METRIC

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MILITARY STANDARD

FIBER OPTIC SYSTEMS DESIGN

AMSC N/A

FSC 60GP

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FOREWORD

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
ARLINGTON, VA 22242-5160

[redacted]

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: Commander, Naval Sea Systems Command, SEA 03R42, 2531 Jefferson Davis Hwy., Arlington, VA 22242-5160 by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. This standard provides detailed information, guidelines, procedures and requirements for selecting fiber optic components required for transmitting optical signals through and between points in Navy command, control, communication and telemetry systems. This standard identifies the significant background consideration used to determine the physical and performance requirements of the components and the approaches to the procedures. The considerations involve the relationship of the fiber optic components and the surface ship and submarine environments. This knowledge will give the designer assurance that the characteristics of the systems he is designing will be compatible with the components.

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1. SCOPE

1.1 Scope. This standard provides design requirements for digital fiber optic systems having data transmission rates not greater than 500 megabits per second (Mbps) installed aboard Navy surface ships and submarines. The proper application of component specifications and other fiber optic standards is addressed herein, as are detailed methods for calculating system design parameters, with examples. This standard concentrates on the design of a simple digital fiber optic link. It does not address most general system design issues such as the terminal equipment design (except for some physical design constraints), the system topology and the physical design of the fiber optic cable plant. It is assumed that these decisions have been made and the information is used as input to the link design process. Furthermore, this document does not address the design of analog links, links using step index fiber and complex fiber optic links containing nonlinear fiber optic components such as fiber amplifiers.

1.2 Applicability. The design requirements in this document apply to equipment and systems on specific ships when invoked by the governing ship specification, system specification, or other contractual document. They are intended for new systems using fiber optics or the conversion or alteration of existing systems to use fiber optics. Where there is a conflict between this document and the ship specification or contract, the ship specification or contract shall take precedence. Where ship design or system performance requirements are such that the methods herein cannot be implemented, users shall submit new methods to Commander, Naval Sea Systems Command, 2531 Jefferson Davis Hwy., Arlington, VA 22242-5160 Attn: SEA 06K31 for approval.

1.3 General. This standard describes the methodology that is required for designing digital fiber optic transmission links with capacities up to approximately 500 Megabaud (Mbaud) which use either single mode or graded index multimode optical fiber and either a light emitting diode (LED) or laser source. This document concentrates on transmission wavelengths in the first and second transmission windows (850 and 1300 nanometers (nm)). The information may be applicable for links operating between 700 and 1600 nm. However, component specifications are normally provided in the 850 and 1300 nm windows only. The types of transmitters, fiber, and receivers available for use in links are addressed as well as the performance characteristics of any passive components within the link. In many cases, the link design will be an iterative process in which various trade-offs between system components are evaluated. For each link being designed, a unique design solution may not exist. Several solutions may be technically viable. The link designers must choose the solution that is best suited to the particular application.

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 to 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 (see 6.2).

SPECIFICATIONS

MILITARY

MIL-C-24621	-	Couplers, Passive, Fiber Optic, General Specification For (Metric).
MIL-S-24623	-	Splice, Fiber Optic Cable, General Specification For.
MIL-S-24623/4	-	Splice, Fiber Optic, Housing, Fiber.
MIL-S-24623/5	-	Splice, Fiber Optic, Cable, Housing.
MIL-R-24720	-	Receiver, Digital, Fiber Optic, Shipboard (Metric) General Specification For.
MIL-T-24721	-	Transmitters, Light Signal, Digital, Fiber Optic, Shipboard (Metric) General Specification For.
MIL-S-24725	-	Switches, Fiber Optic, Shipboard, (Metric), General Specification For.
MIL-S-24725/1	-	Switch, Fiber Optic, Shipboard, Electrical, Nonlatching; Bypass, Multimode Cable, Stand-Alone (Metric).
MIL-I-24728	-	Interconnection Box, Fiber Optic, Metric, General Specification For.
MIL-C-28840	-	Connectors, Electrical, Circular, Threaded, High Density, High Shock, Shipboard, Class D General Specification For.
MIL-C-28876	-	Connectors, Fiber Optic, Circular, Plug and Receptacle Style, Multiple Removable Termini, General Specification For.

MILITARY - (Continued)

MIL-F-49291 - Fiber Optical, (Metric), General Specification For.

MIL-F-49291/6 - Fiber, Optical, 62.5/125 Micrometers, Radiation Hardened (Metric).

MIL-F-49291/7 - Fiber, Optical, Single-Mode, Dispersion Unshifted, Radiation Hardened (Metric).

MIL-C-83522 - Connectors, Fiber Optic, Single Terminus, General Specification For.

MIL-C-83522/16 - Connector, Fiber Optic, Single Terminus, Plug, Adapter Style, 2.5 Millimeters Bayonet Coupling, Epoxy.

MIL-C-83522/17 - Connector, Fiber Optic, Single Terminus, Adapter, 2.5 Millimeter Bayonet Coupling, Bulkhead Panel Mount.

MIL-C-83522/18 - Connector Fiber Optic, Single Terminus, Adapter, 2.5 Millimeter Bayonet Coupling PC Mount.

MIL-C-85045 - Cables, Fiber Optics, (Metric), General Specification For.

MIL-C-85045/13 - Cable, Fiber Optic, Eight Fibers, Cable Configuration Type 2 (OFCC), Application B (Shipboard), Cable Class SM and MM, (Metric).

MIL-C-85045/14 - Cable, Fiber Optic, One Fiber, Cable Configuration Type B (Pigtail), Loose Tube, Cable Class MM or SM, (Metric).

MIL-C-85045/15 - Cable, Fiber Optic, Four Fibers, Cable Configuration Type 2 (OFCC), Application B (Shipboard), Cable Class SM and MM, (Metric).

MIL-C-85045/16 - Cable, Fiber Optic, One Fiber, Cable Configuration Type 2 (Pigtail), Tight Buffered, Cable Class SM or MM, (Metric).

MIL-C-85045/17 - Cable, Fiber Optic, Cross-Linked Eight Fibers, Cable Configuration Type 2 (OFCC), Application B (Shipboard), Cable Class SM and MM, (Metric).

MILITARY - (Continued)

MIL-C-85045/18 - Cable, Fiber Optic, Cross-Linked Four Fibers, Cable Configuration Type 2 (Pigtail), Application B (Shipboard), Cable Class SM and MM, (Metric).

STANDARDS

FEDERAL

FED-STD-1037 - Telecommunication: Glossary of Telecommunication Terms.

MILITARY

DOD-STD-2196 - Glossary, Fiber Optics.

MIL-STD-2042 - Fiber Optic Topology Installation Standard Methods For Naval Ships (Equipment).

MIL-STD-2042/5 - Fiber Optic Topology Installation Standard Methods For Naval Ships (Connectors and Interconnections).

MIL-STD-2051 - Fiber Optic Shipboard Cable Topology Design Standard.

HANDBOOKS

MILITARY

MIL-HDBK-217 - Reliability Prediction of Electronic Equipment.

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

2.2 <u>Non-Government publications</u>. 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 the documents not listed in the DODISS are the issues of the documents cited in the solicitation (see 6.2).

ELECTRONIC INDUSTRIES ASSOCIATION/TELECOMMUNICATIONS INDUSTRIES ASSOCIATION (EIA/TIA)

EIA/TIA-440-A -	Fiber Optic Terminology.
EIA/TIA-455-30 -	Frequency Domain Measurement of Multimode Optical Fiber Information Transmission Capacity.
EIA/TIA-455-34 -	Interconnection Device Insertion Loss Test.
EIA/TIA-455-46 -	Spectral Attenuation Measurement for Long-Length, Graded-Index Optical Fibers.
EIA/TIA-455-50 -	Light Launch Conditions for Long-Length Graded-Index Optical Fiber Spectral Attenuation Measurements.
EIA/TIA-455-51 -	Pulse Distortion Measurement of Multimode Glass Optical Fiber Information Transmission Capacity.
EIA/TIA-455-54 -	Mode Scrambler Requirements for Overfilled Launching Conditions to Multimode Fibers.
EIA/TIA-455-126-	Spectral Characterization of LEDs.
EIA/TIA-455-127-	Spectral Characterization of Multimode Laser Diodes.
EIA/TIA-455-168-	Chromatic Dispersion Measurement of Multimode Graded-Index and Single-Mode Optical Fibers by Spectral Group Delay Measurement in the Time Domain.
EIA/TIA-455-177-	Numerical Aperture Measurement of Graded-Index Optical Fibers.
EIA/TIA-455-180-	Measurement of the Optical Transfer Coefficients of a Passive Branching Device (Coupler).
EIA-458-A -	Standard Optical Waveguide Fiber Material Classes and Preferred Sizes.
EIA/TIA-526-4 -	Optical Eye Pattern Measurement Procedure.
EIA/TIA-526-10 -	Measurement of Dispersion Power Penalty in Digital Single-Mode Systems.
EIA/TIA-526-11 -	Measurement of Single-Reflection Power Penalty for Fiber Optic Terminal Equipment.

EIA/TIA-526-14 -	Optical Power Loss Measurements of Installed Multimode Fiber Cable Plant.
EIA/TIA-526-16 -	Jitter Transfer Function Measurement.
EIA/TIA-526-17 -	Output Jitter Measurement.
EIA/TIA-526-18 -	Systematic Jitter Generation Measurement.

(Application for copies should be addressed to the EIA/TIA, Engineering Department, 2001 Pennsylvania Avenue, Washington, DC 20006.)

(Non-Government standards and other publications are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.)

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

3. DEFINITIONS

3.1 General fiber optics terms. Definitions for the fiber optic terms used in this standard are in accordance with EIA-440-A Fiber Optic Terminology. Definitions for general telecommunications terms used in this standard are in accordance with FED-STD-1037 Glossary of Telecommunications Terms. Definitions for other terms as they are used in this standard are given in the following paragraphs.

3.1.1 Cable transient loss. The difference between the total cable attenuation for an overfilled launch (EIA/TIA-455-54) and the total cable attenuation for a restricted launch (EIA/TIA-455-50) along the length of the cable.

3.1.2 Failure rate. The expected number of failures of a component or link in a given time period. The failure rate is represented by λ.

3.1.3 Fiber exit bandwidth. The value numerically equal to the lowest frequency at which the magnitude of the modulation transfer function of the combination of the optical source and optical fiber decreases to one-half of the zero frequency value.

3.1.4 Fiber optic cable plant (FOCP). The fiber optic cable plant is the portion of the fiber optic topology made up of the trunk cables and interconnection boxes.

3.1.5 Fiber optic local cable. A fiber optic local cable provides a continuous optical path between an end user equipment and interconnection box, and is typically not run through the main cableways.

3.1.6 Fiber optic trunk cable. A fiber optic trunk cable provides a continuous optical path between fiber optic interconnection boxes in the FOCP. Typically, trunk cables are run in the main cableways and have higher fiber counts per cable than local cables.

3.1.7 Fiber optic topology. The fiber optic topology consists of fiber optic interconnection boxes, trunk and local cables and the connectors and splices used to interconnect the trunk and local cables.

3.2 Acronyms. The following acronyms are used in this standard:

a. AMI	Alternate Mark Inverted
b. APC	Automatic Power Control
c. APD	Avalanche Photodiode

d.	BER	Bit Error Rate
e.	BW	Bandwidth
f.	CPR	Coupler Power Ratio
g.	dB	decibels
h.	dBm	decibels referenced to one milliwatt
i.	DIP	Dual Inline Package
j.	DODISS	Department of Defense Index of Specifications and Standards
k.	ECL	Emitter Coupled Logic
l.	EIA	Electronics Industry Association
m.	ELED	Edge Emitting Light Emitting Diode
n.	FBT	Fused Biconical Taper
o.	FDDI	Fiber Distributed Data Interface
p.	FET	Field Effect Transistor
q.	FOCP	Fiber Optic Cable Plant
r.	FWHM	Full Width Half Maximum
s.	LAN	Local Area Network
t.	LED	Light Emitting Diode
u.	LPS	Limited Phase Space
v.	MPN	Mode Partition Noise
w.	MPD	Mode Power Distribution
x.	MTBF	Mean Time Before Failure
y.	NA	Numerical Aperture
z.	NRZ	Non-Return to Zero
aa.	OD	Outside Diameter
ab.	OFCC	Optical Fiber Cable Component
ac.	OFL	Overfilled Launch
ad.	OTDR	Optical Time Domain Reflectometer
ae.	PC	Physical Contact
af.	PIN	Positive Intrinsic Negative
ag.	PINFET	Positive Intrinsic Negative Field Effect Transistor
ah.	RMS	Root Mean Square
ai.	RZ	Return to Zero
aj.	RZ-PDM	Return to Zero Pulse Duration Modulation
ak.	RZ-PPM	Return to Zero Pulse Position Modulation
al.	SAFENET	Survivable Adaptable Fiber Optic Embedded Network
am.	SIP	Single Inline Package
an.	SLD	Superluminescent Light Emitting Diode
ao.	SLED	Surface Emitting Light Emitting Diode
ap.	SNR	Signal to Noise Ratio
aq.	SR	Single Reflection
ar.	TE	Thermoelectric
as.	TIA	Telecommunications Industry Association
at.	TO	Transistor Outline
au.	TTL	Transistor-Transistor Logic
av.	WDM	Wavelength Division Multiplexing

3.3 <u>Design equation variables</u>. The following variables are used in this standard:

a. t_s - transmitter rise time
b. $BW_{s(-3)}$ - transmitter -3 dB bandwidth
c. $BW_{cm(-6)}$ - estimated cable modal bandwidth
d. BW_{mc} - normalized fiber modal bandwidth (-6 dB, measured by the fiber manufacturer)
e. L_c - installed fiber length
f. γ - fiber length scaling factor
g. t_{cd1} - the rise time associated with the first order fiber chromatic dispersion impulse response
h. σ_λ - transmitter RMS spectral width
i. D - fiber dispersion at the transmitter centroid wavelength
j. t_{cd2} - rise time associated with the second order fiber chromatic dispersion impulse response
k. S - fiber dispersion slope at the transmitter centroid wavelength
l. λ_0 - fiber zero dispersion wavelength
m. λ_c - transmitter centroid wavelength
n. S_0 - fiber dispersion slope at the fiber zero dispersion wavelength
o. λ_{FWHM} - the FWHM center wavelength of the source
p. σ_{FWHM} - the FWHM spectral width of the source
q. t_r - receiver rise time
r. $BW_{r(-3)}$ - receiver -3 dB bandwidth
s. t_T - total optical link rise time
t. $BW_{T(-3)}$ - total optical link -3 dB bandwidth
u. E - bit rate to baud conversion factor
v. $BW_{ex(-3)}$ - transmitter/cable exit bandwidth
w. L_x - calculated component loss value
x. $L_{x(LPS)}$ - component LPS loss value
y. $L_{x(OFL)}$ - component OFL loss value
z. $L_{x(RES)}$ - component RES loss value
aa. R_S - difference between total power and low order mode power
ab. R_{RES} - restricted launch power
ac. R_{OFL} - overfill launch power
ad. K - source/fiber mode power distribution constant
ae. T - transient cable loss
af. P_T - mean transmitter output power
ag. σ_T - standard deviation of the transmitter output power
ah. P_R - mean receiver sensitivity

ai. σ_R - standard deviation of the receiver sensitivity

aj. M - safety margin for unexpected losses

ak. μ_E - mean environmental margin for adverse operating conditions

al. σ_E - standard deviation of the environmental margin for adverse operating conditions

am. A - adjustments to the link loss budget

an. l_{jc} - total jumper cable length

ao. μ_{jc} - mean jumper cable attenuation

ap. σ_{jc} - standard deviation of the jumper cable attenuation

aq. l_T - total multifiber cable length

ar. l_c - average multifiber cable length

as. μ_c - mean multifiber cable attenuation

at. σ_c - standard deviation of the multifiber cable attenuation

au. μ_λ - the increase in mean cable attenuation above μ_c at the wavelength within the transmitters center wavelength range at which the largest mean plus two σ loss occurs

av. N_{co} - the total number of connectors

aw. μ_{co} - mean connector loss

ax. σ_{co} - standard deviation of the connector loss

ay. N_s - the total number of splices

az. μ_s - the mean splice loss

ba. σ_s - standard deviation of the splice loss

bb. N_o - number of other passive devices of one type

bc. μ_o - mean loss of other passive devices of one type

bd. σ_o - standard deviation of the other passive devices of one type

be. μ_{RJC} - mean radiation induced jumper cable attenuation

bf. σ_{RJC} - standard deviation of the radiation induced jumper cable attenuation

bg. μ_{RC} - mean radiation induced multifiber cable attenuation

bh. σ_{RC} - standard deviation of the radiation induced multifiber cable attenuation

bi. μ_{RCO} - mean radiation induced connector loss

bj. σ_{RCO} - standard deviation of radiation induced connector loss

bk. μ_{RS} - mean radiation induced splice loss

bl. σ_{RS} - standard deviation of the radiation induced splice loss bm. μ_{RO} - mean radiation induced loss of other components

bn. σ_{RO} - standard deviation of the radiation induced loss of other components

bo. P_{Rmax} - maximum power available at the receiver

bp. P_D - dispersion power penalty

bq. P_{MPN} - mode partition noise penalty

br. DJ_T - total deterministic jitter

bs. DJ_{in} - input deterministic jitter

bt. DJ_{TX} - transmitter deterministic jitter

bu. DJ_f - fiber deterministic jitter

bv. DJ_{RX} - receiver deterministic jitter

bw. RJ_T - total random jitter

bx. RJ_{in} - input random jitter

by. RJ_{TX} - transmitter random jitter

bz. RJ_{RX} - receiver random jitter

ca. t_{ca} - total transmitter/cable exit rise time

cb. J_T - total output jitter

cc. π_T - temperature derating factor

cd. π_Q - quality derating factor

ce. λ_F - fiber optic cable, light duty connector, heavy duty connector, single fiber splice, cable splice, or optical switch, failure rate

cf. λ_b - base optical fiber failure rate

cg. π_E - environmental derating factor

ch. π_n - number of fibers in the cable

ci. π_K - mating/unmating derating factor

cj. π_P - active termini derating factor

ck. π_c - number of switch states

4. GENERAL REQUIREMENTS

4.1 General. This section provides general information and requirements for designing a fiber optic system. General information for those link designers who may not be familiar with the performance details of different types of fiber optic components and their associated tradeoffs is given in 4.2. Guidance and requirements for the physical design of equipment with internal fiber optic links and external fiber optic interfaces are given in 4.3 and 4.4.

4.2 Optical fibers and fiber optic components.

4.2.1 Optical fiber. This section provides a general comparison of several different standard multimode fiber sizes. Since the optical fiber used in typical fiber optic links is in cabled form, the performance values discussed in this section are representative of cabled fibers and will be explicitly noted as such. Common applications of optical fibers include deployment in high data rate, fiber based local area networks such as the Fiber Distributed Data Interface (FDDI) or the Survivable Adaptable Fiber Optic Embedded Network (SAFENET), and in point-to-point fiber optic links.

4.2.1.1 Construction. The basic structure of an optical fiber consists of a center core which is surrounded by an outer layer called the cladding (see figure 1). The core and cladding materials constitute the light-guiding structure. The cladding material has a lower index of refraction than that of the center core material to achieve internal reflection of the light rays. The cladding may be coated with other materials (generally polymers) to provide physical protection, increased product strength, or isolation from external mechanical forces and moisture. Fibers coated with this additional material are called buffered fibers. Navy standard sizes for buffered fibers are 250 and 900 micrometer (μm). For single mode fiber, the core has a constant index of refraction over the entire core area. For multimode fiber, the index of refraction of the core glass may be constant (step index) or may vary over the core area (graded index). For graded index multimode optical fibers, the core has a graduated index of refraction which is highest at the center of the core and equal to the index of refraction of the cladding at the core/cladding interface. For a graded index multimode optical fiber, a plot of the index of refraction versus radial position (called an index profile) is approximately parabolic. The exact shape of the index profile is controlled by the fiber manufacturer to maximize the bandwidth of the multimode fiber (see figure 2).

4.2.1.2 Relative performance characteristics. A number of fiber sizes are commercially available, but only two are recognized as standard sizes by the Navy. These are the 62.5 μm core multimode

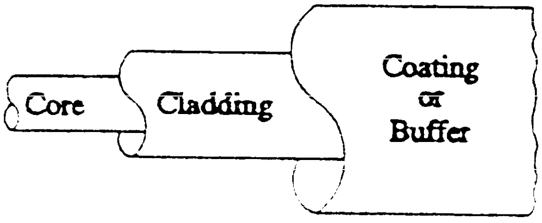

FIGURE 1. Optical fiber structure.

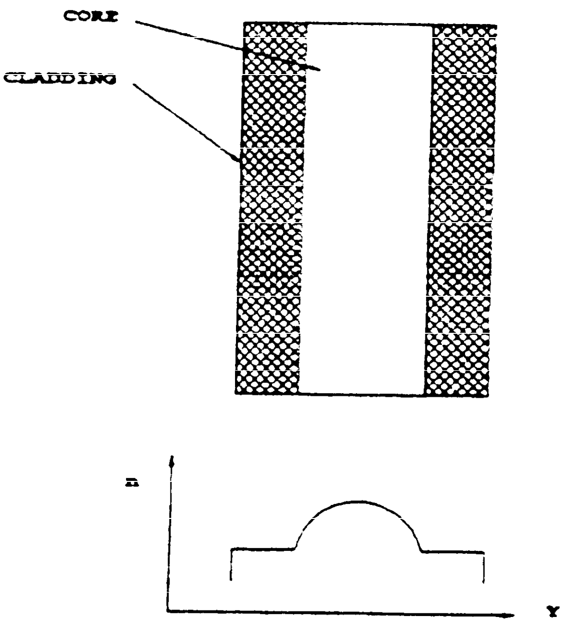

FIGURE 2. Typical index profile for graded index multimode fiber.

fiber (per MIL-F-49291/6) and the 8.5 to 10.1 μm single mode fiber (per MIL-F-49291/7). The Navy standard fibers and the most widely used commercial fiber sizes are shown in table I.

TABLE I. Navy standard and commercial fiber sizes.

Core Diameter (μm)	Cladding Diameter (μm)	Numerical Aperture
8.5 to 10.0 (Navy standard, single mode)	125	N/A
50 (Commercial)	125	0.20
62.5 (Navy standard, multimode)	125	0.275
100 (Commercial)	140	0.29

4.2.1.2.1 Single mode fiber. The single mode fiber is the most widely used fiber in the commercial telephone trunk market. When used with a laser source, this fiber has an extremely high bandwidth capability (many times that of any multimode fiber). However, the use of this size fiber requires a laser source which may be undesirable in some cases (see 4.2.8.1.2). Additionally, this fiber has high connection losses (despite requiring tighter tolerances on connection hardware) and requires highly skilled personnel for installation and repair.

4.2.1.2.2 62.5/125 μm multimode fiber. The 62.5/125 μm fiber is the Navy standard multimode fiber. This fiber has much lower bend sensitivity than other fiber sizes while still having a relatively high numerical aperture, low cabled attenuation rate (1.2 decibels per kilometer (dB/km) typical at 1300 nm), and high modal bandwidth (500 megahertz (MHz)·km typical at 1300 nm).

4.2.1.2.3 50/125 μm multimode fiber. The 50/125 μm fiber has the highest modal bandwidth (800 MHz·km typical at 1300 nm) and a low cabled attenuation rate (1.2 dB/km typical at 1300 nm). This fiber was the first to be used in the telephone network and is used primarily in longer distance applications in private-premise networks. The primary disadvantages of this fiber size are low numerical aperture, higher connector losses and moderate bend sensitivity.

