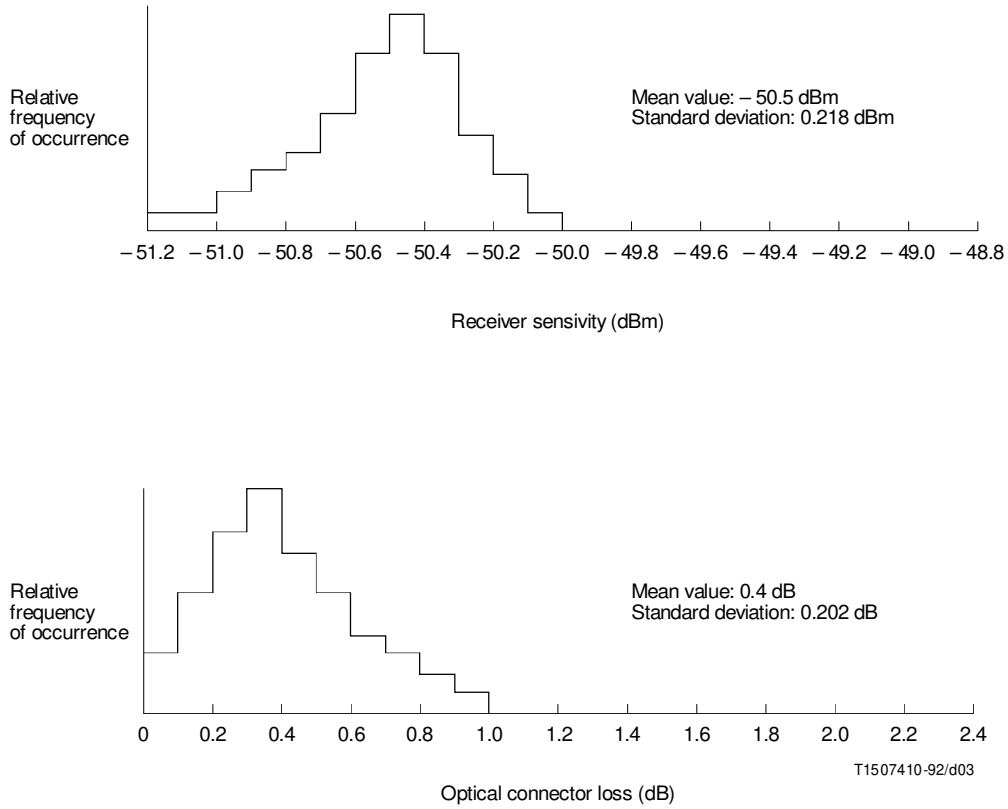


FIGURE I.1/G.955

Typical parameter distribution histograms

Table I.2 shows the budget for the hypothetical system including the worst case (extreme) and typical (mean) values taken from the eleven system parameter distributions. Direct arithmetic summation of these values gives the worst case and typical system margins of 39.05 and 41.80 dB respectively.

TABLE I.2/G.955

Hypothetical system power budgets

		Worst Case	Typical Case
1	Average transmitted power	–2.95 dBm	–2.65 dBm
2	Receiver sensitivity	–50.05 dBm	–50.50 dBm
	Available power ratio	47.10 dB	47.85 dB
	System impairments		
3	Source variations with temperature and time	0.95 dB	0.74 dB
4	Receiver variations with temperatuare and time	2.45 dB	2.04 dB
5	Reflection effects	0.05 dB	0.05 dB
6	Pattern dependant and equalisation impairments	0.95 dB	0.85 dB
7	Transmitter pulse imperfections	0.45 dB	0.39 dB
8	Extinction-ratio and dispersion effects	0.65 dB	0.54 dB
9	Error-rate correction	0.65 dB	0.65 dB
10	Transmitter connector loss	0.95 dB	0.40 dB
11	Receiver connector loss	0.95 dB	0.40 dB
	Total impairments	8.05 dB	6.05 dB
	System margin	39.05 dB	41.80 dB

Figure I.2 shows the result of the statistical analysis; in particular, it gives the system margin as a function of probability of occurrence.

For example, point “A” in Figure I.2 shows that a system margin of 40.4 dB will be achieved with a probability of 999 cases in 1000.

Note that the form of the overall system margin probability distribution is nearly Gaussian despite the non-Gaussian form of the individual parameter distributions as shown in Figure I.2.

Any deterministic parameter, such as No. 9, the “error-rate adjustment”, is represented in the distribution table as a single-column histogram 0.1 dB wide.

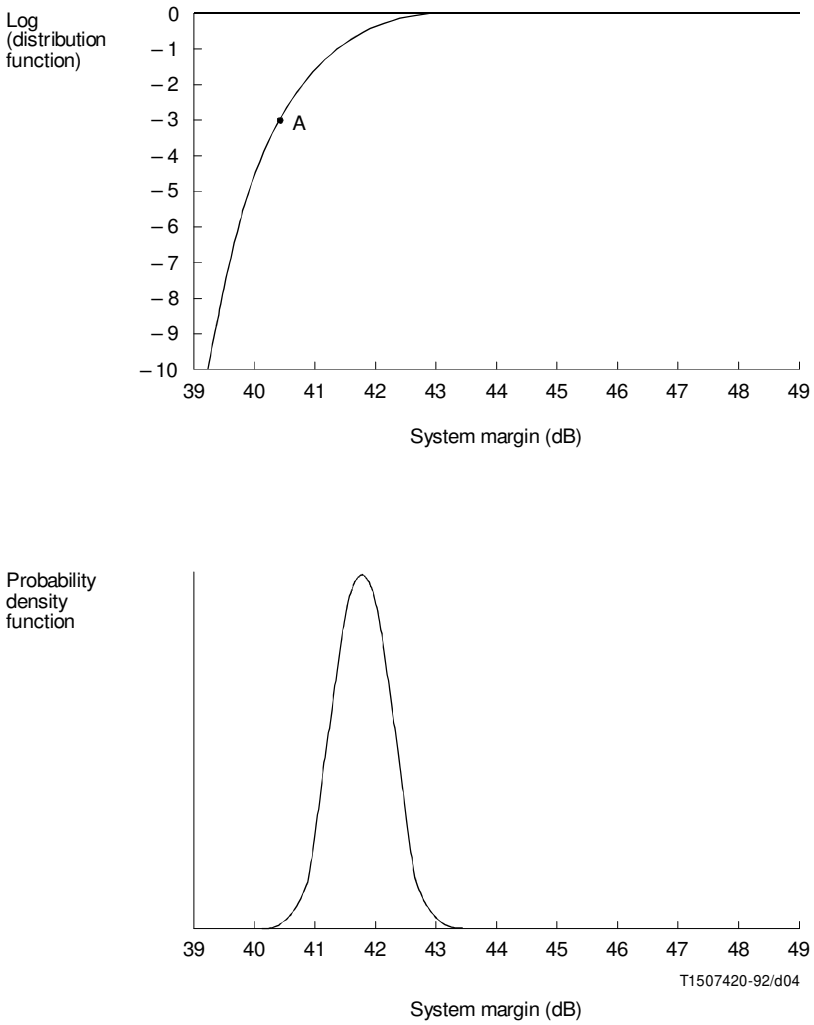


FIGURE I.2/G.955

Probability distribution of system margin