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# MILITARY HANDBOOK

DESIGN HANDBOOK  
FOR  
FIBER OPTIC  
COMMUNICATIONS SYSTEMS



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## FOREWORD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense.
2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: HQ, U.S. Army Information Systems Engineering Command: ATTN: ASQB-OST, Fort Huachuca, Arizona 85613-5300, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.
3. Interoperability of DoD telecommunications systems, and of DoD with non-DoD telecommunications systems, has been and will continue to be a major consideration in the development and adoption of standards and handbooks for military use.
  - a. Military standards in the 188 series (MIL-STD-188-XXX) document telecommunications design parameters that are based on empirical data, and must be used in all new or major upgrades of inter- and intra-DoD systems and equipment to ensure interoperability.
  - b. Military standards in the 187 series (MIL-STD-187-XXX) document evolving telecommunications design parameters and concepts that are subject to change and that have not been adequately proven through the use of empirical test data. MIL-STD-187XXX standards should be used as planning standards and guides until parameter, proven and included in approved federal, allied, MIL-STD- I 88-XXX, or DoD adopted commercial standards.
  - c. Military handbooks developed under the TCSS standardization area provide: implementation guidance, tutorial explanation, and examples of systems level engineering design. The military handbooks provide the "how to" information required to accomplish engineering designs in accordance with the applicable standard in the MIL-STD-188 or MIL-STD-187-series.
4. This handbook supports fiber optic communications design and MIL-STD-188-111.

## ACKNOWLEDGEMENTS

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## CHAPTER 1 SCOPE

**1.1 Purpose.** The purpose of this handbook is to provide uniform Department of Defense (DoD) guidelines for communication engineers, and installation, operation, and maintenance personnel working with fiber optic communications systems. This handbook supports MIL-STD-188-111, *Interoperability, and Performance Standards for Fiber Optic Communications Systems*. Emphasis is on the importance of the major technological advancements in telecommunications, as well as networks and systems, rather than on components and hardware. However, the text does deal with the major components of fiber optic systems, including transmitters, receivers, fiber cable, and associated hardware. Further, it provides practical how-to guidance, including generalized real world examples on implementing the requirements in MIL-STD-188-111.

**1.2 Applicability.** MIL-STD-188-111 is the fiber optic standard which sets the minimum essential requirements for interoperability and performance for long-haul and tactical systems. MIL-HDBK-415 is intended to support the MIL-STD-188-111 requirements with the data and techniques to engineer a compliant fiber system.

**1.3 Application guidance.** The guidance contained herein provides those directly involved in the design of fiber optic communications systems (FOCS), including engineers, acquisitions personnel, communications specialists, and managers, with the information necessary to plan and engineer fiber optic communications systems, using state-of-the-art materials and technologies. This handbook is for use by junior to intermediate technical people who are not fiber optic specialists, but do have a sound general technical background. This handbook may be used in the DoD acquisition process in support of MIL-STD-188-111.

**1.4 Suggestions for use.** The main purpose of MIL-HDBK-415 is to explain how, to implement the requirements described in MIL-STD-188-111. It is assumed that the users will range from those having some basic knowledge of communications systems to senior fiber optic systems engineers.

**1.5 References.** The reader should note that definitions of terms and concepts are from *FED-STD-1037, Telecommunications: Glossary of Telecommunications Terms*. Terms not appearing in this glossary are defined in the Electronic Industries Association (EIA) Standard 440-A, *Fiber Optic Terminology*. An abbreviation and acronym list is provided in chapter 3.

**1.6 Classification.** No classified material is contained in this handbook.

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**CHAPTER 2  
APPLICABLE DOCUMENTS**

**2.1 Government documents.**

**2.1.1 Specifications, standards, and handbooks.** The following specifications, standards, and handbooks form a part of this document of the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS) and supplement thereto, cited in the solicitation.

SPECIFICATIONS

MILITARY

JTC3A 9109	Technical Inter-face Specification: Joint Interoperability via Fiber Optic Cable
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STANDARDS

FEDERAL

FED-STD-1037	Telecommunications: Glossary of Telecommunications Terms
--------------	----------------------------------------------------------

MILITARY

MIL-STD-188-100	Common Long-haul and Tactical Standards (with notices 1 through 3)
MIL-STD-188-111	Interoperability and Performance Standards for Fiber Optic Communications Systems
MIL-STD-188-114	Electrical Characteristics of Digital Interface Circuits
MIL-STD-188-124	Grounding, Bonding, and Shielding
MIL-STD-188-125	High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C <sup>4</sup> I Facilities Performing Time-Urgent Missions

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MIL-STD- 1 88-141	Interoperability and Performance Standards for Medium and High Frequency Radio
MIL-STD- 1 88-200	System Design and Engineering Standards for Tactical Communications
MIL-STD-188-300	System Design and Engineering Standards for Long-Haul Communications
MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics
MIL-STD-882	System Safety Program Requirements
MIL-STD- 1425	Safety Design Requirements for Military Lasers and Associated Support Equipment

### HANDBOOK

MIL-HDBK-232	Red/Black Engineering-Installation Guidelines
MIL-HDBK-411	Power and the Environment for Sensitive DoD Electronic Equipment
MIL-HDBK-419	Grounding, Bonding, and Shielding, for Electronic Equipments and Facilities

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Naval Publications and Forms Center (ATTN: NPODS), 5801 Tabor Avenue, Philadelphia, PA 19120-50990).

To obtain a customer ID: (215) 697-2179, DSN 442-2179

To place an order: (215) 697-1187, DSN 442-1187

**2.1.2 Other Government documents, drawings, and publications.** The following other Government documents, drawings, and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues are those cited in the solicitation.

FEDERAL

National Telecommunications and Information Administration (NTIA) Reports.

- |             |                                                                                                                                                                                                                                                  |
|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| No. 87-21.6 | National Communications System (NCS) Technical Information Bulletin (TIB) 24, Multitier Specification for National Security Emergency Preparedness (NSEP) Enhancement of Fiber Optic Long Distance Telecommunications Networks (Volumes 1 and 2) |
| No. 87-227  | NCS TIB 87-26, NSEP Fiber Optics System Study Background Report. Nuclear Effects on Fiber Optic Transmission Systems                                                                                                                             |
| No. 88-231  | NCS TIB 88-02, Multitier Specification Applied to Modify the Hardness of an Essential NSEP Fiber Optic Link                                                                                                                                      |

MILITARY

- |                        |                                                        |
|------------------------|--------------------------------------------------------|
| DOD Instruction 6050.6 | Exemption for Military, Laser Products                 |
| DOD Directive 5000.1   | Defense Acquisition                                    |
| DOD Directive 5000.2   | Defense Acquisition Management Policies and Procedures |

MANUALS

- |                                                                    |                                                                    |
|--------------------------------------------------------------------|--------------------------------------------------------------------|
| T.O. 31W3-10-12<br>FM 11-372-2                                     | Outside Plant Cable Placement                                      |
| T.O. 31-10-34<br>FM-11-487-5<br>EE169-CA-GYD-010/<br>EI IOTSER E&I | Standard Installation Practices, Fiber Optic Cables and Connectors |

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**2.2 Non-Government publications.** The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are the issues of the documents cited in the solicitation.

### AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI T1.101-1987	Synchronization Interface Standards for Digital Networks
ANSI T1.105-1991	Communications Hierarchy-Optical Interface Rates and Format Specifications (SONET) (FDDI and STS Path Signal Level)
ANSI T1.106-1988	Telecommunication-Digital Hierarchy-Optical Interface Specification (Single-Mode)
ANSI Z136.1-1986	Safe Use of Lasers
ANSI Z136.2-1988	Safe Use of Optical Fiber Communication Systems Using Laser Diode and LED Sources.
EIA 455-50	Light Launch Conditions for Long-Length Graded-Index Optical Fiber Spectral Attenuation Measurements
EIA 455-78	Spectral-Attenuation Cutback Measurement for Single-Mode Optical Fibers
TIA 440-A	Fiber Optic Terminology
TIA 559	Single-Mode Fiber Optic System Transmission Design
TIA 568	Commercial Building Telecommunications Wiring Standard
TIA 590	Standard for Physical Location and Protection of Below Ground Fiber Optic Cable Plant
National Electric Code	National Fire Protection Association Handbook

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(Application for copies should be addressed to the American National Standards Institute, 1430 Broadway, New York, NY 10018-3308.)

**2.3 Order of precedence.** In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a s specific exemption has been obtained.

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### CHAPTER 3 DEFINITIONS

**3.1 Terms.** Definitions of terms used in this handbook shall be as specified in the current edition of FED-STD-1037. In addition, the following definitions are applicable for the purpose of this handbook.

dopant	Material added to optical fibers during manufacture to change optical or mechanical characteristics.
innerduct	Protective tubing, usually made of polyethylene or polyvinyl chloride, installed within regular duct work to provide physical separation of cables.
maximum tensile rating	The maximum pulling tension, usually stated by the manufacturer, which can be applied to a fiber optic (FO) cable without causing damage.
minimum bending radius	The smallest radius to which an FO cable can be bent without causing performance degradation.

**3.2 Abbreviations and acronyms.** The abbreviations and acronyms used in this handbook are defined below. Those listed in the current edition of FED-STD-1037 have been included for the convenience of the reader.

$\alpha$	attenuation coefficient
AEL	accessible emission limit
AM	amplitude modulation
ANII	alternate mark inversion
ANSI	American National Standards Institute
APD	avalanche photodiodes
ASTM	American Society for Testing and Materials
AT&T	American Telephone and Telegraph
ATM	asynchronous transfer mode
B	bandwidth
B-ISDN	Broadband ISDN
BER	bit error ratio
BERT	bit error ratio tester
C <sup>3</sup> I	Command, Control, Communications, and Intelligence
CCITT	International Telegraph and Telephone Consultative Committee
CCTV	closed circuit television

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CPU	central processing unit
dB	decibel
dBm	decibels referenced to one milliwatt
DoD	Department of Defense
DFB	distributed feedback
DID	direct inward dial
DO	design objective
DOD	direct outward dial
DODISS	Department of Defense Index of Specifications and Standards
DS	digital signaling
DS-N	digital tributaries
E/O	electrical-to-optical
EAS	extended area service
EDFA	erbium doped fiber amplifiers
EIA	Electronic Industries Association
ELED	edge-emitting LED
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMP	electromagnetic pulse
EMS	equilibrium mode simulator
FDDI	Fiber Distributed Data Interface
FED-STD	Federal Standard
FET	field-effect-transistor
FITL	fiber in the loop
FM	frequency modulation
FO	fiber optic
FOCS	fiber optic communications systems
FOT	fiber optic terminal
FSG-60	Federal Stock Group 60
FRIA	frequency and time interval analyzer
FTS	Federal Telephone System
FW-HM	full width-half maximum
Ga	gallium
Gbps	gigabits per second
GBS	grounding, bonding, and shielding
Ge	germanium
GHz	gigahertz
GI	graded index
Hz	hertz
HEMP	High-Altitude Electromagnetic Pulse
IEC	International Electrotechnical Commission

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IEEE	Institute for Electrical and Electronics Engineers
IM	intensity modulation
IM/DD	intensity modulation/direct detection
In	indium
InGaAs	indium gallium arsenide
InGaAsP	indium gallium arsenide phosphorous
ISDN	Integrated Services Digital Network
ISI	intersymbol interference
ISO	International Standards Organization
kbps	kilobits per second
km	kilometer
LAN	local area network
LD	laser diode
LED	light-emitting diode
μm	micrometer, micron
mA	milliamper
mm	millimeter
mW	milliwatt
Mbps	megabits per second
MHz	megahertz
MIL-HDBK	Military handbook
MIL-STD	Military standard
MLM	multilongitudinal mode
MPI	maximum permissible irradiation
nm	manometer
NA	numerical aperture
NCS	National Communications System
NEC	National Electric Code
NRZ	nonreturn to zero
NSA	National Security Agency
NSEP	National Security Emergency Preparedness
NTIA	National Telecommunications and Information Administration
OC-N	SONET optical carrier digital rates
OCON-US	Outside the Continental United States
OH-	hydroxyl ions
OSHA	Occupational Safety and Health Administration
OTDR	optical time domain reflectometer
P	phosphorus
pn	positive-to-negative
ps/nm-km	picoseconds/nanometer-kilometer
PC	personal computer

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PDM	pulse-duration modulation
PE	polyethylene
PIN	positive intrinsic negative
PPM	pulse-position modulation
PRBS	pseudo-random bit sequence
rf	radio-frequency
rms	root-mean-square
rss	root-sum-square
RAM	reliability, availability, and maintenance
RC	resistive capacitive
REA	Rural Electrification Administration
RON1	read-only memory
RZ	return-to-zero
SEFS	severely errored frame second
SG	service group
Si	silicon
SLD	superluminescent diode
SLED	surface-emitting LED
SLM	single-longitudinal mode
SM	single mode
SNR	signal-to-noise ratio
SONET	Synchronous Optical Network
STS-N	synchronous transport signal
$\tau_{cl}$	carrier lifetime
T	time interval
Tr	rise time
TBOS	telemetry byte-oriented signal
TIA	Telecommunications Industries Association
TIB	Technical Information Bulletin
VT	virtual tributary
WAN	wide area network
WDM	wavelength division multiplexing

CHAPTER 4  
FIBER OPTIC SYSTEMS OVERVIEW

**4.1 Basic components.** FOCS requires at least three basic components: an optical transmitter, a transmission medium, and a detector or optical receiver (see figure 4-1). Optical transmitters convert electrical signals to optical signals for input to a transmission medium. An optical fiber is used as the transmission medium for these systems. At the distant end, optical receivers convert the signals back to the electrical domain.

**4.2 Basic types.** The basic types of DoD FOCSs are long-haul, tactical, fixed base, and area network.

**4.2.1 Long-haul FOCS.** Long-haul systems normally provide connectivity among many users on a worldwide basis. They typically are high data rate, wide bandwidth single-mode FO networks, with a long service life. These networks are often common user systems, offering a variety of constantly expanding data, video, and voice services. Long-haul systems usually include switching capabilities to provide routing and end-to-end connectivity of subscribers and employ multiplexing techniques to use available capacity more efficiently. New types of services, such as video conferencing, computer interchange, and remote data are adding, to the demand for increased speed and bandwidth.

**4.2.2 Tactical FOCS.** These systems cover relatively short distances, are usually temporary, and are found more often in battlefield and emergency situations. Tactical FOCS must meet stringent requirements for field survivability, ease of deployment, and quick recovery. The low-loss characteristics of optical fiber, minimizing the need for repeaters, make it very attractive for use in tactical systems. The light weight of optical fiber is also very important as it facilitates cable laying, and reduces transport requirements. Tactical systems frequently must be able to interface and interoperate with long-haul systems.

**4.2.3 Fixed base FOCS.** Fixed base communications systems are permanent, backbone arrangements of communications equipment that can accommodate trunking and local distribution of voice, data, and video services. These systems also provide connectivity for area networks, closed circuit television (CCTV) systems, radar remoting, and other special services. In some locations, facilities are available for the termination of tactical networks. User requirements are subject to frequent revision due to changes of base or post missions, personnel, and units.

**4.2.4 Area networks.** The service area of a network is defined by the breadth of territory that an autonomous network can directly support communications among its members. Network members may include, but are not limited to, users, devices, resource servers,

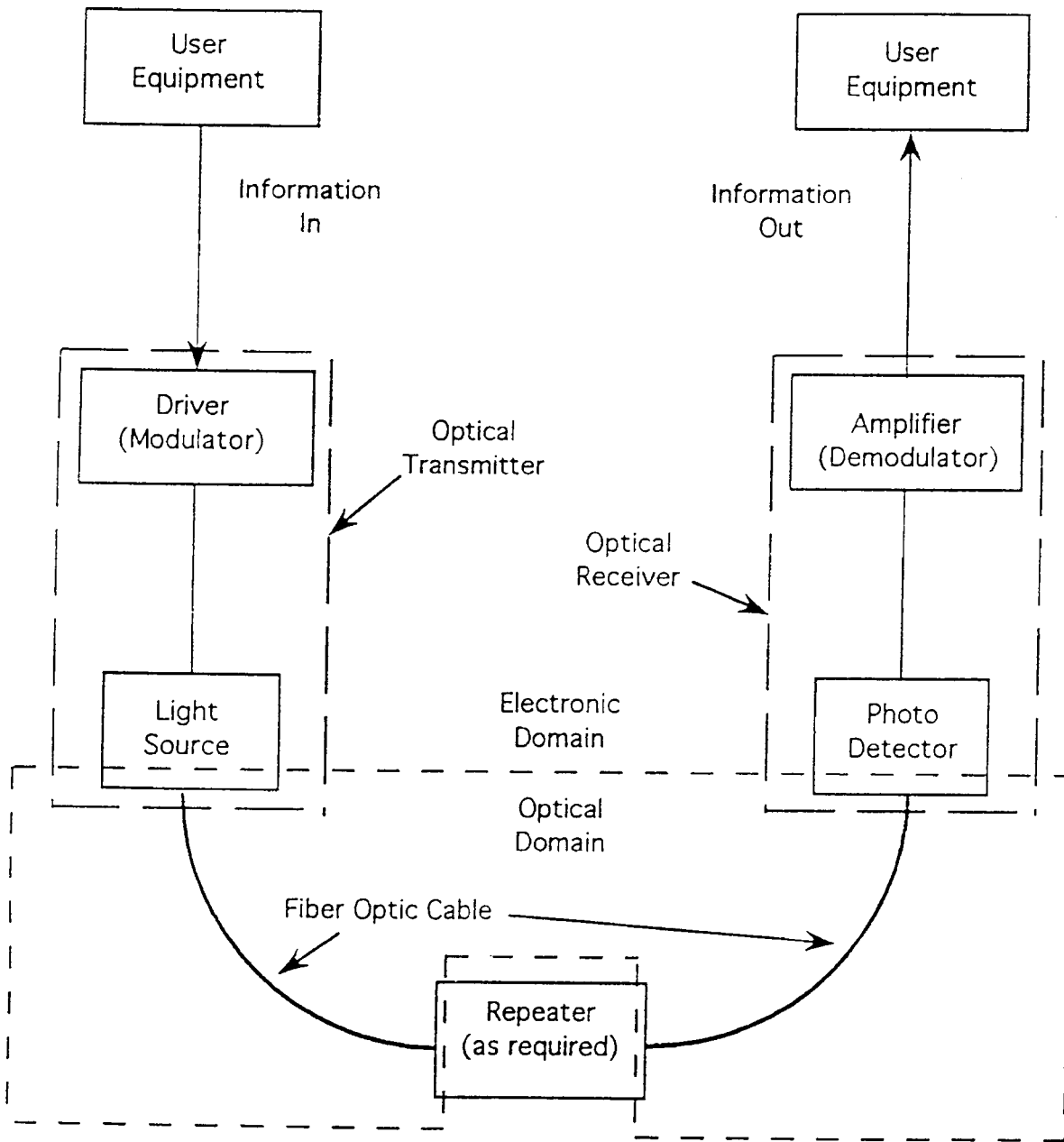


FIGURE 4-1. Simplified fiber optic communications systems.

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traffic switches, routers, as well as other networks. With some networks, the members can be permanently or dynamically associated with the network. It can be difficult to agree on the name of an area network if some of its members have this fluidity of association. In general, the difference between a local area network (LAN) and a wide area network (WAN) is primarily the area of coverage.

**4.3 Special purpose FO systems.** FO links or networks also provide services other than normal voice, data, and video communications. These other services include radar remoting imagery transfer, communications and physical security, environmental sensing, and surveillance data. Special purpose FO systems may also inter-face with communications systems to perform control, monitoring, or signaling functions. Optical fiber also has new applications in sensor equipment, especially for environmental control and monitoring. This handbook provides general guidance within the purpose of MIL-STD-188-111.

### 4.4 Physical properties of optical fiber.

**4.4.1 Optical fiber versus copper cable.** The smaller size and lighter weight of FO cables (compared to copper cables) make them attractive for installation in existing conduit and duct work, especially in congested locales. In some instances, existing metallic networks are being removed, and the services they provide are being integrated into FO networks to save conduit space and the cost of new construction. Smaller attenuation losses in the newer fibers have increased repeater spacing, lowering the costs of initial installation.

**4.4.2 Susceptibility to damage.** Optical fibers are susceptible to physical damage, especially during installation and retrofit operations. Also optical fiber is susceptible to bacterial growth from water contamination. Water corrosion, especially from exposure to basic (alkaline) solutions, causes increased attenuation of the optical signal, and accelerates the aging of the fiber, causing premature loss of strength. These susceptibilities require close attention to proper sheath selection, proper construction methods, and use of encapsulants. Optical fibers are susceptible to damage from radiation (see 4.6).

**4.5 Bandwidth of optical fiber.** A primary reason for adopting fiber as a communications medium is the bandwidth or information-carrying capacity of the fiber. The parameter defining a fiber's ability to preserve bandwidth over distance is known as bandwidth-distance factor. The units of megahertz (MHz)-kilometer (km) are commonly used for this parameter. This performance parameter is dependent on the spectral width of the source. Fiber measured with a laser diode (LD) source will give a higher bandwidth-distance factor than when measuring with a light-emitting diode (LED) source.

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**4.5.1 Multimode fiber.** Typical multimode fibers have a bandwidth-distance factor in excess of 200 MHz-km when an LED, operating in the 1300 nanometer (nm) window, is used as an optical source. A higher bandwidth-distance factor is possible when a laser source is used or if single-mode fiber is used. Higher bandwidths are possible with optimal source selection or through the use of single-mode fiber.

**4.5.2 Single-mode fiber.** Typical single-mode bandwidth-distance factors are in excess of 20 gigahertz (GHz)-km with proper source selection. Several services (voice, data, and video) can be integrated into single digital bit streams for efficient transmission. The wide bandwidth capability of optical fiber reduces the costs of installing multiple cable runs to meet traffic requirements and justifies adding spare fibers in the initial system installation (see appendix A for more information on FO bandwidth).

**4.6 Electromagnetic Interference (EMI)/Electromagnetic Compatibility (EMC) and Electromagnetic Pulse (EMP)[HEMP/radiation exposure concerns of optical fiber.** As a dielectric material, optical fiber is naturally resistant to the EMI/EMC problems of metallic cable. The need is reduced for isolation shielding and special grounding. Also, the non-inductive character of optical fiber adds an element of safety to communications networks. However, associated electronics still need protection. EMI characteristics of electronic systems associated with fiber optic links should be investigated. EMC control requirements are provided in MIL-STD-461. Test methods and measurements taken to determine EMI characteristics are provided in MIL-STD-462.

Whenever electrically conductive cable parts could be exposed to lightning strikes or the EMP/HEMP produced by a nuclear event, precautions need to be taken to isolate electronic devices from damage. Some FO cables have metallic strength members or protective sheaths and coverings which provide paths for induced currents and voltages. These currents and voltages could damage and even destroy FO cable that contains metallic members, and must be isolated from sensitive equipment (see chapter 16 on grounding, bonding, and shielding (GBS)). While FO cables are sometimes lashed to aerial electrical power lines for support, such practice is not recommended. In certain submarine networks, however, metallic conductors may have to be added to FO cables to provide for functions such as remote power distribution to repeaters.

The relative immunity of optical fiber to EMI/EMC problems is exploited to great advantage in the confined space of airborne and shipboard applications. Ground loops and induced interference are non-existent.

Conventional optical fiber is susceptible to degradation from exposure to radiation (see chapter 16). Fibers hardened against nuclear radiation do not have phosphorous dopant which increases susceptibility to damage. The amount of degradation in the form of increased attenuation

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depends principally on the type of cable fabrication and construction, adherence to recommended shielding practices, and the amount of radiation exposure. Radiation-hardened cable is used in systems which must meet certain survivability hardness criteria or is buried in a naturally radioactive soil environment.

**4.7 Transmission medium.** Transmission media are selected based mainly upon the types and estimated volumes of user traffic, location of nodes, total bandwidth requirements, and costs. Advances in fiber technologies and reduction in costs during the past decade have made FO cable the transmission medium of choice for most communications applications.

The telephone industry is extending its use of optical fiber down the system hierarchy from trunking, through feeder lines, to the subscriber loops. Limited subscriber services, currently being provided, cannot justify the costs of the retrofit installation of optical fiber, but future demands for wideband service will provide this justification (see table 4-1 for transmission media characteristics).

**TABLE 4-1. Characteristics of various transmission media.**

Aspect	FO Cable	Paired Cable	Coaxial Cable	Microwave Radio	Millimeter Radio
Install Costs	Moderate	Moderate	Moderate-High	Moderate-High	Low-Moderate
Lifecycle Costs	Moderate	Low	Low	Moderate	High
Bandwidth	Very High	Low	Moderate	High	High
Data Rate	Very High	Low	Moderate	High	High
RAM*	Good	Fair to Good	Good	Poor	Poor
EMI Immunity	Excellent	Good	Good	Poor	Poor
EMP Immunity	Good	None	None	None	None
Environ. Concerns	Water degradation	Water degradation	Water degradation	Atmos & rain attenuation	High atmos & rain atten.
Special Concerns	Right-of-way	Right-of-way	Right-of-way	Freq. Avail Terrain limitations	Freq. Avail Terrain limitations

\* Reliability, availability, and maintainability.

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**4.8 FO system components.** Components include transmitters, receivers, repeaters, regenerators, cables, fiber distribution panels, connectors, and couplers. Components used in FOCS are designed to exploit the wide bandwidth potential of optical fiber (see chapters 6 and 7).

**4.9 FO cable.** Single-mode (both 1300 and 1550 nm) FO cable is normally installed in long-haul systems because it has lower attenuation, lower cost, and lower dispersion (see A.3.3) and provides greater bandwidth than multimode fiber, hence permitting longer distances between repeaters. The relative freedom of optical fiber cable (which does not contain metallic strength members) from EMI problems allows it to be installed adjacent to other cables, even those carrying electrical power. Tactical FO cable sections are typically 1 km long, have two or four fibers and a strength member enclosed in a buffer, all surrounded with an outer jacket for protection against abrasion and impact damage. These cables are fitted with standard connectors for quick installation and tear-down. Minimum interoperability and performance standards for FOCS are specified in MIL-STD-188-111.

**4.10 FO connectors and splices.** As technology improves, splice losses approaching 0.5 decibel (dB) are easily attainable with mechanical splices, and 0.1 dB with fusion splicing. With connectors, state-of-the-art losses are typically 0.5 dB or less (see 7.1). Repeated opening and closing of connectors increases the probability that foreign substances will be introduced into the connection, thus increasing loss.

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## CHAPTER 5 OPTICAL FIBERS AND FIBER OPTIC CABLES

**5.1 Types, parameters, and composition.** Optical fibers typically are classified by the following criteria: (1) modes of propagation, (2) refractive index profile, (3) material composition, and (4) fiber size. The most common types of fiber are multimode step-index fiber, multimode graded-index fiber, and single-mode fiber. The various optical fiber characteristics are contrasted in table 5-1.

### 5.2 Optical fibers.

**5.2.1 Multimode fibers.** The relatively large core diameter of multimode fibers allows several modes of light to propagate, producing multimode distortion (see appendix A). Core sizes of common glass communications multimode fibers are 50 and 62.5 microns ( $\mu\text{m}$ ). MIL-STD-188-111 states that multimode fibers used in tactical applications shall have a nominal core diameter of 50  $\mu\text{m}$  and a nominal cladding outside diameter of 125  $\mu\text{m}$ . MILSTD-188-111 does not give multimode fiber size requirements for LANs. The common commercial size is 62.5/125  $\mu\text{m}$ . An example of an industry standard which addresses the use of 62.5/125  $\mu\text{m}$  optical fiber cable in commercial buildings is EIA/TIA Standard 568.

**TABLE 5-1. Fiber comparison chart.**

Fiber Type	Multimode		Single-Mode
	62.5/125 $\mu\text{m}$	50/125 $\mu\text{m}$	
Attenuation	Low	Lower	Lowest
Bandwidth	High	Higher	Very High
Fiber Core	62.5 $\mu\text{m}$	50 $\mu\text{m}$	8-10 $\mu\text{m}$
Fiber Cladding	125 $\mu\text{m}$	125 $\mu\text{m}$	125 $\mu\text{m}$
Wavelengths	850, 1300 nm	850, 1300 nm	1300, 1550 nm

NOTE: Occasionally the DoD may have to interface with commercial 62.5/125  $\mu\text{m}$  cable.

**5.2.1.1 Multimode step-index fiber.** Conceptually, the simplest fiber is the step-index fiber, with a core of high refractive index and concentric lower index cladding, with sharp interface between the two, illustrated on figure 5-1. Step-index fiber produces higher multimode distortion than does graded-index fiber (see appendix A).

INPUT PULSE

OUTPUT PULSE

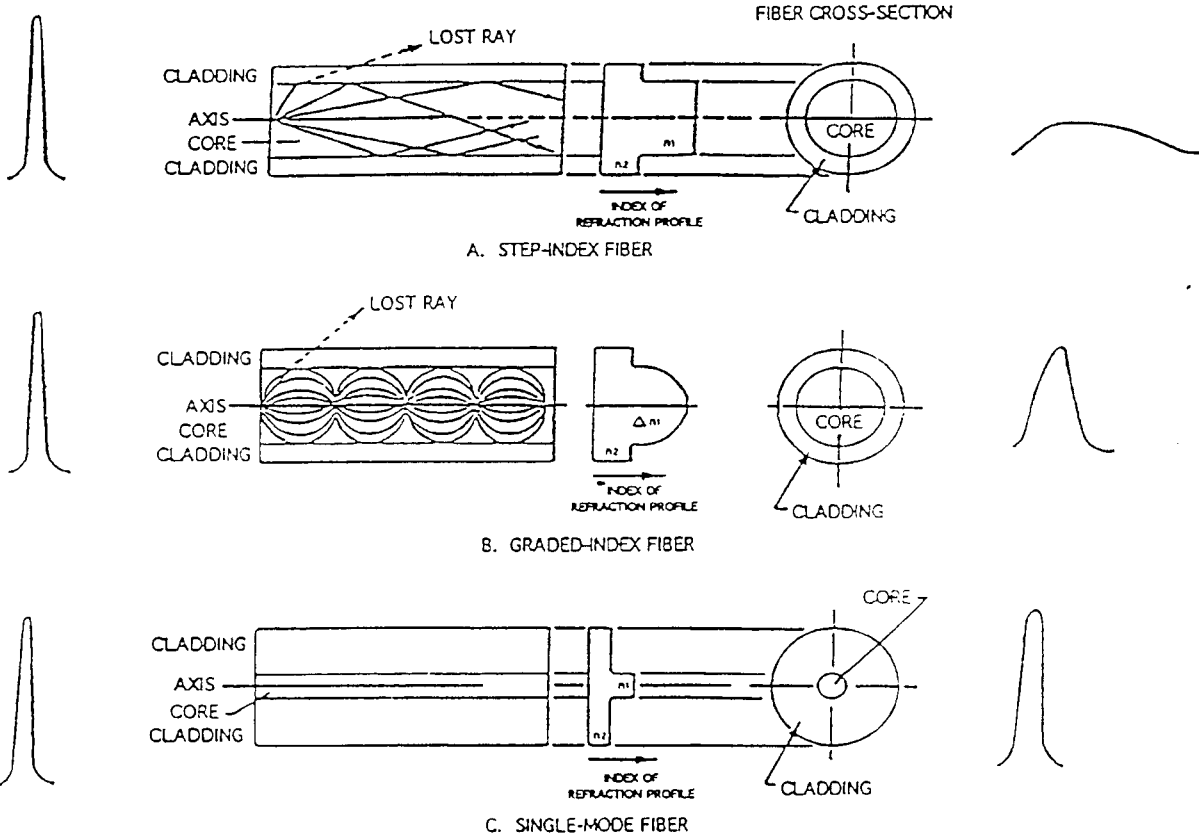


FIGURE 5-1. Fiber index profiles.

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**5.2.1.2 Multimode graded-index fiber.** In a graded-index fiber, the refractive index decreases selectively with the radial distance from the center of the core, giving the fiber a nearly parabolic refractive index profile (figure 5-1). This results in equal propagation times for different modes. High angle rays, directed away from the core, travel more quickly through material of lower refractive index. Because graded-index fiber exhibits less multimode distortion than step-index fiber, the former allows for greater transmission distances and higher data rates.

**5.2.1.3 Comparison of multimode fibers.** Attenuation of the two multimode fiber types is comparable, but a greater bandwidth-distance factor gives graded-index fiber preference for higher data rate use. Step-index fibers generally have a larger numerical aperture than graded-index fibers. Graded-index fiber is the multimode fiber of choice; step-index fiber is almost obsolete for communications purposes. Graded-index fiber is commonly used for all but long-haul communications with high data rate applications, which require single-mode fiber. Increasingly, short-haul, high bandwidth applications may require use of single-mode fiber.

**5.2.2 Single-mode fiber.** MIL-STD-188-111 states that single-mode fibers used in long-haul applications shall have a nominal cladding diameter of 125  $\mu\text{m}$  and that the size of the core is not standardized. The core diameter of a single-mode fiber is significantly smaller than that used in multimode fiber cable. It is typically between 8 and 10  $\mu\text{m}$  and designed to propagate only one optical mode. This eliminates the multimode distortion (see A.2.3 and A.3.2) which restricts the distance-bandwidth product of multimode cable. Chromatic dispersion, however, does affect single-mode fibers, because different wavelengths take different time periods to traverse a fixed-length fiber. Optical transmitters of narrow spectral width reduce this effect. Also, because the fiber is intended to propagate a single-mode, other modes must be prevented from forming within the cable. This is accomplished by choosing the optical wavelength of the transmitter to be a little shorter than a critical value. This critical value is called the "cut-off wavelength". Wavelengths longer than this value are greatly attenuated by the fiber cable. Wavelengths shorter than this value excite increasingly more modes as they increase their distance from it. Within the operational wavelengths of these cables, several kinds are commercially available. These are:

- a. Dispersion unshifted. This fiber has a simple step refraction profile, resulting in no altering of its inherent dispersion, exhibiting zero dispersion near 1300 nm (see A.3.3).
- b. Dispersion shifted. The fiber core/cladding refraction profile has a structure that changes the zero dispersion wavelength from 1300 nm to the lower attenuation region of 1550 nm.

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c. Dispersion flattened. The fiber core/cladding refraction profile has been structured to provide low dispersion over a wide range of wavelengths.

d. Specialty fiber (e.g., polarization preserving). Fiber can be made to preserve polarization of the light signal. Others include fiber which has been doped with substances which provide extremely low attenuation, resistance to radiation (hardened fiber), or provide optical amplification.

**5.2.3 Comparison of single-mode and multimode fibers.** Very wide bandwidths, enabling large data rate capabilities, make single-mode fibers best for long distance or high data rate applications. Single-mode fibers are much more sensitive to connector lateral misalignment than multimode fibers, but are becoming the "fiber of choice" for most applications due to their much higher bandwidth, compared to multimode fiber. Single-mode fiber losses are lower than those for multimode fibers, with typical loss values of 0.5 dB/km at 1310 nm and 0.35 dB/km at 1550 nm. Attenuation characteristics and operating wavelengths for graded index (GI) fiber are compared with single-mode fiber as shown on figure 5-2.

**5.3 FO cable installation.** Cable applications can be aerial, direct buried, underground/ducted, underwater (submarine), or building (indoor wiring). Each of these applications will dictate variations in the cable construction to meet the specific use requirement. Details of cable routing and installation should be well planned from route and site survey information.

**5.3.1 Aerial.** Cable intended for aerial installation must have high tensile strength to withstand the stresses due to the weight of the cable, wind, and ice loading. FO aerial cables either have an internal messenger cable or are lashed to a messenger cable. To keep out the elements (primarily moisture), aerial cables contain a filling compound both in the interstices between buffered fibers, and within the loose buffer tubes themselves.

Horizontal and vertical clearances are an important factor in designing an aerial cable route. The National Electric Safety Code and regional construction practices have specific standards for aerial installations in the United States. Similar regulations exist in other countries and should be consulted before planning an aerial cable network.

**5.3.2 Direct buried.** While the direct burial method of installation is more commonly used than aerial, maintenance activities are more difficult. For protection against rodents, rocky terrain, shifting ground, and the stress of installation, direct burial cable sometimes is wrapped with a metallic steel tape or fabricated with steel reinforcement wires installed in a spiral configuration. A polyethylene jacket is applied over this armor. Gel-filled buffer tubes and filling compound within the cable interstices protect against the entry and migration of moisture.

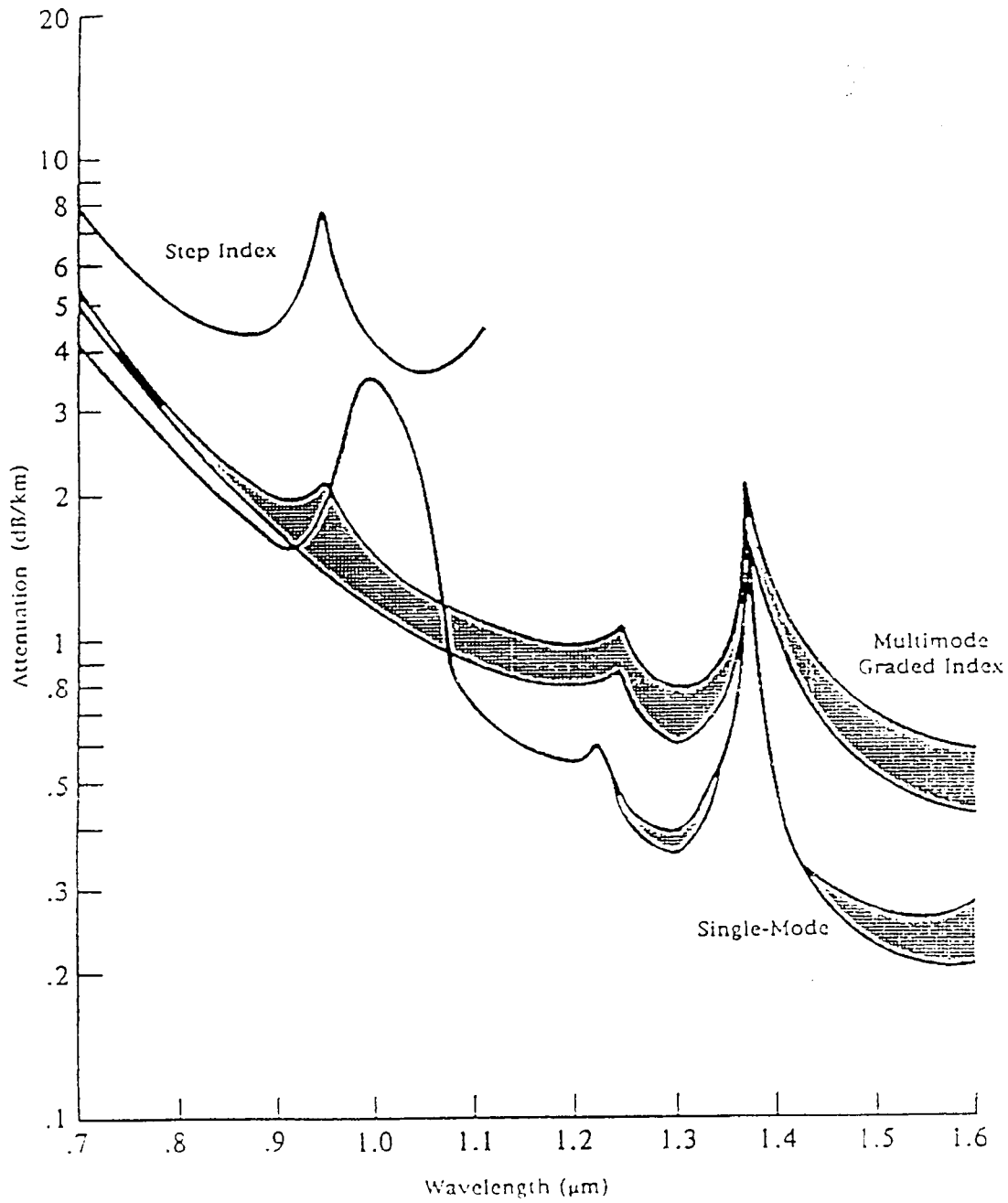


FIGURE 5-2. Wavelength versus fiber attenuation.

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Direct buried cable is often plowed-in, where combination trench digging and cable laying equipment operate to place the cable in the ground through a cable chute positioned directly behind the trench digger. Pre-ripping the route is common practice to ensure the route is free of obstacles which would prevent the cable from being installed at the planned depth.

Buried FO cable is installed in accordance with established and recommended standards created for its protection (see 5.5). In locations where unique terrain features exist, such as extremely rocky soil, cable is placed in trenches which are prepared and routed according to standards for terrain type, soil, area congestion, and the presence of other utilities, as well as special user requirements. Direct buried cable is sometimes placed in duct work in locations such as under roads and across bridges and culverts. At splicing points, a 10-15 meter loop is usually retained to provide flexibility for possible future maintenance and repair activities. Because buried nonmetallic FO cable cannot be located by ordinary means, a metallic foil ribbon is sometimes buried above the cable to mark its location. To protect buried cable from future digging activities, underground warning tapes are buried above the cable. Route marking stakes may also be used. The locations of splicing pits should also be marked (see 5.5).

**5.3.3 Conduit.** Underground cable may also be placed in conduits. Underground Conduit is available in single- and multiple-bore configurations. Typical diameter sizes of conduit ducts range from 2 to 6 inches, with 4 inches being the most common. The type of conduit chosen for an installation depends upon the soil and terrain conditions, amount of trench backfill required, and the need for concrete encasement. Access holes along the conduit route may also be required. Installation standards also exist for FO cable buried in conduit (see 5.5).

The small diameter of FO cable is a distinct advantage in crowded ducts. FO cables are pulled through ducts using the same techniques and equipment as for metallic cable. Strength members absorb the tensile load of pulling. To facilitate installation in crowded ducts, an innerduct technique is commonly used. A pre-lubricated polyethylene-jacketed aluminum or plastic tube is pulled into the duct. The FO cable is then pulled through this innerduct. Standard duct lubricant has no deleterious effect on the cable. The amount of lubrication is determined on a case-by-case basis. It is common to use three to four innerducts in a four-inch conduit.

**5.3.4 Underwater cable.** The most important requirement for underwater cable is reliability over the designed lifetime of the cable. Mineral and bacterial growth from water can change the composition of glass, thereby affecting reliability. Underwater cables are usually double-armored and contain filling compound in all cable interstices. Metallic strength members are protected from corrosion with an anti-flooding, compound.

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**5.3.5 Building cable.** Inside plant FO cables are installed within structures for distribution of terminated long-haul services and provision of local interconnections. These building cables are installed in cableways and risers designed for their routing, or in convenient locations such as in walls, above-ceiling and under-floor spaces, and utility spaces (typically air handling). Building cables installed within the United States must meet the fire resistance and low-smoke regulations of the National Electric Code. For outside the Continental United States (OCONUS), the host country codes must be considered. Specific regulations apply to the type of installation for which the cable was designed, such as in risers or plenums.

Building cables normally are not fabricated to meet the robust requirements of outside plant cables. They are commonly provided with strength members and protective jackets, but normally do not contain metallic elements. They may contain single or multimode fibers. The arrangement of individual fibers in building cables is usually a concentric or ribbon style.

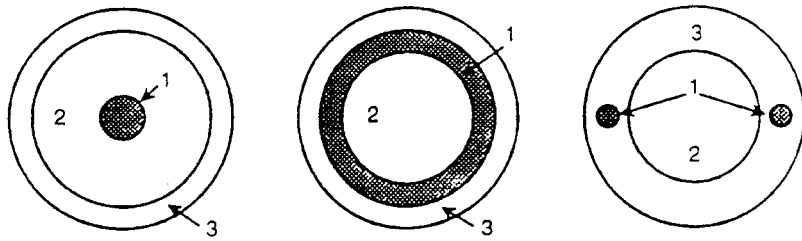
Concentric-type cables come in a variety of patterns, with fibers arranged individually or in bundles. Numbers of fibers range from one to as many as 144.

In ribbon cables, up to 12 fibers are arranged in flat, parallel groups. Greater capacity is achieved by stacking the groups in layers. Ribbon cable with 144 fibers (12 layers) is available commercially.

**5.4 Cable composition.** Representative cable types are shown on figures 5-3 through 5-9. FO cables, like conventional cables, are fabricated to meet the characteristic requirements of aerial, duct, direct buried, and building installations. Military tactical cable is made to withstand the rigors of cross-country deployment and recovery. Delicate optical fibers are insulated with a sheath for protection (buffer) against mechanical and environmental abuse during installation and operation. Unlike metallic conductor cables, optical fibers do not contribute to the strength of a cable. In fact, the fiber itself must be decoupled from tensile, thermal, and vibrational loads. Strengthened FO cables are used in all outdoor and most indoor applications. (Non-strengthened cables are used as links in controlled environments, such as within a rack.) Fibers are cabled with many of the same materials used to cable metallic wire, but employ different fabrication techniques. the following describes typical components of FO cable:

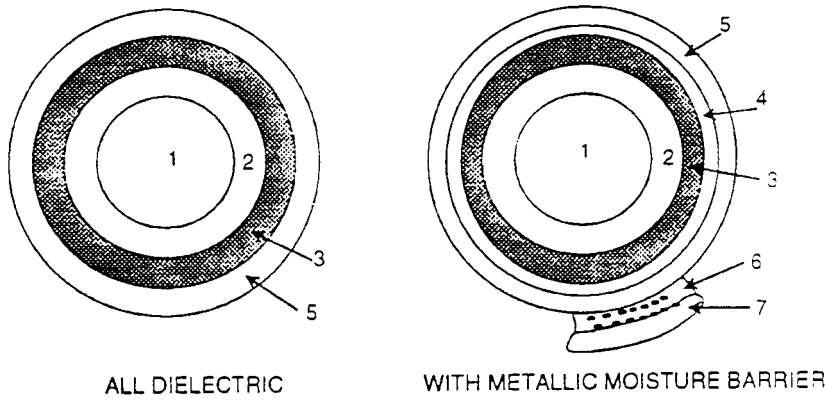
- a. Coated optical fiber, with plastic or silicon elastomer coating (tight buffering) to protect the fiber from abrasion, macrobending, and microbending.

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- 1. STRENGTH MEMBER
- 2. CABLE CORE
- 3. SHEATH

Strength members in an optical cable.



- 1. CABLE CORE
- 2. INTERNAL PLASTIC SHEATH
- 3. STRENGTH MEMBER
- 4. METALLIC MOISTURE BARRIER
- 5. PLASTIC SHEATH
- 6. METALLIC ARMOR
- 7. PLASTIC SHEATH

FIGURE 5-3. Cable strength members and shields.

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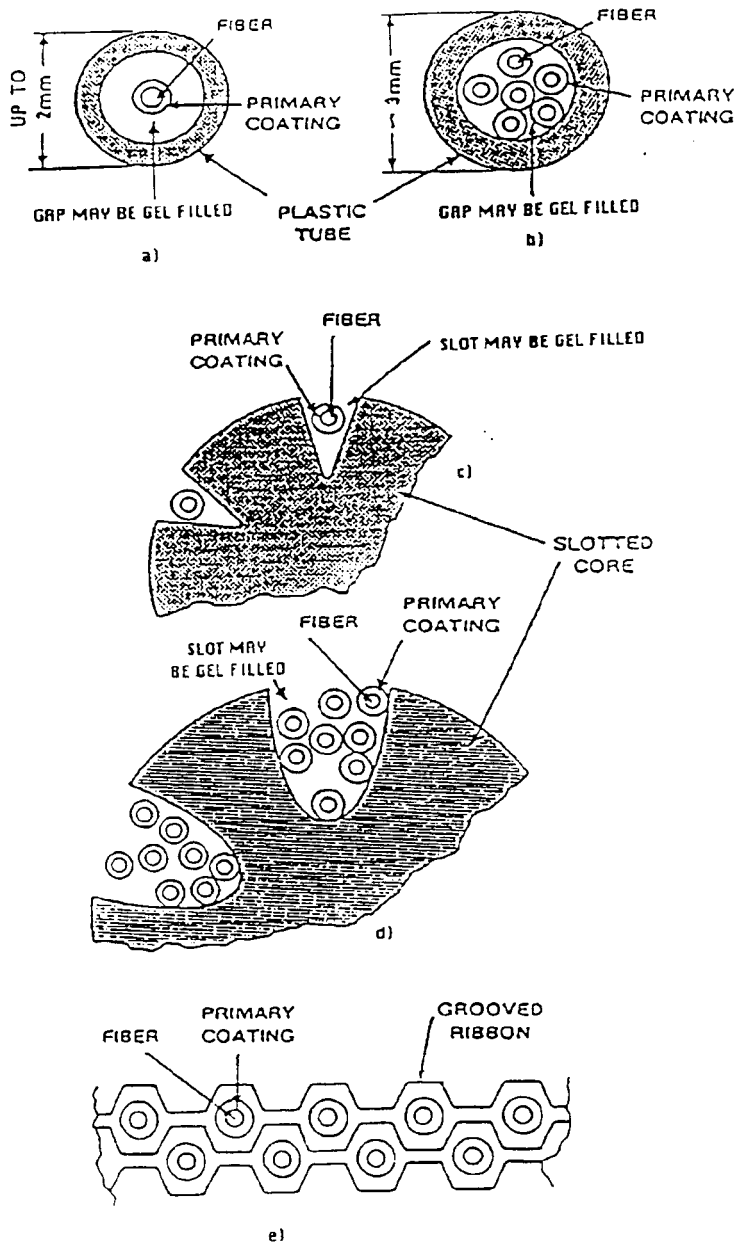
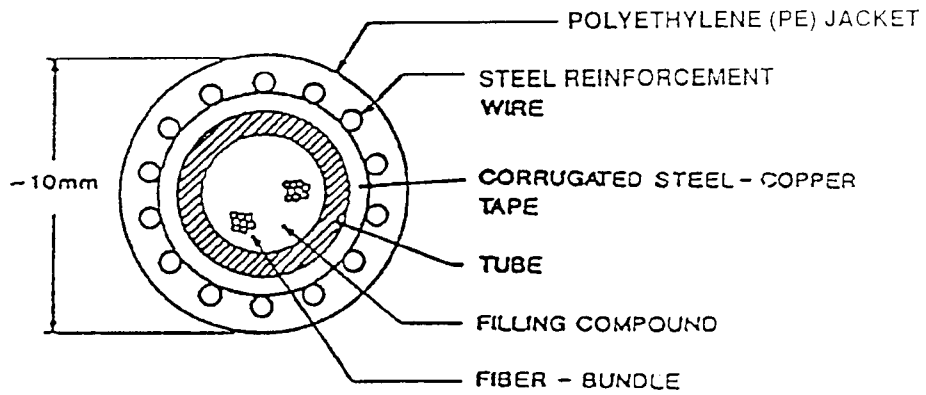
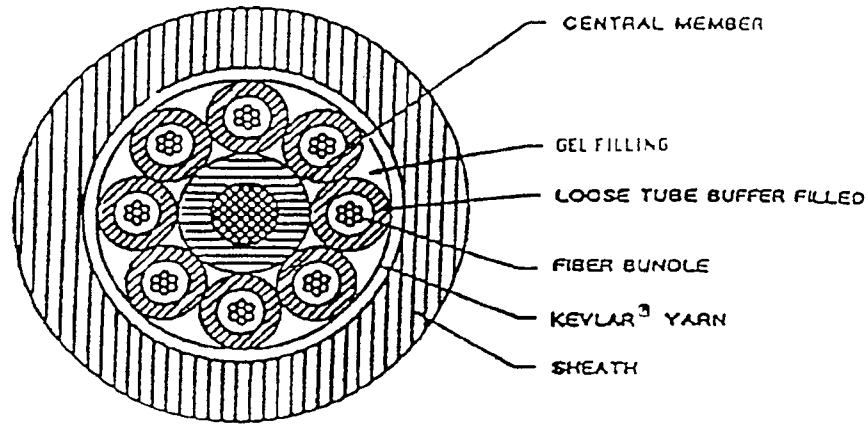


FIGURE 5-4. Loose fiber covering types.

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Loose-Fiber Bundle with Rodent & Lightning Protection

FIGURE 5-5. Types of loose tube cables.

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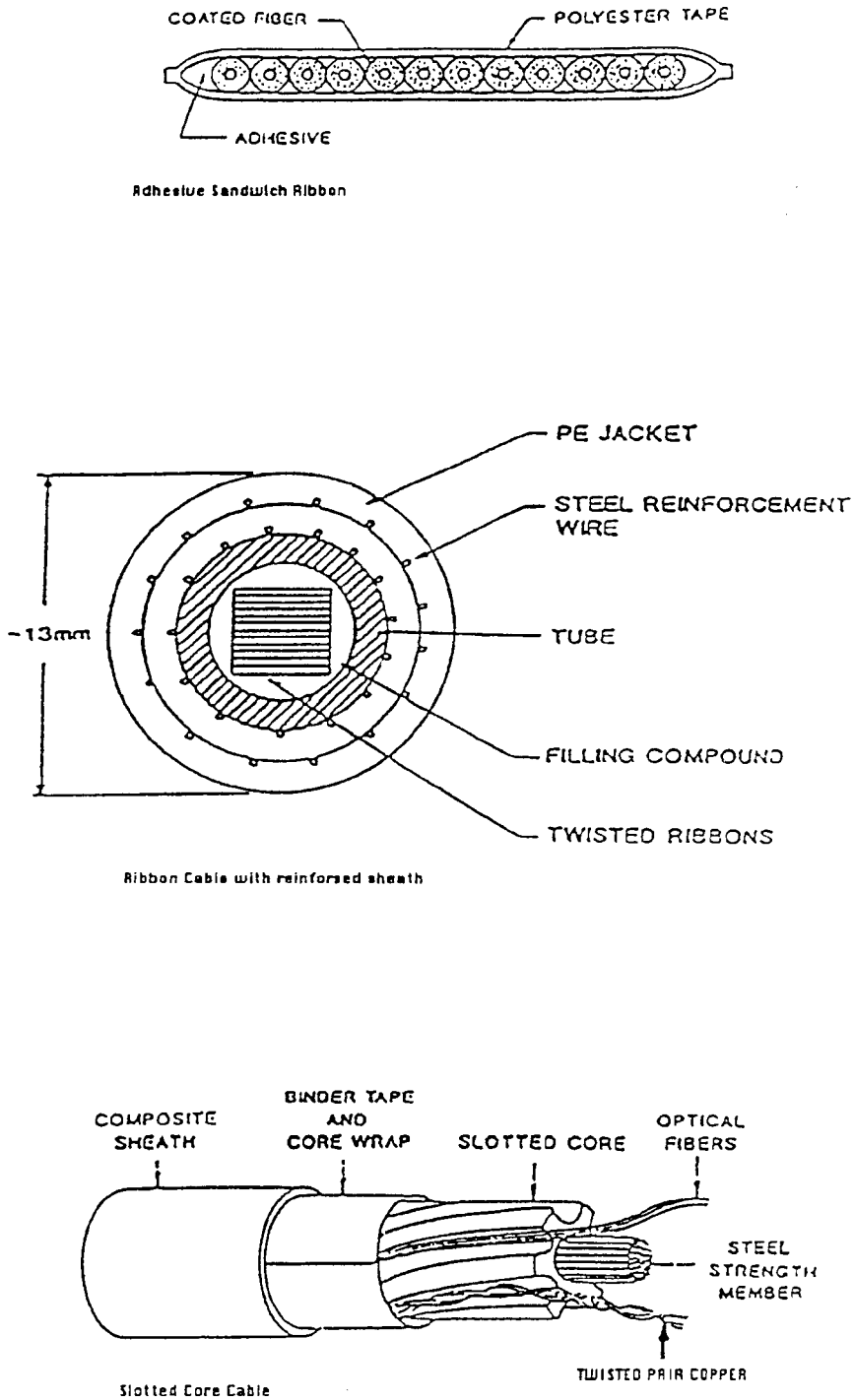
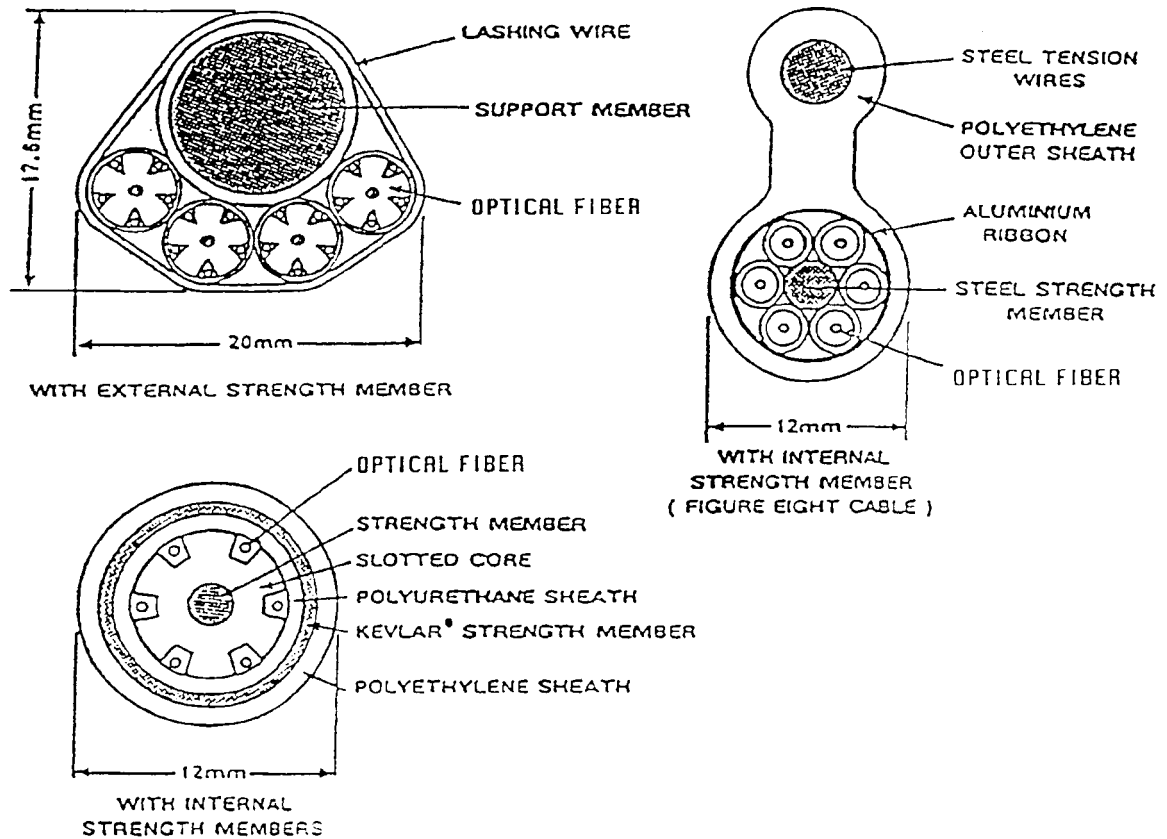
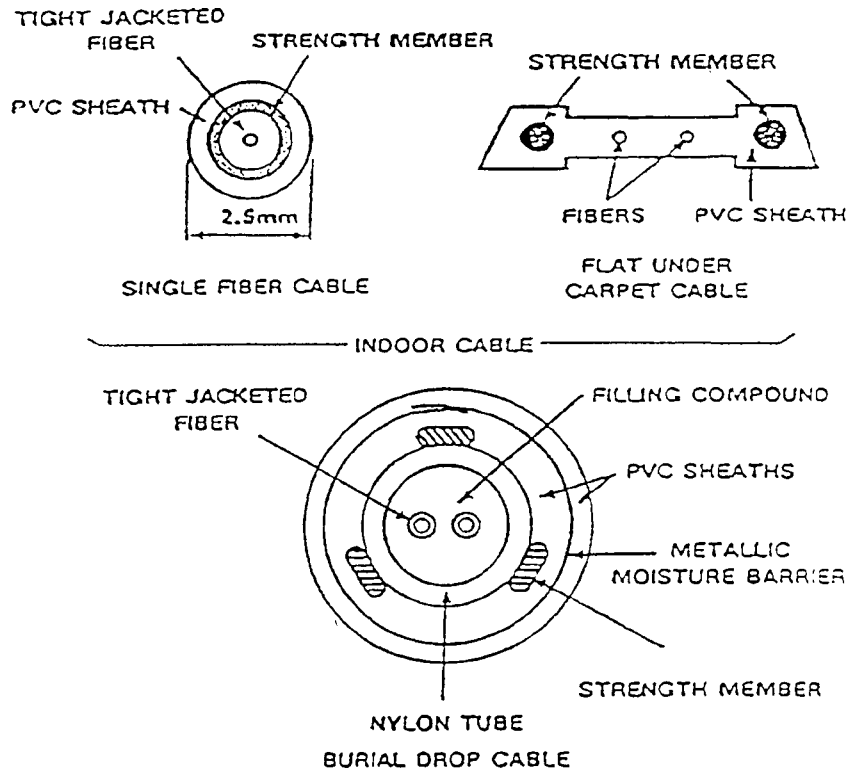


FIGURE 5-6. Types of ribbon and slotted cables.