4.2.1.2.4 100/140 μm multimode fiber. The 100/140 μm fiber is able to couple the most power into the fiber from LED sources and requires the least precision for connectors and splices. It is typically used for short-length computer links and networks. The primary disadvantages of this fiber size are the low modal bandwidth (400 MHz·km typical at 1300 nm) and moderate bend sensitivity. Also, the 100/140 μm fiber requires different connectors and splices than the other fibers because of its larger diameter.

4.2.1.2.5 Performance comparison. The relative performance characteristics of the common commercial multimode fiber sizes can be summarized as shown in table II. The limits shown in table II are typical values for cabled fiber performance. Several grades of fiber optic cables with different attenuation rates and bandwidths can be acquired from cable manufacturers. The typical performance of the Navy standard multimode optical fiber may be different than the limits in table II. Additional information on the relative performance of different multimode fiber sizes can be found in 6.3a, b and c.

4.2.1.3 Attributes. There are five fiber related attributes which affect system performance: coupling efficiency to the optical source, attenuation rate, bend sensitivity, alignment sensitivity at fiber connections, and bandwidth. The input coupling efficiency, attenuation rate and alignment sensitivity are determined by the fiber size and affect the link loss budget. The bend sensitivity of the fiber affects the installed cable attenuation, the link loss budget and may affect cable installation procedures.

TABLE II. Cabled multimode optical fiber performance comparison.

Attribute	Fiber Size					
	50/125 μm		62.5/125 μm		100/140 μm	
	850 nm	1300 nm	850 nm	1300 nm	850 nm	1300 nm
Typical Cabled Fiber Attenuation (dB/km)	3.2	1.2	3.2	1.2	4.5	1.5
Bend Sensitivity	Average		Best		Worst	
Typical Cabled Fiber Modal Bandwidth[1/] (MHz·km)	500	800	300	500	200	400
Alignment Sensitivity and Input Coupling Efficiency	Worst		Good		Best	

[1/] When optical fibers are manufactured, their bandwidth is measured and the fibers sorted into groups (referred to as cells) based on the measured bandwidth. The fiber manufacturer warrants that any product within a cell will meet the minimum bandwidth specified for that particular cell. In many cases, the bandwidth specified for a cabled fiber is the minimum specified bandwidth for the bandwidth cell to which the fiber belonged and may be lower than the actual bandwidth of the cabled fiber. Bandwidth calculations (see section 5) based on fiber bandwidth cell minimum specifications will yield conservative link bandwidth predictions.

4.2.1.3.1 Attenuation. The attenuation of a fiber is a function of wavelength. For multimode fiber links, operating wavelengths in the first transmission window (850 ± 50 nm) and the second transmission window (1300 ± 50 nm) are typically used. In single mode fiber links, operating wavelengths in the second transmission window and the third transmission window (1550 ± 50 nm) are typically used. The second transmission window is the standard window for Navy communication links for either multimode or single mode fiber. A typical spectral attenuation curve for a cabled fiber is shown in figure 3.

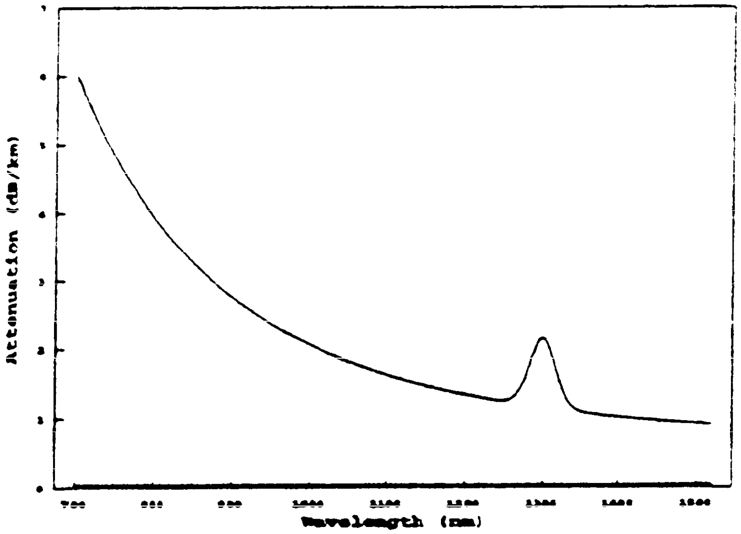

FIGURE 3. Typical cabled optical fiber spectral attenuation.

4.2.1.3.2 Fiber bandwidth. For multimode fiber, the fiber bandwidth is a function of the modal distortion (modal bandwidth), the chromatic dispersion (see 5.4) and the source spectral width. For single mode fiber, the fiber bandwidth is a function of the chromatic dispersion and the source spectral width. The chromatic dispersion of a multimode fiber has a zero dispersion wavelength in the 1300 nm window (see figure 4). The chromatic dispersion of a standard single mode fiber has a zero dispersion wavelength in the second window between 1290 and 1330 nm. Fiber exit bandwidth can be optimized by using an operating wavelength near this zero chromatic dispersion point, minimizing the source's spectral width, minimizing the cable length, or minimizing the source's rise and fall times (see 5.4).

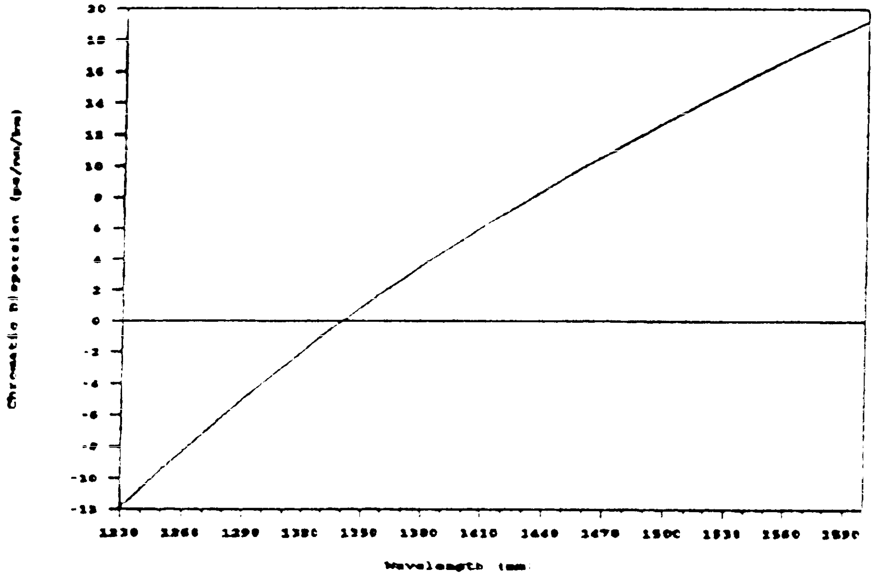

FIGURE 4. Typical optical fiber chromatic dispersion.

4.2.1.4 Applicability. Optical fibers used in Navy tactical applications shall be in accordance with MIL-F-49291, MIL-F-49291/6 and MIL-F-49291/7. All multimode fibers used in Navy nontactical applications shall be compatible with the Navy standard 62.5/125 μm multimode fiber.

4.2.2 Fiber optic cable. The design of a fiber optic cable influences optical performance, environmental and mechanical performance, human factors, and safety. The following paragraphs discuss the structure of four common commercial fiber optic cable designs and the benefits and drawbacks of each of those designs. The designs are the Breakout, Stranded, Loose Tube and Ribbon designs.

4.2.2.1 Cable construction.

4.2.2.1.1 Breakout design. A Breakout design fiber optic cable consists of individual single fiber cables, called Optical Fiber Cable

Components (OFCCs), laid with strength members around a central member and overjacketed for environmental and mechanical protection (see figure 5). Each OFCC consists of a buffered fiber (900 μm total diameter) surrounded by strength members and a protective jacket with an outer diameter of approximately 2 millimeters. The breakout design cable is typically used as local cabling in commercial intrabuilding applications. This cable design is currently the only cable design approved for Navy fiber optic cables and is in accordance with MIL-C-85045, MIL-C-85045/13 (eight-fiber cable, thermoplastic jacket), MIL-C-85045/15 (four-fiber cable, thermoplastic jacket), MIL-C-85045/16 (single-fiber tight buffer cable, thermoplastic jacket) MIL-C-85045/17 (eight-fiber cable, cross-linked jacket) and MIL-C-85045/18 (four-fiber cable, cross-linked jacket).

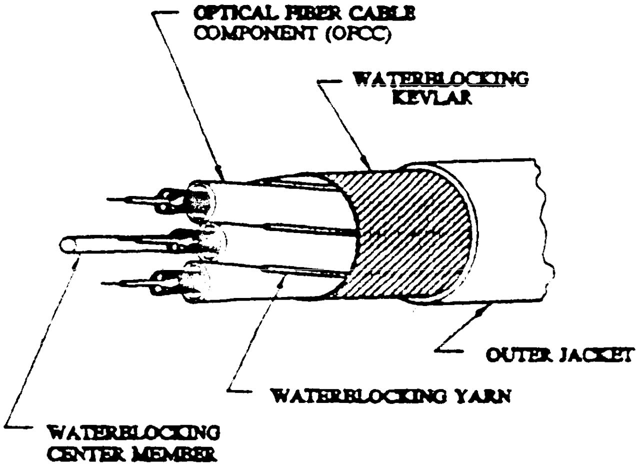

FIGURE 5. OFCC (Breakout) design fiber optic cable.

4.2.2.1.2 Stranded design. A Stranded design cable is a fiber optic cable in which the buffered fibers (900 μm total diameter) are stranded down the center of the cable surrounded by strength members and a protective jacket (see figure 6). This cable design is typically used in commercial inter- and intrabuilding trunk applications.

4.2.2.1.3 Loose Tube design. A Loose Tube cable is a fiber optic cable in which 250 μm coated fibers are loosely grouped in tubes or slots which are stranded down the cable. The tubes are grouped with strength members and surrounded with a protective jacket. This design is typically used in commercial long-haul telephone trunk applications.

4.2.2.1.4 Ribbon design. The Ribbon cable design is a variant

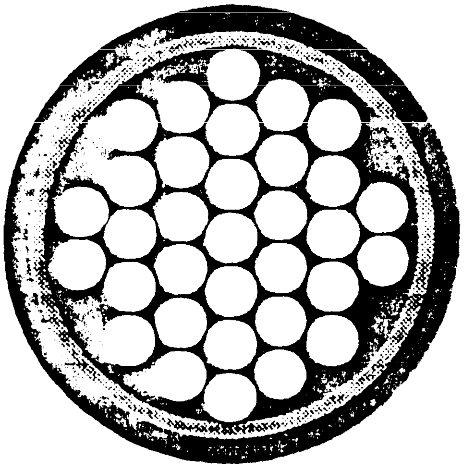

FIGURE 6. Stranded design fiber optic cable.

of the loose tube design in which multiple 250 μm coated fibers (typically 12 each) are sandwiched in a linear array, called a ribbon, and laid in a loose tube down the center of the cable (see figure 7). The ribbons are surrounded by an inner plastic tube, strength members, and an outer protective jacket.

4.2.2.2 Relative performance characteristics. Any cable used in Navy applications must meet minimum levels of performance in safety (low smoke generation, low toxicity, low halogen content, flame

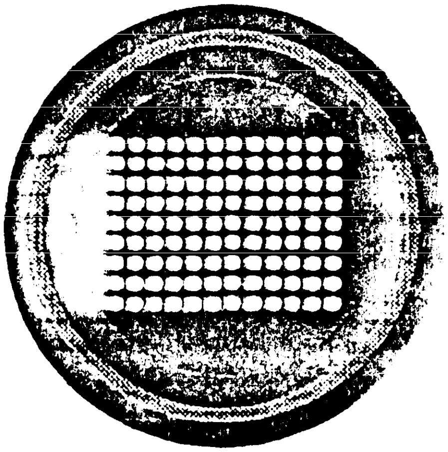

FIGURE 7. Ribbon design fiber optic cable.

resistant, and so forth), durability (able to withstand shock, vibration, mechanical abuse, fluids, and so forth), human factors (ease of installation and repair), and optical performance. The base optical performance of a particular cable design is determined by the optical fiber used and is not a primary consideration in choosing the cable design.

4.2.2.2.1 Safety. The safety performance of a cable is a function of the materials used to manufacture the cable. If appropriate materials are used to manufacture the cable, then the cable will meet the necessary safety requirements. Currently, only the OFCC design cables are manufactured using appropriate materials.

4.2.2.2.2 Durability. Each of the designs can be very durable when properly manufactured. The primary exceptions are the bending and waterblocking performance of the Ribbon cable design and the waterblocking performance of both the Stranded and Loose Tube designs. Table III shows the dynamic bend performance of the four cable designs. The cable's minimum dynamic bend radius is equal to the cable's outside diameter (OD) multiplied by the factor given in table III. The Ribbon cable design has the greatest limitations on bend performance of the four cable designs. Additionally, the Ribbon and Loose Tube cable designs manufactured commercially are not waterblocked with suitable materials (for example, nongreasy, nontacky, and so forth). The thermal and mechanical performance of both of these cable designs would be adversely affected by the use of appropriate compounds. The Stranded design cable is generally not waterblocked in commercial applications. This cable design can be waterblocked, but the effect of the waterblocking on the cable's thermal or mechanical performance is unknown.

TABLE III. Bend performance of fiber optic cable designs.

Cable Design	Minimum Dynamic Bend Radius (Cable OD Multiplier)
Breakout (OFCC)	4
Stranded	4 to 6
Loose Tube	6 to 10
Ribbon	10

4.2.2.2.3 Human factors. The human factor elements for the designs vary widely. The primary area of concern for human factors is in the breakout of individual fibers in the cable plant interconnection boxes or system equipments. The OFCC design is the most suitable for Navy applications because each fiber is protected within its own subcable. In the Stranded design, the individual fibers are more susceptible to accidental damage since they are not protected in an OFCC. In the Loose Tube and Ribbon designs, the individual fibers show a high susceptibility to damage when broken out of the tube or separated from the ribbon.

4.2.2.3 Fiber capacities. The total fiber capacities for the various designs vary widely. The Loose Tube and Ribbon cable designs have the greatest capacity, being able to hold over 200 fibers in a 0.5 inch diameter cable. For the same size cable, the Stranded design can accommodate approximately 48 fibers and the OFCC design can accommodate approximately 12 fibers. OFCC design cables with diameters in excess of 0.5 inch with more than 12 fibers are available commercially and could be modified for use in Navy applications.

4.2.2.4 Applicability. Because of the ease of use and the high degree of ruggedness, the OFCC cable is currently the standard Navy design for low density shipboard applications (eight fibers or less per cable). Higher density cables are in development, but products are not currently available. All fiber optic cables used in Navy shipboard applications shall be in accordance with MIL-C-85045. The NAVSEA Fiber Optic Program Office should be consulted to determine the specification sheets that are approved for use. The Loose Tube and Ribbon cable designs are not suitable for general Navy use because of their limitations in the areas of mechanical performance and human factors. The Stranded design is not suitable for Navy shipboard use because it does not meet the waterblocking requirements.

4.2.3 Connectors. Connectors are found in almost all fiber optic links. Common applications are at transmitter and receiver to cable plant connections, equipment connections and fiber-to-fiber connections in interconnection boxes. Connectors may connect only one pair of fibers together (single terminus connectors) or may connect multiple pairs of fibers (multiterminus connectors). For Navy shipboard applications, connectors are grouped into two classes; light duty single terminus connectors and heavy duty multiterminus connectors. Light duty connectors are used only in protected areas such as within equipment interiors and within fiber optic interconnection boxes. Heavy duty connectors are used in unprotected locations such as external equipment connectors.

4.2.3.1 Construction and relative performance characteristics. The basic structure of a fiber optic connector consists of two mechanical assemblies, one attached to each fiber end; and an alignment assembly. The alignment assembly physically positions the fibers in proximity so that light transmission may occur across the interface. There are many different types and styles of commercial fiber optic connectors available. Basic connector types include cylindrical ferrule, v-groove, biconic, and lensed connectors. SMA, ST, FC/PC, Biconic, and SC connectors are the most common commercial single terminus connectors. The Fiber Distributed Data Interface (FDDI), SC Duplex, and ESCON connectors are the most common commercial duplex connectors.

4.2.3.1.1 ST Connector. The commercial ST connector is the basis of the MIL-C-83522 and MIL-C-83522/16 Navy standard single terminus light duty connector. The ST is a cylindrical ferrule connector and has a bayonet style coupling mechanism (see figure 8). The fiber is epoxied into the ferrule using a heat-cured epoxy and the fiber end face is finely polished. Refer to MIL-STD-2042/5 for more information on the assembly and installation of MIL-C-83522/16 connectors. The ST type connector was chosen as the Navy standard light duty single terminus connector because of its ease of assembly, quick connect/disconnect time, ruggedness and high-grade optical performance. The performance of the ST is equal to, or superior to, that of the other connector types with the exception that the ST is typically more shock sensitive than those styles with screw on type coupling mechanisms.

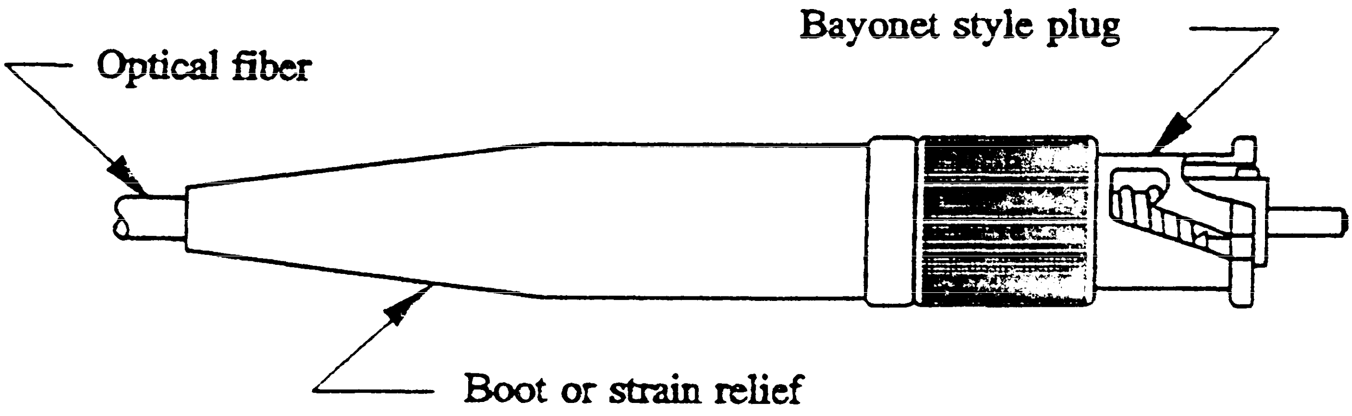

FIGURE 8. Navy standard single terminus light duty connector.

4.2.3.1.2 FSMA and FC/PC connectors. The FSMA and the FC/PC connectors are also cylindrical ferrule connectors, but both have a screw on type coupling mechanism. The FSMA connector typically has high optical loss and poor repeatability, making it unsuitable for Navy use. The FC/PC connector was developed for single mode applications, but has found use in commercial multimode systems as well. This connector has the best optical and mechanical performance of the connectors commercially available, but is difficult to assemble, has a relatively long disconnect/reconnect time and requires larger separation distances on patch panels than either the ST or SC connectors.

4.2.3.1.3 Biconic connector. The biconic connector has a conical ferrule and is used commercially for both single mode and multimode fibers in telephone applications. This connector is larger than the other commercial connector styles, can be difficult to assemble in the field, and requires larger separation distances on patch panels than either the ST or the SC connectors.

4.2.3.1.4 SC connector. The SC connector is a newly developed commercial connector having a push/pull style coupling mechanism and a square footprint. This connector was developed to maximize connector densities at connector patch panels and equipment backplanes and minimize disconnect/reconnect time and difficulty. However, this connector typically is constructed of plastics and has unknown environmental performance, especially at high shock levels.

4.2.3.1.5 Multiterminus connector. The Navy standard heavy duty multiterminus connector, the MIL-C-28876 connector, is a cylindrical ferrule connector based on the MIL-C-28840 Navy electrical connector (see figure 9). This connector is a keyed, mechanically rugged, strain relieved and environmentally sealed connector. Currently the MIL-C-28876 connector can terminate cables with two, four, six, and eight fibers. Each fiber is terminated to a separate ferrule assembly, called a terminus, which is held in the insert within the connector shell. The fibers are epoxied into each terminus using a heat-cured adhesive and the ends are finely polished. Refer to MIL-STD-2042/5 for more information on the assembly and installation of MIL-C-28876 connectors. When plug and receptacle MIL-C-28876 connectors are mated, the pin and socket termini in each mating receptacle or plug engage with their corresponding socket and pin termini to align the mating fibers. The MIL-C-28876 connector was chosen as the Navy standard heavy duty multiterminus connector because of its superior mechanical properties, environmental resistance, and high-grade optical performance.

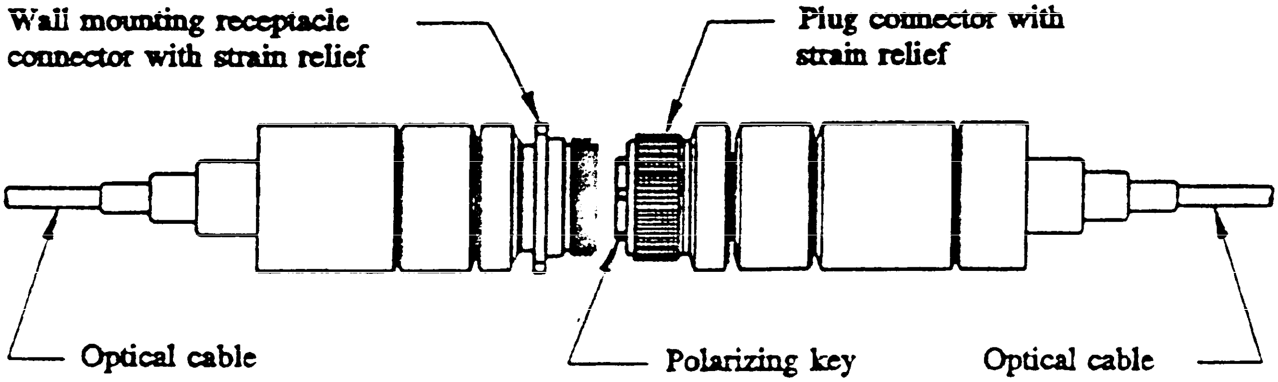

FIGURE 9. Multiterminus (MIL-C-28876) connector.

4.2.3.1.6 FDDI, SC Duplex and ESCON connectors. Both the FDDI and the ESCON connectors are integral units developed for use in datacom and local area network (LAN) applications. The SC duplex connector is commonly produced by ganging two simplex SC connectors in a duplex housing. All three connector types use 2.5 mm ferrule technology, as do the ST, FC/PC, and SC simplex connectors. All three connector types are polarized to prevent reversal of the transmit and receive fibers and can be keyed to prevent connector insertion into incorrect receptacles.

4.2.3.2 Attributes. There are several attributes that describe connector performance: connection loss, back reflection, repeatability, minimum connector to connector spacing on patch panels, disconnect/reconnect time, difficulty of assembly and ruggedness. The connection loss and repeatability affect the link loss budget. The back reflection affects the performance of optical time domain reflectometers (OTDRs) used in link diagnostics and the link source performance if a laser is used. The ruggedness of the connector affects the link reliability and may affect the link loss budget. The minimum connector to connector spacing affects the physical layout of connectors in the link on patch panels or on equipment. The disconnect/reconnect time affects the time required to perform cable plant reconfigurations and the difficulty of assembly affects the installation and repairability of the link and the level of training required for installation and maintenance personnel.

