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Optical Fiber Communications Link Design in Compliance with Systems Performance Standards

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PREFACE

This report results from work supported by the National Communications System, Washington, DC, under Reimbursable Order Number R02-40167 and by the Communications Electronics Engineering Installation Agency, U.S. Army Communications Command, Ft. Huachuca, Arizona, under Project No. CCC-PO-22-82.

The report presents and extends information developed by the MIL-STD-188-111 working group under the chairmanship of Mr. Frank Berg, Naval Electronic Systems Command.

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OPTICAL FIBER COMMUNICATIONS LINK DESIGN IN COMPLIANCE WITH SYSTEMS PERFORMANCE STANDARDS

J. A. Hull and A. G. Hanson*

An engineering approach to the design of optical fiber communication links to meet mandated specifications for performance and interoperability is described. The report follows and expands upon technical guidance originally developed for MIL-STD-188-111, Subsystem Design and Engineering Standards for Common Long Haul and Tactical Fiber Optics Communications. The engineering approach should be useful in the implementation of other Government and voluntary standards under development.

Key words: distortion-limited operation; Gaussian response function; isochronous distortion; jitter; MIL-STD-188-111; optical fiber communication system; optical figure of merit; power budget; power-limited operation; rise time

1. INTRODUCTION AND BACKGROUND

The International Telegraph and Telephone Consultative Committee (CCITT) has concentrated on fiber standardization for long-haul optical fiber telecommunications applications. Comprehensive optical system and subsystem specification will be addressed later by the appropriate international working groups. Most domestic standards relating to optical fiber communication systems are in various stages of development. An exception to this slow evolution of optical systems standards is MIL-STD-188-111, Subsystem Design and Engineering Standards for Common Long Haul and Tactical Fiber Optics Communications, 24 January 1984 (see Appendix A). This military standard has been approved and is mandatory for use by all departments and agencies of the Department of Defense. Military Handbook 415 is being prepared, under the support of U.S. Army Communications Electronics Engineering Installation Agency (USACEEIA), to provide background for this standard. Target completion date for this Handbook is September 1984.

Adoption of MIL-STD-188-111 is opportune in that there is a growing awareness within U.S. voluntary standards organizations that optical fiber system standards are overdue and that prompt coordination of their development is essential. The

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American National Standards Institute (ANSI) called a meeting (ANSI, 1984) in December 1983 to help U.S. standards-developing organizations avoid duplication of each other's work in fiber optics. A recommendation came out of that meeting that ANSI coordinate national standardization in this field as well as U.S. positions for international standards activity.

An organizing meeting of a new Electronic Industries Association (EIA) subcommittee, TR 44.5, Industrial Liaison for Government Optical Fiber Systems, was held in January 1984. The proposed scope of this subcommittee states in part "... to deal with engineering and technical considerations of optical communications systems, for Government and military applications, both guided and nonguided, including the development of voluntary domestic and international standards ... this liaison to include the development and submission of technical comments and recommendations pertinent to the intended applications."

The National Communications System (NCS) plans to develop technical guidelines that may be used by Federal agencies and others in the selection and application of optical fiber intrafacility transmission facilities. An objective is to aid the user in designing systems that can both meet today's needs and interface with expected Integrated Services Digital Networks (IDSN's).

From these current activities, it is clear that Government optical fiber systems applications will be guided by the development of appropriate standards. Such applications will require engineering design guidelines to assist the user in systems implementations that will fulfill both unique user requirements and the performance/interoperability specifications of the emerging standards. The military standard mentioned above will be used as a model in this report because it is the first optical fiber system standard to be adopted by a Government department. The following report describes an approach that may be useful in the design of point-to-point applications to meet the performance specifications of this newly adopted standard. The engineering approach should be equally useful in the implementation of future voluntary standards.

1.1 Purpose

The purpose of this report is to present an engineering approach to the design of optical fiber communication systems in accordance with the intent of MIL-STD-188-111. The engineering approach is not limited to the implementation of just this standard, however.

1.2 Scope

The design approach used in this report is based largely upon an "Applications" Appendix contained in draft versions of MIL-STD-188-111, but which was deleted from the adopted version (see Appendix A). A graphical approach in the draft standard, intended to guide system analysis, has been expanded and included in this report. The use of a figure of merit developed in Appendix B of this report is used in examples to evaluate the bandwidth performance of candidate optical fiber wave-guides. A tutorial on major system components has also been included (Appendix C) to amplify the brief descriptions given in sections of this report devoted to the design approach and example calculations. A bibliography of reports and books used by the authors in preparation of this report is included to assist those users who would like further background information.

1.3 Report Organization

Section 2 develops a system design approach for point-to-point optical fiber transmission links. It begins with a brief description of key subsystem components and required subsystem performance characteristics. Link power budgets are defined and bandwidth limitations are outlined. Section 3 consists of example calculations for typical short-haul and typical long-haul links.* Section 4 provides a comparison of optical throughput for fibers of differing power acceptance parameters. A performance figure of merit for screening candidate optical fiber waveguides to meet system jitter specifications is described in Section 5. Section 6 provides a summary and recommendations for application of the design approach presented in this report. Section 7 gives acknowledgment to the contributions of others to this effort. Sections 8 and 9 present references to major technical sources used by the authors.

Since MIL-STD-188-111 will not be available from the Naval Publications and Forms Center (distribution point for MIL-STD's) until late 1984, a prepublication copy is reproduced in Appendix A. Appendix B is a brief technical note that presents the rationale for the figure of merit used in Section 5. For those readers who require some further background on optical subsystem components, a brief tutorial is presented in Appendix C. Finally, certain engineering approximations used in the design approach are derived in Appendix D.

*For the purpose of this report, short-haul link is $\leq$ 5 km, and long-haul link is > 5 km.

1.4 Summary of MIL-STD-188-111 Requirements

Purpose of the MIL-STD (reproduced as Appendix A) is to standardize the minimum number of parameters that will ensure interoperability of communications equipment and a level of performance acceptable to a majority of users. Performance and interface characteristics specified in the standard, which are pertinent to the system design approach described in this report, are the following:

Wavelength: Wavelength bands and ranges should be selected from

Table 1. Wavelength Bands and Ranges

Band	Wavelength range in Micrometers (μm)
I	0.8 to 1.0
II	1.0 to 1.2
III	1.2 to 1.4
IV	1.4 to 1.6

Optical Connector Attenuation: $\leq$ 1.5 dB for long-haul and $\leq$ 2.5 dB for tactical. For definitions of long-haul and tactical communications, See Federal Standard 1037 (1980).

Optical Splice Attenuation: $\leq$ 0.5 dB.

Optical Fiber Digital Link: Interoperability with MIL-STD-188-114 (which maps to EIA RS-422-A).

Optical Line Code: If an internally generated line code is employed, it shall not be restrictive as to the number of sequential digital "ones" or "zeroes" that can be correctly interpreted at the optical receiver. Clocking and data format shall permit transmission of data over the modulation rate range specified in MIL-STD-188-100 and MIL-STD-188-114. (MIL-STD-188-114 specifies an upper limit of 10 Megabaud (Mbd); this is referenced in MIL-STD-188-111, but is not specifically designated as an upper limit. MIL-STD-188-100 has adopted low level balanced digital interface specifications of MIL-STD-188-114.)

Bit Error Rate (BER): $\leq 10^{-8}$ for tactical [Design Objective (DO) $\leq 10^{-9}$]
$\leq 1.75 \times 10^{-10}$ K for long-haul, where K is link length in km.

Power Margin: $\geq$ 6 dB (DO = 10 dB) for every link.

Dynamic Range: $\geq$ 20 dB for optical receiver.

Jitter: under consideration. [The tentative specification used for draft versions of the MIL-STD was: "$\leq$ 3.5% rms of theoretical data unit interval (input to output of link)." This value is used in this and following sections for link analyses.]

Total Distortion: $\leq$ 25% of theoretical data unit interval.

Signal Sense: shall not invert logic and signal sense of the binary signals required by the input electrical interface.

Transmitter Clocking: when the option for signal conditioning is invoked, clocking is required to accomplish functions of line encoding and to gate the release of data from the data source. Transmitter clocking will be provided from a clock source external to the transmitter.

Receiver Clocking: when the option for signal conditioning is invoked, clocking is required to accomplish the functions of line decoding and signal regeneration, and to serve as output clock to the data side.

2. SYSTEM DESIGN APPROACH

The requirements for performance, safety, security, reliability, cost, space, terrain, and future growth all influence the selection of any transmission system (optical fiber, twisted pair, coaxial cable, or microwave) for a particular application. For metallic wire-pair systems, link equalizers and repeaters are typically required for bit rates of the order of 100's of kbit/s at distances greater than approximately 1.6 km. For optical fiber links, bandwidth is generally not a limitation, and unrepeatered distances of 9 to 19 km are achievable for multimode fibers. [Repeater spacing of 30 km (Harris, 1983) is planned for undersea systems, indicating future trends.]

Optical fibers provide common-mode and ground loop isolation between drivers and receivers, whereas wire or cable systems require isolation transformers, which may also limit bandwidth, to accomplish such isolation. Optical fibers are immune to electromagnetic interference (the drivers and receivers may require shielding), whereas costly shielding may be required for wire systems. The unauthorized tapping of optical fibers requires access to the fiber cladding and sophisticated detection equipment. Crosstalk between fiber channels is generally not measurable provided each optical fiber is contained in its own opaque sheath. (This virtual immunity to crosstalk applies to fibers transporting a single channel per fiber; care must be exercised in use of wavelength division multiplexing of multiple channels over a single fiber.)

Selection of an optical fiber with excess bandwidth (i.e., capacity above current design requirements) permits future upgrading of transmitters, receivers, and repeaters, which may accommodate system growth without changing the transmission medium. Also, optical fibers with low loss transmission "windows" at longer wavelengths than those in the 0.8 to 1.0 µm spectral region, typically used today for shorthaul links, will allow the use of future wavelength division multiplex (WDM) systems for enhanced performance of the system, as WDM component costs decrease.

Some present disadvantages of optical fiber systems include lack of component standardization, system interface incompatibilities, lack of standard test measurement procedures, limited availability of support equipment and supplies, and possible higher initial system costs. Optical fiber technology promises to be less technically complex than conventional systems. This should translate into more reliable and cost effective communication links. Optical fiber has become the medium of choice for central office interconnect (Hardwick, 1984) in several telephone operating companies; a justification for not using it is required from the telephone route-planning engineer.

Technically efficient and cost-effective application of optical fiber links dictates that

(a) the engineer have available a broad choice of functional types of drivers, receivers, and fiber cables from which to select an optimum set for a specific requirement,

(b) various combinations from among these choices permit maximum possible flexibility in design of links with widely differing requirements for maximum digital bit rate and path length, and

(c) selection of the functional type of link component for the specific application be simple and straightforward.

After tentative selection of primary link components from available alternatives, calculations are necessary to assure that the combination of all link components--including drivers, cables, receivers, splices, and connectors--will meet design goal requirements for link length and modulation conditions. This evaluation includes power levels, bandwidth, signal distortion, dynamic range, etc., and permits substitution of higher-performance components if required by the analysis (or, for cost-effectiveness, substitution of lower-performance components if the initial choices result in over-design for the application). Optimization criteria such as minimum cost, size, and weight, and environmental considerations may also apply.

As with subsystems employing metallic transmission lines, digital performance for optical fiber links involves two primary parameters:

(a) Link attenuation. For an optical fiber link, this consists of fiber loss that is the product of the attenuation coefficient, α, and link length, ℓ, and losses associated with optical connectors and splices. Typical link design includes a degradation power margin to account for long-term component aging and the case where the sum of allowable tolerances on components all add to increase loss. Particularly for applications in hostile environments, this power margin may include losses for life-cycle splices (in addition to initial splices). When total attenuation exceeds design limits, the receiver is unable to distinguish between amplitudes representing a binary "0" and "1", thus contributing to system bit-error rate. When this occurs, the link is said to be operating in the power-limited regime.

(b) Intersymbol interference, which is caused by distortion of the transmitted waveform rise time and fall time (system distortion comprises contributions from transmitter, optical fiber, and receiver). This results in timing (transition) jitter at the receiver for synchronous data transmission, and consequent contribution to system bit error rate. When this occurs, the link is said to be operating in the distortion-limited regime.

The following sections will summarize link characteristics and requirements, and procedures for evaluating link performance, and will give some sample calculations, based on a graphic concept, for evaluation of link performance. The digital transmission performance requirements of MIL-STD-188-111 will be used as the design framework, supplemented where necessary with characteristics of typical, commercial subsystem components.

2.1 Summary of Optical Interface Characteristics

2.1.1 Wavelength

The wavelength range for short-haul links should be selected in the 800 to 1000 nm region (MIL-STD-188-111 Wavelength Band I) based on current (1984) technology and cost considerations. (See Section 3.1 for a sample short-haul calculation.) Actual link operation will be determined by the source and detector combination. Longer-wavelength regions should not be excluded for specific applications if economics permit. Current long-haul links use, almost exclusively, a peak wavelength of 1300 nm (MIL-STD-188-111 Wavelength Band III). This wavelength has been employed in a sample long-haul calculation in Section 3.2.

2.1.2 Fiber

The primary parameters that determine the performance of optical fibers are attenuation, bandwidth (maximum bit rate), and numerical aperture (NA). For short-distance applications (e.g., to 2 km), core diameter becomes important to reduce coupling loss from light emitting diode (LED) sources. Many combinations of these parameters may be selected to meet a given specification. Typical parameter values are used in the link design calculations of Section 3 below.

2.1.3 Optical Source and Driver

Solid-state light emitting diodes (LED's) and injection laser diodes (ILD's) are primary sources for optical fiber transmitters because their light output can be rapidly controlled by varying their bias current. Laser sources will produce about 10 dB or more optical power output than an LED. Since the source light output must be coupled into the fiber for transmission, a coupling loss must be considered in evaluating the source. This coupling loss depends on fiber NA, on the core diameter, and on the emission characteristics of the source. ILD's have not only a higher output power but also a narrower emission angle than do LED's. Typically, ILD's will launch (into the fiber) about 18 dB more power than LED's. While ILD's offer high power output, high coupling efficiency, and high modulation efficiency, they must be operated in a restricted current range just above lasing threshold current. This threshold current is sensitive to temperature and to the age of the device. The driver circuitry must be more complex to compensate for these effects.

ILD's have a nominal spectral source width of about 2 nm, whereas LED's have a nominal spectral source width of 40 nm. When the coupled power is adequate, LED's are attractive for use instead of ILD's because of lower cost, longer expected lifetime, wider operating temperature range, and greater long-term stability. The use of LED's, however, requires that each specific application be analyzed carefully to make certain that the LED spectral width, and its associated material dispersion, do not result in unacceptable intersymbol interference (pulse distortion). Distortion-limited system operation is treated in following sections.

2.1.4 Optical Detector and Receiver

The optical receiver consists of an optical detector and amplifier that are generally designed to provide an output that reproduces the input signal. The selection of the optical receiver components (detector and associated amplifier) determines the input noise level and thus the sensitivity of the optical receiver. Two types of solid-state detectors are most suited for moderate to high bit rate (e.g., MIL-STD-188-114) optical fiber receivers. These are PIN (positive - P, intrinsic - I, negative - N layers) diodes and avalanche photodiodes (APD's). The APD provides greater receiver sensitivity but requires an auxiliary high voltage power supply, and is more costly. For strong optical signals, the PIN diode is more attractive.

The front end amplifier used with the detector must provide low noise over the signal bandwidth and must be designed to properly take into account the capacitance and current characteristics of the detector. Other considerations in the design of front end amplifiers must include dynamic range, data pattern dependence (if any), low frequency cut-off, temperature stability, and isolation from extraneous noise.

2.2 Link Power Losses: Power-Limited Regime Evaluation

In addition to fiber attenuation, typical link throughput losses include:

1) Light-source-to-fiber coupling loss: perhaps the largest variable in loss budget considerations, highly dependent on source emission characteristics and fiber core diameter, NA, and, to a lesser degree, index profile characteristics. For a 50-µm core diameter, graded index fiber with NA = 0.2, this transfer loss can be as high as 20 dB for an LED and as low as 3 dB for an ILD.

   Calculation of these losses for numerous source/fiber combinations is complex, laborious, and at best approximate. Most (but not all) driver manufacturers specify source optical output in terms of power coupled into a specified fiber or fibers, usually by means of a short fiber pigtail permanently attached to the optical source. This power value, typically in dBm (sometimes in µW), takes into account the above coupling losses and provides a practical, usable input for link power budget analysis. (Such values are used for source output, P_0, in sample power budget calculations in following sections). No other type specification for optical driver output is considered acceptable. This is not addressed in MIL-STD-188-111.

2) Connector loss: MIL-STD-188-111 specifies loss per connector for long-haul systems $\leq$ 1.5 dB and for tactical systems $\leq$ 2.5 dB. These values are somewhat conservative, but realistic for first-

order approximations. For point-to-point links, only two connectors--one each at driver and receiver--may be assumed.

3) Splice loss: MIL-STD-188-111 specifies loss per splice $\leq$ 0.5 dB, which is typically attainable. (Most 1984 splicing techniques yield appreciably lower loss than this.) Continuous fiber lengths of 1 km are available from all cable manufacturers, and some provide 2-km continuous lengths. Thus, most short-haul links will require no initial splices. Long-haul links will require a minimum number of splices commensurate with those factory-supplied lengths.

4) Fiber-to-detector loss: MIL-STD-188-111 specifies typical loss $\leq$ 1 dB for all detector and fiber types. Consequently, this loss is often ignored for first-order power budget approximations, or included in "blanket" degradation power margin.

5) Long-term loss resulting from component aging and potential environmental hazards that may require splices to repair cable breaks: typically included in power budget analysis under "degradation power margin," which may also include a power safety margin to cover the case where the sum of allowable manufacturer tolerances on link components exceeds the calculated design loss--"Murphy's Law." A word of caution: it may well appear desirable, particularly in new technology applications, to make this excess power margin "fudge factor" as large as possible within other primary design constraints. A negative result of a large degradation power margin is illustrated under Example II power budget calculation in Section 3.2.2: the power margin must be considered as a percentage of the receiver AGC dynamic range, thereby limiting the minimum usable link range and consequently its flexibility of application.

   MIL-STD-188-111 specifies a degradation power margin $\geq$ 6 dB (DO $\geq$ 10 dB) for every link.

2.2.1 Link Power Budget

The optical fiber link design depends upon the signal to be transmitted, its modulation rate, the link length required, and the tolerable signal impairment level, such as BER. The selection of a receiver with a specified minimum input power level is based on the allowable circuit BER and the required circuit bit rate. This minimum input power level is different for PIN and APD detectors. The design procedure requires the selection of the most advantageous combination of source, fiber, and detector types that best meets the system requirements. Cost is also considered.

The engineer must perform evaluations of tentatively selected link components to ensure that their combined performance meets link design goals in terms of both adequate power margin and acceptable signal degradation (e.g., distortion). Power budget analysis is the tool used to determine the first prerequisite--adequate power margin.

The allocation of losses between optical source and detector is referred to as the power budget. The power budget is obtained by first determining the optical power emitted by the source (coupled into a specified fiber), usually expressed in dBm, and subtracting the power (expressed in same units, e.g., dBm) required by the detector to achieve the design quality of performance. This figure represents the total margin of the resultant system. The total loss between source and detector is then calculated, including all link power losses itemized in the preceding section. The difference between total margin and total loss is the excess link power. If this excess link power is negative, a different combination of source, fiber, and detector is required to achieve the desired results. Conversely, an excessively high positive value for excess link power may exceed receiver AGC range, resulting in overload and consequent received signal degradation. Following sections give sample calculations for link power budgets.

2.3 Link Bandwidth: Distortion-Limited Regime Evaluation

Component selection must also be based on bandwidth or rise time. Manufacturers' data sheets provide various information on bandwidth of the fiber, namely: multimode pulse delay (ns-km), material dispersion (ns/nm-km), and/or 3 dB optical bandwidth (MHz-km). The 3 dB bandwidth specification is most common.

For digital systems, a complete rise time analysis including the source, fiber, and detector rise times, is required in addition to the above power budget. The system rise time is given approximately by:

$$\text{System rise time} = 1.1\,(t_t^{\,2} + t_r^{\,2} + t_f^{\,2})^{1/2} \quad \text{(ITT, 1977)}, \qquad (1)$$

where

t_t = transmitter rise time

t_r = receiver rise time

t_f = fiber rise time = $(t_{ma}^{\,2} + t_{mo}^{\,2})^{1/2}$,

and t_{mo} = rise time resulting from intermodal distortion

t_{ma} = rise time resulting from material dispersion.

This total system rise time should not exceed 70% of a bit interval (data unit interval, DUI) for non-return-to-zero (NRZ) data or 35% of a bit interval for return-to-zero (RZ) data (ITT, 1977). Following sections give example calculations for links employing typical sources, fibers, and receivers. For fibers, a figure of merit, Fm_0, based on 3 dB bandwidth is seen to offer a simplified approach to performance characterization.

2.4 Optical Line Coding

When bits or bytes of information are transmitted from one location to another via a transmission line, it is necessary to ensure that a particular bit arriving at its destination is interpreted correctly. To achieve this, both the sender and receiver of the data must (True, 1975):

1) Agree upon the nominal rate of transmission.

2) Agree upon a specified information code providing a one-to-one mapping of information-to-bit pattern and vice versa.

3) Establish a particular scheme whereby each bit can be properly positioned within a byte by the receiver of the data.

4) Define the protocol (e.g. handshaking) sequences necessary to ensure an orderly flow of information.

5) Agree to the electrical states representing the logic values of each bit and the particular pulse code to be used.

The above factors hold for electrical transmission and clearly influence the design of optical systems. A primary reason for considering optical transmission media is that the required nominal bit rate times path length product for a particular application may exceed the capability of conventional electrical transmission media. For the near term future, it will be necessary to translate from electrical to optical codes at the electrical to optical (E/O) interfaces. Line codes will be important to define necessary bandwidth, error correction or detection, self-clocking, and optimum signal reception.

The binary class of pulse codes can be grouped into the following four categories:

1) Non-Return to Zero (NRZ)
2) Return to Zero (RZ)
3) Phase Encoded (PE)
4) Multi-Level Binary (MLB)

Measurement of baseband signal quality in electrical systems is generally based on eye-pattern measurements that are relatable to intersymbol interference and therefore to signal distortion. The time jitter associated with the signal crossing of the threshold detection level, expressed in percent of the data unit interval (DUI), is known as isochronous distortion. (See discussion in Appendix B.) Maximum distance times pulse rate of metallic cables for NRZ signals may be specified as that distance which creates a 5% isochronous distortion (jitter). This percentage value has not been standardized, but is used by at least one metallic cable manufacturer as the basis for catalog performance curves.

Although MIL-STD-188-111 does not specify an upper limit for optical fiber contribution to jitter, draft versions of the document used a value of 3.5% x DUI. This relatively stringent requirement is used in the design calculations of Sections 3.1 and 3.2 below.

Line codes are selected in a way to promote overall system efficiency. A desirable coding scheme will help to:

1) Compress the overall bandwidth normally required to adequately transmit the signal yet ensure the recovery of the binary data.

2) Eliminate dc response so that transformer coupling can be used for phantom power distribution on repeatered lines and allow ac coupling of amplifiers.

3) Provide a clocking scheme within the signal so that no separate clock channel is required for synchronization.

4) Provide built-in error detection.

5) Reduce or eliminate data pattern dependence.

The degree of influence that coding will have on optical fiber link performance requires further study.

3. OPTICAL FIBER LINK DESIGN CALCULATIONS

In Section 3, the methodologies of preceding Sections 2.2 and 2.3 are employed in sample calculations to indicate how optical link design is influenced by individual subsystem components in satisfying requirements dictated by both power and distortion limits. Basic requirements of MIL-STD-188-111, used in these calculations, have been summarized in Section 1.4.

3.1 Example I: Typical Short-Haul Link

Table 2 gives link parameter values for a typical digital short-haul optical fiber link, which will be analyzed in this section.

3.1.1 Power Budget; Example I

The link power budget is the difference between the light source output power (P_o) coupled into a specified optical fiber and the power required at the receiver input (P_i) for the specified maximum data rate and BER:

$$\begin{aligned} \text{Power budget} &= P_o - P_i \qquad (2)\\ &= -10\ \text{dBm} - (-\ 40\ \text{dBm}),\ \text{for a typical LED source and PIN detector}\\ &= 30\ \text{dB}. \end{aligned}$$

The power budget is link-expendable power available for connector and splice losses, degradation power margin, and optical fiber cable attenuation.

Assume a continuous run of cable, without splices.

Assume two connectors, one at each end of link. Assume 2 dB loss per connector; each connector must be $\leq$ 2.5 dB loss (MIL-STD-188-111).

Link power budget after connector loss:

$$\begin{aligned} \text{Link power remaining} &= 30\ \text{dB} - 4\ \text{dB}\\ &= 26\ \text{dB}. \end{aligned}$$

MIL-STD-118-111 requires a minimum 6-dB design degradation power margin [Design Objective, (DO) = 10 dB]. This is made up of the following:

3 dB - Component power degradation due to aging

2 dB - Component power degradation due to worst case environment

1 dB - Component power degradation due to worst case manufacturing tolerance

6 dB - Total margin required to meet minimum requirement.

$$\begin{aligned} \text{Link power remaining} &= 26\ \text{dB} - 6\ \text{dB}\\ &= 20\ \text{dB}. \end{aligned}$$

Table 2. Link Parameters for Example I (Short-Haul Link)

LINK PARAMETERS	PARAMETER VALUES
Max. Data Rate (P)	20 Mbits/s
Max. Path Length (ℓ)	2 km (Power Budget Calculation)
Optical Line Code	NRZ
Driver Source Type	LED
Source Center Wavelength	850 nm ①
Source Spectral Width (W_1)	40 nm
Source Output Power (P_o)	-----
- Coupled into Specified Fiber	-10 dBm
Source Rise Time (t_t)	8 ns
Receiver Detector Type	PIN
Detector Rise Time (t_r)	12 ns
Power Required at Detector	-----
- Input (P_i) for 10^{-8} BER	-40 dBm
Receiver Noise Threshold (0 dB SNR)	-47 dBm
Receiver AGC Power Range	-----
(Specified above P_i)	27 dB (54 dB-V) ②
Receiver Voltage SNR	20 dB
Fiber Type and Core Size	Step Index, 50 μm
Fiber Bandwidth (B_f) (3 dB)	35 MHz-km
Fiber Material Dispersion	0.1 ns/nm-km ③
Fiber Attenuation (α)	10 dB/km
Link Jitter	0.035 DUI ④
Link BER	$\leq 10^{-8}$ ⑤
Link Degradation Power Margin	6 dB ⑥

① MIL-STD-188-111 Wavelength Band I.

② MIL-STD-188-111 specification: $\geq$ 20 dB; does <u>not</u> specify dynamic range lower limit (i.e., could be P_i <u>or</u> noise threshold).

③ Not specified in MIL-STD-188-111; this value used in deleted Appendix of draft versions of the STD.

④ Not specified in MIL-STD-188-111; this value used in draft versions of the STD.

⑤ MIL-STD-188-111 minimum requirement; (DO = 10^{-9}).

⑥ MIL-STD-188-111 minimum requirement; (DO = 10 dB).

Values for other parameters are typical, selected for this example.