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FIGURE 5-7. Examples of self-supporting aerial cables.



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FIGURE 5-8. Examples of indoor and drop cable.

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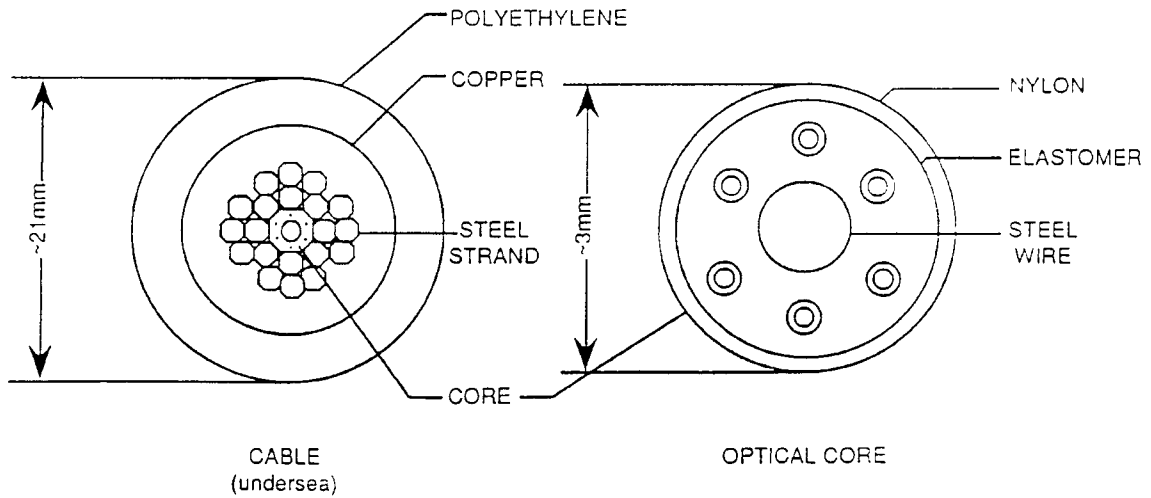
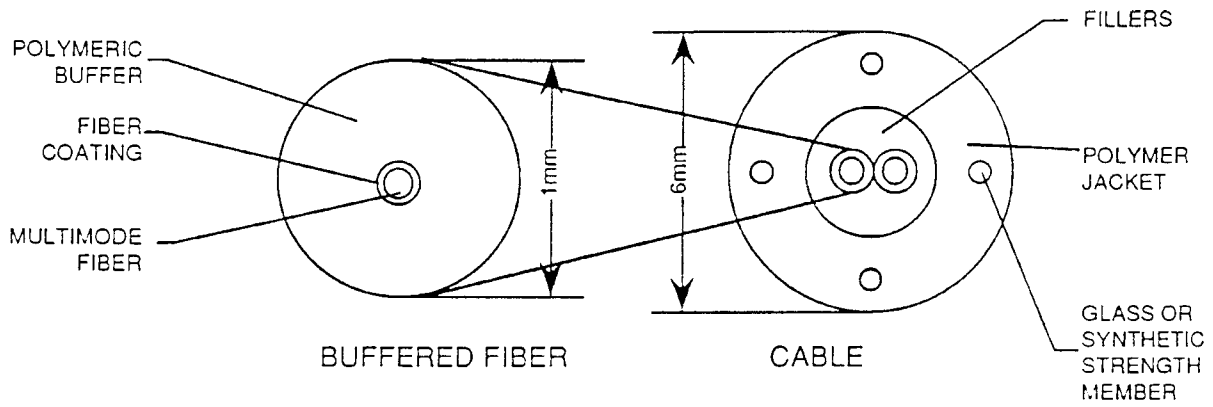


FIGURE 5-9. Tactical and undersea cable.

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b. Additional plastic layers (loose buffering), buffer tubes, or multi-fiber ribbons to cushion fibers and isolate them from longitudinal stresses, macrobending, and microbending during installation. Buffer tubes are not to be confused with the protective plastic or silicone fiber coating.

c. Central and distributed members, composed either of metallic or dielectric materials to ensure adequate tensile strength during installation, and to resist kinking and crushing of the cable. Metallic elements of FO cables may create EMP/HEMP concerns (see chapter 16).

d. Polyester binder tape to hold fibers or buffer tubes in place.

e. Moisture-barrier compounds are used in some FO cables to seal against moisture.

f. Outer and inner non-conducting jackets composed of thermoplastic compounds, which are resistant to abrasion, chemicals, fungus, moisture, and decomposition by ultraviolet radiation. Low density and high density polyethylene are popular jacket materials for outside applications.

g. Corrugated steel tape for rodent protection. (May create EMP/HEMP concerns.)

h. Messenger-cable for support of some aerial cables. (Metallic messenger may create EMP/HEMP concerns.)

i. Radiation hardened fiber used in some FO cables to meet certain hardness criteria required to maintain survivability.

**5.5 Installation standards and practices.** Most of the installation procedures prescribed for conventional metallic communications cables apply to FO cable. Special concerns of installing FO cable are addressed in this section.

**5.5.1 FO cable installation references.** Consult T.O. 31W3-10-12/FM 11-372-2, T.O. 31-10-34/FM 11-487-5/EE169-CA-GYD-010/E110TSER E&I, and commercial practices for detailed installation practices. MIL-HDBK-411 contains information concerning electrical power and the indoor environment recommended for DoD electronic facilities. This guidance is intended to assist in the initial design and installation of communications and data processing systems, and to facilitate later maintenance, relocation, and retrofit activities. GBS standard performance criteria are contained in MIL-STD-188-124 and MIL-HDBK-419. For fire safety concerns of FO cable installations, Article 770 of the National Electrical Code (NEC) should be consulted.

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**5.5.2 FO cable installation.** Strength members and outer jackets help protect fragile silica glass fibers, but some special handling and installation practices are required. The following are important considerations for planning FO installations.

**5.5.2.1 Underground cable depths.** Because of the large traffic capacity of optical fiber and the relative difficulties experienced in repairing and restoring it when damaged, physical protection of FO cables is extremely important. Proposed cable routes should be carefully surveyed and installation carefully planned. Outside plant FO cables are normally buried for concealment and maximum damage protection. The recommended minimum burial depth for DoD FO cable is 40 inches. Other depths may be specified by the designer with specific justification, such as the 48-inch depth recommended by NTIA for external radiation protection. Buried cable specifications recommended by American Telephone and Telegraph (AT&T), Electronic Industries Association/Telecommunications Industry Association (EIA/TIA), and NTIA are contained in the following documents:

- a. AT&T Outside Plant Engineering Handbook.
- b. EIA/TIA Standard-590, Standard for Physical Location and Protection of Below-Ground FO Cable Plant.
- c. NTIA Report 87-226, Multitier Specification for NS/EP Enhancement of FO Long-Distance Telecommunication Networks.

**5.5.2.2 Bending and pulling tension limitations.** FO cables have manufacturer-specified bending and pulling-tension limitations that must be observed and monitored with strain gauges and tensiometers during mechanical pulling operations. Cable sag, pulling friction, and connector snags should be monitored continuously during all installation activities.

a. Usually, an FO cable should not be subjected to more than one 90-degree bend in a single pulling operation. To overcome this constraint in long cable runs, adaptive techniques are employed, such as the use of pulling boxes and pulling in two directions from a central point.

b. Manufacturer-specified minimum bend radii are provided both for cables under tension and for those in storage. *Note: Exceeding the specified minimum bend radius can break or permanently damage optical fibers* (see appendix A). Over-bending an optical fiber can cause it to perform in a degraded manner, usually manifested as excessive attenuation losses. Special cable pulling equipment and mounting hardware are available to prevent over-bending of FO cable by installation personnel. As a general rule, an FO cable under pulling load

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should not be subjected to a bending radius of less than 20-times the outside diameter of the cable. A minimum bend radius of 10-times the outside diameter of the cable is recommended for cables under no load.

c. FO cable is subjected to considerable stress during installation or relocation, especially in mechanical pulling operations through conduits or cable ducts. Strength members are added to FO cable configurations to permit reasonably rough handling during installation or relocation.

The amount of tension used to pull an FO cable is a function of the weight of the cable, the coefficient of friction of the conduit surface, and the geometry of the conduit run. Because optical fiber does not stretch, FO cables are given maximum tensile ratings by manufacturers. Maximum pulling tension should be determined from the manufacturer's specifications. The amount of pulling tension applied to an FO cable during mechanical installation activities must be continually monitored to prevent damage to sensitive optical fibers. The cumulative effects of cable weight and friction in long cable runs are overcome by practical techniques, such as feeding cable in two directions from central points and the use of pulling boxes.

d. FO cables also have a prescribed maximum vertical distance over which they should be installed without permanent support. This parameter also is specified by the cable manufacturer. The maximum vertical rise limitation is a function of the cable weight per unit length and its maximum tensile rating. During installation, FO cables are pulled upward with a cable grip, usually made of a mesh material that holds the cable securely without crushing it. Maximum vertical rise limitations recommended by manufacturers vary greatly, according to type of cable. Typical vertical rise limitations range between 225 and 650 feet for outside plant cables and between 130 and 1,650 feet for inside plant (building,) cables.

**5.5.2.3 Cable ducts and raceways.** Duct work and raceways used to support and route FO cables must be designed to prevent damage to the cables during pulling operations and other installation activities. In designing duct and raceway routes, the number of directional changes should be minimized and sharp bends should be avoided. The use of innerducts is highly desirable to protect the cables and to facilitate retrofit actions.

**5.5.2.4 FO cable storage.** Reels of FO cable should be stored and transported on the reel edges in an upright position rather than lying on their sides. Cable not stored on reels must be protected from damage by crushing and over-bending. Cable ends, especially air-gap type, should be protected from moisture with end caps. Gel-filled cables must be protected from excessive heat, which can cause unwanted migration of the gel. Heating the gel can cause it to migrate to the lower half of the turns of cables stored on reels in an upright

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position, causing severe splicing and cleaning problems during installation. When gel-filled cables are being installed, the use of reflective coating to provide protection from the effects of the sun's radiation should be considered.

**5.5.2.5 FO cable splicing.** Splicing of FO cables can be expensive and time-consuming, and has the potential for introducing attenuation losses. Accordingly, splicing should be kept to a minimum. To minimize the number of required splices during installation, outside plant cable may be extended through regular building cable entrance vaults to special cross-connection locations (see 5.6).

**5.5.2.6 FO cable marking.** All installed communications cables should be labeled or marked with identifying information to minimize accidental damage and installation errors during maintenance or retrofit activities. As a minimum, this information should include cable size, type, use, and manufacturer's identifying data.

**5.5.2.7 Installation records.** All communications systems installations must be fully documented. The availability of accurate records is essential for the continued management, operation, and maintenance of any communications network (see chapter 15).

**5.5.3 Special considerations for installing tactical FO cable.** Tactical FO cable is designed and fabricated to withstand the stresses of field deployment and recovery. However, every effort should be made to install tactical cables with a view toward minimizing the damage potential. Additional protection can be provided, for example, by covering cable with perforated steel plating and wooden planking. Also, it may be highly desirable to conceal the location of the cables. Natural and artificial features of the terrain, such as rock formations, vegetation, bridges, culverts, and sewers can serve as protections of opportunity.

**5.6 Cable entrance points.** The transition of communications cabling from an outside to an inside plant environment at building or structure entrance points presents the following concerns for the network designer:

a. Providing more than one entry point. To improve communications reliability and survivability, buildings are often provided with more than one cable entry point. Protecting communications cables and terminating equipment from the damaging effects of EMP/HEMP and radiation requires special attention to building entry points (see chapter 17).

b. Accommodating for cable pulling and distribution, particularly when other utilities are present.

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- c. Extending outside plant FO cables to a centrally located cross-connect panel or directly into an equipment room to minimize splicing. Refer to the National Electrical Code, Article 770-50, for extending and termination outside cable within a building. Additional local regulations may apply.
- d. Taking dust protection measures, especially during splicing and connectorization.
- e. Protecting maintenance personnel from exposure to gas fumes, high voltage power, and other hazards.
- f. Providing cable distribution conduit and ducts of adequate size and with appropriate surrounding working space.
- g. Accommodating necessary handling procedures for both bulk and pre-connectorized FO cables.
- h. Establishing location of riser space, either pre-built or in elevator shafts, and other utility spaces of older buildings.
- i. Providing proper support (including support racks), storage (such as equipment bays), and physical protection for the cable.
- j. Providing for EMP/HEMP and radiation protection to meet required hardness criteria, especially where cables leave a protected environment.
- k. Providing protection against adverse environmental conditions in locations with climate extremes.

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**CHAPTER 6**  
**TRANSMITTERS, RECEIVERS, REPEATERS, AND REGENERATORS**

**6.1 Transmitters.** A transmitter in an FO communications system converts electrical energy to optical energy and launches that signal into an optical fiber cable. Normally, a transmitter is comprised of a driver, an optical source, and an FO pigtail (see figure 6-1).

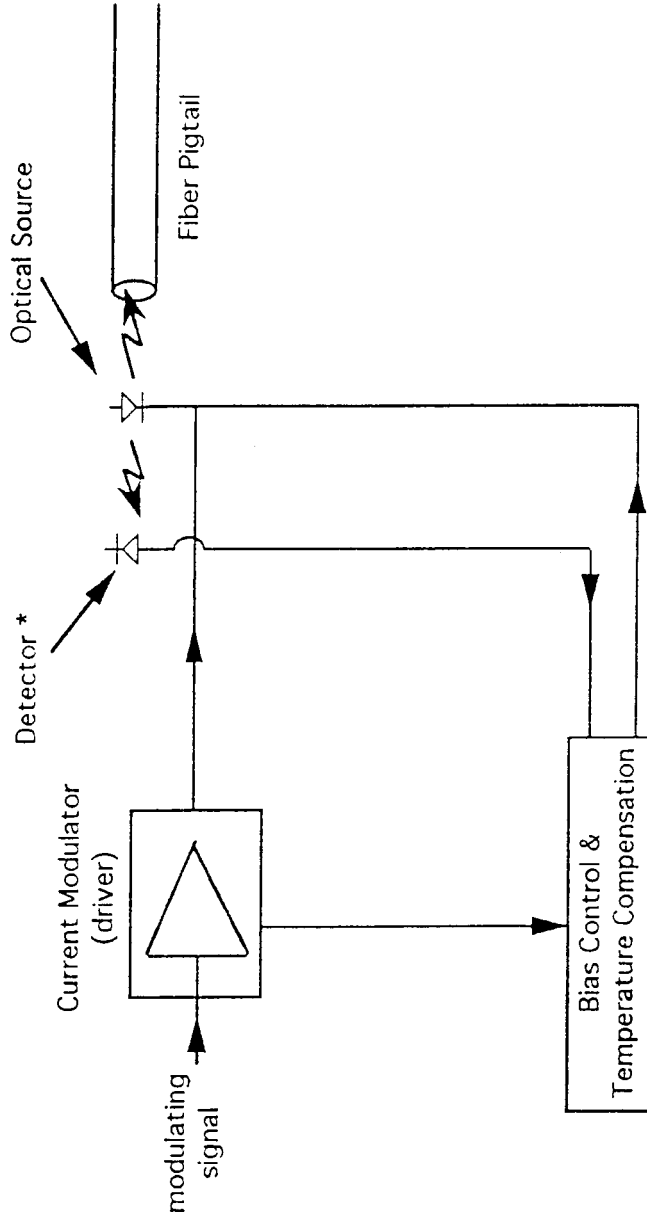
The driver is an electronic circuit that provides the signal current to operate the optical source. Optical sources are typically semiconductor devices, such as light-emitting diodes and laser diodes.

A fiber pigtail provides coupling from the optical source to an FO cable. The pigtail is a section of optical fiber with one end permanently connected to the optical device. The other end is either bare fiber or is terminated with an FO connector.

**6.1.1 LED.** Traditionally, the LED has been the preferred source on short-length, multimode FO links. When a driving current is applied to an LED, injection luminescence occurs through the spontaneous emission of photons. The radiation produced is incoherent (compared to coherent laser light) and has a broad spectral width that can range from 40 to 170 nm. Spectral width is the span of output wavelengths, measured at a point 3 dB below the power output at the peak wavelength, or full-width half-maximum. The broad spectral bandwidth of LEDs results in substantial chromatic dispersion (compared to lasers), thus limiting bandwidth (see appendix A).

LEDs are relatively inexpensive, have a long service life, typically require low drive currents (50-100 milliamperes (mA)), and are more stable than lasers in a varying ambient temperature environment. The two types of LEDs commonly used as sources are the surface-emitting LED (SLED) and the edge-emitting LED (ELED). Characteristics of these devices are addressed below.

**6.1.1.1 SLED.** By virtue of its operation, the active region of a basic SLED radiates in all directions, resulting in approximately half of the generated light energy available for coupling to the optical fiber. The light emissions from SLEDs have a large numerical aperture (NA) (see appendix A). A focusing lens generally is employed to reduce the numerical aperture, thereby optimizing the amount of light coupled to the optical fiber. The Burrus-type SLED has a "well" etched into the semiconductor layers to reduce the space between the active element and the optical fiber, as well as a metallic base under the active element to reflect light energy toward the fiber.



\* The detector within this transmitter module provides LD optical power level feedback for the bias control & temperature compensation circuit.

FIGURE 6-1. Elements of FO transmitters.

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**6.1.1.2 ELED.** In an ELED, the generated optical energy is guided by reflection along a narrow path parallel to the plane of the thin active region and out of the ELED at its edge. The path is determined by the width of the positive-type joined to a negative-type (pn) junction and waveguide action along the length of the junction. The NA of an ELED is smaller, resulting in better coupling to the optical fiber than with an SLED.

### 6.1.2 LD.

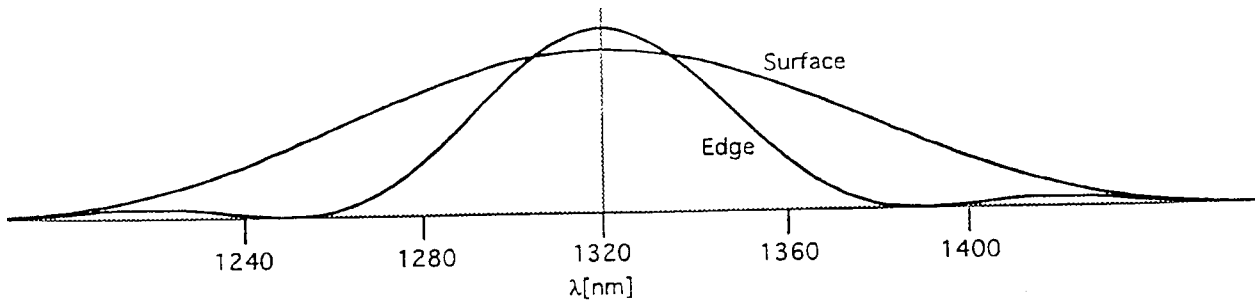
**6.1.2.1 LD operation.** Generation of light in an LD and LED are similar. Photon energy is released spontaneously by the combining of electrons in the conduction band and holes in the valance band, when a low driving current is applied. However, when the current is raised above a threshold level, the emitted radiation is primarily from stimulated emission. In lasing action, the generation of photons "stimulates" the generation of more photons (with similar wavelength and phase) by employing optical feedback. In comparison with LED emissions, radiation from an LD is coherent, more powerful, more directional, and has a much narrower spectral width.

**6.1.2.2 Characteristics.** Laser diodes developed for communications application must have the following characteristics:

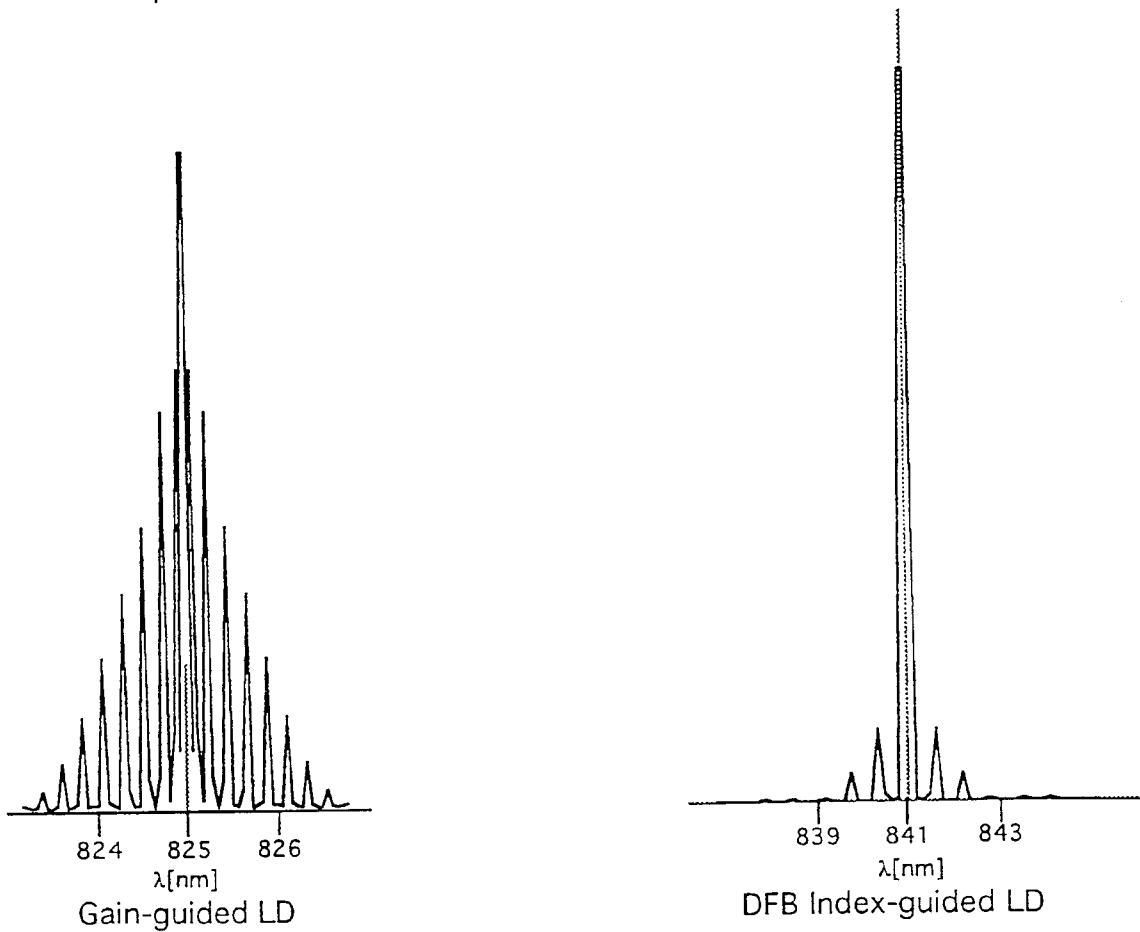
- Low threshold current
- Narrow spectral-width output
- High level of radiance
- Stability of output
- Linearity of output
- Small emission area to facilitate coupling to fiber
- Wide modulation bandwidth (fast rise time)
- Operation at room temperatures
- Long operating life

Stripe (stripe geometry) laser diodes were developed to have these characteristics. There are two types of stripe lasers used as optical communications light sources, gain-guided lasers and index-guided lasers. Gain-guided lasers are multimode devices in which lasing action is concentrated in an area defined by the stripe, laterally oriented across the laser cavity. The multimode output spectrum for gain-guided LDs is shown on figure 6-2. The second type of stripe LD is the index-guided, which produces a few or only one output mode. This narrow spectrum device, used with single-mode fiber, has its active region confined by layers of material with lower refractive index. The resulting narrow output spectrum is shown on figure 6-2.

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A. Relative spectral output for InGaAsP surface and edge emitting LEDs.



B. Relative Spectral output curves for gain-guided and index-guided laser diodes.

Note the relative spectral widths ( $\Delta\lambda$ ) among these sources.

**FIGURE 6-2. Optical source output spectra.**

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The spectral width of commercially available LD transmitters is generally less than a few nanometers. Single-mode lasers are available with spectral widths less than one nanometer. Laser diode output is sensitive to temperature changes. Without thermal stabilization, linearity and wavelength vary with temperature. Laser diodes are normally manufactured with thermoelectric cooling devices.

**6.1.3 Superluminescent diode (SLD).** SLDs are light sources that fall between LEDs and LDs. The physical configuration of the SLD is similar to that of the ELED. Like an LD, the light output of an SLD is from stimulated emission, but at a reduced power output, with a medium spectral width lying between the wide pattern of an LED and the narrow pattern of an LD. Output power and spectral width of SLDs are a function of driver current, as well as the physical dimensions of the active region. Applications of SLDs are currently limited to special FO sensor configurations.

**6.1.4 Comparison of LED and LD transmitters.** When choices exist, the system designer should be aware of the following basic differences in transmitter sources as shown in table 6-1.

**TABLE 6-1. Representative range of LED and LD parameters.**

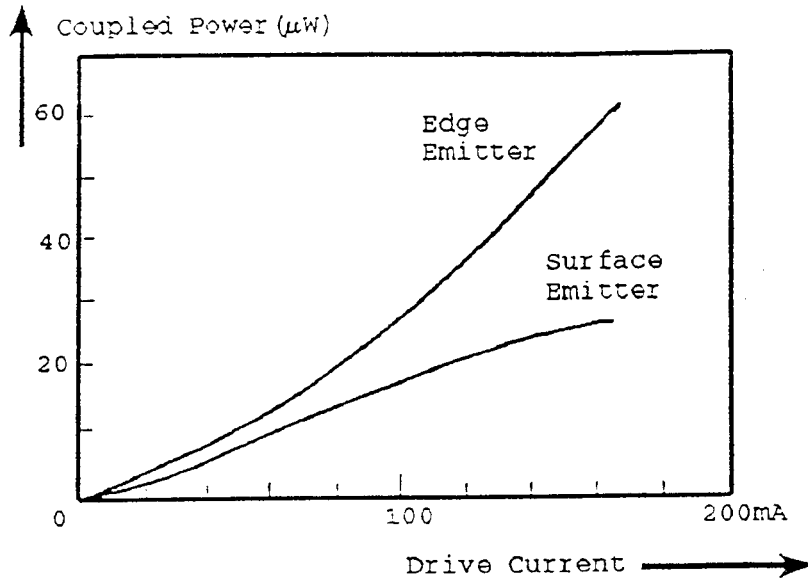
Parameter	LED	LD
Drive current (mA)	50 – 200	10 – 300
Threshold current (mA)	N/A	2 – 250
Power launched into fiber (mW)	0.025 - .05	0.25 – 3
Rise time (ns)	5 - 50 (SLED) 2 – 20 (ELED)	<1
Spectral Width, rms (nm)	25 – 80 (@ 800 nm) Note 1 40 – 170 @ 1300 (nm)	.01 nm – 15 nm (@ 800 nm) .001 nm – 20 nm (@ 1300 nm)
Modulation Bandwidth	To 0.8 GHz	To ~20 GHz

Note 1: Selection of LEDs should make note of spectral width requirements in MIL-STD-188-111.

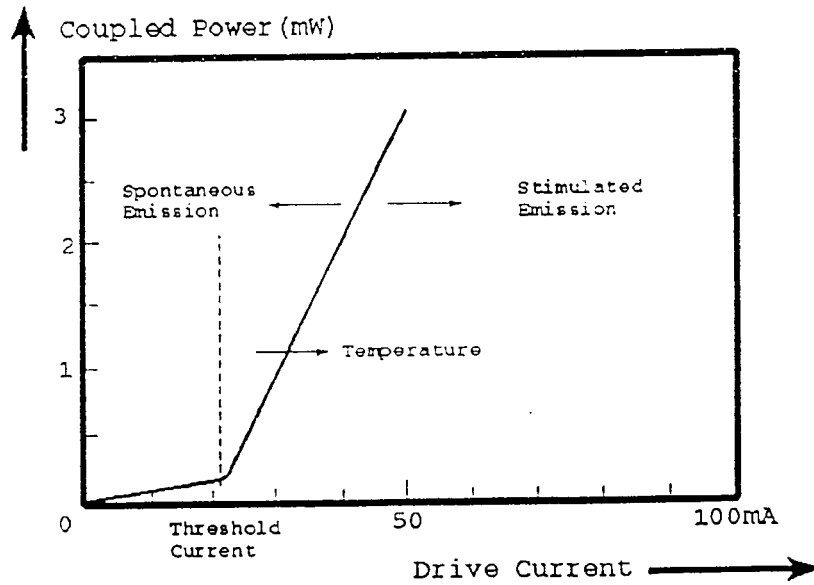
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In addition, the following should be noted:

- a. The spectral purity and optical power output of an LED is much lower than that of an LD (see figure 6-2).
- b. LEDs typically are less expensive and complex than LDs.
- c. LEDs find numerous applications in short-haul (including tactical), low capacity multimode fiber systems, while LDs are used almost exclusively in wide-bandwidth, long-haul systems utilizing single-mode fiber techniques. Recently, component manufacturers have been offering LED-type transmitter modules that operate with single-mode fiber. This allows single-mode FO cabling to be installed with LED transmitters to provide a medium bandwidth capacity (compared to single-mode systems). As transmitters with increased speed are offered, single-mode fiber will allow easier retrofitting to a higher bandwidth capacity.
- d. LEDs are well suited for use in tactical communications. Tactical communications normally do not require the high bandwidth capability of single-mode fiber and can employ multimode fiber, with LED light sources. LEDs require less power and are less sensitive to temperature variations. These features make the LED generally more suitable than the LD for application in tactical communications.
- e. The LED is the preferred light source when lower signaling rate requirements permit its use. An LED light source usually has a longer life and may be operated with less drive current than the higher performance LD. However, some LDs can be operated with lower currents than LEDs to produce the same optical power output. For example, there are LDs that produce 2 milliwatt (mW) of optical power at 30 mA drive current, while some LEDs require 100 mA to produce 0.03 mW of output optical power (see figure 6-3).
- f. The LED may be stable over a longer lifetime than an LD. However, due to its larger numeral aperture, the LED-to-fiber interface suffers from lower optical coupling efficiency than LDs.
- g. LDs can be used to achieve much higher modulation rates than LEDs. Lasers have a much narrower spectral width than LEDs, resulting in less dispersion caused by the FO transmission fiber. Therefore, LDs are better suited for digital and high bandwidth communications in a benign environment.
- h. LDs are better suited than LEDs to analog applications because of their optical linearity; i.e., above the lasing threshold, the LD power output increases very linearly with increasing drive current.



Typical LEDs coupled to 50 μm graded-index fiber (1300 nm InGaAsP: edge emitter and surface emitter)



1300 nm laser diode characteristic (When coupled into single-mode fiber)

FIGURE 6-3. Optical power versus drive current.

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**6.1.5 Laser diode resonant modes.** Optical radiation within the LD resonant cavity sets up a pattern of electric and magnetic field lines. This pattern is called a mode. The LD can oscillate in multiple modes simultaneously; therefore, the LD spectral width is established by the number of mode associated emission frequencies. Single-mode (i.e., single-frequency) operation is obtained by proper design of the cavity geometry and selection of the semiconductor material composition.

Lasers which are single-mode under continuous output operation can become multimode in transient or pulsed operation. During pulsed operation, the individual width can broaden (resulting in wavelength variation, also known as laser chirp and frequency chirp) due to dynamic changes in the refractive index within the laser.

LEDs produce a broad continuous optical spectrum. The LED has a somewhat Gaussian output spectrum that may be up to 170 nm wide at half-power points. In contrast, the highest quality distributed-feedback laser can produce a very narrow spectral width, essentially a single line. Distributed feedback lasers are being marketed with widths down to the order of typically 1 nm.

Transmitter modes may have considerable impact on performance criteria similar to fiber propagation modes. The fewer optical transmitter modes propagated through a fiber, the less dispersion (which causes intersymbol interference).

**6.1.6 Transmitter selection.** Transmitter selection, based on the following types of information, should be documented:

- Terminal equipment identification
- System design application, e.g., single-mode, multimode
- Operating wavelength
- Output power level
- Source type, e.g., LED, LD
- ANSI safety classification, e.g., Class I, Class II (see chapter 13)
- Manufacturer product change designation, e.g., issue, revision
- Material composition of source, e.g., InGaAs
- Generic device structure, e.g., distributed feedback (DFB)
- Spectral width
- Optical rise and fall time
- Data rate
- Bandwidth (analog).

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Additionally, information should be obtained about the pigtail associated with the transmitter in terms of general fiber type, class of fiber, and core diameter (or in the case of single mode, mode field diameter) and NA (multimode fiber only).

**6.2 Receivers.** A receiver converts received optical power into an electrical signal. Figure 6-4 shows a block diagram of a typical FO receiver.

**6.2.1 Photo detectors.** There are two common types of light detectors used in FOCS: positive intrinsic negative (PIN) photodiodes and avalanche photodiodes (APD). PIN photodiodes and APDs are contrasted in table 6-2.

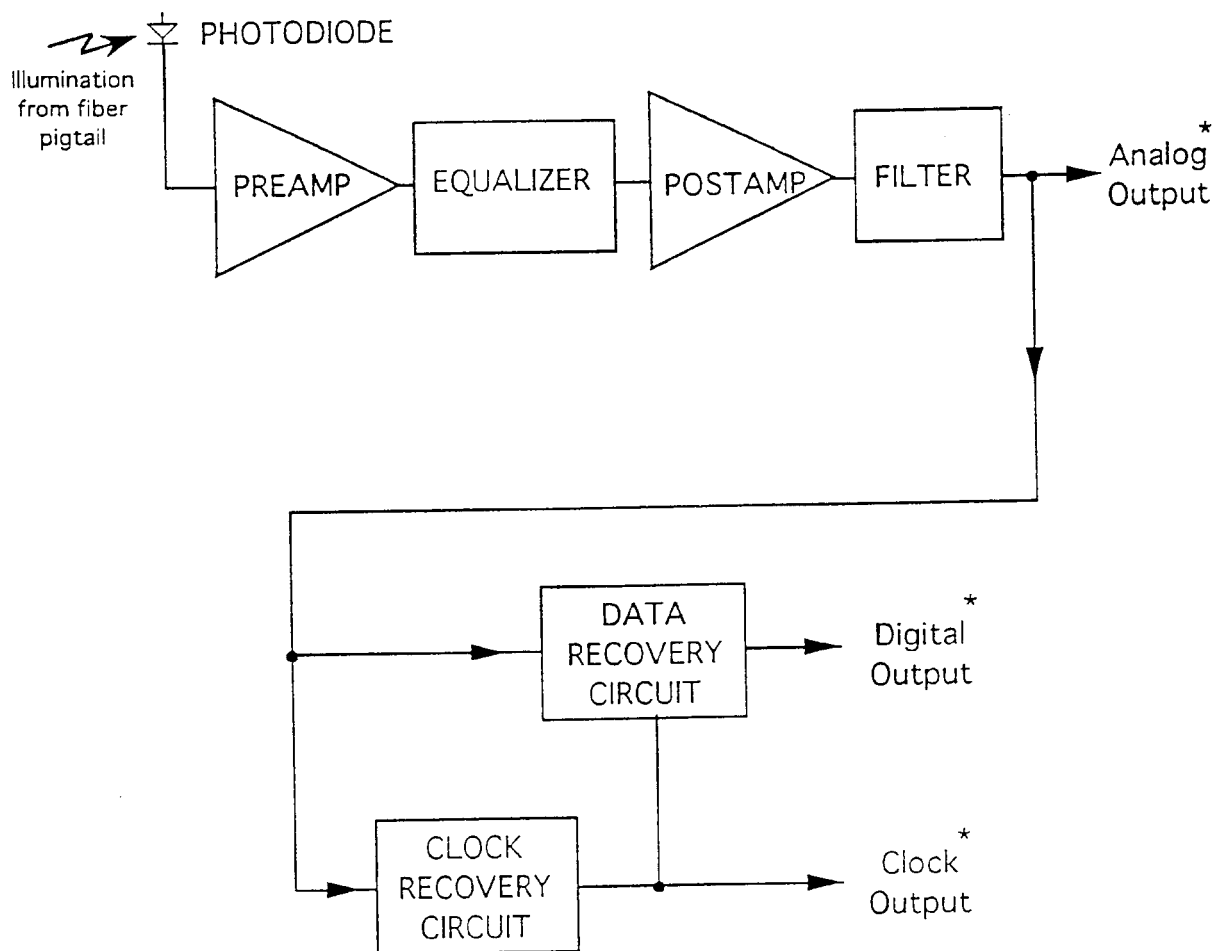
**6.2.2 Receiver selection.** A number of factors enter into selecting receivers in an FOCS. Among them are rated sensitivity, optical wavelength for rated sensitivity, dynamic range, maximum bit rate and bandwidth, and respontivity.

The following additional information (available from the manufacturer of the receiver module) will prove useful if receiver modules are replaced, recalled, or are to be retrofitted:

- Detector type and composition; e.g., PIN and InGaAs
- Temperature controller
- Manufacturer product change designation, issue/revision
- Connector type and model number
- Mating connector model number
- Classification (multimode, single-mode)
- Pigtail information including fiber type, class of fiber, and mode field diameter (if single-mode).

**6.2.2.1 Sensitivity.** Receiver sensitivity is defined as the minimum optical power amplitude at the input of a receiver required to achieve a certain bit error ratio (BER) or signal-to-noise ratio (SNR). Typically, sensitivity is stated in decibels referenced to one milliwatt (dBm) and is related to receiver type (PIN photodiode or APD), receiver design, digital signal coding, and optical line (transition) rate.

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\* A receiver designed for analog applications will not have the digital recovery circuits.

FIGURE 6-4. Receiver block diagram

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**TABLE 6-2. Contrast of typical PIN photodiodes and APDs.**

	PIN		APD
Material:	*Si	InGaAs	**Ge or InGaAs
Sensitivity:	Low	Medium	High
Wavelength:	850 nm	850 & 1310 nm	1310 & 1350 nm
Bit rate:	1 Gbps Typical	10 Gbps Typical	5 Gbps Typical
Circuit Complexity:	Low	Low	Medium
Temp. Sensitivity:	Low	Low	High
Cost:	Low	Low	High
*Si=Silicon			
**Ge=Germanium			

**6.2.2.2 Dynamic range.** Dynamic range is the difference in decibels between the minimum required receiver input power level and the receiver overload level to sustain a required BER or SNR. MIL-STD-188-111 calls for the dynamic range of the optical receiver to be no less than 26 dB. Receivers must be operated within their specified optical power range. If the optical power level arriving at the receiver is below its required threshold, the BER will exceed the specified value due to insufficient SNR. If the light level arriving at the receiver is above the overload level, the BER will also increase. The designer must ensure the receiver will remain operating within its dynamic range initially and after age degradation.

**6.2.2.3 Maximum bit rate and bandwidth.** The optical bandwidth is equal to the modulation frequency at which the power has dropped to half (-3 dB) that of the unmodulated value. Maximum bit rate is directly related to modulation bandwidth and coding scheme (see 9.6).

**6.2.2.4 Responsivity.** Responsivity is defined as the ratio of photocurrent generated to unit of optical power and is expressed in amperes per watt or volts per watt. Responsivity is the ratio of the root-mean-square (rms) value of the output current (or voltage) of a photodetector to the r-ms value of the incident optical power. It is a measure of the electrical power expected at the output of a photodiode, with a given level of optical power input. Responsivity is related to the wavelength  $\lambda$  of the optical energy and to the quantum efficiency  $\eta$ .

$$R = \eta \lambda / 1.24$$

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where:

$$\eta = \frac{\text{Number of emitted electrons}}{\text{Number of incident photons}} \text{ (expressed in percent)}$$

$\lambda$  = expressed in micrometers

R = expressed in amperes per watt

Peak PIN responsivity occurs in the 800 to 900 nm and 1300 to 1500 nm ranges. APDs normally having peak responsivity occurring in the 900 to 1300 nm range are now commercially available in the 1300 nm and 1550 nm wavelength ranges. PIN photodiodes have a wide dynamic range and good linearity with bandwidths exceeding 10 GHz. APD bandwidths are currently limited to about 5 GHz. APD receivers have greater sensitivities (typically about 10 dB) than PIN photodiodes due to the internal gain of the APD. The gain largely negates the noise contribution of the follow-on amplifier. In contrast, since PIN photodiodes have no gain, most noise from the PIN photodiode receivers is caused by the follow-on amplifier.

**6.3 Repeaters, regenerators, and optical amplifiers.** All repeaters, regenerators, and optical amplifiers require a power source to operate the electrical or optical circuitry. This must be planned for, especially in tactical and remotely located repeater sites.

**6.3.1 Repeaters.** Repeaters are devices that take incoming low-level optical signals, convert them to the electrical domain, amplify them, then convert them back to optical signals and pass them on. Repeater applications include analog signaling. These devices are for use along long fiber runs to extend the usable distance beyond that possible with only an optical transmitter and receivers

**6.3.2 Regenerators.** Regenerators (regenerative repeaters) are used for digital signaling. They receive incoming low-level dispersed (distorted) digital pulses. After conversion to the electrical domain, the pulses are regenerated (the leading and falling edges are sharpened and the pulses are amplified). Finally the regenerated pulses are retransmitted optically. The signal output from a regenerator is accurately timed to reestablish the original pulse width and spacing.

**6.3.3 Optical amplifiers.** Optical amplifiers, such as the external optically pumped erbium doped fiber amplifiers (EDFA), can provide approximately 20 dB of direct optical gain. These optical amplifiers perform as direct repeaters without converting to and from the electrical domain for amplification. The EDFA requires a laser optical source acting as a 'pump' signal which provides the amplification mechanism. In addition to EDFAS, solid state optical amplifiers have also been developed but currently are less popular.

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## CHAPTER 7 OTHER COMPONENTS

**7.1 Connectors.** Connectors are used to allow semi-permanent attachment of fiber cables and terminal devices. Connectors join fiber ends for efficient signal transfer and are designed for connection and reconnection. Permissible connector insertion losses are specified in MIL-STD-188-111. For single fiber connectors, the maximum loss is 0.5 dB (design objective (DO) of 0.3 dB) for long-haul applications, and 1.0 dB for tactical applications. For multi-fiber connectors, the maximum loss is 1.0 dB (DO of 0.7 dB) for long-haul, and 1.5 dB for tactical applications. Connectors should be interchangeable throughout a given system to reduce stock item types. Ideally, identical connectors or interchangeable connectors should be specified for the total installation.

**7.1.1 Connector types.** Figure 7-1 illustrates typical optical fiber connector types. Optical fiber connectors are addressed in T.O. 13-10-34/FM 11-487-5. (Jumper cables are available to join different types of connector receptacles.) Connectors are either butt-coupled or lens-coupled. Some butt-coupled connectors use index-matching fluid to reduce insertion loss and increase return loss. Others rely on optical alignment and close physical spacing between both fiber end faces. A lens-coupled connector employs lenses at its tip to focus light exiting one fiber to the end of the adjoining fiber. This reduces sensitivity to performance degradations from lateral and angular misalignment with its mating connector.

Optical connectors are ferrule or biconic, and either can be butt- or lens-coupled. The most typical connector type is the ferrule type. Example types of the ferrule connectors include the SC, ST, FC, and SMA. Ferrule connectors may be keyed or unkeyed. They may have screw-on, bayonet, or push-pull coupling mechanisms. The biconic type connectors were originally used in the public telephone network, and are made with a conical end piece to be inserted into a corresponding receptacle.

**NOTE:** Connectors used for tactical applications are pre-assembled on a ruggedized length of cable. While the "ST" connector is currently the most commonly specified in military and commercial applications, the SC connector is gaining in popularity because there are fewer alignment problems with this connector.

**7.1.2 Selection considerations.** In selecting a connector the following should be considered:

- insertion loss
- return loss
- repeatability
- ease of assembly

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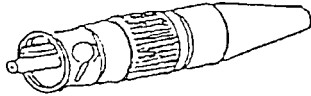
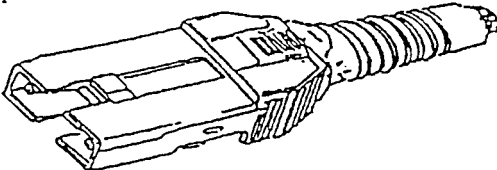
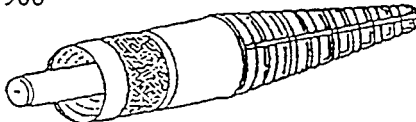
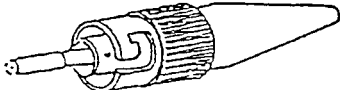
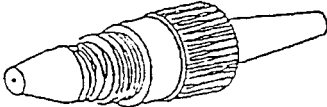
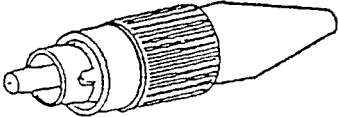
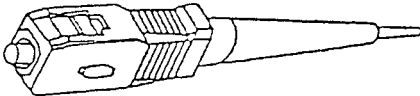
Connector Type	Typical Connector Losses	
	Multimode (62.5 $\mu$ )	Single-Mode
Mini BNC 	0.5	N/A
FDDI 	0.3	N/A
SMA905/906 	0.8	N/A
ST PT Compatible 	0.3	0.3
Biconic 	0.7	0.7
FC PC 	0.4	0.3
SC 	0.3	0.3

FIGURE 7-1. Connector types.

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- survivability
- interchangeability
- pre-connectorized
- costs.

a. Insertion loss. Some of the mechanisms which contribute to insertion loss include imperfections in the fiber concentricity, lateral offset, angular alignment, and fiber end separation between connectors (see figure 7-2).

b. Return loss. Due to imperfections, connectors will reflect some of the incident optical power back toward the source. This characteristic is usually defined in terms of return loss in dB. Return loss is equal to 10 times the common logarithm of the ratio of incident to reflected power. State-of-the-art return loss for typical connectors is on the order of 40 dB or greater. Ideally the return loss should be infinite (no reflected signals). LD sources are susceptible to performance degradation when optical power is reflected back to their output aperture.

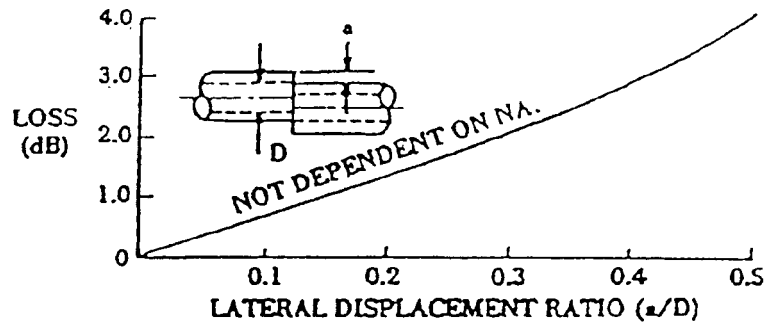
c. Repeatability. Repeatability, or connection durability, is the ability to maintain a performance level after numerous connections, disconnections, and reconnections. The measure of repeatability or variance from a nominal value for insertion loss for a connector may vary by as much as 0.5 dB if the connector has not been optimally assembled.

d. Ease of connector assembly. It is important to select a connector that can be easily installed in the field. The time required for installation of a connector should not exceed ten minutes.

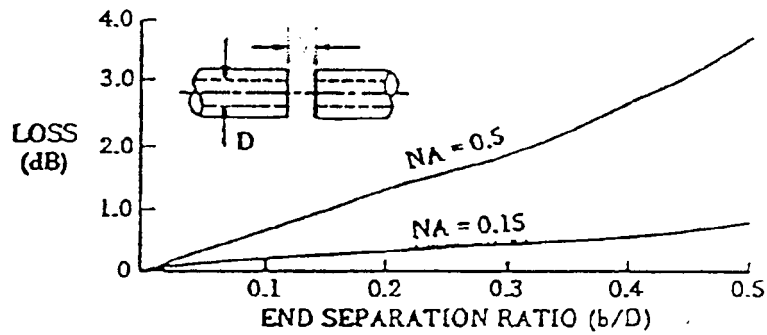
e. Survivability. A term used here to describe relative endurance and robustness among connectors being considered. One such parameter, cable pull out strength, should be greater than 25 pounds. Survivability addresses the special concerns for connectors being deployed in environments which will be subjected to a specified range of natural or human-made disturbance. In cases of temperature change, loss should be stable less than 0.2 dB change) over the temperature range of -20 degrees C to +60 degrees C. Extreme temperature changes can cause the fiber-to-connector integrity to be destroyed by cable jacket shrinkage or expansion.

f. Interchangeability. Connectors should be interchangeable, (preferably identical) throughout a given system to reduce stock item types.

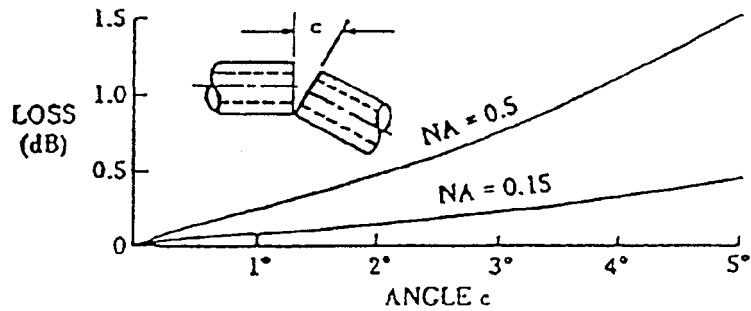
g. Pre-connectorized. Pre-connectorized cable lessens the opportunity for errors in field mounting of connectors. In conjunction with connector selection, the designer should use



A. LOSS DUE TO LATERAL MISALIGNMENT



B. LOSS DUE TO END SEPARATION



C. LOSS DUE TO ANGULAR MISALIGNMENT

FIGURE 7-2. Mechanical losses in fiber optic connectors.

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patch panels wherever possible for easier system administration and to provide for cable plant protection.

h. Costs. Costs should be considered, but standards should not be sacrificed to reduce costs.

**7.2 Splices.** The purpose of a splice is to efficiently and permanently connect optical energy from the end of one fiber to that of another with as little insertion loss as possible (forward attenuation) and minimum reflected power (large return loss). All splices must provide precise alignment of the fiber end faces when completed. There are two main types of splices: mechanical and fusion.

**NOTE:** It is important that the fibers being spliced first be de-energized to avoid eye damage since they are typically given close visual inspection during the splicing procedure.

**7.2.1 Mechanical splices.** Some splices employ an index-matching fluid (applied between the fiber ends) to aid in minimizing Fresnel reflection and scattering loss. Depending on the connector, epoxy may then be applied. Alignment of the prepared ends is usually obtained through an alignment tube. Positive alignment may be obtained with a V-grooved guide, so that the fibers, introduced at a slight angle to the axis of the mechanical splice tube, are forced into alignment. The fiber ends are typically sealed to the mechanical splice housing with epoxy once alignment has been achieved. Types of mechanical splices are shown on figure 7-3.

**7.2.1.1 Grooved-plate, multi-fiber splice.** This splice is suitable for multiple fibers packaged in flat-ribbon configuration. A stack of grooved chips is assembled to clamp the fibers in parallel, joining identically sized fibers. An index-matching gel and adhesive are applied at the fiber interfaces.

**7.2.1.2 Multirod alignment splice.** In this splice, three rods of the correct size act as splints to maintain alignment. An index-matching gel and adhesive are introduced into the splice.

**7.2.1.3 Elastomer splice.** This splice consists of two center inserts and an outer elastic sleeve. One of the inserts has a V-groove; the other is a flat plate. Together they form a triangular cross section to position both fiber ends. The inserts deform slightly under pressure from the sleeve, and the inserted fiber expands the triangular hole, creating forces that hold and align the fibers. An index-matching fluid or gel is inserted into the triangular cavity prior to inserting the fiber.

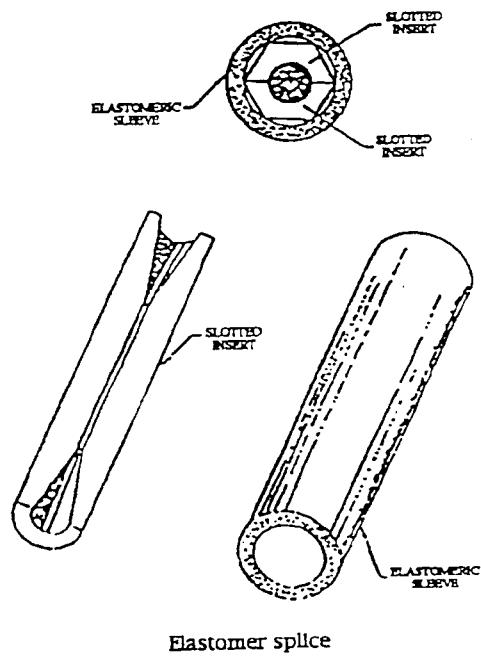
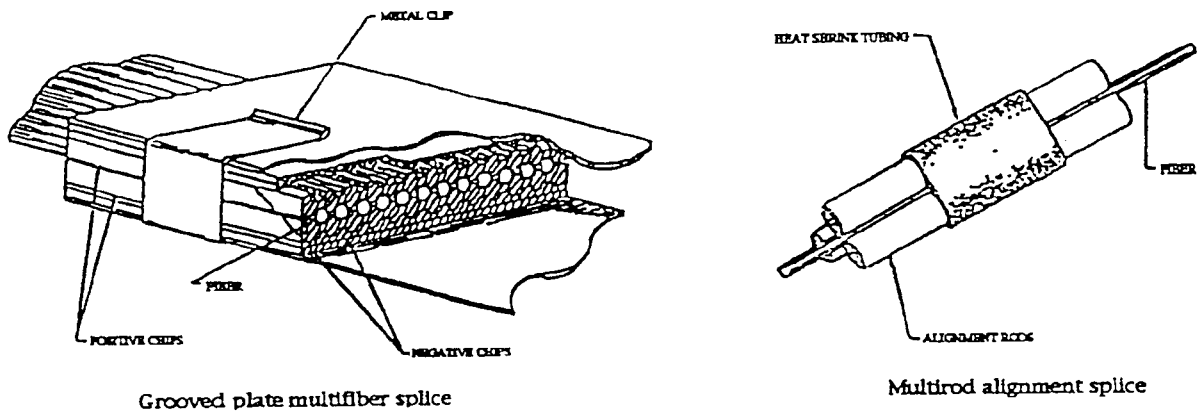


FIGURE 7-3. Types of splices.

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**7.2.2 Fusion splices.** The lowest loss splicing method is fusion splicing. This technique especially requires that the fibers being spliced first be de-energized to avoid eye damage since they are viewed under a microscope. The fiber ends are aligned with a micromanipulator (built into fusion splicers) while being viewed through a microscope.

Another alignment technique is to monitor the optical power through the splice. When positioned with a microscope, a very slight fiber to fiber compression is preferred since a very small amount of fiber will melt to become the splice. The fiber ends are then fused together by an electric arc or other source of heat. Maximum allowable splice loss is 0.5 dB, as standardized in MIL-STD-188-111.

NOTE: The fusion splicer uses an electric arc and should not be used in environments where combustible gases may exist (for example in an access hole) unless it has been determined that electric sparks will not cause harm or interference and that combustible gases are not present.

**7.2.3 Methods of reducing fiber end loss.** Proper connector function requires that the light emitted from one fiber be transmitted efficiently into the other. If the fiber end is not flat and perpendicular to the fiber axis, the light will, to some degree, deviate from the proper path. Lenses reduce this deviation, but only by simulating the effect of the fiber ends in contact. Index-matching fluid eliminates some Fresnel reflection loss from the broken surface.

**7.2.4 Fiber end preparation.** Fiber ends are prepared using, two basic steps: scribe-and-cleave and polishing. The scribe-and-cleave step, sometimes rendering less than an optically perfect finish, is adequate for fusion splices and for connectors using, an index-matching gel. The polishing step, which takes 5 to 10 minutes, ensures the fiber ends are ground flat and perpendicular to the fiber axis for use in connectors and those splices that do not use index-matching fluids.

**7.2.5 Splice enclosures.** The splice trays within the splice enclosure provide a holder for splice placement, organization, and provides individual strain relief for each buffer tube. In addition, splice enclosures offer protection from the weather, terrain, and rodents, and afford a means to organize and anchor multi-fiber terminations.

**7.3 Couplers.** Couplers (also called power splatters) can be multi-port devices for energizing branch fiber(s) or combining branch fiber signals to a main fiber. Couplers are passive optical components which enable the user to tap, split, or inject (combine) optical main transmission line energy for multiple point-to-point optical signal transfer. Couplers support three system functions: data busing, optical wavelength division multiplexing, and monitoring/controlling system status. Couplers provide such capabilities as signal duplexing, directional coupling,

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branching or splitting, and mixing or combining of optical signals. They perform the signal tapping and distribution function in star-topology LANS, where a large number of terminals in a limited geographic area need to communicate on common channels.