4.2.3.2.1 Connection loss and back reflection. Each connector in a fiber optic link introduces both an optical loss into that link and a reflected signal back through the link. The loss occurs because of fiber mismatches as well as connector specific losses including Fresnel reflections at the interface, lateral and angular misalignment, and in some cases, fiber separation. Each different connector type/style minimizes each of the connection related loss mechanisms to some extent. As for the reflected signal introduced by each connector in the link, many of the commonly available connectors are polished so as to minimize this reflection (the physical contact (PC) polish). This polishing technique reduces back reflection from the connector, and connector loss. Loss and back reflections are the primary optical effects from the use of a connector in a fiber optic link.

4.2.3.3 Applicability. Light duty single terminus connectors used in Navy tactical applications shall be in accordance with MIL-C-83522, MIL-C-83522/16 (connector plug), MIL-C-83522/17 (plug adapter), and MIL-C-83522/18 (active device mount). Heavy duty multiterminus connectors used in Navy shipboard applications shall be in accordance with MIL-C-28876 and supporting specification sheets. Light duty connectors used in Navy nontactical applications shall be compatible with MIL-C-83522/16 connectors.

4.2.4 Splices. Splices are also found in many fiber optic links. Common applications are permanent fiber-to-fiber connections in wiring closets and cable repair connections. Splices may connect only one pair of fibers together (single fiber splices) or may connect multiple pairs of fibers (multifiber cable splices). For Navy shipboard applications splices are grouped into two classes: light duty single fiber splices and multifiber cable splices. Light duty single fiber splices are used only in protected areas such as equipment interiors and within fiber optic interconnection boxes or cable splice closures. Light duty single fiber splices used in Navy tactical and nontactical applications shall be in accordance with MIL-S-24623 and MIL-S-24623/4. Multifiber cable splices are used in unprotected areas, such as the cableways or overheads, for the repair of multifiber cables. The multifiber cable splice consists of a cable splice closure and multiple light duty single fiber splices. Multifiber cable splice closures used in Navy tactical and non-tactical applications shall be in accordance with MIL-S-24623 and MIL-S-24623/5.

4.2.4.1 Splice types. The styles of fiber optic splices which are the most common in the commercial market change continually. Fusion and elastomer sleeve splices were among the first developed. Fusion splices are typically used in long haul, telephone outside plant, and other applications where many splices are used and splice equipment costs can be spread out over many connections. To obtain quality fusion splices, highly trained personnel and expensive automated fusion splicing equipment are required. Mechanical splices are commercially used in applications where splice quantities are not as high and the initial investment for a fusion splicer is prohibitive. Most mechanical splices use either index matching gel or index matching adhesive to minimize back reflection and attenuation.

4.2.4.2 Construction and performance characteristics. In a fusion splice, the fibers are fused together to form a single continuous waveguide and placed in a protective holder. For mechanical splices, the basic structure of the fiber optic splice consists of a mechanical assembly that physically positions the fiber ends in close proximity so that light transmission may occur across the interface. There are many different varieties of mechanical fiber optic splices available, the most common being glass capillary, glass rod, and elastomer sleeve splices.

4.2.4.2.1 Light duty single fiber splice. Glass capillary mechanical splices are the most common commercial mechanical splices. This type of splice has low losses and low back reflections. The recommended single fiber splice for Navy light duty applications (per MIL-S-24623/4) is a glass capillary mechanical splice, known as a rotary mechanical splice. This splice consists of two identical precision glass capillaries (ferrules) which hold each fiber end (see figure 10). The fibers are epoxied in each ferrule with an ultraviolet (UV) curable adhesive and then the ferrule ends are polished. The ferrules are mated together using a metal alignment clip and index matching gel. Refer to MIL-STD-2042/5 for more information on the assembly and installation of the MIL-S-24623/4 splice. The MIL-S-24623/4 rotary mechanical splice was chosen as the

Navy standard light duty single fiber splice because of its ease of assembly, ruggedness, high-grade optical performance, and remateability.

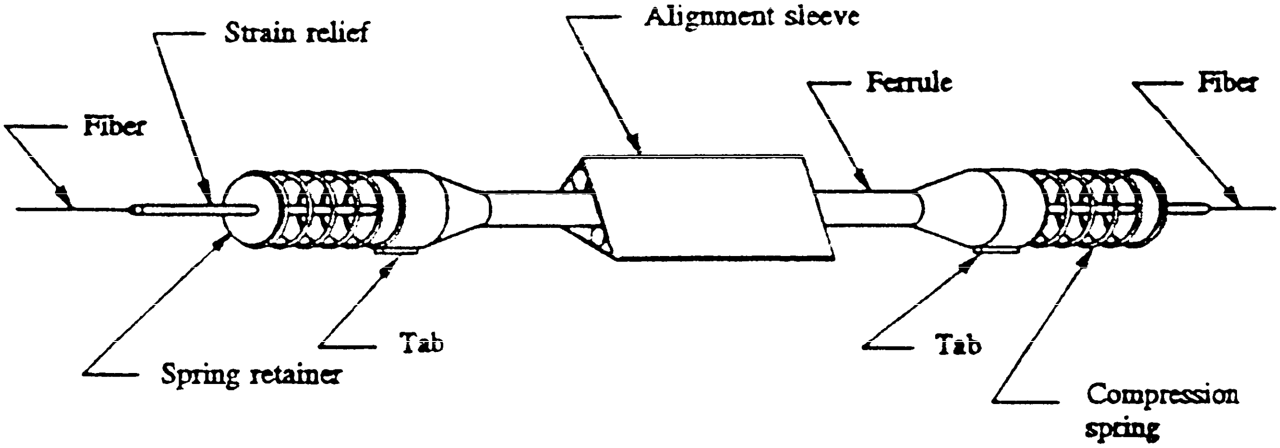

FIGURE 10. Rotary mechanical splice.

4.2.4.2.2 Multifiber cable splice. In commercial applications, multifiber cable splice closures are large housings, typically the size of small interconnection boxes. These types of cable splice closures are not suitable for use in cableways or crowded overheads. The MIL-S-24623/5 multifiber cable splice closure was developed with a small size to allow multifiber cable splicing at almost any installed cable location. The MIL-S-24623/5 multifiber cable splice closure is approximately 8.5 inches in length and 1.4 inches in diameter and can hold up to eight MIL-S-24623/4 single fiber splices.

4.2.4.3 Attributes. There are several attributes that describe splice performance: splice loss, back reflection, re-enterability, remateability, time/skill to assemble and ruggedness. Splice loss affects the link loss budget. Back reflection affects the performance of OTDRs used in link diagnostics and the link source performance if a laser is used. Ruggedness of the splice affects the link reliability, the type of enclosure that the splice must be housed in and may affect the link loss budget. Re-enterability and the remateability of the splice affect the types of maintenance actions possible for maintenance personnel. Time/skill to assemble, reenterability, and remateability affect the installation and repairability of the link and the level of training required for installation and maintenance personnel.

4.2.4.3.1 Splice loss and back reflection. Each splice in a fiber optic link introduces both an optical loss into that link and a reflected signal back through the link. The loss mechanisms for a fiber optic splice are similar to those for a fiber optic connector (see 4.2.3.2.1). Each different type/style minimizes each of these loss mechanisms to some extent. Most of the commonly available mechanical splices utilize an index matching gel or epoxy to minimize the back reflection. As with connectors, the reduction of the back reflection from the splice also reduces the splice loss. Loss and back reflection are the primary optical effects from the use of a splice in a fiber optic link.

4.2.5 Fiber optic switches. Fiber optic switches are primarily used in local area networks (LANs) as failsafe bypasses for equipment. Fiber optic switches for use in Navy tactical and nontactical applications shall be in accordance with MIL-S-24725 and supporting specification sheets. Specification sheet MIL-S-24725/1 describes a light duty 2 x 2 multimode fiber optic bypass switch used in protected areas such as interconnection boxes and system equipment. Currently, there are no specification sheets for stand-alone, heavy duty fiber optic switches.

4.2.5.1 Construction and performance characteristics. There are a number of different types and styles of fiber optic switches commercially available. The most common fiber optic switch types are the moving fiber and moving mirror switches. Both fiber optic switch types can exhibit shock sensitivity. MIL-S-24725 specifies minimum levels of fiber optic switch performance, but does not specify the switching mechanism. Moving fiber switches use an electrical relay to physically move the input and output fibers to produce switching. In moving mirror switches, mirrors are inserted into optical paths by an electrical relay to produce switching. Other switch types are also available depending on the application.

4.2.5.2 Attributes. There are several attributes that describe switch performance: switch loss, back reflection, repeatability, switching time, lifetime, size, power consumption, and ruggedness. Switch loss and repeatability affect the link loss budget. Back reflection affects the performance of OTDRs used in link diagnostics and the link source performance if a laser is used. Lifetime and ruggedness of the switch affect the link reliability, the type of enclosure that the switch may be housed in, and may affect the link loss budget. Switching time, switch size and power consumption may affect the design and performance of the system of which the link is a part.

4.2.5.2.1 Switch loss and back reflection. Each switch in a fiber optic link introduces both an optical loss into that link and a reflected signal back through the link. The loss mechanisms for a fiber optic switch are similar to those for a fiber optic connector when the switch connection is engaged (see 4.2.3.2.1). Each different switch type/style minimizes each of these related loss mechanisms to some extent. In general, loss and back reflections are the primary optical effects from the use of a switch in a fiber optic link.

4.2.6 Couplers. Fiber optic coupler use is more limited than the other passive fiber optic components. Common applications are in passive distribution systems, bidirectional communication links, and wavelength division multiplexed (WDM) links. Fiber optic couplers for use in Navy tactical and nontactical applications shall be in accordance with MIL-C-24621 and supporting specification sheets. These couplers are light duty couplers intended for use inside interconnection boxes or equipments. The NAVSEA Fiber Optic Program Office should be consulted to determine the specification sheets that are approved for use in Navy applications.

4.2.6.1 Construction and performance characteristics. The basic structure of a fiber optic coupler consists of input fibers to a coupling region, the coupling region itself and the output fibers. The number of input fibers and output fibers may be the same or may be different. Within the coupling region there may be additional components such as dichroic filters, as in the case of some wavelength division multiplexers. There are many different types and styles of fiber optic couplers available. The basic coupler types include fused biconical taper (FBT), planar, glass rod and bulk optic. The most common commercial fiber optic coupler type is the FBT type fiber optic coupler. However, planar type fiber optic couplers are available from multiple vendors and are quickly becoming a common coupler type. MIL-C-24621 specifies minimum levels of fiber optic coupler performance, but does not specify the coupling mechanism.

4.2.6.1.1 Bulk optic and glass rod couplers. The bulk optic and glass rod coupler types were the first coupler types developed and show the highest losses and the greatest variability in insertion loss of any coupler types. In the bulk optic coupler, light is directed from the input fiber to the output fiber through the use of lenses, mirrors and beam splitters. In the glass rod couplers the input light is launched into one end of a glass mixing rod, which then launches light into the output fibers.

4.2.6.1.2 FBT coupler. FBT couplers are the most common coupler in the commercial market. They are constructed by heating, twisting, and fusing several fibers together. Initially, the greatest weaknesses of this coupler type were insertion loss uniformity and coupling sensitivity to input light modal conditions. Most current FBT couplers produced still show some nonuniformity in insertion loss (especially for couplers with many input and output fibers), but many do not show excessive sensitivity to input light modal conditions. FBT couplers often show a high sensitivity of the transmittance matrix to input light wavelength.

4.2.6.1.3 Planar coupler. The planar coupler is the newest coupler type introduced into the commercial marketplace and shows the best overall insertion loss uniformity, the least wavelength sensitivity in the set of input to output coupling losses (known as the transfer matrix), and the least sensitivity to input light modal conditions. This coupler type is constructed using glass substrates and either depositing waveguides on the substrate or modifying the substrate material to produce waveguides within the substrate.

4.2.6.2 Attributes. There are several attributes that describe coupler performance: insertion loss, crosstalk (for WDM type devices), temperature sensitivity, wavelength sensitivity of the transfer matrix, and ruggedness. Insertion loss and temperature sensitivity affect the link loss budget. Crosstalk in WDM couplers affects the bit error rate (BER) or signal to noise ratio (SNR) of the other multiplexed channel(s). Ruggedness of the coupler affects the installation of the coupler and may affect the link loss budget. Wavelength sensitivity of the transfer matrix affects the upgradability of the link and may affect the link loss budget if the link source is replaced with source of a slightly different wavelength.

4.2.6.2.1 Coupler loss and back reflection. As with the other passive fiber optic components, each coupler in a fiber optic link introduces both an optical loss into that link and a reflected signal back through the link. For most of the coupler styles, the reflected signal levels are low. The loss between input and output fibers occurs because of the changing waveguide structure within the coupler as well as basic connection losses (see 4.2.3.2.1). The loss between different input and output fiber pairs is slightly different because of differences internal to the mixing region. Furthermore, the transfer matrix is generally different for each transmission window.

As with the other passive fiber optic components, loss and back reflection are the primary optical effects from the use of a coupler in a fiber optic link.

4.2.7 Interconnection boxes. Interconnection boxes are used in fiber optic systems to allow equipment to connect into the fiber optic cable plant (see 4.3.3). Interconnection boxes for use in Navy tactical and nontactical applications shall be in accordance with MIL-I-24728 and supporting specification sheets. These interconnection boxes are watertight and may be used in unprotected locations throughout the ship. These boxes serve to protect and isolate the light duty single fiber connectors, splices or other components from the shipboard environment.

4.2.7.1 Construction. The interconnection box consists of an outer box structure and internal connector patch panels or splice trays. Small interconnection boxes that will accept up to eight or 16 single fiber connectors are available. These small interconnection boxes are not modular in design. Large interconnection boxes are modular with versions available containing one, two or three modules. Each module may contain up to 48 single fiber connectors or 72 single fiber splices. Connector and splice modules may be mixed within the same interconnection box. A connector module consists of a flat plate (the patch panel) and slide channels that the plate mounts in. The patch panel slides out of the box for easy access. The patch panel contains holes for mounting panel mount single fiber connector adapters. The splice module consists of a splice tray holder that will accept up to six removable splice trays that are in accordance with MIL-S-24623/4. Up to 12 splices are mounted in each tray, which organizes the splices and provides limited mechanical protection.

4.2.8 Fiber optic sources and transmitters. In a fiber optic link the optical transmitter converts an electrical signal to a light (optical) signal and launches the light into the fiber. The transmitter normally consists of an interface circuit, an electrical drive circuit, a semiconductor light source and an optical interface (either a connector or fiber optic pigtail). Fiber optic transmitters are available that will accept most logic types including transistor-transistor logic (TTL), emitter coupled logic (ECL) and others. Fiber optic transmitters for use in Navy tactical and nontactical applications shall be in accordance with MIL-T-24721. All transmitters shall be hermetically sealed. Semiconductor sources with center wavelengths in either the 850 or 1300 nm transmission windows are available. For most applications with moderate data rates, sources in the 1300 nm window are used.

4.2.8.1 Optical source types. There are several choices of semiconductor light sources for fiber optic links. These sources can be grouped into two broad categories: light emitting diodes (LED's) and laser diodes. Each of the source types has specific advantages and disadvantages for a particular application as shown herein.

4.2.8.1.1 LED construction and performance characteristics. LEDs are the recommended source type for multimode fiber links because of their low cost and relatively simple drive circuitry. LEDs can be categorized into three basic groups: surface emitting diodes (SLED), edge emitting diodes (ELED), and superluminescent diodes (SLD). The basic differences between the three categories are the direction of light emission relative to the positive-negative (pn) junction and the power launched into the fiber.

4.2.8.1.1.1 SLEDS. In SLEDs the light output is perpendicular to the pn junction (see figure 11). This output light is incoherent, covers a wide spectral range and is distributed over a larger solid angle than a typical fiber can accept.

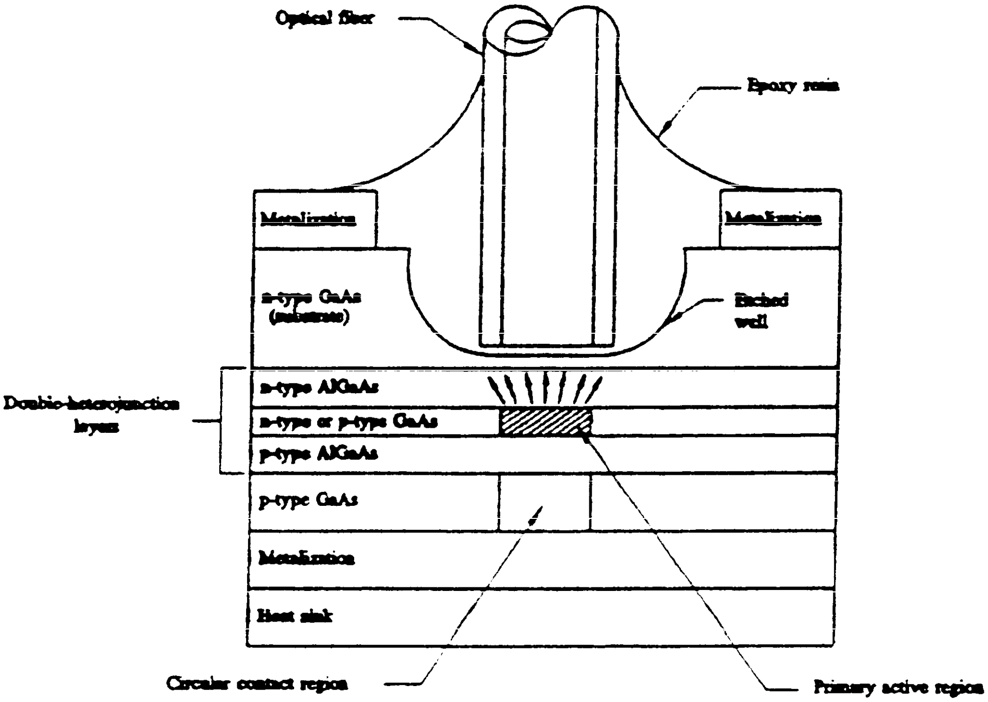

FIGURE 11. Typical SLED construction.

4.2.8.1.1.2 ELED and SLD. In contrast, most ELED and SLD constructions are based on semiconductor laser constructions. The primary difference between the ELED and the laser is that the laser cavity facets are made nonreflective in the ELED so that only spontaneous emission occurs. For ELEDs the light output is parallel to the pn junction (see figure 12). Typically, the light output from an ELED is distributed over a much smaller solid angle and a narrower spectral band than that of an SLED. Additionally, ELEDs typically launch more power into a multimode optical fiber than a SLED (especially for the smaller core sizes/numerical apertures). The primary difference between the ELED and the SLD is that in the SLD the cavity facets are somewhat reflective so that some stimulated emission occurs within the cavity. The output of an SLD is over a smaller solid angle and a narrower spectral width than that of an ELED. However, the output is not fully coherent.

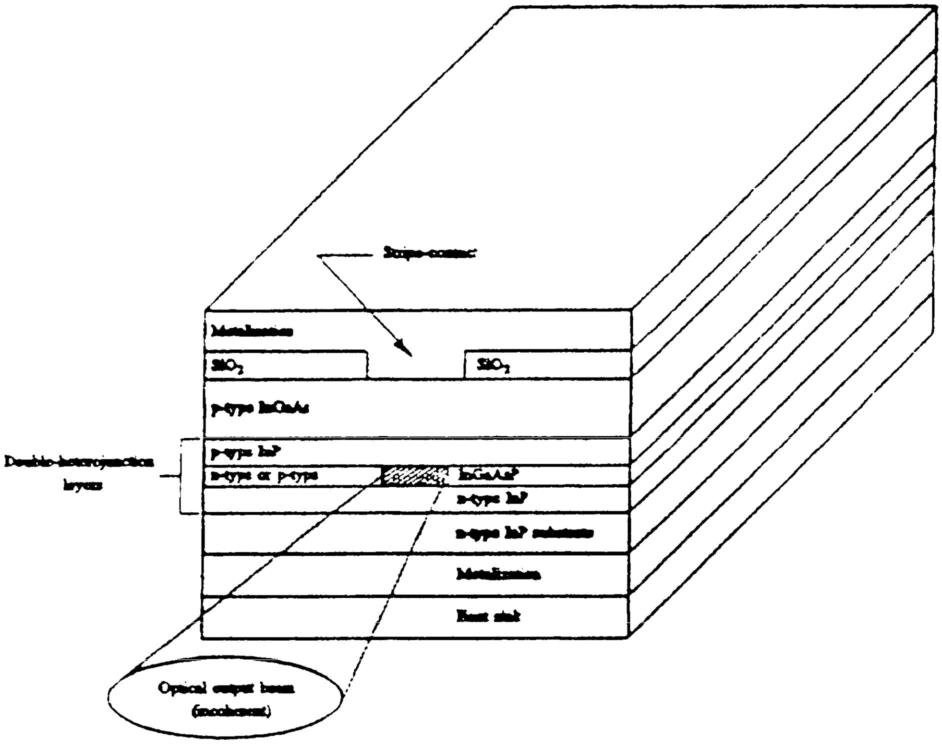

FIGURE 12. Typical ELED construction.

4.2.8.1.1.3 Performance comparison. The power launched by the SLD is the highest for the LED structures. The higher power densities at the pn junction, however, decrease the SLDs reliability. The SLD is not as widely available as SLEDs and ELEDs and is not commonly used as a source in communication applications. Table IV shows a comparison of the typical performances of the different LED types.

4.2.8.1.2 Laser diode construction and performance requirements. Semiconductor laser sources typically have a greater output power at a lower drive current and bandwidth than LEDs. The output power coupled into a 62.5 µm fiber for a typical semiconductor laser is on the order of -3 to +5 dBm. The output is coherent and highly directional. The spectral width of a semiconductor laser may range from 0.5 nm (single longitudinal mode lasers) to greater than 10 nm (multimode laser). Semiconductor lasers are available for use at almost any center wavelength and have modulation bandwidths in excess of 1 gigahertz (GHz).

TABLE IV. LED and laser performance comparison.

Attribute	Typical Source Performance[1]					
	SLED		ELED	SLD	Laser	
	850 nm	1300 nm			850 nm	1300 nm
Launch Power (62.5 µm fiber)	-8 to -15 dBm	-15 to -19 dBm	-12 to -17 dBm	-5 to -10 dBm	5 to 10 dBm	-5 to 3 dBm
Spectral Width (FWHM)	50 to 110 nm	120 to 170 nm	70 to 120 nm	20 to 50 nm	<1 to 10 nm	
Center Wavelength	750 to 900 nm	1200 to 1600 nm	750 to 1600 nm	750 to 1600 nm	770 to 905 nm	1200 to 1600 nm
Maximum Bandwidth	250 MHz		400 to 500 MHz	> 400 Mhz	> 1 GHz	
Lifetime	10^6 hours	10^7 hours	10^6 hours	10^5 hours	10^5 hours	
Linearity	Moderate		Moderate	Poor	Good	
Drive Current	30 to 200 mA		30 to 200 mA	30 to 200 mA	10 to 150 mA	
Temperature Sensitivity (-40 to +70 °C)	4 to 6 dB		6 to 22 dB	10 to 25 dB	10 to 25 dB	

[1] Typical values are shown for comparison purposes only. Check with the manufacturers for exact performance characteristics for system design purposes.