Therefore, for a fiber cable with attenuation coefficient, α = 10 dB/km (a quite conservative value),

$$\text{max. link length } (\ell) = 20 \text{ dB}/10 \text{ dB/km}$$
$$= 2.0 \text{ km.}$$

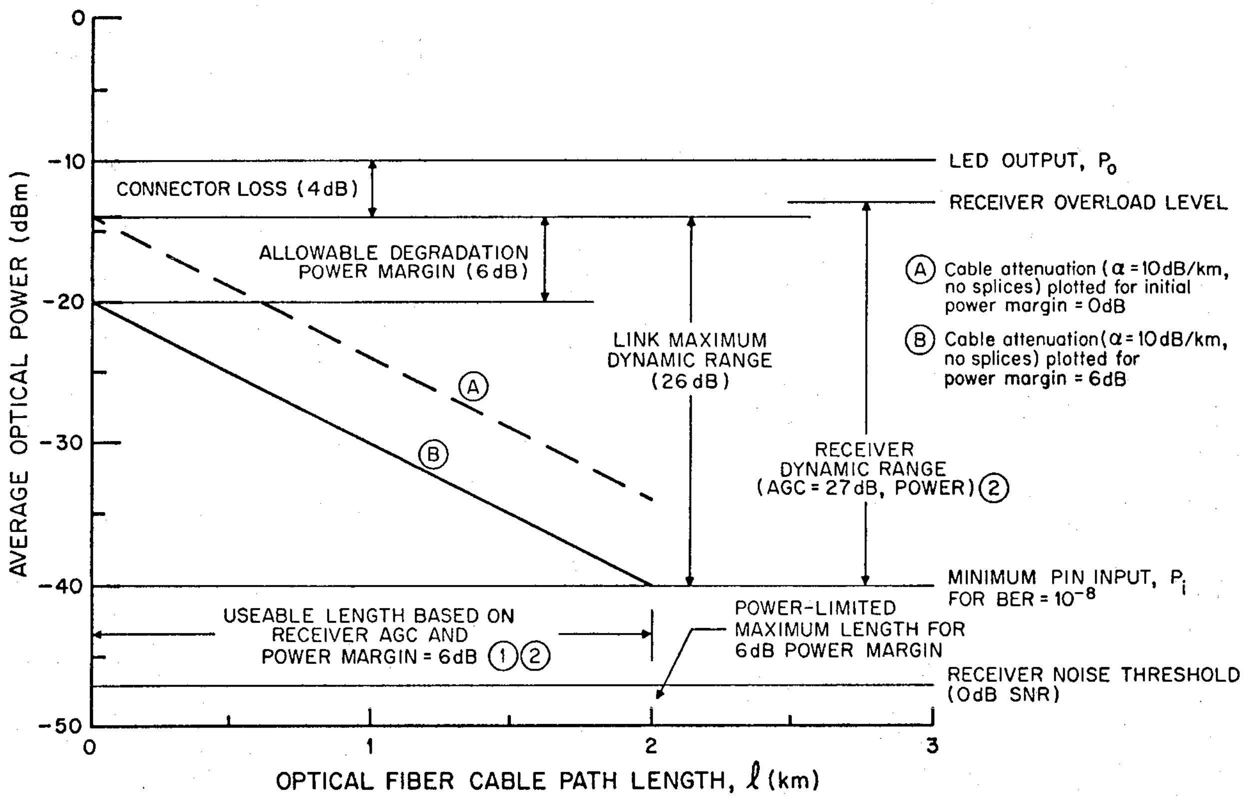
Note that this is a power calculation, and does not consider signal distortion (rise time and jitter); see Sections 3.1.3 and 3.1.4.

As indicated above, this power budget calculation is based on the minimum degradation power margin (6 dB) of MIL-STD-188-111. In some installations, it may be advisable to include excess margin for field effects such as cable damage that might require after-installation splices. Employing the Design Objective of 10 dB would make available an extra 4 dB, which would permit at least 8 splices based on the Standard's maximum allowable 0.5 dB/splice. The designer should consider inclusion of excess power margin for such splices on a case-by-case basis, evaluating the relative hostility of the environment for each installation. As emphasized in the following section, dynamic range must be carefully evaluated when adding appreciable excess power margin.

3.1.2 Dynamic Range; Example I

Figure 1 is a graphic representation of power budget parameters, indicating how these variables determine link dynamic range. A useful design application of this plot (one that is often ignored) is the comparison of the derived link dynamic range to the AGC dynamic range for a given receiver--which fixes the minimum usable path length for any link. (As seen for Example II link, this becomes a far more important limiting factor for long-haul links.) The link values for Figure 1 are those of Example I, but the graphic approach may be considered universal.

For the Example I short-haul link values, Figure 1 shows the link maximum dynamic power range to be 26 dB for the extreme case where the initial degradation power margin = 0 dB, an essential design assumption for evaluating receiver dynamic range. The receiver dynamic power range of 27 dB (54 dB voltage), typical of PIN photodiodes, exceeds the conservative 20 dB requirement of MIL-STD-188-111, and also exceeds the calculated link maximum dynamic range of 26 dB for the extreme case where initial power margin = 0 dB. This permits optimum operation over path lengths from the power-limited maximum of 2.0 km to essentially zero cable length, providing very flexible system applications for this specific combination of link components.



Notes: ① Compare to minimum path limits for long-haul link example (Figure 2).

② CAUTION: RCVR dynamic range is based on definition 2 of FED-STD-1037; definition 1 defines lower limit as RCVR noise threshold. If RCVR AGC specs. are based on definition 1, for above example, AGC range would be lowered 7 dB, resulting in RCVR overload level of -20 dBm. This would limit <u>minimum</u> usable path length to 0.7 km to include power margin in AGC range (for extreme case, initial power margin = 0 dB).

Figure 1. Plot of power budget for Example I typical short-haul optical fiber link.

As indicated in Note 2 of Figure 1, the plot of receiver dynamic range is based on definition 2 of FED-STD-1037, Glossary of Telecommunication Terms (1980) (which supersedes MIL-STD-188-120, and whose use is mandatory for DoD and Federal agency procurement):

> DYNAMIC RANGE .... 2. The difference, in decibels, between the overload level and the minimum acceptable signal level in a system or transducer. (Emphasis added.)

An optical receiver specified by this definition, where the "minimum acceptable signal level" is defined as P_i = signal threshold level for reouired BER (per MIL-STD-188-111, min. of 10^{-8}, DO of 10^{-9}), will provide maximum system's utilization of the specified minimum receiver dynamic range.

The MIL-STD, however, does not define receiver dynamic range, and FED-STD-1037 offers another, less appealing definition:

> DYNAMIC RANGE. 1. In a transmission system, the difference in decibels between the noise level of the system and its overload level .... (Emphasis added.)

A receiver whose AGC range is designed and calibrated based on this systems definition would result in the following modifications to Figure 1:

- o Low range of receiver AGC would be shifted to -47 dBm, noise threshold.
- o High range of AGC (overload level) would be shifted to -20 dBm.
- o This new overload level would result in inadequate dynamic range to accommodate the case where initial power margin = 0 dB, thereby reducing the minimum usable (design) path length to approximately 0.7 km, below which receiver saturation occurs.

This minimum-length penalty is seen to be small for short-haul links, even when using moderately high-attenuation optical fibers. As seen in Example II, the relative penalty becomes quite large for long-haul links. It is thus strongly recommended that optical receiver dynamic range be specified as definition 2 above; at the least, the designer--and installer--must know which of the two AGC approaches is employed in design of receivers to be employed.

If receiver dynamic range is found to be inadequate for short path length applications of a standardized link designed for near-maximum, power-limited operation, the following expedients may prove useful:

- o Specification of receiver sensitivity adjustment for high-level P_i, without sacrifice of dynamic range. Such range adjustment may be limited for some designs and, unless a standard feature, may involve cost tradeoff.

- o Use of a passive optical attenuator at fiber cable/receiver pigtail interface. Such attenuators are the equivalent of precision microwave attenuators or telephony line buildouts (LBO's) for metallic cables. Optical attenuators for this type application are now available from several vendors, in both fixed-attenuation and variable-attenuation models. Various designs employ attenuation techniques such as neutral density filters and axial air gaps between short fiber pigtails within a sealed housing.

- o Use of a higher-attenuation fiber, if available. This may result in cost reduction for very short links. (A word of caution, however: high fiber attenuation typically is associated with low bandwidth, which will contribute to signal distortion (system jitter).

3.1.3 System Rise Time; Example I

For successful detection of NRZ line coding, system rise time should be no more than 70 percent of the minimum bit interval (i.e., reciprocal of data rate, called the data unit interval, DUI) (ITT, 1977):

$$\text{Max. allowable system rise time} = 0.7\ (\text{DUI}) \text{ or } = 0.7\left(\frac{1}{\text{Data Rate}}\right); \qquad (3)$$

$$\text{For 20 Mbits/s, } = 0.7\left(\frac{1}{20 \times 10^6}\right);$$

$$= 35 \text{ ns.}$$

System rise time is calculated as follows:

$$\text{System rise time} = 1.1\ (t_t^{\,2} + t_r^{\,2} + t_f^{\,2})^{1/2} \text{ (ITT, 1977)}, \qquad (1)$$

where:

t_t = transmitter rise time,

t_r = receiver rise time,

t_f = fiber rise time = $(t_{ma}^{\,2} + t_{mo}^{\,2})^{1/2}$, (4)

and: t_{ma} = rise time resulting from fiber material dispersion

t_{mo} = rise time resulting from fiber multimode distortion.

Assume a transmitter rise time of 8 ns and a receiver rise time of 12 ns (typical of LED's and PIN diodes).
Fiber material rise time is:

$$t_{ma} = M \times \ell \times W_1 \qquad (5)$$

where

M = material dispersion (0.1 ns/nm-km),

ℓ = link length in km (2 km),

and W_1 = spectral line width of source in nm (40 nm).

Thus
$$t_{ma} = 0.1 \times 2 \times 40$$
$$= 8.0 \text{ ns.}$$

The rise time resulting from multimode distortion for fiber bandwidth, B_f (3 dB) = 35 MHz-km, and ℓ = 2.0 km, is (see Appendix C):

$$t_{mo} = 350\ \ell/B_f \qquad (6)$$
$$= 350\ (2.0)/35$$
$$= 20 \text{ ns.}$$

Therefore, fiber rise time, $t_f = (t_{ma}{}^2 + t_{mo}{}^2)^{1/2}$

$$= (8^2 + 20^2)^{1/2}$$
$$= 21.5 \text{ ns}$$

and system rise time $= 1.1\ (t_t{}^2 + t_r{}^2 + t_f{}^2)^{1/2}$

$$= 1.1\ (8^2 + 12^2 + 21.5^2)^{1/2}$$
$$= 28.5 \text{ ns.}$$

This is much less than the maximum of 35 ns (from Equation 3) allowable for this example link.

3.1.4 Jitter; Example I

Working drafts of MIL-STD-188-111 specified a maximum system rms jitter of 3.5 percent of the theoretical data unit interval (DUI, or bit interval):

$$\text{Allowable system rms jitter} \leq 0.035 \text{ DUI} \qquad (7)$$
$$\leq 0.035\ (1/P)$$
$$\leq 0.035/(20 \times 10^6), \text{ for } P = 20 \text{ Mbits/s}$$
$$\leq 1.75 \text{ ns.}$$

System jitter is a function of system rise time and signal to noise ratio (SNR) of peak-to-peak signal voltage to rms noise voltage:

$$\text{System jitter (ns)} = \text{System rise time (ns)/SNR.} \qquad (8)$$

A typical SNR corresponding to P_i = -40 dBm is 20 dB (V) which corresponds to a voltage ratio of 10:1. Therefore, for the 28.5 ns system rise time of Example 1,

$$\text{System jitter} = 28.5/10$$
$$= 2.9 \text{ ns.}$$

This does not meet the jitter requirement of 1.75 ns for this example. In order to meet this requirement, the rise time of the transmitter, receiver, or optical fiber (or combinations of these) must be improved to accommodate the 20 Mbit/s transmission rate. Another alternative would be to shorten the length (if possible), but one must be careful not to overdrive the receiver. (As seen above, receiver sensitivity adjustment--if available--or passive optical attenuators may be employed to achieve the required attenuation for very short path lengths, without affecting other transmission parameters.) Section 5.2 gives examples of performance achievable with various combinations of source and detector types, using the same fiber assumed for the above example.

3.2 Example II: Typical Long-Haul Link

Table 3 gives link parameter values for a typical long-haul optical fiber link, which will be analyzed in this section.

3.2.1 Power Budget; Example II

As for Example I, the link power budget is the difference between the light source output power (P_0) coupled into a specified optical fiber and the power required at the receiver input (P_i) for the specified data rate and BER:

Table 3. Link Parameters for Example II (Long-Haul Link)

LINK PARAMETERS	PARAMETER VALUES
Max. Data Rate (P)	20 Mbits/s
Max. Path Length (ℓ)	-----
- Unrepeatered Link	18.25 km (Power Budget Calculation)
Optical Line Code	NRZ
Driver Source Type	ILD
Source Center Wavelength	1300 nm ①
Source Spectral Width (W_1)	2 nm
Source Output Power (P_o)	-----
- Coupled into Specified Fiber	0 dBm
Source Rise Time (t_t)	2 ns
Receiver Detector Type	APD
Detector Rise Time (t_r)	4 ns
Power Required at Detector	-----
- Input (P_i) for 10^{-9} BER	-55 dBm
Receiver Noise Threshold	-62 dBm
Receiver AGC Power Range	-----
- Specified above P_i	25 dB (50 dB-V) ②
Receiver Voltage SNR	20 dB
Cable Fiber Type and Core Size	Graded Index, 50 μm
Fiber Bandwidth (B_f) (3 dB)	500 MHz-km
Fiber Material Dispersion	0.1 ns/nm-km ③
Fiber Attenuation Coefficient (α)	2 dB/km
Link Jitter	0.035 DUI ④
Link BER	$\leq 10^{-9}$ ⑤
Link Degradation Power Margin	10 dB ⑥

① MIL-STD-188-111 Wavelength Band II.

② MIL-STD-188-111 minimum requirement: $\geq$ 20 dB.

③ Not specified in MIL-STD-188-111; this value used in deleted Appendix of draft versions of the STD.

④ Not specified in MIL-STD-188-111; this value used in draft versions of this STD.

⑤ A rounded-off value approximating the MIL-STD-188-111 minimun requirement of 1.75×10^{-10} K, where K is length in km.

⑥ MIL-STD-188-111 DO (minimum requirement is 6 dB).

Values for other parameters are typical, selected for this example.

Power budget $= P_o - P_i$ (2)

$= 0$ dBm $-(-55$ dBm)

$= 55$ dB.

Assume two connectors, each with MIL-STD-188-111 specified loss ≤ 1.5 dB.

Link power budget after connector loss (for maximum allowable 1.5 dB/connector):

Link power remaining = 55 dB - 3 dB
= 52 dB.

Assume 9 initial splices at 0.5 dB/splice = 4.5 dB.

Link power budget after splice loss:

Link power remaining = 52 dB - 4.5 dB
= 47.5 dB.

Assume the MIL-STD-188-111 Design Objective of 10 dB for degradation power margin, plus 1 dB for 2 additional (life-cycle) splices, at 0.5 dB each.

Link power budget after power margin:

Link power remaining = 47.5 dB - 11 dB
= 36.5 dB.

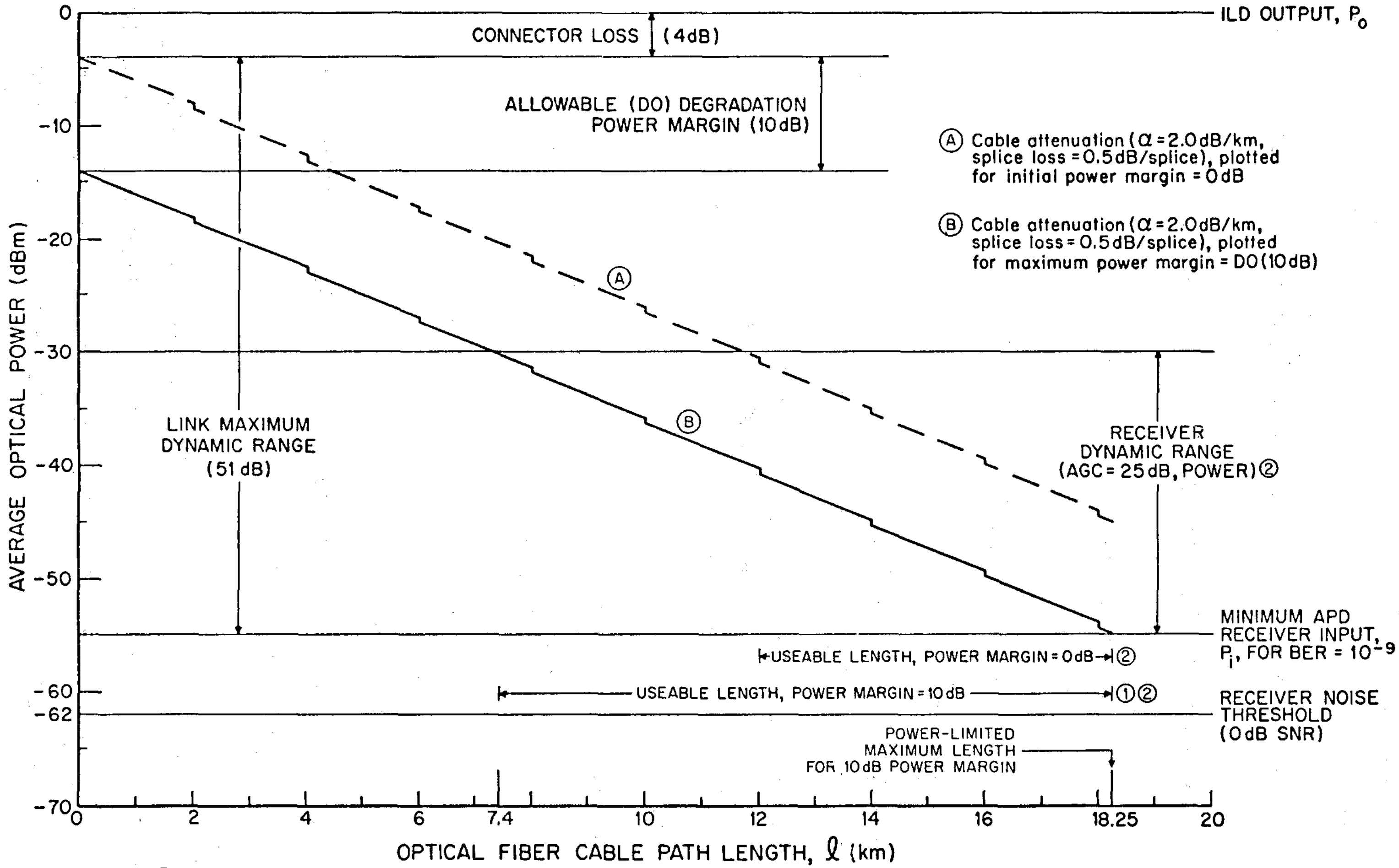
Therefore, for a cable with α = 2 dB/km,

Max. length, ℓ, = 36.5 /2
= 18.25 km.

Note that this is a power calculation, and does not consider signal distortion (rise time and jitter); see Sections 3.2.3 and 3.2.4.

3.2.2 Dynamic Range; Example II

Figure 2 is a graphic representation of power budget parameters, indicating how these variables determine link dynamic range, which is compared to the dynamic range of the receiver. The minimum usable link length, a function of receiver dynamic range, is seen to be far more limited (as a percentage of maximum, power-limited length) than is the case for short-haul links, even those employing high-



Notes: ① Minimum lengths assume maximum source output and maximum receiver sensitivity. Short path lengths than indicated may be accommodated by (a) adjusting receiver AGC range for higher power input (if the receiver is so specified) or (b) insertion of optical attenuators at cable output end.

② CAUTION: RCVR dynamic range is based on definition 2 of FED-STD-1037; definition 1 defines lower limit as RCVR noise threshold. If RCVR specs. are based on definition 1, for example, AGC range would be lowered 7 dB, resulting in RCVR overload level of -37 dBm. This would limit minimum usable path length (with maximum RCVR sensitivity and without optical attenuators) to 15 km to include power margin in AGC range (for extreme case, initial power margin = 0 dB).

Figure 2. Plot of power budget for Example II typical long-haul optical fiber link.

loss fibers (compare to Example I, Figure 1). The link values for Figure 2 are those of Example II, but the graphic approach may be considered universal.

For the Example II long-haul link values, Figure 2 shows the link maximum dynamic power range to be 51 dB for the extreme case where the initial degradation power margin = 0 dB. The receiver dynamic power range of 25 dB (50 dB voltage) is used as a compromise between the minimum MIL-STD-188-111 requirement (20 dB) and 1984 commercial specifications (receivers with 30 dB dynamic range are common, and even better performance is available).

As seen in Figure 2, the 25 dB receiver dynamic range limits the usable minimum path length to 12 km, assuming maximum rated source output and maximum receiver sensitivity. As for Example I, if the alternate definition, using receiver noise threshold (0 dB SNR), is used in receiver design, the 25 dB AGC range will be lowered 7 dB, resulting in a minimum usable length cutoff (representing receiver overload) of 15 km for initial degradation power margin = 0 dB.

This yields a usable link-length range of only 3.25 km--certainly not a flexible design margin for versatile application of links employing standardized components. The following suggestions are offered for optimizing usable range of link lengths for long-haul links; they are particularly pertinent to point-to-point application, but apply equally to repeatered systems where some individual links may be shorter than power-limited maximum due to installation variables not under control of the designer:

- For all receivers, specify AGC lower power limit to be referenced to P_i for specified BER (without sacrifice of dynamic range) - <u>not</u> at noise threshold.
- If cost tradeoffs permit, specify higher receiver dynamic range (AGC) than the minimum 20 dB of MIL-STD-188-111.
- Procure and stock cable with higher attenuation than this example's 2 dB/km at 1.3 μm.
- If cost tradeoffs permit, specify receiver sensitivity adjustments to permit shifting entire AGC range to prevent saturation.
- In preliminary design stages for all links, consider performance tradeoffs of various combinations of types of sources, fibers, and detectors (see Section 5.2). For a required bit rate times path length product, the optimum combination must not exceed <u>either</u> link power limits or distortion limits, and also must not result in receiver saturation at maximum calculated input power level. This approach should permit cost-effective functional specification of link components, avoiding costly over-design.

- Procure and stock passive optical attenuators (discussed under Example I) of various fixed values for insertion at cable output end/receiver pigtail interface. This is a very straightforward long range solution to the problem, and should be pursued. Practical system's use of passive attenuators assumes at least these prerequisites:

  1) Incorporation of optical input/output coupling components compatible with a variety of fiber diameters and NA's.

  2) Provision of mechanical couplers (e.g., bulkhead connectors) that mate with cable connectors to be specified by the user.

  3) Initial recalibration of attenuation devices by manufacturers, using user-standardized fiber cable(s), to take into account variables resulting from specific fiber parameters (e.g., core diameter, NA, and modal characteristics).

Figures 3 and 4 show graphic work sheets used in power budget evaluations. These work sheets are Figures 1 and 2, respectively, with the parameter values and plots for link Examples I and II deleted. The following step-by-step instructions track the approach used in power budget evaluation for these two examples.

1) Plot source output power level, P_o (in dBm, as for all values below), for power coupled into fiber of specified geometry (core diameter, a; NA; and index type). If source P_o value from manufacturer is for different geometry than that for specified fiber, calculate correction (which may be as high as 20 dB) from Equation 9, Section 4.

2) Plot receiver input power level, P_i, for required BER. If receiver has been specified as recommended, this value represents minimum power level for AGC range, and consequently for receiver dynamic range, which establishes the <u>minimum</u> usable link length.

3) If receiver has been specified for minimum AGC power level to be at noise threshold (<u>not</u> recommended), plot receiver noise threshold, which will fix AGC lower limit and reduce minimum usable link length of (2) above.

4) Use manufacturer's value or assume maximum loss allowed in standard and plot total connector loss.

5) Assume a value in the range allowed by the Standard and plot total allowable link degradation power margin.

6) Plot transmission line attenuation (the Fm_o approach of Section 5 should be useful in fiber selection):

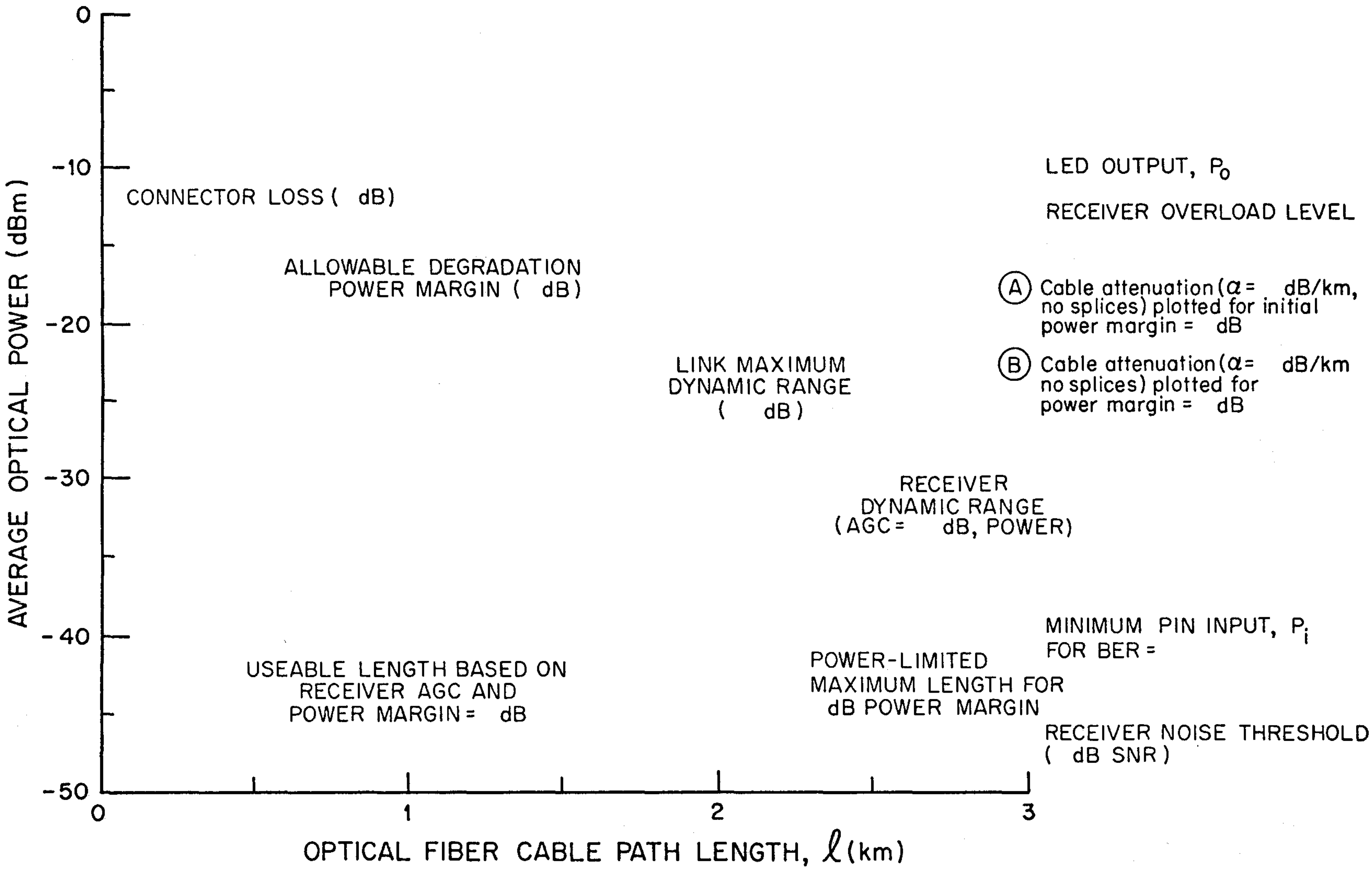


Figure 3. Graphic work sheet for short-haul optical fiber link power budget calculation.