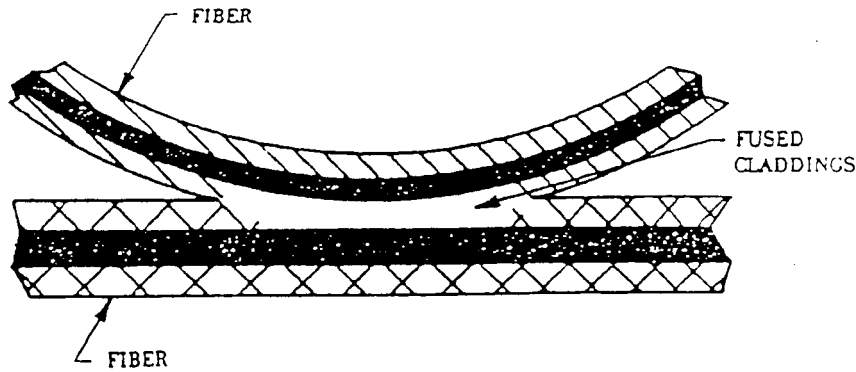
Couplers must be transparent to the wavelength of the intended signals. Loss introduced by couplers consists of splitting loss and excess loss (light radiated or absorbed in the interior of the coupler). Access to couplers is by FO pigtailed (about 50 centimeters long) or by connectors. The signal processing geometry suggests classification of optical couplers as either star or T couplers.

**7.3.1 T couplers.** T couplers (see figure 7-4) find applications in duplexing, wavelength-division multiplexing, and in monitoring fiber system status. The 2X1 couplers have a splitting loss of 3 dB (half power to each of two ports) and excess losses between 1 dB and 2 dB. As an example, the cumulative losses introduced by couplers connected in series (such as to implement a bus topology LAN) limits the maximum number of nodes to about 10. This is because additional nodes and the associated splatters would introduce so much loss that optical power levels would not be within the dynamic range of all receivers in the network. Both the bus and ring LAN topologies use T couplers. For example, the bus is used for connecting a group of central processing units with printers, disk drives, and displays. Each terminal taps into the main distribution line. Coupling techniques are discussed below.

a. **Evanescent wave.** In the evanescent wave method of coupling (the common method employed to produce FO coupling devices), the tap fiber is fused to the main fiber so that their cores have a common cladding region, therefore, high order modes are coupled into the tapping fiber. The amount of light coupled varies with the interaction length and core-to-core proximity.

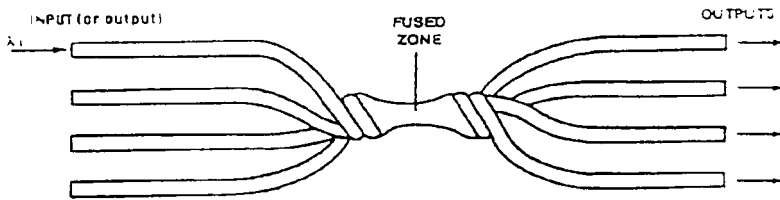
b. **Beam splitter.** Another device, employed primarily in an optical lab, is the beam splitter. The beam splitter consists of a partially reflective plate which transmits and reflects Light. A partially reflective coating applied to the polished fiber ends, with index-matching fluid in the gap, can have the same function as the plate. The strength of the tapped signal can be varied by varying the transmission-reflection ratio of the beam splitter. If the mirror is coated to filter selective wavelengths, beam splatters can be used as wavelength-division multiplexers/demultiplexers. Couplers used this way are called dichroic couplers.

**7.3.2 Star couplers.** Star couplers (see figure 74) allow energy from any one fiber to be distributed equally into several fibers from one power splitter. They are commonly used in star topology LANs having several terminals connected to each other and to a central

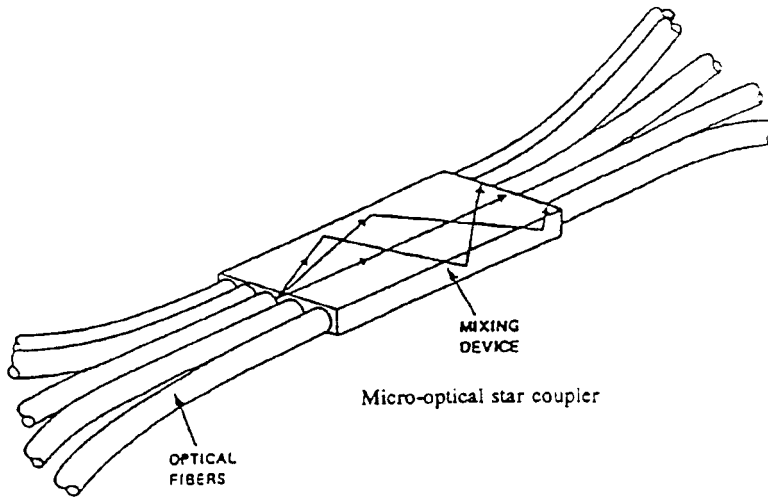


T Coupler (evanescent wave coupler)

NOTE: Although its physical appearance is that of a 4-port coupler, this coupler functions as a T coupler: an input at one port exits only the farthest two.



Schematic representation of a fused biconical taper.



Micro-optical star coupler

FIGURE 7-4. Examples of couplers.

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processing unit (CPU). The advantage of star couplers over a series of T couplers is that the star coupler introduces only a single insertion loss and is more appropriate for splitting power into multiple directions.

Star couplers are inherently bi-directional. In both transmissive and reflective types described below, light input to one fiber is divided equally among all output fibers:

a. Transmissive star coupler. In a transmissive star coupler, the outgoing ports are arranged opposite incoming ports. A common way of creating a transmissive star coupler is with the biconical taper coupler, which is similar in fabrication to the evanescent wave T coupler. The desired number of fibers are lightly twisted and fused so they share a common cladding, and their cores are in close proximity. The fused section functions to diffuse the energy into the other ports.

b. Reflective star coupler. Each fiber in a reflective star coupler could serve as both an input and output path. The rear end face of the mixing device serves as a mirror, with all fibers coupled to the same side of the mixing rod.

**7.4 Optical attenuators.** Optical attenuators are used to reduce the energy level in an FO link. Optical energy levels may require control at selected points in an FOCS or in a testing environment. For example, the optical energy arriving at the receiver of a particular link might be too high and cause receiver saturation. This problem can be solved by either reducing the level of the optical source (transmitter) to the link or attenuating the signal to an appropriate level before introducing it to the receiver. Varying the output level of a transmitter by varying drive current is not recommended for most LED and LD transmitters because of the limited linear range of these devices. Introducing a calculated amount of optical energy loss to the link will lower the signal level at the receiver to an appropriate value. Fixed attenuators provide a specific amount of loss (e.g., 1, 3, 6, 10, 20, 30, or 40 dB), while variable attenuators provide controlled losses over a specified range (e.g., 3-60 dB).

a. Air gap attenuators. A simple and inexpensive fixed attenuator commonly used in communications systems is a "spacer" type adapter inserted between two connectors. This in-line attenuator creates an air gap between the fibers (see figure 7-5A). The resulting divergence of the light across the air gap reduces the amount of optical energy coupled to the receiving fiber. These air-gap attenuators are manufactured for various connector types in appropriate lengths to provide fixed levels of insertion loss. In-line attenuators commonly are integrated into short (e.g., 1 m) jumpers. Variable in-line air-gap attenuators are also available (see figure 7-5B). In the example shown, the air-gap is varied by moving the left inner section to the right or left through screw action. Adjustments are carefully metered to obtain precise attenuation levels.

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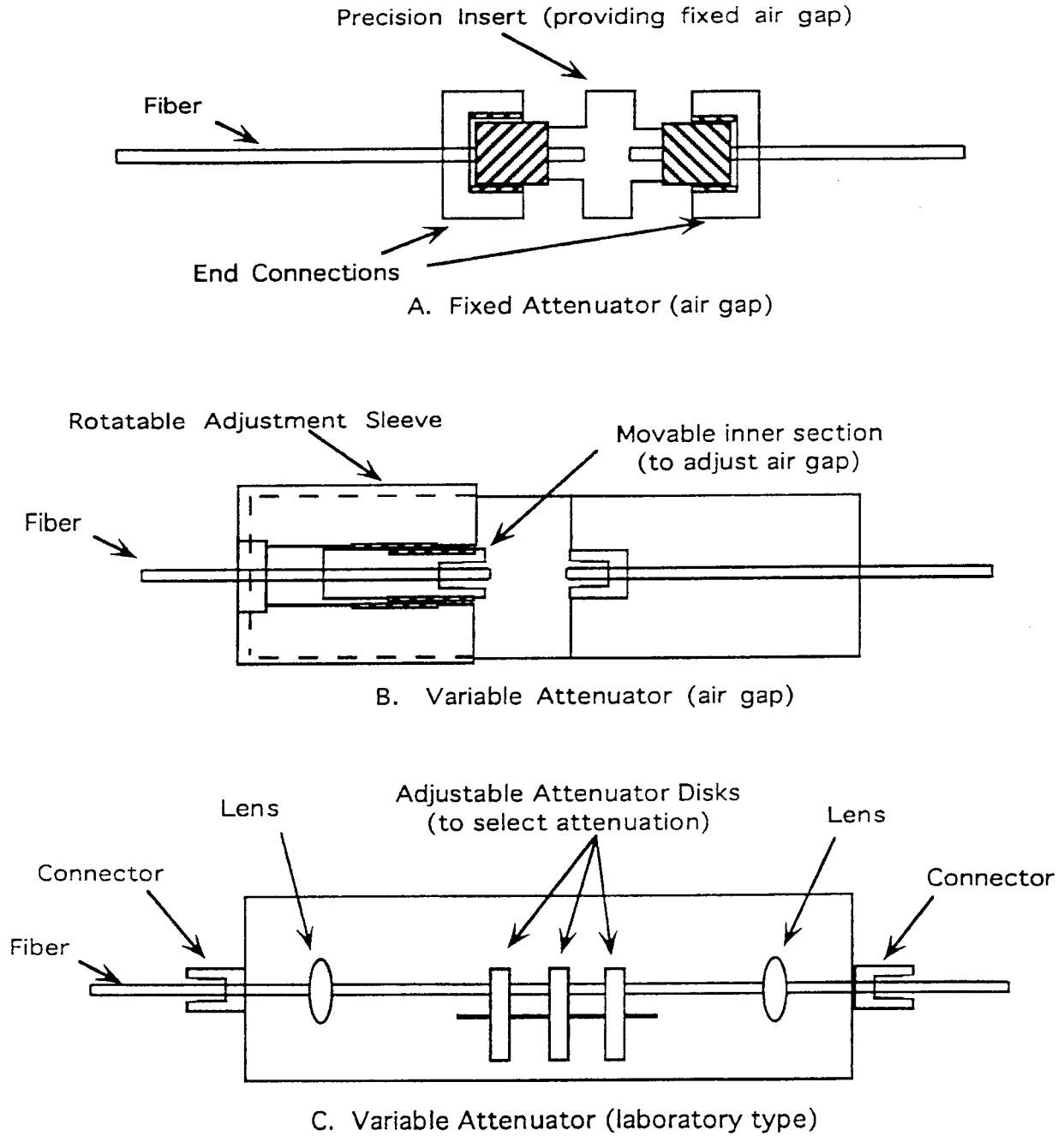


FIGURE 7-5. Internal construction of representative optical attenuators.

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b. Precision variable attenuator. An example of a more complex and expensive attenuator, used most commonly in a laboratory or testing environment where precise signal level control is required, is shown on figure 7-5C. In this attenuator, the light signal is collimated by a lens toward one or more attenuator disks. These disks typically are made of glass and are coated with thin films of anti-reflective, energy absorbing materials. The disks are aligned to minimize reflections and any redirection of the light signal from the fiber axis.

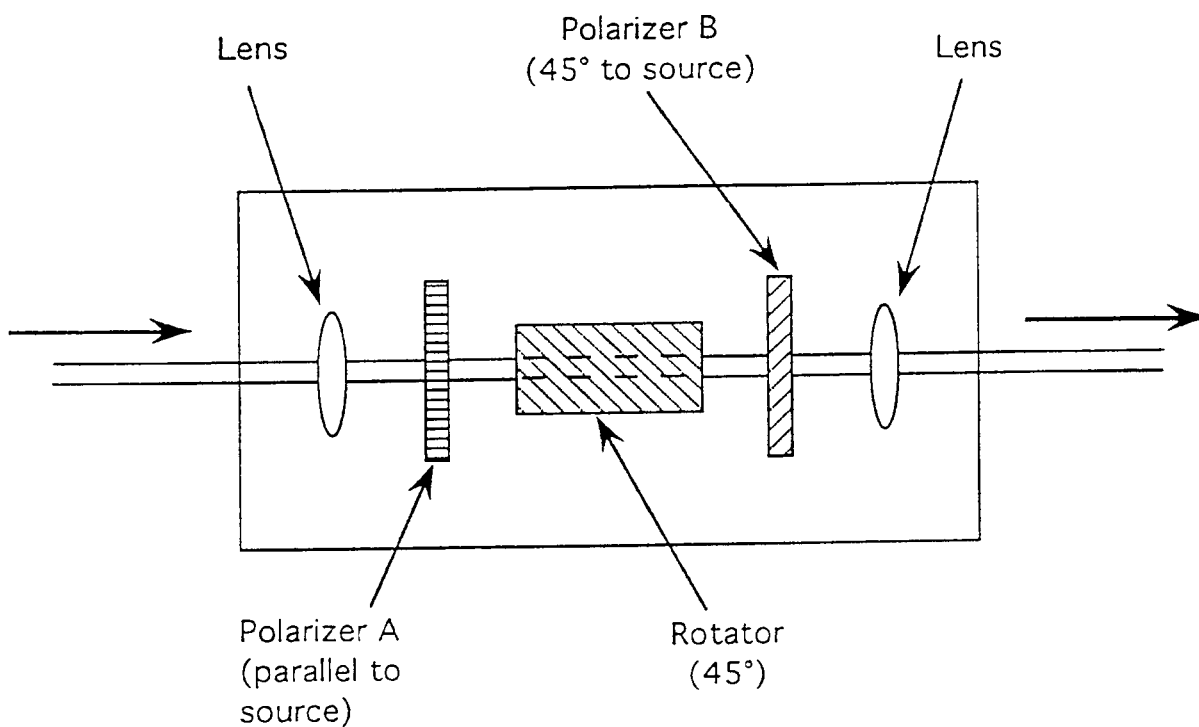
The amount of attenuation depends on the type and thickness of the coating material. Variable attenuators use interchangeable disks or disks with variable thickness coatings that are rotated through the light beam. The attenuation range of commercially available devices is 0-60 dB.

**7.5 Optical isolators.** Optical isolators are components used to suppress reflections which are unwanted but accumulate along the transmission path. Reflections occur at each device along a link such as connectors, splices, couplers, and attenuators. They also occur from fiber imperfections.

**7.5.1 Operation.** Optical isolators minimize reflected optical signals returning to the source by allowing optical power to pass in only one direction. This one-way operation is achieved by controlling the polarization of the original light signal and any reflected light. Commercially available optical isolators typically can provide isolation values of 40 to 60 dB. Optical isolators are manufactured as modular units with specific operating wavelength ranges and estimated losses. They are normally located near the transmitter where original signal polarization is still intact.

**7.5.2 Usage.** Optical isolators are most commonly used in links which employ laser sources. Light reflected back to a laser source from a link can be a cause of noise. Reflections are a particular concern when employing DFB lasers where a very stable signal is essential. Reflected energy from other components along the link cause instability of the laser output.

**7.5.3 Internal construction.** One common type of optical isolator is shown on figure 7-6. The original optical signal (moving from left to right) first passes through a lens that focuses and collimates light energy. The signal then passes through polarizer A which has a plane of polarization parallel to that of the light source. Next, the signal passes through the polarization rotator, which changes the plane of polarization by  $45^\circ$ , and then passes through polarizer B which is oriented for this  $45^\circ$  change. Reflected optical signals arriving at the isolator pass through polarizer B, and the rotator changes the plane of signal polarization an additional  $45^\circ$ . The plane of the reflected signal is now  $90^\circ$  in relation to polarizer A, and is blocked from returning to the source.



**FIGURE 7-6. Internal construction of an optical isolator.**

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**CHAPTER 8**  
**WAVELENGTH-DIVISION MULTIPLEXING**

**8.1 Wavelength-division multiplexing (WDM).** WDM is an optical domain technique which allows transmission of multiple optical signals over a single fiber by simultaneously using different wavelengths of light. By taking advantage of spectrally selective power splatters, the information carrying capacity of a single fiber can be increased significantly. The signal at each wavelength travels through the fiber independently, so each signal represents a discrete high bandwidth channel. Each transmitter and receiver pair is sensitive only to its designated wavelength. For example, video, voice, and data could be transmitted over a single optical fiber using WDM.

**8.2 WDM parameters.** Parameters to consider while analyzing WDM devices are as follows:

- a. Number of channels. This indicates channel capacity of the WDM device.
- b. Cost. A cost analysis should be conducted to determine if WDM techniques should be used or if a separate fiber per channel should be used.
- c. Operating wavelength. The operating wavelength for each WDM channel must precisely match each of the optical transmitter wavelengths.
- d. Crosstalk. This condition occurs when one channel's optical signal interferes with an adjacent channel, raising the noise floor and reducing the signal-to-noise ratio.
- e. Single-mode or multimode. This parameter indicates the type of FOCS the WDM is being used with.
- f. Channel spacing. Channel spacing is the wavelength gap between optical channels on a WDM.

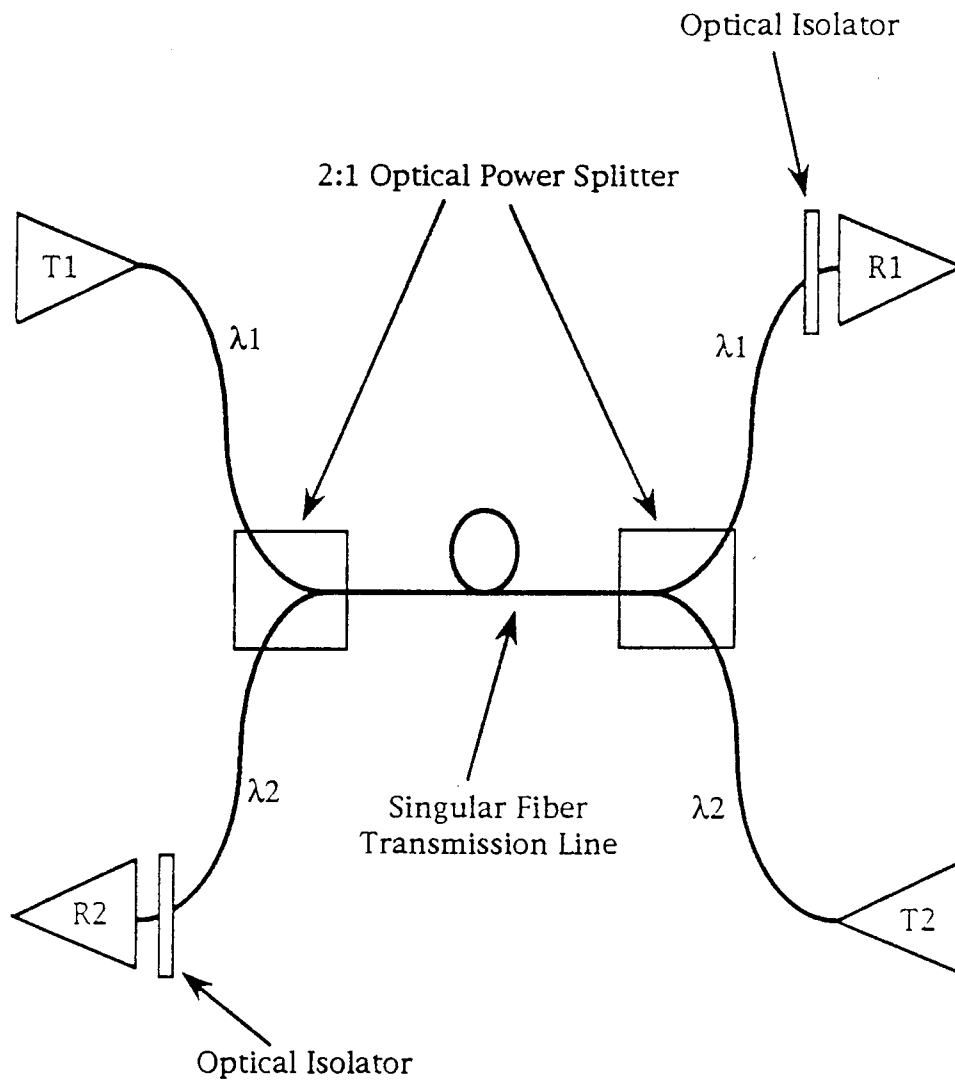
NOTE: Current FO technology supports multiplexing in the optical domain with WDM. When optical heterodyning techniques (coherent lightwave technology) are commercially available, optical multiplexing could then support many more channels per fiber. Frequency-division multiplexing will then be supported in the optical domain.

**8.3 WDM techniques.** Simplex operation (communication in one direction at a time) can be accomplished over simple FO links. To provide duplex (simultaneous communications in both directions) service, a "M at each end of the FO link can provide the separation of optical signals.

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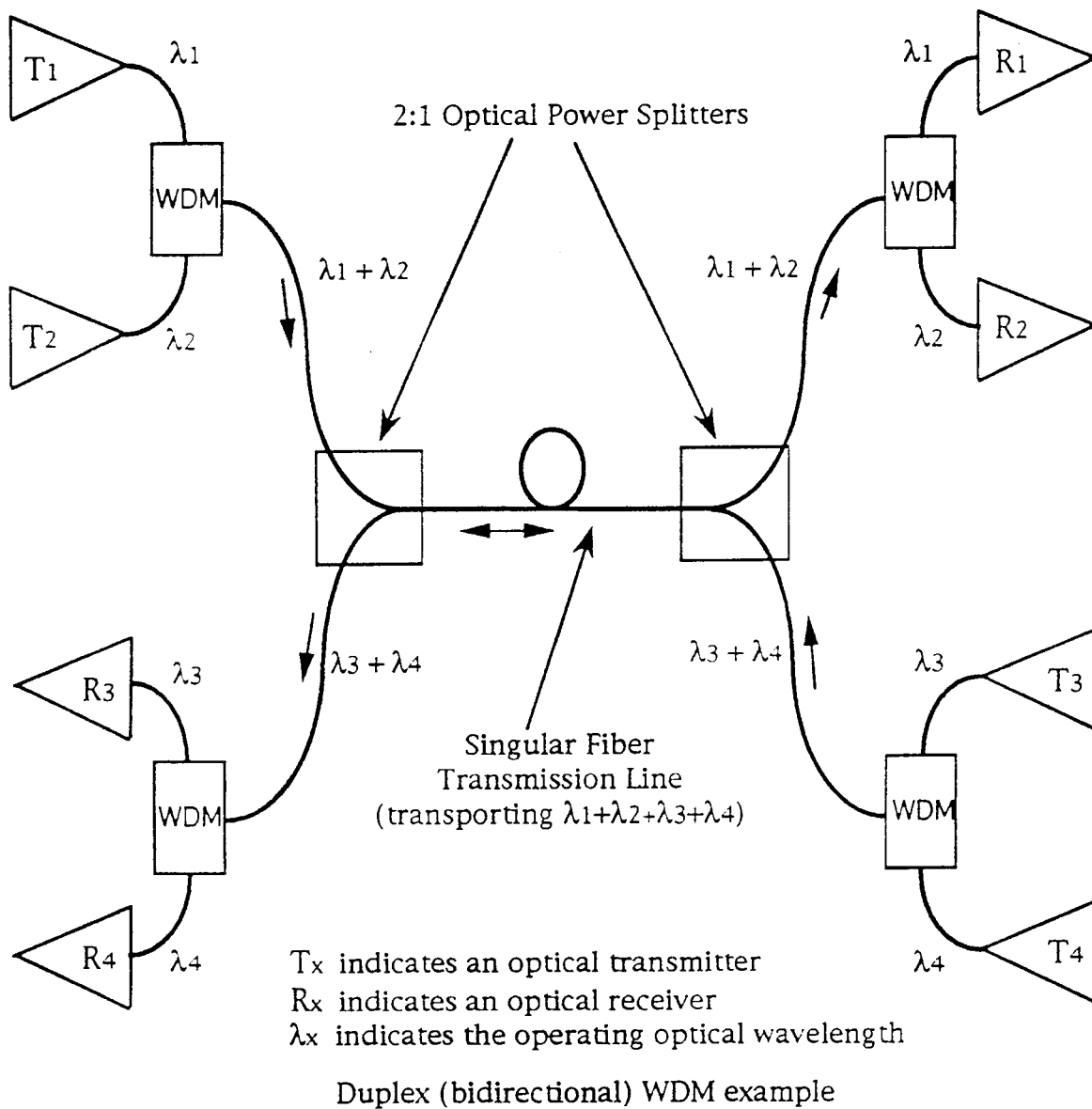
Another method to accomplish duplex operation is to use a power splitter and optical isolator as shown on figure 8-1. A combination of twin 2-channel WDM systems exchanging two channels of information forward and two channels of information in reverse is shown on figure 8-2. The later system can provide two duplex channels. An alternative to using the components of figure 8-2 is to use two 4-channel WDM devices, one WDM at each end of the fiber transmission line. WDM devices are connected at the transmitter and at the receiver, at both ends of the fiber link, to separate multiple input and output signals.

**8.3.1 Methods of accomplishment.** Optical, two basic methods can be employed to accomplish WDM. One uses spectrally selective (dichroic) interference filters to isolate individual channels. Although conceptually simple, this technique requires complex designs and a relatively large number of optical components. The other method uses prisms or diffraction gratings to achieve the combination and separation of wavelengths.



Example use of Power Splitters (couplers)

FIGURE 8-1. Example use of power splitters (couplers).



**FIGURE 8-2. Duplex (bidirectional) WDM example.**

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## CHAPTER 9 MODULATION AND CODING

**9.1 Modulation.** Modulation is the process of varying one or more characteristics of a carrier signal. In current FOCS, the carrier is near-infrared optical power which is changed in accordance with the information to be transported. FOCS may apply either a digital or an analog modulation format through intensity modulation. The optical power output of the transmitter is varied either abruptly (in the case of baseband digital modulation) or continuously (in the case of analog modulation). Intensity modulation W, also known as intensity modulation/direct detection (IM/DD), is the current method of transporting information over optical fiber.

**9.2 Digital modulation.** With digital modulation, the optical power level is varied abruptly. For binary systems, only two states are used. The light from an LED or LD is simply turned on and off in accordance with the data being sent. Most FOCS send binary, two-state signals. This allows unipolar coding (on or off) to be applied directly to an optical transmitter, in that it can only emit light or not emit light. Note that optical output is a function of electrical input. Communications systems interconnected at the optical level must use the same modulation scheme (including the data coding method), data rate, and compatible optical wavelengths and power levels.

**9.3 Analog modulation.** In analog modulation, the intensity or frequency of the carrier varies over a continuous range (rather than with discrete steps) in response to analog information.

**9.3.1 FM.** For coherent frequency sources such as are found in radio transmitters, transmitting analog information by varying the frequency of the carrier is known as frequency modulation (FM).

**9.3.2 AM.** Transmitting analog information by varying the amplitude (or envelope power) of the carrier is known as amplitude modulation (AM). AM is based upon a coherent carrier and it can be detected using either a synchronous or a power detector.

**9.3.3 IM.** Because optical sources are non-coherent and noise-like (true of most LDs and all LEDs), the FO industry commonly uses the term IM rather than AM to refer to this type of modulation. IM differs from AM because IM can only be detected using a power ' detector. In a power detector, the transmitted carrier is used as a reference for demodulating the information contained in the sidebands. The degree of coherence of the carrier is not important as long as the bandwidth of the detector is wide enough to accommodate the entire transmitted signal, a condition easily met with optical components.

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**9.3.4 Compound modulation.** Compound modulation may be used to transmit AM or FM over an IM/DD system if an AM or FM modulated subcarrier is used to intensity modulate an optical carrier. Future advances in coherent optical systems may eventually enable use of all modulation types commonly associated with radio transmission such as AM, FM, quadrature phase shift keying, etc., to directly modulate an optical signal.

**9.4 Analog versus digital.** Digital modulation techniques are usually employed rather than analog to exploit the versatility of digital processing to ensure information integrity. Analog signals are subject to noise accumulation which can compromise signal integrity. On digital links, noise does not accumulate (however, bit errors will accumulate on tandem links).

Techniques exist to detect and correct some transmission errors on digital links. There are, however, certain applications where analog techniques are preferred. The transmission of video using analog techniques is cost effective because no analog to digital and digital to analog conversions are required. The analog transmission of radio-frequency (rf) signals via analog means is also attractive due to the very low signal attenuation of optical fiber compared to coaxial cable or rf waveguides.

The relatively low cost of LEDs make them attractive for analog system applications. In comparison, LDs have more linear characteristics to better support analog signaling. As a result LDs are being used for rf and video transmission. For example, up to 24 video channels can be handled by a single-mode system, using a 1300 nm LD as a source.

**9.5 Controlling factors in modulation.** In conventional analog and digital FOCS, the modulation rate of optical transmitters is limited by the rise and fall time of electro-optical devices. Normally, FO transmitters are driven directly by a modulating current. FO transmitters may, however, utilize external modulation techniques. Light can be externally modulated by a Pockels cell, which creates a polarity disturbance to the light beam in step with a modulating signal. The result is intensity modulated light as seen by the receiver. Advantages of external modulation include faster modulation rates.

**9.6 Modulation bandwidth.** The maximum rate at which an optical source can be modulated is limited by certain performance characteristics of that particular optical source. This parameter is called the modulation bandwidth. Modulation bandwidth is the modulating frequency at which optical power output is reduced 3 dB from the power level at zero modulation. However, a 3 dB drop in optical power becomes a 6 dB drop in electrical power in the receiver, because the photodetector is a square law device. For this reason, some authors define modulation bandwidth as the frequency at which optical power decreases 1.5 dB. This usage permits direct reference to a corresponding 3 dB drop in receiver power, measured in the electrical domain.

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**9.6.1 Modulation bandwidth of LEDs.** The modulation bandwidth of an LED is also called the LED cutoff frequency. LED output power reduces with an increase in modulating frequency when time related limitations in light generating capability are reached. As the modulation frequency increases, some semiconductor carriers (electrons and holes) enter and leave the LED active region without recombining and releasing a photon (quantum of light).

A measure of the average amount of time a carrier remains in the active region without recombining is called the carrier lifetime ( $\tau_{cl}$ ). A variety of subscripts are used to represent this time interval. The modulation bandwidth of an LED is the reciprocal of the carrier lifetime or  $1/\tau_{cl}$ . The carrier lifetime of an LED can be shortened, thereby increasing modulation bandwidth, by doping and reducing the thickness of the active region. An example upper bound of bandwidth for an LED for analog applications is 110 MHz. An example upper bound of data rate for an LED (handling nonreturn to zero (NRZ) data) is 250 megabits per second (Mbps).

**9.6.2 Modulation bandwidth of LDs.** The modulation bandwidth of an LD is also the modulation frequency at which power output falls to the -3 dB level. Time related limitations in LD light generating capability also cause the drop in output power as modulating frequency is increased. In LDs, the reduction in output power is caused by an oscillatory variation in the laser output which occurs with higher modulation frequencies. This phenomenon is caused by delays in the sequential storage and release of energy by the carriers and photons in the LD active region (cavity) during lasing action. This oscillation or resonance can be controlled somewhat by semiconductor geometry and biasing current.

The modulation bandwidth of LD light sources is high and normally not a problem in designing communications systems. LD modulation bandwidths in the tens of GHz are possible and are generally much greater than the capabilities of electronic signal generating equipment. More common LDs are available which will handle NRZ data rates of approximately 1 gigabits per second (Gbps).

**9.7 Coding.** Coding is the conditioning of binary signals for transmission. Coding refers to signal transformations designed to improve communications by enabling the transmitted signal to better withstand the effects of various channel impairments and provide more efficient use of the available bandwidth. The various waveforms commonly used for coding in FOCS are illustrated on figure 9-1.

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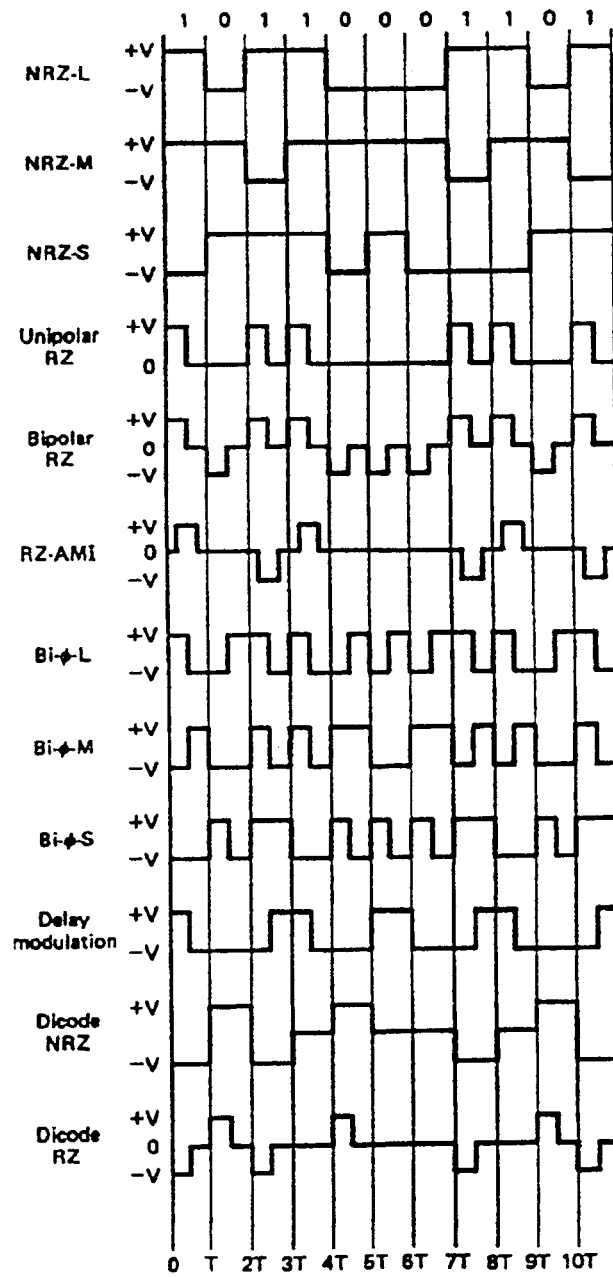


FIGURE 9-1. Digital coding.

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They are classified into the following groups:

- NRZ
- Return-to-zero (RZ)
- Phase encoded
- Multilevel binary.

**9.7.1 NRZ.** This class of signaling represents bit values according to whether the signal (during a bit interval) maintains the current level (for the duration of a bit interval) or makes a level change. The following subgroups have been defined: NRZ-L (L for level), NRZ-M (M for mark), NRZ-S (S for space). The most extensively used waveform is NRZ-L. Limitations include lack of synchronization capability (i.e., data clock is not easily recovered) and a dc component can grow if a long string of mostly the same bit value (1 or 0) is sent (some equipment may produce errors if not designed to handle this scenario). A bit-stuffing (or special bit stream massaging) step can be performed on the data to prevent the 'dc' problem.

**9.7.2 RZ.** RZ waveforms as described on figure 9-1, consist of unipolar-RZ, bipolar-RZ, and RZ-alternate mark inversion (AMI). With RZ codes the signal returns to the neutral state during a bit interval. While this somewhat simplifies clock recovery (bipolar-RZ), the modulation rate is higher than with NRZ for the same data transmission rate. Consequently the bandwidth of an RZ signal is greater than an NRZ signal for the same data transmission rate. As with an NRZ signal, there can be a dc component (solution is comparable to that in the NRZ case).

**9.7.3 Phase encoded.** This signaling class includes the biphas-level (also known as Manchester coding), biphas-mark, biphas-space, and delay modulation (also known as Miller coding). These schemes are popular in optical communications because they provide enough information to support synchronization (data clock) from a predictable transition each bit interval. Additionally, they provide an inherent absence of a dc component and an inherent error detection.

**9.7.4 Multilevel binary.** This signaling class uses more than two level transitions to encapsulate robustness into the binary data stream. This group includes dicode and duobinary formats. With dicode the zero level is sent when there is no signal transition during a bit interval. Duobinary signaling makes ingenious use of pulse shaping and a one-bit memory delay to utilize intersymbol interference (ISI) in a constructive manner; Normally ISI is destructive when received energy pulses are smeared in time to an adjacent pulse. Duobinary coding requires three levels of signaling but produces a narrow bandwidth.

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**9.7.5 Coding levels and timing.** Note that the high and low voltages may be reversed in some electronics. Regardless of the encoding scheme, the receiver must determine when a bit begins and ends. The receiver must resolve for each signaling time element whether the signal represents a high (1) or low (0). Two approaches, asynchronous and synchronous transmission, exist to extract this timing.

**9.8 Asynchronous transmission.** Asynchronous transmission, also called 'bit synchronization,' is accomplished by start-stop bits which are arranged to occur cyclically in time to differentiate them from the data bits. When no character is being transmitted, the transmitter sends an 'idle' signaling element, typically equivalent to the binary 1. The beginning of a character is signaled by a start bit with a binary value of 0. This is followed by the character (data to be transmitted), consisting of (typically) 5 to 8 bits of data and, in some cases, a parity bit. The last bit of the character is followed by a stop bit (or bits), typically equivalent to the binary 1. Asynchronous transmission is simple, but requires overhead of two to three bits per character.

**9.9 Synchronous transmission.** A more efficient means of transport is synchronous transmission. In this mode, blocks of characters or bits are transmitted without start and stop codes, and the exact arrival time of each bit is developed from the signaling algorithm. The clocks in the electrical domain of the transmitter and receiver are periodically synchronized. The clocking information is embedded in the data signal or can be external to it. For digital signals, clocking information can be achieved with biphasic encoding. For analog signals, the carrier itself can be used to synchronize the receiver (commonly based on the phase of the carrier).

**CHAPTER 10**  
**FIBER OPTIC COMMUNICATIONS SYSTEM DESIGN**

**10.1 Introduction.** Fiber optics system design emphasizes the complex arrangement of network topology, media type, and communication system components. The complex arrangement affects bandwidths, data rates, and overall performance of the system.

**10.1.1 Scope.** The scope of this chapter is to introduce the concepts of system planning and design for long-haul and tactical fiber optics communications systems. The handbook addresses interoperability and performance standards for long-haul and tactical fiber optic communications systems. Long-haul is defined by FED-STD-1037 as the Defense Communications System and extends up to global distances. Long-haul communications are generally characterized by higher level of users (National Command Authority), more stringent performance requirements, longer distances between users, fixed and recoverable assets, and interfaces to public telephone networks and satellite communications. This implies complex interconnections, large traffic volumes, and wide system bandwidths. Tactical communications are generally characterized by fixed size, self contained voice and data communication systems to facilitate command and control within and in support of tactical forces. Some tactical communication forces are mobile requiring extremely short installation times (hours) necessitated by relocation. These systems are also characterized by many nodes and networks of users over relatively short distances.

**10.1.2 Relationship to other chapters.** The system design of a FOCS involves a complex arrangement of fiber cable, terminal equipment, and network nodes. Chapter II emphasizes link design, which is a simpler arrangement and usually a subset of a fiber optics communication system. It normally is composed of a point-to-point transmission link where the signal is transmitted from one point and is received at another point. Chapter 12 emphasizes system and link testing, performance monitoring, test equipment, and other operational considerations for fiber optic communications systems.

**10.1.3 Methodology.** The methodology used to describe the system design of a long-haul or tactical FOCS is based on an example of a large geographical field facility telecommunications system as shown on figure 10-1. This example encompasses many types of user requirements.

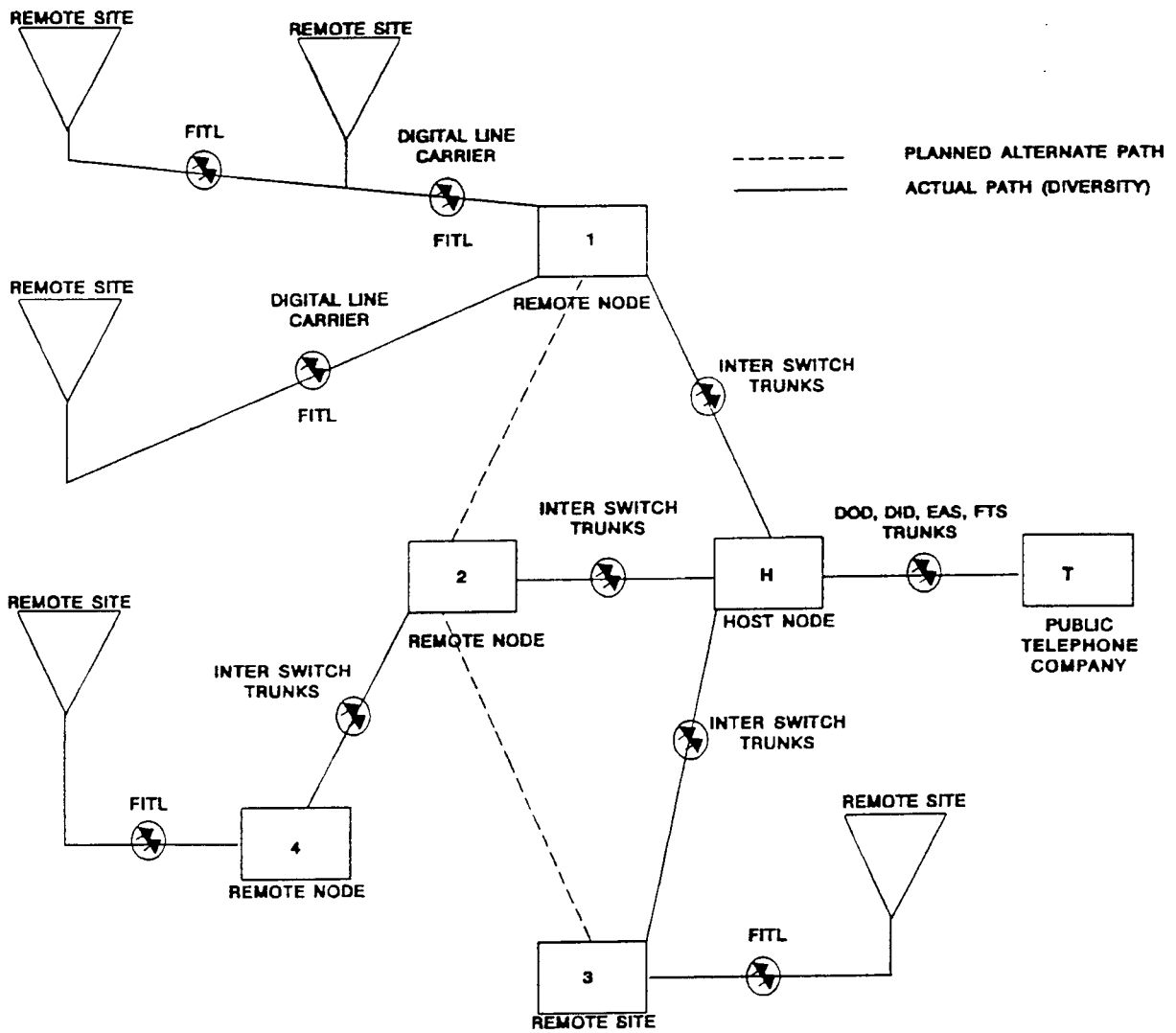


FIGURE 10-1. Typical fixed facility telecommunications system.

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**10.2 System planning and requirements development.** The general method for establishing a FOCS design requires the following system planning and requirements development steps:

- System planning to accommodate current or future user requirements
- System growth projections, move, add, and change provisions
- Identifying detailed user communication requirements
- Identifying current and future node locations, building terminals, equipment rooms, telephone closets, and jack and cable tray locations by site survey
- Identifying outside cable paths, easements, right-of-way, highway, bridge, and railroad crossings, hazardous material locations, and soil conditions by site survey
- System architecture and network topology planning
- System (aggregate) bandwidths, data rates, communication protocols, and traffic models
- System security (protected distribution systems)
- Fiber count development and cable design specifications
- Fiber distribution provisions including cross connect jumpers
- Fiber optic terminal equipment performance specifications and sizing
- System performance monitoring, remote provisioning, synchronization, and testing.

**10.2.1 System block diagram.** Figure 10-1 illustrates a complex long-haul FOCS that can be used to illustrate system planning, requirements development, and design. The system shown has "long-haul trunks" via a fiber link to an adjacent local telephone company. The system has a complex arrangement of on-post communication nodes interconnecting a large number of users with voice, data, and media services from various clusters of buildings, vans, etc., arranged as communication nodes. Each node is assumed to have switching, multiplexing, and fiber optic terminal equipment. The cable between nodes will contain varying quantities of fiber, depending on system bandwidth, growth projections, redundancy, node topology, and alternate paths (diversity).

**10.2.2 System planning.** Figure 10-1 represents a planned conversion of the long-haul fixed facility FOCS from Centrex (local telephone company supplied services) to an integrated voice/data/video telecommunications system located onsite. As shown, this system has a host switching node and several remote switching nodes, plus numerous remote sites. To acquire global connections, the site must connect trunks to the local telephone company. It is assumed that fiber optics transmission medium will be used to connect these nodes and sites together.

The first step in planning a system conversion of this type is to locate a node for the host telephone switch and central data processing, operations and maintenance center. Usually this node will be centrally located and surrounded by a cluster of buildings, trailers, vans,

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etc. This node will serve as the main route to trunk out to the local telephone company, communicate directly with the remote switch nodes and sites, and serve the local user group at this node. Remote nodes and sites are similarly configured, with clusters of buildings, trailers, vans, etc., located within local loop distance limitations (15,000 ft). The system planner then has accomplished the first step in the system design by identifying user population groups and locating telecommunication switching nodes.

The next step in the system planning process is to forecast user growth projections at the selected nodes, as well as to forecast moves in populations, added construction, or changes (upgrades) in technology that require additional bandwidth and data rates. Population shifts can have a very dramatic impact on link bandwidths, and should be considered, particularly if new construction is planned in the area.

System planning must then include detailed user surveys to identify current and future telecommunications needs so that an estimate of fiber optic link bandwidths, data rates, and fiber counts can be obtained. Links that are required to transmit voice, data, and video simultaneously can require immense bandwidths, which can only be accomplished by very high data rates and additional fiber channels. The system planner then must quantify intranode and internode voice, data, and video traffic. This task is normally part of a larger telecommunications planning effort, and would not be the sole responsibility of the fiber optic system planner. However, the information must be obtained in order to determine system bandwidths and data rates for the fiber optic links.

Another required planning step is to survey current and future inside building wiring and the outside cable plant. The purpose of this survey is to provide the information necessary for design of the physical layout of building wiring and outside cable facilities. The fiber optics system designer must participate in this survey to determine:

- locations of building terminal rooms for placement of fiber distribution panels, connectors, jumpers, and cross-connect equipment
- locations of equipment rooms for installation of fiber optic terminal equipment
- locations of cable paths, trays, etc. for inside building placement
- identifying hazardous areas in buildings such as asbestos ceiling plenums
- locating outside cable path routes, buried (and aerial where required)
- locating easements, right-of-way, highway crossings, bridges, and rail crossings where special boring may be required
- locations of hazardous material, identifying cultural archeology sites, and other soil conditions that may require special trenching permits.

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This survey will then permit the fiber optics system designer to identify cable and building wiring paths and determine link distances for trunking between telecommunication nodes.

Also, link distances can be determined for fiber-in-the-loop (FITL) applications used between remote switch nodes and remote sites. This application provides a fiber transmission path from a host or remote telecommunications node directly to customer premise equipment (such as computers, communications controllers, etc.).

**10.2.3 System architecture and network topology.** A system architecture for the required fiber optics links encompasses the overall plan for developing a functionally operational network. It shows how the network is physically and logically configured, describes functional capacities of the communications systems and protocols through which the various parts of the network interoperate.

Some definition of terms is appropriate (FED-S.TD-1037) when discussing the various parts of a system architecture such as links, nodes, networks, and paths. A link is a communication facility existing between adjacent nodes of a network. A node is a terminal of any branch of a network, or an interconnection common to two or more branches of a network. A network is an interconnection of three or more communication entities and usually one or more nodes. A path describes the route a signal takes over the network, and can be composed of many links as diverse as there are types of network topologies. When referring to synchronous optical network (SONET) definitions, a link is essentially the same as a line (see appendix E).

Network topology describes the physical (real) configuration of a network or the logical (virtual) configuration of a network. In most cases for long-haul networks, the topology for the physical network differs from the topology for the logical network. This is because the fiber cable plant is arranged along a path or route that is generally linear, and resembles a bus topology, where the nodes are connected serially. The reason for this arrangement is the fiber cable is buried in one trench, and is composed of only one cable regardless of the number of nodes being served. An example of physical bus topology is the arrangement for the remote site and remote nodes 2 and 4 connecting to the host node as shown on figure 10-1, the two remote sites connecting to the remote node 1 and to the host node, and the remote site connecting to the remote node 3 and to the host node. The host node is shown on figure 10-1 as a hub and the entire network arranged as a physical star when viewing the trunk connections to remote nodes 1, 2, and 3, and the public telephone company. This physical topology has meaning only when discussing route planning or diversity (alternate paths) since the logical topology really determines the functionality of the network.

A true logical bus network requires each node, except those at the ends of the bus, to transmit in and to receive from two directions at once in order for all nodes to communicate

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with all other nodes on the bus. In the example on figure 10-1, the system design requires the remote switches located in the remote nodes to communicate directly to the host switch located at the host node, which acts as a communications hub. Therefore, all the remote nodes are connected as a logical star to the host node, even though, as example, remote nodes 4 and 2 appear on figure 10-1 as a physical bus. Remote sites normally communicate to the remote nodes through digital line carrier equipment which can be linear drop, add/drop, or rings if the alternate path (diversity) is implemented. These type of networks will be explained in the following paragraphs.

Another type of network topology is a ring, where every node has exactly two branches (links) connected to it. There are requirements in long-haul communications networks for ring topology where diversity of physical path is important to avoid loss of communications when one link is cut or damaged. An example of this application would be the implementation of the paths (dotted) shown on figure 10-1. Any single path cut to any of the remote nodes (not sites) would not result in loss of communications to the host node because an alternate path exists. In this example, the implementation of the dotted paths could result in several adjacent ring networks, which now becomes a mesh network.

The logical operation of a star and ring topologies can become complex. However, fiber optic terminal equipment is available to accomplish the required communication links.

Figures 10-2, 10-3, 10-4, 10-5, and 10-6 illustrate fiber optic terminal equipment applications for implementing the various network technologies. The optical carrier digital rates (OC-N) and the synchronous transport signal (STS-N) shown on these figures were established by ANSI T1.106-1988 and are described as part of the SONET communications standard (see appendix E). The digital tributaries (DS-N) are also standard North American digital multiplexing data rates (see appendix E).

Figure 10-2 illustrates a traditional point-to-point FOCS application where each node contains fiber optic terminal (FOT) equipment necessary to multiplex digital (electrical) data at DS-N data rates and transport this data optically at OC-N rates to the other node, and vice versa. Inherent in this drawing is the requirement for a minimum of two fiber cables to permit data to travel in each direction simultaneously. The point-to-point link represents the simplest and most widely used network topology, and is an ideal platform to build more complex hubs (stars), rings, add/drops, and linear drop (tapered) networks.

Figure 10-3 illustrates a hub (star) FOCS application where a host node is in direct communication with a number of remote nodes. On figure 10-1, this represents the host node in communication with remote nodes 1, 2, and 3. There are several methods of treating data at a hub. One method is to dedicate separate FOT equipment at the hub node to serve each remote node in DS-N signal increments, which makes the hub a network of point-

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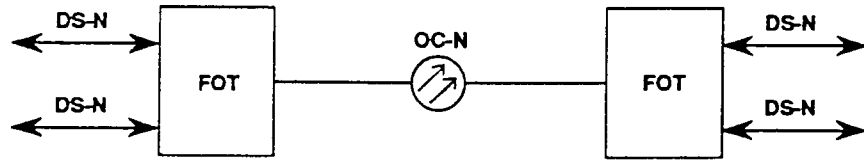


FIGURE 10-2. Point-to-point link.

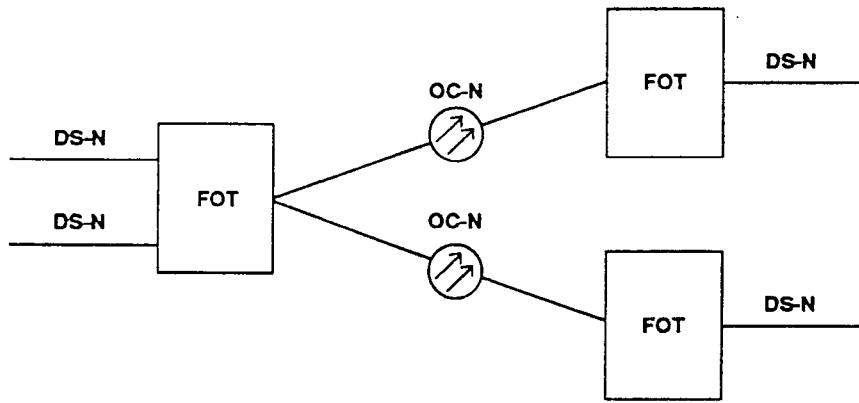


FIGURE 10-3. Hub (star) link.

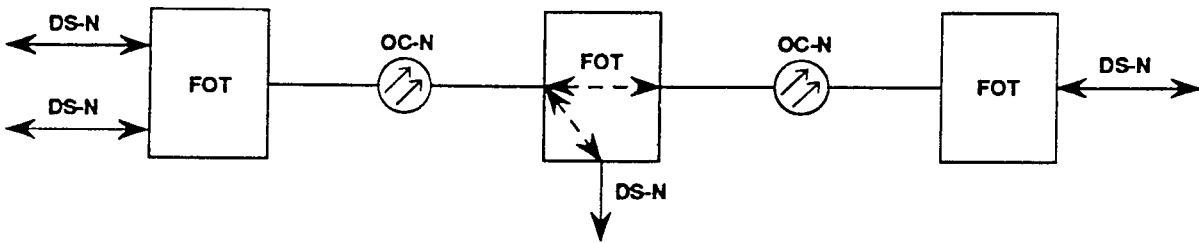


FIGURE 10-4. Linear drop link.

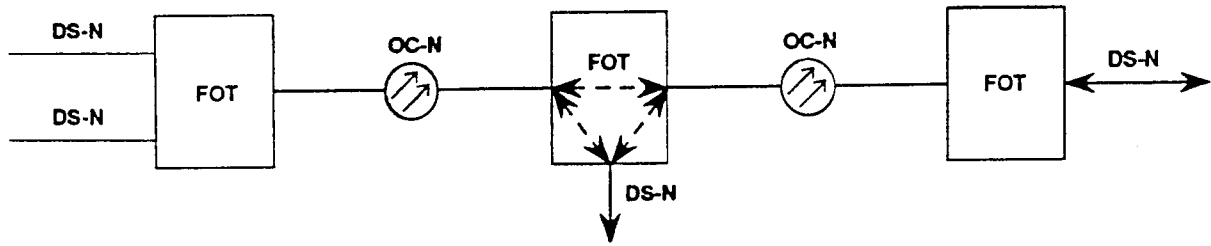


FIGURE 10-5. Add/drop link.

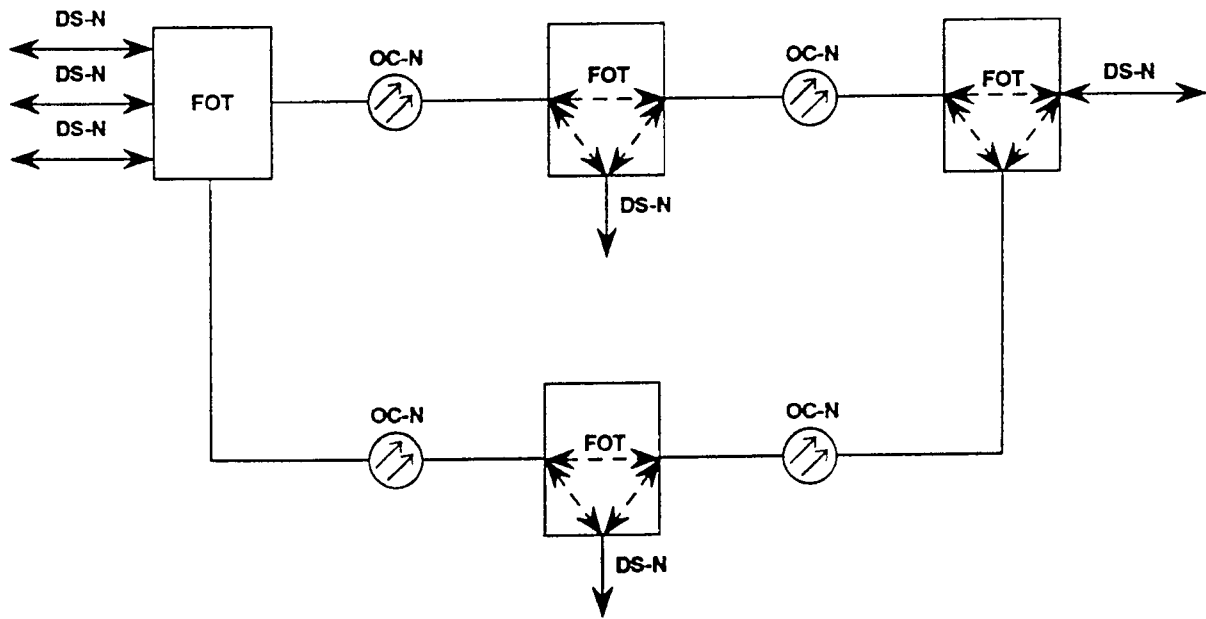


FIGURE 10-6. Self healing ring link.

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to-point links with a common physical hub. The other method is to route traffic to remote nodes in STS- I signal increments using common FOT equipment at the hub node (see appendix E). In this case the optical carrier is multiplexed at only STS-N digital payloads. Current technology requires conversion from electrical-to-optical (and vice versa) regardless of the network topologies and data rates used.

Figure 10-4 illustrates a linear drop FOCS application where a host node serves two or more remote sites from common FOT equipment. On figure 10-1, this could represent remote node I serving the remote sites communicating with it. This application, known as tapering, allows a remote site to send and receive local traffic to the remote node, but does not allow one remote site's traffic to be dropped at another remote site.