4.2.8.1.2.1 Complexity of design. Semiconductor lasers do, however, have some disadvantages. Semiconductor laser lifetimes are generally on the order of 10^5 hours, approximately an order of magnitude less than most LEDs. In addition, most semiconductor lasers are more temperature sensitive, and require some form of automatic power control (APC) circuitry and internal or external thermoelectric (TE) coolers. In some cases the APC circuitry and the TE cooler are internal to the transmitter package, but the control circuitry for the TE cooler is not. The circuitry required for these functions, whether inside or outside of the package, does increase the cost and complexity of the link. The use of internal or external TE coolers tends to decrease the transmitter's reliability.

4.2.8.1.2.2 Interaction with other link components. Some of the disadvantages of semiconductor lasers arise from the semiconductor laser interaction with other link components. When semiconductor lasers are used with multimode systems the number of longitudinal modes (for example, the spectral width) of the laser should be maximized. In general, if the full width half maximum (FWHM) spectral width of the laser is less than 5 nm, interference generated modal noise will be present within the link and the link losses will be unstable. Furthermore, lasers with narrow spectral widths are more susceptible to reflections from link connections and will further degrade the link performance (see 5.6.6). The effects of modal noise can be avoided in systems using narrow spectral width lasers if special modulation techniques are used (see 5.6.7). If lasers with narrow spectral widths are used and these modulation techniques are not, adjustments to the loss budget must be made for modal noise (see 5.6.7). In some cases the link BER may not decrease below a minimum value (known as a BER floor) regardless of the optical power delivered to the receiver.

4.2.8.2 Fiber optic transmitters. Fiber optic transmitters are available in many different forms and with varying degrees of complexity. Transmitter forms include transistor outline (TO) cans, single inline packages (SIPs), dual inline packages (DIPs), butterfly lead packages, or small circuit boards or boxes. The transmitter output interface may be either a fiber optic connector adapter or a fiber optic pigtail. If a fiber optic connector adapter is used as the output interface, an optical fiber may be used internal to the transmitter package to link the optical source to the output connector adapter. Alternatively, the optical source may mount into the output interface connector adapter so that it launches directly into the fiber optic connector mating to the transmitter. For a transmitter with an output fiber optic pigtail, the pigtail is a 250 μm coated fiber within a 1 mm diameter buffer tube, or a 3 mm single fiber cable. For fiber optic pigtails, single fiber cable pigtails are more rugged and are recommended over coated fibers in loose buffer tubes.

4.2.8.2.1 Construction. The most basic transmitters contain a semiconductor source in typically a DIP or a TO can. These transmitters may require separate circuitry in the system equipment to properly condition the electrical signal that is supplied to the transmitter. Other transmitters are more complex and have the input interface circuity and source drive circuitry within the package. Fiber optic transmitters for communications applications typically contain interface circuitry and source drive circuitry as well as the source. Fiber optic transmitters using laser diodes require more complex circuitry than transmitters using LEDs. Simple lasers are available in TO cans, but generally these are not used in communications links. Laser transmitter packages generally contain APC circuitry to monitor and maintain constant laser output power and are in the form of a DIP. LED transmitters do not usually contain APC circuitry. Laser diode transmitter packages may also contain an integral TE cooler, but generally the circuity to control the TE cooler is not contained within the transmitter package and must be included on the printed circuit board where the transmitter is mounted. Complete laser packages (boxes) are available which contain all of the circuitry required to drive and control the laser.

4.2.8.2.2 Attributes. The primary attributes that describe fiber optic transmitter performance are output power, center wavelength, spectral width and rise time. The output power affects the link loss budget and is determined by source material and construction. Center wavelength affects signal attenuation and dispersion and is determined by source material. Spectral width affects link dispersion and is determined by source construction. Transmitter rise times affect their bandwidth capacity and are determined by construction and the source drive circuitry.

4.2.9 Fiber optic detectors and receivers. In a fiber optic link, the optical receiver converts the transmitted optical signal into an electrical signal and, in some cases, removes some of the distortion introduced by the fiber optic link. A receiver normally consists of an optical interface (either a connector or fiber optic pigtail), an optical detector, a low noise amplifier, and other circuitry to produce the output electrical signal (see figure 13). Fiber optic receivers are available that provide electrical output compatible with the common logic types including TTL, ECL and others.

Fiber optic receivers for use in Navy tactical and non-tactical applications shall be in accordance with MIL-R-24720. All receivers shall be hermetically sealed.

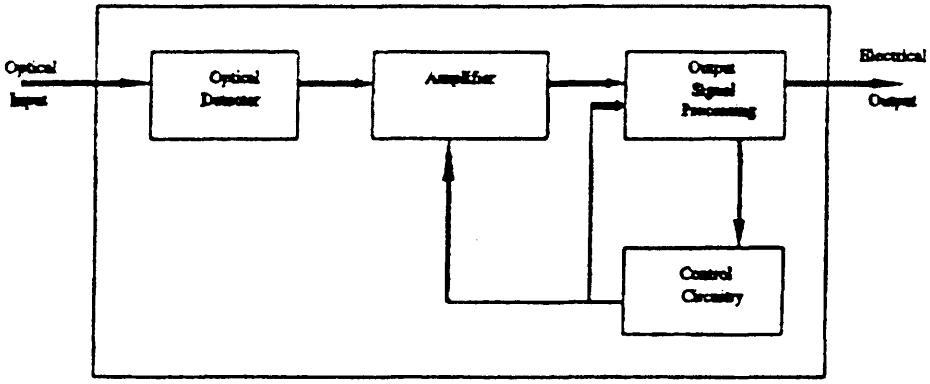

Figure 13. Block Diagram of a Typical Fiber Optic Receiver.

4.2.9.1 Optical detector construction and performance characteristics. Optical detectors can be categorized into two basic groups: positive-intrinsic-negative (PIN) diodes and avalanche photodiodes (APDs). The primary differences between the different detector types are responsivity, reliability, bias voltage and frequency response. Table V shows a comparison of the typical performances of the different detector types.

TABLE V. Detector performance comparison.

Attribute	Typical Detector/Receiver Performance [1]			
	PIN		APD	
	850 nm	1300 nm	850 nm	1300 nm
Material	Silicon	Germanium or InGaAs	Silicon	Germanium or InGaAs
Maximum Sensitivity	-35 dBm	-40 dBm	-50 dBm	-45 dBm
Wavelength Range	< 750 to >900 nm	< 1200 to 1600 nm	< 750 to > 900 nm	< 1200 to 1600 nm
Maximum Bandwidth	> 1 GHz	> 1 GHz	> 1 GHz	> 1 GHz

Temperature Sensitivity	Minimal	Minimal	Moderate	Moderate
Bial Voltage	-5 to -15 V	-5 to -15 V	> 100 V	30 to 100 V
Lifetime	10^9 hours	10^9 hours	10^6 hours	10^6 hours

1/ Typical values are shown for comparison purposes only. Check with the manufacturers for exact performance characteristics for system design purposes.

4.2.9.1.1 PIN diodes. PIN diodes are used as the detector in most fiber optic systems. The size of the active area of the diode can be optimized for the particular application. The frequency response of the diode decreases as the diode active area increases in size. For most applications, especially those with high bandwidth requirements, the diode active area should be minimized. However, the diode active area should be as large as the core size of the link fiber. Typical PIN diodes have lifetimes in excess of 10^9 hours and 3 dB bandwidths in excess of 1 GHz. The sensitivity of a PIN diode can be enhanced by combining it with a field effect transistor (FET). These hybrid detectors are called PINFETs. Receivers utilizing PINFET detectors typically have greater sensitivity than they would if simple PIN diodes were used.

4.2.9.1.2 Avalanche photodiodes. APDs are generally used as detectors in applications where sensitivities are required that cannot be obtained with a PIN or PINFET. Silicon APDs typically require bias voltages of over 100 volts, while germanium APDs require bias voltages up to a few tens of volts. This necessitates the availability of a high voltage source for the receiver, complicates receiver design and decreases thermal stability. APDs have lifetimes on the order of 10^6 hours and bandwidths in excess of 1 GHz. APDs exhibit an inverse relationship between gain and frequency response. That is, the APD bandwidth is maximum when the gain is at a minimum. In general, APDs have a lower frequency response than a PIN or PINFET. However, the responsivity of the APD is much greater than that of either the PIN or the PINFET leading to receivers with much greater sensitivity than possible with PINs or PINFETs.

4.2.9.2 Fiber optic receivers. Fiber optic receivers are also available in many different forms and with varying degrees of complexity. Receivers are available in TO cans, hybrid microcircuit DIPs and butterfly lead packages, or small circuit boards or boxes.

4.2.9.2.1 Construction. The most basic receivers consist of a semiconductor detector and an amplifier in a TO can. These receivers require separate circuitry in the system equipment to condition the output electrical signal and are for use in links with relatively low data rates. Other receivers are more complex and also have the signal conditioning circuitry within the receiver package. Some receivers contain link diagnostic circuitry that monitors the receiver input optical power. The most complex receivers include the amplifiers, signal conditioning circuitry, clock recovery and link diagnostic circuitry within the package. The receiver input optical interface may be either a fiber optic connector adapter or a fiber optic pigtail. The receiver input optical interface is similar to the transmitter optical interface. See 4.2.8.2 for information on the optical interface.

4.2.9.2.2 Attributes. The primary attributes that describe fiber optic receiver performance are sensitivity, frequency response, spectral response range, reliability and dynamic range. The spectral response range is determined by the choice of detector materials. In general, silicon detectors are used in the 850 nm window while germanium and InGaAs are used in the 1300 and 1550 nm windows. The dynamic range of the receiver is determined by the amplifier choices. The receiver sensitivity, reliability and frequency response are determined by the specific detector and amplifier choices.

4.3 Inter-equipment connections.

4.3.1 Equipment external physical interfaces. Equipment external physical interfaces shall be as specified in 4.3.1.1 and 4.3.1.2.

4.3.1.1 Stand-alone equipment. Equipment external physical interfaces for stand-alone equipment shall be either a heavy duty MIL-C-28876 connector or a Navy approved cable penetrator. Cable penetrators include stuffing tubes and multiple cable penetrators (see MIL-STD-2051). In no case shall light duty connectors be used as the equipment external physical interface. Figure 14 shows approved stand-alone equipment external physical interfaces.

4.3.1.2 Rack mounted equipment. Equipment external physical interfaces for rack mounted equipment shall be either a heavy duty MIL-C-28876 connector, light duty MIL-C-83522/16 connectors, or single fiber cable pigtails (MIL-C-85045/14 or /16) with light duty MIL-S-24623/4 splices. If light duty connectors or single fiber cable pigtails with light duty splices are used as the equipment external physical interface, they shall be protected within the equipment rack and the equipment rack shall have an external physical interface as

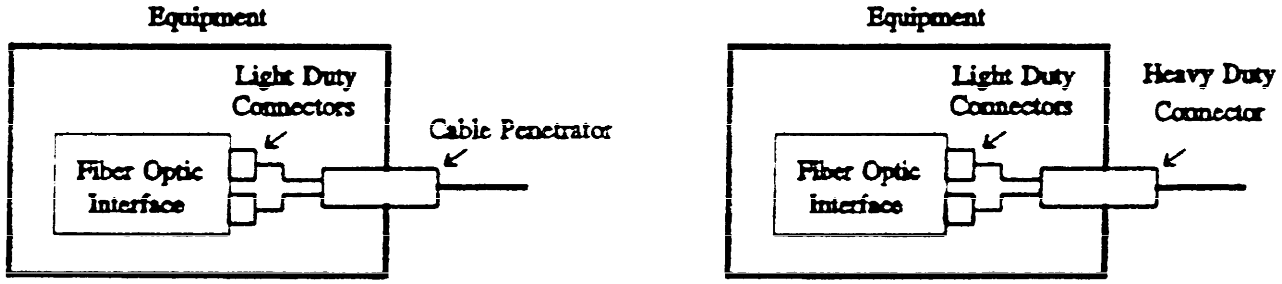

FIGURE 14. Approved external physical interfaces for stand alone equipment.

described herein. Figure 15 shows approved rack mounted equipment external physical interfaces.

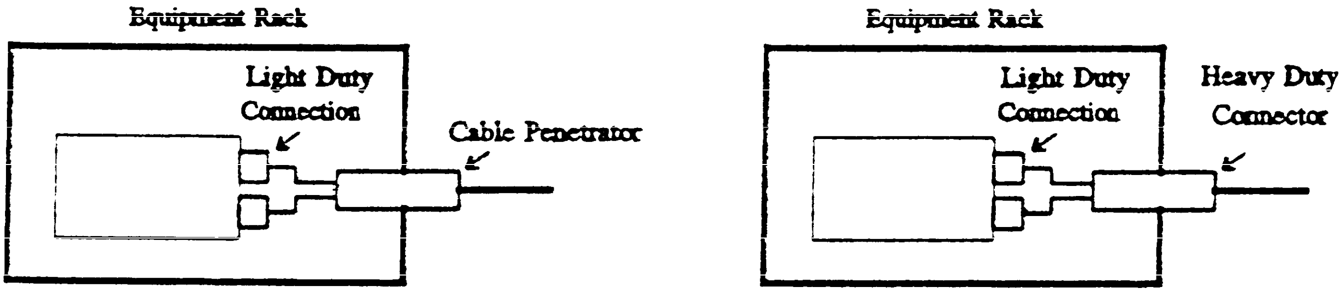

FIGURE 15. Approved rack-mounted equipment external physical interfaces.

4.3.2 Direct inter-equipment or inter-rack connections. The most basic inter-equipment or inter-rack connection is a direct connection (a single cable between the two equipments or racks). Direct inter-equipment or direct inter-rack connections shall be used only when a shipboard fiber optic cable plant (see 4.3.3) is not installed or link requirements cannot be met using the shipboard fiber optic cable plant. If direct inter-equipment or inter-rack connections are used, the heavy duty MIL-C-28876 connector is recommended as the equipment or rack external physical interface.

4.3.3 Fiber optic topology connections. The recommended approach for inter-equipment or inter-rack connections is to use the shipboard fiber optic topology (MIL-STD-XXXX). All systems shall have an acceptable loss budget (see 5.5) for implementations using a fiber optic topology.

4.3.3.1 Fiber optic topology description. The fiber optic topology consists of trunk cable runs, local cable runs and interconnection hardware (connectors, splices and interconnection boxes). Trunk cables optically interconnect compartment interconnection boxes and are typically run through the main cableways. Local cables optically connect the equipment to the compartment interconnection box and typically are not run through the main cableways. Trunk cables generally have higher fiber counts per cable than that found in local cables. Connections between equipment or racks are established by connecting fibers in the local cables from each equipment to common fibers in a trunk cable via single-fiber connectors or splices within a interconnection box. The portion of the fiber optic topology consisting of the trunk cables and the interconnection boxes is referred to as the Fiber Optic Cable Plant (FOCP). Figure 16 is a diagram of a typical fiber optic topology.

4.3.3.2 Topology connection advantages. The primary advantages of using the fiber optic topology for equipment or rack interconnections are a reduction of cables in the main cableways, increased survivability of system cabling, and more economical system and ship growth. The sharing of trunk cables by several systems reduces the number of cables in the ship's cableways. This reduction of cables in the cableways gives ship designers more flexibility in cable routing and allows the addition of survivable redundant cables for the topology trunk cables. The reduction of cables in the cableways also allows the installation of unallocated fibers during initial construction for use in upgrades and new system installations.

4.4 Intra-equipment or intra-rack organization. Equipment internal organization shall be as specified in 4.4.1 through 4.4.3.

4.4.1 Cable routing within equipments or racks. Fiber paths within equipment or racks shall be established using single or multifiber cables. Buffered fibers shall not be routed within equipment except on circuit cards (see 4.4.3). Fiber optic cables shall be routed within equipment or racks using routing hangers or other routing structures. The cable runs shall be routed so that they will not interfere with maintenance activities and do not exceed the specified minimum bend radius. Cable runs shall be made with sufficient cable length to allow for connector replacement or repair. Cable runs shall have ample slack to permit opening and closing of

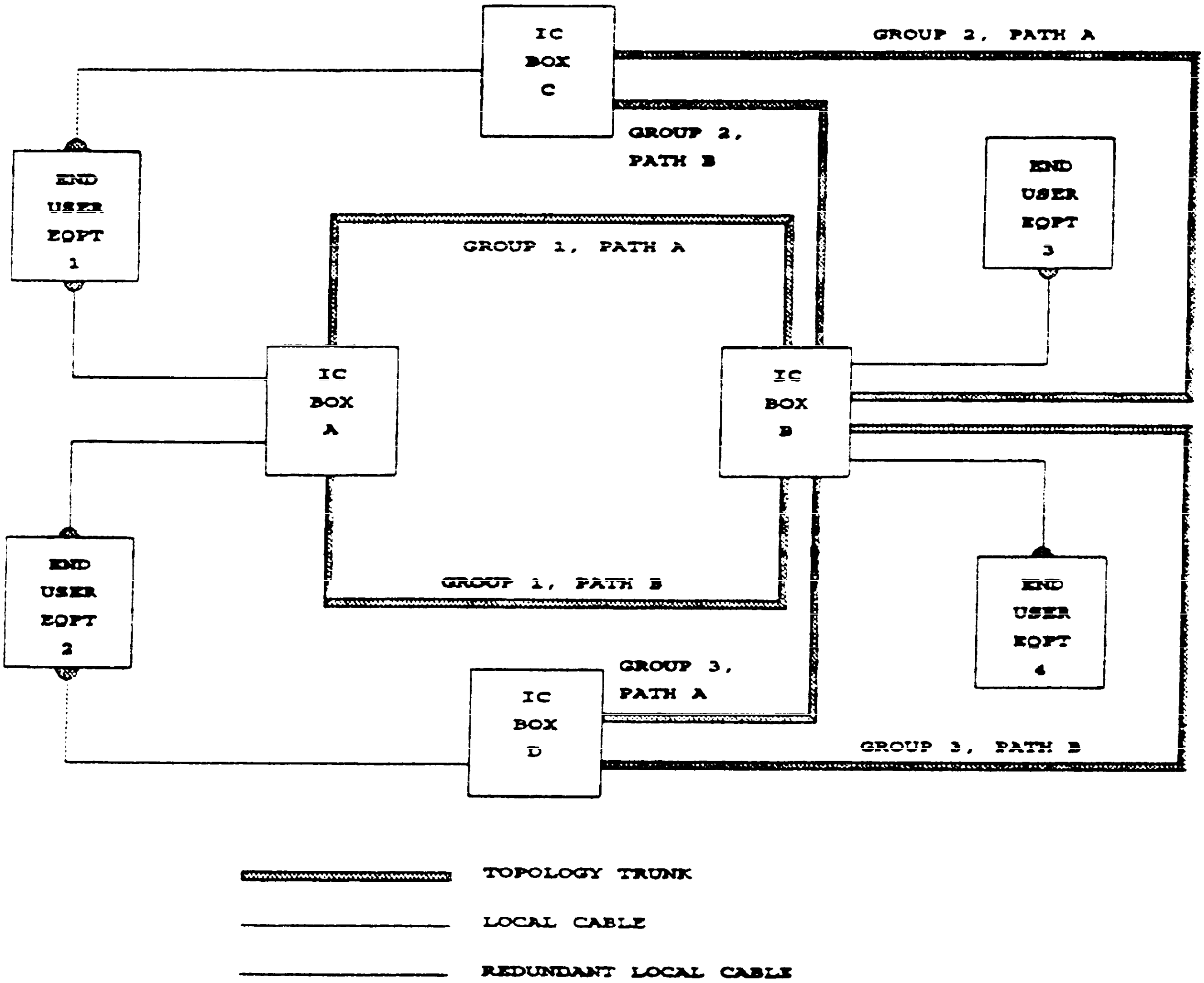

FIGURE 16. Typical fiber optic topology.

doors and sliding of racks. All cables should be fastened at appropriate points to prevent damage caused by excessive motion, bending, chafing or pinching at hinges. Cables may be secured with grasshopper clips, velcro, RTV, adhesive or cable ties if necessary. If cable ties are used, they shall be adjusted so that the cable is loosely held. Do not over-tighten cable ties as they may damage the fibers.

4.4.2 Internal equipment or rack connections.

4.4.2.1 Single fiber internal connections. Single fiber internal equipment or equipment rack connections shall use single fiber connectors in accordance with MIL-C-83522/16 or single fiber splices in accordance with MIL-S-24623/4. Single fiber connectors shall be mounted on custom made patch panels using panel mount adapters or module frames or shall directly mate with equipment transmitters and receivers. Single fiber splices shall be mounted in splice trays (per MIL-S-24623/4) or custom made splice holders mounted within the equipment or the equipment rack. Single fiber connectors or splices shall not be loosely placed inside equipment or equipment racks or held in place with cable ties or safety wires.

4.4.2.2 Multifiber internal connections. Connectors used for multifiber internal equipment or equipment rack connections shall be approved by the Fiber Optic Program Office. This applies to card edge connectors, drawer connectors or module connectors. Internal equipment or equipment rack connections may be made using hybrid connectors containing both electrical and optical connections within equipment or equipment racks. If hybrid connectors are used internal to the equipment or equipment rack, these also shall be approved by the Fiber Optic Program Office.

4.4.3 Cable or buffered fiber routing on circuit cards. Single fiber cables or buffered fibers shall be routed on circuit cards using RTV, adhesives, routing fixtures and clamps. All single fiber cables or buffered fibers shall be mounted to the circuit card at intervals not greater than 100 mm. The height of any part of single fiber optic cables or buffered fibers from the circuit card shall not exceed the height of the tallest component on the circuit card. Buffered fibers shall not extend beyond the edges of the circuit card. Single fiber cables and buffered fibers shall not be routed in contact with circuit card components with external temperatures in excess of 85 degrees Celsius (°C). Single fiber cables and buffered fibers shall not be routed with bend diameters less than 50 mm. Any fiber exiting a circuit card shall be a jacketed fiber.

5. DETAILED REQUIREMENTS

5.1 General. This section details the optical link design process. The system communication requirements and system physical configuration information are required in the optical link design process, so those aspects of the system design must be complete before the link design process begins. This section leads the optical link designer through the design process in an orderly manner. Throughout the process, the information and decisions that are required in order to complete the design are highlighted. This section addresses those decisions involved in the design of the optical link including the fiber tradeoffs, passive component decisions, and optical-to-electrical and electrical-to-optical conversion components. This section does not, however, address the electrical circuit design necessary to support the electro-optical components (for example, source drive circuits, detector amplifiers, and so forth). The tradeoffs associated with the use of different components within the link are discussed in 5.2. An overview of the link design process is given in 5.3, detailing the system configuration and component performance information that the link designer must have available during the design process. Detailed optical loss and bandwidth budgeting formulae are given in 5.4 and 5.5, respectively. Adjustments that can be added to the loss budget are discussed in 5.6. Reliability predictions for the standard Navy fiber optic component types are given in 5.7. Section 5.8 describes the fiber optic design issues covered in the examples in Appendices A and B.

5.1.1 Maintainability considerations. The maintainability considerations herein should be considered when designing the fiber optic link.

5.1.1.1 Repairability. Throughout the design process, the design engineer must ensure that optical components are accessible and easily repairable at the organization and intermediate levels. Special consideration should be given to those components located in equipment drawers and racks as follows:

a. Provide cable service repair loops with enough slack for at least two reconnections.
b. Allow enough slack in cable routing so that minimum bend radii are not exceeded.
c. Route cables to provide protection from sharp edges and moving joints.

5.1.1.2 Logistics. Standardized components, tools, and test equipment should be specified when possible to reduce logistic support problems.

5.1.2 System spare and redundant optical paths. System required spare and redundant fibers should be considered by the system designer. If the FOCP (see 4.3.3) is used, additional spare and redundant fibers will be included in the cable plant design.