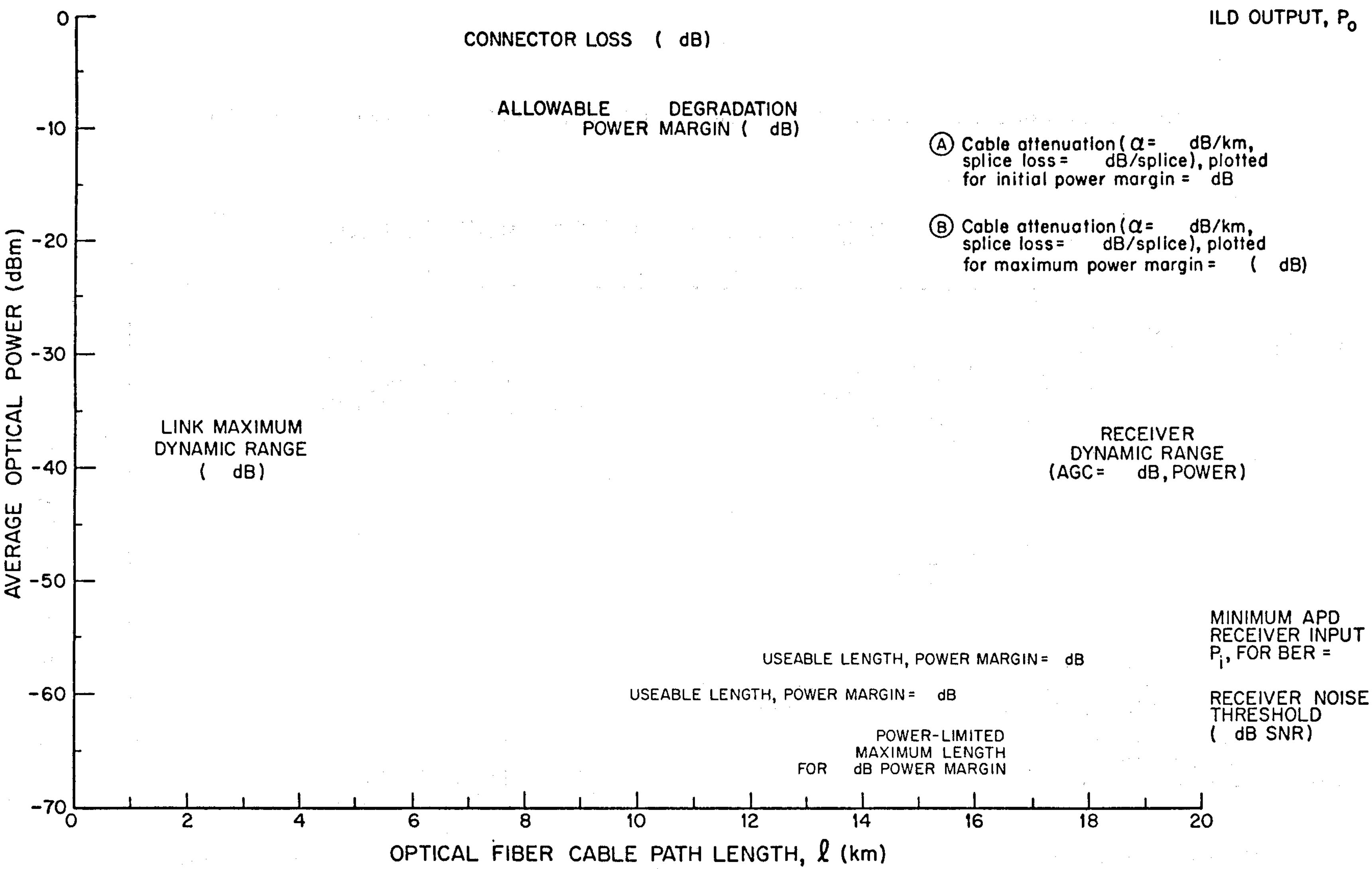


Figure 4. Graphic work sheet for long-haul optical fiber link power budget calculation.

a) If a maximum link length has been calculated (for a specific cable attenuation) using the power budget approach, plot transmission line curves as in Figures 1 and 2 for Examples I and II.

b) If a fixed maximum link length is required for a specific application, use the same approach, plotting for the required length, but calculate the cable attenuation required for the maximum distance. In either case, splice loss must be considered unless continuous cable runs can be utilized (1.1 or 2.2 km, depending on vendor, as of early 1984; longer production runs are promised soon).

7) Plot receiver dynamic range, link maximum dynamic range, and usable link length as in Examples I and II. Minimum-power levels for both will be determined by receiver AGC range and specification of receiver lower limit for AGC range (see 2 and 3, above).

8) If results do not meet all design goals, substitute different values for alternate combinations of source, cable, and receiver.

9) Note that preparation of even the most ideal power budget gives no assurance that the proposed link design will not be distortion limited and therefore may be incapable of meeting maximum design data rate x path length product. Analysis of system rise time and jitter must be performed, as for Examples I and II, to ensure acceptable distortion-limited-regime performance. (Preliminary selection of fiber by using a figure of merit should expedite this: Fm_o = required digital bit rate in Mbits/s times required link length in kilometers $\geq P\ell$. Section 5 explains this in detail.)

3.2.3 System Rise Time; Example II

For successful detection of NRZ line coding, system rise time should be no more than 70 percent of the minimum bit interval (i.e., reciprocal of data rate, called the data unit interval, DUI) (ITT, 1977):

For 20 Mbits/s, maximum system rise time $= 0.7 \left(\frac{1}{20 \times 10^6}\right)$

$= 35$ ns.

System rise time is calculated as follows:

$$\text{System rise time} = 1.1\ (t_t^2 + t_r^2 + t_f^2)^{1/2} \qquad (1)$$

where: t_t = transmitter rise time

t_r = receiver rise time

t_f = fiber rise time $= (t_{ma}^2 + t_{mo}^2)^{1/2}$, (4) where t_{ma} = rise time resulting from fiber material dispersion

t_{mo} = rise time resulting from fiber multimode distortion.

Assume a transmitter rise time of 2 ns and a receiver rise time of 4 ns (typical of ILD's and APD's).
Fiber material rise time is:

$$t_{ma} = M \times \ell \times W_1 \quad (5)$$

where M = material dispersion (0.1 ns/nm-km)

ℓ = link length in km

W_1 = spectral line width of source in nm.

Thus $t_{ma} = 0.1 \times 18.25 \times 2$

$= 3.65$ ns.

The rise time resulting from multimode distortion, for B_f (3 dB) = 500 MHz-km and ℓ = 18.25 km, is (see Appendix C):

$$t_{mo} = 350\ \ell/B_f \quad (6)$$

$$= 350\ (18.25)/500$$

$$= 12.8 \text{ ns.}$$

Therefore

$$t_f = (t_{ma}^{\ 2} + t_{mo}^{\ 2})^{1/2} \quad (4)$$

$$= (3.65^2 + 12.8^2)^{1/2}$$

$$= 13.3 \text{ ns.}$$

and system rise time $= 1.1\ (t_t^{\ 2} + t_r^{\ 2} + t_f^{\ 2})^{1/2}$ (1)

$$= 1.1\ (2^2 + 4^2 + 13.3^2)^{1/2}$$

$$= 15.4 \text{ ns.}$$

This is much less than the maximum of 35 ns (from Equation 3) for this example link.

3.2.4 Jitter; Example II

Assuming a maximum system rms jitter of 3.5 percent of the theoretical data unit interval (DUI, or bit interval):

$$\begin{aligned}\text{Allowable system rms jitter} &= 0.035 \text{ DUI} \quad (7)\\ &= 0.035\ (1/P)\\ &= 0.035/(20 \times 10^6), \text{ for } P = 20 \text{ Mbits/s}\\ &= 1.75 \text{ ns.}\end{aligned}$$

System jitter is a function of system rise time and signal-to-noise ratio (SNR) of peak-to-peak signal voltage to rms noise voltage:

$$\text{System jitter (ns)} = \text{system rise time (ns)/SNR.} \quad (8)$$

A typical SNR corresponding to P_i = -55 dBm is 20 dB (V) which corresponds to a voltage ratio of 10:1. Therefore for the 15.4 ns rise time for Example II,

$$\begin{aligned}\text{System jitter} &= 15.4/10\\ &= 1.5 \text{ ns.}\end{aligned}$$

This is better than the jitter requirement of 1.75 ns allowable for this example.

4. INFLUENCE OF FIBER POWER-ACCEPTANCE PARAMETERS ON THROUGHPUT

For long-haul applications, demanding maximum link length at moderately high data rates, fiber requirements result in small core diameters and low values for NA. For some short-haul applications, where length x data rate product does not impose strict limitations on fiber bandwidth, it is possible to use fibers with much larger cores and higher values for NA, thereby increasing source/fiber coupling efficiency and consequently increasing link power throughput for the same source and detector.

Little attention has been given in the literature to characterizing fiber efficiency for short-haul links. An approach is presented here for comparison of fibers with various physical configurations. To make such comparisons, it is essential to have previously ascertained that all fibers under consideration are not bandwidth limited for the proposed application. The primary parameters of concern are:

- core diameter, a relative measure of power accepting efficiency.
- NA, the angular measure of acceptance efficiency, and
- attenuation coefficient, the measure of throughput efficiency.

To compare two different fibers characterized in terms of these three parameters, the term relative power throughput, PO, is used for the optical power level at the fiber's exit end.

$$\frac{PO_n}{PO_r} = 10 \log \frac{(NA_n)^2 \, (a_n)^2 \, (10^{-\alpha \ell/10})_n}{(NA_r)^2 \, (a_r)^2 \, (10^{-\alpha \ell/10})_r} \qquad (9)$$

where PO_r = the optical power available at output end of the fiber of the last row in Table 4, normalized to 0 dB to permit presentation of values in dimensionless units,

PO_n = power at output end of any other fiber,

NA = fiber numerical aperture,

a = fiber core diameter in μm,

α = fiber attenuation coefficient in dB/km,

ℓ = path length in km,

subscript r = arbitrary reference fiber, and

subscript n = any other fiber, for comparison purposes.

The above expression is empirical, but it does serve to form a basis for comparison among dissimilar fibers. Several commercially available fibers are compared in Table 4.

The power throughput value for cable No. 19 of Table 4 was arbitrarily normalized to 0 dB to permit presentation in that table of relative values in dimensionless units. The reference fiber of Table 4, with 50-μm core and NA of 0.2, presents a typical design for high-bit-rate, long-haul trunking applications, even though the attenuation of 8 dB/km is high. It is seen from row 2 of the table that a fiber of 300-μm core, the same attenuation coefficient, and similar NA yields an 18.2 dB increase in power throughput efficiency--almost exclusively due to the increase in core size. The 200-μm-core fiber of row 1 offers 20 dB relative efficiency improvement with its very large NA of 0.4 and attenuation of 6 dB/km.

Table 4. Relative Power Throughput for Representative, Commercial Optical Cables (1983)

Mfgr./ Supplier	NA	Core Diameter a	Attenuation Coefficient α	Relative Power Throughput (PO_n/PO_r)
		(μm)	(dB/km)	(dB)
1	0.4	200	6	20
2	0.27	300	8	18.2
3	0.3	200	6	17.6
4	0.33	200	8	16.4
5	0.27	200	8	14.6
6	0.3	200	10	13.6
7	0.17	200	6	12.6
8	0.28	100	6	10.9
9	0.3	100	7	10.5
10	0.3	80	6	9.6
11	0.2	100	6	8.0
12	0.22	100	7	7.8
13	0.3	100	10	7.5
14	0.3	100	10	7.5
15	0.2	50	4	4.0
16	0.2	50	4	4.0
17	0.2	50	5	3.0
18	0.2	50	7	1.0
19	0.2	50	8	0 (Arbitrary Reference)

Note: Above manufacturers' data are for the 800 to 1000 nm range, and represent least-expensive cabled fiber product lines for each of the various fiber geometries. All fibers are multimode.

Numerous similar tradeoffs are possible for the various fiber design configurations of Table 4. Costly, premium-grade fibers with ultra-low losses are not required for short-haul applications. The high relative throughput efficiency of large-core, large-NA fibers of moderate loss is of paramount importance in establishing optical power values for the interfaces between the transmission line and optical source and detector. Use of high-efficiency fibers will permit cost tradeoffs involving optical transmitters of reduced power output and receivers of modest sensitivity as compared to requirements for coupling to fibers designed for long-haul trunking.

Caution must be exercised, however, in making such comparisons, to ensure that the manufacturer's stated value for NA is for measured, steady-state NA--not a value calculated from core and cladding indices. This is especially important for large NA's, where radiation losses and mode mixing of higher-order modes typically result in considerable--often drastic--decrease in steady-state values, as compared to calculated (acceptance) values. For example, manufacturers' data for some fibers with a calculated NA of 0.4 indicate a steady-state value of 0.27, measured at 0.5 km.

For Table 4, manufacturers' values for NA have been used, assuming measured data. Analysis of bandwidth capabilities of those fibers indicates that, in some cases, the assumption may have been incorrect. This emphasizes the need for standardized measurement conditions to provide the user with adequate information for comparability among various fiber designs as well as among various manufacturers' products.

One factor that has been ignored in the approximations of the above comparisons is the difference in collection efficiency between otherwise-similar step index and graded index fibers. For the same NA and core diameter, the step index design accepts a maximum of approximately 3 dB more optical power than does the graded index fiber (which offers approximately an order of magnitude higher bandwidth). (Collection efficiency of the semigraded fiber lies between that of the graded and step index designs.) Thus step index fibers, which tend to be less expensive, are viable alternatives for short-haul applications requiring moderately high data rates.

5. APPLICATION OF A PERFORMANCE FIGURE OF MERIT TO LINK DESIGN

As discussed earlier, the optical 3 dB bandwidth, expressed in MHz-km, is the most common parameter value given in manufacturers' data sheets to characterize optical fiber performance limits for quality of signal throughput. The 3 dB bandwidth has been used in Sections 3.1.3 and 3.2.3 to calculate fiber rise time as a function of multimode distortion (see Equations 4 and 6), the primary contributor to waveform degradation for multimode fibers. An even more straightforward characterization of fiber digital performance is by use of a figure of merit, Fm_0, described below.

In a reference paper (Personick, 1973) defining the performance of optical receivers, it was shown that regardless of the pulse shape (rectangular, exponential, Gaussian, etc.) the input power penalty for achieving a bit error rate of 10^{-9} can be limited to 1 dB or less by restricting the DUI (clock period) to be greater than or equal to 4σ, where σ is the rms width of the input pulse. In the case of optical fibers, the maximum data rate, P, would be obtained if very short pulses were used. These pulses would generate an impulse response at the end of the fiber waveguide. Thus a condition which defines the maximum pulse rate (clock rate) is

$$P = \frac{1}{4\sigma\ell}$$

where σ is the rms impulse response width per unit length of the waveguide and

ℓ = length of the fiber waveguide.

Then the product

$$P\ell = \frac{1}{4\sigma} \tag{10}$$

is a constant depending only on the bandwidth characteristic of fiber and is, therefore, a figure of merit, Fm_0.

There is a relationship (Danielson et al., 1982) between σ and 3 dB bandwidth (B_f) such that for any impulse response shape the product

$$\sigma \cdot B_f = \text{constant.}$$

The value for this constant is derived in Appendix D as 0.187 for a Gaussian-shaped impulse response, which is slightly conservative compared to reported (Buckler, 1982) measurements on graded index fibers. From this relationship, the figure of merit for fibers is:

$$Fm_0 = 1.3 \times B_f \text{ (MHz-km)} \tag{11}$$

For any link, the fiber Fm_0 must be equal to or greater than the pulse rate times path-length product required for the system. It should be noted that the $P\ell$

product is a constant for the specific optical fiber transmission medium, and that this constant may comprise any combination of P and ℓ.

This figure of merit provides a useful comparison of fibers for digital applications. Note that this figure of merit is useful for characterizing and comparing multimode fibers where distortion is dominated by the multimode distortion of the fiber. For certain single mode fiber applications, where fiber distortion is caused by material dispersion alone, the figure of merit (Hull et al., 1983) is:

$$Fm_s = P\ell^{1/2} \quad . \tag{12}$$

5.1 The Figure of Merit in Fiber Selection: A Screening Technique

The link designer is faced with what has grown to be a quite large menu of fiber types from which to choose. Among the various specifications offered on manufacturers' data sheets, two are of paramount importance in terms of subsystem performance:

- o For power-limited evaluation, attenuation coefficient, α
- o For distortion-limited evaluation, 3 dB bandwidth.

For short-haul applications, where path lengths impose modest restrictions on the $P\ell$ product, source-fiber coupling efficiency can be improved (sometimes drastically, up to 20 dB) by:

- o Increased core diameter
- o Increased NA.

Successful link design mandates meeting requirements for both power-limited operation (power budget evaluation) and distortion-limited operation (system rise time evaluation). As seen in previous sections, these are two distinct procedures. For a particular application, a fiber must have characteristics that will fulfill requirements resulting from both of the above evaluations. Making detailed comparisons of parameter values among many data sheets can be a laborious task; a preliminary screening process is needed.

Table 5 presents one approach to such a process. The data are summarized from a large number of 1983 manufacturers' data sheets on fiber cables (data on uncabled fiber were eliminated, because the cabling process may introduce some change in parameter values). The purpose of the table is to indicate how the

Table 5. Ranges of Specification for Representative Commercial, Cabled Optical Fibers (late 1983)

	Core Diameter, a	Attenuation Coefficient, α		NA	3 dB Bandwidth (4)			
					0.82 to 0.85 μm		1.3 μm	
		0.82 to 0.85 μm	1.3 μm		Max.	Typical	Max.	Typical
	(μm)	(dB/km)	(dB/km)	--	MHz-km	MHz-km	MHz-km	MHz-km
(A) As a function of index type								
Step Index	50 (1) to 400	3.5 to 12	(2)	0.2 to 0.5	5 to (3) 35	15 to 25	(2)	---
Graded Index	50 to 100	2.8 to 8.0	0.7 to 6.0	0.2 to 0.29	100 to 800	100 to 400	100 to 1200	200 to 600
(B) As a function of bandwidth								
Step Index	50 to 400	3.5 to 12	(2)	0.2 to 0.5	5 to 35	---	(2)	---
Graded Index	50 to 100	3.0 to 7.0	1.5 to 6.0	0.2 to 0.29	100		100	
Graded Index	50 to 100	2.8 to 5.0	0.7 to 3.0	0.2 to .25	200 to 400	---	200 to 400	---
Graded Index	50	2.8 to 4.0	0.7 to 2.0	0.20	600 to 800	---	600 to 1200	---

Notes: (1) For step index fibers, core diameters below 100 μm are rare.

(2) No manufacturers' specifications for step index fibers above 0.85 μm have been identified.

(3) Min. BDW is for maximum core diameter; max. BDW is rare.

(4) For digital transmission, Fm = Pℓ = 1.3 x BDW in MHz-km = Mbits-km/s (maximum distortion-limited fiber performance).

above four parameters (attenuation coefficient, bandwidth, core diameter, and NA) are related for "generic families" of commercially available cable. The goal is to assist the designer by guiding around incompatible combinations of parameter values for separate evaluations of system power budget and rise time. For example, the following combinations do not appear in the table:

- Core diameter of 200 μm and bandwidth of 600 MHz-km
- NA of 0.4 and bandwidth of 400 MHz-km
- attenuation coefficient of 1.0 dB/km and bandwidth of 10 MHz-km (possibly attainable, but not available).

Figure 5 gives plots of the fiber bandwidth ranges of Table 5, converted to length times data rate curves for digital performance by $Fm = P\ell = 1.3\ B_f$. It should be noted that all values for bandwidth, within the ranges for different fiber types, are maximum values; therefore, requirements for Figure 5 between Fm_o of 45.5 and 130 are met by use of graded index fibers below rated maximum performance. Before beginning link performance calculations, sequential use of Table 5 and Figure 5 will permit "ballpark" selection of fiber parameter values. As seen from Figure 5, commercially available optical fiber cables provide digital transmission capabilities far beyond the assumed requirement of 20 Mbits/s used in the examples of this report.

Choice of mechanical cable parameters (e.g., rodent-proof shielding, protection against water intrusion) will be dictated by environmental constraints, as for metallic conductors. A wide range of such options is available from multiple vendors.

5.2 The Figure of Merit and Subsystem Component Tradeoffs

In the example calculations of Sections 3.1 and 3.2, typical subsystem components were used. Tables 6 and 7 illustrate link performance variations resulting from using the same fiber cables employed in the earlier examples, but with different combinations of source and detector types. The tables give comments on performance resulting from these combinations and on suggested design modifications to overcome performance limits where design requirements are not met.

In column 3 of each table, the calculated Fm_o for the example fiber is given. In column 4, the $P\ell$ product required to meet the new power-limited link length is given. For short-haul examples 2, 3, and 4 of Table 6, the required $P\ell$ product is seen to be greater than the Fm_o of the example 35 MHz-km fiber, and consequently

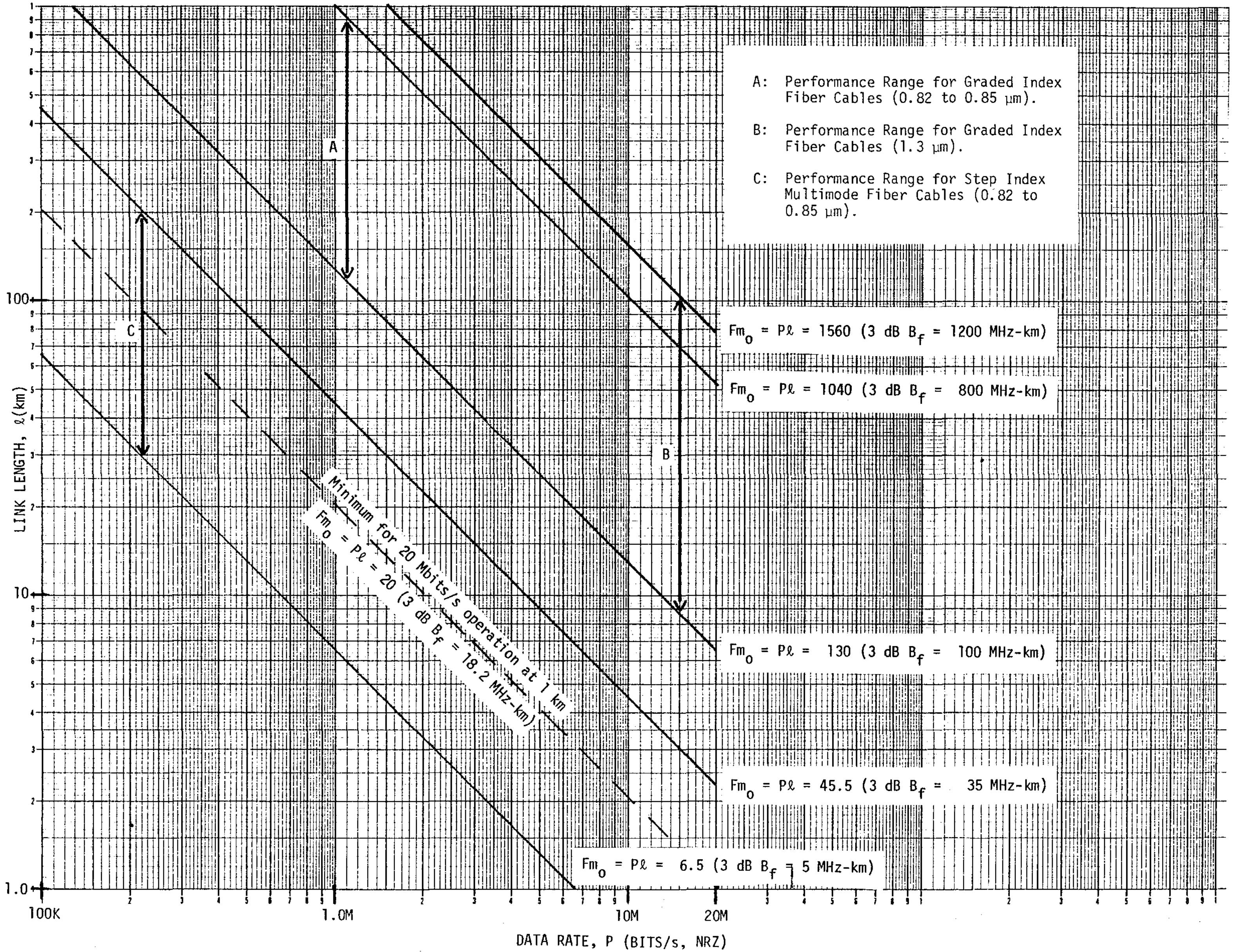


Figure 5. Figure of merit plots for distortion limits of typical step index and graded index optical fiber cables. (See Table 5 for additional fiber parameter values.)

Table 6. Comparative Short-Haul Link Performance with Various Source/Detector Combinations for Step Index, 10 dB/km, 35 MHz-km Optical Fiber Cable (Fm = 45.5); P = 20 Mbits/s

	Source/ Detector	Power-Limited[1] Link Length,[3] ℓ_{max}	Fm for[2] 35 MHz-km Fiber	$P\ell$[2] Required for ℓ_{max} at 20 Mbits/s	Fiber Rise[3] Time, t_f, for ℓ_{max}	System[3] Rise Time for ℓ_{max}	System[3] Jitter for ℓ_{max}	System Jitter Requirement (3.5% DUI) for P = 20 Mbits/s	Comments on Link Performance	Alternative Design[1] Modifications to Meet Distortion (Jitter) Requirements
1	LED/PIN	2 km	45.5	40	21.5 ns	28.5 ns	2.9 ns	1.75 ns	This is Example I (Table 2). Does not meet jitter requirement; link performance is distortion-limited by source/detector combination for power-budget calculated ℓ_{max}.	For ℓ_{max} = 2 km, substitute higher-performance source or detector (probably resulting in limiting minimum usable link length, ℓ_{min}, for MIL-STD-188-111 min. RCVR AGC = 20 dB).
2	LED/APD	3.5 km	45.5	70	37.7 ns	42.6 ns	4.3 ns	1.75 ns	Does not meet jitter requirement; link is distortion-limited by fiber for power-budget ℓ_{max}.	Substitute fiber with higher BDW. If lower α, redetermine ℓ_{min}.
3	ILD/PIN	3.0 km	45.5	60	30.0 ns	35.6 ns	3.6 ns	1.75 ns	Does not meet jitter requirement; link is distortion-limited by fiber for power-budget ℓ_{max}.	Substitute fiber with higher BDW. If lower α, redetermine ℓ_{min}.
4	ILD/APD	4.5 km	45.5	90	45.0 ns	49.7 ns	5.0 ns	1.75 ns	Does not meet jitter requirement; link is distortion-limited by fiber for power-budget ℓ_{max}.	Substitute fiber with higher BDW. If lower α, redetermine ℓ_{min}.

See footnotes on following page.

Notes for Table 6:

① All power-limited values for ℓ_{max} are power-budget calculations, using equations and graphic approach illustrated in Examples I and II of preceding sections. For ℓ_{min} limits (see last column), representing RCVR overload for AGC = 25 dB, the extreme case for link dynamic range (degradation power margin = 0 dB) is assumed. (Minimum AGC for MIL-STD-188-111 is 20 dB.)