Figure 10-5 illustrates an add/drop FOCS application where two or more remote sites share a common optical carrier back to a remote node, but allowing traffic to be dropped or added at each remote site. This technology requires a time slot interchange at each remote site, complicating the terminal equipment by adding the functionality of switching, where the time slots occupied by a particular multiplexed voice/data stream are reassigned to different node paths or addresses or reused for new voice/data streams. The flexibility offered permits site personnel to implement various traffic arrangements, grooming networks for maximum utilization and bandwidth management. The time slot interchange feature allows flexibility in assigning DS-N signals and VT and STS-1 tributaries.

Figure 10-6 illustrates a self-healing ring FOCS application where two or more nodes, remote and host, share two optical carrier paths for protection in case of cable cuts or equipment failure. This ring is dual fed, that is, DS-N and STS-N digital signals are routed in opposite directions around the ring. Performance monitoring by the receiving end FOT equipment determines which digital signal is received and utilized.

A ring requires a separate burial trench for each optical carrier path cable, to fully utilize its benefits. Figure 10-1 illustrates a ring connection with the dotted path shown between nodes 1 and 2.

It is noted that communication path protection can be achieved (in case of equipment failure only) by utilizing the protection feature on FOT equipment, without the need of a ring. This feature essentially monitors the received signal from two redundant point-to-point optical links, sharing a common fiber optic cable (separate fibers). When the signal degrades on the active link, automatic switching occurs to transfer the digital signals to the standby link. An alarm is then sent to the host node for a site maintenance call.

**10.2.4 System bandwidth and data rates.** The system bandwidth and data rates for long-haul or tactical telecommunications networks are usually determined on a link-by-link basis,

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which is the basic building block of optical communications. The system bandwidth and data rates are not the same as the fiber bandwidth, which is limited by material and waveguide dispersion as discussed in chapter 5. These system requirements dictate the types of FOT equipment and fiber cable, allowable distances, allowable BER, and other link parameters as discussed in chapter 11.

Referring to figure 10-1 for a typical military telecommunications network, there are several different types of links. The link from the host node (H, T) to the local telephone company is a voice/data trunk to achieve global connections. These trunks carry Direct Inward Dialing (DID), Direct Outward Dialing (DOD), Extended Area Service (EAS) and Federal Telephone Service (FTS) as well as other data services.

The links between the host node and the remote nodes (H, 1, 2, 3, and 4) are interswitch trunks, carrying local voice/data/video traffic between various on-site users, and long distance traffic. These trunks carry concentrated traffic at digital carrier rates multiplexed to optical carriers (see appendix E).

The links between the remote nodes and remote sites are used to transport concentrated traffic from outlying areas to a switching node (nodes). This traffic can be concentrated on a digital carrier (electrical) such as a DS-1 rate, and multiplexed to an optical carrier (see appendix E).

The FITL carry light traffic from user premises to remote sites for transport to switching nodes. FITL are designed as economical links and are planned to replace copper (twisted pair cable) outside plant to these users. FITL optical carrier rates have not been standardized in the industry, although a low SONET rate could be used. The data rate is usually limited from one to four DS-1 rates. Each one of these links must be designed with appropriate optical carrier data rates for the current, future, and change requirements anticipated from the user survey.

An example of this system design process is the host node connection to local telephone company trunk. On figure 10-1, the entire post population of users will at some time desire to place or receive a long distance call via this trunk (DID, DOD, FTS, EAS). Although this calculation is beyond the scope of this handbook, telecommunication traffic engineering could (as an example) estimate the requirement for the following:

- 40 each DS-1 DID, DOD, EAS trunks
- 25 each DS-1 FTS trunks.

The total aggregate traffic is then 65 DS-1 trunks (each at 1.544 Mbps) for a total optical data rate required of 100.36 Mbps plus optical overhead data rates needed for signaling,

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network synchronization, etc. The standard SONET optical carrier to handle this requirement is OC-3, 155.52 Mbps, which is used in this example.

Separation of the FIS trunks from the remaining trunks may be required because of the different common long distance carriers involved. In this case, the FIS trunks would move to a separate OC-1 carrier, 51.84 Mbps, and the remaining trunks would still require the OC-3 carrier of 155.52 Mbps. The system designer has the information, based on the site survey and telecommunications traffic engineering, to select FOT equipment to accomplish data rates with the assurance that adequate bandwidth exists for future growth requirements.

Another example of the system design process is the interswitch trunks between the remote nodes 1, 2, 3, and 4, and the host node as shown on figure 10-1. The telecommunication traffic engineering must determine the local calling pattern between users and determine appropriate switching equipment trunk requirements to handle the calls. This traffic is usually much larger than off-site traffic, thus, the switching equipment is normally designed at DS-3 digital rates (44.736 Mbps). These trunks are usually protected (redundant) requiring additional links. Assume in the example shown on figure 10-1, that a total of eight DS-3 trunks are required, based on telecommunication traffic engineering and switch design parameters. This will result in a total optical data rate of 357.88 Mbps plus overhead, etc. The closest standard SONET optical carrier to select is the OC-12 (622.06 Mbps), since OC-9 (466.56 Mbps) is not normally offered to the equipment manufacturers.

The remaining remote site and FITL sites could be sized for appropriate optical carrier rates using the same methods as previously described. The designer should consider standard North American SONET data rates where possible to allow for interoperability of equipment and avoiding future obsolescence.

In designing a WAN using LAN type data links, a designer could choose the fiber distributed data interface (FDDI) ANSI standard based on optical tokens circulating on a dual counter-rotating token ring topology. This standard permits connections up to 200 km with maximum distances between nodes of 2 km. The data rate for FDDI standard is fixed at 100 Mbps which determines system bandwidth and data rates. The distance restriction between nodes may require a designer to employ a long-haul transmission link to interconnect distant LANS. Using LAN gateways, or the newer asynchronous transfer mode (ATM) equipment, a SONET long-haul transmission link could be implemented for this application.

Another communication network requirement in use is Integrated Services Digital Network (ISDN), an integrated voice/data telephone network based on International Telegraph and Telephone Consultative Committee (CCRM) standards. Current technology has a basic data rate that supports two 64 kilobits per second (kbps) voice/data channels and one 16 kbps data channel on a single twisted pair. A primary data rate of 1.544 Mbps is also available with

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today's technology. Later improvements will encompass video or multi-media applications, and will be based on the broadband ISDN (B-ISDN) standard. The ISDN type of network starts with the local loop on copper twisted pairs connecting to a telephone switching module. Since standard DS-1, STS-N, and OC-N data rates are employed between switching modules, the system design process follows the previous methods.

**10.2.5 Fiber counts and cable design.** The system designer will be required to calculate fiber counts in link cables to accommodate the various point-to-point connections. Having established system bandwidth and optical carrier data rates, the designer can determine FOT terminal equipment requirements, and then fiber counts for the cable. It is general industry practice to trench (bury) only one cable between adjacent nodes. It is difficult to simultaneously bury two cables in the same trench; therefore, this practice is generally avoided. The same is true if the fiber is pulled through conduit. Since the fiber count per link can vary considerably, each optical link will normally have a different fiber count.

An example of a fiber count calculation is the interswitch trunk between a remote node and a host node discussed previously. An OC-12 optical carrier data rate was selected. To communicate in both directions requires two fibers to the FOT equipment. This type of trunk is usually protected, requiring duplication of the FOT equipment and fibers, which then raises the total fiber count to 4. A designer should plan for bad fibers, either due to the construction trenching process, rodents, or other environmental causes. Thus, additional fibers are added for maintenance purposes. In this case, industry practices would normally add 4 additional fibers.

A designer may be uncertain on future growth requirements, particularly when the FOT equipment and optical carrier rates have little room for growth and the only solution is to add more links. This can occur when the link is close to the attenuation or phase dispersion limits, preventing higher optical data rates (see chapter 11). Another factor will be the explosive growth of data and multi-media applications, which may get transported in the same cable as the interswitch trunks, but on different fiber. Because of these reasons, the interswitch trunk link example may require 4 additional fibers, adding the final total to 12 fibers. Eight of the additional fibers (4 are active for the protected link) can be used for periodic testing to verify attenuation and/or phase dispersion specifications over time, usually yearly tests.

Fiber cable design can take a variety of design approaches, however, it is becoming common practice to order fiber cable in unit sizes that range from 1, 2, 4, 6, 8 ....216. This permits the system designer to implement each link close to the fiber count required. Part of the design process is to allow for terminating the active and dark (unused fiber) on fiber distribution panels, which are patch panels or cross connect panels. Distribution panels are used at all nodes in the network, regardless of whether the fiber will terminate on FOT

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equipment, or be connected to additional fiber for termination on a more distant node. This allows the craft technician maximum flexibility in maintenance testing and allows easy provisioning for growth or changes.

An example of this type of decision can be seen on figure 10-1. The fiber count between the host node and remote nodes 2 and 4 differ because each remote node is directly communicating with the host node on an interswitch trunk. Thus, if for example ' 12 fiber is required for each remote, then 24 fiber would be specified for the cable between the host node and remote node 2, and 12 fiber between remote nodes 2 and 4.

The designer has the choice of splicing 12 fiber from the 24 fiber cable at the remote node 2 for connection to remote node 4. If done in this manner, the splicing would probably be done in a manhole in the street, and 12 fiber would be brought to the remote node 2 and 12 fiber would continue on to the remote node 4, each requiring splicing off the main 24 fiber cable. Figure 10-7 illustrates this approach.

Another design choice which offers better maintenance conditions and flexibility is to bring the 24 fiber cable from the host node, and the 12 fiber cable from the remote node 4 into a fiber distribution panel located in the remote node 2 building (see figure 10-8). At that point connectorized fiber optic jumpers would be used to passively connect 12 fibers from remote node 4 to the appropriate fibers in the 24 fiber cable to the host node. This approach gives the craft technicians better working conditions (inside a building) to perform tests, make changes, or add FOT equipment. This approach has the disadvantage of requiring the burial of two cables in the same trench leading to the node building. If this trench is a short distance, or if inner duct conduit is provided for each cable within the main conduit, then the contractor can pull the cables through this trench.

It should be noted that three separate cables are required for the approach that splices fiber in a manhole and two cables if both cables are brought into the building where a fiber distribution panel is located.

**10.3 System performance.** New FOCS will employ digital transmission techniques. MIL-STD-188-111 establishes mandatory performance standards and optional design objectives for long-haul and tactical FO links. The standard prescribes minimum standards for the following specifications and should be consulted during all design efforts. These are:

- data rate (bit rate)
- BER
- jitter
- optical transmitter and receiver characteristics
- distortion (see appendix A)

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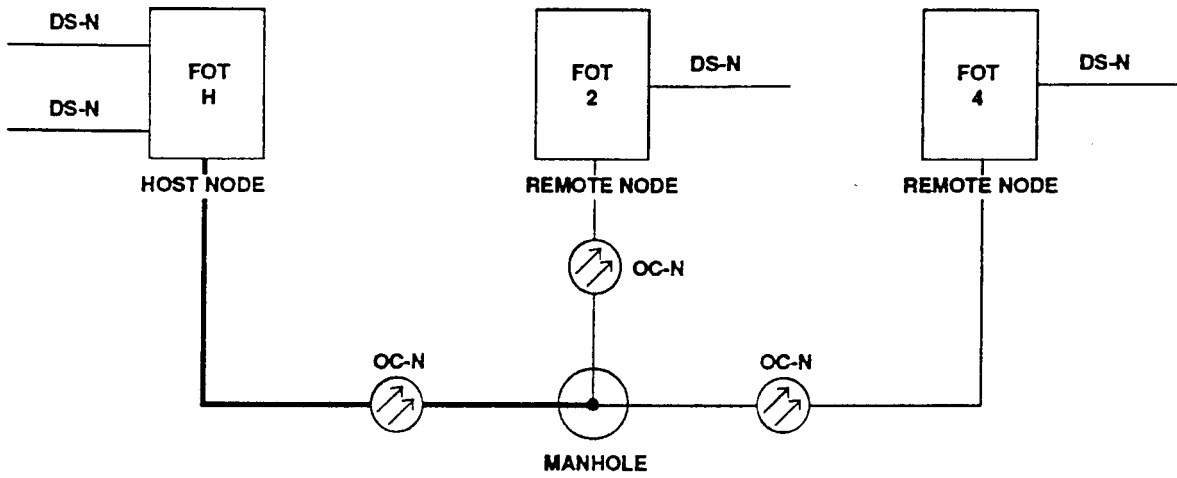
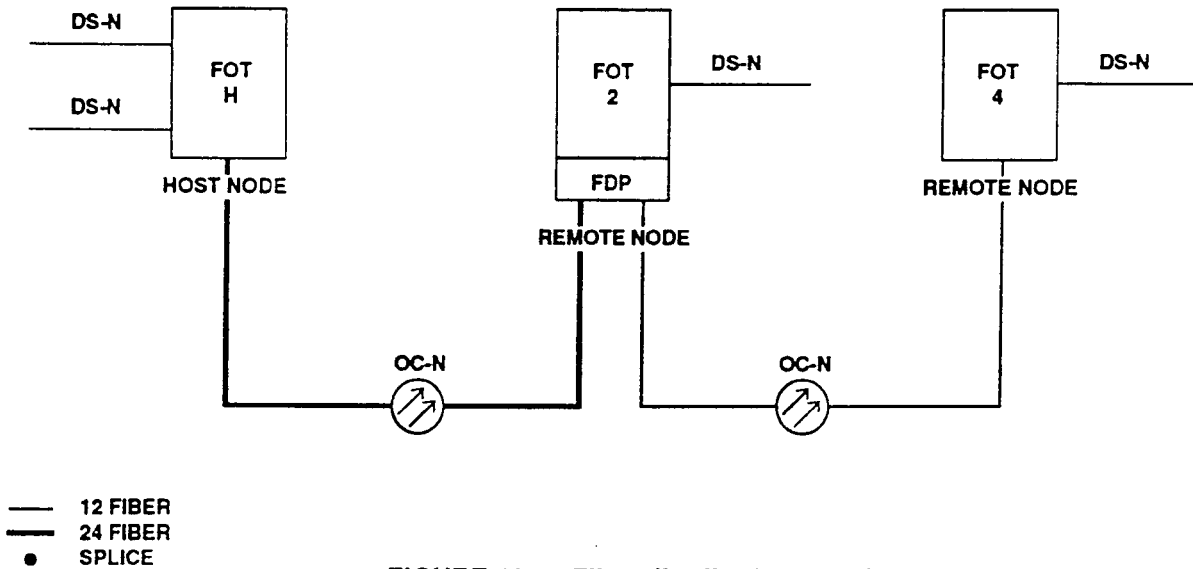


FIGURE 10-7. Fiber manhole splicing.



- 12 FIBER
- 24 FIBER
- SPLICE

FIGURE 10-8. Fiber distribution panel.

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- power margin
- optical fiber cable characteristics
- reliability and link availability.

The system data rate was discussed previously, where system data rate requirements were selected within standard SONET optical carrier rates or LAN rates such as FDDI. A system designer must then follow the link design calculations discussed in chapter 11, accounting for link attenuation and phase dispersion to see if the rates chosen are achievable for the distances required. The key performance requirement is to achieve a low BER for error free communication.

BER is the ratio of the number of erroneous bits in a digital transmission to the number of bits transmitted. MIL-STD-188-111 states that for long-haul use, a Link BER of less than  $10^{-11} \times K$ , where K is the link distance in kilometers. If a 1 db margin is used for certain fiber link characteristics, then this specification is approximated at a BER of  $10^{-9}$ . The tactical BER requirement is  $10^{-9}$  or less regardless of link distance. These specifications require a received signal-to-noise ratio greater than 12 to 15 db. Thus, transmitter power, receiver sensitivity, connector and fiber attenuation, phase dispersion, and jitter all contribute to the performance of the link.

A performance monitoring tool used for FOCS is to measure bit errors distributed over time, by counting actual bit errors in selected time intervals. This approach is called errored seconds and displays error counts by time interval. The method can be used to provide data for tripping alarm thresholds, or for automatic protection switching, in the case of a severely errored frame seconds (SEFS), a measurement parameter for STS-N section per SONET specifications.

Other parameters that can be measured are coding violations, or parity bit violations. These measurements can occur at the DS-N digital tributaries as defined by the SONET standard. Counting registers are built into the FOT equipment and total counts are recorded in quarter hour to current day increments.

**10.3.1 System synchronization.** *The evolution of long-haul transmission networks has been from the present asynchronous networks to the SONET standard, which is a synchronous optical network. Because of this evolution, network timing becomes important so that all network clocks (oscillators) remain synchronous (in phase) to avoid dropping data bits and creating bit errors. Non-synchronized networks, or poorly synchronized networks may appear timed, but over intervals from hours to days, the internal clocks between the various FOT equipment will get out of phase causing periods of loss of data. The actual cause of loss of data is very hard to trace, but is usually attributed to network timing.*

*From the book DDM-2000 Guide, copyright (c) A T&T. Reprinted with permission of ATT&T Current methods of network synchronization or timing for FOT equipment follows three methods: free running from an internal oscillator, loop timing from a high speed interface, or external timing via a dedicated (non-data) DS-1 channel These three methods can be combined*

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*into three network configurations: free running/loop timing as shown on figure 10-9, external timing/loop timing as shown on figure 10-10, and external timing as shown on figure 10-11.*

*The free timing/loop application operates without an external clock. The timing is initiated from the local FOT internal oscillator since it is inherent in the OC-N data stream being transmitted to the remote FOT. The remote FOT recovers the clock from the data stream and uses it to time its transmitted data that is being sent to the local FOT (application is a full duplex network).*

*Another combination of timing is external timing and loop timing as shown on figure 10-10. The host node external timing oscillator is synchronized to an external stratum 3 (see ANSI T1.101-1987) or better clock source whose timing is traceable to a better and higher level primary source. That timing is transmitted to a remote node that is loop timed by recovering timing from incoming OC-N signals. This method of timing is required by the SONET standard, particularly when low speed STS-IE interfaces are used to interconnect these nodes with other SONET networks.*

*A final timing application for optical carriers is shown on figure 10-11. In this application each FOT equipment node has an external clock source which is stratum 3 or better, and each node timing oscillator is synchronized by the other nodes' transmitted signals. This timing is known as plesiochronous timing, referring to multiple primary timing sources. This timing would be used between major host nodes of a long-haul telecommunications network.*

**10.3.2 Line and path protection switching.** Communication path protection can be achieved by line and path protection switching. Line in this discussion is a SONFR term that is synonymous with link. This feature of fiber optics terminal equipment monitors received signals from two redundant point-to-point fiber optic links. Line and path protection switching occurs automatically when a signal fail condition is detected or is activated from external commands by maintenance personnel due to signal degraded conditions. Line protection switching is initiated by an FOT receiver detecting signal failure. This is usually non-revertive switching of the FOT adjacent node transmitter. Signal failure can be loss of signal, loss of frame, line alarm indication signal, or a link BER exceeding  $10^{-3}$  as defined by the SONET standard. Signal degradation is defined as BER exceeding  $10^{-9}$ . Path protection switching, as defined by the SONET standard, is accomplished by self-healing rings, which monitor and transfer data according to a common network management center process, but the basic link protection method in the ring is the same.

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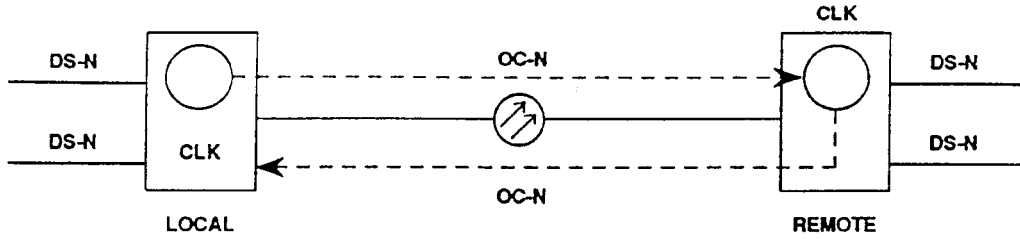


FIGURE 10-9. Free running/loop timing.

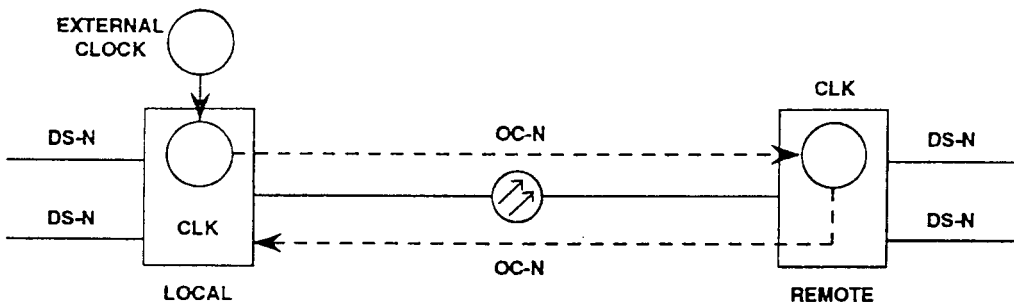


FIGURE 10-10. External timing/loop timing.

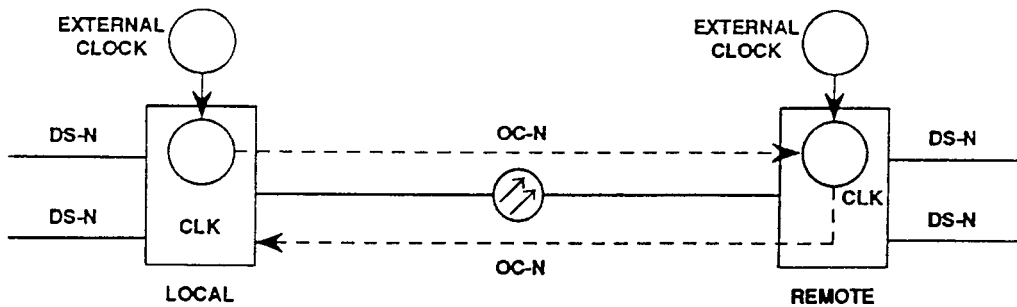


FIGURE 10-11. External timing (plesiochronous).

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**10.3.3 System performance monitoring.** System performance monitoring is used to provide proactive maintenance of a long-haul or tactical network. Proactive maintenance detects signal degradation by alarming on certain network parameter thresholds, and sending those alarms to a network maintenance center for follow-up activity. Thresholds are set so the signal degradation is detected before signal failure, but indicative of problems that require attention. Maintenance personnel then have the option to determine the cause of the problem, and/or implement manual protection switching and change out FOT equipment components. Performance monitoring and protection switching can be accomplished from a remote host node.

When operating a SONET network, sections, lines, and paths within that network are monitored according to the SONET standard. Table 10-1 lists those parameters monitored. Thresholds are set according to desired parameters for degraded performance indication. FOT equipment registers usually provide numerical counts on errored seconds and coding violations from quarter hour to current day. Registers are initialized by maintenance center personnel, usually once a day after retrieving current day reports.

**10.3.4 Transient performance.** Transient performance of a long-haul or tactical network should be specified in the event of loss of power, cable cut, or other loss of signal event where the network must restore communications and synchronization. The transient performance is specified as a time interval before error free transmission of signal can begin. This interval is usually in the range of 1 to 2 seconds.

**10.3.5 Transmission delay.** There are transmission delays between the electrical to optical interface for fiber optics terminal equipment. For a Link, both ends of the link will experience these delays, and this parameter should be specified since the delay may have an effect on the telecommunications protocol used in the path. This delay is not expected to exceed 100 microseconds for a link.

**10.3.6 Environmental specifications.** The environmental specifications of long-haul and tactical FOCS are two-fold: one for a controlled environment within a building, and the other an uncontrolled outside environment. In addition, the DoD might also impose additional chemical, biological, or nuclear requirements on this equipment. Normal industry practice for outside uncontrolled environment specifies the following:

Shelf air inlet temperature: - 40 degrees C to + 75 degree C (noncondensing)

Humidity: 5 percent to 95 percent

Cooling: forced air convection (fans) above +50 degrees C

**TABLE 10-1. System monitoring performance parameters, SONET.\***

<b>FACILITY</b>	<b>PARAMETER</b>
OC-N Optics	Laser Transmitter Bias Current Laser
STS-N Section	Severely Errored Frame Seconds (SEFS)
STS-N Line	B2 Coding Violations (CV) B2 Errored Seconds (ES) B2 Errored Seconds Type A (ESA) B2 Errored Seconds Type B (ESB) B2 Severely Errored Seconds (SES) B2 Unavailable Seconds (UAS)
STS-N Path	B3 Coding Violations (CV) B3 Coding Violations Far End (CVFE) B3 Errored Seconds (ES) B3 Errored Seconds Type A (ESA) B3 Errored Seconds Type B (ESB) B3 Severely Errored Seconds (SES) B3 Unavailable Seconds (UAS)
VT Path	B5 Coding Violations (CV) B5 Coding Violations Far End (CVFE) B5 Errored Seconds (ES) B5 Errored Seconds Type A (ESA) B5 Errored Seconds Type B (ESB) B5 Severely Errored Seconds (SES) B5 Unavailable Seconds (UAS)
DS-3 Low Speed	P-Bit Coding Violations
DD3 Transmux	P-Bit Coding Violations CP-Bit coding Violations CP-Bit Coding Violations Far End F-Bit and M-Bit Coding Violations

\*SONET standards per ANSI.105-1988 and 106-1988

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## CHAPTER 11 LINK DESIGN

**11.1 Introduction.** Fiber optic link design is based on the data rates and nodal locations established in the system design process discussed in chapter 10. The performance requirements are based on the minimum specifications contained in MIL-STD-188-111. Industry practices are incorporated in the design process where appropriate.

**11.2 Scope.** The link design steps outlined in this chapter are limited to digital circuits. Analog concepts and concerns are briefly covered in earlier chapters and a detailed method for calculating SNR is contained in appendix C. This chapter primarily addresses long-haul and tactical link design; however, most of the concepts can be applied to any type of optical link.

**11.3 General design objectives.** Maximum commonality of components is recommended in order to achieve efficiencies in procurement, installation, testing, and maintenance. Commercial off-the-shelf components and performance specifications should be incorporated in the design. Bit rates, transmitter powers, receiver sensitivities, and fiber characteristics should be consistent with those commercially available. Tactical designs must consider the special requirements inherent in field applications. The most important objective is to meet, as a minimum, the BER requirements specified in MIL-STD-188-111. If all links in a system meet or better the BER standard, the probability is high that the system BER performance will be satisfactory.

**11.4 Link design steps.** The design of fiber optic links should follow a logical sequence of steps. However, some of these steps may loop back if a problem is encountered. Major steps that must be taken are:

- (1) identify node locations
- (2) survey for best link routing
- (3) measure total fiber path length
- (4) determine optical line rate from system design information
- (5) select operating wavelength and spectral width
- (6) select fiber, transmitter, and receiver
- (7) make power budget calculations
- (8) make rise time and dispersion calculations
- (9) repeat steps 5-8, seeking the best design.

The design process is relatively simple with the exceptions of determining power penalties, calculating rise time, and verifying that the link is neither power nor dispersion limited. A worksheet is provided in the following pages to assist the designer. As indicated on the

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worksheet, a worst case design approach is recommended. Designers should obtain worst case parameter values from vendors that represent manufacturing tolerances, aging, temperature, supply voltages, etc. The following paragraphs address those worksheet line items that are complex or require clarification.

**11.5 Optical line rate.** The optical line rate is related to data rate in accordance with the digital coding employed. Since NRZ coding is the most bandwidth efficient, it has become the standard for most applications. The line rate for NRZ is equal to the data rate, but the line rate for RZ, biphase, Manchester, bipolar, and dicode is twice the data rate.

In practice, coding and the optical line rate are fixed by the electrical multiplexing equipment and are therefore determined by the system designer.

**11.6 Operating wavelength.** The selection of the nominal operating wavelength (i.e., 850, 1310, 1550 nm) is directly related to fiber type, optical line rate, and link distance. Also, the requirement to match the fiber, transmitter, and receiver to a particular wavelength must be considered. Typical relationships between these parameters are shown on figure 11-1. This figure illustrates the limitations that can be imposed by attenuation and dispersion.

For example, a 3 dB decrease in transmitter power will decrease the power limited distance of 1310 nm multimode fiber, which has an attenuation coefficient ( $\alpha$ ) of 0.8 dB/km, by 3.75 km [ $3 \text{ dB}/(0.8 \text{ dB/km})$ ]. A 3 dB decrease in receiver sensitivity would produce the same result. This distance reduction applies to all optical line rates. The downward slope of the power limited lines is based on a decrease in receiver sensitivity proportional to  $10 \log R$ , where  $R$  is the optical line rate. Dispersion limited distances are based on typical dispersion coefficients.

Figure 11-1 is not intended to provide a final answer to wavelength selection, but is intended to present a starting point. Detailed power budget and dispersion calculations which follow may lead to a different choice.

**11.7 Optical Fiber selection.** From a link design standpoint, the most critical factors to consider are the fiber's attenuation and dispersion coefficients. Since single-mode (SM) fiber is superior to multimode in both these areas, it has become the fiber of choice for all high-bit-rate long distance links. In industry, single-mode fiber is also being used in local distribution (fiber-in-the-loop) trunking.

Since most tactical configurations utilize LED based transmitters, which do not couple well with single-mode fiber, graded-index multimode fiber is normally used. However, MIL-STD-188-111 does not preclude the use of LD transmitters or SM fiber.

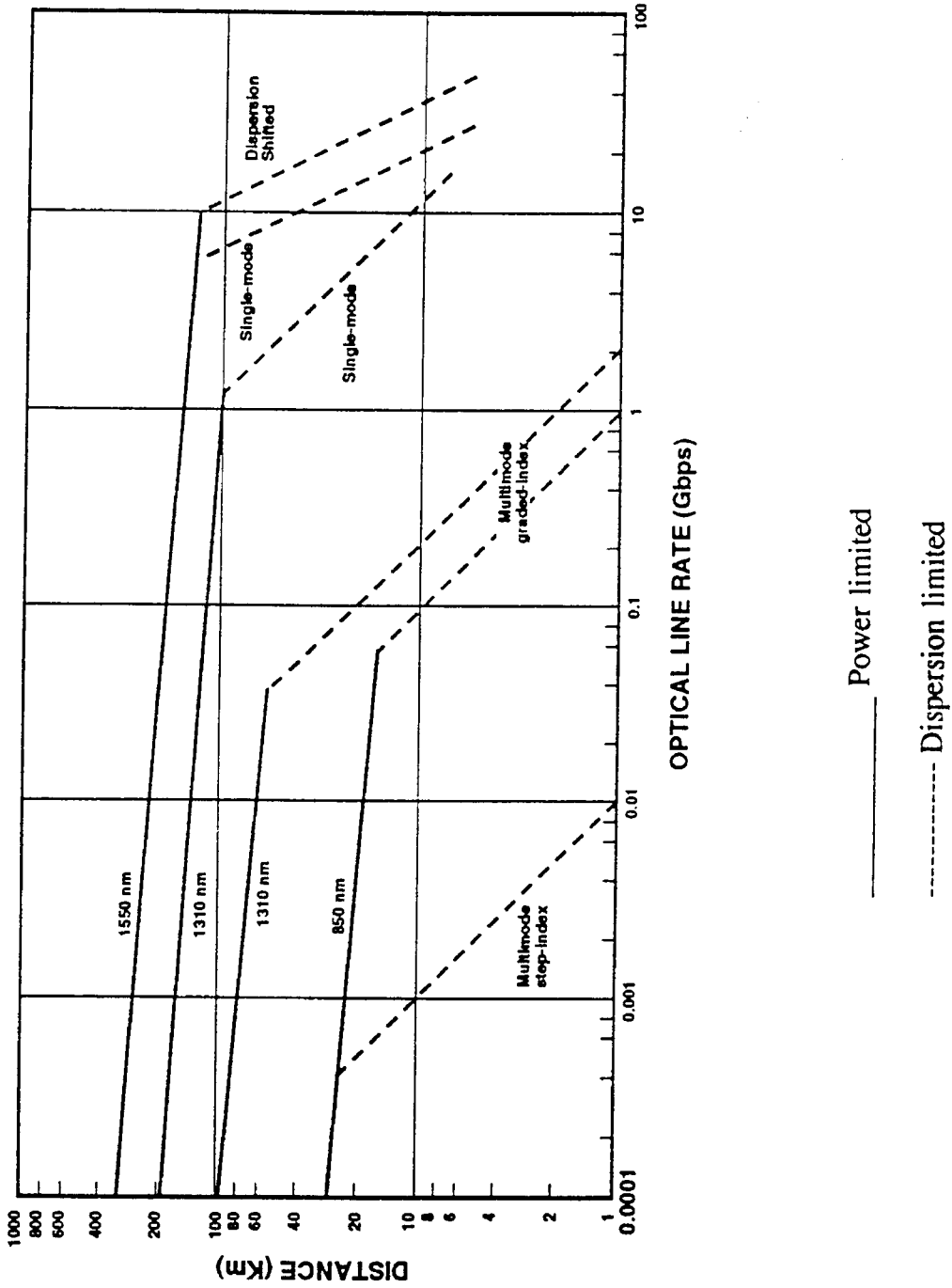


FIGURE 11-1. Power and dispersion limited distances.

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MIL-STD-188-111 specifies that for long-haul links the attenuation coefficient for multimode fiber shall not be more than 3.5 dB per km at 850 nm, nor more than 1.0 dB per km at 1310 nm. It also specifies that the attenuation coefficient for single-mode fiber shall not be more than 0.5 dB per km at 1310 nm, nor more than 0.3 dB per km at 1550 nm. Standard commercial fiber meets these requirements. The tactical specification is that 'the attenuation coefficient for cabled fibers used in tactical applications shall be in accordance with appropriate Military Specifications within Federal Stock Group (FSG) 60' (see MIL-STD-188-111 for more information on FSG-60).

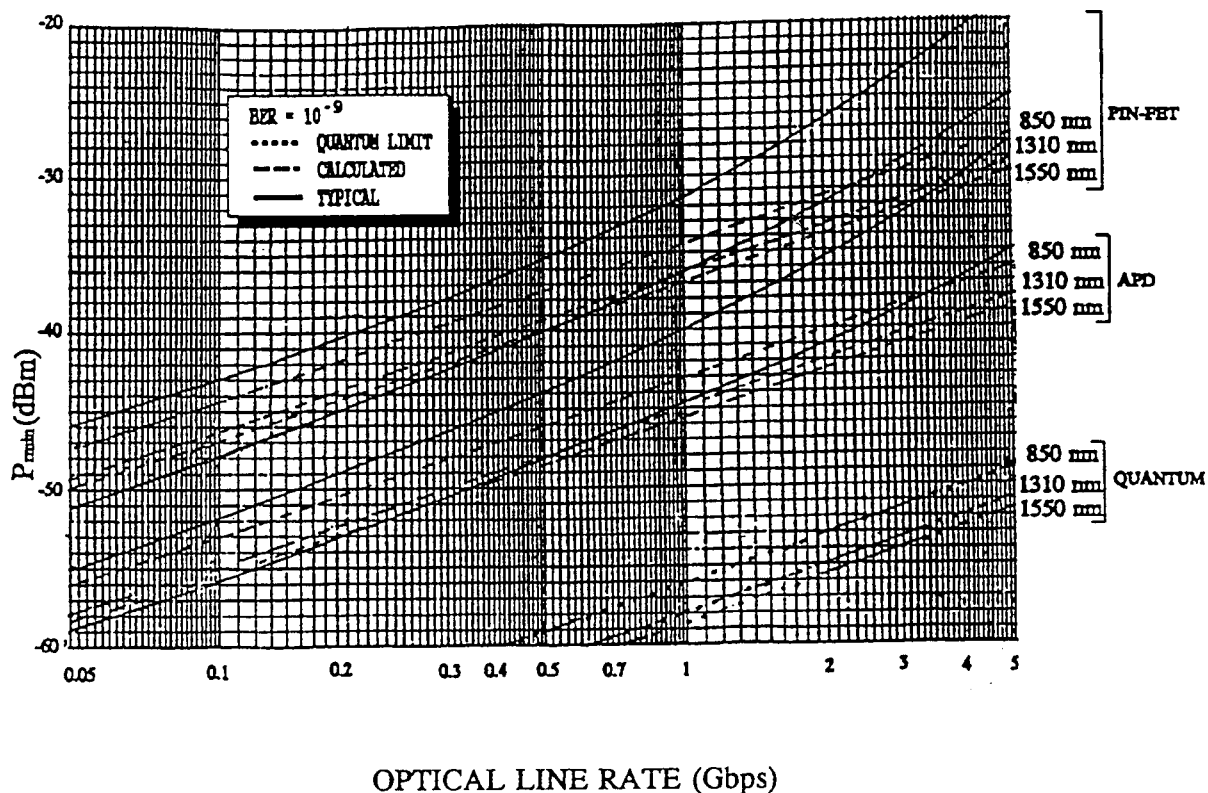
MIL-STD-188-111 specifies that multimode fiber dispersion coefficients for long-haul links shall not exceed 120 picoseconds/nanometer-kilometer (ps/nm-km) at 850 nm nor 6 ps/nm-km at 1310 nm. For single-mode fiber, the requirements are 3.5 and 20 ps/nm-km at 1310 and 1550 nm, respectively. The tactical requirement for multimode fiber at 1290 nm is 6 ps/nm-km maximum. The remaining standards are under consideration. Standard commercial fiber meets all these requirements.

Detailed fiber specifications should be obtained from the manufacturer. Additional information which might assist in the selection process is contained in chapter 5.

**11.8 Optical transmitter selection.** Transmitter characteristics are discussed in chapter 6. From a link design standpoint, the three most important considerations are output power, spectral width, and modulation bandwidth. In general, LD based transmitters are employed in high-bit-rate long distance applications due to their relatively high power outputs, narrow spectral widths, and high modulation bandwidths.

MIL-STD-188-111 does not address transmitter power requirements, other than power stability. This requirement is that the power output shall not vary from its nominal value by more than 3 dB over the life of the transmitter (attributable to aging only). The only spectral width specification is that LED widths (full-width-half-maximum) shall not exceed 120 nm. However, MIL-STD-188-111 (in appendix C) recommends that widths for LDs meet the standards established by ANSI T1.106-1988. Modulation bandwidths are not standardized, but they must be directly related to the maximum bit rate. To allow for additional fiber and receiver bandwidth restrictions, the minimum transmitter modulation bandwidth (-3 dB) should be approximately 1 hertz (Hz) per bit (NRZ coding).

**11.9 Optical receiver selection.** The most critical receiver characteristic is sensitivity, which is defined as the minimum optical input power (normally expressed in dBm) required to meet a specified BER. Calculated and typical sensitivity curves are shown on figure 11-2. Values for N (required photons per bit) are based on a BER of  $10^{-9}$  and selected receiver characteristics. The quantum limits to receiver sensitivity are based on a Poisson distribution of detected photoelectrons. This distribution gives a  $10^{-9}$  probability that zero photoelectrons will be detected



Calculated Receiver Sensitivity

$$P_{min} \text{ (dBm)} = 10 \log(NhfR_o/2) + 30 \text{ dB}$$

where:

$N$  = required number of photons/bit

$h$  = Planck's constant =  $6.626 \times 10^{-34}$  joule-sec

$f$  = light frequency in hertz =  $3 \times 10^8 / \lambda$

$\lambda$  = wavelength in meters

$R_o$  = optical line rate in bits/sec

$N(\text{APD}) = 400$  photons/bit

$N(\text{PIN}) = 3200$  photons/bit

$N(\text{Quantum limit}) = 21$  photons/bit

FIGURE 11-2. Receiver sensitivity curves.

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when a pulse is received which on average should generate 21 photoelectrons. Due to noise generated in the receiver plus other imperfections, an N of about 400 is an excellent number for avalanche photodiodes (APD) designs. PIN type receiver N values are typically 5 to 10 times greater than those for APD receivers. A theoretical analysis of receiver sensitivity is contained in appendix B.

MIL-STD-188-111 does not provide standards for receiver sensitivity. However, it does specify link BER limits that impact the sensitivity requirements. The limit for tactical links is  $10^{-9}$  (regardless of link length) and that for long-haul links is  $10^{-11} \times K$ , where K is link length in km. If receiver sensitivities are not obtainable from the manufacturer for BER values other than for  $10^{-9}$ , these can be estimated by using figure 11-3. The indicated relationships between BER and relative received powers normalized to  $10^{-9}$  illustrate the minor differences between  $10^{-9}$  and  $10^{-11}$  power requirements. But note, however, that the PIN diode receiver is 10 dB less sensitive absolute power than the APD receiver as shown on figure 11-2.

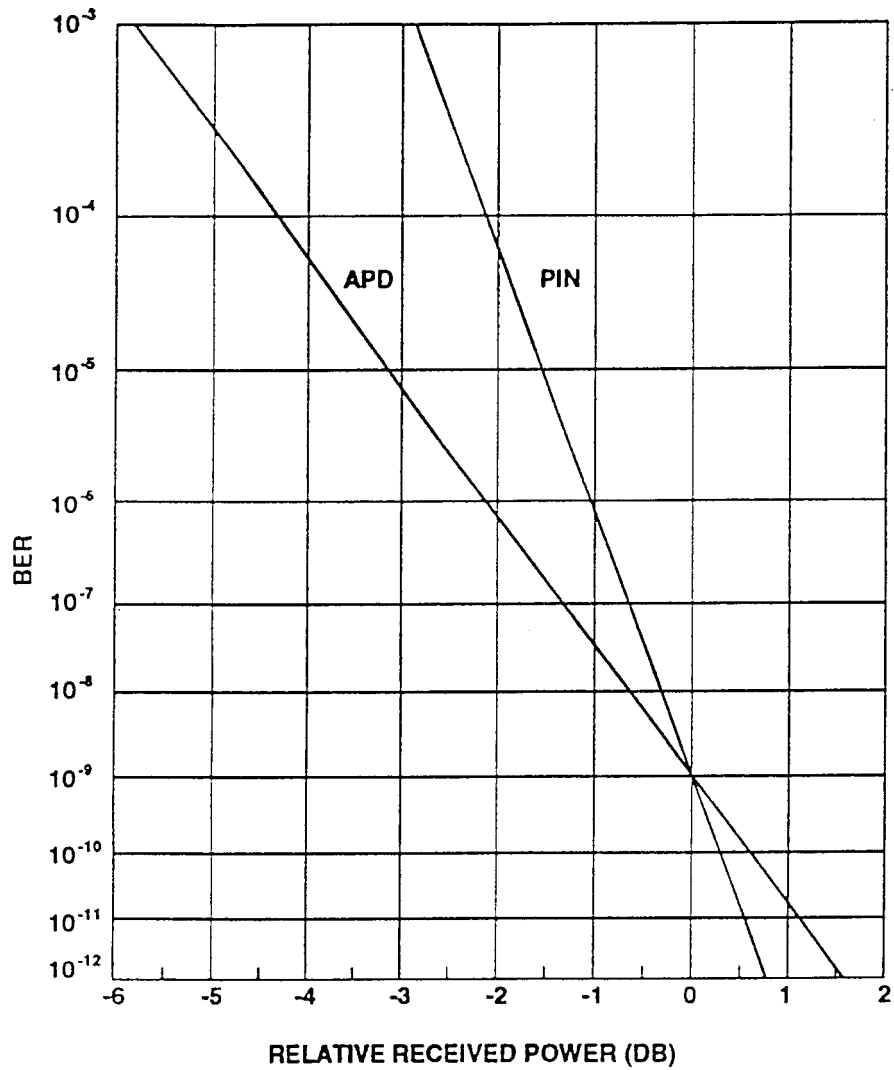
**11.10 Connectors, splices, and other passive devices.** Maximum and minimum losses for connectors and splices used in the design process should be in agreement with measurements of state-of-the-art connectors and with splice field test statistics. However, the use of maximum splice losses when a large number of splices are required may result in the needless rejection of an otherwise acceptable design. In such cases, an average value would be more appropriate.

It is easy to under count the number of connectors that may be required. Figure 11-4 depicts a typical link configuration which illustrates this point.

MIL-STD-188-111 limits long-haul single-fiber connector loss to 0.5 dB and multi-fiber connector loss to 1.0 dB. The corresponding tactical limits are 1.0 and 1.5 dB. These limits apply to both multimode and single-mode fiber. The maximum splice loss is set at 0.5 dB but the average cannot exceed 0.3 dB. With current fusion splicing techniques, average losses of 0.05 to 0.07 dB and maximum losses of 0.1 to 0.15 dB are obtainable. Losses for WDM equipment, couplers, and splitters should be obtained from the manufacturer if any of these passive devices are included in the link configuration.

**11.11 Power budget calculations.** Power budget calculations are made to determine whether or not the received optical input power will fall between the minimum and maximum allowable for a particular receiver. These budgets can be expressed by the following formulas. The formula symbols are in accordance with those used in the link design worksheets at the end of this chapter. Examples of this design approach are shown in paragraph 11.17 and 11.18.

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**ASSUMPTIONS:**

- APD - PREAMP NOISE IS NEGLIGIBLE**
- PIN - PREAMP NOISE IS DOMINATE**
- GAUSSIAN DISTRIBUTED NOISE**

**FIGURE 11-3. Relative received power versus BER.**

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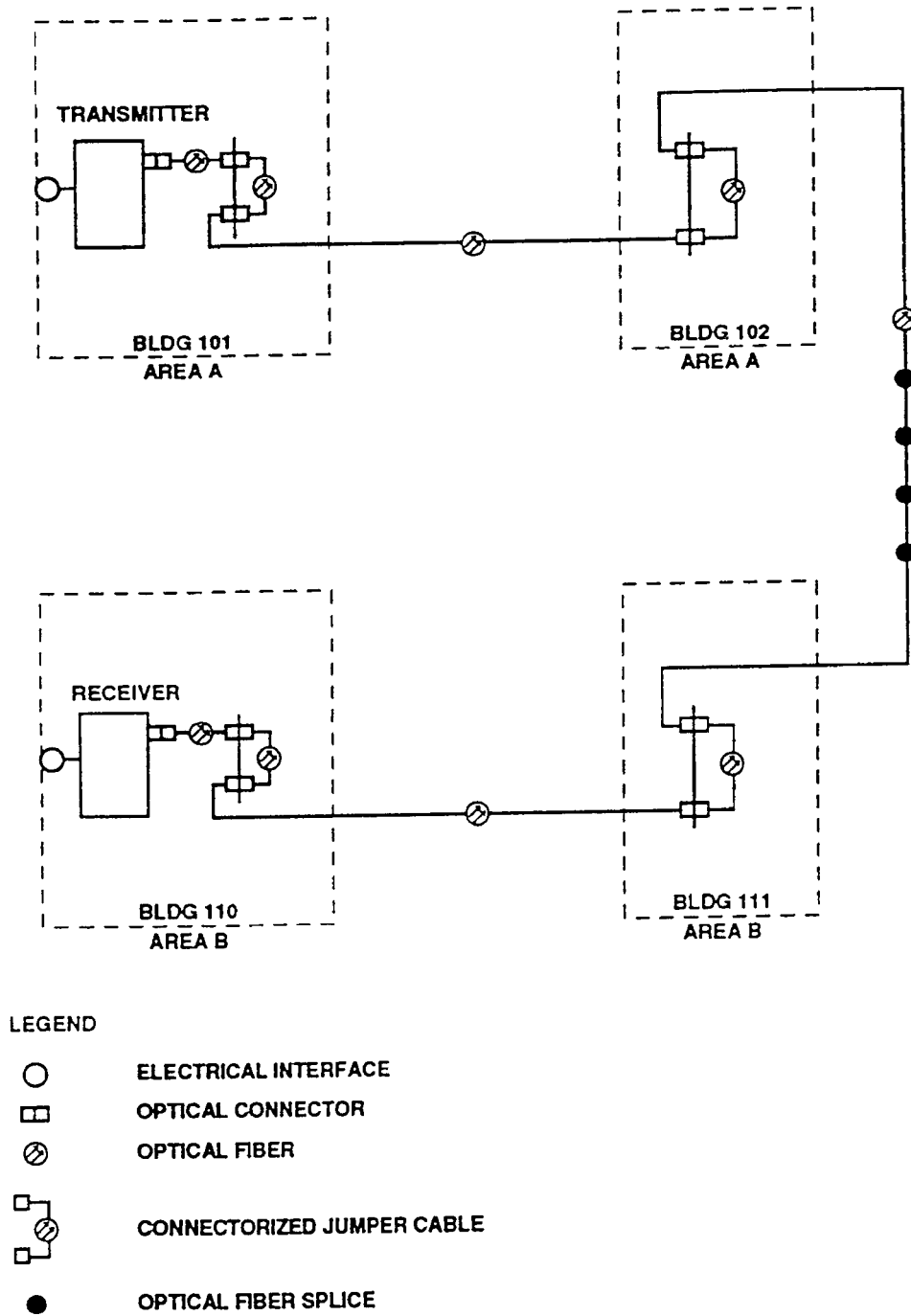


FIGURE 11-4. Fiber link example.

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maximum loss budget  $P_{\text{min}} - P_{\text{rmin}} \geq L_{\text{fmax}} + L_{\text{cmax}} + L_{\text{smax}} + L_{\text{p}} + P_{\text{p}} + 3 \text{ dB}$

minimum loss budget  $P_{\text{tmax}} - P_{\text{rmax}} \leq L_{\text{ftyp}} + L_{\text{ctyp}} + L_{\text{styp}} + L_{\text{p}} - 3 \text{ dB}$

The maximum loss budget is designed to determine whether an adequate power margin exists at the receiver of a link. It is based on the minimum transmitter output rating and maximum fiber, connector, and splicing losses, with the possible exception of splicing losses as discussed in paragraph 11.10. It also includes a 3 dB unallocated margin as specified in MIL-STD-188-111 and an additional unspecified allowance for power penalties (see appendix D).

The minimum loss budget is designed to prevent receiver power overload, due to insufficient link losses. As a safety feature, it also includes a negative 3 dB margin in link attenuation. The required receiver performance at the overload point is not clearly defined in MIL-STD-188-111, but it is reasonable to base it on the same BER which defines the minimum power level acceptable at the receiver. Since high-quality low-cost optical attenuators are available, preventing receiver overload is a simple process.

**11.12 Power penalties.** To determine a realistic value for a power penalty to use in the link design loss budget, one must consider a number of factors that degrade the received SNR. By definition, a power penalty is the increase required in received power to offset these degradation's in received SNR. The sources of this degradation are:

- transmitter extinction ratio
- transmitter intensity noise
- timing jitter
- fiber dispersion
- fiber modal noise
- fiber mode-partition noise
- laser frequency chirp
- fiber reflections and feedback.

The above mentioned factors are complex to evaluate, and not all factors are applicable in a link design. This depends upon whether the link is digital or analog, whether LDs or LEDs are used, and whether the fiber link is multimode or single-mode. It is recommended that a system designer initially assign a 3 dB power penalty in the link design loss budget for these factors in addition to a 3 dB unallocated power margin, for a total of 6 dB. With further refinement of the link design and by obtaining data from manufacturers, this 3 dB power penalty can be reduced as appropriate. For example, some manufacturers will include transmitter extinction ratio and laser frequency chirp power penalties in either transmitter or receiver sensitivity worst case parameters. Also transmitter intensity noise is only significant for analog systems.

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Modal noise is only appropriate for multimode fibers, and can be avoided by use of noncoherent sources such as LEDs. Mode partition noise is only applicable to single-mode dispersive fibers using multilongitudinal mode lasers and can be avoided with use of a single-longitudinal mode laser. Reflections from fiber discontinuities occurring at splices, connectors, and fiber terminations will degrade both transmitters and receivers, and will depend upon actual values achieved in installations. The effects of fiber dispersion degrades the system data pulses due to pulse broadening and intersymbol interference. Fiber dispersion is a length dependent parameter, and thus, is not a problem for short links. Timing jitter is dependent on the quality of the electronic circuitry and external clock synchronization methods. A more detailed discussion of these factors is explained in appendix D.

**11.13 Rise time calculations.** Rise time calculations are made to determine if a link design is bandwidth or dispersion limited. To accomplish this objective, fiber bandwidth (see 11.15) and dispersions are converted to corresponding rise times and then added, in a root-sum-square (rss) manner, to transmitter and receiver rise times. The result is then multiplied by a constant of 1.1 to account for a Gaussian or raised cosine shaped pulse. This total is compared to the maximum allowable, which is generally considered to be equal to 70% of a bit interval period. The differences between multimode and single-mode dispersion contributions to the total rise time are indicated on the worksheet.

Since a worst case design approach is being followed, assuming operation at a zero dispersion wavelength is not realistic. With most practical design cases, it is difficult to have complete knowledge about the location of the fiber's zero dispersion wavelength and the exact operating wavelength of the optical source. Generally the fiber manufacturer will specify a worst case dispersion coefficient in a given band of wavelengths (e.g., 3.5 ps/nm-km in the 1290 to 1330 nm band). Transmitters are also specified within a band bounded by a minimum and a maximum wavelength. This allows the designer to make a worst case calculation.

MIL-STD-188-111 requirements for fiber dispersion limits are cited in paragraph 11.7. In addition, a zero-dispersion slope limit of 0.093 ps/nm<sup>2</sup>-km is imposed in the 1310 nm wavelength band. This second order contributor to pulse distortion has to be taken into consideration if operation at or near the zero-dispersion wavelength is anticipated. However, since this assumption is not consistent with a worst case design philosophy, the dispersion related to the zero-dispersion slope is not included in the rise time calculations.

As indicated on the worksheet, the transmitter spectral width is given as an rms value. The rms widths of LEDs and single-longitudinal mode lasers are approximately equal to their full-width-half-maximum (FWHM) values. The rms widths of multilongitudinal mode lasers can be related to their FWHM values by assuming a Gaussian optical spectrum and using the

following approximation:

$$\Delta_{\text{rms}} = \Delta_{\text{FWHM}} / 2.4.$$

**11.14 Dispersion limited path length calculations.** Rise time calculations, as described in the preceding paragraph, generally can be used to determine if a given link design is dispersion limited. However, a more direct method may be available when single-mode fiber and laser based transmitters are considered in combination. Manufacturers of transmitters and receivers usually specify these as matched pairs in terms of maximum allowable fiber dispersion (in ps/nm). This value is usually given in conjunction with a specific power penalty in dB. It should be noted that transmitter and receiver rise times and the transmitter spectral width are already considered in the maximum allowable fiber dispersion value. Dividing that value by the dispersion coefficient of single-mode fiber (in ps/nm-km) will give the dispersion limited distance in km.

For example, an OC-12 (622.08 Mbps) transmitter-receiver pair might have an allowable rating for fiber dispersion of 100 ps/nm in conjunction with a 1 dB power penalty. If this pair were used with single-mode fiber having a dispersion coefficient of 2.5 ps/nm-km, the dispersion limited distance would be 40 km. The same equipment pair might be rated at 150 ps/nm with a 2 dB power penalty, thereby increasing the dispersion limit to 60 km. In general, these relationships are not continued beyond a 2 dB dispersion penalty.

**11.15 Rise time versus bandwidth calculations.** The basic relationship between rise time and bandwidth is that they are inversely proportional. The rise time ( $T_r$ ) of a linear system is defined as the time during which the response increases from 10 to 90 percent of its final output value when the input is changed abruptly (a step function). The bandwidth of a linear system is usually defined as the frequency difference between the upper and lower -3 dB values. However, since the low end response of optical components approaches 0 Hz, the bandwidth (B) is assumed to be equal to the high frequency (-3 dB) value. An additional approximation is made that the frequency response can be equated to that provided by a single pole RC low pass filter. This filter has the following characteristics:

$$V_{\text{out}} = V_{\text{in}} (1 - e^{-t/RC}), \text{ step input}$$

$$T_r = 2.2RC, \text{ 10-90 percent elapsed time}$$

$$V_{\text{out}} = V_{\text{in}} (1 + j2\pi fRC)^{-1}, \text{ sinusoidal input}$$

$$f_{-3\text{dB}} = (2\pi RC)^{-1}, \text{ where } (V_{\text{out}}/V_{\text{in}})^2 = 0.5$$

$$T_r = 2.2/(2\pi f_{-3\text{dB}}) = 0.35/f_{-3\text{dB}}, \text{ or } 0.35/B$$

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where:

R is in ohms

C is in farads

f and B are in hertz

t and Tr are in seconds.

In more convenient dimensions this can be expressed as

$$T_r = 350/B$$

where:

$T_r$  is in ps

B is in GHz.

**11.16 Other design considerations.** MIL-STD-188-111 includes several performance standards not addressed in the link design process. These standards are discussed in the following subparagraphs.

**11.16.1 Link availability.** As specified, the availability of the active elements within a long-haul link shall be a minimum of 0.999984. Unavailability is defined as link degradation that results in a BER exceeding  $10^{-4}$  for a period in excess of 60 consecutive seconds.

As a practical matter, an increase in BER of that magnitude most certainly would result in a totally useless link. The down time would be on the order of milliseconds if automatic switching to back-up equipment or to an alternate route were incorporated in the system design. Otherwise, the down time would be determined by the length of time it would take for maintenance personnel to isolate and repair or replace the defective component. In this sense, link availability is determined by the degree of redundancy selected by the system designer (see chapter 10).

**11.16.2 Jitter.** MIL-STD-188-111 provides a very minimal coverage of jitter standards. It is difficult to translate these into the link design process. However, industry practice is to assign a jitter power penalty to offset receiver sensitivity degradations caused by jitter. This complex issue is addressed in appendix D.

**11.16.3 Receiver dynamic range.** The MIL-STD-188-111 requirement is that "the dynamic range of optical receivers shall not be less than 26 dB (DO 30 dB). The lower end of the dynamic range shall be the minimum receiver input value at which a BER of  $10^{-9}$  is attained." Although not explicitly stated, it is reasonable to define the upper end of the dynamic range as the maximum receiver input value at which a BER of  $10^{-9}$  is attained. Typically, this definition is used in industry.

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As there can be an inverse relationship between a receiver's dynamic range and sensitivity, the requirement for a 26 dB dynamic range can present a problem for many receiver types. However, with the advent of low-cost-high-quality optical attenuators, which can be inserted at the receiver input, the problem of receiver overload on short links has been eliminated. Therefore, maximum receiver sensitivity should be given priority over dynamic range.

**11.16.4 Total distortion.** MIL-STD-188-111 specifies that 'maximum total distortion, due to any combination of causes and including both rise and fall times, shall not exceed 25 percent of the theoretical data unit interval for pulses transmitted from the input to the output of the fiber optic link.'

Aside from the problem of defining total distortion and the lack of a standard test method, this specification appears to be in conflict with the generally accepted concept that total rise time should not exceed about 70 percent of the data interval for NRZ coded transmissions. The 70 percent limit applies to the input of the receiver's decision circuit. It should be noted that the shape of receiver's output pulses are unrelated to those at the input to its decision circuit. If the MIL-STD-188-111 distortion limit is applied to the receiver output, its regenerator circuit should provide pulses with less than 25 percent distortion using any reasonable definition of distortion.