5.2 Component selection. There are several basic component tradeoffs that must be considered during the optical link design process. Component requirements and recommendations of component selections for different applications are discussed in 5.2.1 through 5.2.12.

5.2.1 Optical fiber. Two standard fiber types are available for use, 62.5/125 µm multimode and single mode fiber. The standard multimode fiber is recommended for use unless the link data rate requirements are beyond the bandwidth limits of multimode links. For high data rate systems (data rates beyond the limits of available LED sources) single mode fiber is recommended. Optical fibers used in Navy tactical applications shall be in accordance with MIL-F-49291/6 and MIL-F-49291/7. Multimode fibers used in Navy nontactical applications shall be compatible with the 62.5/125 µm fiber.

5.2.2 Fiber optic cable. All fiber optic cable used in Navy tactical and nontactical applications shall be in accordance with MIL-C-85045.

5.2.3 Single terminus connectors. Single terminus connectors used in Navy tactical applications shall be in accordance with MIL-C-83522/16. Connectors used in Navy nontactical applications shall be compatible with MIL-C-83522/16 connectors. Use of the connectors within a given link or location shall be as specified in 5.2.10 and 5.2.11.

5.2.4 Multiterminus connectors. Multiterminus connectors used in Navy tactical and nontactical applications shall be in accordance with MIL-C-28876 and supporting specification sheets. Use of the connectors for external connections shall be in accordance with 5.2.10.

5.2.5 Splices. Single fiber splices used in Navy tactical and nontactical applications shall be in accordance with MIL-S-24623/4. Multifiber cable splices used in Navy tactical and nontactical applications shall be in accordance with MIL-S-24623/5. Use of the splice within a given link or location shall be as specified in 5.2.10 and 5.2.11.

5.2.6 Switch. The fiber optic switches used in Navy tactical applications shall be in accordance with MIL-S-24725.

5.2.7 Coupler. The fiber optic couplers used in Navy tactical applications shall be in accordance with MIL-C-24621.

5.2.8 Interconnection box. The interconnection boxes used in Navy tactical and nontactical applications shall be in accordance with MIL-I-24728.

5.2.9 Transmitter types and features. Fiber optic transmitters for use in Navy tactical applications shall be in accordance with MIL-T-24721. DIP or butterfly lead hybrid microcircuit packages are recommended.

5.2.9.1 Transmission wavelength. The standard Navy transmission wavelength is 1335 ± 45 nm. All tactical data links shall operate in this wavelength range. Nontactical links may operate in other wavelength ranges, but general purpose test equipment for fiber optics may not be available shipboard to support other wavelengths. All links with data rates beyond 20 Mbps should use the standard Navy transmission window.

5.2.9.2 Multimode fiber links. Multimode systems with either SLED or ELED transmitters are recommended for use aboard Navy ships. In links that are marginal in power or bandwidth, ELED transmitters are recommended. In links where the transmitter will experience large temperature variations, SLED transmitters and constant power control circuitry is recommended. The use of SLD transmitters is not recommended. If LED transmitters do not have sufficient data rates or cannot provide a sufficient loss budget, laser transmitters may be used. If laser transmitters are used the laser FWHM spectral width shall be greater than 5 nm.

5.2.9.3 Single mode fiber links. For single mode fiber links laser transmitters are recommended. It is also recommended that laser transmitters have output power control circuitry. In links where the transmitter will experience large temperature variations, TE heaters and coolers are also recommended.

5.2.10 Equipment external connections.

5.2.10.1 Stand-alone equipment. Heavy duty MIL-C-28876 connectors are recommended for stand-alone equipment external interfaces. Cable penetrations shall be used for equipment external interfaces only when link loss budgets are not acceptable using a heavy duty connector interface.

5.2.10.2 Rack mounted equipment. Light duty MIL-C-83522/16 connectors are recommended for rack mounted equipment internal interfaces in multimode fiber links. Single fiber cable pigtails with light duty splices shall be used for rack mounted equipment internal interfaces in multimode fiber links only when link loss budgets are not acceptable using a light duty connector interface. Single fiber cable pigtails with light duty splices are recommended for rack mounted equipment internal interfaces in single mode fiber links. The recommended rack external interface for all links is a cable penetrator. A heavy duty MIL-C-28876 connector shall be used only when quick rack disconnects and reconnects are required.

5.2.11 Cable plant terminations. Light duty MIL-C-83522/16 connectors are recommended for all connections within interconnection boxes for multimode fiber systems. Light duty MIL-S-24623/4 splices shall be used within interconnection boxes for multimode fiber systems only when loss budgets are not acceptable using light duty connectors. Light duty MIL-S-24624/4 splices shall be used for all connections within the interconnection boxes for single mode fiber links.

5.2.12 Receiver types and features. Fiber optic receivers for use in Navy tactical applications shall be in accordance with MIL-R-24720. DIP or butterfly lead hybrid microcircuit packages are recommended. Receivers using PIN diode or PINFET detectors are recommended for all data links. Receivers using APDs are not recommended. All receivers shall contain link diagnostic circuitry.

5.3 Link definition and design.

5.3.1 General. This section details the system and component information that is needed in order to complete the link design. In some cases the required information may be obtained directly from the component manufacturers. In other cases the information may be calculated or estimated from manufacturer information or a related parameter. In those instances when calculations from one section are required as input to another section, the appropriate section from which the information can be obtained is identified. In those instances where the component information may not be available, guidance on how to estimate the value of each unknown parameter is provided or typical values are suggested. The use of estimated values for most parameters is not recommended except in the initial design process where the general feasibility of the link is being determined.

5.3.1.1 Design process. Fiber optic link design is a multistage process. Figure 17 is a flow diagram of one approach to the link design process. Figure 17 indicates the information required and the decisions to be made at each stage of the design process. Other

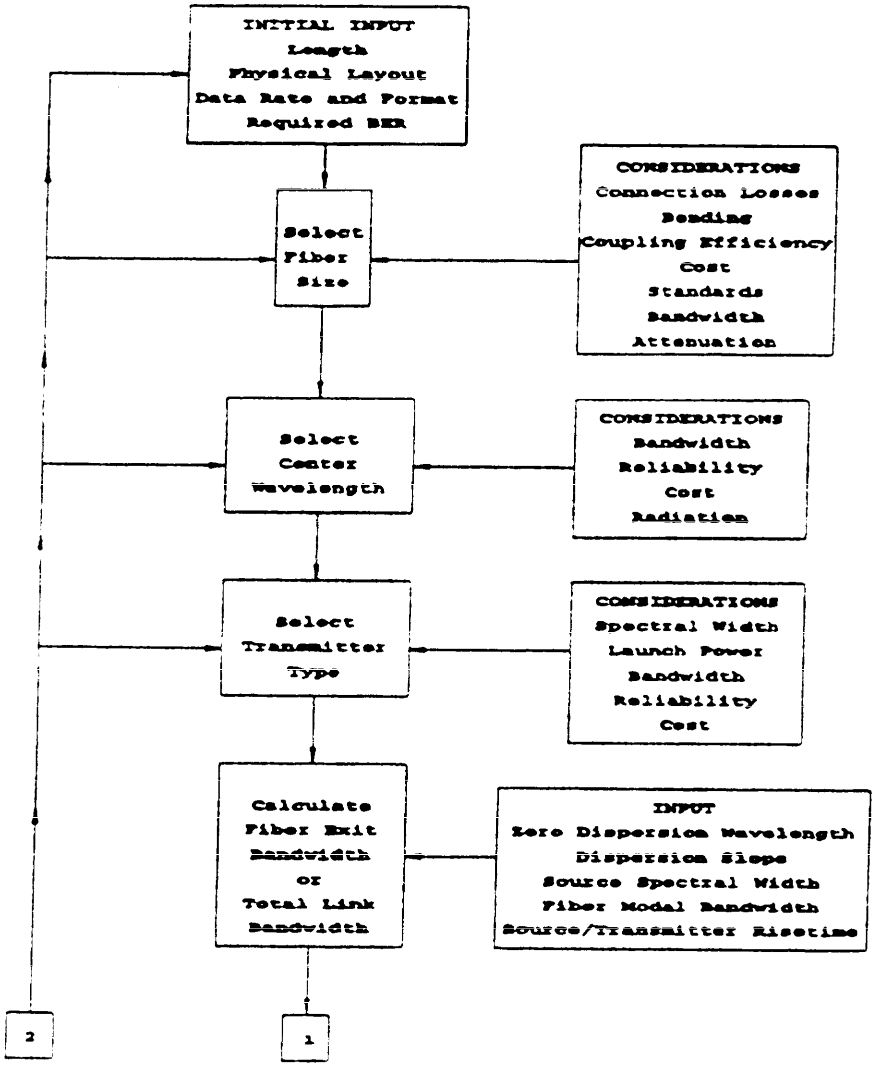

FIGURE 17. Fiber optic link design process.

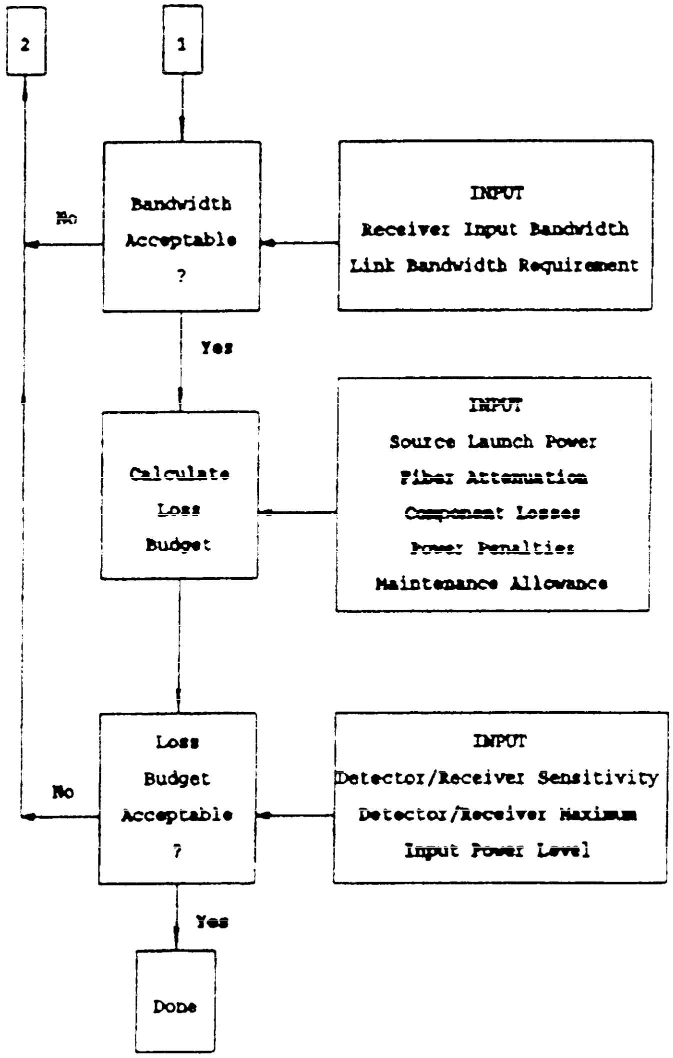

FIGURE 17. Fiber optic link design process - Continued.

design processes in which different initial conditions are given and the decision process is rearranged may be required in some cases. Regardless of the link design process used, it may be iterated numerous times to compare different link designs and evaluate tradeoffs. This section divides the information required into groups, each group corresponding to a different aspect of the design and to a different section of this document. If specific evaluations are being made (such as the end-to-end loss budget), the equations necessary to perform the evaluation can be used individually.

5.3.2 Initial link definition. Before beginning the link design process, the following system information must be obtained:

a. the total link length (or the lengths of all the sections)
b. the types and number of passive components in the link (for example, the number of connectors, splices, switches and so forth, including any components allowed for repair situations)
c. the general layout of the link including the order of components and the distances between components
d. the link data rate, data format (manchester, 4B/5B, and so forth), and required BER

After the initial link information has been obtained, the following choices must be made:

a. the fiber type
b. the optical transmitter central wavelength
c. the type of optical transmitter (ELED,SLED, laser and so forth)

5.3.3 Design evaluations.

5.3.3.1 Bandwidth. When the initial link definition is complete, the candidate design is evaluated to determine if any distortion limitations exist. This is accomplished through distortion budgeting. In order to calculate the link distortion budget, the following information must be obtained:

a. the fiber zero dispersion wavelength of the fiber (EIA/TIA-455-168) or its numerical aperture (EIA-455-177) (see 5.4.3.4.3)
b. the dispersion slope at the fiber zero dispersion wavelength (EIA/TIA-455-168)
c. the root mean square (RMS) or FWHM spectral width of the optical source/transmitter (EIA/TIA-455-126 or EIA/TIA-455-127)

d. the modal bandwidth of the cable or the minimum specified modal bandwidth of the cable (EIA/TIA-455-30 or EIA/TIA-455-51) (multimode fiber only)
e. the source/transmitter 10 to 90 percent rise time (EIA/TIA-526-4)

After the distortion budget is calculated, the source/fiber exit bandwidth is compared to candidate receiver input bandwidth requirements and acceptable receivers are identified. If specific manufacturer receiver specifications are not known, the source/fiber exit bandwidth should be compared with Navy receiver specifications to assess the link design.

5.3.3.2 Loss. After the link design has been evaluated for distortion limitations, it is evaluated for optical power loss limitations. This is accomplished through loss budgeting. In order to calculate a link optical loss budget, the following information must be obtained:

a. the installed cable attenuation rate for a restricted launch condition (EIA/TIA-455-46 with EIA/TIA-455-50) at the nominal wavelength of operation
b. typical cable transient loss data for the overfilled launch (OFL) condition (see section 3.1.1) at the nominal wavelength of operation
c. the loss of each connector, splice, attenuator, or switch path in the link for a restricted launch condition (EIA/TIA-455-54 Method B) at the nominal wavelength of operation
d. the loss of each connector, splice, attenuator, or switch path in the link for an OFL launch condition (EIA/TIA-455-34 Method A) at the nominal wavelength of operation
e. the loss of each passive branching device path in the link (EIA/TIA-455-180) for both the restricted and OFL launch conditions at the nominal wavelength of operation
f. the loss of any other component in the link for both the restricted and OFL launch conditions at the nominal wavelength of operation
g. the average output power of the source/transmitter
h. the typical coupled power ratio (CPR) value of the source/transmitter (see appendix A)

NOTE: The cabled fiber attenuation and the cabled fiber transient loss generally will not be the same as the precabled bare fiber attenuation or the precabled fiber transient loss.

NOTE: In this document the loss of a fiber optic component does not include the losses of the connectors/splices required to connect that component into the link. The connectors/splices used to connect fiber optic components into the link should be identified separately from the components that they are connecting.

In calculating the loss budget there are a number of correction terms which may be included. In order to calculate these adjustments to the link loss budget the above information must be supplemented with the source/fiber exit bandwidth (see 5.4). The link loss budget is calculated for the maximum loss situation and for the minimum loss situation (for applications where the active devices are to be used with cable plants of different lengths or complexities). Once the minimum and maximum link loss budgets have been calculated, the power available at the receiver can be compared to the candidate receivers' average sensitivities and maximum average input optical power levels at the desired BER and the link receiver can be selected.

5.3.4 Link viability. At each stage of the design process there are numerous decisions to be made which may affect the viability of the link design. If, after the distortion and link loss budget calculations are complete, no receivers are found that will meet the link requirements, the link designer should reconsider earlier component decisions.

5.4 Distortion budgeting.

5.4.1 General. This section details the calculations for determining the source/fiber exit bandwidth as well as the total fiber optic link bandwidth. This information is compared to the fiber optic receiver input specifications or to optical link requirements to determine if distortion limitations exist. This information can also be used to calculate link loss budget correction factors for distortion effects (see 5.6.4 and 5.6.5). Only the fiber optic transmitter, optical cable, and fiber optic receiver are included in calculations for the total optical link bandwidth. The effects of any other components on link bandwidth are negligible and, except for extreme cases, tend to increase the measured bandwidth. (The discrete link components filter out higher order modes in the link, causing an increase in the measured bandwidth. Therefore, ignoring their effect is a conservative approach.) Throughout this standard, all references to component rise times refer to the 10 to 90 percent rise time of the component when stimulated with an input step function. The bandwidths are specifically referred to as either a -3 dB or -6 dB bandwidth measured in the electrical domain. Relationships between commonly specified parameters for each of the components are identified to help convert manufacturer's information into the proper form. In each equation the units of each variable are stated. If the manufacturer's information is in units other than those stated, the information must be converted to the stated units before the equation is used.

5.4.2 Fiber optic transmitters. The fiber optic transmitter is generally specified by the 10 to 90 percent rise time. If the transmitter is specified by a -3 dB bandwidth, this bandwidth can be converted to a rise time assuming that the transmitter has an exponential time response. The rise time associated with the -3 dB bandwidth is given by

$$t_s = \frac{0.35}{BW_{s(-3)}} \qquad (1)$$

where t_s is the transmitter rise time (in seconds) and BW_s is the transmitter bandwidth (in Hz).

5.4.3 Optical cable. The optical fiber may cause temporal degradation of the optical signal in two ways. In a multimode fiber each different mode has a slightly different group velocity, so that relative delays are introduced between different modes at the fiber output end. This type of distortion, called multimode or modal distortion, is described by the modal bandwidth of the installed cable. Modal distortion affects only multimode fibers. The other distortive effect introduced by the fiber is caused by the relative delays experienced between different wavelengths of light at the fiber exit end. This type of distortion arises from several factors and is called chromatic dispersion. The chromatic dispersion is dependent upon the actual shape of the fiber optic transmitter optical spectrum and the fiber's response to this spectrum. Chromatic dispersion affects both single mode and multimode optical fibers.

5.4.3.1 Modal distortion (multimode fibers only). The modal bandwidth reported by the fiber or cable manufacturer (EIA/TIA-455-30 or EIA/TIA-455-51) is defined as the -6 dB electrical bandwidth (-3 dB optical bandwidth). Generally, the installed cable modal bandwidth is not measured. It may be estimated from the cable manufacturer's normalized modal bandwidth data or normalized modal bandwidth minimum specifications as

$$BW_{m(-6)} = \frac{BW_{mc}}{(L_c)^{\gamma}} \qquad (2)$$

where $BW_{m(-6)}$ is the estimated cable modal bandwidth in hertz, BW_{mc} is the normalized cable modal bandwidth (-6 dB, in Hz·km), L_c is the installed cable length (in km), and γ is a length scaling factor. For different cables γ ranges between 0.5 and 1.0 (the fiber manufacturer may provide, upon request, a recommended value of γ for their fiber). If a value of γ is not available a value of 1.0 should be used for lengths greater than 1 km and a value of 0.5 should be used for lengths less than 1 km.

5.4.3.2 Chromatic dispersion. Chromatic dispersion is commonly divided into two types: first order chromatic dispersion and second order chromatic dispersion. At wavelengths far from the fiber zero dispersion wavelength, λ_0, first order chromatic dispersion effects dominate the overall chromatic dispersion. At wavelengths near λ_0, second order chromatic dispersion effects dominate the overall chromatic dispersion.

5.4.3.2.1 First order chromatic dispersion. If the fiber optic transmitter is assumed to have a Gaussian spectrum, the first order chromatic dispersion impulse response is Gaussian (see 6.3e for more information) and the rise time, t_{cd1} (in seconds), associated with first order chromatic dispersion is given by

$$t_{cd1} = 2.6\ \sigma_\lambda D L_f \qquad (3)$$

where σ_λ is the fiber optic transmitter RMS spectral width (in nm), D is the fiber dispersion at the fiber optic transmitter centroid wavelength (in s/nm·km), and L_f is the installed fiber length (in km).

5.4.3.2.2 Second order chromatic dispersion. If the fiber optic transmitter is assumed to have a Gaussian spectrum, the second order chromatic dispersion impulse response is a modified exponential and the rise time t_{cd2} (in seconds) associated with second order chromatic dispersion, is given by

$$t_{cd2} = 1.4\ (S + 2D/\lambda_c)\ \sigma_\lambda^2\ L_f \qquad (4)$$

where σ_λ is the fiber optic transmitter RMS spectral width (in nm), D is the fiber dispersion at the fiber optic transmitter centroid wavelength (in s/nm·km), L_f is the installed cable length, S is the dispersion slope at the fiber optic transmitter centroid wavelength (in s/nm^2·km), and λ_c is the fiber optic transmitter centroid wavelength (in nm). Additional information can be found in 6.3d and e.

5.4.3.3 Approximations. If some of the information required to calculate the first order and second order chromatic dispersion (in s/nm·km) is not known the following approximations can be made. The fiber dispersion and the dispersion slope (in s/nm$^2\cdot$km) at the fiber optic transmitter centroid wavelength can be obtained as follows:

$$D = \frac{S_o}{4}\lambda_c\left[1 - \left(\frac{\lambda_o}{\lambda_c}\right)^4\right] \qquad (5)$$

$$S = \frac{S_o}{4}\left[1 + 3\left(\frac{\lambda_o}{\lambda_c}\right)^4\right] \qquad (6)$$

where λ_o is the zero dispersion wavelength of the fiber (in nm), S_o is the dispersion slope at the zero dispersion wavelength (in s/nm$^2\cdot$km), and λ_c is the centroid wavelength of the fiber optic transmitter (in nm).

5.4.3.3.1 Centroid wavelength. If the centroid wavelength of an LED transmitter is not known, it may be approximated using the FWHM center wavelength (in nm) as follows

$$\lambda_c = \lambda_{FWHM} - 7\,nm \qquad (7)$$

where the 7 nm shift is introduced to take into account the nonGaussian shape of the typical fiber optic transmitter optical spectrum. For laser sources the centroid wavelength is approximately equal to the FWHM center wavelength. Additional information can be found in 6.3f.

5.4.3.3.2 Source RMS spectral width. If the source RMS spectral width is not known, it may be approximated (assuming a Gaussian optical spectrum) using the FWHM spectral width (in nm) as follows:

$$\sigma_\lambda = \frac{\sigma_{FWHM}}{2.4} \qquad (8)$$

5.4.3.3.3 Zero dispersion wavelength. For germanium doped silica optical fibers, the zero dispersion wavelength (in nm) of the fiber is not known, but the fiber numerical aperture is, the zero dispersion wavelength may be estimated using the following relation

$$\lambda_o = 1221 + 426\,NA \qquad (9)$$

where NA is the fiber numerical aperture. The fiber numerical aperture can be obtained from the fiber manufacturer or can be approximated by using the specification value for the fiber. If the dispersion slope at the fiber zero dispersion wavelength is not known a value of 1.1 x 10^{-13} s/nm^2·km is used. Additional information can be found in 6.3g.

5.4.4 Fiber optic receivers. The fiber optic receiver is generally specified by the 10 to 90 percent rise time. If the receiver is specified by a -3 dB bandwidth, this bandwidth can be converted to a rise time assuming that the receiver has a raised cosine frequency response. The rise time associated with the -3 dB bandwidth is given by

$$t_r = \frac{0.35}{BW_{r(-3)}} \qquad (10)$$

where t_r is the fiber optic receiver rise time (in seconds) and $BW_{r(-3)}$ is the fiber optic receiver -3 dB bandwidth (in Hz). Additional information can be found in 6.3d.