② Pulse rate, P(Mbits/s) = 1.3 x B_f (MHz)

③ Calculations based on assumptions of previous sections where:

- Source power output, P_o

  for a typical LED = -10 dBm
  for a typical ILD = 0 dBm

- Detector power input, P_i

  for a typical PIN = -40 dBm
  for a typical APD = -55 dBm

- Transmitter rise time, t_t

  for a typical LED source = 8 ns
  for a typical ILD source = 2 ns

- Receiver rise time, t_r

  for a typical PIN detector = 12 ns
  for a typical APD detector = 4 ns

- Spectral source width, W,

  for a typical LED = 40 nm
  for a typical ILD = 2 nm

Table 7. Comparative Long-Haul Link Performance with Various Source/Detector Combinations for Graded Index, 2 dB/km, 500 MHz-km Optical Fiber Cable (Fm = 650); P = 20 Mbits/s

	Source/ Detector	Power-Limited[1] Link Length,[3] ℓ_{max}	Fm for[2] 500 MHz-km Fiber	Pℓ[2] Required for ℓ_{max} at 20 Mbits/s	Fiber Rise[3] Time, t_f, for ℓ_{max}	System[3] Rise Time for ℓ_{max}	System[3] Jitter for ℓ_{max}	System Jitter Requirement (3.5% DUI) for P = 20 Mbits/s	Comments on Link Performance	Alternative Design[1] Modifications to Meet Distortion (Jitter) Requirements
A	ILD/APD	18.25 km	650	365	13.3 ns	15.45 ns	1.5 ns	1.75 ns	This is Example II (Table 3). Meets jitter requirement; link is power-limited at ℓ_{max}.	None required. Min. usable link length, ℓ_{min}, fixed at 10.8 km for RCVR AGC = 25 dB.
B	ILD/PIN	11.25 km	650	230	8.2 ns	16.1 ns	1.6 ns	1.75 ns	Meets jitter requirement; link is power-limited by detector at ℓ_{max}.	None required. This fixes ℓ_{min} at 4.8 km for 25 dB AGC.
C	LED/APD	13.75 km	650	275	55.8 ns	62.2 ns	6.2 ns	1.75 ns	Does not meet jitter requirement; link is distortion-limited by source for ℓ_{max}.	Substitute higher-performance source. Determine ℓ_{min}.
D	LED/PIN	7 km	650	140	28.4 ns	35.1 ns	3.5 ns	1.75 ns	Does not meet jitter requirement; link is distortion-limited by source/detector combination for ℓ_{max}.	Substitute higher-performance source or detector. Determine ℓ_{min}. Consider tradeoffs of lower performance fiber with new source/detector combination.

See footnotes on following page.

Notes for Table 7:

① All power-limited values for ℓ_{max} are power-budget calculations, using equations and graphic approach illustrated in Examples I and II of preceding sections. For ℓ_{min} limits (see last column), representing RCVR overload for AGC = 25 dB, the extreme case for link dynamic range (degradation power margin = 0 dB) is assumed. (Minimum AGC for MIL-STD-188-111 is 20 dB.)

② Pulse rate, P(Mbits/s) = 1.3 x B_f (MHz)

③ Calculations based on assumptions of previous sections where:

- Source power output, P_o

  for a typical LED = -10 dBm
  for a typical ILD = 0 dBm

- Detector power input, P_i

  for a typical PIN = -40 dBm
  for a typical APD = -55 dBm

- Transmitter rise time, t_t

  for a typical LED source = 8 ns
  for a typical ILD source = 2 ns

- Receiver rise time, t_r

  for a typical PIN detector = 12 ns
  for a typical APD detector = 4 ns

- Spectral source width, W,

  for a typical LED = 40 nm
  for a typical ILD = 2 nm

the resultant system does not meet jitter requirements. A fiber with higher bandwidth, and consequently higher Fm_0, is required. Using the Fm_0 approach is more direct than trial-and-error recalculation of required fiber rise time.

For Table 7, the long-haul examples, the Fm_0 for the original fiber exceeds the required $P\ell$ Product. For examples A and B, fiber bandwidth specification could be reduced, still meeting system jitter requirements. For examples C and D, which do not meet system jitter requirements, fiber bandwidth should be re-evaluated after selecting different source and/or detector, to examine potential cost tradeoffs of using a lower-performance fiber if overall system jitter is appreciably lower than the MIL-STD-188-111 requirement.

6. SUMMARY AND RECOMMENDATIONS

Optical fiber system performance standards are needed to assure interoperability and adequate performance levels for a majority of Federal Government users. A first example of such a standard is MIL-STD-188-111. Using this standard as a model, a design approach for the selection of subsystem components from commercially available products to assure compliance with the standard has been presented.

A graphical representation has been developed to guide the preparation of a power loss budget. A figure of merit for optical fibers is recommended as a screening technique for selecting fibers with adequate bandwidth. This figure of merit allows the conversion of 3 dB optical bandwidth for multimode fibers (which is generally available from product bulletins) to a maximum baseband pulse rate times length performance characteristic. Overall system rise time depends upon the rise time characteristics of the driver and receiver components as well as the bandwidth of the optical fiber.

The approach and examples presented in this report should provide guidance in system design to assure conformance with the military standard used as a model. It may also be useful in the application of other standards and guidelines which will be developed for multimode optical fiber systems by other organizations.

7. ACKNOWLEDGMENTS

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8. REFERENCES

ANSI (1984), ANSI to coordinate standards for fiber optics, American National Standards Institute Reporter 18, No. 1, January 6.

BUCKLER, M.J. (1982). Measurement of bandwidth versus impulse response in multimode fibers, Technical Digest - Symposium on Optical Fiber Measurements, 1982, pp. 33-35, NBS Special Publication 641, Oct. (U.S. Dept. of Commerce, National Bureau of Standards, Boulder, CO 80303).

Danielson, B. L., D. L. Franzen, G. W. Day, M. Young, and E. M. Kim (1982), Optical fiber characterization, NBS Special Publication 637, Volume 1 (U.S. Dept. of Commerce, National Bureau of Standards, Boulder, CO 80303).

Federal Standard 1037 (1980), Glossary of telecommunication terms (July); available from General Services Adm. (GSA) Business Service Centers in major metropolitan cities or from GSA, Specification and Consumer Information Distribution Branch (WFSIS), Bldg. 197, Washington Navy Yard, Washington, DC 20407.

Hardwick, David (1984), Cable's coming era of specialization, Lightwave, p. 14, January.

Harris, Marilyn A. (1983), AT&T gets $250 million contract to lay the first transatlantic light-wave cable, Electronics, pp. 50-52, December 1.

Hull, J. A., A. G. Hanson, and L. R. Bloom (1983), Alternative transmission media for third-generation interface standards, NTIA Report 83-121, May; available from the National Technical Information Service, Springfield, VA 22161, Accession No. PB-83-238345.

ITT (1977), Optical fiber communications link design, ITT Technical Note R-1, ITT Electro-optical Products Div., Roanoke, VA 24019 (April).

Personick, S. D. (1973), Receiver design for digital fiber optic communication systems, I, Bell System Tech. J. 52, pp. 843-874, July-August.

True, K. M. (1975), The interface handbook: line drivers and receivers, Fairchild Semiconductor, Mt. View, CA 94039.

9. BIBLIOGRAPHY

In addition to the references cited within this report, the following documents have been found to represent invaluable sources of background information pertinent to optical fiber communications applications.

Barnoski, M. K. (1981), Fundamentals of Optical Fiber Communications, 2nd ed., (Academic Press, New York, N.Y.).

CSELT, technical Staff (1981), Optical Fibre Communication, Centro Studi e Laboratori Telecommunicazioni, Turin, Italy; published in U.S. by McGraw-Hill, ISBN 0-07-014882-1.

Gloge, D. (1976), Optical Fiber Technology, IEEE, (New York, N.Y.).

Hanson, A. G., L. R. Bloom, A. H. Cherin, G. W. Day, R. L. Gallawa, E. M. Gray, C. Kao, F. P. Kapron, B. S. Kawasaki, P. Reitz, and M. Young (1982), Optical waveguide communications glossary, NBS Handbook 140; available from the National Technical Information Service, Springfield, VA 22161, Accession No. PB-821666257, January.

Hewlett-Packard (1984), Optoelectronics Designer's Catalog, Hewlett-Packard Components, Palo Alto, CA 94304.

Kao, C. K. (1982), Optical Fiber Systems: Technology, Design, and Applications, (McGraw-Hill), ISBN 0-07-033277-0.

Lacy, E. A. (1982), Fiber Optics, (Prentice-Hall, Inc.).

Midwinter, J. E. (1979), Optical Fibers for Transmission, (Wiley).

Personick, S. D. (1981), Optical Fiber Transmission Systems, (Plenum Press).

MILITARY STANDARD

SUBSYSTEM DESIGN AND ENGINEERING STANDARDS FOR COMMON LONG HAUL AND TACTICAL FIBER OPTICS COMMUNICATIONS

NO DELIVERABLE DATA REQUIRED BY THIS DOCUMENT

SLHC/TCTS

DEPARTMENT OF DEFENSE
Washington, D.C. 20301

Subsystem Design and Engineering Standards
For Common Long Haul and Tactical
Fiber Optics Communications

MIL-STD-188-111

1. This Military Standard is approved and mandatory for use by all Departments and Agencies of the Department of Defense in accordance with the Under Secretary of Defense (Research and Engineering) memorandum dated 16 August 1983. (See APPENDIX A.)

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to:

Commander
Naval Electronic Systems Command (ELEX 81111)
Washington, D.C. 20363

by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

1. In the past, Military Standard 188 (MIL-STD-188), covering military communications system technical standards, has evolved from one document applicable to all military communications (MIL-STD-188, MIL-STD-188A, and MIL-STD-188B) to one applicable to tactical communications only (MIL-STD-188C).

2. The Defense Communications Agency (DCA) published DCA Circulars (DCAC) promulgating standards and criteria applicable to the Defense Communications System (DCS) and to the technical support of the National Military Command System (NMCS).

3. Standards for all military communications are now being published as part of a MIL-STD-188 series of documents. Military communications system technical standards are subdivided into common long haul/tactical standards (MIL-STD-188-100 series), tactical standards (MIL-STD-188-200 series), and long haul standards (MIL-STD-188-300 series).

4. This document contains technical standards and design objectives for fiber optic links to be used in digital and analog long haul and tactical communication ground-based systems. Technical standards and design objectives for common long haul and tactical symmetrical-pair and coaxial communication subsystems are published in MIL-STD-188-112 (Subsystem Design and Engineering Standards for Common Long Haul/Tactical Cable and Wire Communications).

ACKNOWLEDGMENT

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CONTENTS (continued)

1. SCOPE

1.1 Purpose. This document provides mandatory system standards and optional design objectives that are considered necessary to ensure interoperability and to promote compatibility and commonality among long haul and tactical fiber optic transmission subsystems. An additional purpose is to ensure interoperability between fiber optic links and other transmission links, such as radio or metallic cable links standardized in other documents of the MIL-STD-188 series. This document also establishes a level of performance of long haul and tactical fiber optic links considered necessary to satisfy the requirements of a majority of users.

This document is not intended to serve as a stand-alone, comprehensive reference containing all technical details required for the design of new equipment and facilities or the preparation of specifications. Consequently, such design details as size and weight limitations, cable assemblies, and power supply requirements are not contained herein. These and other design details have to be established, based on specific requirements, and have to be carefully tailored in accordance with the policies of Department of Defense Directive (DoDD) 4120.21.

1.2 Application. This document applies to the design and development of new fiber optic equipment, assemblages, and subsystems used in long haul and tactical communications systems. This document applies also to the engineering and installation of existing long haul and tactical fiber optic equipment, subsystems, and systems. This standard is not mandatory for use in the design of fiber optics for highly mobile platforms, such as ships, aircraft, and tanks, but may be employed if desired. It is not intended that existing fiber optic facilities be immediately converted to comply with the standards contained herein. New facilities and those undergoing major modification or rehabilitation shall comply with the standards contained herein subject to the applicable requirements of current procurement regulations.

It is not intended that the standards contained herein inhibit advances in communications technology. Such advances are encouraged by including design objectives which should be achieved or exceeded if economically feasible and by standardizing design parameter values, but not the technology that will be used.

1.3 Objectives. The objectives of this document are:

a. To ensure a high degree of interoperation of long haul and tactical equipment, subsystems, and systems consistent with military requirements.

b. To provide a degree of system performance acceptable to a majority of users of tactical communications systems.

c. To achieve the necessary degree of interoperation, performance, and compatibility in the most economical way.

1.4 System standards and design objectives. The parameters and other reuirements specified herein are mandatory subsystem standards (see APPENDIX A) if the word "shall" is used in describing the subsystem's adherence to the parameter value under consideration. Nonmandatory design objectives (DO) are indicated by use of the word "should" in connection with the parameter value under consideration. For a definition of the terms "system standard" and "design objective," see FED-STD-1037.

2. REFERENCED DOCUMENTS

2.1 Issues of documents. The following documents of the issue in effect on date of invitation for bids or request for proposal, form a part of this standard to the extent specified herein.

STANDARDS

FEDERAL

FED-STD-1037	Glossary of Telecommunication Terms

MILITARY

MIL-STD-188-100	Common Long Haul and Tactical Communication System Technical Standards
MIL-STD-188-114	Electrical Characteristics of Digital Interface Circuits
MIL-STD-188-200	System Design and Engineering Standards for Tactical Communications

PUBLICATION

MILITARY

DoDD 4120.21	Application of Specifications, Standards, and Related Documents in the Acquisition Process

(Copies of standards and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publication. The following document forms a part of this standard to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)/ELECTRONIC INDUSTRIES ASSOCIATION (EIA)

EIA RS-440-78	Fiber Optic Connector Terminology

(Application for copies should be addressed to the Electronic Industries Association, 2001 Eye Street, N.W., Washington, D.C. 20006.)

Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies.

3. DEFINITIONS

3.1 Definition of terms. Except as specified in 3.1.1, terms used herein shall be as defined in FED-STD-1037. Definition of terms unique to fiber optics shall be as specified in EIA RS-440-78.

3.1.1 Optical line code. Sequences of optical pulses suitably structured by waveform or other characteristics to permit information transfer over the optical link.

3.2 Abbreviations and acronyms. The abbreviations and acronyms used herein are listed in APPENDIX B.

4. GENERAL REQUIREMENTS

4.1 Introduction. A fiber optic link includes, as a minimum, a fiber optic transmitter, a fiber optic receiver, and a fiber optic cable. In this document, "link" means fiber optic link, "transmitter" means fiber optic transmitter, "receiver" means fiber optic receiver, and "cable" means fiber optic cable. The link may also include fiber optic repeaters, connectors, and splices. Normally the transmitter accepts an electrical input signal and delivers an optical output signal, and the receiver accepts an optical input signal and delivers an electrical output signal. The cable serves as the medium for propagating optical signals between transmitter and receiver.

A representative digital fiber optic link is shown in FIGURE 1. A representative analog fiber optic link is shown in FIGURE 2. Both figures show only one direction of transmission. A full-duplex link would have a transmitter and receiver at each end. Transmitters and receivers could incorporate additional functions such as multiplexing/demultiplexing. The fiber optic interfaces may be built into the data terminal equipment/data circuit-terminating equipments (DTE/DCE). Equipment may have major elements of the optical transmitter and the optical receiver (including the optical sources and optical detectors) in a single unit. Certain economies of design and manufacture are therefore attainable. The technique is applicable both to analog and to digital applications of fiber optics. In the typical analog application, for example, the fiber optic elements may be built into a video camera for the video baseband analog signals or they may be combined within frequency-division multiplexing (FDM) or other analog signal processing equipment. In the typical digital application, the fiber optic elements may be built into the DTE or, as in the more general case, they may be combined within time-division multiplexing (TDM) or other digital processing equipment.

4.2 Parameters for digital and analog fiber optic links. Parameters specified in 4.2.1.1 through 4.2.1.4 are common to digital and analog fiber optic links.

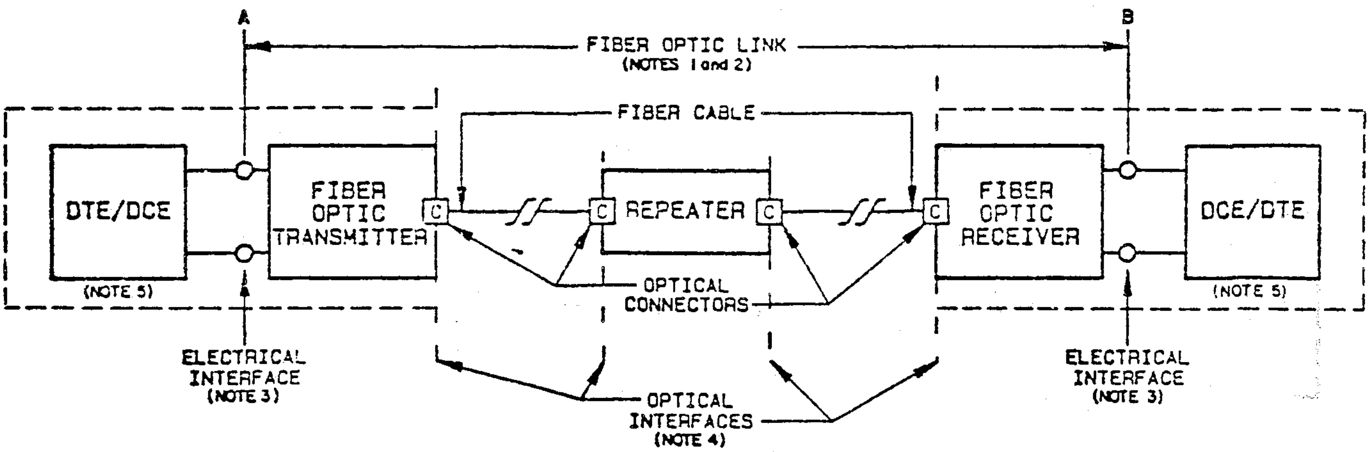
4.2.1 Optical interface characteristics.

4.2.1.1 Wavelength. Wavelength bands and ranges should be selected from TABLE I.

TABLE I. Wavelength bands and ranges.

Band	Wavelength range in micrometers (μm)
I	0.8 to 1.0
II	1.0 to 1.2
III	1.2 to 1.4
IV	1.4 to 1.6

NOTE: The above table indicates an arbitrary division of the optical communications spectrum into bands for the purpose of facilitating identifications.



NOTES:

1. The link may include connectors, splices, and repeaters.

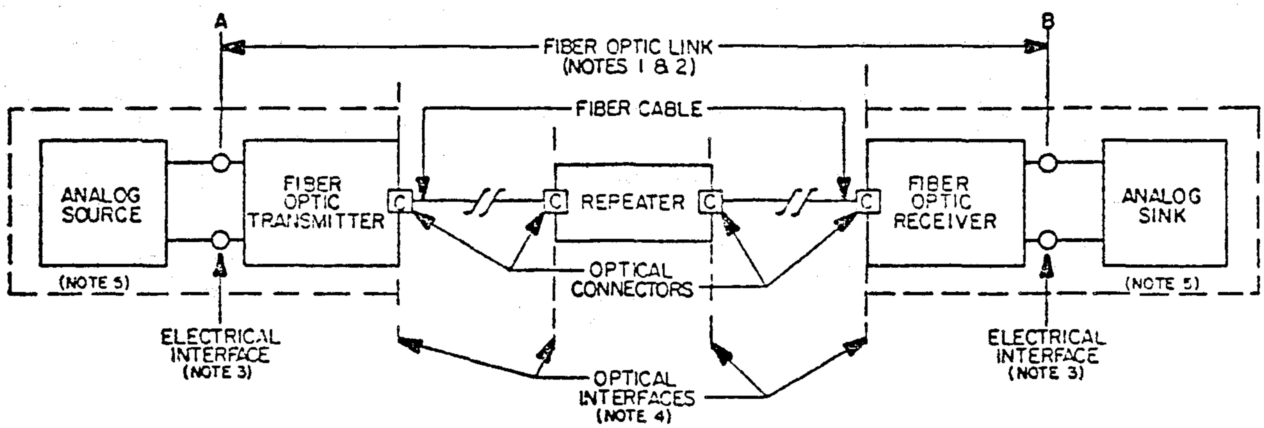
2. The link could be full duplex with a fiber optic transmitter and receiver at each end.

3. For electrical interfaces, see 5.2.1.

4. For optical interfaces, see 5.2.2.

5. DTE/DCE and fiber optic transmitter or receiver may be combined into a single unit.

FIGURE 1. Representative digital fiber optic link.



NOTES:

1. The link may include connectors, splices, and repeaters.
2. The link could be full duplex with a fiber optic transmitter and receiver at each end.
3. For electrical interfaces, see 5.3.2.
4. For optical interfaces, see 5.3.3.
5. Analog source and transmitter, analog sink and receiver may be combined into a single unit.

FIGURE 2. Representative analog fiber optic link.

4.2.1.2 Cable/fiber characteristics. Cable/fiber characteristics can be found in the applicable specifications established under Federal Supply Group (FSG) 60. (APPENDIX D explains the FSG 60 Program.)

4.2.1.3 Optical connector attenuation. The attenuation of an optical connector (insertion loss in the mated parts) shall not exceed 1.5 decibels (dB) for long haul systems and 2.5 dB for tactical systems. Specifications for fiber optic connectors are established under FSG 60.

NOTE: Decibels in optical systems refer to power ratios.

4.2.1.4 Optical splice attenuation. The attenuation of an optical splice shall not exceed 0.5 dB under all conditions imposed upon the splice parts. Specifications for fiber optic splices are established under FSG 60.

4.3 Optical multiplexing. Under consideration.

5. DETAILED REQUIREMENTS

5.1 Introduction. Fiber optic links covered herein shall consist of interfacing subsystems which, when assembled, satisfy the link performance and interchangeability requirements stated herein. Therefore, it is desirable to describe those system performance parameters which are required for satisfactory link operation, and to specify the acceptable limits of performance needed for each link to meet the overall subsystem requirements. Paragraphs 5.2 and 5.3 describe the fiber optic link performance parameters required for digital and analog transmissions, respectively.

5.2 Digital fiber optic link.

5.2.1 Electrical interface characteristics. The input/output electrical interfaces are represented in FIGURE 1. A digital fiber optic link shall provide the capability (see NOTE 3, below) for a digital interface characteristic for binary signals at the link input and output terminals (points A and B, FIGURE 1), in accordance with the applicable requirements of MIL-STD-188-114.

NOTE 1: In those cases where a fiber optic link has to interoperate with a DCE or DTE that has a nonstandard digital interface, it is expected that an interface per MIL-STD-188-114 will be provided at the DCE or DTE, either by modifying the DCE or DTE or by other means, such as replacing the nonstandard DCE or DTE with standard equipment complying with MIL-STD-188-114, or by an additional interface box that performs the necessary conversion between the nonstandard characteristics of the DCE or DTE and the MIL-STD-188-114 interface of the fiber optic link.

NOTE 2: In those cases where it is unfeasible to modify or replace a nonstandard DCE or DTE (for example, the equipment is the property of a commercial carrier), or where it is uneconomical to modify or replace nonstandard DCE or DTE due to the large quantity of the equipment involved, it is considered to be an acceptable solution to equip the fiber optic link with the nonstandard interface characteristic that is required to connect and interoperate with the nonstandard DCE or DTE. The nonstandard interface of the fiber optic link shall be in addition to the capability of the link to provide an interface characteristic per MIL-STD-188-114.

NOTE 3: The phrase "... provide the capability for an interface characteristic per MIL-STD-188-114..." should be understood to mean that a fiber optic link either shall have terminals with interface characteristics per MIL-STD-188-114 or shall be designed with the necessary provisions (for example, replaceable modules or plug-in printed circuit cards) to provide a MIL-STD-188-114 interface when needed. It is considered part of the tailoring requirements per DoDD 4120.21 that the procurement activity make the necessary decisions regarding the required interface capabilities of a fiber optic link and the engineering solutions to implement the required capabilities.

NOTE 4: The reason for requiring a fiber optic link to provide the capability for an interface characteristic per MIL-STD-188-114, even if not immediately needed for a particular application, is the capability at a later time to replace older nonstandard DCE or DTE operating into the fiber optic link with new equipment that can be designed in accordance with MIL-STD-188-114 without the need to change the existing fiber optic link. If the fiber link would not have a standard interface capability per MIL-STD-188-114, the replacement of older nonstandard equipment would require new nonstandard equipment. The additional cost of a MIL-STD-188-114 interface capability for new fiber optic links, even if not immediately needed, is considered acceptable since the MIL-STD-188-114 capability will greatly facilitate the introduction of future generations of standardized equipment and reduce the proliferation of nonstandard equipment.

5.2.1.1 Data signaling rates. Not standardized. (See NOTES 1 and 2 below).

NOTE 1: The data signaling rate transmitted over a fiber optic link depends on the signaling rate transmitted by the data terminal equipment that is standardized in the MIL-STD-188-100, General digital parameters paragraph and on any additional information that may be transmitted over the fiber optic link, such as orderwires, telemetry, and error detection and correction coding.

NOTE 2: MIL-STD-188-114, Modulation rate range paragraph identifies 10 megabaud as an upper limit modulation rate for the balanced voltage digital interface circuits.

5.2.1.2 Signal conditioning. Under consideration.

5.2.1.3 Electrical coding and modulation. Under consideration. See APPENDIX C.

5.2.2 Optical interface characteristics. The optical interfaces are represented in FIGURE 1.

5.2.2.1 Wavelength. Wavelength bands and ranges should be selected from the bands listed in TABLE 1.

5.2.2.2 Optical line code. As a basic requirement, the line code shall not restrict the number of sequential binary "ones" or "zeros" that may be contained in the electrical signal to be transmitted over a fiber optic link. Additional standards for optical line code are under consideration.

5.2.2.3 Cable/fiber characteristics. See 4.2.1.2.

5.2.2.4 Optical connector attenuation. Optical connector attenuation shall be as specified in 4.2.1.3.

5.2.2.5 Optical splice attenuation. Optical splice attenuation shall be as specified in 4.2.1.4.

5.2.3 Transfer characteristics. Transfer characteristics shall be as stated in 5.2.3.1 through 5.2.3.6.

NOTE: Test procedures for the following transfer characteristics are covered in APPENDIX E. Tests are considered generic in nature.

5.2.3.1 Bit error rate (BER). The BER introduced by any digital fiber optic link shall not exceed 10^{-8} for tactical use (DO = 10^{-9}), and 1.75 X 10^{-10}K for long haul communications where K is the link length in kilometers (km).

NOTE: The duration of the BER measurement and other details will be defined in applicable equipment and subsystem specifications.

5.2.3.2 Power margin. The power margin at the receiver shall not be less than 6 dB (DO = 10 dB) for every link.

5.2.3.3 Dynamic range. The dynamic range of the optical receiver shall not be less than 20 dB.

5.2.3.4 Jitter. Under consideration.

5.2.3.5 Total distortion. The maximum total distortion, due to any combination of causes including rise and fall time, shall not exceed 25 percent of the theoretical data unit interval for pulses transmitted from the input to the output of a fiber optic link (points A to B, FIGURE 1).

5.2.3.6 Protection of signal sense. A fiber optic link shall not invert the logic and signal sense of binary signals transmitted from the input to the output of the fiber optic link (points A to B, FIGURE 1).

5.2.4 Clock equipment, control, and timing. A provision shall be made for fiber optic transmitters, receivers, and regenerative repeaters, where applicable, to include encoders and decoders for the purpose of clock recovery whenever synchronous data and clock are required. The equipment shall be designed to provide or accommodate, appropriately, clock, control, and timing circuits in accordance with the MIL-STD-188-100, Clock equipment, control, and timing paragraph except that the electrical interface characteristics shall comply with the balanced voltage criteria of MIL-STD-188-114. (See APPENDIX C).

5.2.4.1 Transmitter clocking. When the option for signal conditioning is invoked, clocking is required at the optical transmitter to accomplish the functions of line encoding and, as an option, to gate the release of data from the data source. The source of clocking shall be external to the transmitter. One arrangement shall be selected from those shown in FIGURE 3 to meet a specific application.