**11.17 Long-haul link design example.** The following example is based on a hypothetical requirement to design a 60 km link at an OC-12 (622.08 Mbps) data rate with NRZ coding. This places the optical line rate at about 622 Mbps. The parameter values chosen on the worksheet represent current industry worst case values; the designer, however, should obtain these values from industry for each specific application. This worksheet represents one of several possible solutions, and is meant to be illustrative of the design process, but not for any specific design. Since the design process is iterative, the design shown should be the result of several iterations.

As a start, from figure 11-1 it is apparent that single-mode fiber must be used since multimode fiber would be dispersion limited. The results in the power budget section indicate that a combination of LD transmitters and APD receivers are necessary to satisfy the maximum power budget requirement since the resulting system margin (maximum link budget minus total losses) is 2.9 dB.

Both the rise time and dispersion limited length calculations indicate a satisfactory design. As pointed out in paragraph 11.14, the short-cut dispersion limited length calculations can only be used with single-mode fiber. If the transmitter-receiver manufacturer can provide its specifications for maximum allowable fiber dispersion in ps/nm, this short-cut method should be used in lieu of computing total link rise time. The optical fiber dispersion coefficient shown on the worksheet at 2.0 ps/nm-km represents the maximum allowable (worst case)

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value. Calculating this coefficient from the zero dispersion slope, operating wave-length, and spectrum width would yield a much lower value. However, a designer cannot be certain these values, as shown on the worksheet, are worst case, and more likely are only typical. This preference is based on the fact that rise time calculations incorporate simplifying approximations, where the limited length calculations normally would be based on laboratory measurements made by the manufacturer.

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## LINK DESIGN WORKSHEET

Project Name EXAMPLE LINK (OC-12)  
 Engineering Agency \_\_\_\_\_ Date \_\_\_\_\_  
 Link Classification (Tactical, Long-haul) LONG-HAUL  
 Link from Node A to Node B  
 Optical Line Rate,  $R_o$  0.622 Gbps  
 Nominal Operating Wavelength,  $\lambda$ , (850, 1310, 1550) 1310 nm

### OPTICAL FIBER

Type (SI, GI, SM) SM  
 Size (8-10/125, 50/125, 65/125) 9/125  $\mu\text{m}$   
 Attenuation Coefficient,  $\alpha_{\text{max}}$ ,  $\alpha_{\text{typ}}$  0.40, 0.35 dB/km  
 Length, K 60 km  
 Link Loss,  $L_{\text{fmax}}$ ,  $L_{\text{fyp}}$  24.0, 21.0 dB  
 Zero - dispersion Wavelength,  $\lambda_0$  1305 nm  
 Zero-dispersion Slope,  $S_0$  0.09 ps/nm<sup>2</sup>-km  
 Fiber Dispersion Coefficient at Operating Wavelength  $d_{\text{ma}}$  2.0 ps/nm-km  
 Bandwidth - distance Factor,  $B_d$  N/A GHz-km

### OPTICAL TRANSMITTER

Type (LED, LD) LD  
 RMS Spectral Linewidth,  $\Delta_f$  1.0 nm  
 Power Coupled Into Fiber,  $P_{\text{umax}}$ ,  $P_{\text{umin}}$  +2.0, -2.0 dBm  
 Rise Time,  $t_r$  500 ps  
 Modulation Bandwidth 0.70 GHz

### OPTICAL RECEIVER

Type (APD, PIN, PIN-FET) APD  
 BER (Tactical 10<sup>-9</sup>, Long-haul 10<sup>-11</sup> x K) 6x10<sup>-10</sup>  
 Minimum Input Power,  $P_{\text{min}}$  -40.0 dBm  
 Overload Power,  $P_{\text{max}}$  -12.0 dBm  
 Rise Time,  $t_r$  700 ps

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## CONNECTORS, SPLICES, AND OTHER PASSIVE DEVICES

Type of Connector (SC, ST,....)	<u>SC</u>	
Number of Connectors	<u>6</u>	
Loss per Connector, maximum, typical	<u>0.50</u> , <u>0.30</u>	dB
Total Connector Losses, $L_{cmax}$ $L_{ctyp}$	<u>3.0</u> , <u>1.8</u>	dB
Type of Splice (mechanical, fusion)	<u>fusion</u>	
Number of Splices	<u>22</u>	
Loss per Splice, maximum, typical	<u>0.10</u> , <u>0.05</u>	dB
Total Splice Losses, $L_{smax}$ , $L_{styp}$	<u>2.2</u> , <u>1.1</u>	dB
Other Passive Losses (WDM, Coupler, Splitter), $L_p$	<u>N/A</u>	dB

## POWER BUDGET CALCULATIONS

Minimum Available Power ( $P_{tmin}$ minus $P_{rmin}$ )*	<u>38.0</u>	dB
Maximum Excess Power ( $P_{tmax}$ minus $P_{rmax}$ )**	<u>14.0</u>	dB

	<u>Maximum Loss Budget</u>	<u>Minimum Loss Budget</u>
Fiber Losses	$L_{tmax}$ <u>24.0</u> dB	$L_{ftyp}$ <u>21.0</u> dB
Connector Losses	$L_{cmax}$ <u>3.0</u> dB	$L_{ctyp}$ <u>1.8</u> dB
Splice Losses	$L_{smax}$ <u>2.2</u> dB	$L_{styp}$ <u>1.1</u> dB
Other Passive Losses	$L_p$ <u>0</u> dB	$L_p$ <u>0</u> dB
Power Penalties, $P_p$	<u>3.0</u> dB	N/A
Unallocated Power Margin	3.0 dB	N/A
Receiver Overload Margin	N/A	-3.0 dB
Total (sum of above)	<u>35.2</u> dB	<u>20.9</u> dB
Minimum Available Power minus Total	<u>2.8</u> dB***	N/A
Total minus Maximum Excess Power	N/A	<u>6.9</u> dB****
Optical Attenuator (if required)	N/A	<u>0</u> dB

- \* Determines the Maximum Allowable Link Loss for 0 dB power margin at the Receiver. Also called Available Link Gain
- \*\* Relative to Receiver Overload Level, Determines Minimum Link Loss Required to Keep the Receiver Out of Saturation
- \*\*\* Must be 0 dB or Greater
- \*\*\*\* Add Attenuator if Negative

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### RISE TIME CALCULATIONS

Optical Line Rate, $R_o$	<u>0.622</u> Gbps
Allowable Rise Time, $t_a$ , $(0.7/R_o) \times 10^3$	<u>1125</u> ps
Transmitter Type (LED, LD)	<u>LD</u>
Transmitter Rise Time, $t_t$	<u>500</u> ps
Transmitter rms Spectral Linewidth, $\Delta_t$	<u>1.0</u> nm
Receiver Rise Time, $t_r$	<u>700</u> ps
Fiber Type (MM, SM)	<u>SM</u>
Fiber Length, K	<u>60</u> km
Nominal Operating Wavelength, $\lambda_1$	<u>1310</u> nm
Fiber Bandwidth-distance Factor, $B_d$	<u>N/A</u> GHz-km
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	<u>2.0</u> ps/nm-km
Rise Time due to Material Dispersion, $t_{ma} = d_{ma} \times \Delta_t \times K$	<u>120</u> ps
Rise Time due to Multimode dispersion, $t_{mu} = 350K/B_d$	<u>N/A</u> ps
Fiber Rise Time (SM), $t_{sm} = t_{ma}$	<u>120</u> ps
Fiber Rise Time (MM), $t_{mm} = (t_{ma}^2 + t_{mu}^2)^{0.5}$	<u>N/A</u> ps
Link Rise Time (SM), $t_{lsm} = 1.1(t_t^2 + t_{sm}^2 + t_r^2)^{0.5}$	<u>954</u> ps
Link Rise Time (MM), $t_{lmm} = 1.1(t_t^2 + t_{mm}^2 + t_r^2)^{0.5}$	<u>N/A</u> ps
Allowable Minus Calculated Rise Time, $t_a - t_l$ (sm, mm)	<u>251</u> ps

### DISPERSION LIMITED LENGTH CALCULATIONS

Maximum Allowable Fiber Dispersion*, $D_{max}$	<u>150</u> ps/nm
Power Penalty associated with $D_{max}$	<u>2.0</u> dB
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	<u>2.0</u> ps/nm-km
Dispersion Limited Length, $D_{max}/d_{ma}$	<u>75</u> km

\* The maximum dispersion that the transmitter-receiver pair can tolerate and still meet its BER and bit rate specifications.

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**11.18 Tactical link design example.** The worksheet example is based on a hypothetical requirement to design a 10 km link composed of 1 km segments of multimode cable to support a 4.608 Mbps data rate. As with the long-haul design example, conservative values of the critical parameters were chosen for this initial iteration of the link design to assess how closely these parameters must be controlled. The results obtained show that available link gain and link rise time are adequate to support communications without further parametric restrictions.

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## LINK DESIGN WORKSHEET

Project Name EXAMPLE LINK (4.608 Mbps)  
 Engineering Agency \_\_\_\_\_ Date \_\_\_\_\_  
 Link Classification (Tactical, Long-haul) tactical  
 Link from Site A to Site B  
 Optical Line Rate,  $R_o$   $4.608 \times 10^{-3}$  Gbps  
 Nominal Operating Wavelength,  $\lambda_o$ , (850, 1310, 1550) 1310 nm

### OPTICAL FIBER

Type (SI, GI, SM) GI  
 Size (8-10/125, 50/125, 65/125) 50/125  $\mu\text{m}$   
 Attenuation Coefficient,  $\alpha_{\text{max}}$ ,  $\alpha_{\text{typ}}$  1.0, 0.8 dB/km  
 Length, K 10 km  
 Link Loss,  $L_{\text{fmax}}$ ,  $L_{\text{fyp}}$  10.0, 8.0 dB  
 Zero - dispersion Wavelength,  $\lambda_o$  N/A nm  
 Zero-dispersion Slope,  $S_o$  N/A ps/nm<sup>2</sup>-km  
 Fiber Dispersion Coefficient at Operating Wavelength  $d_{\text{ma}}$  6.0 ps/nm-km  
 Bandwidth - distance Factor,  $B_d$  0.40 GHz-km

### OPTICAL TRANSMITTER

Type (LED,LD) LED  
 RMS Spectral Linewidth,  $\Delta_l$  100 nm  
 Power Coupled Into Fiber,  $P_{\text{tmax}}$ ,  $P_{\text{tmin}}$  -15.0, -20.0 dBm  
 Rise Time,  $t_r$   $25 \times 10^{-3}$  ps  
 Modulation Bandwidth  $10 \times 10^{-3}$  GHz

### OPTICAL RECEIVER

Type (APD, PIN, PIN-FET) PIN-FET  
 BER (Tactical  $10^{-9}$ , Long-haul  $10^1 \times K$ )  $10^{-9}$   
 Minimum Input Power,  $P_{\text{min}}$  -48.0 dBm  
 Overload Power,  $P_{\text{max}}$  -20.0 dBm  
 Rise Time,  $t_r$   $40 \times 10^3$  ps

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## CONNECTORS, SPLICES, AND OTHER PASSIVE DEVICES

Type of Connector (SC, ST,...)	<u>ST</u>	
Number of Connectors	<u>12</u>	
Loss per Connector, maximum, typical	<u>0.6</u> , <u>0.3</u>	dB
Total Connector Losses, $L_{cmax}$ $L_{ctyp}$	<u>7.2</u> , <u>3.6</u>	dB
Type of Splice (mechanical, fusion)	<u>Mechanical</u>	
Number of Splices	<u>2</u>	
Loss per Splice, maximum, typical	<u>1.0</u> , <u>0.5</u>	dB
Total Splice Losses, $L_{smax}$ , $L_{styp}$	<u>2.0</u> , <u>1.0</u>	dB
Other Passive Losses (WDM, Coupler, Splitter), $L_p$	<u>N/A</u>	dB

## POWER BUDGET CALCULATIONS

Minimum Available Power ( $P_{tmin}$ minus $P_{rmin}$ )*	<u>28.0</u>	dB
Maximum Excess Power ( $P_{tmax}$ minus $P_{rmax}$ )**	<u>5.0</u>	dB

	<u>Maximum Loss Budget</u>	<u>Minimum Loss Budget</u>
Fiber Losses	$L_{fmax}$ <u>10.0</u> dB	$L_{ftyp}$ <u>8.0</u> dB
Connector Losses	$L_{cmax}$ <u>7.2</u> dB	$L_{ctyp}$ <u>3.6</u> dB
Splice Losses	$L_{smax}$ <u>2.0</u> dB	$L_{styp}$ <u>1.0</u> dB
Other Passive Losses	$L_p$ <u>0</u> dB	$L_p$ <u>0</u> dB
Power Penalties, $P_p$	<u>3.0</u> dB	N/A
Unallocated Power Margin	3.0 dB	N/A
Receiver Overload Margin	N/A	-3.0 dB
Total (sum of above)	<u>25.2</u> dB	<u>9.6</u> dB
Minimum Available Power minus Total	<u>2.8</u> dB***	N/A
Total minus Maximum Excess Power	N/A	<u>4.6</u> dB****
Optical Attenuator (if required)	N/A	<u>0</u> dB

- \* Determines the Maximum Allowable Link Loss for 0 dB power margin at the Receiver. Also called Available Link Gain
- \*\* Relative to Receiver Overload Level, Determines Minimum Link Loss Required to Keep the Receiver Out of Saturation
- \*\*\* Must be 0 dB or Greater
- \*\*\*\* Add Attenuator if Negative

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## RISE TIME CALCULATIONS

Optical Line Rate, $R_o$	$4.6 \times 10^{-3}$ Gbps
Allowable Rise Time, $t_a$ , $(0.7/R_o) \times 10^3$	$152 \times 10^3$ ps
Transmitter Type (LED, LD)	<u>LED</u>
Transmitter Rise Time, $t_t$	$25 \times 10^3$ ps
Transmitter RMS Spectral Linewidth, $\Delta\lambda$	<u>100</u> nm
Receiver Rise Time, $t_r$	$40 \times 10^3$ ps
Fiber Type (MM, SM)	<u>MM</u>
Fiber Length, K	<u>10</u> km
Nominal Operating Wavelength, $\lambda_1$	<u>1310</u> nm
Fiber Bandwidth-distance Factor, $B_d$	<u>0.40</u> GHz-km
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	<u>6</u> ps/nm-km
Rise Time due to Material Dispersion, $t_{ma} = d_{ma} \times \Delta\lambda \times K$	$6 \times 10^3$ ps
Rise Time due to Multimode dispersion, $t_{mu} = 350K/B_d$	$8.75 \times 10^3$ ps
Fiber Rise Time (SM), $t_{sm} = t_{ma}$	<u>N/A</u> ps
Fiber Rise Time (MM), $t_{mm} = (t_{ma}^2 + t_{mu}^2)^{0.5}$	$10.6 \times 10^3$ ps
Link Rise Time (SM), $t_{lsm} = 1.1(t_t^2 + t_{sm}^2 + t_r^2)^{0.5}$	<u>N/A</u> ps
Link Rise Time (MM), $t_{lmm} = 1.1(t_t^2 + t_{mm}^2 + t_r^2)^{0.5}$	$53 \times 10^3$ ps
Allowable Minus Calculated Rise Time, $t_a - t_l$ (sm, mm)	<u><math>99 \times 10^3</math></u> ps

## DISPERSION LIMITED LENGTH CALCULATIONS

Maximum Allowable Fiber Dispersion*, $D_{max}$	<u>N/A</u> ps/nm
Power Penalty associated with $D_{max}$	<u>N/A</u> dB
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	<u>N/A</u> ps/nm-km
Dispersion Limited Length, $D_{max}/d_{ma}$	<u>N/A</u> km

\* The maximum dispersion that the transmitter-receiver pair can tolerate and still meet its BER and Bit Rate Specifications.

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## CHAPTER 12 FIBER OPTICS TESTING

**12.1 Introduction.** Fiber optics testing generally parallels the approach used for testing of electrical communications systems. The purpose of the testing is to verify performance during component and subassembly manufacturing, equipment installations system acceptance, operational performance monitoring, and maintenance. The test types can include performance, mechanical, environmental, reliability, and maintainability for the components and the fiber cable.

**12.2 Scope.** This chapter will emphasize the extent of testing needed to determine FOCS link/system performance during the installation, acceptance and system operational phases of equipment deployment. Installation phase tests will be confined to those needed to verify satisfactory component quality before and after installation. Acceptance phase tests that demonstrate system performance in accordance with MIL-STD-188-111 performance specifications will be discussed. Monitoring tests performed during the system operational phase are designed to detect system deterioration or failure. These tests commonly locate and isolate faulty components for replacement action.

**12.3 Relationship to other chapters.** For a fuller appreciation of the rationale, method, and performance specifications of each test, the reader should consult the chapters corresponding to the element being tested (component, fiber/cable, transmitter, receiver, system) and the required performance specifications in MIL-STD-188-111.

**12.4 Test methods and test equipment.** Test methods will vary with each manufacturer, installer, and user; however, recommended test standards developed by industry through EIA have been adapted by the DoD through FSG-60. Current issue of the DODISS lists all adopted FIOP's. All test methods assume the use of calibrated test equipment. Calibration support for test equipment should be obtained from activities or primary calibration laboratories, which have the required standards which are traceable to national primary standard equivalents. Field calibration services are available through normal DoD metrology channels.

**12.5 Component level test procedures.** The following test procedures are given to acquaint the reader with the general concepts of fiber optics component testing, test equipment, and test parameters.

**12.5.1 Optical power.** The purpose of this test is to measure the output power of an optical source (transmitter) in absolute terms (dbms or watts). Since a calibrated optical power meter is used to determine the power measurement, the conditions for which the measurement is valid must be noted. Optical power meters use an array of optical sensors to measure input power

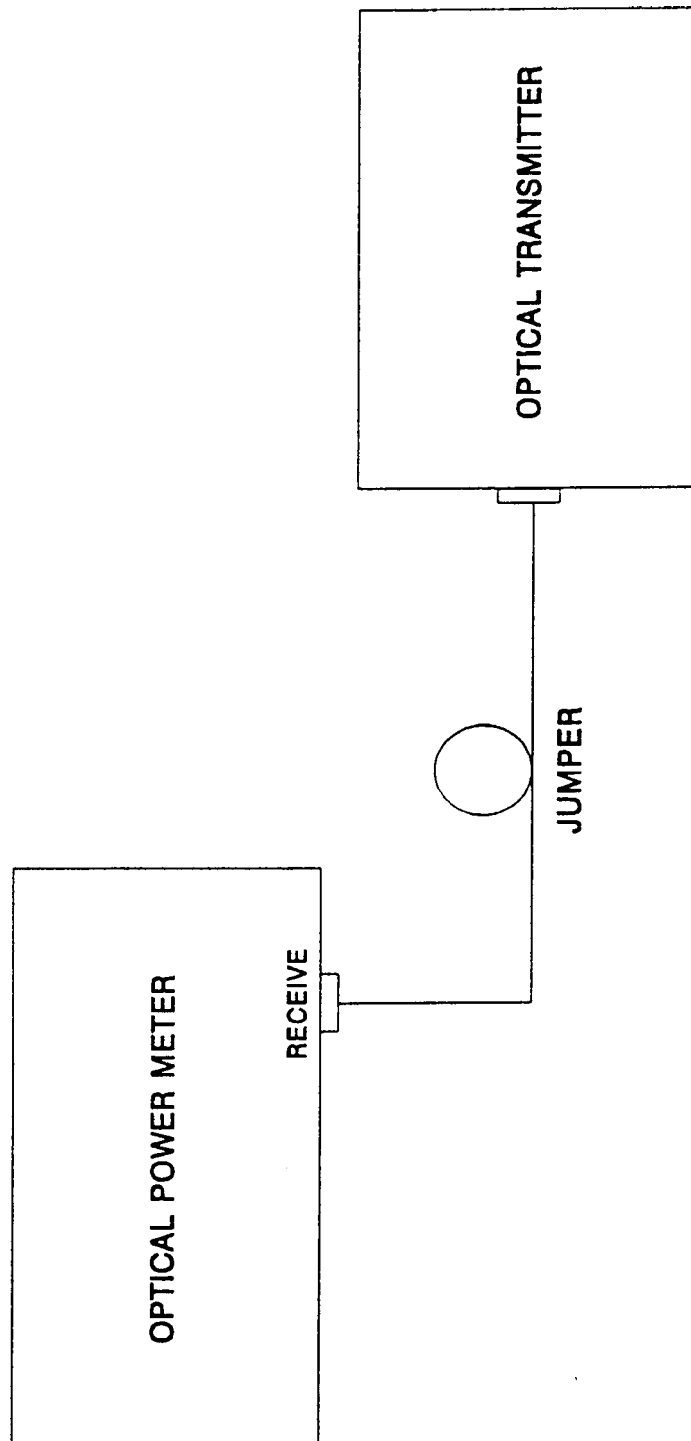
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over a range of wavelengths from optical sources. The responsivity of the arrays of photodiodes can vary widely with the actual power level, temperature, and wavelength of the optical source under test. The manufacturer of the power meter usually provides an accuracy specification to a reference power level, wavelength, and temperature. To achieve accuracy over a wide range of measurement conditions, one must either consult manufacturer linearity curves to correct measurements from the reference (calibrated) conditions, or the manufacturer will store the linearity corrections in a read-only memory (ROM) in the power meter and a microprocessor will automatically correct for the input conditions. Accuracy can vary considerably if there is uncertainty in input conditions and in manufacturers calibration and linearity measurements. This can range from a few percent to over ten percent.

Another useful test, conducted at the manufacturing level for the optical transmitter, is a transfer curve that shows the optical power output versus the LD or LED input bias current. This data provides useful information in the field for determining if deterioration of the diode is occurring when optical power is measured in the field. In conducting a field test, one should ensure that the power meter is connected to the point at which the power is specified for the optical transmitter, usually at the connector on the transmitter pigtail jumper. Figure 12-1 shows a power measurement test setup.

**12.5.2 Central wavelength and spectral width (bandwidth).** The purpose of this measurement is to measure the central wavelength and spectral width (bandwidth) of the optical transmitter. This measurement is required for determining the maximum range of a phase dispersion limited system (single-mode fiber systems). Since it is not a normal field maintenance test, a detailed explanation of the test method will not be discussed, except to note that it is accomplished with an optical spectrum analyzer measuring the received optical signal from a modulated optical transmitter source.

It is important for a system designer to understand the parameters to be measured, since different parameters can be attributed to the different optical transmitter types, such as broad spectra from LEDs, multilongitudinal mode (MLM) spectra and single-longitudinal mode (SLM) spectra from LDs. For the multimode LED systems, only the amount of spectra coupled into the fiber is important, since the system is attenuation limited in range due to mode partition noise. For the MLM and SLM LD systems, spectral width is a basic parameter in determining the phase dispersion limits on range. In the case of SLM LDs, a frequency chirp caused by the initial ramp-up of laser bias current causes a corresponding wavelength shift, and a wider spectral width.



**FIGURE 12-1. Test configuration for optical power measurements.**

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The wavelength measurements with a modulated transmitter are:

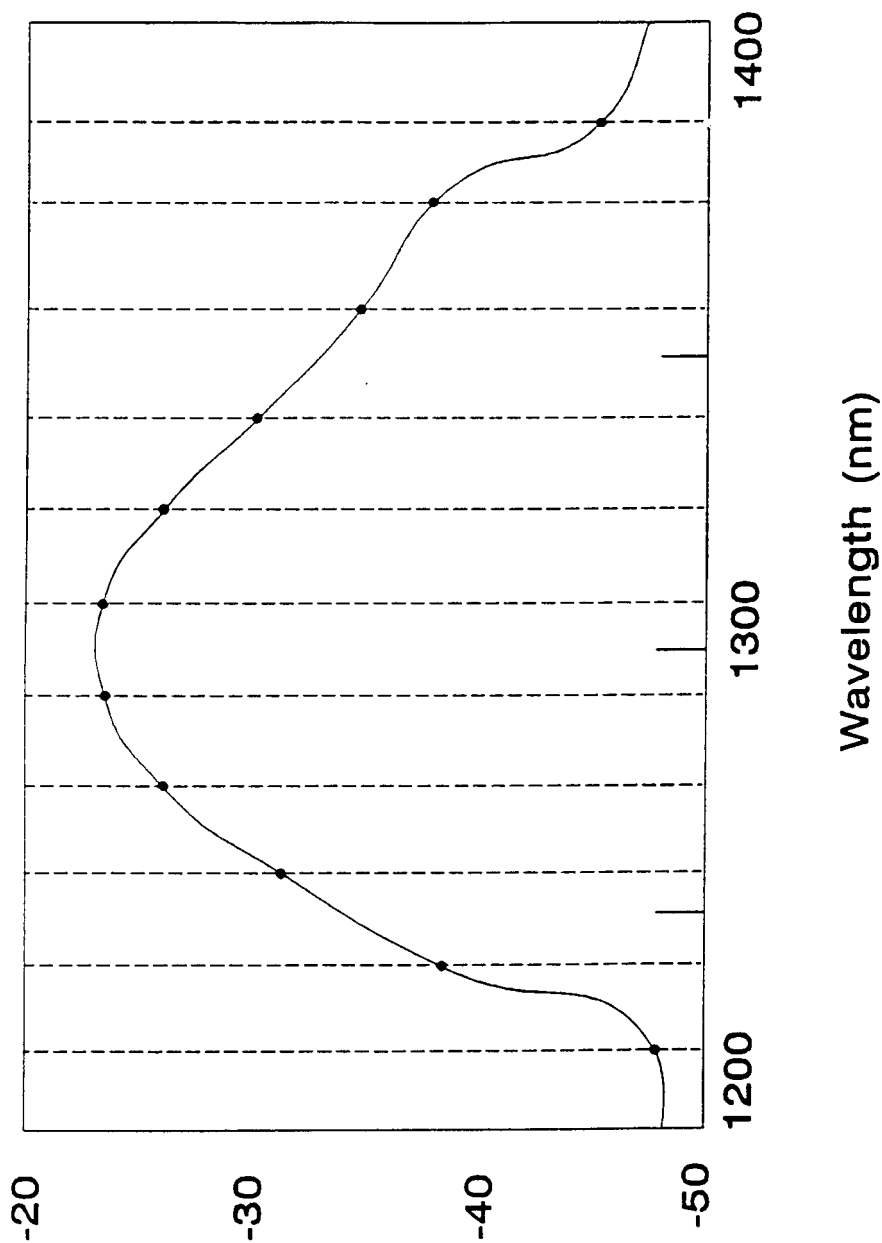
- 1) Central Wavelength: the mean of the closest spaced half-power wavelengths, one above and one below the peak wavelength,
- 2) Half-Power Wavelength: a wavelength corresponding to a value of the spectral power density that is half of (-3 dB below) the peak value,
- 3) Peak Wavelength: the wavelength corresponding to the peak value of the spectral power density,
- 4) Centroidal Wavelength: the mean wavelength of an optical spectrum, calculated as the average wavelength of the spectral power density.

The spectral widths are:

- 1) Root-Mean-Square n-dB Down Width: the width between the closest spaced wavelengths, one above and one below the peak wavelength, at which the spectral power density is n-dB down from its peak value.
- 2) Full-Width at Half Maximum: a special case of the rms n-dB Down Width where  $n=3$ .

Figure 12-2 shows typical spectrum waveforms and measurement points. The MLM laser shows a full-width at half maximum spectral width. The SLM laser shows a considerable chirp band width due to turn-on and turn-off.

12.5.3 Receiver sensitivity and maximum receiver input. The purpose of this test is to measure the minimum and maximum optical power a receiver can detect to maintain the specified system BER (see MIL-STD-188-111 and Link Design Chapter 11). The test method is to insert an optical attenuator and splitter between a BER test (BERT) set, optical power source (transmitter) and the receiver. An optical power meter is used to monitor the actual received power at the receiver (see figure 12-3). Since the power measurement has been attenuated by test pigtailed, attenuator insertion loss, splitter insertion loss, etc., one must calibrate the system by measuring the ratio of power directly from the optical transmitter to the power measured at the splitter. This ratio is then used to adjust the power meter measurements for the true power at the receiver, accounting for system losses. To test for maximum optical power at the receiver, a high power optical transmitter may have to be used.



A. Example of an LED Optical Spectrum

FIGURE 12-2. Typical LED and laser spectrum waveforms.

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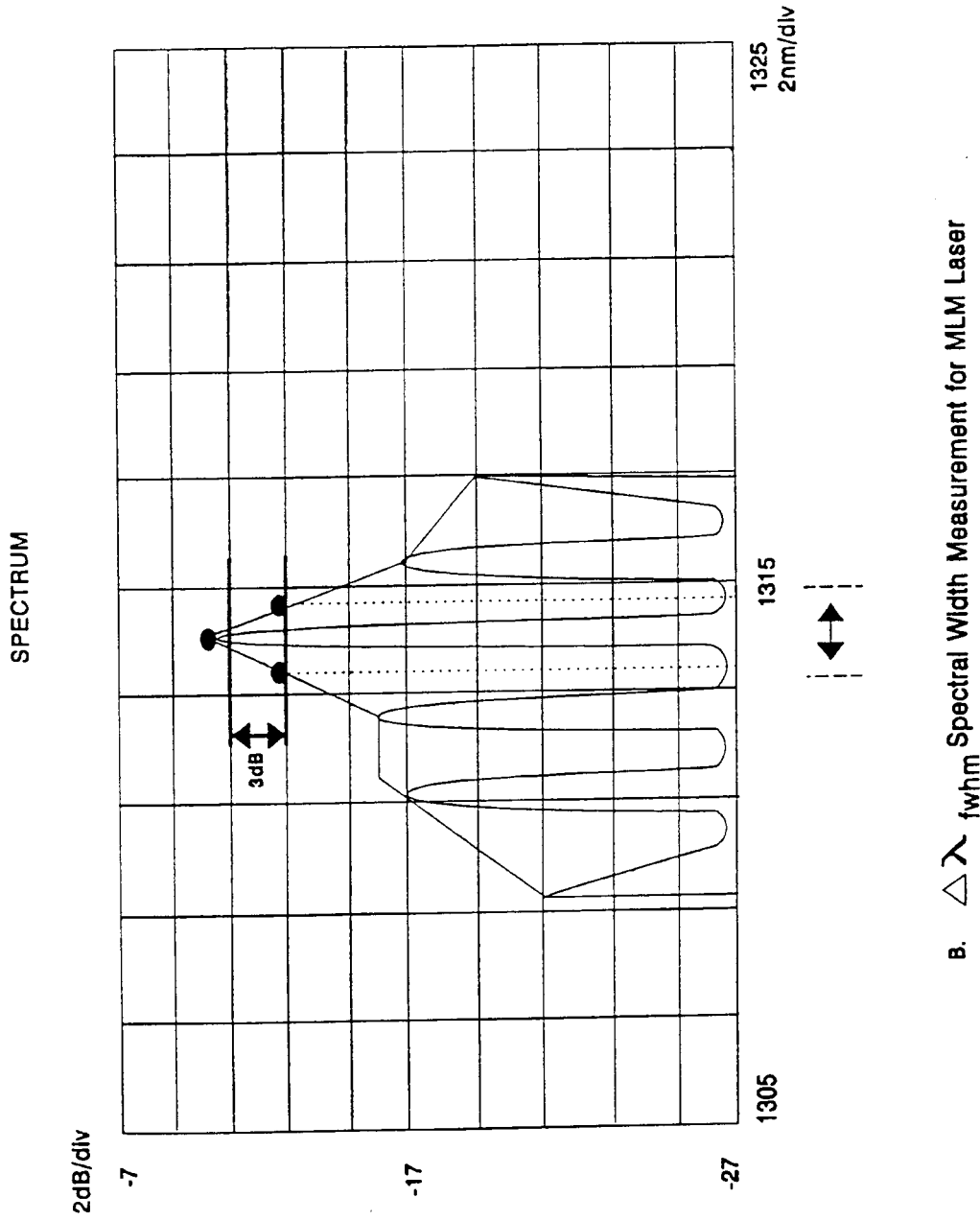
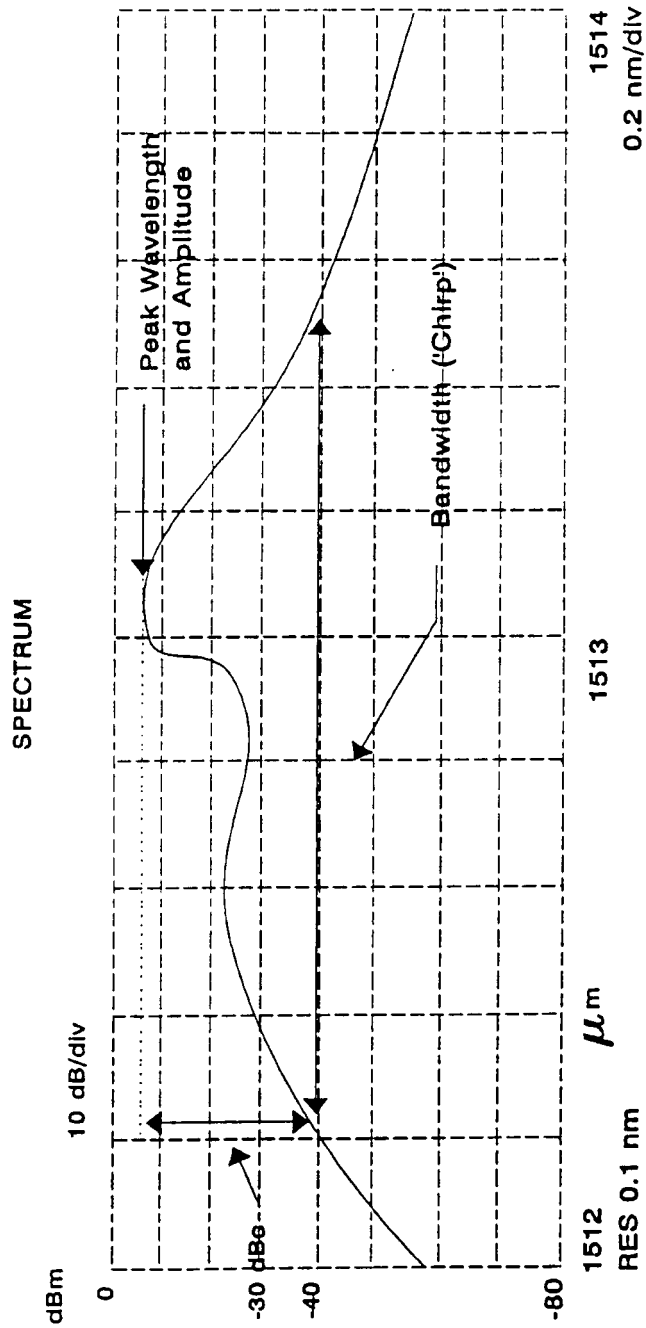


FIGURE 12-2. Typical LED and laser spectrum waveforms.

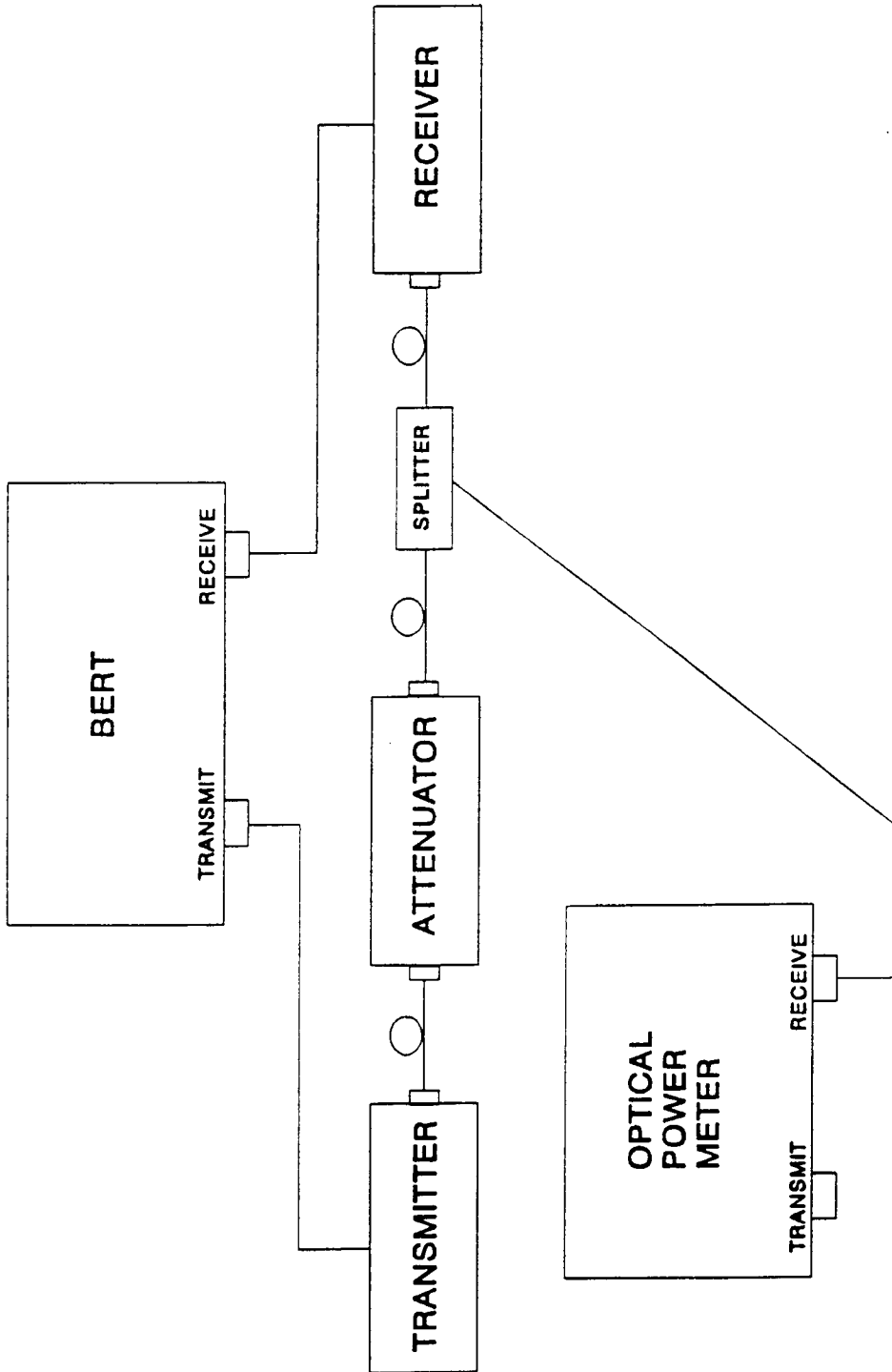
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C. Peak Emission and  $\Delta\lambda_{30}$  Measurement for SLM Laser

FIGURE 12-2. Typical LED and laser spectrum waveforms.

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**FIGURE 12-3. Test configuration for receiver sensitivity and maximum receiver input measurements.**

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The test is conducted by adjusting the optical attenuator in steps and recording the BER and received power for each step. Obviously one should start the test a few dB above the minimum expected receiver sensitivity and a few dB below the expected maximum receiver input level to minimize test times.

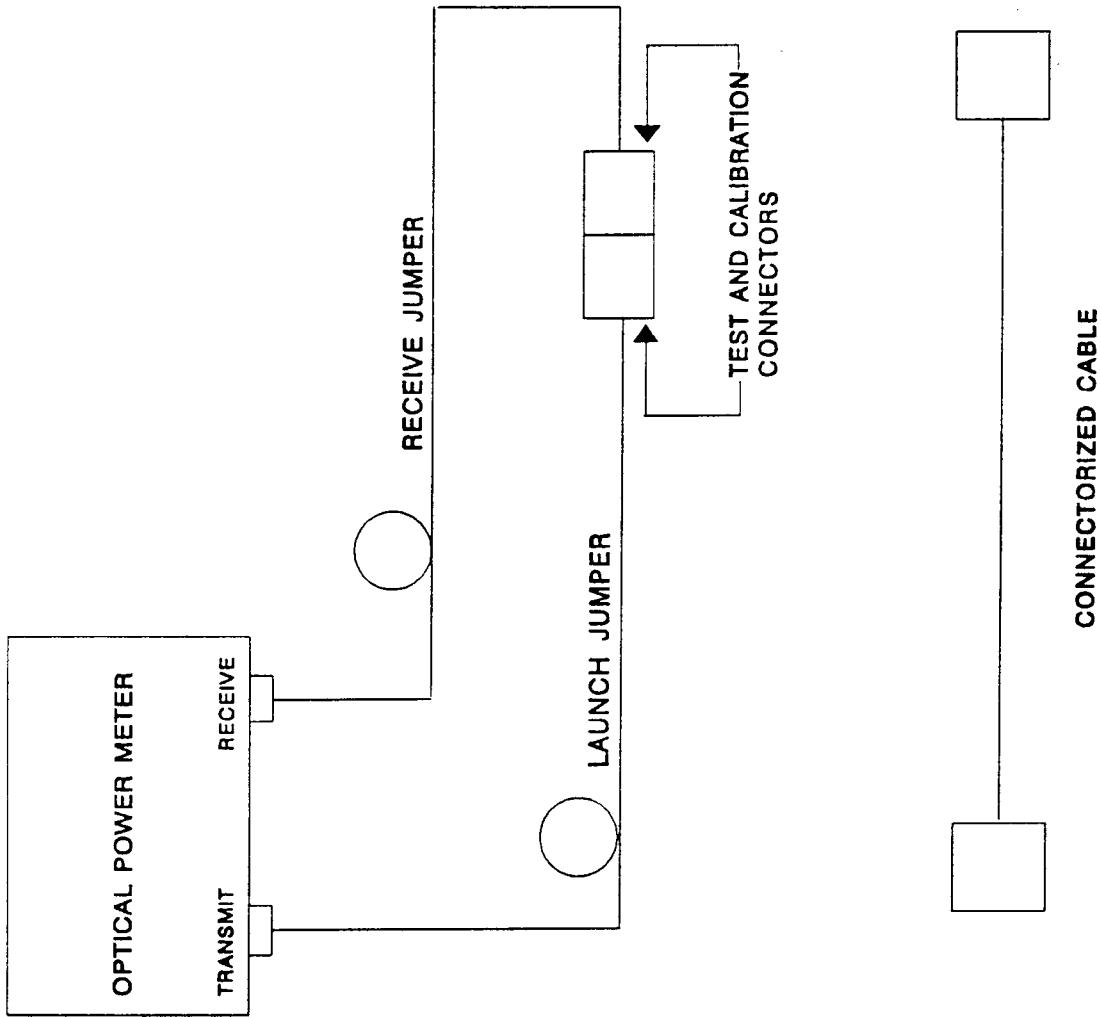
NOTE: It is important to ensure (for both multimode and single-mode) that jumper cables have been stripped of radiation modes in the cladding region of the cable, which can cause variations in loss at the received sensing point. The radiation in the cladding region must be stripped within the first two meters of test cables used in a test setup. If not, one must develop an equilibrium mode simulator (EMS), such as a mandrel wrap, or suitable optics capable of simulating EMS. This means that within a short distance down the fiber the equilibrium mode distribution is identical to that exiting a long fiber under steady state conditions. An example of cladding mode stripping is a mandrel wrap of 50/125  $\mu\text{m}$  graded-index fiber with five wraps on a 20 millimeter (mm) diameter rod to simulate the far field pattern of a fiber 1 km in length. Another approach is to use a 1 km spool of fiber cable. For further information on this problem, consult EIA Fiber Optic Test Procedures in EIA-455-50 and EIA-455-78.

**12.5.4 Passive components insertion loss.** The purpose of this test is to measure the insertion (attenuation) loss of passive components such as splinters, attenuators, jumpers, and connectors. The insertion test method is made by measuring power into the device and the power out of the device. Measurements must be specified for wavelength and care must be taken to attenuate radiation in the cladding region of test cables, as discussed in paragraph 12.5.3.

The insertion loss test is shown on figure 12-4 where an optical power meter is used with jumpers to measure the loss through a connector. In reality, only the loss through a pair of connectors can be measured. One can mate the test connector with a previously calibrated connector to ascertain the true loss of the test connector.

A known reference must be obtained. Connect one end of the launch jumper to the transmit port of the meter. The opposite end of the launch jumper is connected directly to the receive port of the meter. A measurement is then made that reflects the loss through the launch jumper. The launch jumper is disconnected from the receive port of the meter and connected to the cable and connectors to be tested. The opposite end of the cable to be tested is connected to the receiver port of the meter. A measurement is made. The difference in measurements is the loss of the test cable and connectors.

Another fiber loss measurement is shown on figure 12-4, where a cable having the same connectors on each end is tested. In this measurement, the test cable is inserted between the launch jumper and the receive jumper for measurement. As in the previous method, the



**FIGURE 12-4. Test configuration for insertion loss measurements.**

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jumper losses have been previously measured and used calibrating the test setup. One should repeat the test cable measurement by reversing the cable ends, to account for any differences in connector loss when reversing the cable.

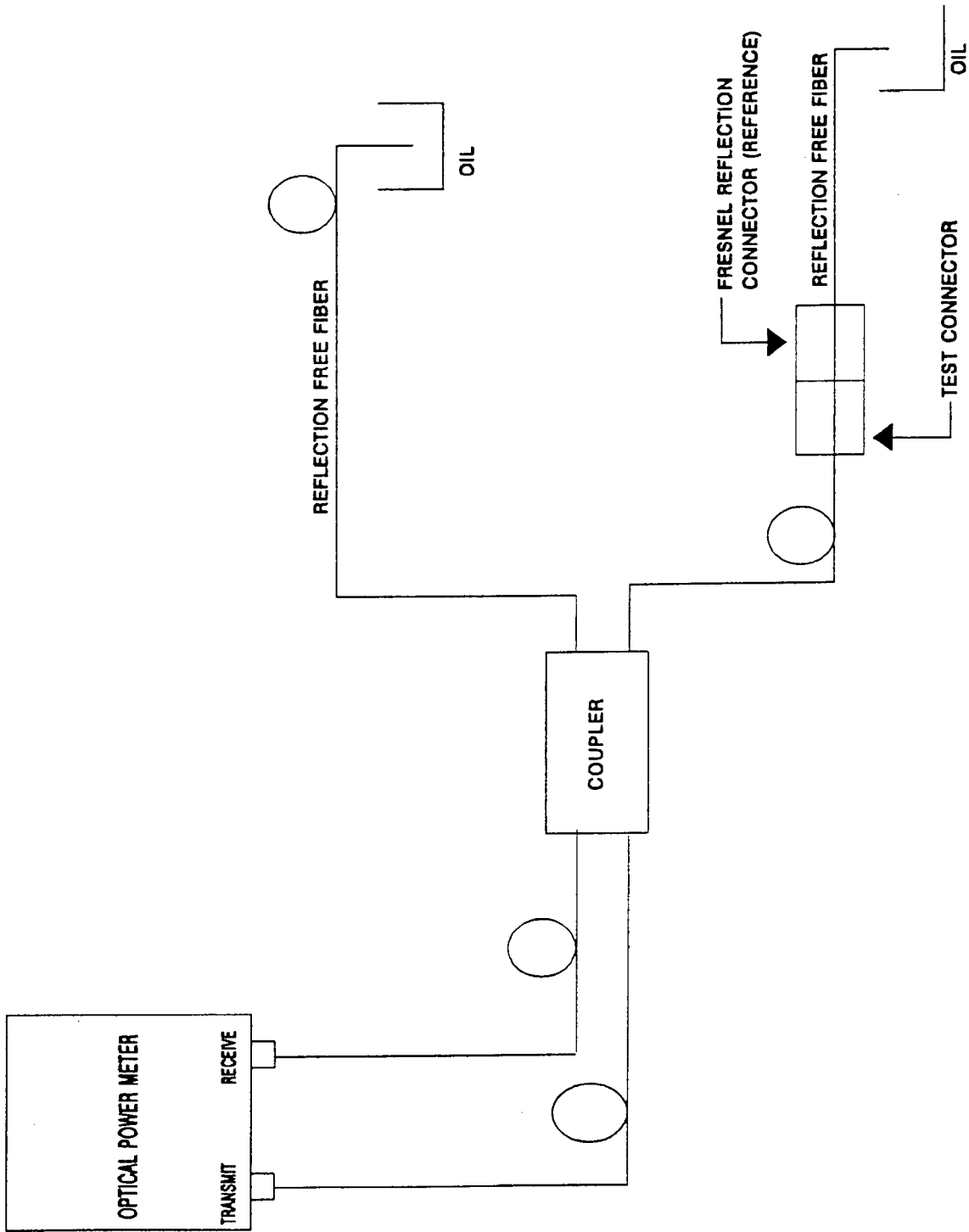
This same approach can be used for any passive component such as attenuators, couplers, and splitters. Fiber loss measurements are discussed in paragraph 12.6.

**12.5.5 Passive component return loss.** The return loss test is used to measure the reflected power from a passive device back to the optical source. This measurement is important for laser transmitters that are sensitive to reflected light, such as high data rate, narrow spectral width, distributed feedback (DFB) lasers. The test method uses an optical power meter, an optical coupler, a reference, and a test connector as shown on figure 12-5. The coupler is terminated from one port with a reflection free fiber terminated in an index-matching oil or by tying in a knot. The other port is terminated in a reference connector initially with an open end to generate a known reflection level. The connector is normally polished and generates a Fresnel reflection of 14.8 dB. This measurement is used to calibrate the test setup. Following this measurement, the connector under test is connected to the reference connector for test. The fiber end of the test connector is also terminated in a reflection free termination. The second measurement displays the return loss value of the test connector.

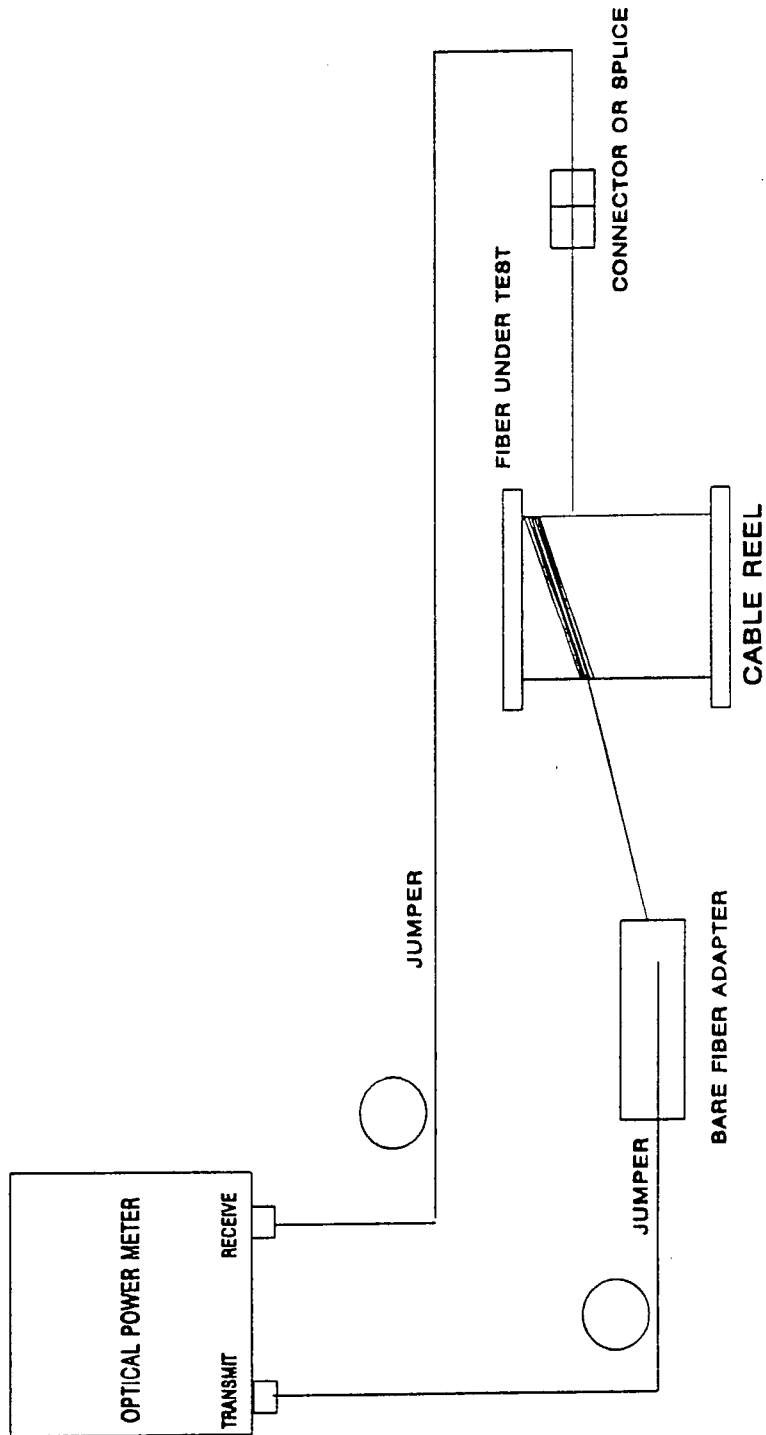
**12.6 Fiber cable test procedures.** The fiber test procedures described below are normally used to test a fiber cable or cable assembly as a component and not part of a system. The cable is not normally connectorized or installed as part of a system. Most of these tests will have been performed at the manufacturing level or the pre-installation period; however, it is important for the system designer to understand how the fiber parameters are derived and tested. It is recommended that the system designer specify fiber loss (attenuation) tests before final installation while the fiber cable is still on the cable reel at the installation site. This is to verify quality and to establish a data baseline for further site tests. During installation, loss tests can be done to verify the quality of field splices and to ensure no damage has been caused by cable pulls. Post installation tests are done when links fail to isolate failures or to check for gradual degradation.

**12.6.1 Fiber loss (attenuation).** The fiber cable loss (attenuation) can be measured by a number of methods: insertion loss (discussed in 12.5.4), optical time domain reflectometer (OTDR) (discussed in 12.7.1), and the cut-back method discussed below.

The cut-back method is the most accurate measurement, since it eliminates a dominant test parameter, the connector or splicing loss from the measurement. As shown on figure 12-6, an optical power meter is connected to a fiber cable under test from a jumper cable. The test cable is normally without connectors, with one end spliced (mechanically) to the jumper cable and the other end connected to a bare fiber adapter at the optical sensing input of the power meter.



**FIGURE 12-5. Test configuration for return loss measurements.**



**FIGURE 12-6. Test configuration for fiber loss measurements.**

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A loss measurement of the fiber cable under test is made. Normally this will be done on a full reel of cable as shown on figure 12-6. The next step will be to cut the fiber cable under test, 2 meters or less, from the jumper cable. The measurement will be repeated and used to calibrate the loss of the test setup (subtracted from the actual measurement). This approach completely removes connector or splicing losses from the final measurement, resulting in the actual fiber loss value, and is specified in dB loss per kilometer.

NOTE: For all loss measurements, the wavelength and temperature of the optical source must be recorded, since these affect the loss parameter. In addition, a steady state excitation of the fiber must be accomplished, as discussed in 12.5.3, to achieve the equilibrium mode condition of a long fiber. This use of a mode stripper is very important for single-mode and multimode fibers, because of the ambiguities of loss measurements caused by modes excited in the cladding region of the fiber.

**12.6.2 Fiber dispersion and bandwidth.** Single-mode fiber propagation and coupling properties differ from those of multimode fiber in many ways, and this affects the measurements required on them. In multimode fibers, the multiplicity of modes combined with modal velocity differences generally provides the largest limitation to bandwidth. In single-mode fibers, only one mode can propagate, making the measurements simpler. Another factor on single-mode fiber bandwidth is noise in partitioning of power from the optical source longitudinal noise (mode partition noise). This is usually the limiting bandwidth factor for the high data rate systems, because it depends upon the fiber chromatic dispersion which is the pulse delay due to the material and waveguide properties of the fiber. For lasers that emit multilongitudinal mode spectrum, dispersion results in a temporal broadening of the received pulse, based on the length of the fiber and the spectral width of the laser source.

For lasers that emit single-longitudinal mode spectrum, mode partition noise can be negligible, however, other dispersion related phenomena such as laser chirping, chirp noise, and spectral sidebands due to modulation can limit system range (see appendix D). Therefore, for single-mode fibers, a measurement of chromatic dispersion is required to properly specify the maximum range of a high data rate fiber optics system. Otherwise, pulse broadening will cause digital intersymbol interference resulting in high BER.

The bandwidth for single-mode fiber is too high to measure directly, except for extremely long fibers, since direct detection receivers can not handle extremely short pulse widths. Also, bandwidth is influenced by the optical source spectral properties, such as frequency chirp due to the ramp up of laser input bias current. Therefore, it is more practical to measure chromatic dispersion related to the group delay with wavelength, once the optical source properties are known.

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The dispersion measurement can be accomplished by using a time delay technique of measuring the dependence of time it takes a pulse to traverse a fiber based on the wavelength of the pulse. A second method is based on phase shift measurements using a sinusoidal modulated light source to excite a fiber and measuring the phase shift that occurs over the length of the fiber at a particular wavelength.

These measurements are normally performed at the manufacturing level and will not be discussed here. However, it is important for the system designer to understand that this measurement is described by three parameters:

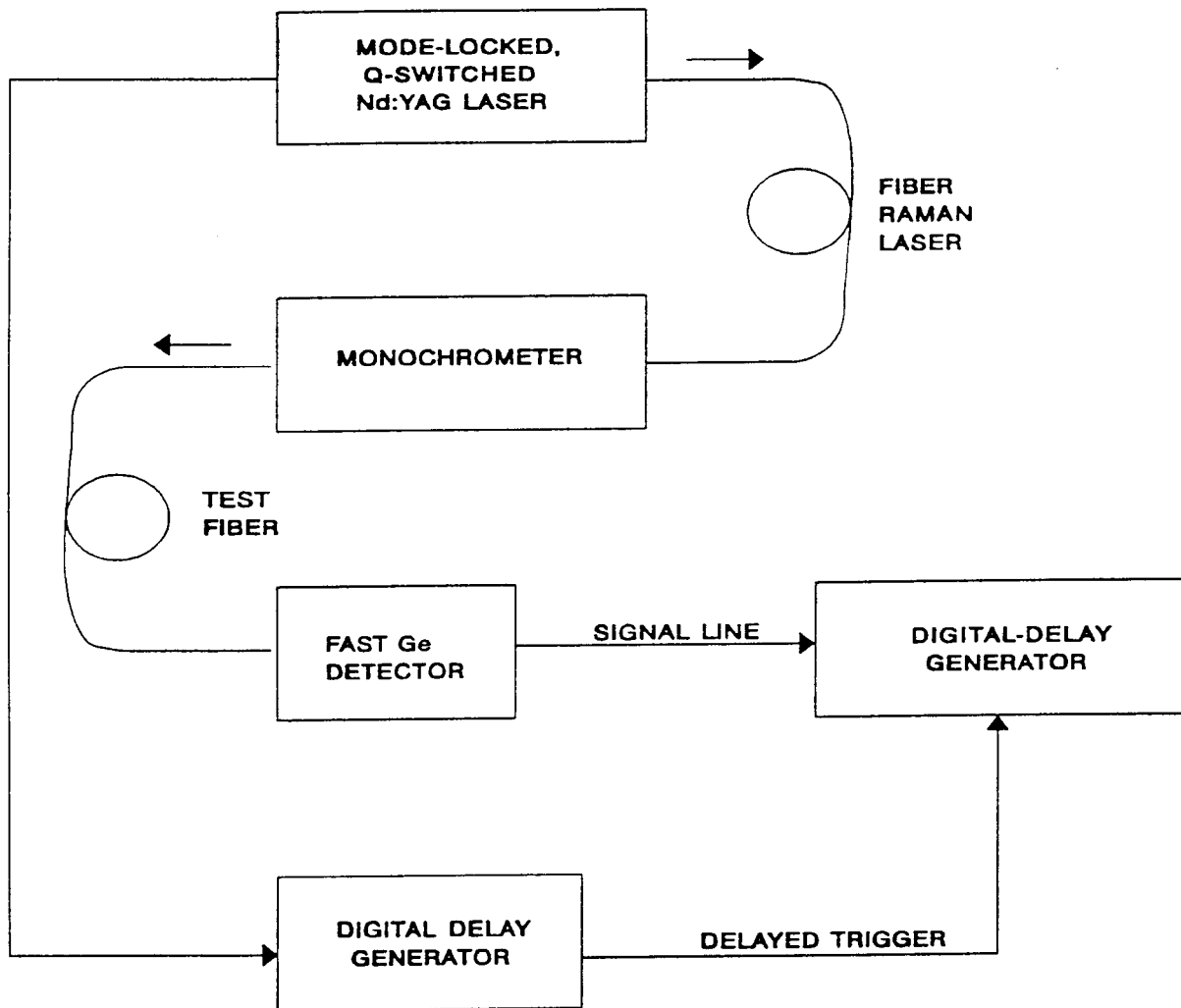
- 1) the minimum dispersion wavelength
- 2) the dispersion slope,  $\text{dB/d}\lambda$
- 3) the dispersion curvature.