5.4.5 System bandwidth. The fiber optic transmitter, receiver, fiber modal, first order chromatic and second order chromatic distortions are effectively independent. Therefore, the RMS widths of the components' impulse responses may be added in a RMS fashion and conversions made to bandwidth and risetime. If this is done, the result gives the total optical link or system rise time. It is given by

$$t_T = \left[(1.2\ t_s)^2 + t_{cd1}{}^2 + \left(\frac{1.9\ t_{cd2}}{\sqrt{2}}\right)^2 + \left(\frac{0.65}{BW_{m(-6)}}\right)^2 + (0.94\ t_r)^2\right]^{\frac{1}{2}} \qquad (11)$$

where t_T is the total optical link or system rise time and the other variables are defined as before. The total optical link or system -3 dB bandwidth is given by

$$BW_{T(-3)} = \left[\left(\frac{t_s}{0.29}\right)^2 + \left(\frac{t_{cd1}}{0.34}\right)^2 + \left(\frac{t_{cd2}}{0.25}\right)^2 + \left(\frac{1}{0.52\ BW_{m(-6)}}\right)^2 + \left(\frac{t_r}{0.36}\right)^2\right]^{-\frac{1}{2}} \qquad (12)$$

where $BW_{T(-3)}$ is the total optical link or system -3 dB bandwidth (in Hz) and the other variables are defined as before. If the source/fiber exit rise time or bandwidth is being calculated, remove the term for the receiver from each of the above equations. For single mode systems calculations, remove the modal bandwidth term from each of the above equations. Additional information can be found in 6.3d.

5.4.6 Applying the equations. The above equations are used in many ways. During initial link design, these equations are used to conduct tradeoff analyses for different transmitter, receiver or fiber choices (see 5.3). If the link design utilizes a previously installed fiber optic cable plant or previously obtained fiber optic transmitters and receivers, the above equations are used to determine the requirements for the undetermined components of the link and evaluate the suitability of any proposed components, or component changes, for the link.

5.4.6.1 Evaluation of the viability of link construction. Most fiber optic receiver manufacturers define a specific maximum input rise time or a minimum input bandwidth required for proper receiver operation. In this case, the above equations allow the calculation of either source/fiber exit bandwidth or rise time to evaluate the viability of the particular link design. If the calculated source/fiber exit bandwidth or rise time is not adequate for the system receiver, the fiber optic transmitter central wavelength, spectral width, or the link length (if possible) should be changed to allow proper operation. Proper operation in some cases is accompanied by a requirement for a slightly higher input power level to the fiber optic receiver. This effective change in the fiber optic receiver sensitivity as a function of the fiber optic transmitter/cable exit rise time/bandwidth is referred to as the dispersion power penalty and is described in 5.6.4.

5.4.6.2 Bandwidth limitations due to dispersion. In those cases where either the detailed fiber optic receiver information is not known or the general use of a fiber optic link is being evaluated, general distortion design guidelines based on classical communications theory are used to identify bandwidth limitations. Using the Nyquist criteria, the minimum channel -3 dB bandwidth must be at least one-half the link baud. This lower limit for the link -3 dB bandwidth does not take into account many errors which may be introduced in the link due to timing and phase distortions. A more conservative approach is to require the total optical link -3 dB bandwidth to be greater than 0.7 of the link baud. That is

$$\begin{aligned} BW_{T(-3)} &\geq 0.7\ baud \\ &\geq 0.7\ \mathrm{E}\ bit\ rate \end{aligned} \tag{13}$$

where $BW_{T(-3)}$ is the total optical link -3 dB bandwidth (in Hz) and the link baud is equal to the bit rate multiplied by the link's bit rate to baud conversion factor (E). The conversion factors for some typical digital coding formats are given in table VI. If the above total optical link -3 dB bandwidth is equally allocated to the fiber optic receiver and the source/fiber pair, the minimum -3 dB bandwidth (in Hz) for the fiber optic receiver and the minimum source/fiber exit electrical bandwidths are given by

$$BW_{r(-3)} = BW_{ex(-3)} = baud \tag{14}$$

Table VI. Bit rate to baud conversion factors.

Digital Coding Format	E
NRZ (level, mark or space)	1
RZ	2
Manchester	2
RZ-PPM (pulse position)	4
RZ-PDM (pulse duration)	3
Biphase (level, mark or space)	2
Miller	2
NRZ Bipolar	1
RZ Bipolar	4
Bipolar AMI (alt mark inv)	4
mB/nB	n/m

5.5 Loss budget.

5.5.1. General. This section details methods for the calculation of a loss budget for a fiber optic link. These methods allow a system designer to evaluate the tradeoffs between the system length, number of connectors, cable loss, and different transmitter and receiver combinations. The purpose of a loss budget is to ensure that sufficient optical power is delivered to the receiver over the anticipated life of the system.

5.5.1.1 Point-to-point fiber optic link. The most basic fiber optic link consists of a transmitter, a receiver, and an interconnecting optical fiber. Figure 18 is a schematic diagram of a point-to-point fiber optic link. (The diagram is generic in nature and is not intended to be a design recommendation or representative of any particular installed link. It is intended to aid in describing the loss budgeting process by showing common fiber optic components and their possible configuration in a link.) Although individual point-to-point links are considered for analysis, the overall fiber optic topology may contain branching devices such as splitters and switches. If this is the case, then every possible transmitter-to-receiver fiber path must be modeled as a point-to-point link in the loss budget process. An optical transmitter, receiver, multifiber cables, jumper cables, connectors, splices, and "other passive device" comprise the system in figure 18. It is assumed that the transmitter optical output is located at a connector. The connector may terminate an internal or external pigtail or be integral to an active device mount. Likewise, the receiver optical input is assumed to be located at a connector. The link may include jumper cables for interconnection purposes, such as interconnecting a transmitter to a cable at a patch panel. There may be one or more multifiber cables including local cables and trunk cables. The total length of each jumper or cable must be known. As described in 4.2.2, splices are used to provide permanent connections between two optical fibers, and connectors are used to provide changeable connections between two fibers. The "other passive device" represents an optical switch, coupler/splitter, wavelength division multiplexer (WDM), and so forth. The total number of splices (including allocated repair splices), the total number of connectors, and the total number of "other passive devices" must be known in order to determine the loss budget.

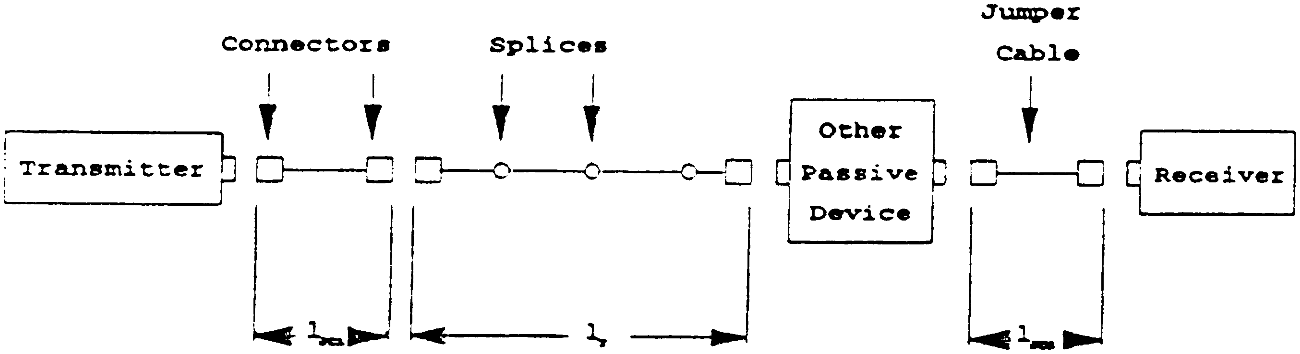

FIGURE 18. Fiber optic system schematic.

5.5.2 Component loss parameters. The manufacturers should provide attenuation values (dB/km) for any jumper cables and multifiber cables, loss values (dB) for the discrete components, the transmitter output power (dBm), and the receiver sensitivity (dBm). For single mode systems, the values of cable attenuation (EIA/TIA-455-78), interconnection device loss (EIA/TIA-455-34), and passive device loss (EIA/TIA-455-180) should be provided. For multimode systems, in order to obtain the most accurate design, cable attenuation values (EIA/TIA-455-46 with EIA/TIA-455-50) and cable transient loss data (see section 3.1.1) should be provided. In addition, values for both restricted launch conditions (EIA/TIA-455-34 Method B for interconnection devices, or EIA/TIA-455-180 for passive branching devices) and overfill launch conditions (EIA/TIA-455-34 Method A for interconnection devices, or EIA/TIA-455-180 for passive branching devices) should be provided for the passive components. If the manufacturer does not normally provide cable transient loss data or both the restricted and overfill launch loss values for multimode products, the manufacturer should be asked for guidance on how to estimate the missing information for their product. The provided values should be representative of current production and should be measured in accordance with the military specification for the component. The values may be either worst case values or the mean and standard deviation of a large population of components.

5.5.2.1 Component loss dependencies. The loss of a component in a multimode link is dependent upon the Mode Power Distribution (MPD) (EIA-455-109) of the source, the component's location in the link, the types of components which precede it in the link, and the component's own MPD sensitivity. The loss values provided by component manufacturers do not account for these dependencies. Furthermore, these dependencies are complex and not easily predictable. The procedures outlined in this document take these dependencies into account and provide a means of predicting multimode link loss performance.

5.5.2.2 Total link loss. For the most conservative link loss design, overfill loss values for all of the passive components and the transient loss of the cable should be used in the link loss calculation. In most cases this conservative approach will overestimate the total link loss. The total loss of a multimode fiber optic link is best estimated by using loss values that are between a restricted launch condition loss value and the OFL loss value (Additional information can be found in 6.3h.). The exact value of this loss number is dependent upon the mode volume excited by the source, the complexity of the link and the effect of each component on the mode volume. This loss value is expressed as

$$L_x = L_{x(LPS)} + K(L_{x(OFL)} - L_{x(RES)}) \qquad (15)$$

where $L_{x(OFL)}$ is the component overfill loss value (in dB), $L_{x(LPS)}$ is the component restricted launch condition loss value and K is a constant which can have a value between 0 and 1. A K value of 1 indicates that the light source tends to fill most of the fiber modes and is typical of most surface emitting LEDs. A K value of 0.5 indicates that the source does not fill some of the fiber higher order modes and is typical of most edge emitting LEDs. A K value of 0.0 indicates that the source only fills the lower order modes of the fiber and is typical of most lasers. The value of K that should be used can be determined from Table VII if the source CPR value is known. The source CPR value is defined as the difference (in dB) between the total source power launched into the multimode fiber and the power launched into the low order modes of the multimode fiber (see Appendix A). If the source CPR value is not known, the most conservative link design is obtained by using a K value of 1.

5.5.2.2.1 Transient loss. If the link source substantially overfills the fiber, the fiber may exhibit a transient loss. A convenient way to handle this effect is to include a single term in the design equations to account for this additional loss. The term is called the transient loss and is represented by the letter T. The transient loss for the link can be estimated from the cabled fiber transient loss data using the cabled fiber transient loss value for the cable at a length equal to that of the total link length. Table VII indicates when the transient loss term should be included in the loss budget equation.

TABLE VII. Recommended values for K.

Fiber Size	Source CPR Value (dB)	K	Include Transient?
62.5/125 μm	0 to 17.0	0.0	no
	17.0 to 21.0	0.5	no
	21.0 to 25.0	0.7 to 1.0 (Conservative)	yes

5.5.3 Loss budget equation. There are two basic loss budget methods that may be used. They are the statistical method and the worst case method. The statistical loss budget method considers the probabilities of the worst case loss values for all link components occurring simultaneously in a single transmitter-to-receiver link. Each link component is modeled as a normally distributed random variable. The total passive component loss is equal to the summed mean component losses plus a multiple (X) of the RMS sum of the components' standard deviations. The value of X used can be correlated to the degree of confidence that any transmitter-to-receiver section will operate properly. Table VIII indicates the level of confidence in a statistical design using specific multiples of the standard deviation. For all Navy applications a minimum value of 2 shall be used for X (a 2 sigma statistical design). The worst case method is based on the small probability that the worst case component loss values for all link components has occurred simultaneously in a single link. The use of the statistical budgeting method can provide a more efficient use of resources than the worst case method by reducing excess design margin.

TABLE VIII. Confidence levels for statistical designs.

Value of X	Confidence Level
1	0.841
2	0.977
3	0.999

5.5.3.1 Statistical loss budget. For statistical design, the mean (μ) and standard deviation (σ) of the loss values are used in the design equation for each link component. If statistical values for a component are not available, then the worst case method must be used as described in 5.5.3.2. The statistical loss budget equation is:

$$0 \leq P_T - P_R - M - T - A - \mu_E - l_{JC}\mu_{JC} - l_T(\mu_C + \mu_\lambda) - N_{CO}\mu_{CO} - N_S\mu_S - N_O\mu_O \quad (16)$$

$$- X\left[\sigma_T^2 + \sigma_R^2 + \sigma_E^2 + (l_{JC}\sigma_{JC})^2 + l_T l_C \sigma_C^2 + N_{CO}\sigma_{CO}^2 + N_S\sigma_S^2 + N_C\sigma_C^2\right]^{\frac{1}{2}}$$

where:

P_T, σ_T = The mean and standard deviation of the transmitter output power (dBm). Aging and temperature effects may be accounted for in the mean and standard deviation.

P_R, σ_R = The mean and standard deviation of the receiver sensitivity (dBm) required to achieve the desired bit error rate or signal to noise ratio. Aging and temperature effects may be accounted for in the mean and standard deviation.

M = Safety margin (dB) for unexpected losses. For Navy non-tactical applications a value of 3 dB shall be used. For Navy tactical applications a value of 3 dB shall be used if an environmental margin is calculated (see 5.6.3). If an environmental margin is not calculated, a value of 6 dB shall be used for Navy tactical applications.

μ_B, σ_E = The mean and standard deviation of the environmental margin (dB) for adverse operating conditions (see 5.6.3).

A = Adjustments (dB) to the link loss budget including power penalties associated with specific system designs and the allowance for future upgrading (higher bit rates or wavelength division multiplexing) including additional component losses as well as any additional power penalties (see 5.6.1, 5.6.2, 5.6.4, 5.6.5, 5.6.6, 5.6.7, 5.6.8, and 5.6.9).

T = Transient loss (dB). This term accounts for the higher fiber loss associated with the launching of power into higher order modes by some link sources.

l_{JC} = The total jumper cable length (km).

μ_{JC}, σ_{JC}, = The mean and standard deviation of the jumper cable attenuation (dB/km).

l_T = The total multifiber cable length (km). This value may include an allowance for cable repair or rearrangement.

l_C = The average multifiber cable length (km).

μ_C, σ_C = The mean and standard deviation of the multifiber cable attenuation (dB/km) at the transmitter's nominal center wavelength. σ should include an allowance for the supplier's loss measurement uncertainty.

μ_λ = The increase in mean cable attenuation (dB/km) above μ_C at the wavelength within the transmitter's center wavelength range at which the largest mean plus two sigma loss occurs. (The cable attenuation will tend to be higher at one end of the transmitter central wavelength specification range than at the middle of the range.)

N_{CO} = The total number of connectors.

μ_{CO}, σ_{CO} = The mean and standard deviation of the connector loss (dB). For connectors which will be mated and demated repeatedly these values should include the degradation in loss expected over the lifetime of the connector.

N_S = The total number of splices.

μ_S, σ_S = The mean and standard deviation of the splice loss (dB).

N_O = The total number of "other passive devices" of one type.

μ_O, σ_O = The mean and standard deviation of the "other passive device" loss (dB). For switches which will experience repeated state changes these values should include the degradation in loss expected over the lifetime of the switch.

In calculating the minimum link loss to evaluate possible receiver saturation, the same equation as shown in equation (17) is used. However, the receiver sensitivity, the safety margin, transient loss, adjustments, the environmental margin and the standard deviations of these terms should not be included. Additionally, the multiple of the remaining standard deviations is added so that the equation becomes

$$\begin{aligned} P_{Rmax} \geq {} & P_T - l_{JC}\mu_{JC} - l_T(\mu_C + \mu_\lambda) - N_{CO}\mu_{CO} - N_S\mu_S - N_O\mu_O \\ & - X\left[\sigma_T^2 + (l_{JC}\sigma_{JC})^2 + l_T l_C \sigma_C^2 + N_{CO}\sigma_{CO}^2 + N_S\sigma_S^2 + N_O\sigma_O^2\right]^{\frac{1}{2}} \end{aligned} \tag{17}$$

where all of the variables are defined as in equation (17).

5.5.3.2 Worst case loss budget. This method is used to ensure that all transmitter receiver sections will operate properly under worst case conditions or when statistical values are not available for the components. The maximum loss value is substituted for the mean and zero is substituted for the standard deviation for each component in the link. The total passive component loss is equal to the summed maximum component losses.

5.5.4 Statistical assumptions. If the statistical design method is used, the following assumptions are inherent in equation 16:

a. All splice losses are uncorrelated with fiber losses.
b. Cable losses, except those associated with transmitter wavelength variation, are correlated over the mean reel length, but are uncorrelated from reel to reel.
c. The averages and standard deviations are representative of the products over time and sample sizes are sufficient to warrant the use of Gaussian statistical theory.
d. The product distributions are reasonably Gaussian in shape. That is, they are not severely truncated, skewed, and do not have large kurtosis (thicker than Gaussian at the extremes). For links with more than a few elements, the link loss probability distribution will approach Gaussian regardless of the shape of the product loss probability distributions.

5.6 Adjustments to the loss budget. This section lists and explains various adjustments which may be made to a link loss budget to account for degradations that may occur in fiber optic links due to component interactions and any future changes to the link configuration. Future changes may include such items as change of operating wavelength, conversion to WDM or duplex operation. It is straightforward to calculate the effect of these changes on the loss budget. Other adjustments for various link degradations (for example, dispersion, jitter, modal noise, operating environment) are more difficult to assess. Some may be determined by means of complex calculations; others are merely rules of thumb obtained from experienced system designers. For each link degradation adjustment, the following information is provided:

a. the common terms for the degradation (if applicable)
b. a brief discussion of its causes
c. how to determine whether the adjustment is applicable for the design under consideration
d. how to determine its effect on the loss budget

5.6.1 Growth and future unknowns. Optical fiber systems are often upgraded during the lifetime of the ship to provide more information capacity than the requirements of the initial installations. Typically, upgrades consist of either a change in operating wavelength, an increase in the transmission bit rate or the use of WDM techniques. If upgrades are planned or can be predicted, distortion budgets and loss budgets shall be calculated for each planned upgrade. Loss budgets shall be calculated as described in 5.5 for each wavelength planned and shall include any additional components to be added in the link (such as WDM couplers) and the dispersion power penalty for that wavelength and transmission bit rate. For upgrades which involve the use of WDM techniques, the additional adjustments described in 5.6.9 shall also be included.

5.6.2 Aging. In general, the excess power margin of a fiber optic link decreases as the components within that link age. Most of this is due to the effects of aging on the link active components and has already been taken into account in the values used in the link loss budget in 5.5. If the effects of aging on the transmitter and receiver are not known, they shall be approximated by derating the mean or worst case source output power and the mean or worst case receiver sensitivity by the amount shown in table IX. The values shown are used as the failure definitions for active devices in the determination of those device mean times before failure (MTBF). For the link passive components, aging is not generally considered to affect their optical performance (except for catastrophic failures). Exceptions to this are the insertion loss of connectors and switches that are expected to see repeated matings and dematings or repeated state changes during their lifetime. The mean or maximum loss increase over the lifetime of these components and the standard deviations shall be obtained from the component manufacturer and included in the mean or maximum loss value used in the loss budget (see 5.5.3).

TABLE IX. Active device aging derating factors.

Active Device	Derating Factor (dB)
LED/Transmitter	- 1.5
Laser/Transmitter (with constant current)	- 1.5
Laser/Transmitter (with constant power feedback loop)	0.0
Detector/Receiver	+ 1.0

5.6.3 Environmental/thermal considerations. In general, the link loss budget is affected by the environments that each of the components is subject to. These environments may include extreme conditions of temperature, bending, shock, vibration, or radiation. Other environments may be present in specific applications.

5.6.3.1 Standard environments. Degradations that can be expected of the Navy standard components in a worst case Navy environmental scenario (excluding radiation) are listed in table X. Fiber optic transmitters and receivers are not listed because their performance specifications should be stated for all conditions. If the link design is to account for radiation, see 5.6.3.2. The effects of adverse environments on the link passive components can be incorporated into the link loss budget by including into μ_E the mean or maximum induced degradation of each component and including into σ_E the standard deviation of that degradation (see equation 17).

TABLE X. Component environmental degradation factors.

Fiber Optic Component	Environmental Derating Factor (dB)			
	Multimode		Single mode	
	Mean	Sigma	Mean	Sigma
Cable	1.35	0.45	1.35	0.45
Light Duty Connector	0.25	0.08	[1]	[1]
Heavy Duty Connector	0.25	0.08	[1]	[1]
Light Duty Fiber Splice	0.16	0.05	0.16	0.05
Cable Splice	0.16	0.05	0.16	0.05
Switch	0.35	0.12	[1]	[1]
Coupler	[1]	[1]	[1]	[1]

[1] Values for these components are not available. Contact the NAVSEA Fiber Optic Program Office for recommended values.

5.6.3.2 Nuclear radiation. The presence of nuclear radiation may cause the total link loss to increase. This is due to the increase in the fiber attenuation rate (fiber darkening) and the increase in the loss of any lenses present in the fiber optic link. The amount of the attenuation or loss increase in the fiber or lenses is dependent upon the total dose of radiation received, the dose rate of the exposure, and the temperature of the component. Radiation also affects the link active components by reducing transmitter output power and decreasing receiver sensitivity. In those links where radiation is expected, the transmitters and receivers should be protected from the radiation so that only passive components are affected. The effect of radiation can be incorporated into the loss budget by including into μ_E the mean or maximum radiation induced degradation of each component affected by radiation and including into σ_E the standard deviation of that degradation (see equation 18).

5.6.3.3 Total environmental margin. The mean and standard deviation of the total environmental margin are given by:
where:

l_{JC} = The total jumper cable length (km).

$$\mu_E = l_{JC}(\mu_{JC}+\mu_{RJC}) + l_T(\mu_C+\mu_{RC}) + N_{CO}(\mu_{CO}+\mu_{RCO}) + N_S(\mu_S+\mu_{RS}) + N_O(\mu_O+\mu_{RO})$$

$$\sigma_E=\left[l_{JC}^2(\sigma_{JC}^2+\sigma_{RJC}^2)+l_T l_C(\sigma_C^2+\sigma_{RC}^2)+N_{CO}(\sigma_{CO}^2+\sigma_{RCO}^2)+N_S(\sigma_S^2+\sigma_{RS}^2)+N_O(\sigma_O^2+\sigma_{RO}^2)\right] \tag{18}$$

μ_{JC}, σ_{JC}, = The mean and standard deviation of the environmentally induced jumper cable attenuation (dB/km).

μ_{RJC}, σ_{RJC}, = The mean and standard deviation of the radiation induced jumper cable attenuation (dB/km).

l_T = The total multifiber cable length (km). This value may include an allowance for cable repair or rearrangement.

l_C = The average multifiber cable length (km).

μ_C, σ_C = The mean and standard deviation of the environmentally induced multifiber cable attenuation (dB/km) at the transmitter's nominal center wavelength.

μ_{RC}, σ_{RC} = The mean and standard deviation of the radiation induced multifiber cable attenuation (dB/km) at the transmitter's nominal center wavelength.

N_{CO} = The total number of connectors.

μ_{CO}, σ_{CO} = The mean and standard deviation of the environmentally induced connector loss (dB).

μ_{RCO}, σ_{RCO} = The mean and standard deviation of the radiation induced connector loss (dB).

N_S = The total number of splices.

μ_S, σ_S = The mean and standard deviation of the environmentally induced splice loss (dB).

μ_{RS}, σ_{RS} = The mean and standard deviation of the radiation induced splice loss (dB).

N_O = The total number of "other passive devices" of one type.