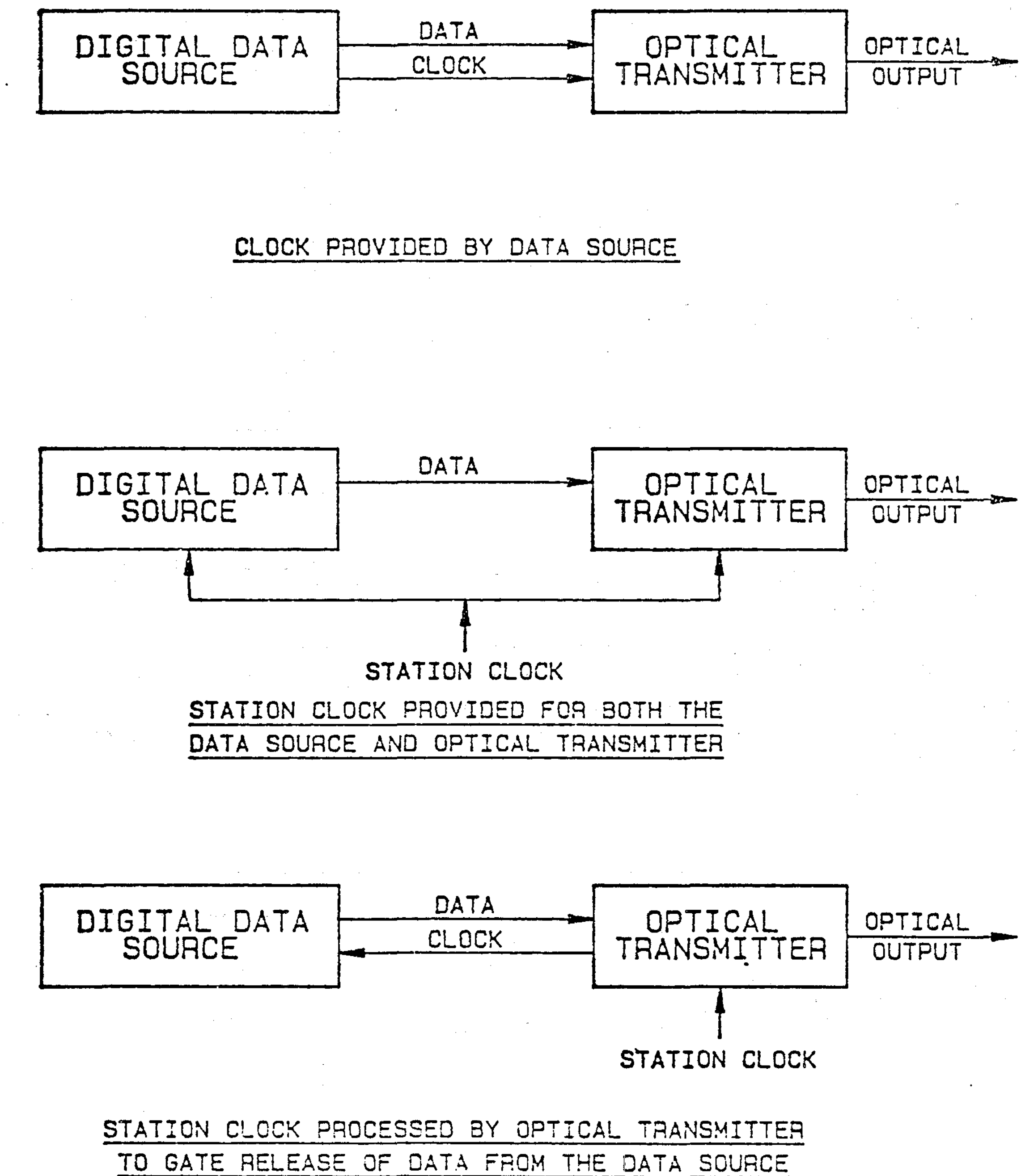


FIGURE 3. Standard clocking arrangements.

5.2.4.2 Receiver clocking. When the option for signal conditioning is invoked, clocking is required at the optical receiver to accomplish the functions of line decoding, signal regeneration, and to serve as output clock to the data sink. The optical receiver shall derive clock from the receiver signal. The standard arrangement shall be as shown in FIGURE 4.

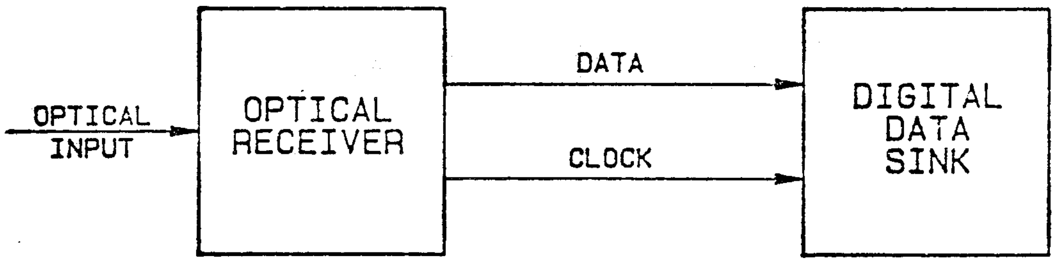


FIGURE 4. Clock recovered at optical receiver used as a data sink receive clock.

5.2.4.3 Repeater clocking. When the option for signal conditioning is invoked, clocking is required at the repeater to permit data regeneration and retransmission. Clock recovered in the repeater optical receiver is used to transmit clock in the repeater optical transmitter. The standard arrangement shall be as shown in FIGURE 5.

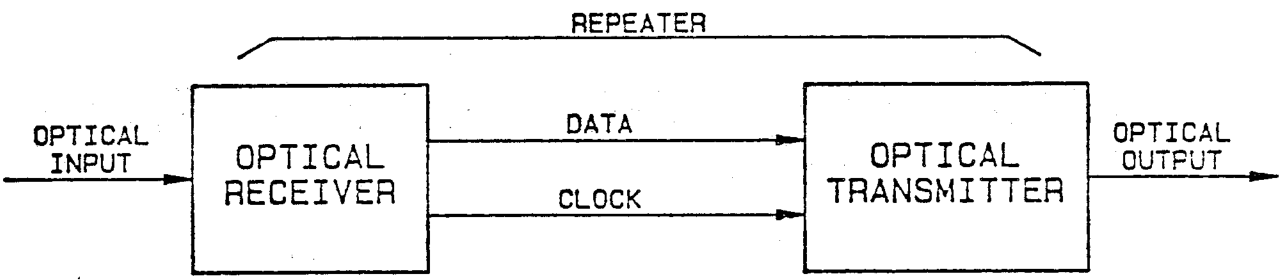


FIGURE 5. Recovered clock used as a transmit clock in repeater applications.

5.3 Analog fiber optic link.

5.3.1 General. Analog fiber optic links may carry FDM voice and data baseband signals, composite video/audio television signals, radar relay video and trigger signals, telemetry signals, or any combination of these signals, in analog form.

5.3.2 Electrical interface characteristics. Not standardized. Characteristics vary with application.

5.3.3 Optical interface characteristics. The optical interfaces are represented in FIGURE 2. The characteristics of these interfaces shall meet the requirements of 5.3.3.1 through 5.3.3.5.

5.3.3.1 Wavelength. Wavelength bands and ranges should be selected from the bands listed in TABLE I.

5.3.3.2 Optical line modulation. Under consideration.

5.3.3.3 Cable/fiber characteristics. See 4.2.1.2.

5.3.3.4 Optical connector attenuation. Optical connector attenuation shall be as specified in 4.2.1.3.

5.3.3.5 Optical splice attenuation. Optical splice attenuation shall be as specified in 4.2.1.4.

5.3.4 Transfer characteristics.

5.3.4.1 Net loss variation. The net loss variation over the optical fiber link shall not exceed 10.5 dB over any consecutive 30 days.

5.3.4.2 Intermodulation distortion. Intermodulation distortion shall be at least 40 dB below the signal level.

5.3.4.3 Power margin. The power margin at the receiver input shall not be less than 6 dB.

5.3.4.4 Dynamic range. The dynamic range of the optical receiver shall not be less than 20 dB.

5.3.4.5 Signal-to-noise ratio. Not standardized. Signal-to-noise ratio varies with application.

Custodians:

Army - SC
Navy - EC
Air Force - 90
Defense Communications Agency - DC

Review activities:

Army - CR
Air Force - 13
Navy - OM
DoD/NASA - TT

User activities:

Navy - YD
Air Force - 02
DoD/NASA - NS

Preparing activity:

Navy - EC

Civil Agency Coordinating Interest:
National Communications System - NCS

(Project TCTS-1110)

APPENDIX A (of the MIL-STD)

MEMORANDUM FROM THE UNDER SECRETARY OF DEFENSE (RESEARCH AND ENGINEERING) DATED 16 AUG 1983; SUBJECT: MANDATORY USE OF MILITARY TELECOMMUNICATIONS STANDARDS IN THE MIL-STD-188 SERIES

APPENDIX A IS A MANDATORY PART OF THIS STANDARD

THE UNDER SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301

RESEARCH AND ENGINEERING

16 AUG 1983

MEMORANDUM FOR ASSISTANT SECRETARY OF THE ARMY (INSTALLATIONS, LOGISTICS & FINANCIAL MANAGEMENT)
ASSISTANT SECRETARY OF THE NAVY (SHIPBUILDING & LOGISTICS)
ASSISTANT SECRETARY OF THE AIR FORCE (RESEARCH DEVELOPMENT & LOGISTICS)
COMMANDANT OF THE MARINE CORPS
DIRECTOR, DEFENSE COMMUNICATIONS AGENCY
DIRECTOR, NATIONAL SECURITY AGENCY

SUBJECT: Mandatory Use of Military Telecommunications Standards in the MIL-STD-188 Series

On May 10, 1977, Dr. Gerald Dinneen, then Assistant Secretary of Defense(C^3I), issued the following policy statement regarding the mandatory nature of the MIL-STD-188 series telecommunications standards:

"...standards as a general rule are now cited as 'approved for use' rather than 'mandatory for use' in the Department of Defense.

This deference to the judgment of the designing and procuring agencies is clearly appropriate to standards dealing with process, component ruggedness and reliability, paint finishes, and the like. It is clearly not appropriate to standards such as those in the MIL-STD-188 series which address telecommunication design parameters. These influence the functional integrity of telecommunication systems and their ability to efficiently interoperate with other functionally similar Government and commercial systems. Therefore, relevant military standards in the 188 series will continue to be mandatory for use within the Department of Defense.

To minimize the probability of misapplication of these standards, it is incumbent upon the developers of the MIL-STD-188 series to insure that each standard is not only essential but of uniformly high quality, clear and concise as to application, and wherever possible compatible with existing or proposed national, international and Federal telecommunication standards. It is also incumbent upon the users of these standards to cite in their procurement specifications only those standards which are clearly necessary to the proper functioning of the device or systems over its projected lifetime."

This statement has been reviewed by this office and continues to be the policy of the Department of Defense.

APPENDIX B (of the MIL-STD)

ABBREVIATIONS AND ACRONYMS

10. GENERAL

10.1 Scope. This appendix contains a list of abbreviations and acronyms used in MIL-STD-188-111.

10.2 Application. This appendix is a nonmandatory part of MIL-STD-188-111.

BER	bit error rate
cm	centimeter
dB	decibel
dBm	decibels referred to 1 milliwatt
dc	direct current
DCA	Defense Communications Agency
DCAC	Defense Communications Agency Circular
DCE	data circuit-terminating equipment
DCS	Defense Communications System
DO	design objective
DoDD	Department of Defense Directive
DODISS	Department of Defense Index of Specifications and Standards
DOD-STD	Department of Defense Standard
DTE	data terminal equipment
EIA	Electronic Industries Association
FED-STD	Federal Standard
FDM	frequency-division multiplex (ed) (ing)
FSC	Federal Supply Class
FSG	Federal Supply Group
ILD	injection laser diode
kHz	kilohertz
km	kilometer
LED	light-emitting diode
Mb/s	megabits per second
MHz	megahertz
MIL-STD	Military Standard
MLB	multi-level binary
μm	micrometer
mV	millivolt
mW	milliwatt
nm	nanometers
NMCS	National Military Command System
nW	nanowatt
NRZ	nonreturn-to-zero
NRZ-L	nonreturn-to-zero level
NRZ-M	nonreturn-to-zero mark
NRZ-S	nonreturn-to-zero space
PAM	pulse-amplitude modulation
PCM	pulse-code modulation

PDM	pulse-duration modulation
PE	phase encoded
PPM	pulse-position modulation
PRBS	pseudorandom bit sequence
PRM	pulse rate modulation
rms	root mean square
RZ	return-to-zero
TDM	time-division multiplex (ed) (ing)
TTL	transistor-transistor logic
W	watt

APPENDIX C (of the MIL-STD)

TUTORIAL TREAMENT OF OPTICAL LINE CODING AND CLOCKING AND SIGNAL FORMATS

CONTENTS

APPENDIX C of the MIL-STD

TUTORIAL TREATMENT OF OPTICAL LINE CODING AND CLOCKING AND SIGNAL FORMATS

10. GENERAL

10.1 Scope. Tutorial information on analog and digital signaling formats, especially digital formats suitable for encoding information for transmission over optical fibers, is presented in this appendix.

10.2 Application. This appendix is a nonmandatory part of MIL-STD-188-111.

20. REFERENCED DOCUMENTS

20.1 Publications. The following document forms a part of this standard to the extent specified herein.

Tau-Tron, Inc. The Pulse

(Application for copies should be addressed to Tau-Tron, Inc., 27 Industrial Avenue, Chelmsford, Massachusetts 01824.)

NOTE: 30.1, 30.1.1, and 30.1.2 which follow have been excerpted, and reprinted from the publication, The Pulse, with permission from Tau-Tron, Inc.

30. LINE CODING AND SIGNAL FORMATS

30.1 Optical line coding. Optical line coding refers to the optical signaling format employed in the transfer of information from one point to another by optical fiber. There are many signaling formats available to the fiber optics system design engineer today. A survey of these signaling formats and a discussion of their relative advantages and disadvantages is the subject of this tutorial. In general, optical-signaling formats may be categorized as either analog or digital. Both require the intensity modulation of an optical source such as a light-emitting diode (LED) or injection laser diode (ILD).

30.1.1 Analog formats. The analog formats have two distinct forms. These forms are continuous or pulsed. In continuous analog signals, the signal takes on any value between predetermined high- and low-level limits of the optical source. An example of a continuous analog signal format used in fiber optics is amplitude (intensity) modulation. In amplitude modulation, the power output of the optical source is varied in intensity by the modulating signal. The quality of the transmitted signal is dependent upon the linearity of the source. This presents a problem for the fiber optic design engineer, since both LED and ILD devices are inherently nonlinear devices. The power output is not linear in relation to the drive current modulating the source. In ILD devices, this nonlinearity may be further complicated by the presence of severe nonlinear regions (kinks) as seen in their power output versus drive current characteristic plots. The net result is that in amplitude modulation, distortion of the sampled signal occurs which may severely limit the use of such a signal format. This is particularly true in long distance applications where regenerative repeaters, which add distortion, may be required.

Other examples of continuous analog signal formats are frequency modulation and phase modulation of the optical carrier. These schemes, which employ external modulators, require a more complex treatment regarding their adaptability and utility. Such a discussion is beyond the scope of this tutorial.

In pulsed analog formats the continuous signal is sampled at a rate such that the information in the signal is completely retained in the periodic sample values. Examples of pulsed analog formats are pulse-amplitude (intensity) modulation (PAM), pulse-duration modulation (PDM), pulse-position modulation (PPM), and pulse rate modulation (PRM). In PAM, a periodic pulse train is generated such that the amplitude of each pulse is proportional to the magnitude of the sampled signal at the time of sampling. It is similar to the continuous amplitude modulation format, except for the fact that it is in pulsed form. Like the continuous form, however, it is also subject to the same distortion problems because of the nonlinearity of the optical source. In PDM, a train of pulses (generally of equal amplitude) is formed. The duration of each pulse is proportional to the sampled value of the signal. PPM requires that a train of pulses of equal width be formed such that the position of each pulse in time relative to its predecessor be made to vary proportionally with the amplitude of the sampled value. In PRM, a pulse train is formed, composed of many short duration pulses for each analog sample, and the repetition rate of these is made to vary proportionally to the sampled value. PDM, PPM, and PRM (but not PAM) vary a time parameter of the pulse train, making any time multiplexing scheme of the data incorporating these formats difficult to achieve.

30.1.2 Digital formats. The second category of signal formats available to the fiber optics designer is the family of digital formats. In a digital format, the signal samples are restricted to discrete values. This differs from the pulsed analog formats wherein the signal samples are permitted to take on any value between predetermined upper and lower limits. The primary advantage of the digital over the analog format is that the transmitted signal is not as susceptible to the nonlinear characteristics of the optical source. As a result, digital signaling does not suffer the signal distortion problems encountered in both the continuous or pulsed analog signal formats. Digital formats also do not require as complex a detection scheme, since only a discrete number of levels (two in a binary system) need be detected. This provides a high level of noise immunity when compared to an analog system in which a continuous amplitude or time parameter must be detected. Digital signals can also be regenerated and retimed at intermediate repeaters, which means that the noise and distortion effects of each cable link are not additive as in an analog link. The primary disadvantage of digital transmission is the increased bandwidth required over analog transmission. However, should bandwidth and not signal-to-noise considerations be of primary importance, then M-ary as opposed to binary codes may represent a possible alternative. In general, since modulation of the optical carrier is accomplished in the same manner (regardless of whether one is using a pulsed analog format or a digital format) the pulsed analog formats offer little, if any, advantage over their digital counterparts, and should be converted to one of the digital formats--if this option is available to the designer.

Many of the digital line coding schemes available to the designer are derived from the most common digital signaling format, pulse-code modulation (PCM). PCM for a binary system having 0 and 1 as the only allowable states consists of coding each discrete level of the sampled carrier signal into a binary number. The number of discrete levels selected for the PCM signal thus determine the number of binary bits required to represent each level. As a result, one amplitude sample of the carrier signal may require many pulses to define the magnitude of the sample in a PCM format.

PCM binary codes may in general be categorized as unipolar and polar. A unipolar signal involves signal levels having the same algebraic sign and possible magnitude differences. A polar signal has pulse sequences whose individual pulse amplitudes assume levels of different algebraic sign about an intermediate level. Both unipolar and polar forms may similarly be divided into various code groups. In the unipolar grouping the binary codes are nonreturn-to-zero (NRZ), return-to-zero (RZ), and phase encoded (PE). In the polar grouping the binary codes and NRZ, RZ, and multi-level binary (MLB).

A simple on-off keying modulation scheme, lending itself to the unipolar signal format, is the preferred modulation scheme, as opposed to the modulation of the optical intensity about the continuously ON level of the optical source that is required in a polar format.

The more commonly used unipolar NRZ codes are of three different types. These are NRZ-L (level), NRZ-M (mark), and NRZ-S (space) (see FIGURE 6). NRZ-L is characterized by a change in level only when the data cnanges from a logic 1 to a logic 0 and from a logic 0 to a logic 1. In NRZ-M, a level change corresponds to a logic 1 while no change in the level corresponds to a logic 0. NRZ-S is the complement of NRZ-M, in that, a level change corresponds to a logic 0, while no change in the level corresponds to a logic 1. In general, NRZ codes are the simplest to generate and decode. They also have the lowest receiver bandwidth requirement of the digital code formats. However, NRZ formats have no error correcting or detecting characteristics, nor do they possess self-clocking features, because of the relatively few transitions; hence, they are generally not recommended for long distance data transmission.

The more commonly used unipolar RZ codes are standard RZ, RZ-PPM, and RZ-PDM, also represented in FIGURE 6. Standard RZ, as well as the other RZ formats are characterized by having the common property that the line signal state returns or maintains a zero level during each bit interval. In standard RZ, there are pulses only during the logic 1 levels, and none during the logic 0 levels. The pulse width in this case is half the bit interval positioned in the first half of the total bit interval. In RZ-PPM, a logic 0 is represented by a pulse width of one-quarter the bit interval positioned in the first quarter of the total bit interval, while a logic 1 is represented by a pulse width of one-quarter the bit interval located in the third quarter of the total bit interval. In RZ-PDM, a logic 0 is represented by a pulse of width one-third the bit interval positioned in the first third of the total bit interval while a logic 1 is represented by a pulse width of two-thirds the total bit interval positioned in the first two-thirds of the total bit interval. The required bandwidth is at least twice that of the NRZ codes,

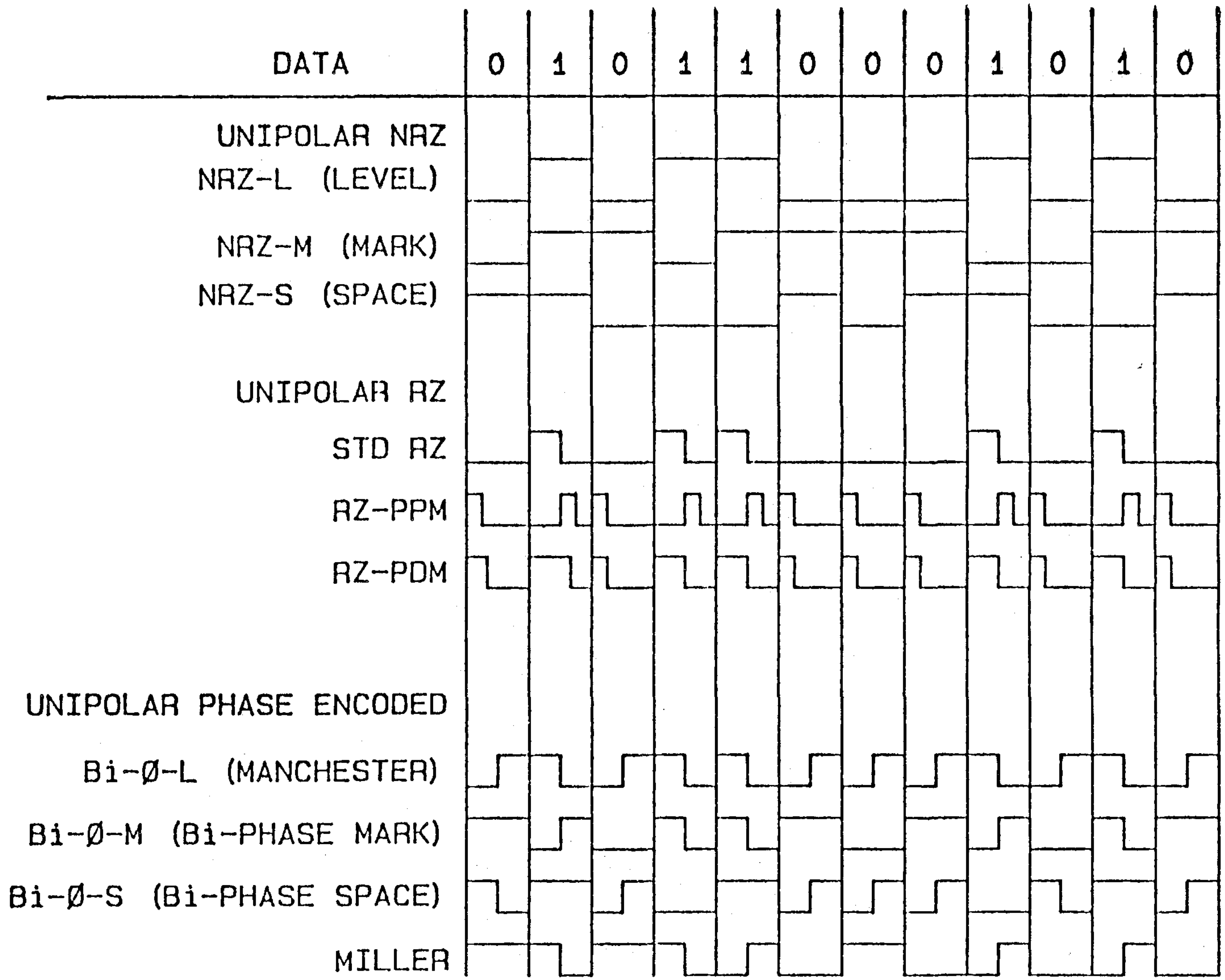


FIGURE 6. Unipolar digital signal formats. (Adapted and reprinted with permission from The Pulse, Tau-Tron, Inc.)

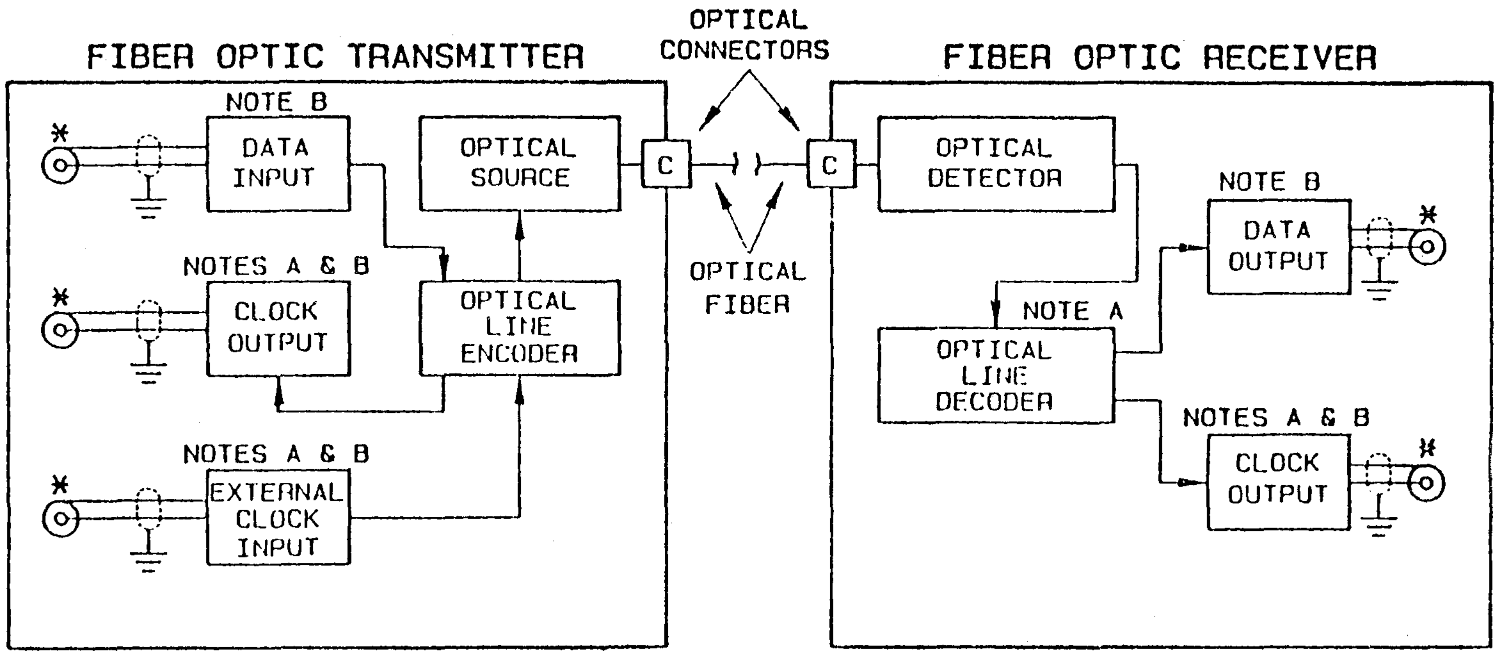
and, consequently, requires greater power to achieve a comparable error rate. Compared to NRZ formats, RZ code formats possess clocking features that, although limited, make them a preferred format, as opposed to NRZ, for long distance data transmission.

The unipolar PE formats consist of four principal types: bi-phase level, commonly called Manchester; bi-phase mark; bi-phase space; and delay modulation (DM), which includes such codes as Miller, Modified Miller, and Wood codes. PE format codes are also illustrated in FIGURE 6. In bi-phase level, a logic 1 is represented by a pulse width of one-half the bit interval, located in the first half of the total bit interval, whereas a logic 0 is represented by a pulse width of one-half the bit interval, located in the second half of the total bit interval. In bi-phase mark, there is a transition at the beginning of each bit period, but it is during the second half of the bit interval that the logic state is determined. If there is a transition during the second half of the bit interval, the logic state is 1. If there is no transition, the logic state is 0. Bi-phase space differs from bi-phase mark only in that a transition during the second half of the bit interval implies a logic state of 0, while no transition implies a logic state of 1.

A typical example of a delay modulation PE format is the Miller code. In the Miller code, a logic 1 is represented by a midband transition, while a logic 0 is represented by a transition at the beginning of a bit interval. A constraint of the code is that a transition must occur at the beginning of all two-zero sequences.

The phase encoded formats, in particular bi-phase level (Manchester) and Miller, are of particular interest to the fiber optic design engineers because of their inherent clock recovery characteristics and relative ease of implementation. Additionally, the Miller code possesses capabilities for single-bit error detection.