Figure 12-7A shows a time delay test setup for fiber dispersion measurements, and figure 12-7B shows group delay and dispersion curves versus wavelength.

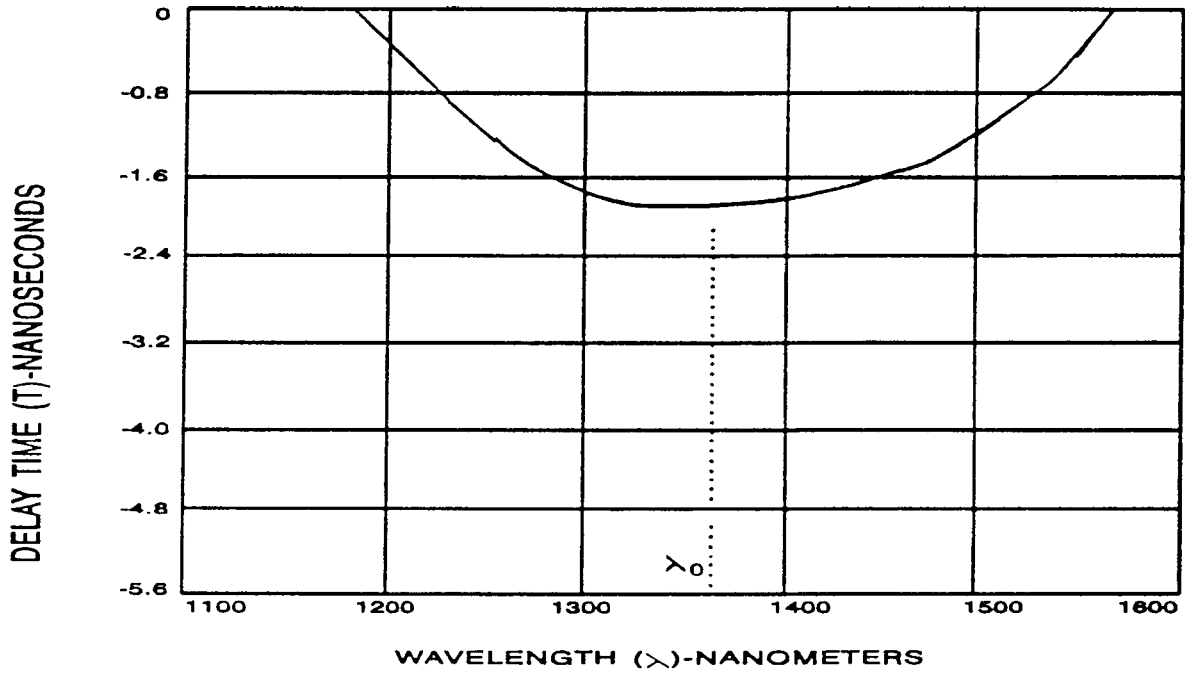
Typically, manufacturers specify the fiber cable dispersion in terms of a maximum value over a wavelength range. This description is not precise, and can be a disadvantage for a system designer for a high data rate long-haul system. In addition, for dispersion shifted fiber or dispersion flattened fiber, other types of expressions must be used by the system designer to achieve maximum accuracy. Therefore, a designer must investigate the fiber dispersion specifications when calculating range limits, as discussed in chapter 11.

For system bandwidth measurements of multimode fiber, the test method measures the highest modulation frequency that can be transmitted at a specified wavelength, with optical power loss not greater than 50 percent (-3 dB) of the zero frequency component. The swept frequency method is the accepted technique of measuring bandwidth in the field. The equipment necessary to make this measurement are a frequency generator, optical transmitter, and receiver, and a spectrum analyzer or selective level meter. The test jumper cables should be stripped of radiation modes in the cladding region (see 12.5.3).

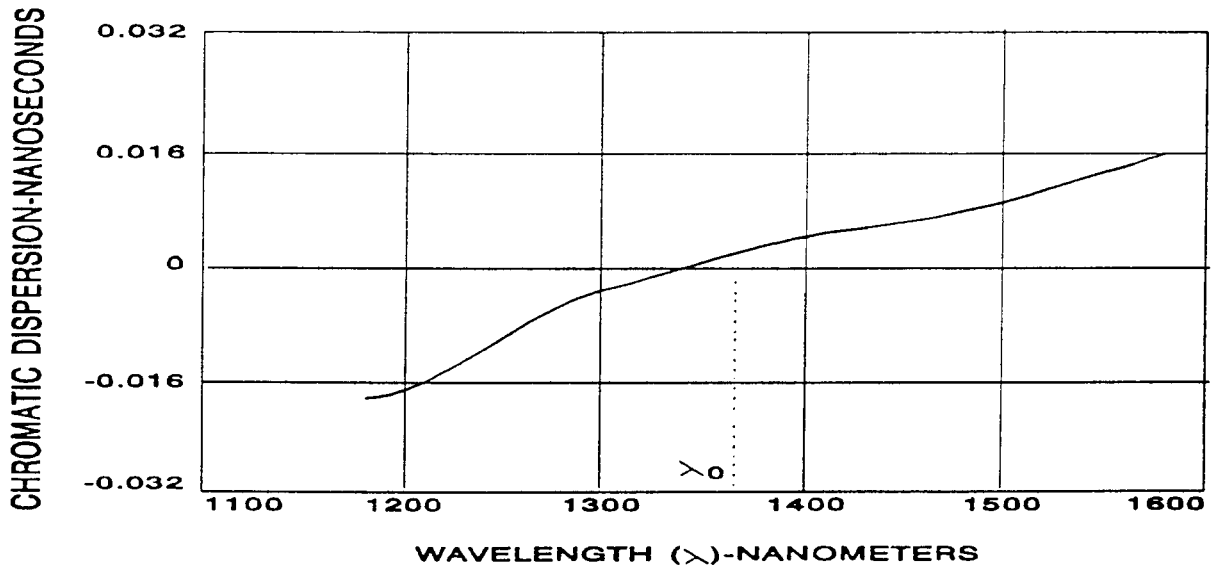
The equipment is first measured by plotting received power through the specified frequency range, typically from 10 MHz to 350 MHz. Variations in level from a straight line over the frequency band are used to calibrate the equipment and test setup (see figure 12-8). The next step is to measure the received power at the far end of the cable under test. The frequency at which the received optical power is reduced by 3 dB (6 dB if measured at the detector electrical signal output) becomes the point defined as the fiber bandwidth. This will be the limit for the information carrying capacity of the fiber.



**FIGURE 12-7A. Fiber dispersion measurements.**



B. Group delay



C. Dispersion

FIGURE 12-7B. Fiber dispersion measurements.

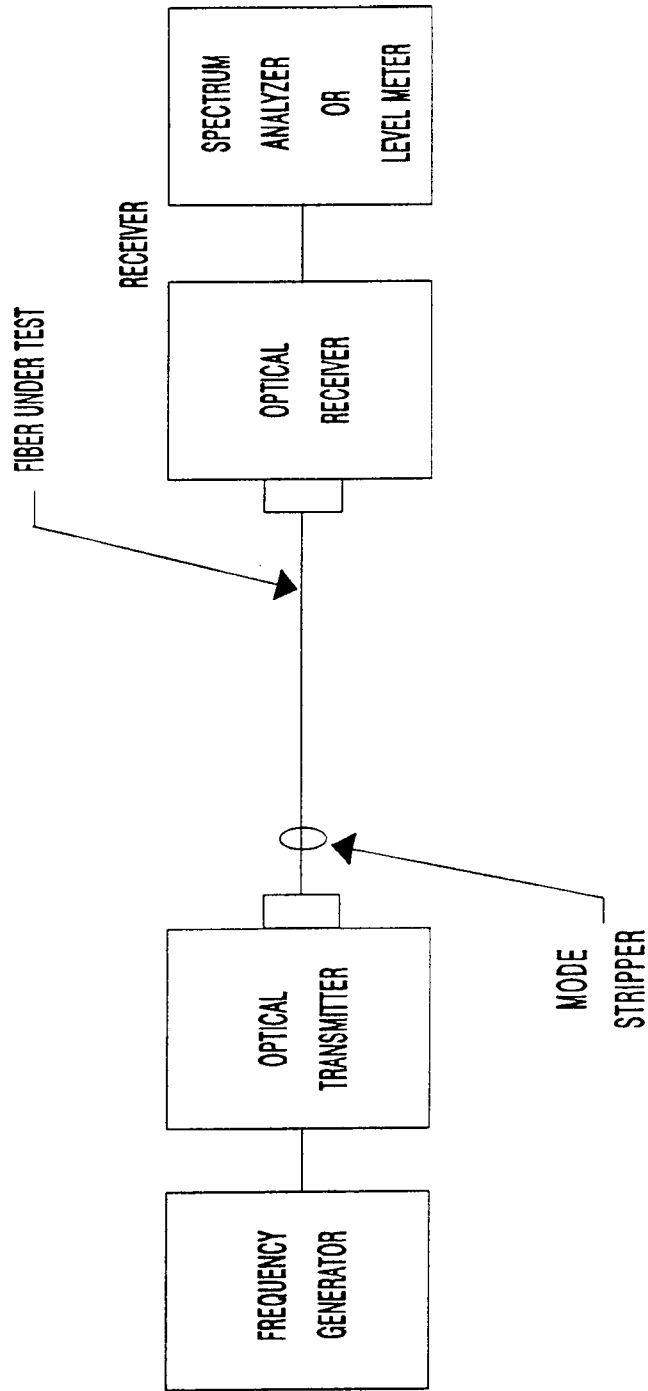


FIGURE 12-8. Test configuration for bandwidth measurements.

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**12.6.3 Fiber cable mechanical tests.** Fiber cable mechanical tests are performed to assure that performance is not affected by installation practices or environmental conditions. Two categories of tests are important for verifying the mechanical properties of the cable: material tests and performance tests. A number of materials have already been proven in copper cables, and test standards are available in American Society for Test and Materials (ASTM), Rural Electrification Administration (REA), etc. For performance tests, a comprehensive compilation of mechanical test procedures is available from the EIA Committee on Fiber Optics.

**12.7 System tests.** System tests are performed on FOCS to verify performance after installation for acceptance purposes, or to monitor operational performance for deteriorating conditions. System tests are also performed to isolate faults and to periodically verify performance of standby electronics or dark (unused) fiber.

**12.7.1 OTDR.** The purpose of an OTDR is three-fold: total system link loss (attenuation), discrete connector or splice losses, and a distance measurement for locating faults (cable breaks or lousy connections), and distance to the far end of the link.

Figure 12-9 shows a block diagram of an OTDR test setup. The OTDR acts as an optical radar by launching high intensity pulses into the installed fiber cable and detecting reflections and backscatter signals. Time measurement from launch of the transmitted signal determines the distance to the detected reflection. The OTDR calculates the distance to reflected signals and displays or plots the distance on a horizontal axis. The vertical axis displays the relative power loss in dB as the launched pulse travels down the fiber.

An example of this measurement and the events it displays are shown on figures 12-10 and 12-11. These figures show the attenuation increasing along the length of the fiber where the OTDR measures the received noise floor of the system. Along the length of the fiber, splice losses, if prominent, and losses and reflections from connectors can be seen. The return loss from a connector can be estimated by measuring the height of the reflection and applying a mathematical formula. The distant end of the fiber can be determined by measuring the horizontal distance to the reflection at the end connector. Most OTDRs provide markers for this purpose and automatically display the parameter marked. A cable break can be located accurately using this technique, with the only inaccuracies being in the difference between the actual cable length and that shown on the OTDR screen (cable factor).

The fiber end-to-end attenuation is measured by the difference in the total drop of attenuation from the start to the end. The maximum distance that can be measured in a cable will be the point where the attenuation hits the noise floor of the system. This is determined by the dynamic range of the OTDR and the total attenuation of the fiber cable under test. OTDRs

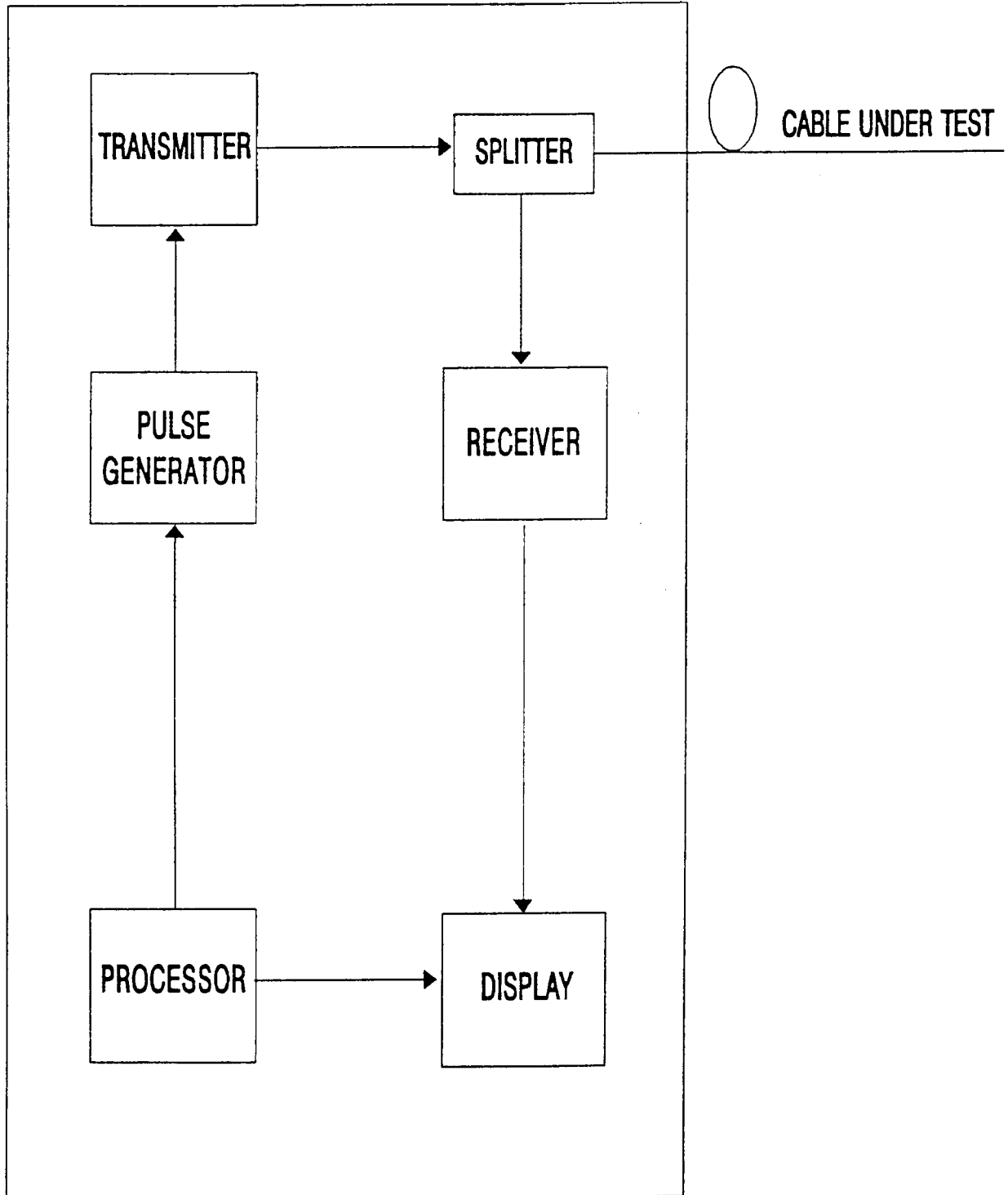
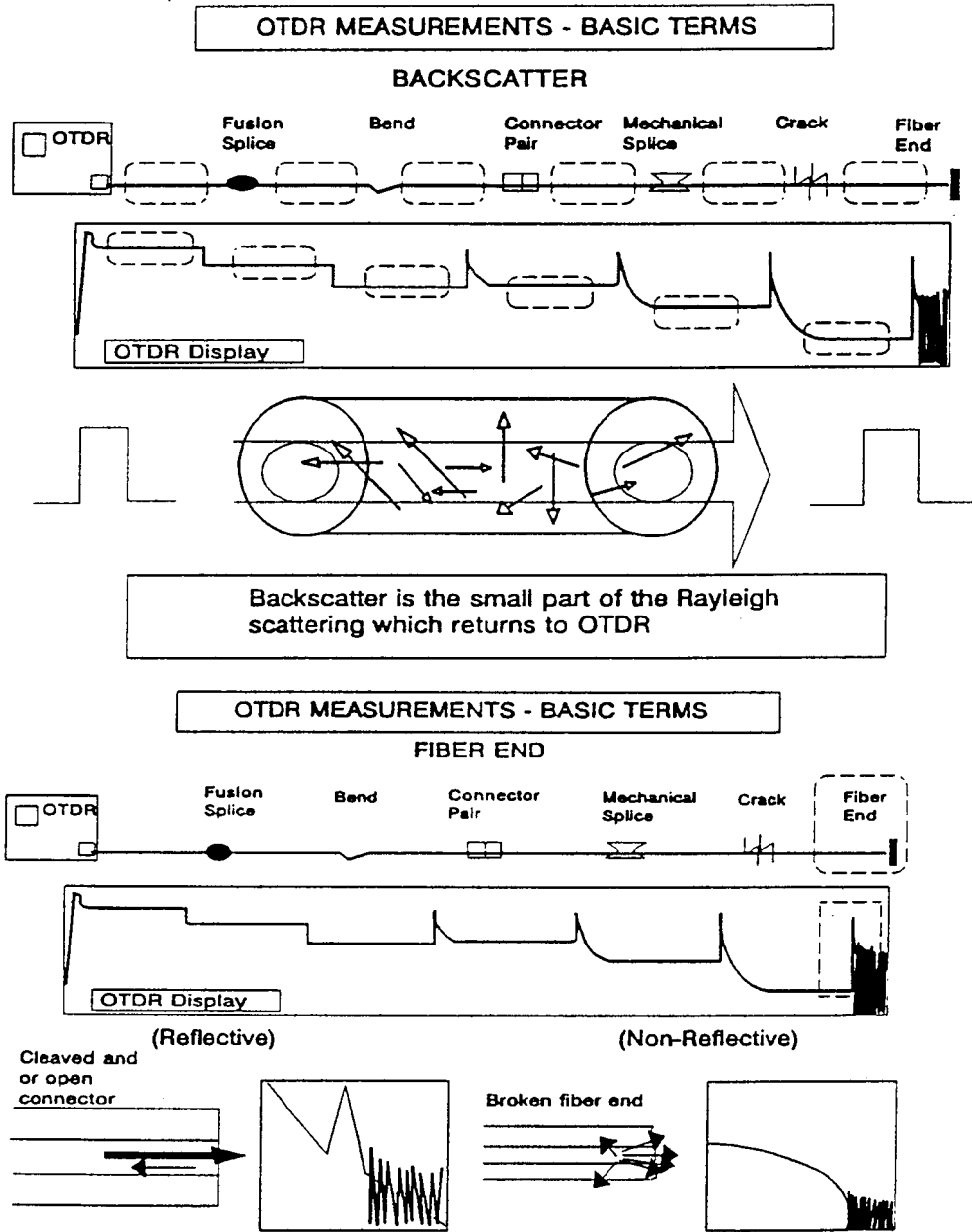
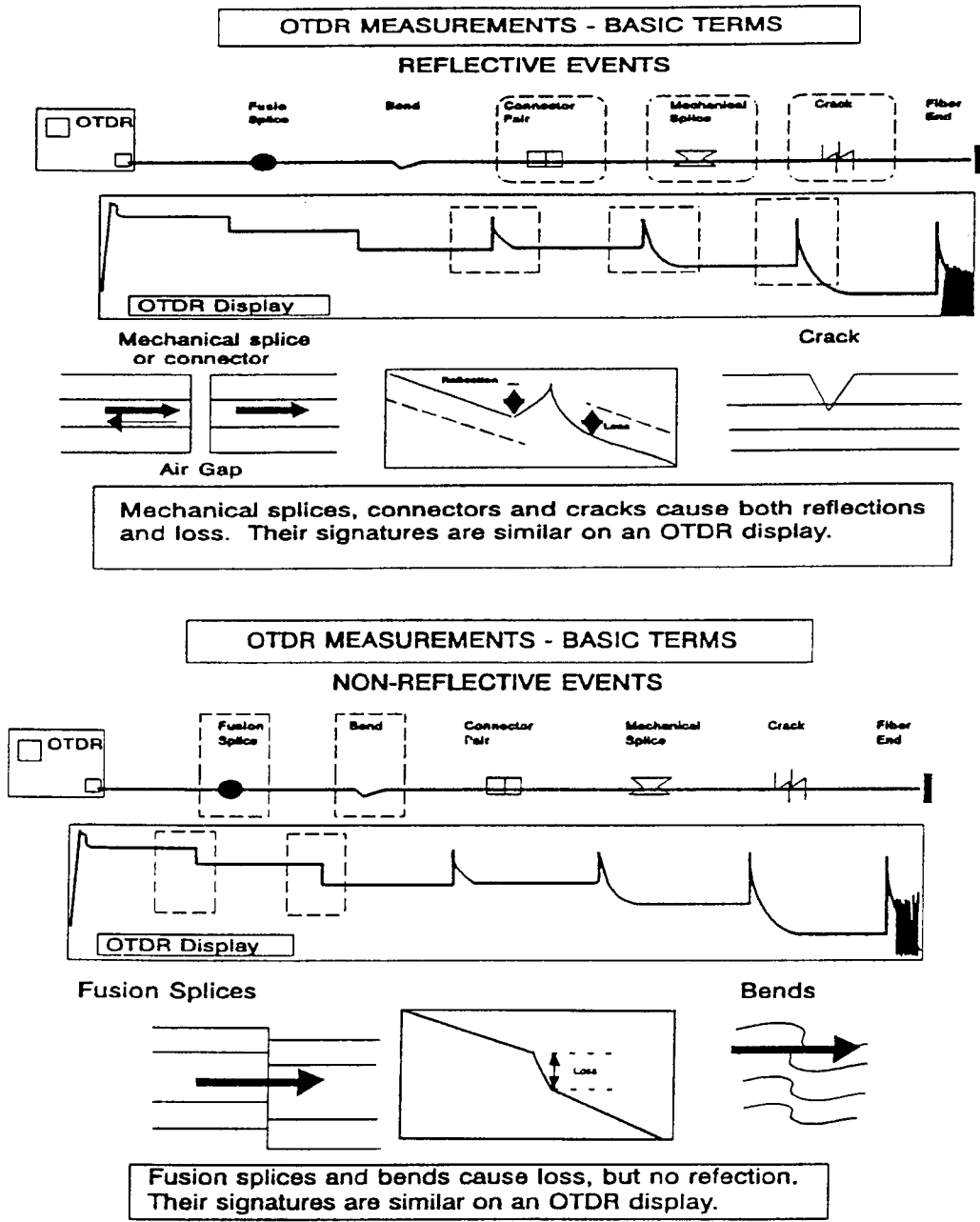


FIGURE 12-9. OTDR block diagram.



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FIGURE 12-10. Backscatter and fiber end OTDR displays.



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FIGURE 12-11. Reflective and non-reflective OTDR displays.

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can be designed for short range or long range measurements, the determining factors are generally the pulse width and averaging time selected. Longer pulse widths will achieve longer ranges, but measurement resolution is less because of receiver dead zone time. Most OTDRs will zoom on selected points by marker control.

Some OTDRs that are personal computer (PC) based are available. These will record and store cable measurements for future comparisons for evaluating possible degradation. Unused (dark) fibers in cable are normally tested periodically for this reason.

**12.7.2 BER**, system power margin, or bit rate tolerance. The purpose of this test is to verify the system BER under increased steps of induced attenuation to determine the system power margin at an acceptable level of BER. This test is also called bit rate tolerance of the FOCS under specified conditions.

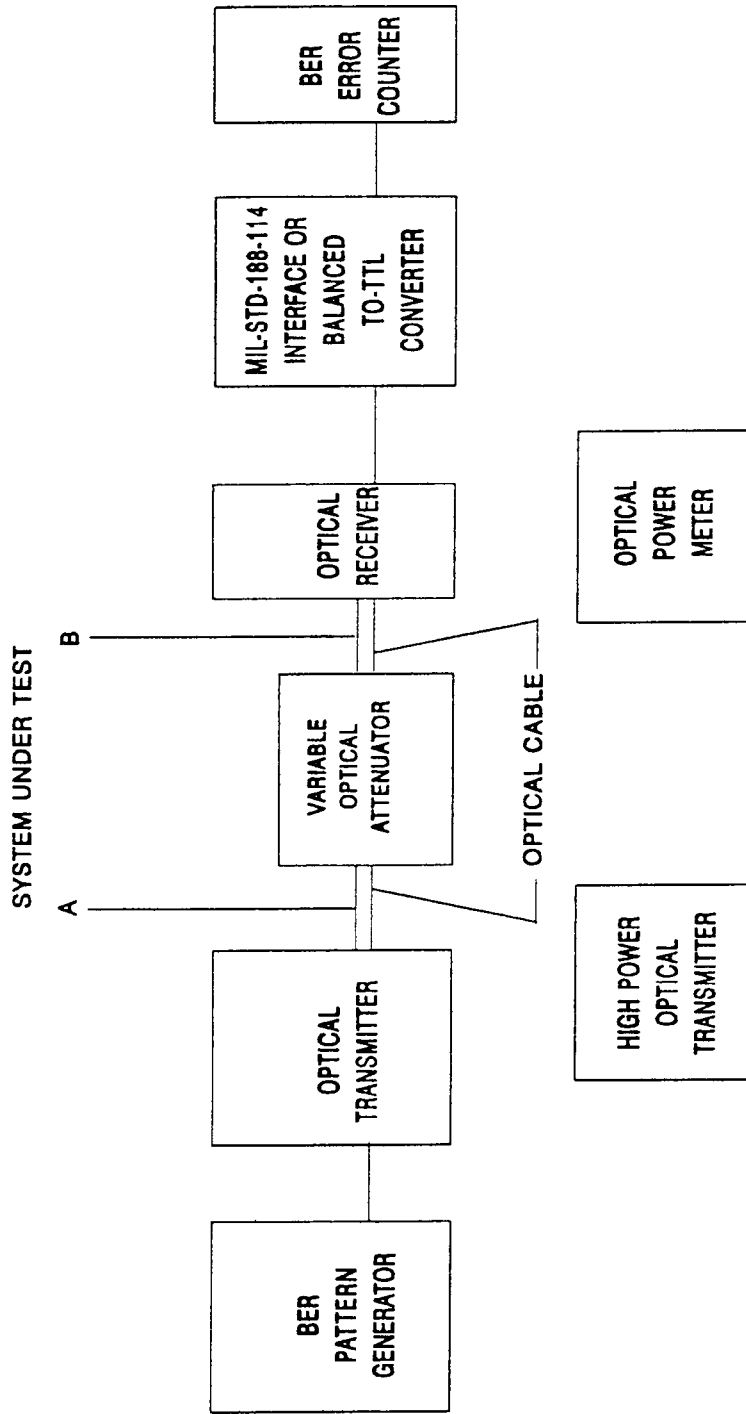
BER is a function of the system SNR at the received terminal. It is defined as the ratio of the number of received bit data errors to the number of received bits. The dominant noise source in a FOCS is usually the receiver. Signal losses (attenuation) caused by cable splices, connectors, or deteriorating laser power degrades the SNR, and thus, the BER. Other possible causes may be lack of synchronization of the external data stream or excessive jitter in the bit stream.

For a transmitter receiver pair and the installed fiber cable, the difference between available power and the power required to maintain an acceptable (specified) BER is the system power margin. MIL-STD-188-111 specifies that the BER of a long-haul FOCS link shall not exceed  $K \times 10^{-11}$ , where K is the length of the link in kilometers, and the BER shall not exceed  $10^{-9}$  for tactical links.

The test method is to place an optical attenuator in the FOCS link and precisely induce attenuation in steps, while measuring BER at the receiver until the maximum allowable BER is reached (see figure 12-12). A BER test set is used to modulate the transmitter with a pseudorandom bit sequence. The received part of the BER test set will count received bit errors compared to transmitted bit sequence for determining the ratio of errors to the number of bits transmitted in a specified time interval.

There are a number of variations to this test, however, each accomplish slightly different objectives. They are described as follows:

- 1) a subsystem receiver test to determine receiver sensitivity and receiver dynamic range for maximum receiver input (see 12.5.3),



NOTE: A BALANCED TO-TTL CONVERTER MAY BE USED IN LIEU OF TEST EQUIPMENT PROVIDING A MIL-STD-114 INTERFACE.

FIGURE 12-12. Test configuration for bit tolerance.

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2) a subsystem transmitter receiver pair test to determine system margins of minimum and maximum power levels,

3) an in-service monitoring test of the entire system to determine BER under actual link operating conditions.

The normal procedure for a BER test setup is to adjust the measurement time interval M for the highest data rate to minimize the time counting interval when measuring for such low error ratios. However, industry practice is to use standard North American data rates such as DSI (1.544 Mbps) and DS3 (44.736 Mbps). These rates are normally available from standard BER test sets, and several loop-back configurations to test the transmission in both directions for full duplex operation.

To determine the appropriate pseudo-random bit sequence length (PRBS), one should refer to recommended values from standards provided by International Telegraph and Telephone Consultative Committee (CCITT). The following lists recommended values that will provide a suitable smooth spectrum for a specified data rate.

### Recommended Pseudo-random Bit Sequence Length

<u>Data Rate</u>	<u>Sequence Length (bits)</u>
Up to 20 kbps	$2^9-1$
20 kbps to 13 Mbps	$2^{15}-1$
13 Mbps to 1 Gbps	$2^{23}-1$

One must determine the time interval required to measure BER for a specified system data rate. An example of this determination is providing an in-service monitoring test that uses the standard DS 1 data rate of 1.544 Mbps with a BER test set. To measure a BER objective of  $1 \times 10^{-9}$ , one must select a confidence level to determine this statistical parameter assuming the errors are independently distributed over the time interval. A confidence level of 95 percent is normally used by industry. A statistical calculation will show that for 10 observed bit errors, there exists a 95 percent confidence that the true bit errors will be less than 1.5 times the measured bit errors. The following formula will calculate the required time interval for measurement.

$$T = 1.5 \times K / (D \times \text{BER}),$$

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where:

- T = the required time interval in seconds
- K = the number of measured bit errors
- D = the data rate in bps
- BER = the specified BER.

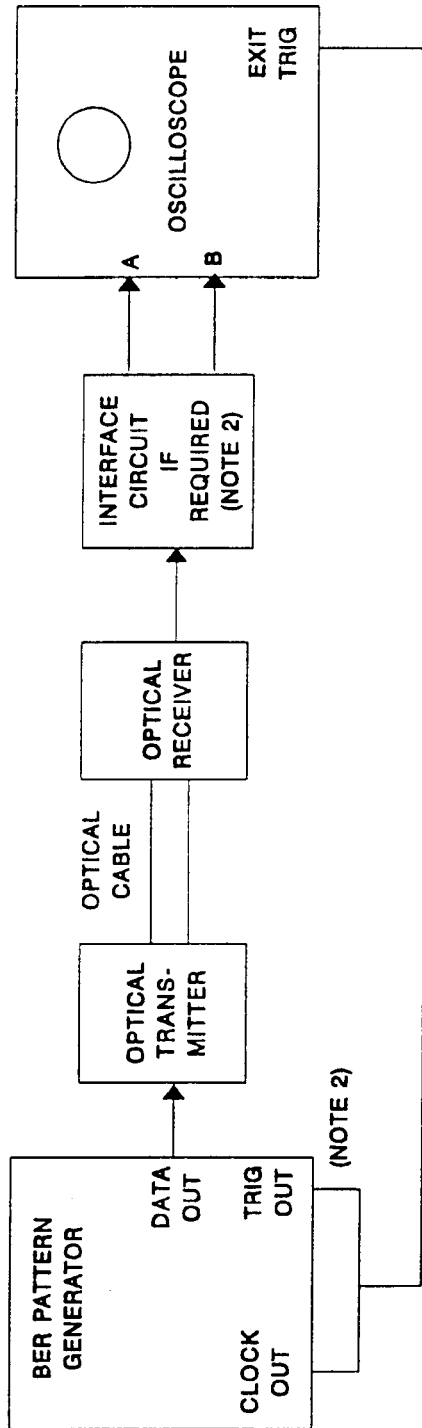
As an example, for a data rate of 1.544 Mbps over a time interval of one hour, at a BER of  $10^{-9}$ , no more than 4 (actually 3.7) bit errors should be recorded. This process for service monitoring is normally done with specified time intervals (hours, quarter days, etc.) and the allowable measured bit errors are specified for those intervals according to the data rates monitored. For a sample of these parameters measured, see Chapter 10.

**12.7.3 System jitter and waveform distortion.** Jitter and waveform distortion can contribute to the system BER, therefore, measurements should be made to determine whether FOCS equipment or external communications interfacing with FOCS equipment are in compliance with standards established on these problems. The issue will be to isolate the source of the problem. To isolate the problem to FOCS equipment, measurements should be made on the electrical signal at the input to a FOCS link, and at output of a FOCS link.

Jitter is defined as short term variations of the significant instants of a digital signal from their ideal positions in time. Jitter can only be related to a specific data signal and its associated clock, since the clock signal controls the instant of time when the data signal is sampled to determine a specific data bit value. Thus, timing errors, and consequently bit errors, occur when sampling is done too early or too late. However, system noise or distorted waveforms can contribute to sampling errors so the source of the problem is sometimes difficult to assess.

There are two methods to measure jitter: the use of a frequency and time interval analyzer (FTIA) or a dual trace oscilloscope. The FTIA will provide the most accurate measurement of jitter by displaying a histogram of the standard deviation and the mean of the time interval between the positive slope of a positive data pulse (for example), and the negative slope of the clock pulse. Use of a sampling oscilloscope will also provide histogram outputs of jitter.

Using an oscilloscope to measure jitter will be . more subjective, and less accurate, since it will require viewing waveforms to determine widths of horizontal a= movements to assess jitter. To perform this measurement, connect the data pulse input to the signal input of the oscilloscope. The clock pulse, which is used to trigger the horizontal trace is connected to the external trigger input (see figure 12-13). By displaying these two inputs over a period



NOTES:

1. CONNECT SCOPE EXT TRIG TO CLOCK OUT TO MEASURE DISTORTION.  
CONNECT SCOPE EXT TRIG TO TRIG OUT TO MEASURE JITTER.
2. A MIL-STD-188-114 INTERFACE OR A BALANCED TO-TTL CONVERTER MAY SATISFY THE REQUIREMENT FOR AN INTERFACE CIRCUIT.

FIGURE 12-13. Test configuration for distortion and jitter measurements.

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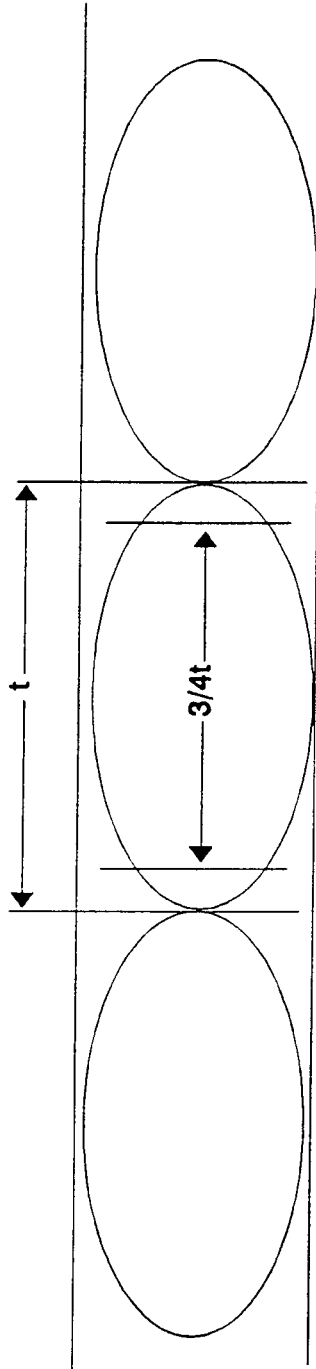
of time, one can see the peak-to-peak jitter between the two inputs on the horizontal trace. The standard deviation of the jitter can be estimated by dividing the peak-to-peak jitter dimension by a factor of four.

To measure the mean time interval jitter between the data pulse and the clock, use the single shot trigger feature on the oscilloscope to measure the average phase offset (the time displacement) between the center of the data pulse and the falling edge of the clock pulse. By taking a number of samples (at least 25), the mean of this time interval can be calculated and subtracted from the average phase offset to determine the mean time interval jitter. To accomplish waveform distortion measurements on FOCS transmitter/receiver pairs, a dual trace oscilloscope should be connected to the optical receiver output (see figure 12-13). On an appropriate communications channel, setup a BER pattern generator to modulate the optical transmitter with the appropriate pseudo-random bit sequence for the data rate being observed (see 12.7.2). Connect the oscilloscope dual trace inputs so that one trace has an inverted receiver output, the other non-inverted (see note 2 on figure 12-13). Connect the BER test set clock to trigger the oscilloscope external trigger. In the case of a link test, the clock from the receiver will have to suffice as a trigger for the oscilloscope.

The resulting waveform on the oscilloscope will resemble an eye pattern as shown on figure 12-14. Many patterns are possible due to coding sequences, however, distortion tends to fill in the eye with noise, leaving a smaller opening, and the size of this opening can be used to calculate distortion. Using figure 12-14 as an example, shrinkage of the opening to 75 percent of its undistorted opening width "t" would indicate a 25 percent distortion.

**12.8 System performance monitoring.** Modern long-haul fiber optics communication systems employ continuous monitoring of critical network parameters to detect signal deterioration, cable faults, and other problems in optical networks. As discussed in the Chapter 10, system monitoring provides proactive maintenance by detecting signal degradation before complete fault occurs, sending alarms to a remote maintenance center for follow-up action. Table 10-1 in chapter 10 lists the performance parameters of the SONET, provided by the communications overhead in the optical link data rates. Each SONET section, link, and path (see appendix E) is monitored for specific parameters, such as coding violation counts, parity bit errors, severely errored frame seconds, etc. This allows a system maintenance center to determine the location of the problem in a multiple link network.

Performance parameter threshold counting intervals are standardized at current quarter hour and current day for each parameter monitored. Whenever the threshold is exceeded, which is a counting register for parameters such as coding violations, parity bit errors, etc.,

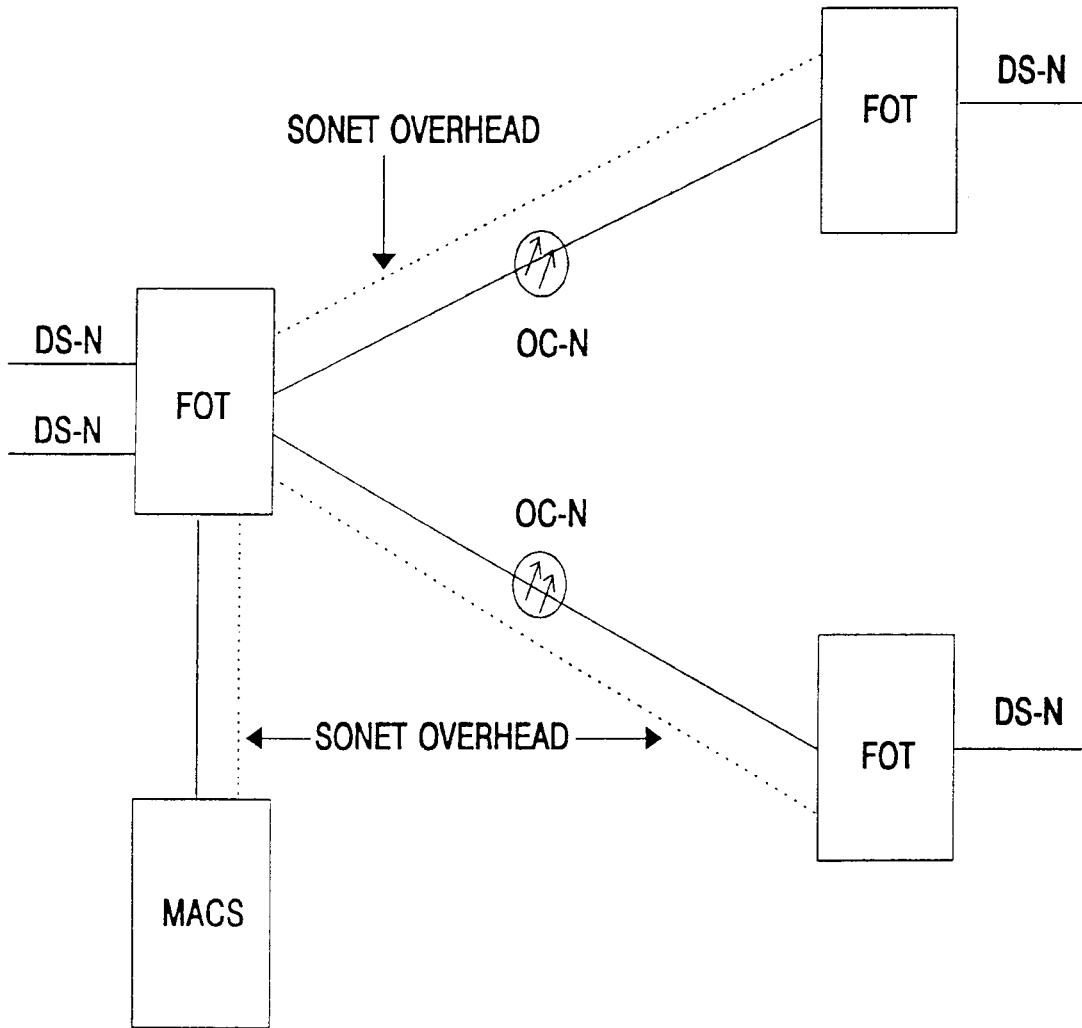


t = WIDTH OF EYE PATTERN WHEN NO DISTORTION IS PRESENT.

**FIGURE 12-14. Eye pattern oscilloscope display.**

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a threshold crossing alert message is sent to the remote maintenance center. A normal industry practice is to employ a telemetry byte-oriented serial (TBOS) communications protocol to send information to and from remote maintenance centers. This allows standardization of equipment so a variety of vendor equipment will operate on this type of network. Figure 12-15 illustrates a generic form of this type of system monitoring network. The proactive part of network maintenance operates from control signals, which communicate to the remote nodes to remotely switch into or out of operation FOCS subassemblies as required to maintain performance.



FOT: Fiber Optic Terminal Transmitter and Receiver

MACS: Maintenance Center

FIGURE 12-15. System monitoring network.

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### CHAPTER 13 SAFETY

**13.1 General safety concerns.** An FOCS designer has at least three areas of safety concerns: (1) the work place; (2) the environment in which the FOCS is situated; (3) equipment selection, arrangement, system construction, and maintenance procedures. Occupational Safety and Health Administration (OSHA) regulations require a safe work place at all times. Although OSHA does not approve specific tools or products, there are Federal specifications for equipment safety listed in the appropriate qualified products lists.

**13.2 Central purpose of laser safety.** Concentrated optical energy is emitted by lasers, either as visible light, invisible energy, or in communications systems, as near-infrared energy. Lasers typically are encountered using OTDRs or optical transmitters. All laser safety rules revolve around one premise: lasers can be dangerous. **Under no circumstances should a person look directly into a laser or at an end of a fiber when laser light is being sent through it from the other end.** The eye's retina can be permanently damaged. A number of safety practices have been established to aid system personnel in avoiding accidents.

**13.3 Required laser safety standards.** Lasers must comply with the requirements of MIL-STD-1425, ANSI Z136.1 and ANSI Z136.2. DOD-INST 6050.6 and MIL-STD-1425 specify requirements for military exempt lasers, such as those used in combat or combat training, or those classified in the interest of national security. Lasers used for other purposes, such as general communications, must comply with applicable parts of the Code of Federal Regulations, issued by the U.S. Food and Drug Administration (see MIL-STD-1425). Detailed safety procedures are described in T.O. 31-10-34/FM 11-487-5, EE169-CA-GYD-010/E110 TSER E&I and should be consulted before installing any FOCS.

**13.4 Recommended laser safety guides.** An example of useful safety standardization was promoted by ANSI and adopted subsequently by the International Electrotechnical Commission (IEC). IEC Standard 825, Radiation Safety of laser Products, Equipment Classification Requirements, and User's Guide, offers a substantial checklist of safety concerns for fiber laser products. ANSI Standard Z136.2, The Safe Use of Optical Fiber Communications Systems Utilizing Laser Diode and LED Sources outlines laser safety practices. It should be used for FOCS, where radiant energy is contained within an optical fiber during normal use.

**13.5 Laser safety practices and procedures.** FOCS require special discussion because potentially harmful light is utilized. Direct emission of harmful light can occur from an exposed active fiber end. If a break has occurred, harmful optical power may be present at a location not suspected as risky. The intensity of the light source (including optical magnification), the

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distance from which the source is viewed, and the duration of eye exposure to the source determine the extent of damage to the eye. Therefore, all FO cable should be considered active and possibly dangerous. Personnel should not test the continuity with a flashlight. An optical test set, an indirect image converter, or equivalent device should be used.

ANSI Standard Z136.1 covers laser safety in general. Four classes of lasers exist, based upon the hazards posed to human health. Class 1 usually does not emit harmful radiation and does not need specified consideration. Class 2 systems use low power and have visible emission (0.4  $\mu\text{m}$  to 0.7  $\mu\text{m}$ ). Class 3 systems use medium power levels and mandate against direct exposure to the radiation. Class 4 systems use high power and are the most dangerous. MIL-STD-1425 should be consulted to determine the shielding and labeling needed for each class.

When FOCS energy sources are enclosed, a Class 1 status exists. When the system is opened, a danger exists. In FOCSS, the risk of injury is dependent upon different wavelengths, power, and divergence resulting from the optical fiber. Accordingly, a service group (SG) hierarchy has been established in ANSI Z136.2 to clarify the degree of safety necessary for an FOCS.

**13.6 SG parameters.** Each SG has a top limit on the amount of power or energy emitted by a laser, and to which humans can be exposed. This is the accessible emission limit (AEL). In addition, there is a value for maximum permissible irradiance (MPI).

NOTE: For practical purposes, SGs, except SG1, represent conditions that discourage direct viewing of light sources, hence mandate control measures. If safety regulations have been followed, lasers will be marked accordingly.

**13.7 Other safety concerns.** While laser safety is of prime focus for personnel, electrical components, chemicals, and fiber itself (especially small pieces that could penetrate the skin), must also be handled with extreme caution. Contact lenses should not be worn where danger exists of getting chemicals or fiber fragments in the eyes.

**13.8 Applicable DoD documents.** Individual DoD agency documents containing safety requirements applicable to electronic equipment employing high voltages or radiating high energy fields should be reviewed prior to designing systems in accordance with guidance contained herein.

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**13.9 Electrical hazards and fiber.** When threading fiber cable through conventional wiring systems, an installer should take extra precaution against touching 'live" wires. The power supplies and other electronics used in FOCS should comply with requirements of MIL-STD-882, paragraphs 1 and 8 of MIL-STD-454, and other applicable safety requirements of MIL-STD-454. The NEC provides useful guidelines in adhering to safety practices and procedures. The following four rules summarize major electrical safety practices.

- a. Ground all electronic equipment enclosures that can present an electrical shock hazard.
- b. Keep electricity separate from equipment and components (including cable) not to be electrified.
- c. Keep heat and sparks away from electrical conductors and equipment, thereby preventing a fire or triggering an explosion.
- d. Do not assume an item is safe. Electrical equipment is dangerous until proven safe.

**13.10 Materials.** When using solvents or other chemicals in FO applications, avoid skin contact, keep them away from heat, and use in a well-ventilated area.

**13.11 Safety and testing.** Inasmuch as hazardous materials, equipment, and procedures may be involved in field testing, safety practices must be followed scrupulously.

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### CHAPTER 14 DOCUMENTATION

**14.1 General.** Procedures and responsibilities for engineering documentation are contained in regulations and other guidance documents of the individual military departments and agencies of the DoD. Requirements and applicable references which apply to the physical preparation of engineering drawings (format, size, symbology, etc.) are established by MIL-STD-100, Engineering Drawing Practices. For the purposes of this handbook, the following discussion of documentation is limited to as-built installation drawings and plant-in-place drawings for the FOCS being designed. It is assumed that all other documents, such as specifications, equipment lists, procurement papers, operating and maintenance manuals, and system performance records, will be developed, stored, and maintained in accordance with appropriate military department or agency procedures.

**14.2 As-built installation drawings.** Accurate and up-to-date records of inside and outside cable plants are an important element of the life-cycle management of any DoD communications system. As-built installation drawings, sometimes called "red-lined drawings," reflect actual network configurations, including on-site changes made to original installation plans. Continuing operations and maintenance activities use the record information contained in as-built drawings. *Without good records, network changes and upgrades cannot be made in a timely and efficient manner,* and maintenance and retrofit actions cannot be taken with minimum damage and disruption of service. Proper documentation begins with a complete record of the initial installation of the system. It continues with accurate, timely updates of all changes and modifications. As-built drawings are the basis for plant-in-place records which form the permanent record of how a network is configured.

**14.3 Plant-in-place drawings.** Master copies of plant-in-place drawings are normally stored and maintained by a repository agency. This is in accordance with military department and agency procedures and regulations. Working copies are available at major network installations and appropriate organizational headquarters. Plant-in-place records of existing cable plants should be the starting point for system changes and upgrades. They must provide detailed descriptions of cable type, size, capacity, routing, types of splices and connectors, as well as locations of components.

The physical characteristics of installed cable and how it is configured in building conduits, duct work, and plenum areas must be known. Without this knowledge, existing cable plant and facilities can be subjected to serious damage when new cables are being installed and existing plant is relocated. For example, attempting to pull new cable through unfamiliar conduit can result in severe damage to the cables. The practice of leaving replaced and unused cable in plenums and other distribution paths should be avoided.

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Failure to record changes to existing communications systems is a serious malpractice. Proper updating of records in accordance with established procedures should be verified before system changes and retrofits are accepted. Documentation must be part of all design efforts.

**14.4 Engineering documentation systems.** Facilities and procedures for the automated preparation, storage, and retrieval of engineering drawings and records are in place within the military departments and agencies of the DoD. Organizations responsible for management of documentation should be contacted for guidance during the communications system design process.

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## CHAPTER 15 INTERFACE AND INTEROPERABILITY

15.1 Interface and interoperability. The ultimate purpose of connecting equipment or systems together is to have them interoperate. Systems are made to interoperate by the interface devices which connect them.

a. Interface is a concept involving the definition of the interconnection between two equipment items or systems. The definition includes the type, quantity, and function of the interconnecting circuits and the type, form, and content of signals to be interchanged via those circuits. Mechanical details of plugs, sockets, and pin numbers, etc., may be included within the context of the definition.

b. Interoperability is- the condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users. The degree of interoperability should be defined when referring to specific cases.

**15.2 Defense Standardization Program.** The Defense Standardization Program (DoD 5000.1 and 5000.2) is organized into two parts: Federal Supply Classification Classes (more than 600) and Standardization Areas (more than 30). Within the DoD, system level communications standards are documented in the MIL-STD-188 series. Standards common to both long-haul and tactical communications are issued in the MIL-STD-188-100 series. Tactical communications standards are contained in the MIL-STD-188-200 series and long-haul communications standards are contained in the MIL-STD-188-300 series. Through the MIL-STD-188 series, the DoD places emphasis on interoperability and performance. Federal and non-Government standards that have been adopted by the DoD are listed in the DoD Index of Specifications and Standards.

**15.3 Digital and analog interface circuits.** Digital interface circuits provide for the proper exchange of data, clocking signals, control signals, and grounding or common return requirements between equipment. MIL-STD-188-114 establishes electrical standards for digital interface circuits.

**15.4 FOCS standards.** A number of Government and civilian agencies are making a concerted effort to develop standards for FO communications.

In recognition of the growing use of optical fiber within the DoD, MIL-STD-188-111 and JTC3A Specification 9109 were developed. MIL-STD-188-111 establishes operating parameters and technical, non-mechanical interoperability requirements for new long-haul and tactical

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FO communication within the DoD. It also specifies that FO links must satisfy certain MIL-STD-188-114 digital interface requirements at the link input and output terminals. JTC3A Specification 9109 establishes the technical parameters necessary to ensure joint interoperability between Command, Control, Communications, and Intelligence (C<sup>3</sup>I) systems (which are employed in joint and combined tactical operations) that utilize fiber optic cable and electrical-to-optical (E/O) converter boxes as a replacement for coaxial cable carrying multichannel time division multiplexed communications.

Civilian agencies involved in the development of communications standards include the following:

- ANSI
- EIA
- Institute for Electrical and Electronics Engineers (IEEE).

International agencies playing an active role in communications standards include the following:

- International Standards Organization (ISO)
- CCITT.

**15.5 Interface selection.** The effects of electrical noise upon digital systems performance (BER) may also be reduced by giving design preference to noise immune interfaces between electrical parts of an FO cable system. Components being interfaced should conform to the interface specification in MIL-STD-188-114. Design preference should be given to balanced interfaces due to their relatively high immunity to common mode noise (i.e., the same noise voltage is applied to both signal leads). Preference should also be given to polar signals (e.g., NRZ) over unipolar (e.g., RZ) because the smaller voltage swing associated with the latter and the consequential smaller voltage difference between the nominal signal voltage and the decision threshold voltage.

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## CHAPTER 16 GROUNDING, BONDING, AND SHIELDING

**16.1 Purpose of grounding, bonding, and shielding (GBS) protection against stress.** GBS is concerned with problems of personal safety, equipment protection, noise reduction, lightning and EMP/HEMP protection, and control of electromagnetic emanations. As a dielectric material, optical fiber has a natural immunity from most of the EMI/EMC problems which exist with metallic cables. Metallic components of FO cables, such as strength members, power carrying conductors, and protective coverings are susceptible, of course, to the problems of conventional cable and must be given GBS consideration.

All communications cables must be protected from physical damage from natural sources, accidents and deliberate human acts. The amount of protection depends upon the importance of information transmitted over these cables and the degree of survivability they must have. Optical fiber can be damaged by some types of radiation and certain vital DoD FOCS must, therefore, be protected from radiation sources such as nuclear detonations. Further information should be obtained from MIL-STD-188-124, MIL-STD-188-125, and .MIL-HDBK-419.

**16.2 GBS of FOCS metallic components and cable elements.** The all encompassing statement, "fiber optics is immune to EMI/EMC and EMP problems," can be misleading and the cause of serious design omissions in a communications system. Optical fiber, per se, operating in the optical domain of the frequency spectrum, is immune to the interference and compatibility problems of metallic cable. However, in a communications system using optical fiber as the transmission medium, terminal equipment, interface devices, and supporting structures may well be highly susceptible to these problems and thus need protection. Metallic components of FO cables, such as protective sheaths and strength members, also are susceptible and must be afforded protection.

a. Protection of personnel from electrical hazards and protection of components from damage and noise interference is provided by the facility earth electrode, lightning protection, fault protection, and signal reference grounding subsystems.

b. Communications devices that operate in the electrical domain may require shielding to control electromagnetic emanations and to provide protection from radiation, EMP/HEMP, and lightning. Equipment enclosures and cabinets, and even an entire room or structure, may serve as the shield. Of particular concern to the designer of vital DoD communications networks is protection from the effects of EMP/HEMP and gamma radiation produced by nuclear detonations.

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c. Protective coverings and shields must be properly installed and maintained to retain their electrical integrity. They must also be bonded correctly to grounding and neutralizing points.

**16.3 Protection of FO cable from physical damage.** FO communications cables are protected from accidental and deliberate (sabotage) damage by burial, encasement, and selective routing (see chapter 5). Optical fiber can also be damaged by exposure to radiation from both natural and human sources. Natural sources include concentrations of radioactive elements in the Earth's upper crust. The three major natural sources of nuclear radiation are uranium, potassium, and thorium. Human sources include nuclear power plants, other industrial activities, and nuclear detonations. The radiation of major concern is gamma rays in the fallout from nuclear detonations. The effects of the radiation on optical fiber depend upon dopants in the core and cladding, the refractive index profile, and system parameters such as operational wavelength and temperature, plus the amount of radiation (dose) received.

a. When an optical fiber is exposed to damaging levels of radiation, changes in molecular structure occur and the fiber discolors. This discoloration represents a change in the optical properties of the fiber, resulting in greater light absorption (see appendix A). Different types of optical fibers exhibit various degrees of intrinsic recovery from radiation damage. Fiber containing phosphorous as a dopant material is most susceptible to permanent damage. Accordingly, the use of phosphorus and other dopants, which increase the effects of radiation, is being eliminated by optical cable manufacturers.

b. Buried cable is more survivable than aerial cable in a radiation environment. The recommended minimal burial depth for DoD FO communications cable is 40 inches (see 5.5.2.1.).