μ_O, σ_O = The mean and standard deviation of the environmentally induced "other passive device" loss (dB).

μ_{RO}, σ_{RO} = The mean and standard deviation of the radiation induced "other passive device" loss (dB).

5.6.4 Dispersion power penalty. There are a number of power penalties related to temporal distortion. In this document, the dispersion power penalty is defined as the power penalty arising from intersymbol interference problems generated by temporal distortion and dispersion related pulse broadening. Because of the fiber's finite bandwidth, higher modulation frequencies are attenuated more than lower frequencies, leading to an effective reduction of power at the receiver. This power penalty can be thought of as the additional power needed to be launched by the transmitter to compensate for the reduction of power within each bit period due to distortion effects within the link. The dispersion power penalty can be expressed as ten times the logarithm of the system frequency response evaluated at a frequency equal to the reciprocal of two times the bit period. If the total link response is assumed to be Gaussian, this becomes

$$P_D = 1.42\left[\frac{baud}{BW_{T(-3)}}\right]^2 \qquad (19)$$

where P_D is the dispersion power penalty (in dB), baud is the link baud (in bits per second) and $BW_{T(-3)}$ is the total link bandwidth (in Hz) (see 5.4). Additional information on the dispersion power penalty is found in 6.3i and j. If the link transmitters and receivers are available the dispersion power penalty can be measured using EIA/TIA-526-10.

5.6.5 Mode partition noise penalty. The mode partition noise (MPN) penalty is a dispersion related noise penalty which arises from the use of multilongitudinal mode lasers as fiber optic link sources. MPN in multilongitudinal lasers (the time varying distribution of power among the laser longitudinal modes) coupled with the fiber chromatic dispersion reduces the signal to noise ratio (SNR) at the link receiver. In multimode fiber optic links, MPN also produces time varying connection losses and results in increased modal noise (see 5.6.9). As long as LEDs or lasers with many longitudinal modes are used in a multimode fiber optic link MPN does not need to be considered. In single mode links and multimode links using lasers with only a few longitudinal modes, the MPN penalty can be calculated from

where baud refers to link baud (in bits per second) and $BW_{cx(-3)}$ is the

$$P_{MPN} = 0.5 \left[\frac{baud}{BW_{ax(-3)}} \right]^4 \qquad (20)$$

source/fiber exit bandwidth (in Hz). Additional information on mode partition noise can be found in 6.3i, k, l and m.

5.6.6 Single reflection power penalty. Another noise penalty that arises when lasers are used as fiber optic link sources is the single reflection (optical feedback noise) power penalty. The length of fiber between the laser and the first point of reflection acts as an (poor) external cavity. The power reflected back into the laser from this external cavity disturbs the laser's internal oscillation. The properties of this external cavity are time varying due to mechanical and environmental variations around the cavity. Because of the time variations of the external cavity properties, the laser cannot lock onto a mode of the external cavity and the laser output becomes noisy. The single reflection (SR) power penalty is dependent upon the particular design and construction of the laser used. The laser manufacturer should provide a value of the SR power penalty as a function of the return loss of the first reflection. If the link transmitters are available the SR power penalty can be measured using EIA/TIA-526-11.

5.6.7 Modal noise penalty. An additional noise penalty that occurs when lasers are used as optical sources in multimode links is the modal noise power penalty. Modal noise is generated when coherent light is launched into a multimode optical fiber and is characterized by a speckle pattern at the exit face of the fiber. This speckle pattern is the result of the random interference of the many different propagation modes in the fiber. Changes in the source wavelength or MPN, as well as any mechanical or environmental variations around the fiber, cause changes in the speckle pattern. At each interface, the speckle pattern is dependent upon distribution of constructive or destructive interference in the various modes. Since connector and splice insertion loss and coupler splitting ratios are affected by modal noise, the component's loss may vary in time. Modal noise is avoided in multimode fiber optic links if the laser used has many longitudinal modes or is made relatively incoherent (see 6.3m). The laser coherence can be destroyed by pulsing the laser at a repetition rate much in excess of the link baud (for example, dithering the laser as done in self-pulsating lasers). When standard lasers with only a few longitudinal modes are used with multimode fiber the modal noise power penalty is not predictable. Values of the modal noise power penalty may be as high as several dB depending upon the system design and the particular laser used. Modal noise is not a problem in single mode fiber optic links as long as connectors and splices with losses less than 1 dB are used. In some cases the modal noise power penalty will be infinite (for example, the link will experience a BER floor); no amount of additional power will decrease the link BER. Additional information on modal noise can be found in 6.3h, p and q.

5.6.8 Jitter power penalty. Previous sections have considered noise only with respect to signal amplitude. The relative amplitude of such noise is expressed by the SNR. This section discusses jitter which concerns a noise-like property of signal phasing or timing. Jitter is defined as the short-term noncumulative variations of the significant instants of a digital signal from their ideal positions in time. Generally, the significant instants refer to that portion of the digital waveform used for timing. Jitter is divided into two types; deterministic and random.

Deterministic jitter is the component of jitter that is correlated with a device transfer parameter and includes duty cycle distortion and pattern dependent jitter. The magnitude of pattern dependent jitter is a function of the data pattern employed to measure it. In practice, pattern dependent jitter measurements include both pattern dependent jitter and duty cycle distortion so represent the total deterministic jitter.

Random jitter is defined as that component of jitter that is uncorrelated with any component of the affected signal or device transfer parameters. Random jitter is generated when a noise contaminated, bandwidth-limited signal is processed by a threshold device. Each component of the link contributes to random jitter either directly by increasing the noise of the signal or indirectly by further bandwidth-limiting the signal.

Jitter is manifested in a digital signal as the reduction of the eye width in a eye pattern diagram due to the temporal spreading of the transition region for both the leading and trailing edge of the pulses (see Figure 19).

The jitter in a link is a function of the SNR and is usually accompanied by an increase in the link BER. Typically, the increase in the BER can be offset by increasing the power available at the receiver by some amount referred to as the jitter power penalty. The effect of jitter on system performance depends on the application as well as the design and performance of the electronic components after the link receiver. For applications in which repeaters are not used, jitter is generally not an issue in link design. In many cases the spectral content of the jitter is just as important as the magnitude of the jitter. For example, when post-receiver components with low-

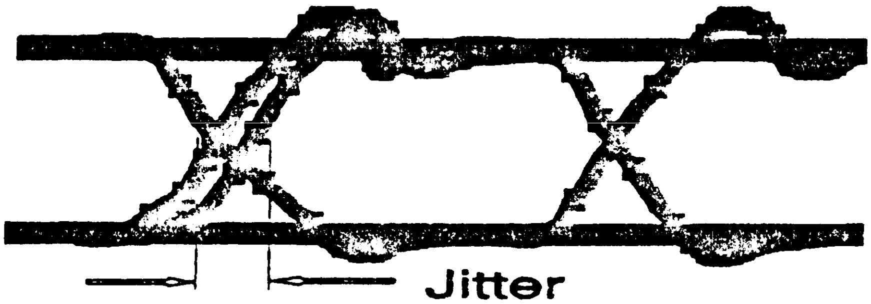

Figure 19. Eye Pattern.

pass frequency responses are used, these components will be relatively insensitive to higher frequency jitter components. Typically, jitter specifications cover a specified frequency range and test procedures include filters to limit the spectral content of the measured jitter.

5.6.8.1 Total output jitter. The total output jitter in the link is a function of the input jitter in the electrical signal driving the transmitter and the jitter introduced by the transmitter, the fiber, the receiver, and the clock recovery module. Each component introduces both random and deterministic jitter except for the fiber, which only directly introduces deterministic jitter (the fiber contributes to the random jitter by decreasing the link bandwidth). The transmitter contributes to the random jitter because of noise present within the transmitter that modulates the digital signal timing. It contributes to the deterministic jitter in the form of pattern dependent jitter. The transmitters contribution to both the random and deterministic jitter in the link is usually small. The optical fiber contributes to deterministic jitter in the form of data dependent jitter due to its degrading of the signal bandwidth. The optical receiver contributes to the random jitter by increasing the noise level on the signal and deterministic jitter in the form of data dependent jitter. The total deterministic jitter of the link is the algebraic sum of the constituent components' deterministic jitters. The total random jitter of the link is the RMS sum of the constituent components' random jitter. The worst case total jitter of the link is calculated by algebraically summing the total deterministic jitter with the total random jitter.

5.6.8.2 Jitter budget. A jitter budget may be performed to evaluate the jitter performance of a fiber optic link. Typically, the total output jitter from the receiver is compared to the maximum input jitter requirement for the clock recovery module. The total deterministic jitter (in seconds) is
where DJ_{in} is the input deterministic jitter to the transmitter (in

$$DJ_T = DJ_{in} + DJ_{TX} + DJ_f + DJ_{RX} \tag{21}$$

seconds), DJ_{TX} is the transmitter deterministic jitter (in seconds), DJ_f is the fiber deterministic jitter (in seconds), and DJ_{RX} is the receiver deterministic jitter (in seconds). The total random jitter (in seconds) is

$$RJ_T = \left[RJ_{in}^2 + RJ_{TX}^2 + RJ_{RX}^2\right]^{\frac{1}{2}} \tag{22}$$

where RJ_{in} is the input random jitter to the transmitter (in seconds), RJ_{TX} is the transmitter random jitter (in seconds), and RJ_{RX} is the receiver random jitter (in seconds). The jitters of the input signal to the transmitter are obtained from the manufacturer of the component or equipment generating that signal. The jitters introduced by the transmitter and receiver are obtained from the transmitter and receiver manufacturer. If these values are not available they can be measured using EIA/TIA-526-16, EIA/TIA-526/17 and EIA/TIA-526-18. The value of the deterministic jitter of the fiber can be determined from the input and output rise times of the fiber by comparing defined best case and worst case data patterns. An exponential impulse response is assumed at the input to the fiber and a gaussian impulse response is assumed at the output of the fiber. In this document the best case data pattern was considered to be one "on" state followed by an "off" state and the worst case data pattern was assumed to be three consecutive "on" states followed by an "off" state. The deterministic jitter of the fiber (in seconds) is then given by

$$DJ_f = Bt_{ex} - At_s \tag{23}$$

where t_s is the source rise time (in seconds), t_{ex} is the source/fiber exit rise time (in seconds), and the deterministic jitter constants A and B are given by table XI. (To determine the constant B, use the source/fiber exit rise time to baud period ratio. For A, use the source rise time to baud period ratio.) If more than three consecutive "on" states are considered in a link's data format the constants A and B will be slightly different. The total output jitter, J_T (in seconds), then is given by

$$J_T = DJ_T + RJ_T \tag{24}$$

5.6.8.3 Maximum input jitter requirement. In general, the clock recovery module specification will include a maximum input jitter requirement. The total jitter out of the receiver should be less than the maximum input jitter requirement of the clock recovery module. If the total output jitter from the receiver is greater than the maximum allowed for the clock recovery module, the receiver manufacturer should be contacted to determine the tradeoffs between receiver sensitivity and receiver jitter. The jitter budget can be recalculated for the differing values of receiver jitter (corresponding to different receiver sensitivities) until the clock recovery input requirement is met. The jitter power penalty is the difference in the initial and final values of the receiver sensitivity. If the input jitter specification for the clock recovery module is not known, the total output jitter from the receiver shall be less than 70 percent of the baud period. If calculations determine that the total output jitter from the receiver is more than 70 percent of the baud period, the designer should select a different transmitter or receiver with improved rise time or jitter specifications. Additional information on jitter can be found in 6.3r.

TABLE XI. Fiber deterministic jitter constants.

Rise time to Baud Period Ratio	Deterministic Jitter Constant	
	A	B
≤ 0.35	0.001	0.000
0.40	0.002	0.001
0.45	0.003	0.001
0.50	0.006	0.001
0.55	0.008	0.001
0.60	0.012	0.002
0.65	0.015	0.005
0.70	0.019	0.011
0.75	0.024	0.020
0.80	0.028	0.030
0.85	0.033	0.042
0.90	0.038	0.057
0.95	0.043	0.073
1.00	0.047	0.090

5.6.9 Other power penalties. In fiber optic systems other power penalties may exist, but in general are not significant. The exceptions to this are penalties due to crosstalk from WDM couplers in WDM links and to back-reflections from the transmitter to the receiver in bidirectional systems. In link designs that are bidirectional or where WDM techniques are being used, a loss budget for the crosstalk channel is calculated to verify that the power level of the crosstalk channel at the detector/receiver is well below the detector/receiver sensitivity.

5.7 Component reliability calculations. This section establishes uniform predictions for the reliability of Navy fiber optic components. The intent of this section is to augment MIL-HDBK-217 in the area of fiber optic component reliability calculations. Two of the derating factors used are generally applicable for all of the components. The temperature derating factor, π_T, for each component is given by

$$\pi_T = 1.6^{\frac{(T2 - 298)}{10}} \qquad (25)$$

where T2 is the expected operating temperature in Kelvin (the temperature in Celsius plus 273 degrees). The quality derating factor, π_Q, for each component is given in table XII.

TABLE XII. Fiber optic component quality factors.

Type of Component	π_Q
Listed on Qualified Parts List or first article tested	1.0
Manufactured to specification, but untested	1.5
Commercial, high quality	2.0
Commercial, average quality	4.0

5.7.1 Optical cable. The optical cable failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E X \pi_T X \pi_D X \pi_Q)$$

where: λ_p = Fiber optic cable failure rate
λ_b = Buffered optical fiber, fiber within an OFCC or a fiber within a multifiber cable base failure rate (see table XIII)

π_E = Environmental derating factor (see table XIV)
π_T = Temperature derating factor
π_s = Number of fibers in the cable
π_Q = Quality factor

TABLE XIII. Fiber optic component base failure rates.

Component	λ_b[1]
Buffered optical fiber	5.85
Fiber Within OFCC	1.09
Fiber Within Multifiber Cable	0.282
Light Duty Connector	0.110
Heavy Duty Connector	0.080
Single Fiber Splice	0.037

[1] (Failures/10^6 Hours)

TABLE XIV. Optical cable environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	13
Naval Surface Ship Sheltered	5.3
Naval Submarine	4.1

5.7.2 Light duty single terminus connectors. The light duty single terminus connector failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E X \pi_T X \pi_K X \pi_Q)$$

where:
λ_p = Light duty single terminus connector failure rate
λ_b = Single terminus connector base failure rate (see table XIII)
π_E = Environmental derating factor (see table XV)
π_T = Temperature derating factor
π_K = Mating/unmating derating factor (see table XVI)
π_Q = Quality factor

TABLE XV. Light duty connector environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	13
Naval Surface Ship Sheltered	5.3
Naval Submarine	4.1

TABLE XVI. Mating/unmating derating factors.

Mating/Unmating Cycles (per 1000 hours)	π_K
0 - 0.05	1.0
>0.05 - 0.5	1.5
>0.5 - 5	2.0
>5 - 50	3.0
>50	4.0

5.7.3 Heavy duty multiterminus connectors. The heavy duty multiterminus connector failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E X \pi_T X \pi_K X \pi_P X \pi_Q)$$

where:
λ_p = Heavy duty multiterminus connector failure rate
λ_b = Single connection base failure rate (see table XIII)
π_E = Environmental derating factor (see table XVII)
π_T = Temperature derating factor
π_K = Mating/unmating derating factor (see table XVIII)
π_P = Number of active termini in the connector (see table XIX)
π_Q = Quality factor

TABLE XVII. Heavy duty connector environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	13
Naval Surface Ship Sheltered	5.3
Naval Submarine	4.1

5.7.4 Light duty single fiber splices. The light duty single fiber splice failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E \times \pi_T \times \pi_Q)$$

where:
λ_p = Light duty single fiber splice failure rate
λ_b = Single fiber splice base failure rate (see table XIII)
π_E = Environmental derating factor (see table XX)
π_T = Temperature derating factor
π_Q = Quality factor

TABLE XVIII. Heavy duty connector mating/unmating derating factors.

Mating/Unmating Cycles (per 1000 hours)	π_K
0 - 0.05	1.0
>0.05 - 0.5	1.5
>0.5 - 5	2.0
>5 - 50	3.0
>50	4.0

TABLE XIX. Number of active termini derating factor.

Number of Active Termini	π_P
1	1.00
2	1.36
3	1.55
4	1.72
5	1.87
6	2.02
7	2.16
8	2.30

TABLE XX. Light duty splice environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	9.9
Naval Surface Ship Sheltered	4.4
Naval Submarine	3.5

5.7.5 Cable splices. The cable splice failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E X \pi_T X \pi_K X \pi_P X \pi_Q)$$

where: λ_p = Cable splice failure rate
λ_b = Single fiber splice base failure rate (see table XIII)
π_E = Environmental derating factor (see table XXI)
π_T = Temperature derating factor
π_P = Number of fibers in the cable splice (see table XXII)
π_Q = Quality factor

TABLE XXI. Cable splice environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	9.9
Naval Surface Ship Sheltered	4.4
Naval Submarine	3.5

TABLE XXII. Number of fibers in cable splice derating factor.

Number of Active Termini	π_P
1	1.00
2	1.36
3	1.55
4	1.72
5	1.87
6	2.02
7	2.16

8	2.30

5.7.6 Optical switches. The optical switch failure rate model is given by

$$\lambda_p = \lambda_b(\pi_E X \pi_T X \pi_K X \pi_c X \pi_Q)$$

where:
λ_p = Optical switch failure rate
λ_b = Optical switch base failure rate (see table XXIII)
π_E = Environmental derating factor (see table XXIV)
π_T = Temperature derating factor
π_c = Number of switch states (see table XXV)
π_Q = Quality factor

TABLE XXIII. Optical switch base failure rate.

Switching Mechanism	λ_b
Electro-optic, Moving Fiber	0.431
Electro-optic, Moving Mirror	0.321
Solid State	0.100

TABLE XXIV. Optical switch environmental derating factors.

Environment	π_E
Naval Surface Ship Unsheltered	13
Naval Surface Ship Sheltered	5.3
Naval Submarine	4.1

TABLE XXV. Number of switch states derating factor.

Number of switch states	π_c
2	1.0

5.8 Fiber optic system design examples. Appendices B and C contain fiber optic system design examples that illustrate the proper application of the equations presented herein. Table XXVI shows the topics covered in each example.

TABLE XXVI. Topics covered in fiber optic design examples.

Topic	Appendix B		Appendix C
	Example 1	Example 2	Example 1
Network Topology	SAFENET	SAFENET	SAFENET
Multimode or Single Mode	Multimode	Multimode	Single Mode
Source Type	SLED	ELED	Laser
Loss Budget Equation	Worst Case	Statistical	Worst Case
Calculate Environmental Margin	No	Yes	Yes
Aging Included in Transmitter/Receiver Specifications	Yes	No	Yes

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. The design requirements contained in this standard are intended to be used for all applicable systems, to ensure system operability when fielded, interoperability between systems designed by different organizations, and proper operation when connected to the fiber optic topology.

6.2 Issue of DODISS. When this standard is used in acquisition, the applicable issue of the DODISS must be cited in the solicitation (see 2.1.1 and 2.2).

6.3 References. The following references may be used to obtain additional information on different aspects of component performances and system design. These documents are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.

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o. Das, S., et al., "Modal Noise and Distortion Caused by a Longitudinal Gap Between Two Multimode Fibers," Applied Optics, 1984, Vol. 23, No. 7, p. 1110.

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6.4 Subject term (key word) listing.

Optical fiber
Exit bandwidth
Cable
Connectors
Splices
Switches
Couplers
Interconnection boxes
Transmitters
Receivers
Inter-equipment connections

Topology
Intra-equipment organization
Link definition end design
Bandwidth
Wavelength
Loss budget
Link loss budget
Adjustments to link loss budget
Component reliability calculations

Preparing activity:
Navy - SH
(Project 60GP-N011)

APPENDIX A

TEST PROCEDURE TO DETERMINE LOW ORDER MODE POWER RATIO FOR MULTIMODE OPTICAL FIBERS

10. SCOPE

10.1 Scope. The intent of this procedure is to measure the logarithmic ratio of the total optical power coupled into a Class Ia graded-index multimode optical fiber to the effective optical power coupled into the low order modes of the fiber by a fiber optic source or transmitter.

20. APPLICABLE DOCUMENTS

This section does not apply to this appendix.

30. TEST EQUIPMENT

30.1 Optical power meter (calibration traceable to NIST Standard). An optical power meter shall be used which has a resolution of at least 0.1 dBm, and which has been calibrated for the wavelength range and dynamic range of operation for the equipment to be tested.

30.2 Input signal source. An input signal source which modulates the optical transmitter with a suitable modulation signal.

30.3 Class Ia jumper cable. A jumper cable constructed with Class Ia graded -index multimode optical fiber with near nominal core size and NA equipped with appropriate connectors. The jumper should be sufficiently long that all launched cladding mode power is completely attenuated before the output connector.

30.4 Class IVa jumper cable. A jumper cable constructed with Class IVa dispersion unshifted single mode fiber with near nominal mode field diameter equipped with appropriate connectors. The jumper should be sufficiently long that all launched cladding mode power is completely attenuated before the output connector.

40. TEST SAMPLE

The test sample shall be a fiber optic source or transmitter operating under normal operating conditions.

50. TEST PROCEDURE

50.1 Setup.

a. Apply the appropriate input modulation signal to the optical source or transmitter under test. Allow sufficient time (15 minutes unless otherwise specified) for the source or transmitter under test to reach a steady-state temperature and performance condition.
b. Turn on the optical power meter and allow the manufacturer's recommended warm-up and settling time before starting any measurements.
c. Clean the optical connectors of the multimode test jumper cable, the single mode test jumper cable, and the optical source or transmitter under test.

50.2 Multimode jumper measurement.

a. Connect one end of the multimode test jumper cable to the optical source or transmitter under test and the other end to the input connector of the optical power meter.
b. Observe the optical power reading. If the optical power meter reading fluctuates more than 0.4 dB (peak-to-peak), the reading should be disregarded (either the optical source or transmitter under test is not sufficiently stabilized or the optical power level is too low for the optical power meter). When the meter reading is sufficiently stable, record the value (in dBm).
c. Disconnect the multimode test jumper cable from the optical source or transmitter under test, clean the jumper connector, and reconnect the jumper to the optical source or transmitter under test.
d. Repeat steps A5.2.2 and A5.2.3 until five stable readings are obtained.

50.3 Single mode jumper measurement.

a. Connect one end of the single mode test jumper cable to the optical source or transmitter under test and other end to the input connector of the optical power meter.
b. Observe the optical power reading. If the optical power meter reading fluctuates more than 0.4 dB (peak-to-peak), the reading should be disregarded (either the optical source or transmitter under test is not sufficiently stabilized or the optical power level is

too low for the optical power meter). When the meter reading is sufficiently stable, record the value (in dBm).

c. Disconnect the single mode test jumper cable from the optical source or transmitter under test, clean the jumper cable connector, and reconnect the jumper to the optical source or transmitter under test.

d. Repeat steps A5.3.2 and A5.3.3 until five stable readings are obtained.

60. CALCULATIONS

a. Calculate the average of the five stable readings for the multimode test jumper cable.

b. Calculate the logarithmic ratio of the optical power coupled into the multimode optical fiber to the optical power coupled into the single mode optical fiber

$$R_S = P_{mm} - P_{sm}$$

where P_{sm} is the optical power coupled into the single mode fiber and P_{mm} is the optical power coupled into the multimode optical fiber.

APPENDIX B

MULTIMODE DESIGN EXAMPLES

10. SCOPE

10.1 Scope. This appendix contains examples for calculating bandwidths, loss budgets, and other factors necessary to design multimode fiber optic systems. This appendix is not a mandatory part of this standard. The component specifications and network topologies presented herein were developed for instructional purposes only and are not representative of any particular installation.