30.2 Clocking. If clocking information can be extracted from the incoming data (self-clocking), the data signal may directly modulate the optical source, as shown in FIGURE 7. If external clocking of the data is required due to nonclocked input data format, data clocking may be provided by the external clock, with subsequent data synchronization and optical source modulation of the data signal.



NOTES:

A. The use of optical line codes, external clock, and clock recovery is optional.

B. MIL-STD-188-114 balanced interface.

* Electrical connectors shown are twinaxial-type suitable for wideband applications.

FIGURE 7. Representative fiber optic diagram showing data and clock connections with optical line coding.

APPENDIX D (of the MIL-STD)

THE FIBER OPTIC COMPONENT STANDARDIZATION PROGRAM

CONTENTS

APPENDIX D (of the MIL-STD)

THE FIBER OPTIC COMPONENT STANDARDIZATION PROGRAM

10. Scope. This appendix provides information on the fiber optic components standardization and specifications program being conducted under Federal Supply Group 60 (FSG-60). This appendix is a nonmandatory part of MIL-STD-188-111.

10.1 Group organization. This group is assigned under the Defense Standardization and Specification Program for developing, applying, and managing standards and specifications applicable to fiber optic components used in the Department of Defense. FSG 60 consists of Federal Supply Classes (FSC) designated by four digit numbers as follows:

FSG 60 - Fiber Optics Materials, Components, Assemblies, and Accessories
FSC 6010 - Fiber Optic Conductors
FSC 6015 - Fiber Optic Cables
FSC 6020 - Fiber Optic Cable Assemblies and Harnesses
FSC 6030 - Fiber Optic Devices
FSC 6060 - Fiber Optic Interconnectors
FSC 6070 - Fiber Optic Accessories and Supplies
FSC 6080 - Fiber Optic Kits and Sets

This group establishes the framework used to buy, classify, stock, store, and issue fiber optics hardware. It is also being used as a framework structure around which the DoD fiber optics components standardization and specification effort is built. Specifications and standards are being classified and written to meet acquisition needs according to this structure.

10.2 Standardization program. The goal of the FSG-60 is to establish acquisition and engineering documentation which will meet the requirements of the military services in obtaining necessary fiber optic hardware with which to construct systems. A successful program will result in the identification of preferred devices for design which are interchangeable and can be obtained from multiple sources under competitive conditions. The devices will also, in the process, develop a history of reliable performance under defined conditions which will give designers confidence in using them. Good standardization through the disciplined use of specifications gives definition to a technology which is highly important in making commitments to its application rather than the use of a competing technology.

10.3 Standardization Program Analysis. A Standardization Program Analysis is published yearly which establishes and assigns projects and tasks and outlines the effort over a period of five fiscal years. The analysis includes projected tasks required to accomplish new initiatives and ongoing programs. Copies of the FSG-60 Program Analysis can be obtained at the following address:

Commander
Defense Electronics Supply Center
ATTN: DESC-ESS
Dayton, OH 45444

10.4 Non-Government standards. A major policy emphasis in this program is the use of non-Government standards and specifications whenever possible in order to preclude the unnecessary preparation of such documents by the Department of Defense. The goal is to align DoD hardware requirements with those of the commercial sector to the greatest extent possible, the intent being a set of unified national standards and specifications which will reduce the need for DoD activities to buy sole source items at premium prices and to alleviate diminishing manufacturing sources.

10.5 Annual planning meeting. A Military-Industry Standardization Planning Meeting is held annually to coordinate the entire specifications and standards preparation program. The purpose of this meeting is to exchange information and develop a unified program which will lead to a large reduction in duplicative efforts.

10.6 FSG-60/MIL-STD-188-111 relationship. MIL-STD-188-111 provides electro-optical interface and end-to-end fiber optic links standard performance criteria. The standard does not specify which FSG-60 component specifications are to be used in a given link design. This is determined by the system design engineer and based upon the specific link performance requirements. FSG-60 provides a group of componentry specifications approved by the DoD from which an applicable selection can be made.

10.7 Further information. Further information on any aspect of this program can be obtained at the address shown in 10.3.

APPENDIX E (of the MIL-STD)

TEST METHODS FOR FIBER OPTICS PARAMETERS IN MIL-STD-188-111

CONTENTS

APPENDIX E of the MIL-STD

TEST METHODS FOR FIBER OPTIC PARAMETERS IN MIL-STD-188-111

10. Scope. The test methods specified herein may be used for testing the digital characteristics listed in TABLE II. These tests are a nonmandatory part of MIL-STD-188-111.

10.1 Cross-reference to standards. The cross-references are listed in TABLE II.

TABLE II. Cross-reference.

Test	MIL-STD-188-111 Paragraph Number
Distortion	5.2.3.5
Jitter	5.2.3.4
BER	5.2.3.1
Power margin	5.2.3.2
Dynamic range	5.2.3.3
Sensitivity	part of tests for 5.2.3.1-3
Optical transmitter rise and fall time	None
Optical receiver rise and fall time	None

NOTE: The tests listed pertain to digital transmission. Tests for analog transmission vary widely depending upon analog application and, consequently, are not suitable for inclusion here.

10.2 Test equipment. The test equipment required for the performance of the tests in this appendix is listed in TABLE III.

TABLE III. Test equipment for fiber optic system testing.

Equipment	Characteristics
BER Pattern Generator	Patterns: 2^{15}-1 PRBS in NRZ format, as a minimum Outputs: Clock, with delay trigger data Output Levels: In accordance with MIL-STD-188-114
Resistance Loads	Resistance : 100 ohms ±10 percent, tapped Power Rating: 1/4 W
Optical Attenuator	Attenuation: 0 to 60 dB Optical Connectors: Compatible with system under test
Optical Power Meter	Wavelength Range: 800-1300 nm Sensitivity: 1 nW to 10 mW
MIL-STD-188-114 to TTL Converter	Input: In accordance with MIL-STD-188-114, balanced Output: TTL
BER Counter	Data Input: NRZ 15-bit pattern PRBS Error Readout: To 10^{-11} Data Input Levels: TTL
High-Power Optical Test Transmitter	Optical Power Output: $\geq$ +3 dBm Input: In accordance with MIL-STD-188-114, balanced Jitter: $<$ 1 ns, for leading or trailing edge
Optical Test Receiver	Optical Sensitivity: $\leq$ -50 dBm Jitter: $<$ 1 ns Dynamic Range: $>$25 dB Output: Compatible with MIL-STD-188-114, balanced
Square Wave Generator	Output: In accordance with MIL-STD-188-114 Rise/Fall Time: $\leq$ 20 ns @ 10 MHz

TABLE III. Test equipment for fiber optic system testing. (continued)

Equipment	Characteristics
Oscilloscope	Frequency Response: dc to 350 MHz Rise Time: $\leq$ 1 ns Sensitivity: $\leq$ 10 mV/cm Time base: 1 ns/division or better, delayed sweep Dual trace, capable of differential measurements

The test configuration for measurement of each test parameter listed in 10.1 is depicted in FIGURES 8 through 13.

NOTE: The test equipment is connected to the fiber optic system as configured for future operation.

10.3 Tests.

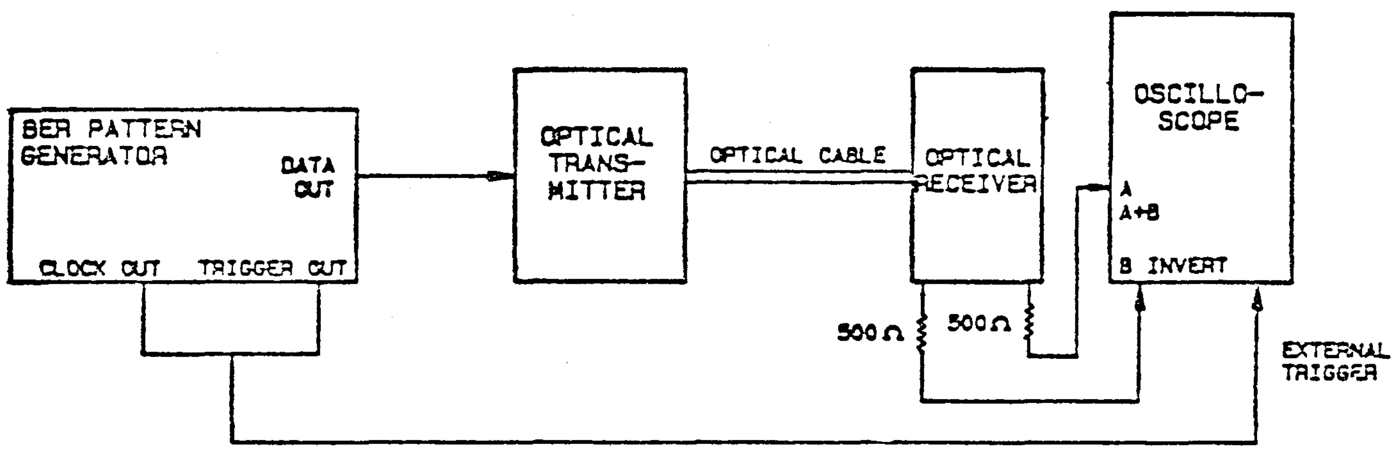
10.3.1 Distortion and jitter.

1. Adjust the BER pattern generator for a pseudo-random bit sequence of 2^{15}-1 bits at the highest system bit rate. Set the oscilloscope for dual trace, with A and B inputs, and one channel inverted, as shown in FIGURE 8.

2. Measure distortion as follows:

a. Connect the BER pattern generator CLOCK OUT to the oscilloscope EXTERNAL TRIGGER.

b. Observe the resulting "eye" pattern on the oscilloscope. Referring to FIGURE 9, identical eye openings would indicate a linear system. Asymmetries indicate nonlinearities. Closing of the eye, measured on the horizontal scale from the zero-crossing points, indicates the amount of distortion. The minimum eye opening for 25 percent distortion is 3/4 of the unit time interval, T. The maximum opening for 25 percent distortion is 1 1/4 T.



NOTES:

1. Connect scope external trigger to "clock out" for distortion measurement and external trigger to "trigger out" for jitter measurement.

2. A TTL-to-balance converter may be used in lieu of test equipment providing a MIL-STD-188-114 interface.

FIGURE 8. Test configuration for distortion and jitter.

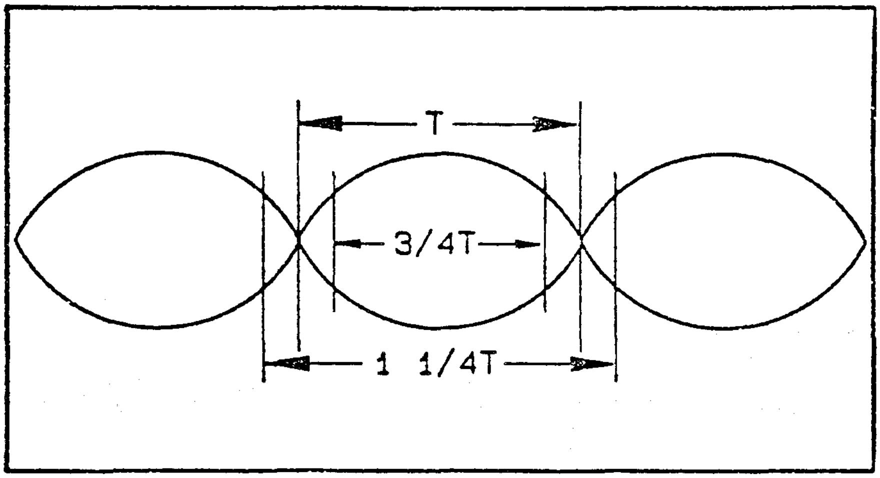


FIGURE 9. Eye diagram.

3. Measure jitter as follows:

a. Connect the BER pattern generator TRIGGER OUT to the oscilloscope EXTERNAL TRIGGER.

b. Set the oscilloscope for a delayed time base mode and adjust to display a bit transition near the end of the 2^{15}-1 bit sequence. Spread the time base as required for accurate measurement, observing that the proper sync is maintained.

c. Referring to FIGURE 10, the extent of jitter is determined by the ratio of the transition uncertainty, N, to the pulse period, T. It is given as a percentage by:

$$\text{Jitter (percent)} = 100(N/T)$$

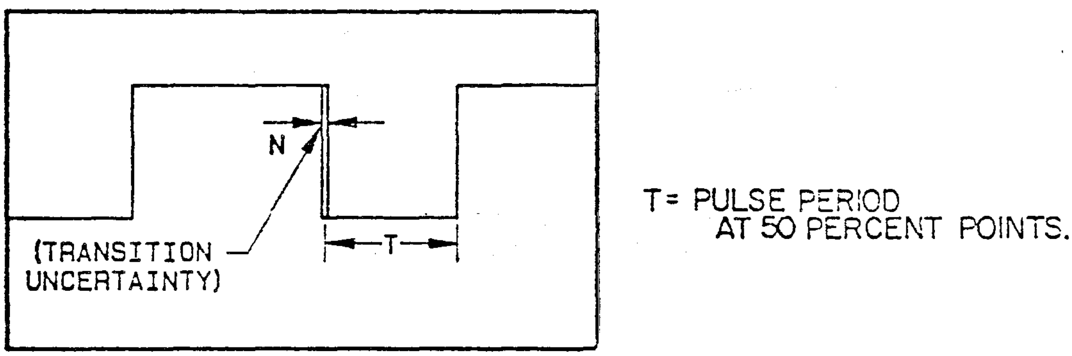
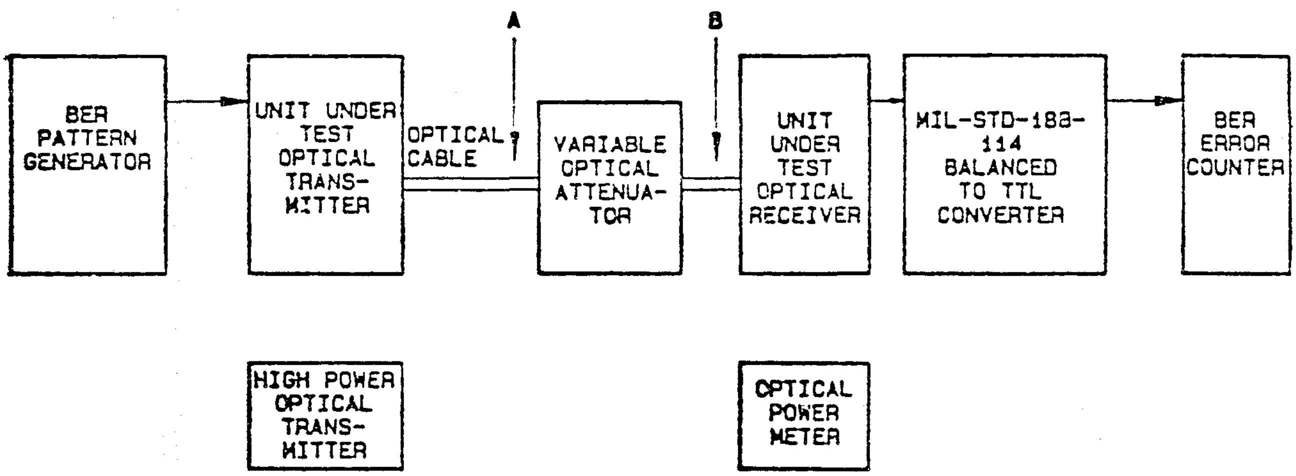


FIGURE 10. Waveform jitter.

10.3.2 BER, power margin, dynamic range, and receiver sensitivity.

1. Adjust the BER pattern generator (see FIGURE 11) for a pseudorandom sequence at the highest system bit rate. (The sequence selected depends upon system application. If the application is unknown, use a standard $2^{15}-1$ pattern. In some applications, a fixed word pattern would be appropriate.)



NOTE: A TTL-to-balanced converter may be used in lieu of test equipment providing a MIL-STD-188-114 interface.

FIGURE 11. Test configuration for BER, power margin, dynamic range, and receiver sensitivity.

2. Measure receiver sensitivity as follows:

a. Starting from the maximum position, decrease the attenuation of the optical attenuator until the specified BER is achieved.

b. Use the optical power meter to measure the power at the attenuator output.

c. Subtract the loss due to the coupler used to connect the fiber to the receiver under test.

3. Measure receiver dynamic range as follows:

a. Substitute the high power test transmitter for the system transmitter.

b. Repeat the receiver sensitivity measurement (step 2).

CAUTION: Do not exceed maximum rated input power for the receiver.

c. Reduce the attenuation of the optical attenuator while observing the receiver analog output signal with an oscilloscope. Inspect this signal and identify the point at which the overload just begins to occur.

d. Measure the power at the attenuator output and subtract the connector loss. The difference in power between the receiver overload level and the sensitivity reading is the dynamic range.

4. Measure power margin as follows:

a. Set the BER pattern generator for a pseudorandom sequence of $2^{15}-1$ bits at the highest system bit rate.

b. Starting from the zero dB position, increase the attenuation of the optical attenuator until a BER performance of 10^{-10} for long haul and 10^{-8} for tactical is observed.

c. Measure the optical power at the attenuator output (B) and at the attenuator input (A).

d. Calculate the power margin from
$\text{Power Margin} = 10 \log (P_A/P_B)$

e. The result of this calculation is interpreted as the power margin at the specified BER. To reverse the procedure and measure BER with a high power margin would be impractical since it could take years to establish the BER.

5. Measure BER as follows:

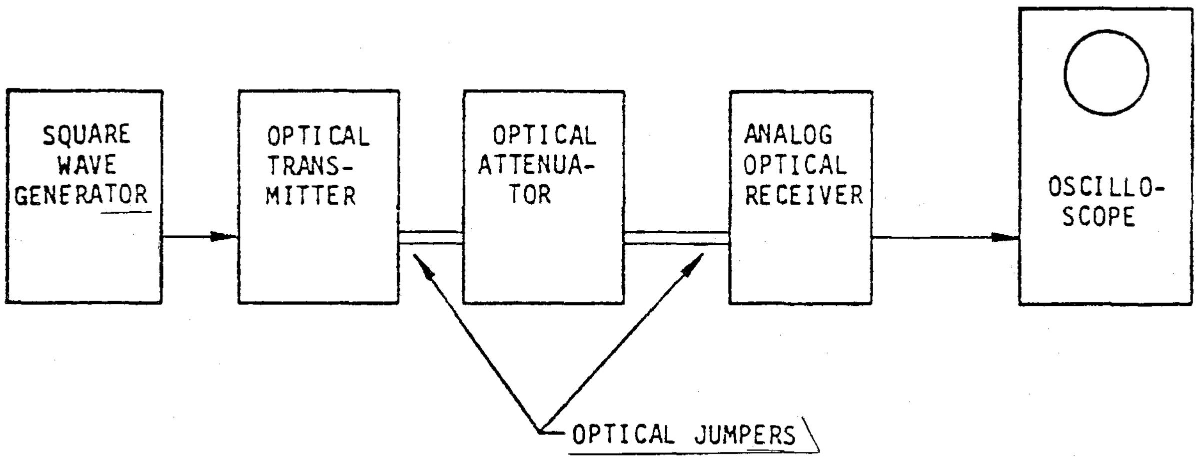
a. Set the BER pattern generator for a pseudorandom bit sequence of $2^{15}-1$ bits at the highest system bit rate.

b. Adjust the optical attenuator to provide an input signal power level to the reciever terminal at the minimum specified sensitivity for the receiver to be used.

c. Measure the received signal BER on the BER counter. This BER level shall meet the values specified for the system under test.

10.3.3 Optical transmitter rise and fall times.

1. Set the square wave generator (see FIGURE 12) to a bit rate corresponding to the highest system signaling rate and adjust the output to 400 millivolt (mV) peak-to-peak, referenced to ground.



NOTE: A TTL-to-balanced converter may be used in lieu of test equipment providing a MIL-STD-188-114 interface.

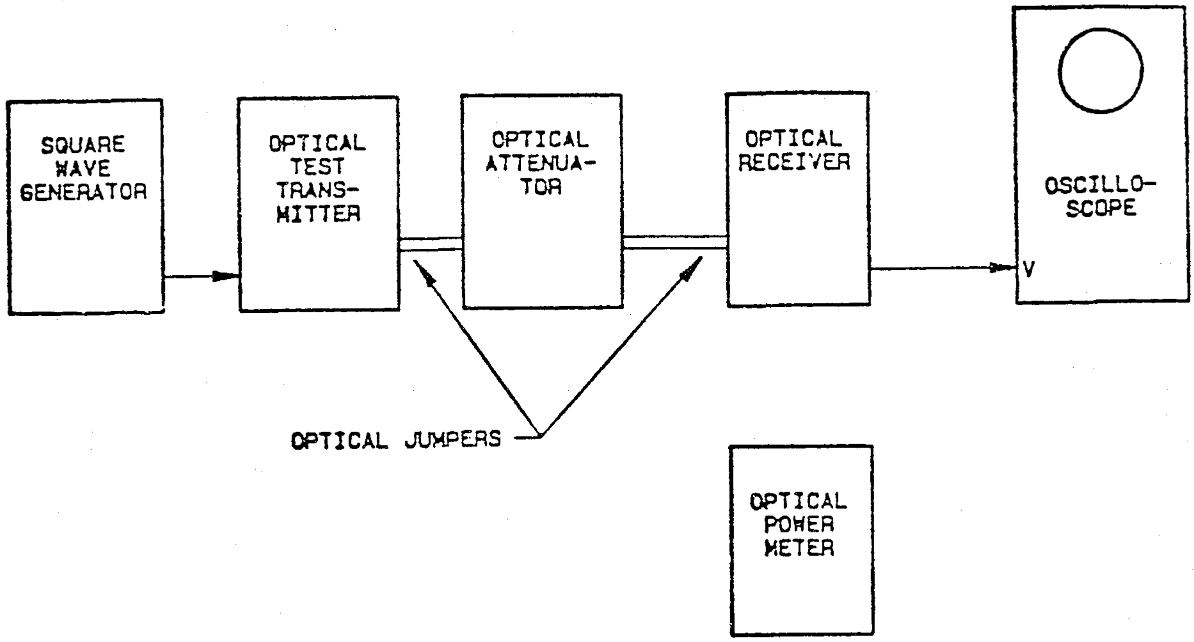
FIGURE 12. Test configuration for optical transmitter rise and fall times.

2. Adjust the optical attenuator so that no distortion appears on the oscilloscope.

3. Measure the 10 percent to 90 percent rise and fall times on the oscilloscope.

10.3.4 Optical receiver rise and fall times.

1. Set the square wave generator (see FIGURE 13) to a bit rate corresponding to the highest system signaling rate and adjust the output to be compatible with the appropriate MIL-STD-188-114 levels.



NOTE: A TTL-to-balanced converter may be used in lieu of test equipment providing a MIL-STD-188-114 interface

FIGURE 13. Test configuration for optical receiver rise and fall times.

2. Disconnect the optical fiber from the receiver and connect it to the optical power meter.

3. Adjust the optical attenuator to give -40 dBm (100mW).

4. Reconnect the cable to the receiver and measure the 10 percent to 90 percent rise and fall times of the received signal with the oscilloscope.

Characterization of Transmission Media

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The technology for transmission of digital bit streams over short and medium distances has matured rapidly. Digital transmission media are being used in telephone local loop plant, intrabuilding wiring, interpanel connections, local area networks, and the familiar data terminal equipment/data circuit-terminating equipment (DTE/DCE) interchange circuits. In many cases, twisted-wire-pair circuits are already in place and in use for analog (voice) circuits. A new characterization of such transmission media that describes the maximum bit rate and distance performance of new designs or installed plant, rather than the familiar analog measure known as characteristic impedance, is needed. An approximate characterization, i.e., figure of merit, has been developed from classical transmission line theory.

METALLIC CABLE LIMITS

Intersymbol Interference

Baseband digital transmission generally is limited by intersymbol interference, i.e., succeeding pulses overlap at the input to the receiving system. In order to compare transmission media, the case where no compensation is introduced in the receiver should be considered. If the signal, for example, is a non-return-to-zero (NRZ) coded bit stream, the input signals to the cable will be a series of rectangular pulses, as shown in **Figure 1a.** The output from a sufficiently long coaxial cable or twisted wire pair will be a series of exponential waveforms. The data unit interval (DUI) is determined by the clock frequency and for a NRZ code, transitions occur only when a "1" bit is followed by a "0" bit or vice versa. Note that when a "1 0 1" bit sequence occurs, the exponential response at the end of the cable does not reach a steady-state value before the following pulse begins (i.e., this causes intersymbol interference). Variations in the zero crossing times (i.e., middle of the oscilloscope trace) result from the different response times (**Figure 1b**). In the eye pattern shown, the amplitude levels of the bit sequence "1 0 1" are approximately 10 percent and 90 percent of the steady-state values. Steady-state amplitude is reached by all other bit sequences, e.g., "1 1," "0 0," and "1 1 1" as shown in **Figure 1a.** The ΔT which occurs at the eye-pattern crossovers is a measure of the isochronous distortion or jitter. This jitter is expressed as a percentage of the DUI.

Distortion Measure

Limiting the bit rate, R = 1/DUI, for a given transmission line length such that the jitter does not exceed 5 percent generally is considered to be a conservative measure of allowable upper performance. Some manufactures show laboratory-measured curves of bit rate versus length based on this 5 percent jitter limitation for metallic transmission media. The limiting bit rate corresponding to this distortion level for a given length of cable is then a measure of the upper digital performance bound, or "figure of merit," of the particular transmission media. The derivation of such a figure of merit is outlined next.

Figure of Merit

It has been shown that the electric field on a metallic transmission line when the series resistance is dominated by skin effect impedance can be expressed as:

[Continued on page 71]

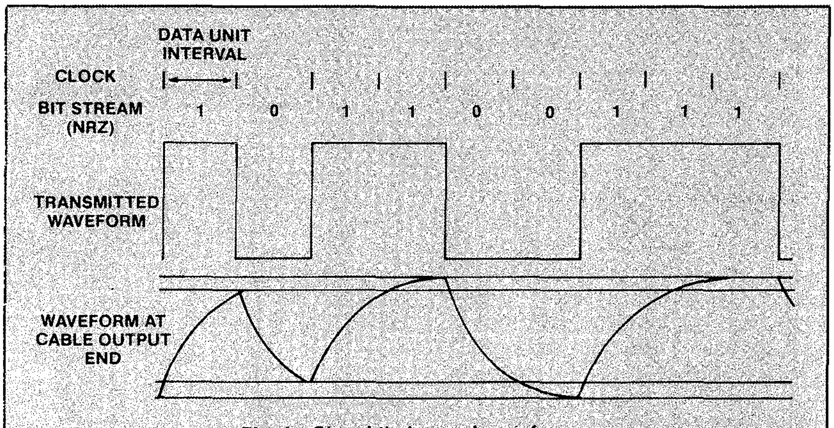

Fig. 1a Signal timing and waveforms.

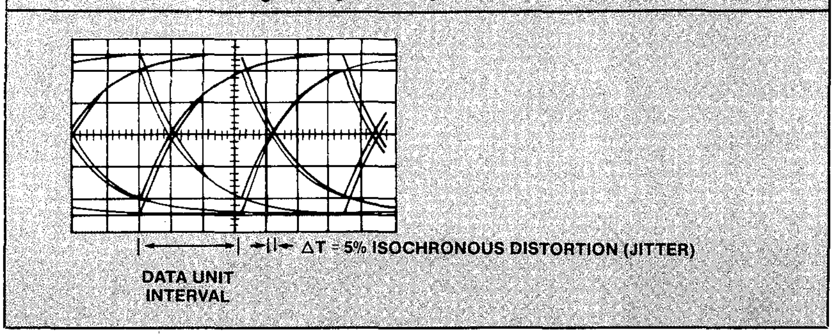

Fig. 1b Eye pattern.

Editor's Note: The article is a summary of a portion of the results of a technical report by J.A. Hull, A.G. Hanson, and L.R. Bloom, "Alternative Transmission Media for Third-Generation Interface Standards," NTIA Report 83-121.