**16.4 Multitier hardness levels for FO cable.** In NTIA Report 87-226, Multitier Specification for NSEP Enhancement of Fiber Optic Long-Distance Telecommunication Networks, the NTIA of the U.S. Department of Commerce has provided recommendations for protection of FO telecommunications systems of the NCS against artificial and natural stress. The NTIA report establishes five hardness levels of resistance to stress and includes a variety of construction and installation measures designed to provide protection against anticipated threats. Recommended levels of hardness are applied to communications networks on the basis of required survivability. Two of the most serious threats to FOCS, HEMP and gamma radiation from nuclear events, are addressed in detail. The application of Multitier Specification hardness levels to an FO network design should be based on the need for system survivability established by the user.

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## CHAPTER 17 SECURITY

**17.1 Scope of security.** Security, here, means protecting communications equipment and the information it carries from damage and unauthorized access. Both natural and human factors affect design plans. While security measures often are unique to the environment in which a system is situated, much can be said about FO communications security in general. Before implementing these measures, the designer should be aware of how systems become compromised.

In a natural environment, destruction of a FOCS can result from component deterioration and natural disasters. Each system's geographical location poses different risks for disaster and system design plans should reflect this. Placing a tactical communications line through the middle of the Mohave Desert will subject components to intense heat, wind, sand abrasion, and sunlight. Hurricanes are a likely problem in places Like Florida. Submarine cables need special treatment, such as burial in regions with high fishing activity.

Human destruction of an FOCS can be intentional or accidental. Table 17-1 is a guide for anticipating the elements that could disrupt or compromise information transmission.

**17.2 Multitier specification.** While not a Government or private industry standard yet, the Multitier Specification for National Security/Emergency Preparedness, being developed by the NTIA, suggests security measures to ensure the integrity of FOCS. Hardness levels are discussed and what construction may be required to meet them (see chapter 16, which also discusses security responses in terms of GBS). Other components must be protected from physical intervention not only with passive protection but by plant and personnel security.

**17.3 Data compromise.** Data compromise can occur through intentional intervention, such as virus implantation in the traffic, and through line taps. Incompetent or accidental management of data transmission may affect information integrity. Intentional human damage is the most difficult area to address. This can be minimized by understanding the importance of protecting information and screening individuals having access to the communications system. No amount of physical protection will guarantee stopping an individual determined to access data or destroy communications. For example, while difficult, it is still possible to intercept information going through an FO cable with macrobends.

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TABLE 17-1. FOCS security evaluation.

	Event	Effect on System	
N A T U R A L	DETERIORATION Temperature Light Moisture Wind	Component and, especially, cable destruction and deterioration. Water affects cable composition. Cable and component breakage and weakening.	
	DISASTER Earthquake Hurricane Tornado Lightning Animals	Type of physical and data destruction depends upon element affected	
	H U M A N	ACCIDENTAL Incompetence Normal	Type of physical and information destruction depends upon element affected.
		INTENDED Terrorism War Theft Vandalism Sabotage	Type of physical and information destruction depends upon element affected.
		ENVIRONMENTAL	
		Smog	Corrosion.
Power lines		Cable damage.	
Directed currents		Electrolytic corrosion.	
Petroleum	Cable sheath damage.		
Machinery and Transportation	Vibrational and shock damage. Cable damage and hazards to personnel.		
Power supplies	Cable sheath and component damage.		
Steam and other Heat	Cable damage and danger to personnel. Fiber darkening and increased loss, cable and component damage		
AC traction systems			
Gamma radiation and EMP			

**17.4 Classified and sensitive information.** Classified and unclassified-sensitive information must be safeguarded against unauthorized disclosure, modification, access, use, destruction, and denial of use by authorized persons. Security measures should be designed to ensure data confidentiality, data integrity, and data availability. The specific measures will depend upon the relative importance of these factors. Data integrity and availability often depend upon data security classification, which depends upon how the personnel protect the communications facilities. This includes checking interfaced devices, procedures, communications equipment, physical plant, networks, electronic equipment, and personnel.

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MIL-HDBK-232, *Red/Black Engineering-Installation Guidelines*, gives guidance on how communications systems should be installed to meet adequate security measures. However, no specific guidance for FOCS is provided.

**17.5 Measures taken to protect communications.** Making personnel accountable by providing an audit trail of facility use allows responsible staff to monitor access to the communications system. Personnel should be made aware of security needs and policies through regular turning programs. Physical controls need to be designed to prevent unauthorized disclosure, destruction, or modification of information. Cable burial or embedding makes unauthorized intrusion less likely.

Equipment should conform to TEMPEST (control of compromising emanations) standards whenever applicable. FO lines can be protected adequately by optical communications systems that detect intrusion and are approved by the National Security Agency (NSA) and listed in that agency's Information Security Products and Services catalog (which includes products to encrypt data). Marking equipment according to the level of security required will enhance system protection. Individuals are to be allowed access to the facility and information only on a need to know basis. Fail-safe detection systems will identify unauthorized system access. Data compromise, modification, or destruction can be mitigated by contingency plans, such as invoicing redundant systems. Overall, there should be a risk management program to determine the protection required, how much exists, and the most economical way of providing the needed protection.

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## APPENDIX A FUNDAMENTALS OF FIBER OPTICS

**A.1 Basic principles.** Electromagnetic signals with wavelengths in the optical (commonly called 'visible range') manifest themselves as light. Just like other electromagnetic waveforms, light can be modulated to produce optical signals which carry information. Transmission of optical signals can be guided or unguided. Unguided optical signals are transmitted into the atmosphere or space, using methods similar to radio transmission. Guided optical signals are transmitted through optical fibers. The physical properties and dimensions of the dielectric materials from which optical fibers are made, determine the communications parameters of the fiber and FO cable. Optical communications systems, just like conventional systems, are subject to signal degradation through attenuation, distortion, and the introduction of unwanted noise.

**A.2 Signal propagation in optical Fibers.** How optical energy travels down an optical fiber is sometimes explained in terms of light rays, where light is viewed as discrete particles, and also in terms of electromagnetic wave theory, which follows Maxwell's equations. For reasons of clarity and simplicity, this handbook discusses light propagation in terms of both ray and wave theory. The transparent dielectric materials used in FOs, usually high quality glass but sometimes plastic, guide light signals along the length of a cable by internal reflection and refraction. Two materials, each with a different index of refraction, are arranged concentrically to form an optical fiber, as shown on figure A-1. The index of refraction of a material is the ratio of the speed of light in a vacuum to its speed in that material. The central solid cylinder is called the core and the outer cylinder is called the cladding. The index of refraction of the core is higher than that of the cladding. The index of refraction of silica glass is about 1.45. Cladding material is made by adding (doping) oxide impurities, called "dopants," to silica glass to change the refractive index. Dopants are also commonly added to core materials to produce desired refractive indices and control refractive index profiles. Light introduced into the core is reflected and refracted at the core-cladding boundary. The relationships of light reflection and refraction for materials of different optical properties are partly defined by Snell's law (see figure A-2).

**A.2.1 Snell's Law.** Snell's Law establishes the following relationship:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

or,

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2 \cos \theta_1}{n_1 \cos \theta_2}$$

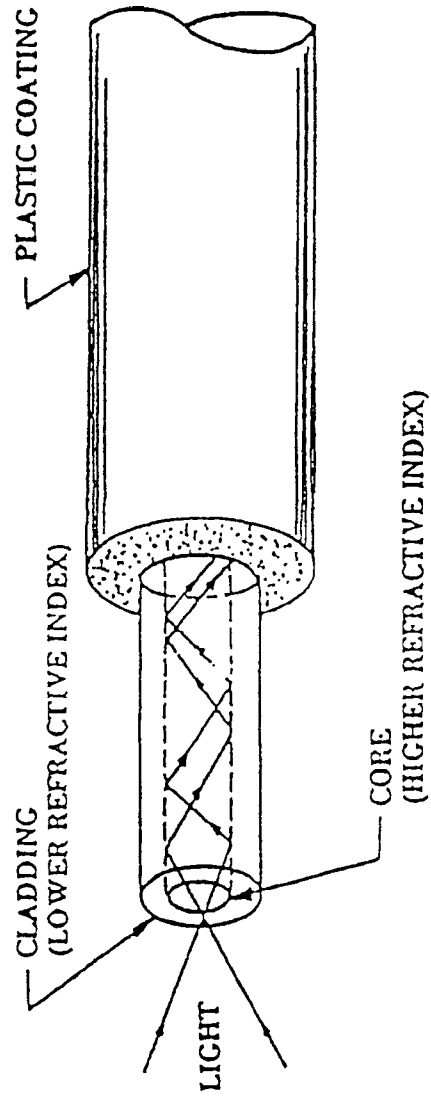


FIGURE A-1. Basic optical fiber composition.

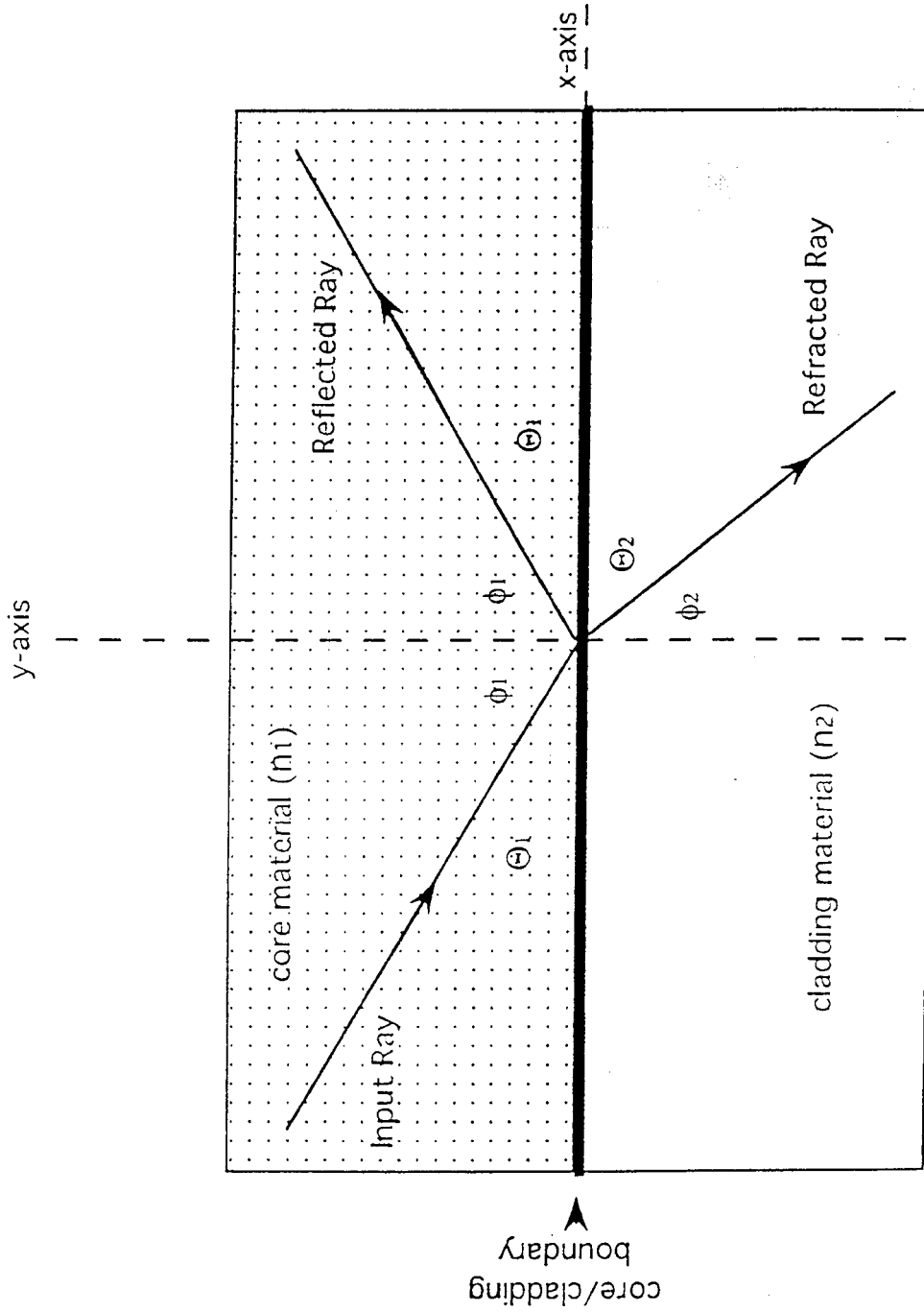


FIGURE A-2. Snell's Law relationships.

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where:

$\phi_1 =$  angle of the input ray with the perpendicular y-axis. It is called the Angle of Incidence. The reflected ray has the same angle with the y-axis,

$\phi_2 =$  angle of the refracted ray with the perpendicular y-axis. It is called the Angle of Refraction,

$\theta_1 =$  complementary angle of  $\phi_1$ , sometimes called the input angle,

$\theta_2 =$  complementary angle of  $\phi_2$ ,

$n_1, n_2 =$  indices of refraction for the core and cladding, materials, respectively.

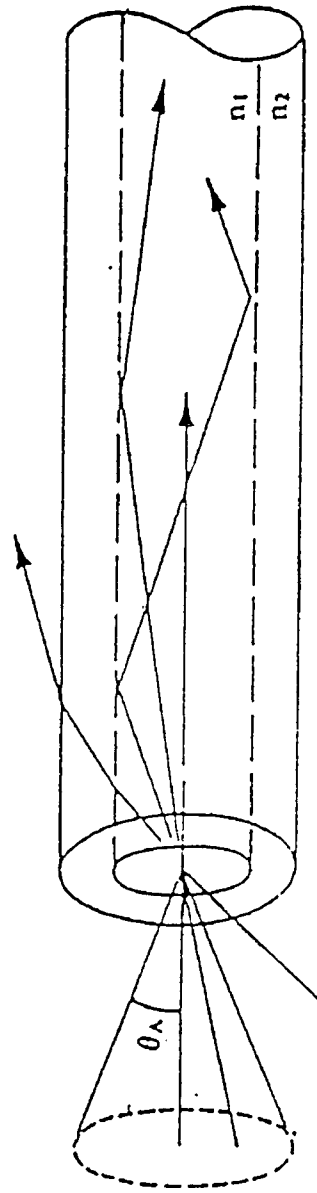
The ray diagram on figure A-2 shows what happens to light rays which are introduced into the optical fiber. When the light rays arrive at the core/cladding boundary, they are reflected or refracted according to the input angle and index of refraction relationships of Snell's Law. When  $n_1$  is greater than ( $>$ )  $n_2$ ,  $\theta_1 > \theta_2$ . As  $\theta_1$  decreases, by controlling the input angle of the light ray,  $\theta_2$  also decreases. However, because  $\theta_1$  is larger,  $\theta_2$  will be the first to reach zero, and no light will be refracted into the cladding material. There is, therefore, a value of  $\theta_1$ , called the Critical Input Angle,  $\theta_c$ , at which all of the light ray energy is reflected down the core of the optical fiber, with:

$$\theta_c = \text{Cos}^{-1} \frac{n_2}{n_1}$$

The Critical Angle of Incidence,  $\phi_c$  which is the compliment to  $\theta_c$ , is defined by the corresponding relationship:

$$\phi_c = \text{Sin}^{-1} \frac{n_2}{n_1}$$

In order that all of the light energy introduced into the optical fiber is reflected down the core,  $\theta_1$ , must be equal to or less than  $\theta_c$ , and  $\phi_1$ , must be equal to or greater than  $\phi_c$ . This working area, called the "acceptance cone," is shown on figure A-3. The angular relationship demonstrates that using materials with selected indices of refraction and introducing light at proper angles maximizes the amount of light which is propagated down the optical fiber.



$$\text{Sin}\theta_A = \sqrt{n_1^2 - n_2^2}$$

$n_1$  = CORE REFRACTIVE INDEX

$n_2$  = CLADDING REFRACTIVE INDEX

$$n_1 > n_2$$

FIGURE A-3. Acceptance cone.

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**A.2.2 Numerical aperture (NA).** NA is a measure of the light-gathering ability of a fiber. It is defined as the sine of the maximum input angle which will allow all light rays to pass down the core.

$$NA = \sin \theta_{\max} = (n_1^2 - n_2^2)^{1/2}$$

**A.2.3 Modes of propagation.** An optical fiber that has a core with a fixed index of refraction and cladding of another index of refraction is called a step-index fiber (see 5. 1). Signals emitted by a typical light source are introduced into the fiber at different input angles, even within the cone of acceptance. These light signals are reflected down the core, following zig-zag paths with different angles. The total lengths of the paths of these light rays will, therefore, be different. In wave theory, these variations in paths are called propagation modes. Rays which enter the fiber at small input angles propagate in low-order modes. Rays with larger input angles propagate in high-order modes (see figure A-4). These different propagation paths or modes can degrade the performance of step-index fibers. In graded-index fibers, the refractive index of the core varies with radial distance from the fiber axis. The typical index profile is parabolic, with the highest refractive index at the center of the core. As the rays move away from the center of the core through an area of lower refractive index, their speed increases. Accordingly, low-order rays travel slower than high-order rays, because they spend more time in the areas of the fiber nearest the axis. Rays passing through areas with different refractive indices also change the direction of their paths. By choosing the correct index profile, the paths and speed of the rays can be effectively focused at various points along the fiber. Graded-index fibers perform better than step-index fibers. While both single-mode and multimode fibers can be step-index in design, only multimode fibers are graded-index. In single-mode fibers, the core size is designed so that only one propagation mode is possible.

**A.3 FO properties.** Factors which contribute to signal degradation in an optical fiber include distortion, dispersion, and attenuation. Often, there is confusion over use of the terms distortion and dispersion, in discussing the performance of optical fiber. In accordance with FED-STD-1037, distortion is a generic term, defining "any departure from a specified input-output signal relationship over a range of frequencies, amplitudes, or phase shifts, during a time interval." Dispersion is defined as 'a term used to describe the frequency dependence of a parameter.' In FOs, dispersion generally refers to pulse spreading phenomena which occur because the parameters of optical fiber vary according to the interaction of signal component wavelengths (frequencies) and the physical characteristics of the fiber.

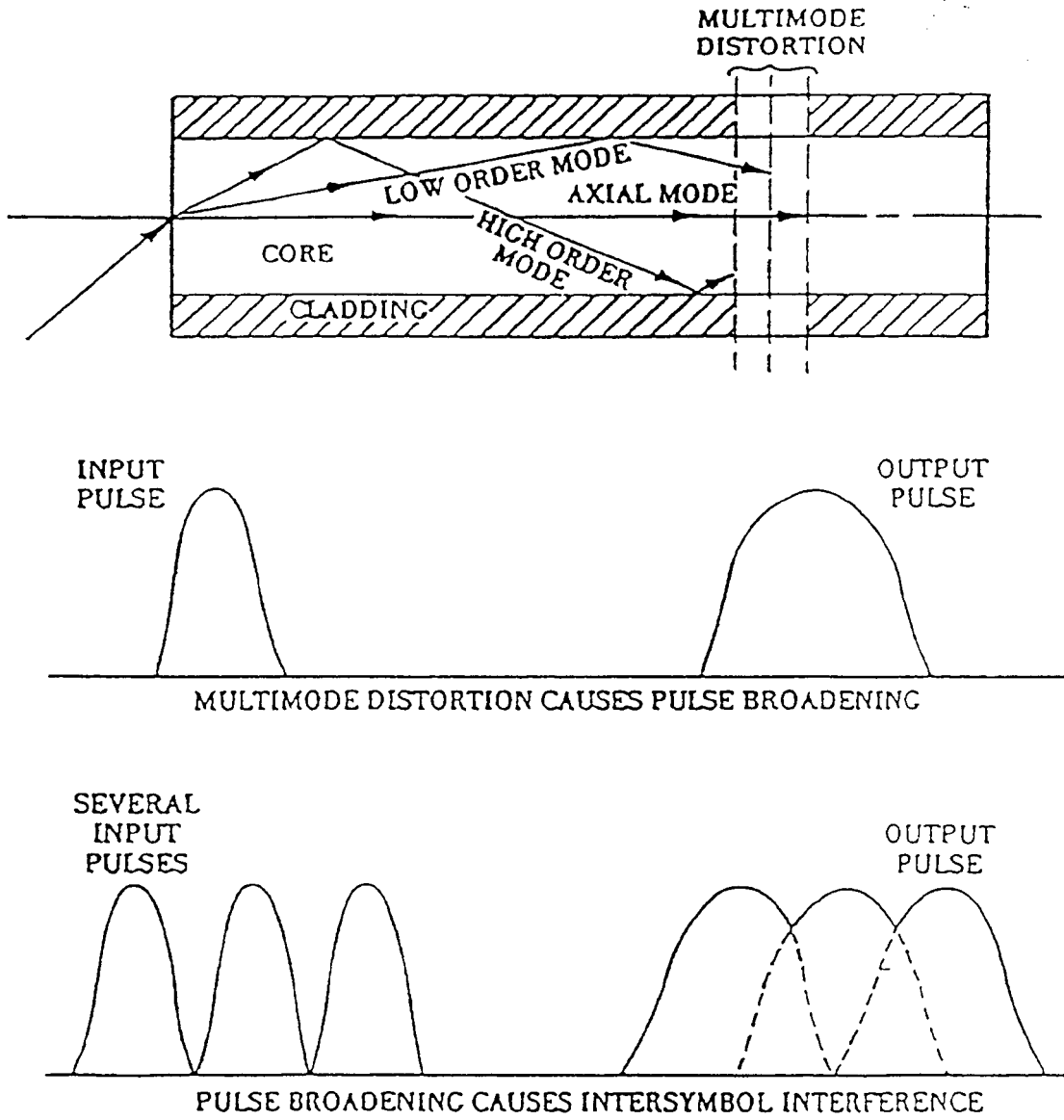


FIGURE A-4. Multimode distortion, broadening, and interference.

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**A.3.1 Attenuation.** The loss of average optical power in an optical fiber is called attenuation and is expressed in dB. The attenuation per unit length of a fiber is called the Attenuation Coefficient ( $\alpha$ ) which equals dB/km. Attenuation in optical fiber is usually attributed to three causes: absorption, scattering, and bending. Absorption is the conversion of optical power into heat. Scattering is the loss of optical energy through ejection out of the fiber core. Bending losses are of two types, macrobending and microbending.

**A.3.1.1 Absorption.** Absorption is caused by the characteristics of the materials used to fabricate optical fiber, impurities introduced during manufacture, and defects from exposure to environmental hazards, such as nuclear radiation. The major causes of absorption in optical fiber are hydroxyl ions (OH<sup>-</sup>), from the presence of water, even in the purest silica glass (see figure 5-2). Broad near-infrared and ultraviolet absorption regions contribute additional absorption loss at the wavelengths shown.

**A.3.1.2 Scattering (Rayleigh Scattering).** Scattering is defined as a change in the direction of light rays after striking a small particle or particles. Scattering caused by refractive index fluctuations, as a result of variations in material density or composition, is called Rayleigh Scattering. The optical power lost to Rayleigh Scattering is inversely proportional to the fourth power of the signal wavelength and has a value of approximately 1 dB/km at 1000 nm. Rayleigh Scattering is the primary cause of losses in today's fibers operating in the 800 to 1600 nm wavelength. The overall loss from absorption and Rayleigh Scattering is least in the 1300 and 1500 nm regions.

**A.3.1.3 Bending losses.** Large radius bends (greater than 10 cm) in optical fibers have negligible effects on attenuation. Small radius bends (below 10 cm), can cause macrobending losses. Microscopic irregularities in optical fiber geometry cause microbending losses.

Macrobending typically occurs during installation. Losses of optical power are due to decreased reflection at the core-cladding boundary and increased radiation through the cladding. In single-mode fibers, macrobending causes radiation losses of the fundamental mode signal. Smaller-core fibers are less prone to macrobending losses. Sensitivity to macrobending losses is also reduced by increased doping.

Microbending losses in -an optical fiber are caused by microscopic imperfections in the fiber geometry, such as irregularities at the core-cladding boundary and variations in core dimensions. These imperfections result from shortcoming in the fiber-manufacturing process, as well as improper handling during movement or installation. The losses due to microbending are light radiation and mode coupling, in which light rays from different propagation modes are combined. Differential contraction of a tight buffer tube will sometimes cause microbending. This can be avoided by using a loose buffer tube, a uniform cushion, or a filling compound

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to prevent accumulation of moisture and to insulate the fiber from impressed microbends. Bending can cause microcracks, which increase attenuation and can even result in mechanical failure of the fiber.

**A.3.2 Multimode (modal) distortion.** In multimode fibers, especially step-index fibers, light rays traveling at the same speed, but with different paths, will arrive at the end of the fiber at different times. As a result, the received signals will be spread by a phenomenon called multimode distortion. This phenomenon is sometimes called multimode dispersion, but this usage is considered to be incorrect. Dispersion depends only on wavelength (see figure A-4). As stated above, in wave theory, rays of propagating energy are called modes. In wave terminology, multimode distortion, is called internodal distortion, or more commonly, modal distortion. Multimode distortion can be a significant problem in digital transmission, when pulse spreading makes recognition uncertain. Multimode distortion is reduced by designing fiber with a lower NA, (allowing only the lower-order modes to enter the fiber), or by using graded-index fibers.

**A.3.3 Dispersion.** Dispersion is the phenomenon in which wave propagation parameters are a function of wavelength (frequency). Dispersion occurs because the effects of fiber material and geometry vary with wavelength. The different arrival times of the various wavelength components of an optical signal result in a broadening of received digital pulses. Dispersion is normally expressed in picoseconds per nm-km. The specific actions which make up dispersion are material dispersion, waveguide dispersion, and profile dispersion.

**A.3.3.1 Material dispersion.** The refractive index of glass fiber is not constant with respect to wavelength, causing different wavelengths to travel at different speeds. Light having a greater wavelength at which the refractive index is lower will travel faster than light at a shorter wavelength at which the refractive index is higher. This cause of signal spreading is called material dispersion. The effects of material dispersion are reduced by using light sources with narrow spectral widths and selecting fibers made from optical material, which produces smaller refractive index variations with respect to the wavelengths to be used. Material dispersion is a major contributor to distortion in single-mode fibers.

**A.3.3.2 Waveguide dispersion.** Dispersion due to velocity dependence on the effects of optical fiber geometry with varying wavelengths is called waveguide dispersion. In the circular waveguide geometry of an optical fiber, this dependence relates to the ratio of the core radius (half the core diameter) to the particular propagating wavelength. Waveguide dispersion is small, compared to material dispersion, but can shift the zero dispersion wavelength toward lower frequencies (see A.2.3).

**A.3.3.3 Profile dispersion.** Profile dispersion is caused by the varied effects of the core/cladding refractive index profile with different wavelengths. These effects relate to the contrast of the fiber profile. Contrast is defined as the difference between the maximum refractive index of the core and that of the cladding. Profile dispersion is primarily a

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concern in graded-index multimode fiber designs. In single-mode applications, profile dispersion is considered part of waveguide dispersion.

**A.3.4 Zero-dispersion wavelength.** Material dispersion and waveguide dispersion are of opposite mathematical signs. Accordingly, in single-mode fibers, these effects can be effectively balanced at a particular wavelength by use of dopants. The result is a dispersion approaching zero. The exact frequency at which this occurs is a function of core diameter and refractive index profile. Low-dispersion single-mode fibers for 1310 nm operation are currently available. For fibers which operate at 1550 nm, zero-dispersion wavelength is achieved by doping and modification of the step-index configuration to a triangular-shaped profile.

**A.4 leaky modes.** Leaky modes are higher-order modes whose power is trapped partly in the fiber core and partly in the cladding. Leaky modes are attenuated through radiation after traveling a distance, but may appear as transmitted energy in a short-length test fiber. Leaky modes attenuate in shorter distances in smaller diameter fibers. Mode stripping, achieved by wrapping fiber around a mandrel, removes leaky modes.

**A.5 Chirping.** A rapid change in the output wavelength (frequency) of a signal source is called chirping. Chirping occurs commonly in pulsed operations. For example, a directly pulsed laser diode produces a frequency shift in its output. Changes in the refractive index of the lasing material in the semiconductor active region, associated with changes in carrier density, produce a shift in the mode frequency. This oscillation effectively broadens the output spectrum, reducing both system data rate and transmission distance. It should be noted that the pulsed driving current is actually frequency (and phase) modulating the optical carrier signal.

**A.6 Bandwidth in FOs.** In designing FO communications networks and links, losses of the optical signal from attenuation of the fiber and bandwidth limitations of the fiber are major considerations (see A.2.4). The bandwidth of any communications device is defined generically as the difference between limiting frequencies within which performance, with respect to some characteristic, falls within specific limits. The bandwidth of a communications system is a measure of its information-carrying capacity. Bandwidth also limits the rate at which information can be transmitted.

**A-6.1 FOCS bandwidth.** In FOCS, available bandwidth is limited by attenuation, distortion, and dispersion in the optical fiber transmission media, as well as by the performance characteristics of transmitting and receiving equipment.

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Fiber losses in today's technology are approximately 2-3 dB/km for multimode fiber and 0.25 dB/km for single-mode fiber. The FO communications cable specified in a system design is commonly rated by a parameter called the bandwidth-distance (or length) factor (see 4.8).

The bandwidth capability of an optical fiber link is often defined in terms of the required receiver output. In communications receiver technology, bandwidth is generally in terms of half-power points (-3 dB) of the receiver output. It should be noted that the -3 dB points defining the upper and lower frequency limits of an optical signal are reflected as -6 dB points in receiver electrical output power (i.e., this is because the photo detector is a square law device). The electrical signal current or voltage produced by the receiver in the photodiode detection process is proportional to the square of the photocurrent.

**A.6.2 Fiber bandwidth.** The bandwidth of optical fiber is limited by degradation, in the form of pulse broadening, of a transmitted digital signal. As pulse broadening increases, bandwidth decreases. This spreading of the received pulses is the result of multimode distortion and dispersion of the optical signal as it travels the length of the fiber (see A.2). When bandwidth limitations are exceeded, pulse spreading causes unacceptable intersymbol interference and high BERS. Multimode fiber is generally rated in terms of its multimode distortion parameter, while single-mode fiber is more commonly characterized by its dispersion parameter. In actual performance measurements, fiber bandwidth can be determined by the application of test equipment which operates in either the time or the frequency domain (see chapter 12).

In time domain measurements, the section of optical fiber being tested is terminated at the input end with a short-pulse-generating LD transmitter. The output end is terminated with a matched receiver. Oscilloscopes are then used to compare the width of the output pulse from the receiver to that of the original transmitter output pulse. This time domain information is then converted mathematically to the frequency domain. Fourier transforms are used to convert between the time and frequency domains. Time domain measurements are usually performed in laboratories or other controlled areas.

In frequency domain measurements, devices such as spectrum analyzers are used to compare input and output pulses, giving direct bandwidth readings. Spectrum analyzers are convenient for use in the field. Fiber bandwidth can also be determined by transmitting sinusoidal signals of increasing frequency down a section of fiber and noting signal loss. Loss of optical power due to attenuation will increase directly with increasing frequency. This attenuation is plotted against frequency. As previously noted, a bandwidth limit is defined by the frequency value at a -3 dB power level.

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**A.7 The optical signal spectrum.** The optical signals generated by light sources have spectral shape characteristics that impact the capabilities and performance of an FOCS. The outputs of LED and LD light sources are made up of various wavelengths around a central value (see figure 6-2). The extent or spectral width (nm) of these optical outputs is determined by measuring the difference between FWHM -3 dB points, or applying a special root-mean-square deviation procedure. FWHM is the range of frequencies over which a pulse intensity is greater than 50 percent of its maximum value. Measuring between the -3 dB points assumes that the output spectrum has a Gaussian shape. Irregularly shaped spectra are measured by applying a Gaussian shaped overlay or interpolating an approximate Gaussian shape.

**A.7.1 LED spectrum.** LED outputs form a continuous spectrum with an approximate Gaussian shape. As shown in table 5-1, the spectral width of LEDs ranges from 35-50 nm at 800 nm and 70-125 nm at 1300 nm. The center (or peak emission) wavelength of an LED is determined essentially by its physical characteristics. Increasing the driving current, temperature, and doping of the semiconductor active layer increases spectral width. The center (or peak emission) wavelength is also affected by these changes.

**A.7.2 LD spectrum.** The spectral width of an LD is much narrower than that of an LED, typically in the range of 0.1-5 nm. The output wavelength of an LD is determined primarily by the material of which it is made. The physical characteristics and dimensions of an LD determine its width. With regard to the width of their output spectra, lasers may be generally classified as multiple-mode or single-mode devices. The output spectrum of multiple-mode lasers, such as gain-guided lasers, is made up of a number of modes (typically 10-20) of essentially monochromatic light (see figure A-5). Single-mode lasers, such as index-guided lasers, include mode-control features in their design and produce a spectrum that is dominated by one mode. Of light sources commercially available today, the DFB laser, which is a type of index-guided laser, provides the most narrow spectral width. It should be noted that the spectral width of very narrow lasers is usually measured between the -25 dB points. Single-mode lasers are highly desirable for long-haul communications networks and essential for both wide-bandwidth direct-detection and coherent systems.

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## APPENDIX B

### CALCULATION OF REQUIRED DETECTOR INPUT POWER FOR DIGITAL LINKS

**B 1 General.** This appendix presents methods and supporting theory for calculating the detector input power required for a specified BER.

**B.2** Detector input power for digital links. The signal power required at the detector input,  $P_d$  watts, for digital links can be calculated by

$$P_d = E_p \times (R/2), \quad \text{(Equation B-1)}$$

where:

$E_p$  = the required energy per pulse (in joules)

$R$  = the optical line rate in bits/s. (NOTE: One watt = one joule/sec.)

**B.3 Energy per pulse.** The required energy per pulse is the product of the required number of photons per pulse and the energy of a photon

$$E_p = N \times hf, \quad \text{(Equation B-2)}$$

where:

$N$  = the number of photons per pulse

$hf$  = the energy of a photon ( $h$  = Planck's constant =  $6.626 \times 10^{34}$  joules-s

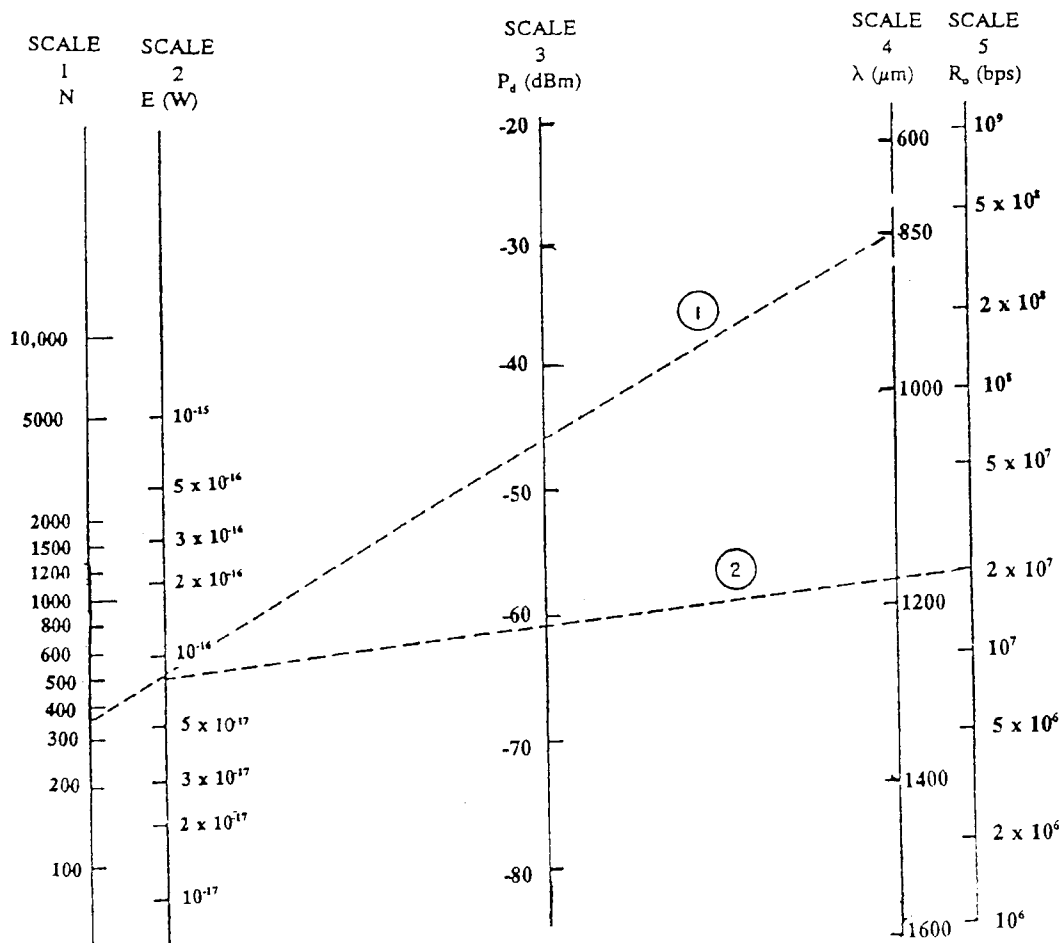
$f$  = light frequency in hertz).

Figure B-1 is a nomograph for determining required detector input power as a function of photons/pulse, wavelength, and optical line rate.

**B.3.1 Photodetection.** Optical power incident on the detector input generates hole-electron pairs in the photodiode. The pairs separate under the influence of electrical fields in the photodiode, producing a displacement current. On the average, the number of hole-electron pairs generated per second is proportional to the number of incident photons per second. It follows that the detector output current is also proportional to the number of incident photons per second.

**B.3.2 Quantum noise.** The detector output waveform is an electrical replica of the signal incident on the input except for perturbations which occur in photodetection. Statistical uncertainty as to whether an incident photon will generate a hole-electron pair in the photodiode produces perturbations in the output current. The perturbations manifest

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1. The first scale reads the number of photons per pulse (N).
2. The second scale reads energy (in joules per pulse ( $E_p$ )).
3. The third scale reads average detector input power ( $P_d$ ) in dBm.
4. The fourth scale reads the wavelength ( $\lambda$ ) in micrometers ( $\mu\text{m}$ ).
5. The last scale reads the optical line rate ( $R_d$ ) in bits per seconds (bps).
6. In the example, a line (1) is drawn between known values on scale #1 (photons per pulse) and scale #4 (wavelength). A second line (2) is then drawn from the intersection of line (1) and scale #2, to a known optical line rate value on the last scale ( $R_d$ ). The intersection of line (2) and scale #3 gives the input power required at the receiver.

**FIGURE B-1. Nomograph for determining required receiver power for digital links as a function of photons per pulse and wavelength.**

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themselves as noise, referred to as "quantum noise." (Quantum noise should not be confused with "quantization noise," which results from sampling processes such as that used for pulse code modulation.)

**B.3.3 Thermal noise.** The electronic amplifier portion of the optical receiver adds thermal noise. Thermal noise has two components: Johnson noise and shot noise. Johnson noise results from random molecular motion in resistive components of the amplifier, in particular, those in the "front end" circuitry. Shot noise occurs when a current of charge carriers passes through a surface at statistically independent times for example, transistor bias current.

**B.3.4 Receiver noise with PIN photodiode.** If the detector is a PIN photodiode, thermal noise in the electronic amplifier is the controlling receiver noise. The PIN photodiode has no internal gain to provide a high signal input to the electronic amplifier input and thereby reduce the effect of the thermal noise. By the same token, the PIN photodiode does not introduce significant noise. Its only noise output is quantum noise and its quantum limit is so far below the receiver noise threshold (10 to 13 dB below) that it is negligible for link design purposes.

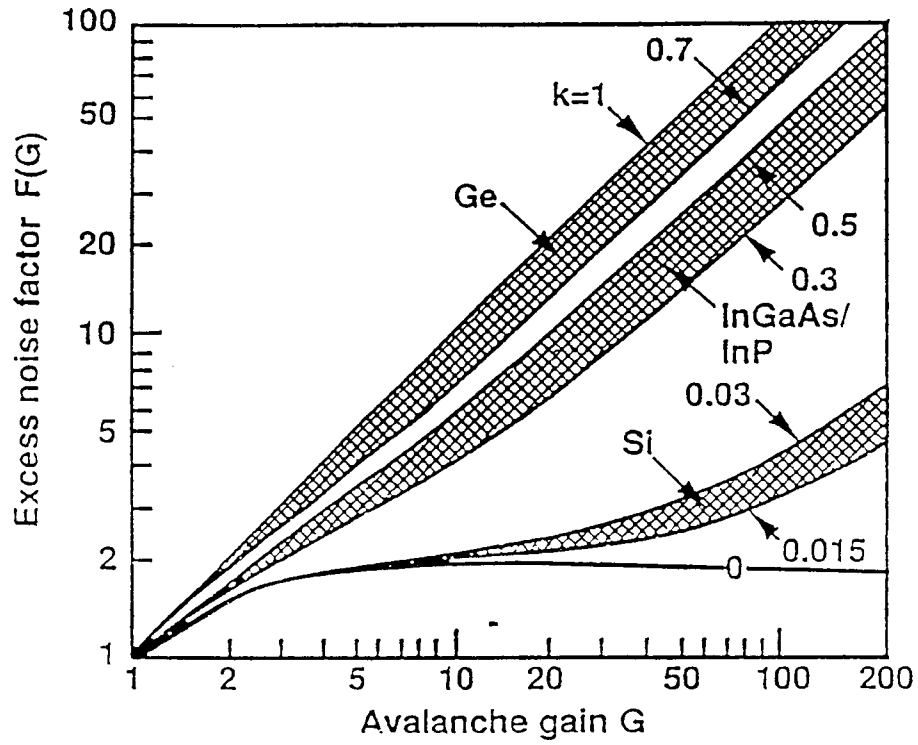
**B.3.5 Receiver noise with APD.** An APD provides signal gain which reduces the effect of the electronic amplifier thermal noise. In so doing, however, it introduces avalanching or APD noise. Avalanching occurs when electrons moving in the photodiode internal field generate hole-electron pairs and the "new" electrons do the same, in a sort of chain reaction. The statistical uncertainties of avalanching, however, corrupt the output signal. This APD noise power is taken into account in link design by a dimensionless quantity, called "noise factor." The noise factor is a measure of the degradation in SNR produced by avalanching. It increases with avalanching gain and there is a point of diminishing returns beyond which further increases in gain do not provide any increase in receiver output SNR. The gain at this point is the optimum gain for the receiver.

**B.3.6 Relationship between gain and noise factor.** Gain (G) and noise factor (F) for an APD are related by ionization ratio (k), a measure of the characteristic that enables avalanching.

$$F = kG + (2-1/G)(1-k) \quad \text{(Equation B-3)}$$

Figure B-2 gives F as a function of G with k as a parameter. If k is not known, the mid-range values of 0.1 or 0.05 will give reasonable results. (The gain and noise factor for PIN photodiodes are both generally taken as unity.)

**B.3.7 Receiver figure of merit.** Because of the current rapid development of FOs as a communications medium, there is little commonality among manufacturers regarding which



$$F(G) = kG + (1-k)(2 - 1/G)$$

FIGURE B-2. Detector excess noise factor.

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performance parameters are specified. This is particularly true of receiver noise performance. One useful approach proposes a receiver "figure of merit." Figure of merit is given the symbol,  $Z$ , and defined as the ratio of rms output noise to the response produced by a single hole-electron pair. Besides its usefulness as a common way of stating receiver noise performance, it assists in link design by effectively combining a number of receiver component variables whose real values are not normally available to the system engineer. From the manufacturers' point of view, it has the advantage of being easily measured.

**B.3.8 Calculation of figure of merit.** In the absence of a manufacturer specified figure of merit, it can be calculated using the concept of equivalent load resistance,  $R_1$ .

a.  $R_1$  is a real resistance only in the case of an electronic amplifier with a resistive input. Most amplifiers in FO applications have field-effect-transistor (FET), bipolar, or transimpedance front ends. Such front ends have complex input circuitry utilizing resistors, capacitors, and transistors. The input circuitry introduces the shot noise component of thermal noise.

b. Rarely does the link designer have access to the details of amplifier front-end circuitry. The equivalent load resistance concept provides a way around this lack of information, even though, ideally, it must be supplied by the manufacturer. Equivalent load resistance is defined as the load resistance that would produce a noise current equivalent to the sum of all the noise currents produced in the front-end components (e.g., feedback resistor and transistors). It includes the effect of gain in the transistors.

c. Using the equivalent load resistance,  $R_1$ , the receiver figure of merit,  $Z$ , can be found from the equation

$$Z = (4kTB/R_1)^{0.5}/eB \quad \text{(Equation B-4)}$$

where:

$k$  = Boltzman's constant ( $1.38 \times 10^{-23}$  joules/K)

$T$  = temperature in Kelvin (room temperature is taken as 290 Kelvin)

$e$  = the charge on an electron ( $1.6 \times 10^{-19}$  coulombs)

$B$  = amplifier 3- dB bandwidth (Hz) (from manufacturer).

$Z$  is shown on figure B-3 for common FO bandwidths as a function of  $R_1$ . If  $R_1$  is not specified, it is reasonable to assume a value of 10,000 ohms.

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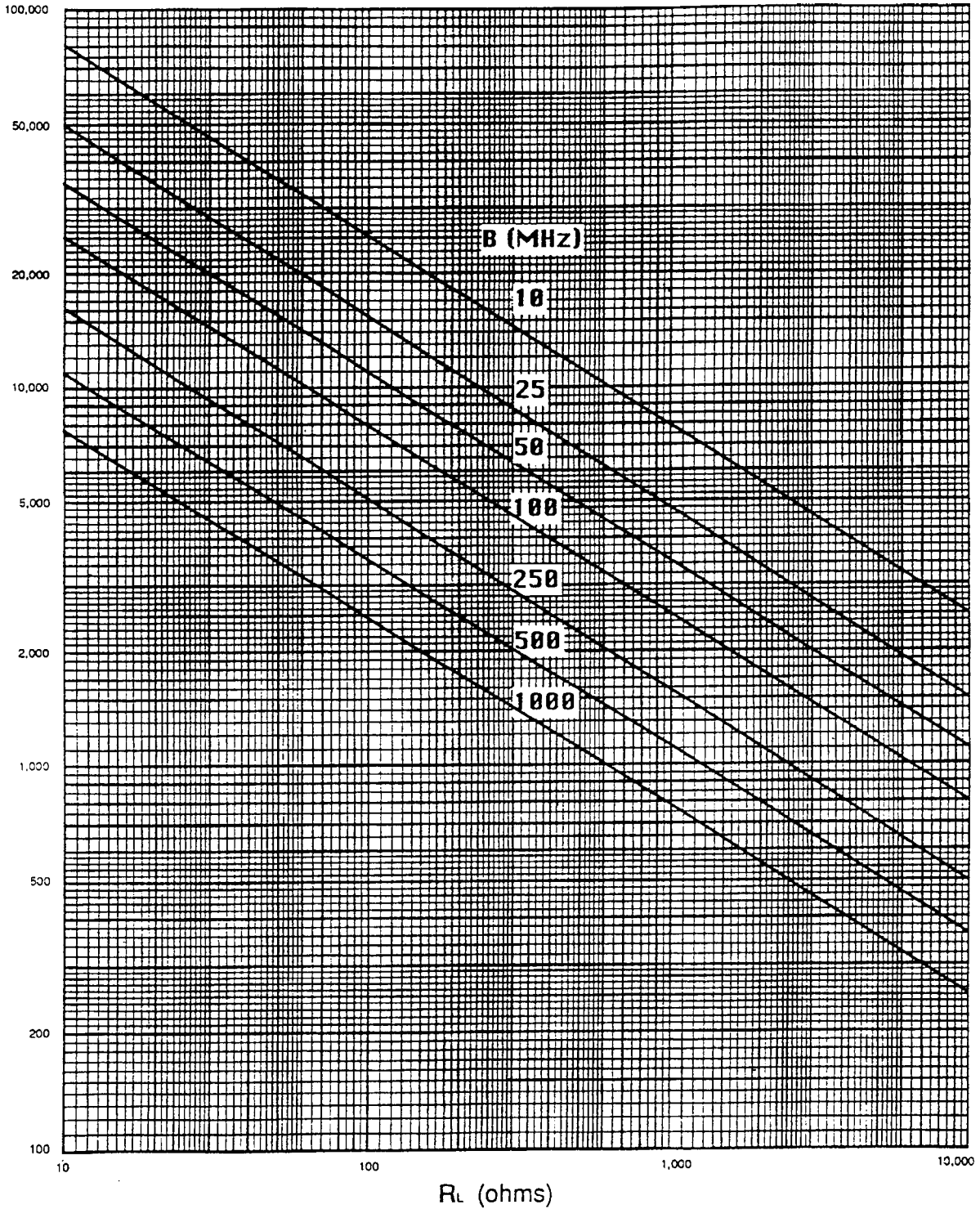


FIGURE B-3. Fiber optic receiver figure of merit,  $Z$ , as a function of bandwidth,  $B$ , and equivalent load resistance,  $R_L$ .

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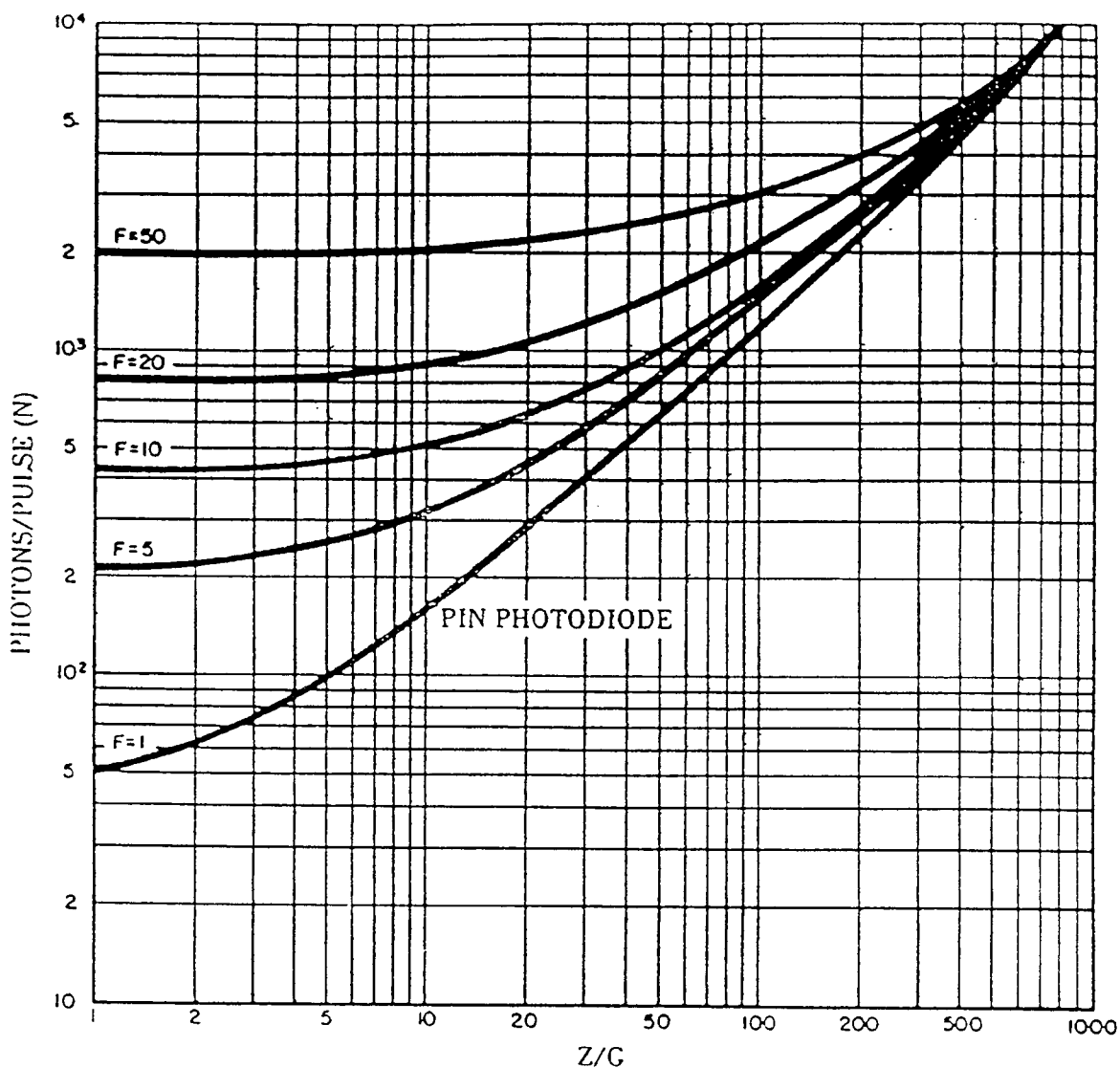
**B.4 Calculation of the number of photons per pulse.** A reasonably straight forward calculation of the number of photons per pulse required to provide a specific BER involves an approximation referred to as a Gaussian approximation. The Gaussian approximation assumes that the output voltage resulting from an optical pulse sequence input is a Gaussian random variable. Thus, the error probability can be calculated from knowledge of the mean and standard deviation of the output voltage. With the additional assumption of perfect extinction (no light incident on the detector input during a pulse "off" state), a simple relationship yielding the number,  $N$ , of photons per pulse can be derived:

$$N = x^2F + 2x(Z/G) \quad \text{(Equation B-5)}$$

where  $x$  is the number of standard deviations in a Gaussian probability distribution corresponding to a specific BER. For a BER of  $10^{-9}$ ,  $x$  is 6.29 and the equation becomes

$$N = 39.6F + 12.6(Z/G) \quad \text{(Equation B-6)}$$

Table B-1 gives the number,  $x$ , of standard deviations for other BER'S. Figure B-4 gives  $N$  for the ratio  $Z/G$  with  $F$  as a parameter, for a BER of  $10^{-9}$ .



$$N = x^2 F + 2x (Z/G)$$

$$\text{BER} = 10^{-9}$$

FIGURE B-4. Photons/pulse as a function of Z/G and F.

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TABLE B-1. Number,  $x$ , of standard deviations for BERs.

BER	$x$
$1.76 \times 10^{-8}$	5.82
$1.66 \times 10^{-8}$	5.83
$1.57 \times 10^{-8}$	5.84
$1.48 \times 10^{-8}$	5.85
$1.39 \times 10^{-8}$	5.86
$1.31 \times 10^{-8}$	5.87
$1.24 \times 10^{-8}$	5.88
$1.17 \times 10^{-8}$	5.89
$1.10 \times 10^{-8}$	5.90
$1.04 \times 10^{-8}$	5.82
$9.79 \times 10^{-8}$	5.82
$9.22 \times 10^{-9}$	5.94
$8.19 \times 10^{-9}$	5.95
$7.72 \times 10^{-9}$	5.96
$7.72 \times 10^{-9}$	5.97
$6.85 \times 10^{-9}$	5.98
$6.45 \times 10^{-9}$	5.99
$6.08 \times 10^{-9}$	6.00
$5.72 \times 10^{-9}$	6.01
$5.39 \times 10^{-9}$	6.02
$5.07 \times 10^{-9}$	6.03
$4.78 \times 10^{-9}$	6.04
$4.50 \times 10^{-9}$	6.05
$4.23 \times 10^{-9}$	6.06
$3.98 \times 10^{-9}$	6.07
$3.75 \times 10^{-9}$	6.08
$3.53 \times 10^{-9}$	6.09
$3.32 \times 10^{-9}$	6.10
$3.12 \times 10^{-9}$	6.11
$2.94 \times 10^{-9}$	6.12
$2.76 \times 10^{-9}$	6.13
$2.60 \times 10^{-9}$	6.14
$2.44 \times 10^{-9}$	6.15
$2.30 \times 10^{-9}$	6.16
$2.16 \times 10^{-9}$	6.17
$2.03 \times 10^{-9}$	6.18
$1.91 \times 10^{-9}$	6.19
$1.79 \times 10^{-9}$	6.20
$1.69 \times 10^{-9}$	6.21
$1.58 \times 10^{-9}$	6.22
$1.49 \times 10^{-9}$	6.23
$1.40 \times 10^{-9}$	6.24
$1.31 \times 10^{-9}$	6.25
$1.23 \times 10^{-9}$	6.26
$1.16 \times 10^{-9}$	6.27

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TABLE B-1. Number, x, of standard deviations for BERs – Continued

BER	x
1.09x10 <sup>[-9]</sup>	6.28
1.02x10 <sup>[-9]</sup>	6.29
9.60x10 <sup>[-10]</sup>	6.30
9.01x10 <sup>[-10]</sup>	6.31
8.46x10 <sup>[-10]</sup>	6.32
7.94x10 <sup>[-10]</sup>	6.33
7.46x10 <sup>[-10]</sup>	6.34
7.00x10 <sup>[-10]</sup>	6.35
6.57x10 <sup>[-10]</sup>	6.36
6.16x10 <sup>[-10]</sup>	6.37
5.78x10 <sup>[-10]</sup>	6.38
5.42x10 <sup>[-10]</sup>	6.30
5.09x10 <sup>[-10]</sup>	6.40
4.77x10 <sup>[-10]</sup>	6.41
4.48x10 <sup>[-10]</sup>	6.42
4.20x10 <sup>[-10]</sup>	6.43
3.94x10 <sup>[-10]</sup>	6.44
3.69x10 <sup>[-10]</sup>	6.45
3.46x10 <sup>[-10]</sup>	6.46
3.24x10 <sup>[-10]</sup>	6.47
3.04x10 <sup>[-10]</sup>	6.48
2.85x10 <sup>[-10]</sup>	6.49
2.67x10 <sup>[-10]</sup>	6.50
2.50x10 <sup>[-10]</sup>	6.51
2.34x10 <sup>[-10]</sup>	6.52
2.20x10 <sup>[-10]</sup>	6.53
2.06x10 <sup>[-10]</sup>	6.54
1.93x10 <sup>[-10]</sup>	6.55
1.80x10 <sup>[-10]</sup>	6.56
1.69x10 <sup>[-10]</sup>	6.57
1.58x10 <sup>[-10]</sup>	6.58
1.48x10 <sup>[-10]</sup>	6.59
1.39x10 <sup>[-10]</sup>	6.60
1.30x10 <sup>[-10]</sup>	6.61
1.21x10 <sup>[-10]</sup>	6.62
1.14x10 <sup>[-10]</sup>	6.63
1.06x10 <sup>[-10]</sup>	6.64
9.96x10 <sup>[-11]</sup>	6.65

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## APPENDIX C CALCULATION OF REQUIRED DETECTOR INPUT POWER FOR ANALOG LINKS

**C.1 General.** This appendix presents a method and supporting theory for calculating the detector input power required for a specified SNR.

**C.2 Detector input for analog links.** Although the required SNR determines the power required at the detector input, the nonlinear equation can be solved for  $P_d$  only through a successive substitution process such as the Newton-Raphson Method. The less cumbersome graphical solution is sufficiently accurate for system design purposes and is used here.

$$\text{SNR} = (k_m P_d / hf)^2 / [(2 P_d BF/hf) + (2ZB/G)^2] \quad \text{(Equation C-1) where:}$$

Where:

$k_m$  = modulation index

$h$  = Planck's constant =  $6.626 \times 10^{-34}$  joules-sec

$f$  = optical frequency =  $(3 \times 10^8 / \text{wavelength (m)})$  Hz

$B$  = 3- dB bandwidth of electronic amplifier (Hz)

$G$  = gain of photodetector (1 for PIN diodes)

$F$  = detector noise factor (1 for PIN diodes)

$P_d$  = power required at the detector

$Z$  = receiver offer of merit (see paragraph B.2.7 appendix B).