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$$E = E_o \exp - \left[p\sqrt{LC} + \frac{K\sqrt{p}}{2Z_o} \right] l \quad (1)$$

where

E = electric field at distance l
E_o = input electric field
p = $j\omega = j2\pi f$ where f is the circular frequency
L = inductance per unit length
C = capacitance per unit length
K = skin effect impedance of the conductors per unit length
Z_o = characteristic impedance = $\sqrt{\frac{L}{C}}$
l = length of transmission line.[1]

The cable output voltage waveform resulting from a step function input is shown to be:

$$f(t) = f(X + l\sqrt{LC}) = \text{Cerf}\sqrt{\beta/X} \quad (2)$$

where Cerf (z) is the complementary error function of (z),

$$\beta = \left(\frac{lK}{4Z_o}\right)^2$$

= a response function of a particular transmission line,

X = time measured at the output of the transmission line.

This expression can be solved using mathematical tables of error functions to find β/X such that $f(t) = 0.5$; the result is $\beta/X = 0.23$ or $X = 4.35\beta$. From **Figure 1b,** X is the time interval from the beginning of a transition to the crossover point on the eye diagram. In this figure, the bit sequence "1 0 1" produces the inner "eye" of the eye pattern. For conditions corresponding to approximately 5 percent jitter, the inner eye is roughly symmetrical (this would be exactly true if the rise and decay were linear rather than exponential). The minimum DUI corresponding to this condition is then 2X or DUI = 8.7β.

Refer to Equation (1) and note that, except for a delay term $(p\sqrt{LC})\,l$,

$$E = E_o \exp - \left(\frac{Kp^{1/2}}{2Z_o}\right) l \cdot$$

The attenuation coefficient of the transmission line is the real part of

$$\frac{Kp^{1/2}}{2Z_o} \text{ or}$$

Attenuation Coefficient = $\alpha(\omega)$ = real part of

$$\frac{K\sqrt{j\omega}}{2Z_o} = \frac{K\sqrt{\frac{\omega}{2}}}{2Z_o}$$

thus, $K = \dfrac{\alpha(\omega)\, 2Z_o}{\sqrt{\omega/2}}$.

This value of K may be substituted into the definition of β in Equation (2), yielding:

$$\beta = \frac{l^2\alpha^2(\omega)}{2\omega} = \frac{l^2\alpha^2(\omega)}{4\pi f}.$$

The DUI corresponding to an upper pulse rate is then:

$$DUI = \frac{1}{R} = \frac{8.7\,l^2\alpha^2(\omega)}{4\pi f}$$

or

$$R = \frac{1}{DUI} = 1.44\,\frac{f}{\alpha^2(\omega)\,l^2}.$$

The product

$$Rl^2 = 1.44\,\frac{f}{\alpha^2(\omega)} \quad (3)$$

will apply to any transmission line for which Equation (1) is valid. The attenuation is produced by skin effect impedance, which is proportional to $\sqrt{f}$; the product Rl^2 is, therefore, a constant and represents a figure of merit, Fm_α, for the transmission line. In Equation (3), R is in bits per second, l is in meters, f is in hertz, and $\alpha(\omega)$, the attenuation coefficient, is in nepers per meter. A more convenient expression is

$$Fm_\alpha = Rl^2 = 109\,\frac{f}{\hat{\alpha}^2(\omega)} \quad (4)$$

where

R = megabits per second,
l = length in kilometers,
f = frequency in megahertz at which $\hat{\alpha}(\omega)$ is measured, and
$\hat{\alpha}(\omega)$ = attenuation coefficient in dB/km.

For any metallic transmission line (coaxial cable, twisted wire pair, twin-axial), this Fm_α can be calculated, provided a measured attenuation coefficient at a known frequency is available. The only restriction is that f must be sufficiently high so that the skin effect impedance dominates the loss ($f \geq 100$ kHz for copper transmission lines).

The significance of this Fm_α is that it permits the comparison of the digital performance of different cables within a general cable class such as coaxial, twin-axial, or twisted wire pair. It is not necessary that all attenuation coefficients be measured at the same frequency. For any given application requirement, a required Rl^2 product is easily calculated from the maximum desired bit rate and required distance. The Rl^2 product must be equal to or less than the Fm_α determined from Equation (4) for a given transmission medium to be satisfactory. Note that the units of l in this equation must be the same as the unit of length in the attenuation coefficient (i.e., l in km, $\hat{\alpha}(\omega)$ in dB/km; l in miles, $\hat{\alpha}(\omega)$ in dB/mile; etc.). For installed trans-

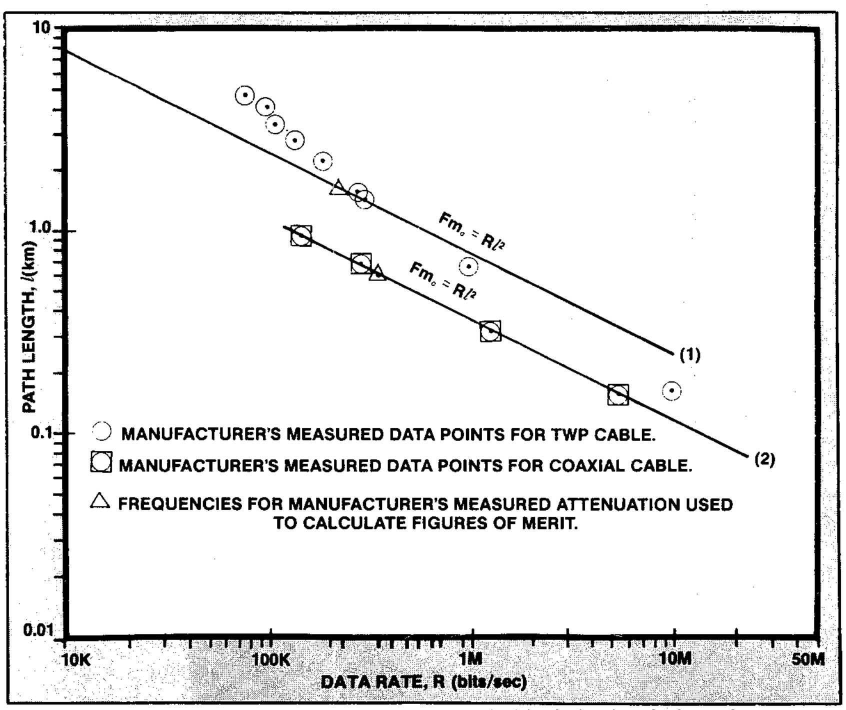


Fig. 2 Figure of merit, Fmα, curves for (1) shielded twisted wire pair and (2) coaxial cable.

mission media, digital characterization can be made by measuring the attenuation coefficient at a known frequency (subject to the frequency lower bound defined above). Thus, Fm_a is a first-order approximation for characterizing the digital performance of metallic transmission media.

Figure 2 shows a plot of Fm_a derived from attenuation coefficient measurements for 1) a solid-center conductor coaxial cable and 2) a 22-gauge twisted wire pair. Plotted on these curves are bit rate versus distance points derived from eye-pattern measurements, where the isochronous distortion (jitter) was limited to 5 percent.

In the case of the twisted wire pair, the bit rate goes down much lower than the 100-kHz frequency limit imposed on the $\hat{a}(\omega)$ measurement. Since the limitation assumed in this analysis is based on intersymbol interference, the rise and decay times of the input pulses are assumed to be fast compared to the response time of the transmission line; therefore, the skin effect impedance still will dominate at the equivalent Fourier component frequencies of these transitions.

LIMITING PERFORMANCE OF OPTICAL FIBERS

Attenuation Limitations

Optical fibers are dielectric waveguide structures that are used to confine and guide light. The performance of optical fibers is limited both by attenuation and bandwidth. Attenuation in an optical waveguide is caused by absorption, scattering, and leaky modes. Absorption and scattering are primarily functions of the purity of the dielectric material. For moderate-bit-rate systems, the attenuation ultimately reduces the energy transmitted in a pulse to a level that is not distinguishable from the noise of the receiver. This condition may determine the maximum length of waveguide that can be used without repeaters or other amplification. Attenuation is a power loss factor and is not related only to digital performance. Attenuation of optical fiber must be considered carefully — along with such other losses as splices, connectors, and coupling — in system design, in order to ensure adequate system margin.

Bandwidth Limitations

Limits to digital performance may be imposed by the bandwidth characteristics of the optical fiber. The bandwidth of optical fibers may be specified as the rms width (σ) of the impulse response function of the fiber. This measure has the units ns/km. Another measure which is provided more often by manufacturers is the modulation frequency at which the power measured at the output of the fiber is reduced by 3 dB from that at zero frequency. This measure may be designated as f(3-dB) and has the units MHz-km.

In defining the performance of optical receivers, it has been shown that regardless of the pulse shape (rectangular, exponential, Gaussian, etc.) the input power penalty for achieving a bit error rate of 10^{-9} can be limited to 1 dB or less by restricting the DUI (clock period) to be greater than or equal to 4σ, where σ is the rms width of the input pulse.[2] In the case of optical fibers, the maximum data rate "R" would be obtained if very short pulses were used. These pulses would generate an impulse response at the end of the fiber waveguide. Thus, a condition which defines the maximum pulse rate (clock rate) is:

$$R = \frac{1}{4\sigma l},$$

where

σ is the rms impulse response width per unit length of the waveguide and

l = length of the fiber waveguide.

Then, the product

$$Rl = \frac{1}{4\sigma} \quad (5)$$

is a constant, depending only on the bandwidth characteristic of fiber and is, therefore, a figure of merit Fm_o analogous to the Fm_a derived for metallic cables.

There is a relationship between σ and f(3-dB) such that for any impulse response shape the product

$\sigma \bullet f(3\text{-dB}) = \text{constant}.$[3]

Measurements on several graded-index fibers indicate that this constant should be 169 ± 11, where σ is in ns/km and f(3-dB) is in MHz-km.[4] From this relationship the figure of merit for fibers is

$$FM_o = 1.5\, f(3\text{-dB}). \quad (6)$$

This figure of merit provides a useful comparison for digital applications of fibers. Again, the selection of an adequate bandwidth for digital applications can be made by multiplying the maximum pulse rate and the distance to be spanned by the fiber. Note that this figure of merit is useful for characterizing and comparing multimode fibers where the distortion is dominated by the multimode distortion of the fiber. For certain single-mode applications where distortion is caused by material dispersion alone, the figure of merit is $Fm = Rl^{1/2}$.[5]

SUMMARY

First-order approximations defining the limiting digital performance of metallic and optical-fiber transmission media are derived. These figure of merit characterizations of the transmission media can be used to estimate how fast and how far a particular bit stream can be carried without significant degradation in performance (bit error rate or jitter). A required figure of merit can be calculated for a specific application, and a transmission medium with a figure of merit that is equal to or higher than the required Fm can then be selected. Installed metallic transmission media can be characterized for digital transmission by a single measure of an attenuation coefficient, subject to a lower limit of the frequency at which the measurement is made. This figure of merit characterization of transmission media is as significant to the users of such media in digital transmission applications as the familiar characteristic impedance Zo is to users of such media in analog applications.

REFERENCES

1. R.L. Wigington and N.S. Nahman (1957), "Transient Analysis of Coaxial Cables Considering Skin Effect," *Proceedings of the IRE*, Feb., pp. 166-174.
2. S.D. Personick (1973), "Receiver Design for Digital Fiber Optic Communication Systems, I," *Bell System Tech. Journal*, 52, July-August, pp. 843-874.
3. B.L. Danielson, D.L. Franzen, G.W. Day, M. Young, and E.M. Kim (1982), "Optical Fiber Characterization," NBS Special Publication 637, Volume 1 (US Dept. of Commerce, National Bureau of Standards, Boulder, CO 80303).
4. M.J. Buckler (1982), "Measurement of Bandwidth versus Impulse Response in Multimode Fibers," *Technical Digest — Symposium on Optical Fiber Measurements, 1982*, pp. 33-35, NBS Special Publication 641, Oct. (US Dept. of Commerce, National Bureau of Standards, Boulder, CO 80303).
5. J.A. Hull, A.G. Hanson, and L.R. Bloom (1983), "Alternative Transmission Media for Third-Generation Interface Standards," NTIA Report 83-121 (National Technical Information Service, Springfield, VA 22161, Accession No. PB 83-238345). □

APPENDIX C: OPTICAL FIBER SUBSYSTEM COMPONENTS: A BRIEF TUTORIAL

Because optical fiber communication is a relatively new technology--and to provide a technical base for the approach of this report to subsystem analysis--a concise summary is given, in this appendix, of characteristics and capabilities of applicable optical sources, fibers, and detectors. This deliberately brief tutorial covers component types that are commercially available and that are considered practical for current and near-term system applications. Discussion is intended not to duplicate either in-depth theoretical analyses or detailed "hands-on" treatment of hardware, both of which are readily available in the form of published texts. One useful book, basically in the second category and written for the application engineer and senior technician, is by Lacy (1982).

Optical fiber digital links consist of interfaced subsystems which, when assembled, satisfy the link performance and interchangeability requirements. The overall system performance parameters that determine the link operating characteristics are estimated and the acceptable limits of performance needed for each link to meet overall subsystem requirements are outlined.

The basic optical fiber system is shown schematically in Figure C-1. The optical fiber transmission link will typically transmit a serial digital bit stream incorporating data, timing, and control information. As compared to links employing metallic transmission lines, three new components are added:

- the optical transmitter, consisting of electrical optical-driver circuitry and the electrical-to-optical (E/O) transducer (light source);
- the optical fiber transmission line and associated optical connectors, and
- the optical receiver, consisting of the optical-to-electrical (O/E) transducer (optical detector) and electrical conditioning circuitry.

The optical transmitter converts an input electrical signal into an optical signal that is carried by the optical fiber to the optical receiver. The receiver converts the optical signal back to an electrical signal that matches the original input signal. In comparison with metallic conductors, the optical fiber transmission offers wider bandwidth over longer distances, smaller cable cross sections with lower weights, and freedom from electromagnetic interference and crosstalk. (As discussed in the body of this report, crosstalk may be of concern when transporting multiple channels over a single fiber by use of wavelength division

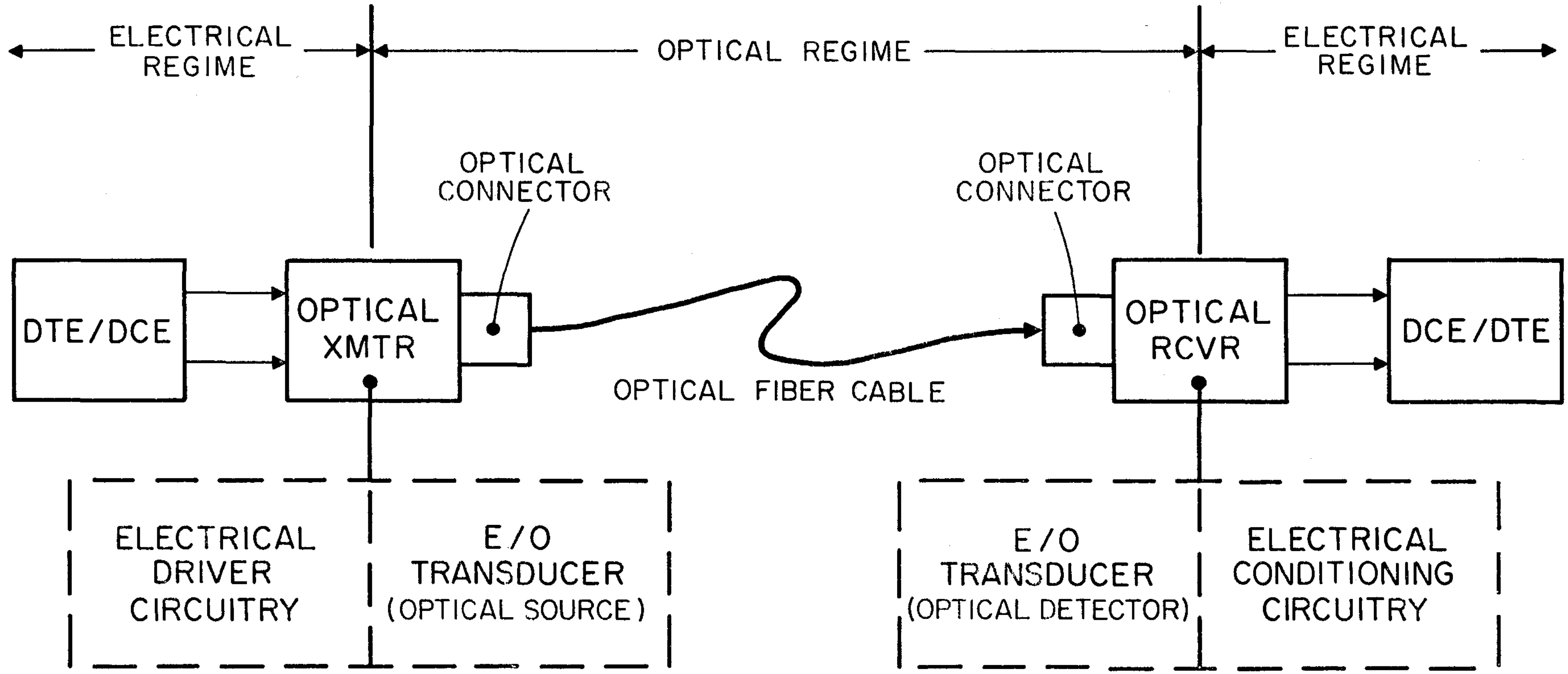


Figure C-1. Block diagram of typical optical fiber point-to-point link.

multiplexing.) The system must be designed to permit input signals at a required digital bit rate to be transmitted over a given distance with an acceptable quality of performance.

C.1 Optical Fiber Sources and Transmitters

In principle, many different types of optical sources could be used with optical fiber for communication systems. The small size of the fiber core, the fiber wavelength transmission characteristics, and the required source response characteristics, however, dictate the use of semiconductor diodes. The coupling of optical power from the source into the fiber core requires that the radiating area of the source be approximately equal to the cross-sectional area of the core. This small area also reduces the capacitance of the source, which favorably affects the rise time and pulse repetition rate.

The semiconductor diodes are of two types, namely: light emitting diodes (LED's) and injection laser diodes (ILD's). LED's and ILD's produce radiation of suitable wavelength by charged carrier recombination across a forward biased P-N ("positive" doped, "negative" doped) junction of the semiconductive materials. Aluminum gallium arsenide (AlGaAs) doped materials are usually used to provide radiation in the 800 to 900 nm wavelength region. Materials such as indium-arsenic-phosphide (InAsP), indium gallium arsenide (InGaAs), and indium gallium arsenide phosphide (InGaAsP) are used to produce longer wavelength radiation in the 1100 to 1600 nm region. In addition to providing radiation at a suitable wavelength, the source diode should provide radiation with narrow spectral width, means for efficient and adequate optical power coupled into the fiber core, capability of being modulated at high data rates, and operational conditions suitable for permitting diode lifetimes of tens to hundreds-of-thousands of hours.

LED's generally produce lower output power than ILD's. LED's produce greater spectral widths near their center operating wavelengths and generally operate at lower maximum data rates than do ILD's.

LED's may be homojunction or heterojunction devices. Homojunction refers to producing the radiative junction using two layers of the same material (e.g., GaAs) in electrical contact across the junction but with one layer P-doped and the other N-doped. Heterojunctions are formed by layers of dissimilar composite alloys (e.g., AlGaAs/GaAs) each suitably P or N doped. Heterojunction diodes show superior radiation containment and emission efficiency for both surface and edge emitting types. Surface emitting diodes provide a junction that produces a radiation pattern comparable to that of a diffuse scattering surface, that is a cosine distribution perpendicular to the junction plane. Edge emitting diodes may be of two types, namely: side emitting or forward emitting. Disk shaped side emitters produce ring-like radiation patterns confined to a narrow angle centered parallel to the P-N junction plane. This diode type requires a suitable reflector or lens to direct the edge-emitted radiation toward the fiber end face. Forward or frontal emitters (also called stripe-contact devices) permit the radiation to be directly coupled to the fiber in a manner similar to that of the surface emitter. A high-radiance, nonhermetic, surface emitter source configuration in common use is the Burrus (etched well) diode which is attached via epoxy cement to a short pigtail fiber. The junction area of the LED is designed to be about the same area as the fiber core area. The Burrus diode provides high coupling efficiency, high data rates (due to its small area and resultant low capacitance), and good stability and lifetime (due to good heat sinking and low thermal resistance).

The word "injection" in ILD devices refers to the creation of stimulated optical emission by injection and confinement of charge carriers to a small recombination region in a solid, single-crystal, semiconductor region that has cleaved (highly polished) parallel end faces that form a laser cavity. Radiation generated in the region is repeatedly reflected from the end surfaces to stimulate additional radiation. One of the surfaces (facets) is purposely made somewhat transmissive to allow the output of radiation from the device. In some cases, the leakage radiation from the better reflector is monitored to provide feedback to the laser power source to stabilize the output of the signal radiation. The laser cavity shape may be thought of as a rectangular volume with lasing occurring along the longer dimension and the emitted radiation coming from a stripe of fixed width and thickness on the cleaved end face of the cavity. These diode lasers are referred to as "stripe-contact" devices. The stripe thickness affects the modal nature of the laser output and the stripe width affects the achievable power output. ILD constructions are designed to optimize the properties for continuous wave (CW) or pulse operation at room temperature, and for high efficiency and extended lifetime.

ILD's may be homojunction or heterojunction devices. Heterojunction diode constructions may be single heterojunction (SH) or multiple heterojunction (usually double heterojunction, DH) structures. SH ILD (close confinement) constructions are large cavity, diffused P-N junction devices with electrical and thermal properties that make them suitable for pulse operation only. DH ILD's are designed and optimized for pulse and CW operation.

With present-day ILD's, tens of milliwatts of optical power can be coupled into an optical fiber (Lacy, 1982, Chapter 3). A typical LED will couple about 18 dB less power into a fiber. In comparing the output of these devices, a reference power level of 1 milliwatt is generally used, which is referred to as 0 dBm. LED power outputs typically range from 0.05 to 0.5 mW (-13 dBm to -3 dBm) while that of ILD's range from 1 to 40 mW (0 dBm to 16 dBm). Because of their greater output power, ILD's are best suited for long-distance transmissions, especially when repeaters are required. The spectral width of lasers is typically 2 nm whereas LED's are about 40 nm in the 800 to 900 nm operating regions. Some disadvantages of ILD's are:

1) Cost is much higher than for LED's; typically hundreds of dollars for ILD's and as low as $5 for some LED's.

2) ILD's are extremely sensitive to temperature. Control circuits must be added to compensate for temperature variations making the system more complex and possibly less reliable.

3) Lifetime at room temperatures is much less than for LED's. Lifetimes of order 10,000 hours are typical for ILD's while LED's may have operating lives of 10^6 to 10^7 hours. (These lifetime expectations are based on accelerated life testing.)

The LED output is nearly linear with drive current input, which makes LED's more applicable than ILD's to analog transmission systems. This is particularly true for short distances and modulation rates less than 50 MHz. At higher modulation rates, analog modulation becomes impractical because of signal distortion caused by the spectral width of the LED output. LED's are typically used for digital systems to 50 Mbits/s. ILD's are typically used for digital systems above 50 Mbits/s, although experimental LED sources have been developed (1300 nm region) for 276 Mbits/s operation. Modulation of ILD's up to rates of 4 Gbits/s have been achieved.

Fiber optic transmitters provide the supporting functions required by the optical sources to assure their satisfactory operation. LED sources radiate energy which is essentially proportional to the current conducted by the device. ILD sources, however, provide outputs which are proportional to drive current only above their threshold current levels. The threshold current level is both temperature and age dependent. Generally, optical transmitters provide for source output coupling and level control and power for other circuit functions.

An ideal optical communication transmitter would provide adequate output power over all selected link lengths to permit repeaterless (point-to-point) transmission of all data modulation rates or analog frequencies with no signal distortion. Such ideal transmitters do not now exist; however, reduced fiber loss and dispersion at wavelengths in the 1000 to 1500 nm region will significantly improve the distance that a transmitter can operate over. (It should be noted that current (1984) typical standard grade fibers have hydroxyl ion (OH) absorption peaks at approximately 950 nm and 1400 nm.) Future single mode waveguide systems will virtually eliminate bit rate limitations and extend again the distance over which a given transmitter power can operate.

C.2 Optical Fiber Waveguides

Optical waveguides form the transmission medium for fiber optic links in a manner analogous to the coaxial cable and wire pair for metallic systems; however, optical sources and detectors are characterized by their power responses so that the electric field equations used to define a complex propagation constant are not directly applicable to this medium. The fibers are composed of dielectric (insulating) materials and cannot be used for the transmission of electrical power. The parameters of primary interest may be considered under optical, material, configurational, and mechanical characteristics.

C.2.1 Optical Parameters

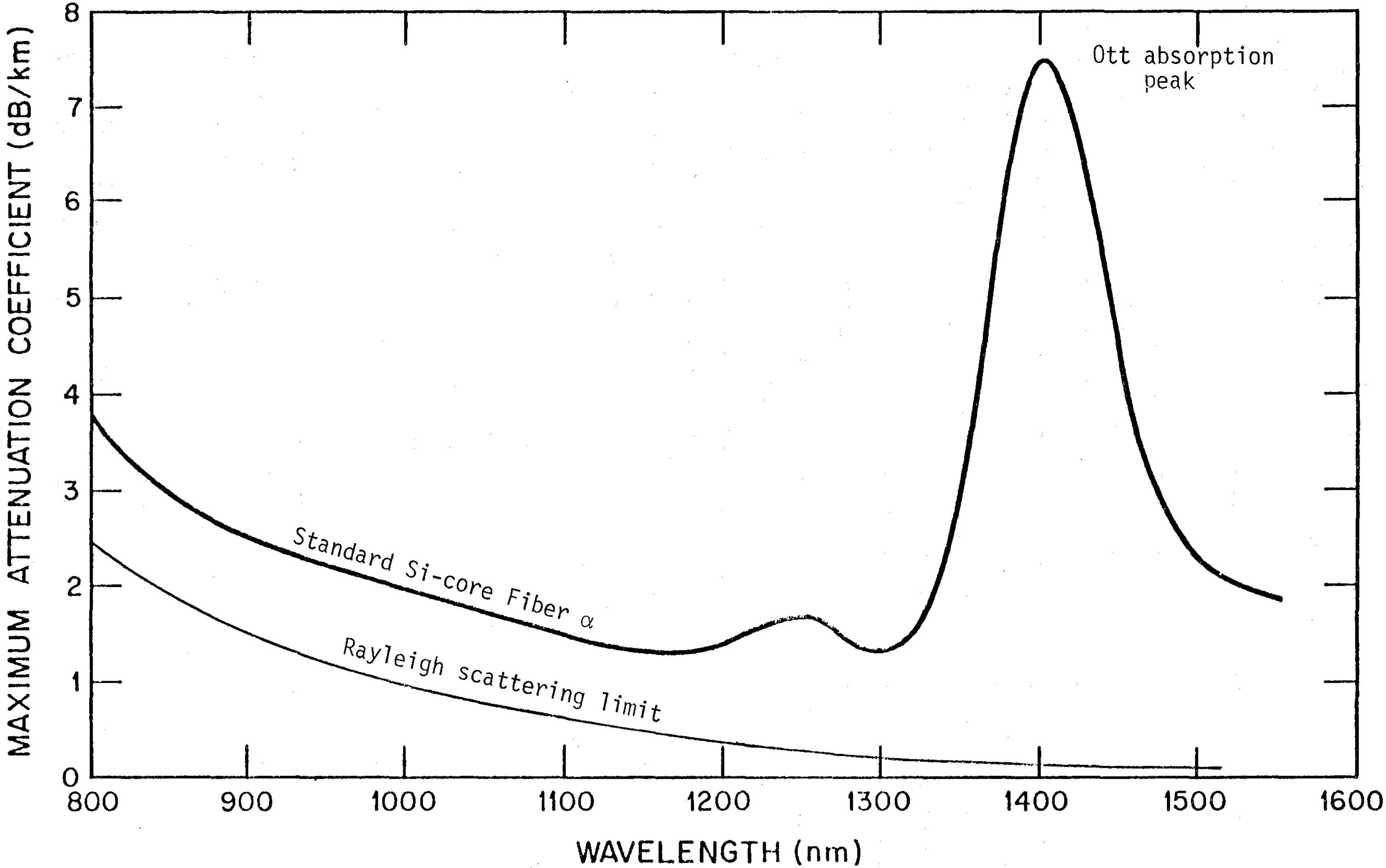
The optical parameters needed to specify fiber waveguides are (CSELT, 1981, Chapter 1):

- attenuation coefficient, α,
- core radius, a,
- numerical aperture, $NA = \sqrt{n_1^2 - n_2^2}$ (where n_1 = core refractive index, n_2 = cladding refractive index), and
- a characteristic parameter, $V = (2\pi a/\lambda)\sqrt{n_1^2 - n_2^2}$ (where λ is the light wavelength in vacuum), which is related to the number of modes that can be propagated in a fiber (number of modes $\doteq V^2/2$).

The attenuation coefficient is a measure of the loss per unit length (e.g., dB/km) at a specific wavelength. Attenuation as a function of wavelength for high-quality silica core fibers is shown in Figure C-2. Also plotted on this curve is the Rayleigh scatter limit, which can be considered to be the ultimate limit of attenuation. This limit varies as λ^{-4}. The attenuation decreases with increasing wavelength so that operating "windows" above 1000 nm are desirable as the cost and reliability of sources and detectors become competitive with the currently proven technologies in the 800-900 nm region.

Manufacturers' data sheets specify the attenuation coefficient for typical operating wavelengths. This attenuation produces a decrease in the optical power that is directly proportional to the length of the waveguide after equilibrium mode power distribution has been attained. (Equilibrium mode power distribution is defined (Hanson et al., 1982) as the condition in a multimode optical waveguide in which the relative power distribution among the propagating modes is independent of length; power in high order modes may have been lost, and the exchange of power among modes due to mode coupling has reached statistical equilibrium.) Depending on fiber type, this may require a 1-to-2-km length, explaining why major manufacturers measure α over 2-km fiber cable lengths. [A word of caution for multimode fibers (defined below) regarding the use of short lengths (typically $<$ 1 km) is that the attenuation coefficient may not be a constant function of the length. If high-order modes are coupled into the fiber, excess loss can be experienced due to the loss of power into the cladding and beyond. This leaky mode loss is generally a second-order effect that may not be of interest provided adequate system margin is used in the design. Another loss mechanism is that due to microbending which is a function of mechanical stresses on the fiber.] It is important to select the attenuation times length product such that ample system margin remains after all loss factors are accounted for. The calculation of a loss budget is treated in Section 3 of this report.

The core radius or diameter is one factor that determines the coupling efficiency from a given source to the fiber. The Consultative Committee on International Telegraphy and Telephony (CCITT) has initially recommended a core diameter of 50 micrometers (μm) and a cladding diameter of 125 μm. As of late 1983, the following combinations are also under consideration: core 62.5 μm/cladding 125 μm, core 85 μm/cladding 125 μm, and core 100 μm/cladding 140 μm (CCITT, 1983a). The smallest of such fibers are used predominately in long-haul application. So



Notes: 1. Hydroxyl ion (OH) absorption band at 1400 nm can be almost totally eliminated, but at extra production cost.

2. Lower curve is for ultimate lower attenuation limit imposed by Rayleigh scattering, which varies with λ^{-4}.

Figure C-2. Attenuation vs wavelength for typical, low loss, silica-core optical fiber.

called "fat" fibers have core diameters of 100, 200, or 300 μm and are useful in short haul applications employing moderately high data rates, when relatively large-area LED sources can couple adequate power into such fibers. For LED sources, difference in input power coupling between 50-μm and 300-μm cores may be 20 dB (see Section 4). For single mode operation, a typical core diameter may be ~5 μm. This small diameter results from the minimum required value for V; see example below.

Numerical aperture defines the maximum acceptance angle for light rays that will propagate down the fiber. It is determined by the indices of refraction of the core and cladding materials. It may also be defined as the sine of one-half of the acceptance angle of the fiber. For long haul communication fibers, the NA is typically about 0.2. For typical short haul applications (distance less than ~1 km), NA values up to 0.4 may be used for moderately high modulation rates.

The characteristic parameter V is related to the number of modes that can be propagated in a fiber. Note that this parameter is proportional to the core radius divided by the center wavelength of the source radiation times the numerical aperture. The condition for single mode operation is obtained when $V \leq 2.4$, and the waveguide can support only the HE_{11} mode, whose propagation characteristics completely determine the waveguide propagation characteristics. Single mode operation achieves the ultimate in bandwidth since multimode distortion (discussed below) is not present. Through proper optimization, other bandwidth-limiting factors can be designed to cancel so that Gigabit transmission rates will ultimately be achievable. The single mode requirement for $V \leq 2.4$ results in small maximum allowable core sizes. For example, for a high-silica fiber operating at $\lambda = 1.3$ μm, with a core refractive index of 1.47 and a cladding index of 1.458, the maximum core size for single mode operation is defined by:

$$V = \frac{2\pi a}{\lambda} (n_1^2 - n_2^2)^{1/2} = 2.4 \text{ (Kao, 1982, p. 33)},$$

and solving for "a" yields a core radius of 2.65 μm.

Attenuation in an optical waveguide is caused by absorption, scattering, and leaky modes. Absorption and scattering are primarily functions of the purity of the core and cladding material. The ultimate lower limit of these losses is determined by Rayleigh scattering from random fluctuation of material composition. This loss amounts to about 1 dB/km at 1 μm wavelength and varies as λ^{-4}. Figure C-2 shows a composite of several current attentuation characteristics of low loss, silica-core optical fibers. The Rayleigh scattering limit is also shown. Note that as the wavelength increases, this scattering limit decreases. In multimode guides, attenuation may be different for different modes. This is known as differential mode attenuation. In this case, the attenuation coefficient (generally expressed in dB/km) is not a constant function of distance. The fabrication process gives rise to dimensional fluctuations, expressible as diameter variations, ellipticity, eccentricity, and birefringence. These imperfections cause mode conversion and result in increased attenuation. The leaky mode loss is particularly of concern over short distance links when the fiber is "overfilled" with high-order modes. Thus, launch control is of particular concern in the precision measurement (calibration) of the optical waveguide attenuation coefficient. Launch control may include restriction of the cone angle impinging on the input end of the fiber, or use of a mode stripper to eliminate high-order modes.

Recent advances in materials and manufacturing processes have greatly reduced the absorption losses in high-quality optical waveguides. The attenuation peak at λ = 1400 nm results from hydroxyl ion (OH) absorption, which can be almost totally removed, but at increased production cost. A similar very high absorption peak exists at about 900 nm in fibers manufactured without the recent improvements. Current high-performance fibers have transmission "windows" at several wavelengths. The wavelengths of particular interest (because of source and detector state-of-art) are 800-1000 nm and 1300 nm, corresponding respectively to MIL-STD-188-111 Wavelength Bands I and III. Devices operating at 1500 nm have proven very efficient in experimental systems, but are not as yet (early 1984) commercially available. Research at longer wavelengths is receiving more emphasis.

The attenuation coefficient as measured by the manufacturer is generally sufficient for calculating system power budget. The attenuation ultimately reduces the energy transmitted in a pulse to a level that is below a required signal input level of the receiver to assure a desired performance level such as bit error rate (BER). This condition may determine the maximum length of waveguide that can be used without repeaters or other amplification. In this case, the system is said to be operating in the power-limited regime. The attenuation of the optical fiber must be carefully considered in system design, along with other losses such as splices, connectors, and coupling in order to assure adequate system margin. System design requires the development of a loss (power) budget, example calculations for which have been presented in Sections 3.1.1 and 3.2.1 above.

When distortion of the received signal, rather than its amplitude (power), limits performance of a digital transmission, the system is said to be operating in the distortion-limited regime. Multimode distortion and material dispersion are the two primary distortion-limiting mechanisms of concern in optical fiber system design. Multimode distortion results from differential mode delay which is defined as the variation in propagation delay that occurs because of the different group velocities of the various modes. This is a time-dependent parameter as distinguished from the wavelength dependence of material dispersion. Material dispersion is attributable to the wavelength dependence of the refractive index of the material used to form the waveguide core. It is independent of the waveguide geometry and is therefore common to both multimode and single mode fiber waveguides.

Multimode fibers may be either step index or graded index. In step index fibers, the index of refraction is uniform in both the core and cladding with the cladding having a lower index (n_2) than that of the core (n_1). In graded index fibers, the core index of refraction is varied continuously from a maximum value, n_1, on the axis to n_2 at the cladding interface, usually in a nearly parabolic manner. In such fibers, light rays will travel at different velocities at different radial positions because of the refractive index change. Near the outer edge of the core, the index is lower; therefore, rays in this region will travel faster than rays near the center of the core. This variation in velocity causes all modes to have about the same group velocity and thus arrive at the end of the waveguide at approximately the same time. Thus, the graded index minimizes the time dispersion caused by multiple modes.

The effect of multimode distortion is to limit the bandwidth of the fiber. Bandwidth is most often characterized on manufacturers' data sheets as the 3 dB optical bandwidth. Fiber bandwidth is defined (Hanson, et. al, 1982) as:

FIBER BANDWIDTH.

> The lowest frequency at which the magnitude of the fiber transfer function decreases to a specified fraction of the zero frequency value. Often, the specified value is one-half the optical power at zero frequency.

To the extent that differential mode distortion is linear with distance, the bandwidth can be characterized as the above frequency in MHz-km. For system calculations, it is often desirable to relate this 3 dB bandwidth (B_f) to an equivalent rise time for the fiber:

$$\text{Rise time } (\mu s) = \frac{0.35 \cdot \ell \text{ (km)}}{B_f \text{ (MHz-km)}}$$

Since fiber rise time is typically expressed in nanoseconds,

$$\text{Rise time (ns)} = \frac{350 \cdot \ell \text{ (km)}}{B_f \text{ (MHz-km)}}$$

(See Appendix D for derivation).

A figure of merit, Fm_0, for multimode optical waveguides analogous to that derived in a reference paper (Hull et al., 1983) for metallic transmission media is

$$Fm_0 = P\ell = \text{a constant.}$$

This is equivalent to saying that a figure of merit for multimode optical waveguides is the maximum pulse rate per unit length (km). It should be noted that <u>any combination</u> of P and ℓ may be used, and that the resultant $P\ell$ product must be equal to or less than the Fm_0 constant. Systems design applications of this figure of merit are given in the examples of Section 5 above. For waveguides in which multimode distortion dominates, the maximum pulse rate is given by

$$P_{max}\text{(Mbits-km/s)} = 1.3 \times B_f \text{ (MHz-km)} \quad . \qquad \text{(C-2)}$$

For single mode fibers, where the only distortion is from material dispersion, and for very short input pulses (e.g., from mode locked lasers), the figure of merit can be proportional to $P(\ell^{1/2})$.

C.2.2 Material Parameters

The significant breakthrough that has made possible low-loss optical fiber waveguides was the recognition that optical attenuation is mainly produced by impurities contained within the optically transparent material and not by losses produced by the intrinsic material. Fiber materials suitable for optical communications are primarily of two fundamental types, pure or doped silica and multicomponent glasses. The distinction between these two fundamental material types is not very clear and is usually correlated with the fiber fabrication processes. The basic core component is usually silica (SiO_2), either natural or synthetic. Several competitive techniques are used to combine high purity silica with appropriate additives to vary the index of refraction. [See Kao (1982), pp. 62-69 for process descriptions.]

The materials selected for optical fiber use must provide the optical, mechanical, and environmental properties required for the intended application. Silica with different levels of dopants is used normally for both the core and cladding materials. It is also possible to use a plastic coating with a lower index of refraction than silica to provide a plastic cladded silica (PCS) combination that may be less expensive than a totally glass system. Properties of the plastic coating generally limit both the high and low ambient temperature applications of the PCS fibers. All PCS fibers are step index fibers. Manufacturers' data sheets describe these material characteristics and the relevant performance advantages.

In addition to the silica and compound glass fibers, all-plastic fibers are available for special applications. The attenuation of all-plastic fibers is generally much higher than that necessary for communications, and the bandwidth is more limited. As the result of recent research, plastic fibers with somewhat lower attenuation are expected to be available in the near future. The special mechanical flexibility of these fibers makes them attractive for some short distance applications.

C.2.3 Configurational Parameters

Configurational parameters include the fiber dimensions, dimensional tolerances, use of protective coatings, and buffering or lubricants intimately associated with individual single fibers.

Fiber core and cladding diameters as well as concentricity must be maintained within specified tolerances in order to facilitate splicing and connectorization at acceptable loss levels. Standards for these dimensional parameters are being developed by international agreement through the work of CCITT Study Group XV. For example, the dimensional characteristics currently of most interest are:

Material	Core/Cladding Diameters
Silica (optionally glass) core and cladding	50 μm/125 μm 62.5μ/125 μm 85 μm/125 μm 100 μm/140 μm
Plastic clad silica	200 μm/----

In order to preserve the optical and mechanical characteristics of an individual fiber (glass or silica), the surface must be protected by a suitable polymer coating. This coating prevents physical damage to the surface and deterioration from environmental contaminants. Its thickness is generally only a few micrometers. The coating must be removed in preparation for splicing or connectorization. This is necessary to assure alignment accuracies required for low loss in the resultant junctions. Other buffer layers or lubricants may also be present to protect the fiber during cabling processes or to eliminate exposure to excessive humidity or water under some application environments.

C.2.4 Mechanical Parameters

The mechanical properties of optical fibers must be adequate to permit the nondestructive handling of the fiber during cable manufacture, connectorization and splicing processes. The manufacturers' data sheets usually provide maximum tensile and minimum bending radius data on the specific product. These data are not easy to apply in all of the connecting and splicing methods needed for field installations. Special characteristics of cables are designed to protect the fibers from excess mechanical stress under various installation procedures and installation requirements (ducts, aerial, buried, etc.). Study Group VI of the CCITT is preparing a Handbook (CCITT 1983b),"... to describe practical construction of optical fiber cables and methods for installing, splicing, and maintaining these cables in the outside plant .... This Handbook covers junction, trunk, and distribution network applications." This document, based on current experience of the participant CCITT administrations, should be available in the near future.

Environmental exposures, which primarily affect fiber performance and lifetime, include effects of temperature and humidity. All-glass (and silica) fibers are relatively unaffected by temperature as far as their performance (loss, bandwidth) characteristics are concerned when used within their specified temperature ranges. Plastic clad silica and all-plastic fibers, however, have loss characteristics that change with temperature. At high temperatures, dimensional changes may take place and at low temperatures, plastic fibers tend to become inflexible and bending stresses become important. Various jacket and cable designs, functionally similar to those used for metallic conductors, are used to protect fibers from water intrusion.

Optical communication fibers are placed in cables of various configurations to provide the mechanical and physical protection required for installation and environmental stresses. Some cables are all-dielectric in order to eliminate any electrical continuity between the input and output ends of the cable. This electrical isolation eliminates ground loop problems, particularly important when primary power sources at the two ends of the cable are different. Such all-dielectric cables essentially eliminate vulnerability to electromagnetic interference and eliminate the possibility of electrical spark generation when the cable is located in hazardous areas. Other cable structures may also contain electrical conductors for the transmission of power, for example, to repeaters or terminals or to provide control circuits for conventional interconnections. Such designs are known as hybrid cables.

Strength members are incorporated into cables to provide the necessary properties for pulling, aerial installation, or other special protection. All-dielectric cables, using nonmetallic strength members, are available. Other cable designs provide metallic strength members for use in specialized applications. Generally, optical cables can be procured that meet or exceed all of the test requirements of metallic-conductor cables such as bend, compression, torsion, and strength capabilities.

No special installation or environmental considerations beyond those for metallic cable need be considered for optical fiber cables. Applicable standards for cables have been and are under development. Two standards of interest are DOD-STD-1678 (Test Methods and Instrumentation for Fiber Optics, 1978), and RS-455 (Standard Test Procedures for Fiber Optic Fibers, Cables, Transducers, Connectors and Terminating Devices, 1980) of the Electronic Industries Association.

C.3 Optical Detectors and Receivers

Photodetectors must have high sensitivity (responsivity) to weak light signals, have sufficient bandwidth or speed of response to handle incoming signals, have low inherent noise, and be relatively insensitive to temperature variations.

Optical detectors used for fiber optic applications generally fall into two classes: PIN (positive-intrinsic-negative) photodiode and APD (avalanche photodiode). PIN detectors are basically unity-gain devices that convert incident photons of radiation into electron-hole pairs with a conversion efficiency of about 60-80 percent. The APD detector produces many electron-hole pairs for each captured photon with a resultant improved sensitivity over the PIN devices. APD's operate with a much higher reverse bias voltage than do PIN's. The wavelength sensitivity of both detectors depends on the material, with silicon (Si), germanium (Ge), and gallium-indium-arsenic-phosphide/indium-phosphide (GaInAsP/InP) technologies being the most dominant. For operation in the 800-900 nm wavelength region, silicon devices are preferred. Detector lifetimes have been projected to exceed 10^6 hours under normal operating conditions.

Optical receivers provide a variety of support functions for the detectors, such as electrical bias power and output impedance, signal amplification, automatic gain control (AGC), data recovery (decoding), and matching of electrical output to characteristics of source input. Optical coupling into PIN's and APD's may be accomplished by butting and cementing output fiber end faces (properly polished) to diodes, use of a similar butt arrangement employing a pigtail cemented directly over the diode chip, or arrangements using optical windows. Large core size, high NA fibers are generally used for detector pigtails to maximize the collection and transfer of optical power from the link fiber to the detector sensitive area. Data sheets do not generally indicate coupling loss at the fiber-detector interface but worst-case coupling loss should not exceed 1 dB, and in most cases will be substantially less.

Critical system performance parameters of optical receivers are required optical input power for a specified bit rate and bit-error-rate (BER) performance, dynamic range, bandwidth or rise time, and external interface. The difference between the required input power of the receiver and the power output of the driver provides the total power budget available for the system design. The receiver dynamic range (AGC) permits variations in this optical input level which will still produce a desired electrical output level to the decision circuit of the receiver where bit recognition takes place. This dynamic range provides additional flexibility in system design. (See Sections 3.1.2 and 3.3.3 above.)

C.4 References

CCITT (1983a), A graded index fiber for use in the local networks, AT&T contribution to Study Group XV on Question 13, July.

CCITT (1983b), Handbook (Introduction), Study Group VI - Contribution 79 on Questions 15, 16, 17, and 18/VI, November.

CSELT, Technical Staff (1981), Optical Fibre Communication, Centro Studi e Laboratori Telecommunicazioni, Turin, Italy. (Published in U.S. by McGraw-Hill; ISBN 0-07-014882-1.)

Hanson, A. G., L. R. Bloom, A. H. Cherin, G. W. Day, R. L. Gallawa, E. M. Gray, C. Kao, F. P. Kapron, B. S. Kawasaki, P. Reitz, and M. Young (1982), Optical waveguide communications glossary, N.B.S. Handbook 140, January. (Available from National Technical Information Service, Springfield, VA 22161, Accession No. PB-82166257.)

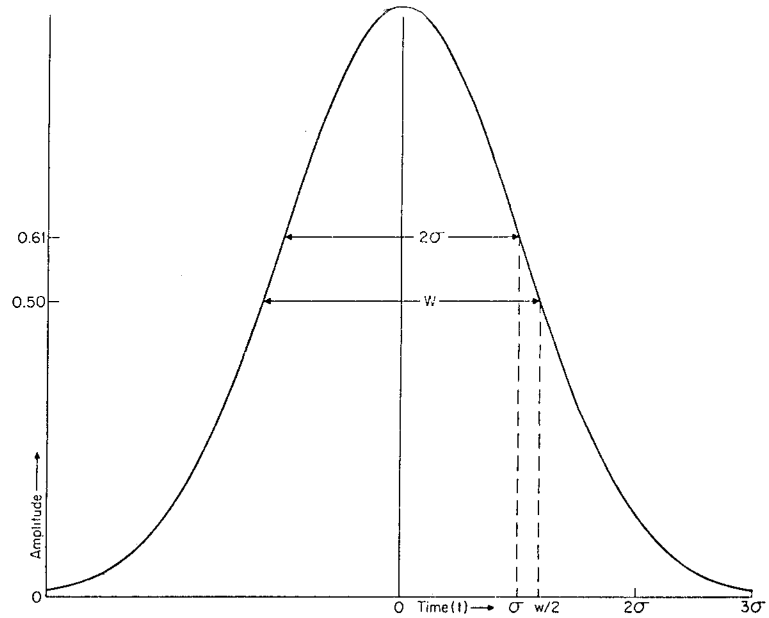
Hull, J. A., A. G. Hanson, and L. R. Bloom (1983), Alternative transmission media for third-generation interface standards, NTIA Report 83-121, May; available from the National Technical Information Service, Springfield, VA 22161, Accession No. PB-83-238345.

Kao, C. K. (1982), Optical Fiber Systems: Technology, Design, and Applications, McGraw-Hill; ISBN 0-07-03327-0.

Lacy, E. A. (1982), Fiber Optics, Prentice-Hall; ISBN 0-13-314278-7.

APPENDIX D: SOME RELATIONSHIPS WHICH DERIVE FROM A GAUSSIAN RESPONSE FUNCTION

The impulse response function of optical fibers is frequently considered to be Gaussian in shape. This assumption permits relatively easy mathematical derivations. In fact, recommendations (CCITT, 1984) regarding the bandwidth characterization of fibers are in process which would fit the frequency response data measured on any given multimode fiber to a Gaussian response via appropriate weighting factors. Some of the relevant approximations are developed below:



Consider the Gaussian shaped pulse, generally described by:

$$f(t) = \exp\left[- \frac{t^2}{2\sigma^2}\right] \quad \text{(D-1)}$$

where σ is the RMS pulse width or one standard deviation of events represented bv the waveform.

This waveform may also be described by:

$$f(t) = \exp\left[- k\left(\frac{t}{w}\right)^2\right]$$

where w is the full width at half maximum (FWHM).

The function will have a value of 0.5 when t = w/2, so that the value of k is:

$$\ell n\ 0.5 = -k\ (\frac{1}{2})^2$$

$$-0.69315 = -k/4$$

$$k = 2.77259 = 2.77$$

$$f(t) = \exp\ [-\ 2.77\ (\frac{t}{w})^2] \qquad \text{(D-2)}$$

when t = σ, expression (D-1) shows that the amplitude is:

$$f(t) = \exp\ [-\ \frac{1}{2}] = 0.606 = 0.61$$

and from (D-2), let t = σ

$$0.606 = \exp[-\ 2.77\ (\frac{\sigma}{w})^2]$$

$$\ell n\ 0.606 = -0.500 = -2.77\ (\frac{\sigma}{w})^2$$

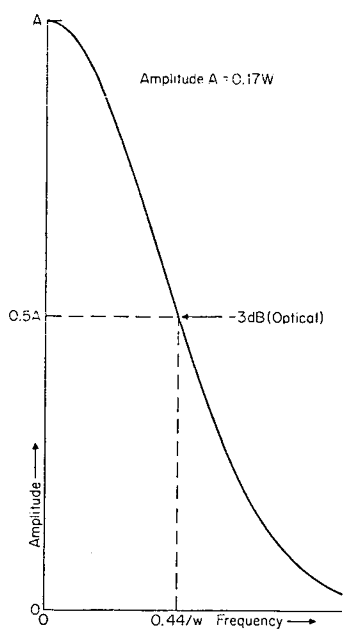
$$\frac{\sigma}{w} = 0.425$$

or

$$\sigma = 0.425\ w$$

The Fourier transform (Hentschel, 1983) of (D-2) is

$$F(f) = 0.17\ w\ \exp[-\ 3.56\ (fw)^2] \qquad \text{(D-3)}$$



This is a frequency transformation of the Gaussian pulse. This transformation is also Gaussian.

Assume that an optical fiber responds to a zero-width pulse in a manner represented by (D-2). This is called the impulse response of the fiber. The Fourier transform (D-3) is the transfer function of the fiber (Hanson, et. al., 1982) and may be taken to be the ratio of output optical power to the input optical power as a function of modulation frequency. The frequency at which F(f) is reduced to 1/2 of its amplitude at zero frequency is called B_f (3dB) (optical). This will occur when

$$0.5A = A \exp - 3.56 [B_f W]^2$$

from which

$$\ell n\ 0.5 = -0.69315 = -3.56 [B_f W]^2$$

or
$$B_f W = 0.441 \quad \cdot \qquad \text{(D-4)}$$

This says that for any fiber with Gaussian impulse response, the product of B_f and W (its FWHM) is a constant. Also, since σ is proportional to W, the product of B_f and σ is

$$B_f \cdot \sigma = 0.441\ (0.425) = 0.187 \quad \cdot \qquad \text{(D-5)}$$

The rise time (RT) or transition time for the response of the fiber from 10% to 90% may be obtained from (D-1).

$$f(t_1) = 0.1 = \exp\left[- \frac{t_1^2}{2s^2} \right]$$

from which

$$\ell n\ 0.1 = -2.303 = - \frac{t_1^2}{2s^2}$$

and

$$t_1 = 2.146\sigma$$

$$f(t_2) = 0.9 = \exp\left[- \frac{t_2^2}{2s^2} \right]$$

from which

$$\ell n\ 0.9 = -0.105 = -\frac{t_2^{\ 2}}{2\sigma^2} \quad .$$

and

$$t_2 = 0.459\sigma \quad .$$

Thus

$$RT = t_1 - t_2 = 1.687\sigma \quad . \tag{D-6}$$

Substituting from (D-5) yields:

$$RT = \frac{0.315}{B_f} \tag{D-7}$$

This relationship is approximated in MIL-STD-188-111 (Appendix A) to relate RT and measured B_f (3dB) with the conventional units published in manufacturers' data sheets as follows:

$$RT\ (ns) = \frac{350\ \ell\ (km)}{B_f(3dB)\ (MHz - km)} \quad . \tag{D-8}$$

This same relation between rise time and B_f is derived in a recent NTIA report (Hull et al., 1983). The relationship derived in the subject report is based on the assumption that the multimode distortion of the fiber produces a rectangularly-shaped pulse and that the receiver responds as a single-pole Resistance-Capacitance (RC) filter.

D.1 References

CCITT (1984), Modifications to test methods in multimode fibre Recommendation G.651 (Paragraph 1.1, Gaussian fitting to the baseband frequency response), AT&T contribution on Question 13 to Study Group XV, February.

Hanson, A. G., L.R. Bloom, A. H. Cherin, G. W. Day, R. L. Gallawa, E. M. Gray C. Kao, F. P. Kapron, B. S. Kawaski, P. Reitz, and M. Young (1982), Optical waveguide communications glossary, NBS Handbook 140; available from the National Technical Information Service, Springfield, VA 22161, Accession No. PB-82166257, January.

Hentschel, C. (1983), Fiber Optics Handbook, Hewlett-Packard GmbH, Boeblingen Instruments Division, Federal Republic of Germany, October.

Hull, J. A., A. G. Hanson, and L. R. Bloom (1983), Alternative transmission media for third-generation interface standards, NTIA Report 83-121, pp. 41-42, May. (Available from the National Technical Information Service, Springfield, VA 22161, Accession No. PB-83-238345.

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14. SUPPLEMENTARY NOTES

15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

An engineering approach to the design of optical fiber communication links to meet mandated specifications for performance and interoperability is described. The report follows and expands upon technical guidance originally developed for MIL-STD-188-111, Subsystem Design and Engineering Standards for Common Long Haul and Tactical Fiber Optics Communications. The engineering approach should be useful in the implementation of other Government and voluntary standards under development.

16. Key Words *(Alphabetical order, separated by semicolons)*
distortion-limited operation; Gaussian response function; isochronous distortion; jitter; MIL-STD-188-111; optical fiber communication system; optical figure of merit; power budget; power-limited operation; rise time

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