**C.3 SNR for PIN photodiodes.** Thermal noise from the electronic amplifier controls SNR for PIN photodiode detectors up to SNR of approximately 40 dB. At that point the influence of quantum noise commences. Figure C-1 is a graph of SNR versus  $P_d$  with bandwidth as a parameter. It assumes a modulation index,  $k_m$ , of 0.7, which is a typical value for amplitude modulation (i.e., intensity modulation of the optical source). The graph also assumes an equivalent load resistance of 10K ohms. This quantity is not included directly in equation C-1, but is inherent in the receiver figure of merit,  $Z$  (see figure B-3). The graph is based on a wavelength of 850 nm.

**C.3.1 Adjustment for modulation index.** Modulation indexes in amplitude modulation range in practice from 0.5 to 1.0. (Frequency modulation is treated later under C.4. 1.) To correct the SNR value for a modulation index other than 0.7, add the value indicated to the value in the graph, figure B-1.

For  $k_m = 0.5$ : -2.9 dB

For  $k_m = 1.0$ : +3.1 dB.

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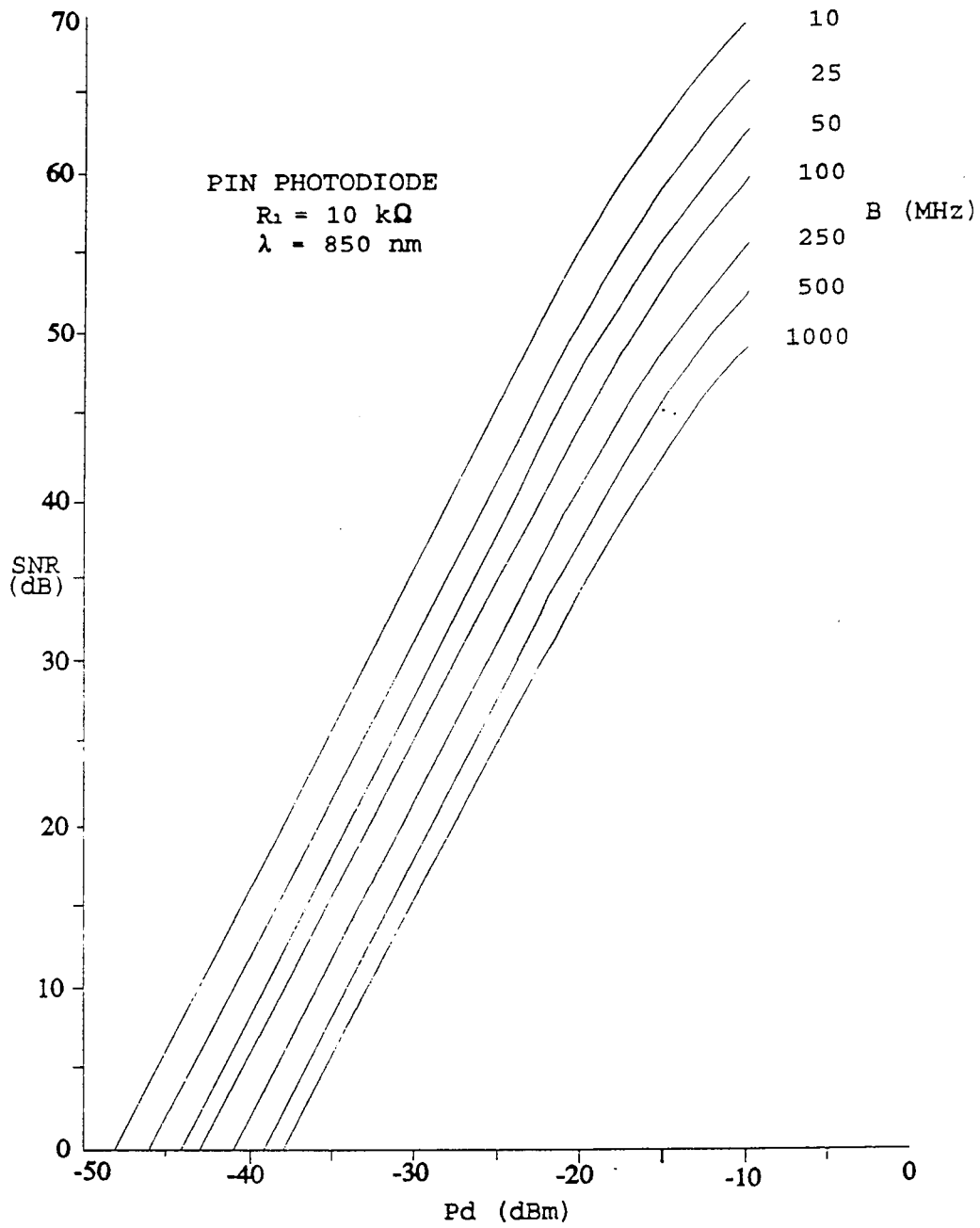


FIGURE C-1. SNR as a function of input power, PIN photodiode.

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**C-3.2 Adjustment for equivalent load resistance.** In appendix B, figure B-3, Z is given for load resistances from 10 to 10,000 ohms. For a power of 10 increase in load resistance (i.e., from 10,000 ohms to 100,00 ohms), add 10 dB to the SNR read from the graph. For each power of 10 decrease, subtract 10 dB.

**C.3.3 Adjustment for wavelength.** For optical source wavelengths other than 850 nm, apply the following adjustment factors to SNR values:

1310 nm: +3.8 dB

1550 nm: +5.2 dB.

**C.4 SNR for avalanche photodiodes.** In normal receivers using APDS, the APD noise factor controls SNR when optimal gain is applied. Optimal gain ranges from 15 to 100 in most cases. Figure C-2 is a graph of SNR versus P, with bandwidth as a parameter. It assumes a modulation index ( $k_m$ ) of 0.7, gains (G) of 15 and 100, noise factor (F) of 7, and wavelength of 850 nm. SNR for APDs is insensitive to variations in load resistance and, hence, receiver figure of merit, Z. It is also relatively insensitive to G. It is sensitive to F, however, which is related to G.

**C.4.1 Adjustment for modulation index.** To correct SNR for modulation indexes other than 0.7, apply the following adjustment factors:

For  $k_m = 0.5$ : -2.9 dB

For  $k_m = 1.0$ : +3.1 dB.

**C.4.2 Adjustment for APD noise factor.** SNR varies with APD noise factor, F. Figure C-3 gives the SNR adjustment factor in the form of relative SNR, with SNR normalized to 0 dB at  $F = 7$ .

**C.4.3 Adjustment for wavelength.** For wavelengths other than 850 nm, apply the following adjustment factors to SNR values:

1310 nm: + 1.9 dB

1550 nm: +2.6 dB.

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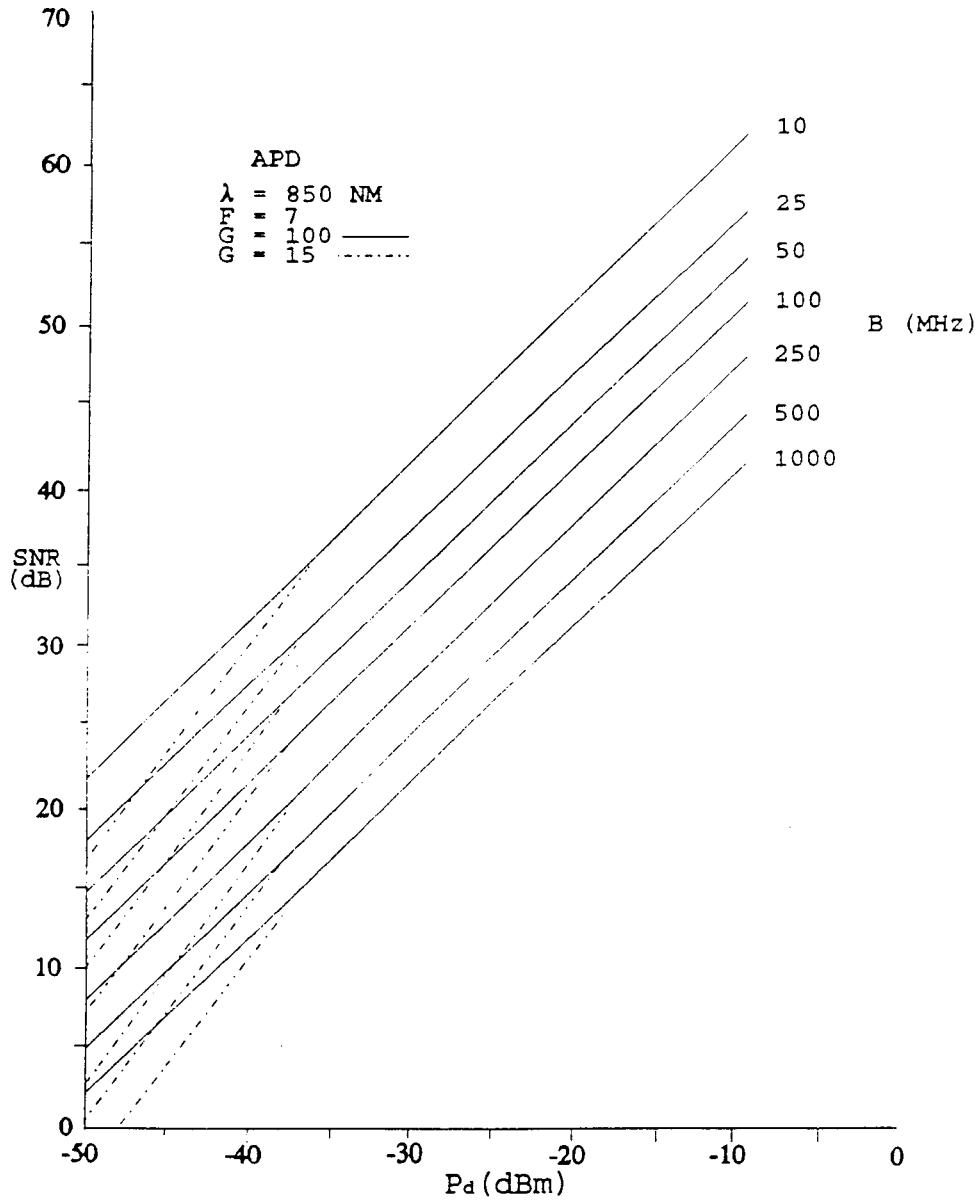


FIGURE C-2. SNR as a function of input power, APD.

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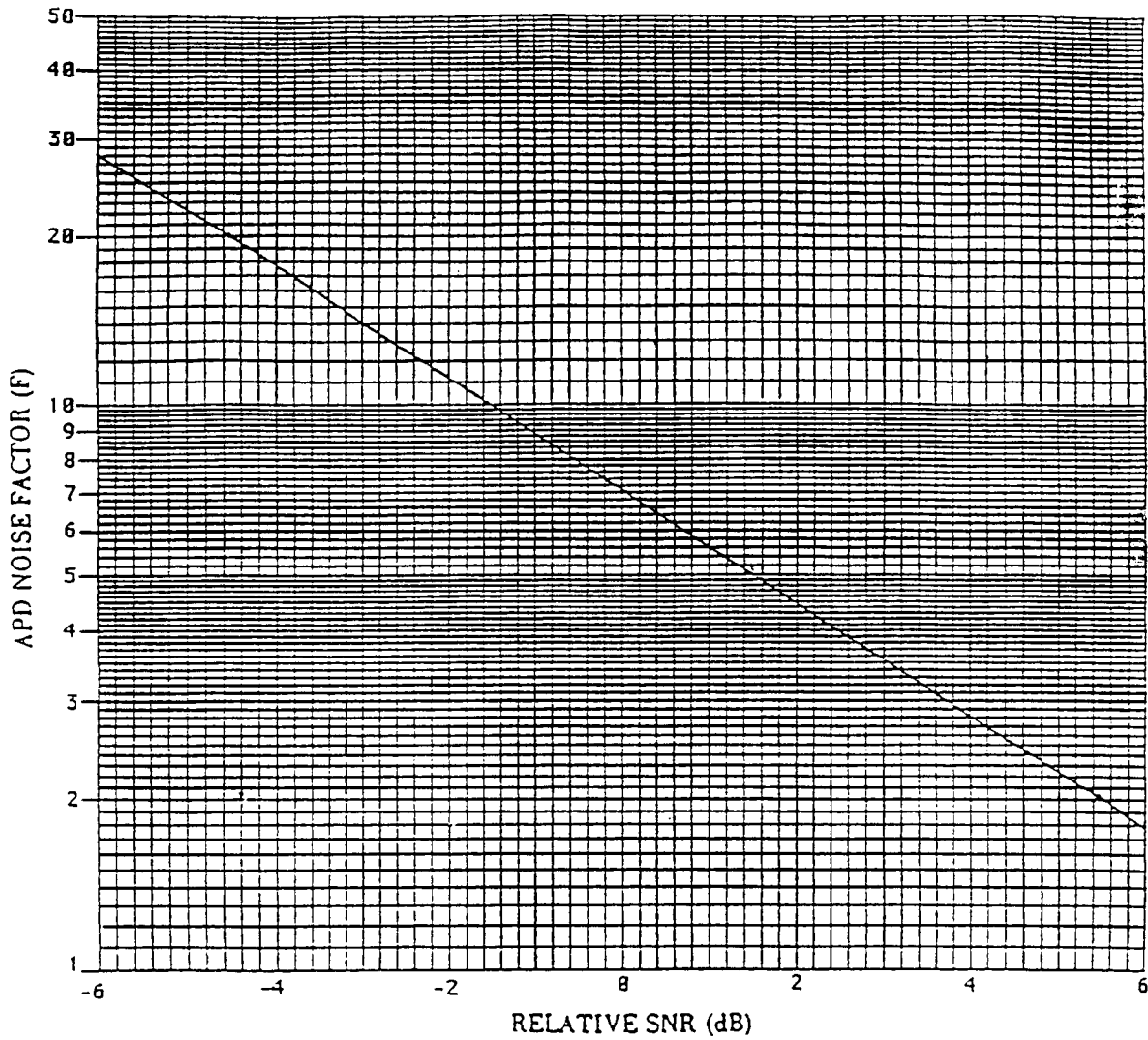


FIGURE C-3. SNR adjustment for APD noise factor F.

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**C.5 Bandwidth expansion techniques.** Bandwidth expansion techniques involve modulation where FM, pulse-position modulation (PPM) and pulse-duration modulation (PDM), modulate subcarriers which are then used to intensity modulate the optical carrier. These techniques provide significant improvements in SNR over direct IM.

**C.5.1 Frequency modulation.** Frequency modulation is applied to FO links as subcarrier FM-EM. That is, the optical source is intensity modulated by an FM subcarrier. This method provides an SNR improvement in direct proportion to the bandwidth expansion. The typical bandwidth expansion is a factor of 3, resulting in an SNR improvement of almost 10 dB.

**C.5.2 Pulsed analog modulation.** The improvement in SNR due to PPM and PDM is more difficult to determine. Exact performance depends on whether a PIN or an APD detector is used, whether the transmitter is peak power limited or average power limited, whether the fiber bandwidth is the limiting factor, and other variables. Because of the wide variations encountered, SNR improvements due to these modulation methods must be quoted by the manufacturer.

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## APPENDIX D POWER PENALTY BUDGET

**D.1 Introduction.** The link design method assumes a power penalty budget for a variety of interrelated variables involving the transmitter, receiver, and fiber transmission system. If a designer chooses not to use a power penalty budget for these variables, then the link design analysis will require several more iterations before it is satisfactorily completed. Changing one parameter (or assuming several values) has a cascading effect on other variables of the link design. Another difficulty is obtaining the component design parameters from the manufacturers to perform these iterative analyses. Therefore, it has been common industry practice is to assign a power penalty to these variables with the understanding that the component parameters will fall within the budget for worst case design purposes.

The following link design variables that fall within the power penalty budget are:

- transmitter extinction ratio
- fiber dispersion coefficient
- system rise time or bandwidth
- system Jitter
- modal noise (multimode systems)
- mode partition noise (single-mode systems)
- laser chirp
- reflection feedback.

**D.2 Transmitter extinction ratio.** The output transmitter power is characterized by average power and extinction ratio. The pulse duty cycle is key to interpreting the average power output. Average power is expressed as:

$$P_{ave} = (P_1 + P_0)/n,$$

where:

n = 2 for NRZ coding and n is 4 for RZ coding.

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The extinction ratio  $r_{\text{ext}}$  is:

$$r_{\text{ext}} = P_0 / P_1.$$

The extinction ratio is sometime expressed as the reciprocal by some manufacturers. This ratio expresses the fact the output power is not completely extinguished by the modulation process, and an additional amount of optical power must be supplied to overcome this effect. The penalty must take into account whether a pin diode or avalanche diode receiver is used. Extinction ratios greater than 0.1 produce a power penalty greater than 0.5 dB in pin diode receivers and 1.0 dB in avalanche photo diode receivers.

Figure D-1 shows how power penalty increases with the extinction ratio  $r_{\text{ext}}$ . A 1 dB penalty occurs for  $r_{\text{ext}} = 0.12$  and increases to 4.8 dB for  $r_{\text{ext}} = 0.5$ . In practice for lasers biased below threshold,  $r_{\text{ext}}$  is typically below 0.05, and the corresponding power penalty is equal to 0.4 dB.

**D.3 Fiber dispersion coefficient.** In the initial link design worksheet, a designer would assume there was no pulse broadening in the optical signal. Pulse broadening can result in intersymbol interference at the receiver with the attendant reduction in receiver sensitivity to avoid errors in interpreting pulse "ones" from "zeros".

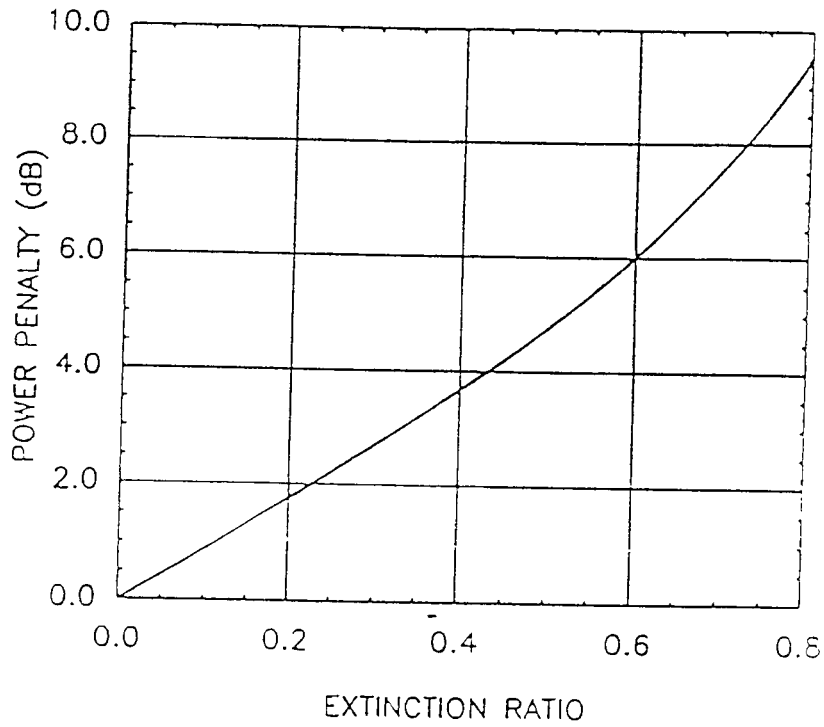
Fiber dispersion is classified as intermodal or intramodal dispersion. Intermodal dispersion (also known as modal dispersion) is due to the differential delay time of the different propagating modes of the optical source pulse at the receiver. Intramodal dispersion (also known as chromatic dispersion) is due to the variations of group velocity of a mode with wavelength and is a characteristic of the fiber.

Fiber dispersion causes pulses to spread and overlap as they propagate down the fiber. System wavelength and transmitter spectral width changes result in different delay values from fiber dispersion, and are examples of the interrelation between parameters of a link design. Changing one parameter will affect the value of the other parameter. Other interrelated effects are temperature and device-to-device (or fiber-to-fiber) variations.

For multimode fiber, the dominant mode is intemodal, and is not normally a distance limiting factor. To determine the total fiber dispersion, one should combine both types to determine total fiber dispersion.

For single-mode systems, intramodal dispersion is the only source of pulse broadening and can limit the link design distance one can achieve, because the attenuation of single-mode fiber has a low value per unit length and can be less of a penalty.

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FIGURE D-1. Power penalty versus extinction ratio.

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Since intramodal dispersion is dependent on the optical wavelength used with the fiber, the corresponding time delay will vary with wavelength also. Figure D-2 shows the time delay of a mode versus wavelength and also the fiber dispersion coefficient. If one differentiates the time delay with respect to wavelength, one has the first order dispersion coefficient, as shown on the figure. The term "D" is usually stated in picoseconds per nanometer-kilometer.

The dispersion coefficient comes from measurements made by the manufacturer (e.g. 3 ps/nm-km). The pulse broadening due to intramodal dispersion can be computed from:

$$P_b = \Delta_{\text{wrms}} DL,$$

where:

$\Delta_{\text{wrms}}$  = the rms spectral width of the source  
L = the link span.

For pulses with a temporal Gaussian response through the received system, (a reasonable assumption for most fiber optic systems), one can derive the relationship between the rms pulse width, the full width half maximum pulse width, and the 3 dB electrical and optical frequency bandwidths:

$$f_{-3 \text{ db}} (\text{optical}) = 187/\Delta_{\text{wrms}},$$

where:

f is in gigahertz

$$f_{-3 \text{ db}} (\text{electrical}) = 133/\Delta_{\text{wrms}},$$

where:

f is in gigahertz

$$\Delta_{\text{wrms}} = 0.425 \Delta_{\text{fwhm}}$$

where:

$\Delta_{\text{fwhm}}$  is spectral full width half maximum.

It has been common industry practice to design the interrelation between system parameters (variables) so that when the optical system bandwidth is chosen to be equal to the system bit rate, the received power penalty is less than 1 dB.

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To calculate the maximum link distance for such a designed system, and using the 1 dB as part of the power penalty budget yields:

$$L_{\max} = 187/(\Delta_{\text{wrms}} \text{ DB}),$$

where:

B = the system bandwidth ( $f_{-3 \text{ dB}}$  optical) in gigahertz.

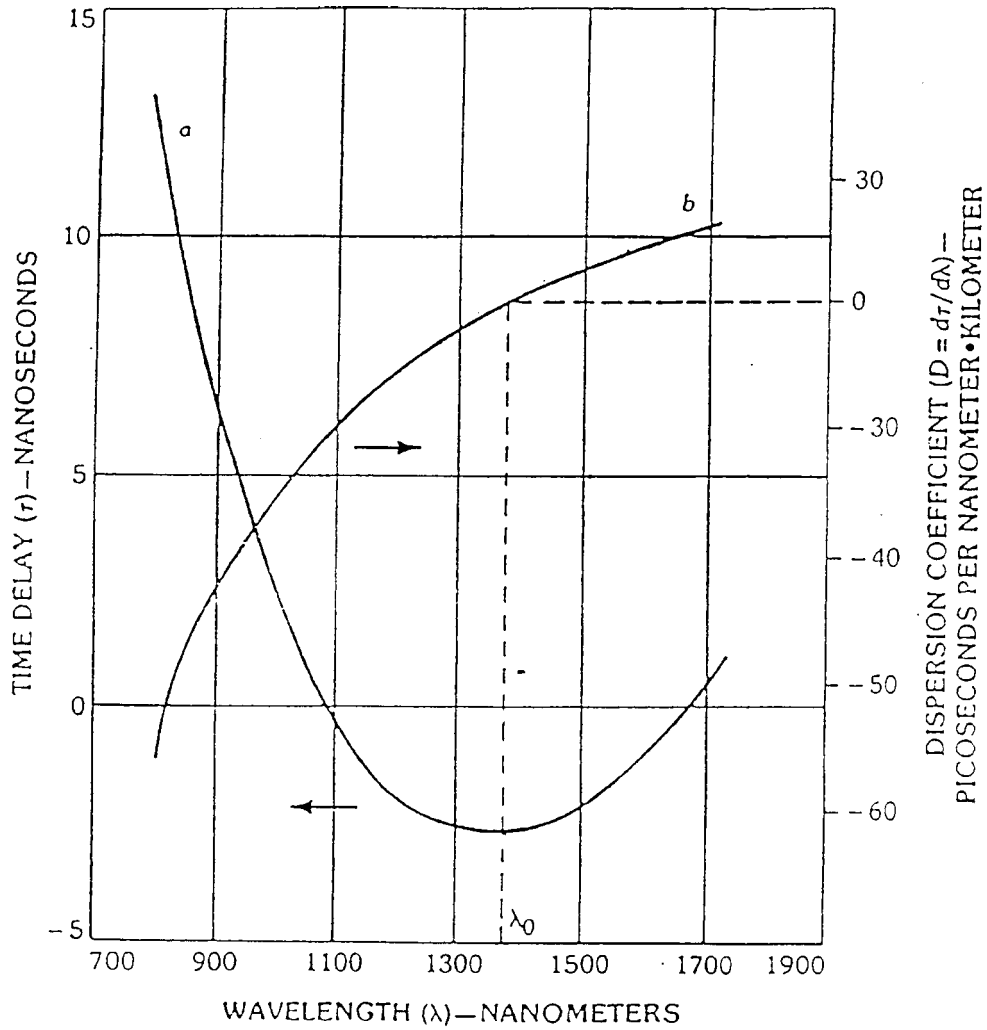
An example of this calculation is: 1) a single-mode fiber that has a dispersion coefficient of 3 picoseconds per nanometer-kilometer, 2) a system data rate and optical bandwidth of 1 gigahertz, and 3) a source rms spectral width of 2 nanometers:

$$L_{\max} = 187/(\Delta_{\text{wrms}} \text{ DB}) = 187/(2 \times 3 \times 1) = 31 \text{ km}.$$

A review of figure D-2 shows that dispersion passes through a zero at the wavelength where minimum delay occurs. This is known as the zero dispersion wavelength. One could conclude that there is no pulse broadening at that wavelength, and also that the fiber would have infinite bandwidth. For a source operating at or near the zero-dispersion wavelength, there is a second-order dispersion effect that becomes important because of the finite width of the spectral source. This residual coefficient is expressed in picoseconds per nanometer-squared-kilometer, usually less than 0.1 ps/(nm<sup>2</sup>-km). For most system designers it is difficult to precisely determine the exact location of a given fiber zero-dispersion wavelength, and also the exact operating wavelength of a particular optical source. Therefore the manufacturer will specify for the system designer the worst case dispersion coefficient in a band of wavelengths (i.e. 3.5 ps/nm-km in the 1285 nm to 1325 nm band).

Dispersion induced pulse broadening affects the receiver performance two ways: 1) as part of the pulse energy spreads beyond the allocated bit period, intersymbol interference occurs, and 2) the energy within the bit period is reduced requiring a higher average received power to maintain the same SNR. These effects cause one to assign a power penalty to the link design to account for this source of received power loss.

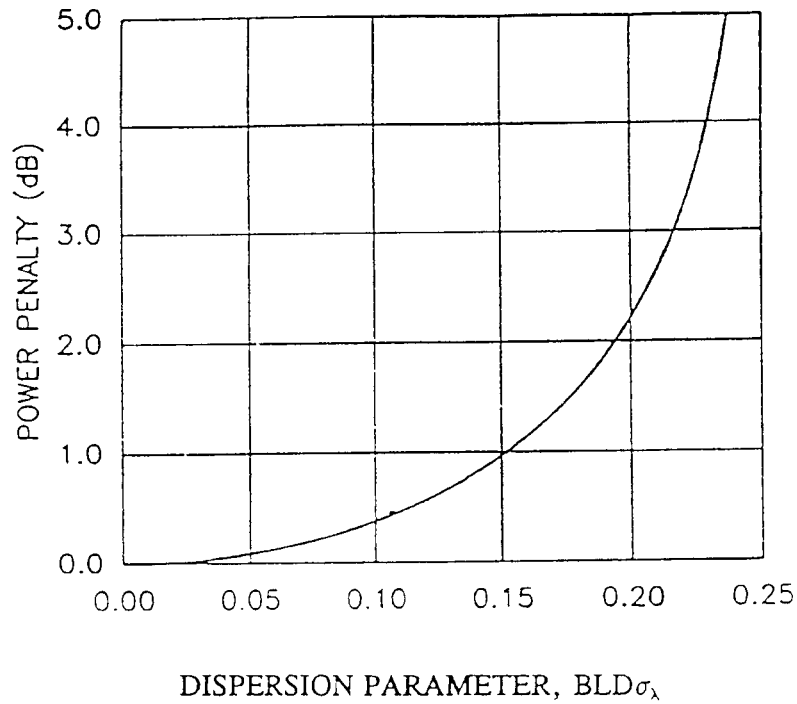
Figure D-3 shows how the penalty increases with a dimensionless dispersion factor  $BLD\sigma_{\lambda}$ , where B is the bit rate, L is the link distance, D is the dispersion coefficient, and  $\sigma_{\lambda}$  is the laser transmitted spectrum width. One should note this effect increases with link distance and system bit rate. Therefore, not all links will be affected since not all links are designed to maximum dispersion limited distances or have the maximum bit rates. Also, the laser spectrum width can affect the power penalty, a parameter controlled by the transmitter supplier, as well as the dispersion coefficient which is controlled by the cable manufacturer. Thus, for most system designs, the link calculations will have to be an iterative process until all variables are accounted for. For the initial design, limiting the link distance to the recommended maximum will ensure the power penalty lies below 2 dB. Further refinements will require more exact calculations as the link parameters are established.



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**FIGURE D-2. Single-mode chromatic dispersion.**

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Where:

**B**=the bit rate in bps

**L**=the Link Length in kms

**D**= dispersion coefficient

**$\sigma_\lambda$** =Laser transmitted spectrum width in nanometers

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**FIGURE D-3. Power penalty versus dispersion parameter,  $BLD\sigma_\lambda$ .**

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**D-4 System rise time or bandwidth.** As discussed in the fiber dispersion section, a designer initially assumes no pulse broadening in the initial design link worksheet. Also, if the system was optimally designed where the optical bandwidth is equal to system bit rate, the power penalty for a receiver with fiber dispersion effects (within maximum range limits calculation) would be 1 dB. However, transmitter and receiver bandwidths can ultimately limit link distances and bit rates.

Analysis of optical receivers has shown that if the product of the bit rate B and the rms width of the impulse response of the system is equal to or less than:

$$B I_{\text{resp}} = \leq 0.25,$$

the loss in receiver sensitivity will be less than 1 dB.

For designers, it is easier to measure the rise time in system response than to calculate the impulse response using a delta function. A rule of thumb used in industry, for intersymbol interference to cause less than 1 dB of penalty in receiver sensitivity, is that the pulse rise time of the system should not exceed 70 percent of the bit period for NRZ pulses and 35 percent for RZ pulses, where the bit period is defined as the reciprocal of the data rate.

The total system rise time can be calculated by combining the rise time of each component of the system (transmitter, fiber, receiver) as the square root of the sum of the squares:

$$t_{\text{sys}} = [\sum t_i^2]^{1/2},$$

where:

$t_{\text{sys}}$  = total system rise time  
 $t_i$  = individual component rise times.

If the electrical bandwidth of the transmitter or receiver is known, the rise time can be estimated from:

$$t_r = 350/b,$$

where:

$t_r$  = rise time in picoseconds  
 $b$  = -3dB electrical bandwidth in gigahertz.

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The value represents the response of a single pole filter, which may only approximate the rise time of a transmitter or receiver.

**D.5 System jitter.** System jitter affects the received SNR because the received data pulse is not sampled at its peak value. The timing of the sampling is dependent upon the system clock, which is usually derived from the data stream. Thus, any noisy inputs to the clock recovery circuit will cause fluctuations in sampling time, causing degradation of received signal values.

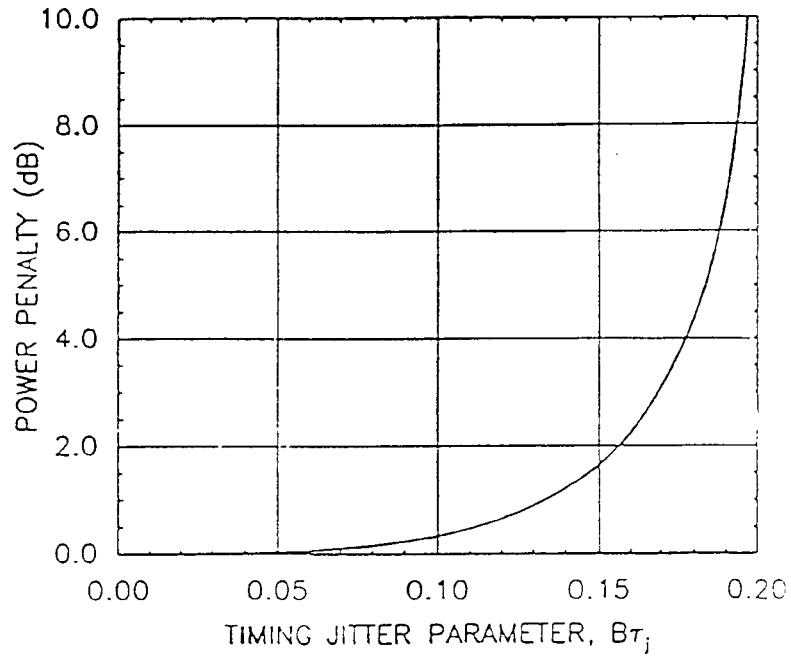
Figure D-4 shows the power penalty incurred for a timing jitter parameter for a pin diode receiver, where  $B$  is the bit rate and  $\sigma_j$  is the rms (standard deviation) of the jitter when measured against a bit time period. A 1 dB penalty occurs for a 13 percent timing jitter parameter and a 2 dB penalty occurs for a 16 percent factor. The equivalent power penalty curve for an APD receiver would be greater. The curve plotted assumes specific pulse shapes, jitter distribution, zero extinction current, and Gaussian statistics for receiver current. Therefore, an exact analytical value of power penalty is difficult to obtain for a specific application; however, the analysis shows the timing jitter parameter should be kept to less than 10 percent to achieve a negligible power penalty.

**D.6 Modal noise.** Modal noise is caused by mode dependent losses and changes in phase between modes or fluctuations in the distribution of energy among modes. If light from a coherent optical source is launched into a multimode fiber, a speckle pattern exists from interference of the propagating modes. Laser chirping, intensity modulation at splice joints, etc., will cause modal noise. Since this noise is dependent on an installation and is unpredictable, the use of a laser (coherent) with multimode fiber is best avoided. This noise can exceed the receiver noise level. Modal noise can be entirely avoided by use of LED (incoherent) optical light sources.

**D.7 Mode partition noise.** Mode partition noise is caused by the combination of a multilongitudinal-mode laser source with a dispersive single-mode fiber. Noise is created by the random partitioning of the optical power between different longitudinal modes of the semiconductor laser. With fiber dispersion, each mode has a unique propagation velocity and noise occurs from the combination of random mode partition and interlongitudinal-mode delay. The use of dispersion shifted fiber has the advantage of reducing the mode-partition noise and minimizing fiber dispersion effects. The best performance is obtained with the use of a single frequency laser, which will define a spectral width only created by the modulation rate. The narrower the spectral width, the greater allowable distance (see fiber dispersion calculations in D-3).

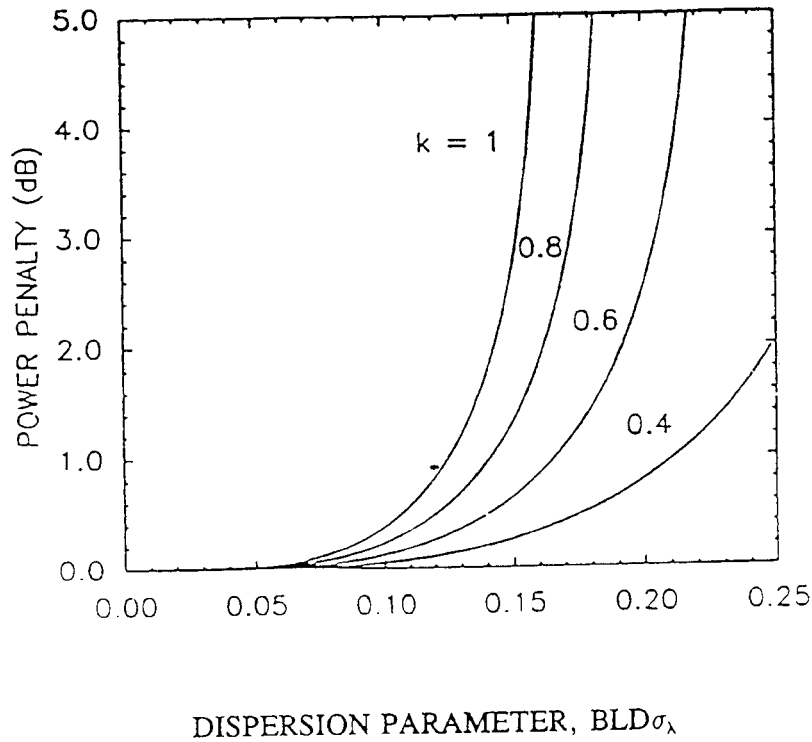
Figure D-5 shows the power penalty at a BER of  $10^{-9}$  ( $Q = 6$ ) as a function of the normalized dispersion parameter  $BLDA$ . (discussed in paragraph D-4) for several values of the mode-partition coefficient  $k$ , which is a measure of the cross-correlation coefficient of the various mode coupling effects. The coefficient usually varies between 0.6 and 0.8 from laser to laser. As shown, the effect can be minimized by designing a link to have a normalized dispersion parameter less than 0.1 when using a multilongitudinal mode laser transmitter.

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FIGURE D-4. Power penalty versus timing jitter.



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**FIGURE D-5.** Power penalty versus  $BLD\sigma_\lambda$  for various values of the mode-partition coefficient.

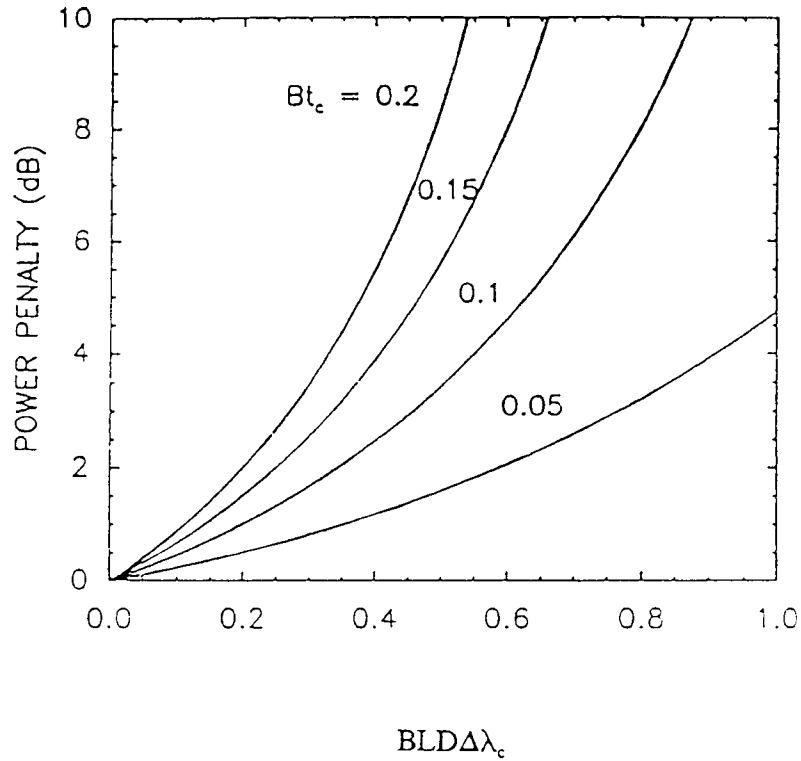
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**D-8 Laser frequency chirping.** As mentioned above, the use of a single frequency laser minimizes degradation due to fiber dispersion and mode-partition noise. However, laser chirping (frequency shifts) caused by direct modulation of the injection current will cause pulse broadening. The power penalties associated with laser chirping have led manufacturers to the use of external modulators, operation at the zero-dispersion wavelengths, and use of dispersion shifted fiber.

Figure D-6 shows the power penalty on a pin diode receiver due to laser chirping over a fraction of the bit period.  $Bt_c$  is the bit rate times the chirp duration period,  $\lambda_c$  is the wavelength shift occurring because of frequency chirp, and BLD is the normalized dispersion parameter. As expected the power penalty increases with both chirp frequency shift and chirp duration. The power penalty can be kept below 1 dB if the system is designed such that  $BLD \lambda_c < 0.1$  and  $Bt_c < 0.2$ . Obviously this will depend upon the manufacturer of the laser transmitter that has been selected for the link design.

**D.9 Reflection feedback.** In fiber optic communications systems, some light gets reflected back from splices and connectors, degrading performance accordingly. Semiconductor lasers are extremely sensitive to reflected light, even with feedback as low as -80 dB. However, generally speaking, most lasers operate satisfactorily, as far as feedback induced side modes are concerned, when the reflection feedback is less than -30 dB. This problem can be eliminated if an optical isolator is used within the transmitter module.

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FIGURE D-6. Power penalty versus  $BLD\Delta\lambda_c$ .

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## MIL-HDBK-415A

### APPENDIX E SONET (SYNCHRONOUS OPTICAL NETWORK)

The optical carrier line rates have been standardized by ANSI T1.106-1988 specification, and are referred in MIL-STD-188-111, appendix C, general requirements. These optical carrier line rates are:

OC-Level	Line Rate (Mbps)
OC-1	51.840
OC-3	155.520
OC-9	466.560
OC-12	622.080
OC-18	933.120
OC-24	1244.160
OC-36	1866.240
OC-48	2488.320

These optical carrier line rates are integer multiples of 51.840 Mbps, and use NRZ/RZ coding. The basic 51.840 Mbps rate is related to the North American Standard Multiplexing digital signaling (DS) line rates as follows:

DS-Level	Line Rate
DS0	64 kbps
DS1	1.544 Mbps
DS3	44.736 Mbps
OC-1	51.84 Mbps; 672 DS0 user channels 51.84 Mbps; 28 DS1 user channels 51.84 Mbps; 1 DS3 user channel

The remaining channel capacity in the OC-1 rate is used for implementing the synchronous optical communications protocol in the network, which is called SONET. For higher OC rates, since they are integer multiples of the OC-1 rate, the number of user channels expands accordingly. For example, the OC-3 rate would serve 2016 DS0 user channels, or 84 DS1 channels, or 3 DS3 channels. This standard is described in ANSI T1. 105-1988 as the standard optical interconnect at the SONET interface. The International Telegraph and Telephone Consultative Committee (CCITT) has also approved this standard for the European community.

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The advantages of SONET are the use of standardized optical carrier rates and communication protocol. This allows interoperability of many different types of networks through a long-haul transmission medium. The standard defines optical carrier rates, and a synchronous frame structure for simplified multiplexing and demultiplexing of lower rate digital tributaries.

The SONET synchronous frame structure is based on a signal frame called the synchronous transport signal level 1 (STS-1). This frame structure is shown on figure E-1, and is composed of 810 eight bit bytes. As shown, the frame has 9 rows of 90 bytes. The first three bytes of each row are used for communications called the transport overhead. The remaining 87 bytes are the actual synchronous payload envelope (SPE). In the SPE, a column (one byte per row) carries additional communications called the path overhead, as shown on figure E-1.

The SONET divides its communication protocol processing into layers that correspond to the network elements as shown on figure E-2. The three layers used are section, line, and path. The section is the transmission span between optical repeaters. The line is the span between fiber optics terminating equipment at the STS-1 cross-connect level. A path is an end-to-end span for a digital tributary such as DS1, DS3, etc., and includes cross connects and multiplexers.

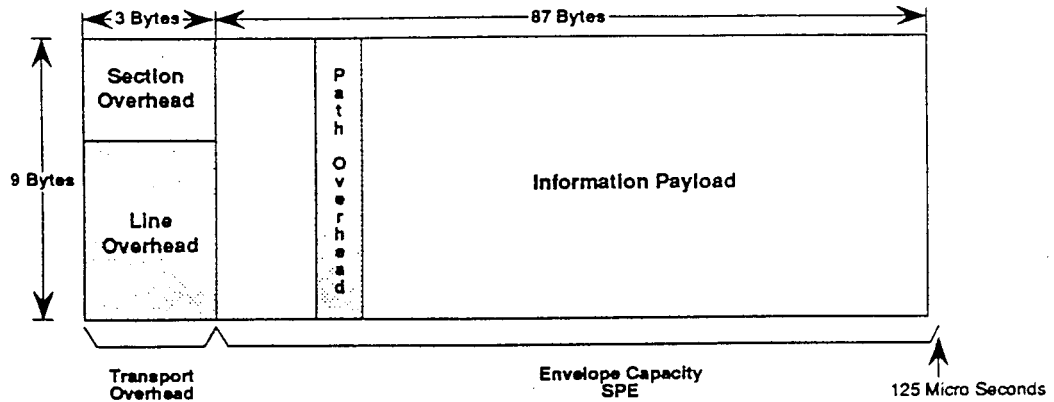
Each layer has its communications overhead. The section layer overhead contains information used by all SONET equipment including repeaters. It contains framing bytes, STS-1 frame identification, parity, and order-wire channels. Data communication channels are also provided at this level for network maintenance and provisioning.

The line layer overhead is used by all SON-ET equipment except repeaters, and contains STS-1 pointer bytes, additional parity bytes for line monitoring, automatic protection switching messages, data communications, and order-wire bytes.

The path layer overhead is carried within the payload envelope and is used by all terminating equipment. It carries the path parity, a signal level byte which identifies the type of payload, path status bytes carrying maintenance information, a multiframe alignment byte that shows virtual tributary (VT) and DS I super-frame bit phase, and a path trace byte that uniquely identifies the synchronous payload envelope.

Figure E-3 shows how a DS 1 frame gets mapped into the SONET frame. Single DS1s or groups of DS0s (24 each) are bundled into an intermediate payload called a VT. When carrying DS1 payloads, this VT is called VT1.5. These VTs are bundled into groups of four, defined as a VT group (VT-G).

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Rate = 51.840 Mb/s

FIGURE E-1. STS-1 frame format.

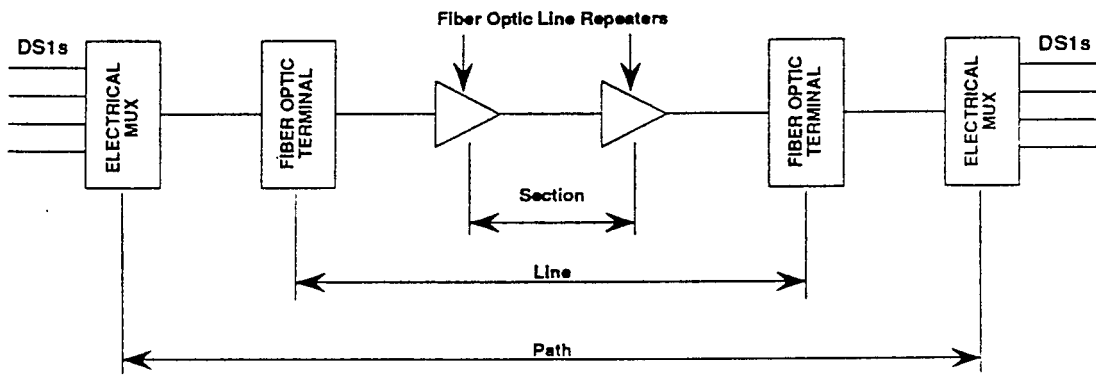


FIGURE E-2. Sonet network elements.

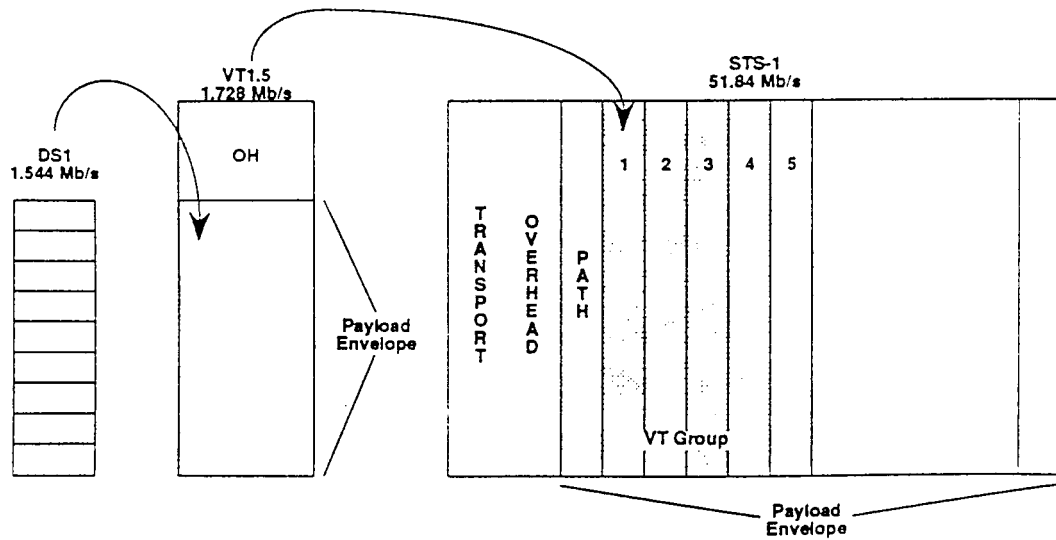


FIGURE E-3. DS1 - VT1.5 - STS-1 functional relationship.

## **MIL-HDBK-415A**

Higher rate SONET signals are produced by byte-interleaving N STS-1s to form a STS-N signal. The STS-N signal is then scrambled and converted to an optical carrier N (OC-N). N is an integer going from 1, 3, 9, 12, 24, and 48.

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**APPENDIX F  
BLANK WORKSHEETS**

# MIL-HDBK-415A

Project Name \_\_\_\_\_  
 Engineering Agency \_\_\_\_\_ Date \_\_\_\_\_  
 Link Classification (Tactical, Long-haul) \_\_\_\_\_  
 Link from \_\_\_\_\_ to \_\_\_\_\_  
 Optical Line Rate,  $R_o$  \_\_\_\_\_ Gbps  
 Nominal Operating Wavelength,  $\lambda$ , (850, 1310, 1550) \_\_\_\_\_ nm

## OPTICAL FIBER

Type (SI, GI, SM) \_\_\_\_\_  
 Size (8-10/125, 50/125, 65/125) \_\_\_\_\_  $\mu\text{m}$   
 Attenuation Coefficient,  $\alpha_{\text{max}}, \alpha_{\text{typ}}$  \_\_\_\_\_, \_\_\_\_\_ dB/km  
 Length, K \_\_\_\_\_ km  
 Link Loss,  $L_{\text{fmax}}, L_{\text{ftyp}}$  \_\_\_\_\_, \_\_\_\_\_ dB  
 Zero - dispersion Wavelength,  $\lambda_o$  \_\_\_\_\_ nm  
 Zero - dispersion Slope,  $\xi$  \_\_\_\_\_  $\text{ps}/\text{nm}^2\text{-km}$   
 Fiber Dispersion Coefficient at Operating Wavelength  $d_{\text{ma}}$  \_\_\_\_\_  $\text{ps}/\text{nm-km}$   
 Bandwidth - distance Factor,  $B_d$  \_\_\_\_\_ GHz-km

## OPTICAL TRANSMITTER

Type (LED, LD) \_\_\_\_\_  
 RMS Spectral Linewidth,  $\Delta_f$  \_\_\_\_\_ nm  
 Power Coupled Into Fiber,  $P_{\text{tmax}}, P_{\text{tmin}}$  \_\_\_\_\_, \_\_\_\_\_ dBm  
 Rise Time,  $t_r$  \_\_\_\_\_ ps  
 Modulation Bandwidth \_\_\_\_\_ GHz

## OPTICAL RECEIVER

Type (APD, PIN, PIN-FET) \_\_\_\_\_  
 BER (Tactical  $10^{-9}$ , Long-haul  $10^{-11}$  x K) \_\_\_\_\_  
 Minimum Input Power,  $P_{\text{rmin}}$  \_\_\_\_\_ dBm  
 Overload Power,  $P_{\text{rmax}}$  \_\_\_\_\_ dBm  
 Rise Time,  $t_r$  \_\_\_\_\_ ps

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Optical Line Rate, $R_o$	_____ Gbps
Allowable Rise Time, $t_a, (0.7/R_o) \times 10^3$	_____ ps
Transmitter Type (LED, LD)	_____
Transmitter Rise Time, $t_t$	_____ ps
Transmitter RMS Spectral Linewidth, $\Delta_t$	_____ nm
Receiver Rise Time, $t_r$	_____ ps
Fiber Type (MM, SM)	_____
Fiber Length, K	_____ km
Nominal Operating Wavelength, $\lambda_1$	_____ nm
Fiber Bandwidth-distance Factor, $B_d$	_____ GHz-km
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	_____ ps/nm-km
Rise Time due to Material Dispersion, $t_{ma} = d_{ma} \times \Delta_t \times K$	_____ ps
Rise Time due to Multimode dispersion, $t_{mu} = 350K/B_d$	_____ ps
Fiber Rise Time (SM), $t_{sm} = t_{ma}$	_____ ps
Fiber Rise Time (MM), $t_{mm} = (t_{ma}^2 + t_{mu}^2)^{0.5}$	_____ ps
Link Rise Time (SM), $t_{lsm} = 1.1(t_t^2 + t_{sm}^2 + t_r^2)^{0.5}$	_____ ps
Link Rise Time (MM), $t_{lmm} = 1.1(t_t^2 + t_{mm}^2 + t_r^2)^{0.5}$	_____ ps
Allowable Minus Calculated Rise Time, $t_a - t_l$ (sm, mm)	_____ ps

### DISPERSION LIMITED LENGTH CALCULATIONS

Maximum Allowable Fiber Dispersion*, $D_{max}$	_____ ps/nm
Power Penalty associated with $D_{max}$	_____ dB
Fiber Dispersion Coefficient at Operating Wavelength, $d_{ma}$	_____ ps/nm-km
Dispersion Limited Length, $D_{max}/d_{ma}$	_____ km

\* The maximum dispersion that the transmitter-receiver pair can tolerate and still meet its BER and Bit Rate Specifications.

## MIL-HDBK-415A

Type of Connector (SC, ST,...)	_____	
Number of Connectors	_____	
Loss per Connector, maximum, typical	_____, _____	dB
Total Connector Losses, $L_{cmax}$ , $L_{ctyp}$	_____, _____	dB
Type of Splice (mechanical, fusion)	_____	
Number of Splices	_____	
Loss per Splice, maximum, typical	_____, _____	dB
Total Splice Losses, $L_{smax}$ , $L_{styp}$	_____, _____	dB
Other Passive Losses (WDM, Coupler, Splitter), $L_p$	_____	dB

### POWER BUDGET CALCULATIONS

Minimum Available Power ( $P_{tmin}$ minus $P_{rmin}$ )*	_____	dB
Maximum Excess Power ( $P_{tmax}$ minus $P_{rmax}$ )**	_____	dB

	<u>Maximum Loss Budget</u>	<u>Minimum Loss Budget</u>
Fiber Losses	$L_{fmax}$ _____ dB	$L_{ftyp}$ _____ dB
Connector Losses	$L_{cmax}$ _____ dB	$L_{ctyp}$ _____ dB
Splice Losses	$L_{smax}$ _____ dB	$L_{styp}$ _____ dB
Other Passive Losses	$L_p$ _____ dB	$L_p$ _____ dB
Power Penalties, $P_p$	_____ dB	N/A
Unallocated Power Margin	3.0 dB	N/A
Receiver Overload Margin	N/A	-3.0 dB
Total (sum of above)	_____ dB	_____ dB
Minimum Available Power minus Total	_____ dB***	N/A
Total minus Maximum Excess Power	N/A	_____ dB****
Optical Attenuator (if required)	N/A	_____ dB

\* Determines the Maximum Allowable Link Loss for 0 dB power margin at the Receiver. Also called Available Link Gain

\*\* Relative to Receiver Overload Level, Determines Minimum Link Loss Required to Keep the Receiver Out of Saturation

\*\*\* Must be 0 dB or Greater

\*\*\* Add Attenuator if Negative

# MIL-HDBK-415A

## CONCLUDING MATERIAL

### Custodians:

Army – SC  
Navy - ED  
Air Force - 90

### Preparing activity:

Army - SC

### Review activities:

Army - CR  
Navy - EC, MC  
DoD - DC, NS, DI

(Project TCSS-4151)

### User activities:

Army - AC, PT  
Navy - NC, TD, OM, CG  
Air Force - 02, 13, 21  
DoD - DH, ECAC, MP  
DOT - FAA, OST

### Civil agency coordinating activities:

NCS

# MIL-HDBK-415A

# STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

## INSTRUCTIONS

1. The preparing activity must complete blocks 1, 2, 3, and 8. In block 1, both the document number and revision letter should be given.
2. The submitter of this form must complete blocks 4, 5, 6, and 7.
3. The preparing activity must provide a reply within 30 days from receipt of the form.

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<b>I RECOMMEND A CHANGE:</b>	1. DOCUMENT NUMBER: <b>MIL-HDBK-415A</b>	2. DOCUMENT DATE (YYMMDD) <b>941017</b>
3. DOCUMENT TITLE: Design Handbook for Fiber Optic Communications Systems		
4. NATURE OF CHANGE <i>(Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)</i>		
5. REASON FOR RECOMMENDATION		
6. SUBMITTER		
a. NAME <i>(Last, First, Middle Initial)</i>	b. ORGANIZATION	
c. ADDRESS <i>(Include Zip Code)</i>	d. TELEPHONE <i>(Include Area Code)</i> (1) Commercial (2) AUTOVON <i>(if applicable)</i>	7. DATE SUBMITTED (YYMMDD)
8. PREPARING ACTIVITY		
a. NAME: Department of the Army USAISEC	b. TELEPHONE <i>(Include Area Code)</i> (1) Commercial (2) AUTOVON (602) 538-3188 879-3188	
c. ADDRESS <i>(Include Zip Code)</i> ATTN: ASQB-OST Fort Huachuca, Arizona 85613-5300	<b>IF YOU DO NOT RECEIVE A REPLY WITHIN 45 DAYS, CONTACT:</b> Defense Quality and Standardization Office 5203 Leesburg Pike, Suite 1403, Falls Church, VA 22041-3466 Telephone (703) 756-2340 AUTOVON 289-2340	