20. APPLICABLE DOCUMENTS

This section does not apply to this appendix.

30. EXAMPLES

30.1 General. These examples are intended to provide guidance to the design engineer on the application of the formulae used to evaluate the viability of two hypothetical fiber optic topologies. As will be seen when comparing the examples, the equations used and their application vary in accordance with the topology design, system specifications and available data. The equations, paragraphs and tables referenced in the examples can be found in Section 5 of this standard.

30.2 Example 1. Example 1 demonstrates the selection and application of equations used to evaluate the survivable adaptable fiber optic embedded network (SAFENET) topology shown on figure 20 and described in 30.2.1. The topology and component specifications have been provided by a system design team as a proposed tactical shipboard network. Is the proposed system viable under worst case conditions?

30.2.1 System specifications.

a. Fiber Specifications:

Type:	multimode, graded index
Size:	62.5/125 μm
Attenuation:	2.0 dB/km @ 1300 nm ± 20 nm, (RES) max 4.5 dB/km @ 850 nm ± 20 nm, (RES) max
Transient Loss:	0.5 dB for lengths greater than 0.5 km
Modal Bandwidth:	400 MHz•km @ 1300 nm, min 200 MHz•km @ 850 nm, min

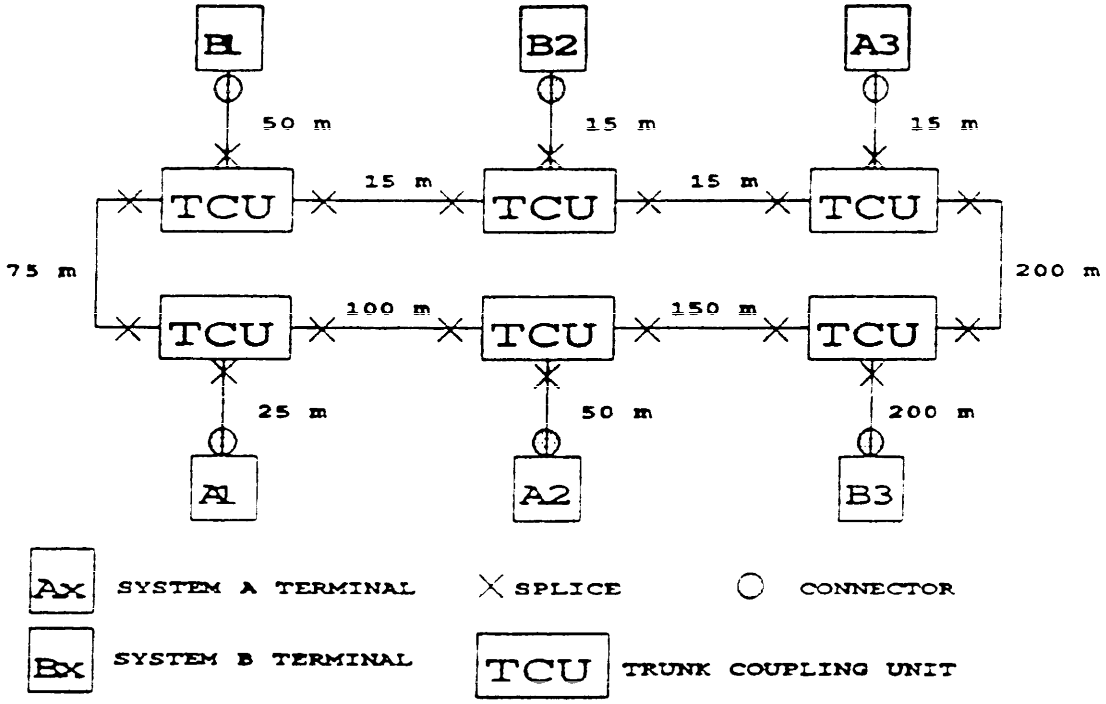

FIGURE 20. Multimode SAFENET topology for example 1.

Dispersion Slope at Zero Dispersion Wavelength:	1×10^{-13} s/nm^{2}•km
Fiber Zero Dispersion Wavelength:	1340 nm
μ_λ:	0.06 dB/km

b. **Transmitter specifications:**

Source Type:	Surface Emitting LED (SLED)
Center Wavelength:	1300 nm ± 30 nm
Spectral Width:	130 nm FWHM

Optical Output Power: -18 dBm, min @ 1300 nm into 62.5/125 μm fiber over the rated lifetime

Rated Rise Time: 2 ns, max

c. Receiver specifications:

Detector Type: Positive-Intrinsic-Negative (PIN) Diode

Sensitivity: -36 dBm, min for BER of 10^{-9} over the rated lifetime

Rated Rise Time: 2 ns, max

d. SAFENET specifications:

TCU Loss: 0.8 dB, (OFL) max, through any path

Splice Loss: 0.6 dB, (OFL) max

Connector Loss: 1.0 dB, (OFL) max

Bit Rate: 100 Mbps

Coding Format: 4B/5B

e. System integrity: All terminals of an individual system (System A or System B) must be able to communicate when alternate system terminals are bypassed.

30.2.2 Design evaluation. The design evaluation illustrated in this example assumes a worst case scenario, aging included in the transmitter/receiver specifications, and uses the additional 3 dB safety margin in lieu of calculating the environmental margin.

30.2.2.1 Bandwidth and rise time calculations. The path from B1 to B2 is the longest (605 meters going counter-clockwise) and the shortest (80 meters going clockwise). This link, being the most critical link of the topology, will be analyzed for dispersion and attenuation limitations. Starting with Equation (7), and realizing that the link minimum performance will occur when the transmitter is operating at the lower limit of its wavelength range, the source centroid wavelength is

&2

$$\lambda_c = (1300-30)-7 = 1263\ nm$$

From Equation (8), the RMS spectral width is

$$\sigma_\lambda = \frac{130}{2.4} = 54.2\ nm$$

From Equations (5) and (6), the fiber dispersion and the dispersion slope at the fiber optic transmitter centroid wavelength are

$$D = \frac{1x10^{-13}}{4}1263\left[1-\left(\frac{1340}{1263}\right)^4\right] = -8.4\ x\ 10^{-12}\ s/(nm\text{-}km)$$

$$S = \frac{1x10^{-13}}{4}\left[1+3\left(\frac{1340}{1263}\right)^4\right] = 1.2x10^{-13}\ s/(nm^2\text{-}km)$$

The minimum bandwidth will occur in the longest link in the topology. If the bandwidth is sufficient for the longest link, then it can be assumed that it will be sufficient for all other links. For this example, the cable length (L_t) equals 605 meters. The rise times associated with the first and second order chromatic dispersion for the longest path length are given by Equations (3) and (4) to be

$$t_{cd1} = (2.6)(55.2)(-8.4x10^{-12})(0.605) = -720\ x\ 10^{-12}s$$

$$t_{cd2} = 1.4\left(0.12+\frac{2(-8.4x10^{-12})}{1263}\right)(55.2)^2(.605) = 270\ x\ 10^{-12}\ s$$

From Equation (2), the estimated cable modal bandwidth is

$$BW_{m(-6)} = \frac{400x10^6}{(0.605)^{0.5}} = 510\ x\ 10^6\ Hz$$

From Equation (12), by excluding the receiver contribution, the transmitter/cable exit bandwidth is

$$BW_{ex(-3)} = \left[\left(\frac{2x10^{-9}}{0.29}\right)^2+\left(\frac{-720x10^{-12}}{0.34}\right)^2+\left(\frac{270x10^{-12}}{0.25}\right)^2+\left(\frac{1}{0.52(510x10^6)}\right)^2\right]^{-1/2}$$

$$= 120x10^6\ Hz$$

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Also from Equation (12), the total optical link -3dB bandwidth is calculated to be

$$BW_{T(-3)} = \left[\left(\frac{2x10^{-9}}{0.29}\right)^2 + \left(\frac{-720x10^{-12}}{0.34}\right)^2 + \left(\frac{270x10^{-12}}{0.25}\right)^2 + \left(\frac{1}{0.52(510x10^6)}\right)^2 + \left(\frac{2x10^{-9}}{0.36}\right)^2\right]^{-1/2}$$

$$= 100x10^6\ Hz$$

The minimum acceptable total optical link -3 dB bandwidth, according to Equation (13), must be equal to or greater than 70 percent of the optical baud. SAFENET utilizes a 4B/5B coding format and a 100 Mbps electrical line bit rate. From table VI, the bit rate to baud conversion factor, E, is 5/4. The optical line baud is thus

$$baud = 5/4(100x10^6) = 125x10^6\ baud$$

After substituting, Equation (13) becomes

$$BW_{T(-3)} \geq 0.7(125x10^6) \geq 87.5x10^6\ Hz$$

This condition is satisfied.

30.2.2.2 Loss budget calculation. The loss budget equation must be satisfied for both the longest and shortest path lengths. This will verify that the optical power incident on the detector will be in the proper range for correct demodulation at the receiver. Since a worst case analysis is desired, Equation (16) may be simplified by eliminating the last term of the equation (that is $-X[\sigma_T^2 + \ldots]^{1/2}$). Also, this is a tactical link and it has been decided that an environmental margin (μ_E) should not be calculated, so a 6 dB safety margin (M) shall be used in the loss budget equation. Adjustments, A, include a 2.22 dB dispersion power penalty calculated from Equation (19) as follows

$$P_D = 1.42\left[\frac{125x10^6}{100x10^6}\right]^2 = 2.22\ dB$$

The transient cable loss, T, provided by the cable manufacturer for this type of cable is 0.5 dB. Jumper cables are internal to the transmitter and receiver and are considered to be negligible (l_{JC}, μ_{JC}, σ_{JC} = 0). From information provided by the cable manufacturer, μ_λ was determined to be 0.06 dB/km. Starting with the longest cable path of 605 meters, the path includes two connectors, 12 splices, and six

TCUs. The loss budget equation, from Equation (16), is

$$0 \le -18 -(-36) -6 -0.5 -2.18 -[(0.605)(2+0.06)] -2(1) -12(0.6) -6(0.8)$$

$$= -5.9\ dB$$

30.2.3 Conclusions. The right hand side of the above equation is equal to -5.9 dB, and thus the conditions represented in the loss budget equation are not satisfied. Therefore, the proposed topology presented for analysis is not a viable solution under worst case conditions and the analysis is completed.

30.3 Example 2. Example 2 demonstrates the selection and application of the equations used to evaluate the SAFENET topology shown on figure 21 and described in 30.3.1. The topology and component specifications have been provided by a system design team as a proposed tactical shipboard network. Is the proposed system viable at a 97 percent confidence level?

30.3.1 System specifications.

a. Fiber specifications:

Type:	multimode, graded index
Size:	62.5/125 µm
Attenuation:	1.3 dB/km (RES) avg; 0.5 dB/km std deviation @ 1300 nm ± 20 nm 4.5 dB/km (RES) @ 850 nm ± 20 nm, max
Transient Loss:	0.5 dB @ 0.3 km, 0.75 dB @ 0.4 km, and 1.0 dB for lengths greater than 0.5 km
Modal Bandwidth:	400 MHz•km @ 1300 nm, min 200 MHz•km @ 850 nm, min
Dispersion Slope at Zero Dispersion Wavelength:	0.1 ps/nm^2•km
Fiber Zero Dispersion Wavelength:	1340 nm

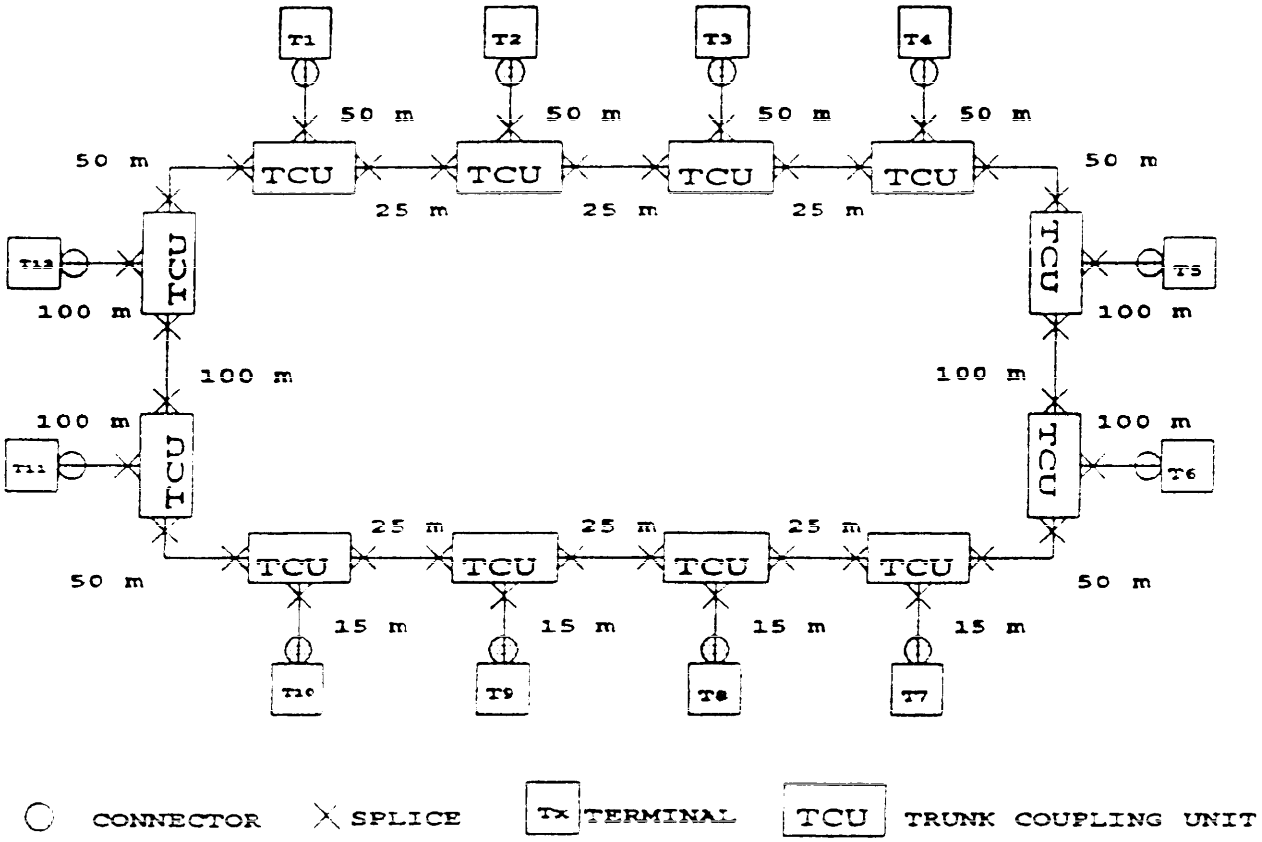

FIGURE 21. Multimode SAFENET topology for example 2.

μ_λ: 0.06 dB/km

b. Transmitter specifications:

Source Type: Edge Emitting LED (ELED)

Center Wavelength: 1300 nm ± 20 nm

Spectral Width: 90 nm FWHM

Optical Output Power: -10 dBm, avg; -12 dBm, min; and 1 dBm std deviation @ 1300 nm into 62.5/125 μm fiber.

Rated Rise Time: 1 ns, max

c. Receiver specifications:

Detector Type: Positive-Intrinsic-Negative (PIN) Diode

Sensitivity: -38 dBm avg; -36 dBm min; and 1 dBm std deviation for BER of 10^{-9}

Maximum Input Power: -11 dBm

Rated Rise Time: 2 ns, max

d. SAFENET specifications:

TCU (Bypass Switch) Loss: 0.5 dB, avg (RES); 0.7 dB, avg (OFL); 0.8 dB, max (OFL); 0.1 dB std deviation, through any path

TCU Environmental Derating Factor: 0.35 dB avg, 0.12 dB std deviation

Splice Loss: 0.3 dB, avg (RES); 0.5 dB, avg (OFS); 0.6 dB, max (OFL); 0.1 dB std deviation

Splice Environmental Derating Factor: 0.16 dB avg, 0.8 dB std deviation

Connector Loss: 0.8 dB, avg; 1.0 dB, max; 0.1 dB std deviation

Connector Environmental Derating Factor: 0.25 dB avg, 0.08 dB std deviation

e. System integrity: Each network terminal must be able to bypass at least three (3) adjacent, consecutive out-of-service terminals.

30.3.2 Design evaluation. The design evaluation illustrated in this example use statistical methods, including a calculation for environmental margin.

30.3.2.1 Bandwidth and rise time calculations. The longest path

APPENDIX B

length for this analysis is 350 meters (between T2 and T6, and between T11 and T3). Therefore, this will be the link chosen for analysis. Starting with Equation (7) and using the transmitter's minimum wavelength, the source centroid wavelength is

$$\lambda_c = (1300-20)-7 = 1273\ nm$$

From Equation (8), the RMS spectral width is

$$\sigma_\lambda = \frac{90}{2.4} = 37.5\ nm$$

From Equations (5) and (6), the fiber dispersion and the dispersion slope at the fiber optic transmitter centroid wavelength are

$$D = \frac{1x10^{-13}}{4}1273\left[1-\left(\frac{1340}{1273}\right)^4\right] = -7.2x10^{-12}\ s/(nm\text{-}km)$$

$$S = \frac{1x10^{-13}}{4}\left[1+3\left(\frac{1340}{1273}\right)^4\right] = 1.2x10^{-13}\ s/(nm^2\text{-}km)$$

The systems minimum bandwidth will occur in the link with the longest length of cable. For this example, L_c equals 350 meters. The rise times associated with the first and second order chromatic dispersion are given by Equations (3) and (4) to be

$$t_{cd1} = (2.6)(37.5)(-7.2x10^{-12})(0.35) = -250x10^{-12}\ s$$

$$t_{cd2} = 1.4\left(1.2x10^{-13}+\frac{2(-7.2x10^{-12})}{1273}\right)(37.5)^2(.35) = 76x10^{-12}\ s$$

From Equation (2), the estimated cable modal bandwidth is

$$BW_{B(-6)} = \frac{400x10^6}{(0.35)^{0.5}} = 670x10^6\ Hz$$

From Equation (12), by excluding the transmitter contribution, the transmitter/cable exit bandwidth is
Also from Equation (12), the total optical link -3dB bandwidth is calculated to be

$$BW_{ax(-3)} = \left[\left(\frac{1x10^{-9}}{0.29}\right)^2 + \left(\frac{-254x10^{-12}}{0.34}\right)^2 + \left(\frac{76x10^{-12}}{0.25}\right)^2 + \left(\frac{1}{0.52(670x10^6)}\right)^2\right]^{-1/2}$$

$$= 220x10^6\ Hz$$

$$BW_{T(-3)} = \left[\left(\frac{1x10^{-9}}{0.29}\right)^2 + \left(\frac{-250x10^{-12}}{0.34}\right)^2 + \left(\frac{76x10^{-12}}{0.25}\right)^2 + \left(\frac{1}{0.52(670x10^6)}\right)^2 + \left(\frac{2x10^{-9}}{0.36}\right)^2\right]^{-1/2}$$

$$=140x10^6\ Hz$$

To satisfy the conditions of Equation (13), the total optical link -3dB bandwidth must be equal to or greater than 70 percent of the optical baud. SAFENET utilizes a 4B/5B coding format and a 100 Mbps electrical line bit rate. With E equal to 5/4 from table VI, the optical line baud is thus

$$baud = 5/4\,(100x10^6) = 125x10^6\ baud$$

After substituting, Equation (13) becomes

$$BW_{T(-3)} \geq 0.7\,(125x10^6) \geq 88x10^6\ Hz$$

This condition is satisfied.

30.3.2.2 Loss budget calculation. This is a tactical link and it has been decided to calculate the environmental margin neglecting the effects of radiation, so only a 3 dB safety margin (M) shall be used in the loss budget equation. The path from T2 to T6 includes two connectors, 10 splices, five TCUs, and six cables. Jumper cables are internal to the transmitter and receiver and are considered to be negligible (l_{JC}, μ_{JC}, σ_{JC} = 0). The mean and standard deviation of the environmental margin (μ_E and σ_E) as calculated from Equation (18) are

$$\mu_E = 0.35(1.35+0) + 2(0.25+0) + 10(0.16+0) + 5(0.35+0) = 4.32\ dB$$

$$\sigma_E = [(0.35)(0.35/6)(0.45^2+0) + 2(0.08^2+0) + 10(0.05^2+0) + 5(0.12^2+0)]^{1/2} = 0.34\ dB$$

Adjustments, A, include a 1.15 dB dispersion power penalty calculated from Equation (20) as follows

$$P_D = 1.42\left[\frac{125x10^6}{140x10^6}\right]^2 = 1.13\ dB$$

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Because the specifications for transmitter output power and the receiver sensitivity are not given over the lifetime of the device, these values must be derated according to table IX. The lower order mode power ratio for the optical source is not known so a value of K=0.5 was chosen from table VII for ELED sources. The high order mode loss, H, from table VII for ELED sources is 0 dB. From information provided by the cable manufacturer, μ_λ was determined to be 0.06 dB/km. The loss of the cable and each of the components is calculated using equation (15)

$$\mu_c=1.0+0.5(1.3-1.0)=1.15 \qquad \mu_s=0.3+0.5(0.5-0.3)=0.4$$

$$\mu_{co}=0.5+0.5(0.8-0.5)=6.5 \qquad \mu_{rw}=0.5+0.5(0.7-0.5)=0.6$$

The loss budget equation, Equation (16), is

$$0\leq-(10-1.5)-(-38+1)-3-1.13-4.32-(0.35)(1.15+0.06)-2(0.65)-10(0.4)$$

$$-5(0.6)-2[1^2+1^2+0.34^2+(0.35)(0.35/6)(0.5)^2+(2)(0.1)^2+10(0.1)^2+5(0.1)^2]^{1/2}$$

$$0\leq 8.3\ dB$$

The right hand side of the above equation is equal to 8.3 dB, and thus the conditions represented in the loss budget equation are satisfied. This part of the analysis shows that a transmitter is able to bypass three TCU's over the longest possible path length and deliver sufficient power to the receiver. Now, the shortest path length must be analyzed to ensure that the transmitter is not saturating the receiver. The shortest path length is 30 meters and will occur when the TCUs serving terminals T7, T8, T9, or T10 are in loopback mode (that is, 15 meters from the terminal to the TCU, loop back through the TCU, and back to the terminal). In this condition, the path would include two connectors (two different termini pair in the multiterminus connector), two splices (of a multifiber cable splice), and one TCU (in loop back mode). From Equation (18), the maximum power available at the receiver would be

$$P_{Rmax}=-10-0.03(1.15)-2(0.65)-2(0.4)-1(0.6)$$

$$+2[(1.0)^2+(0.03)(0.03/2)(0.5)^2+2(0.1)^2+(0.1)^2]^{1/2}$$

$$=-11.71\ dB$$

30.3.3 Conclusions. Since the maximum receiver input power is

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-11 dBm, the link can operate in loop back mode without saturating the receiver. Therefore the proposed system is a viable network solution at a 97 percent confidence level.

APPENDIX C

SINGLE MODE DESIGN EXAMPLE

10. SCOPE

10.1 Scope. This appendix contains examples for calculating bandwidths, loss budgets, and other factors necessary to design single mode fiber optic systems. This appendix is not a mandatory part of this standard. The component specifications and network topology presented herein were developed for instructional purposes only and are not representative of any particular installation.

20. APPLICABLE DOCUMENTS

This section does not apply to this appendix.

30. EXAMPLE

30.1 General. This example is intended to provide guidance to the design engineer on the application of the formulae used to evaluate the viability of a hypothetical fiber optic topology. The equations, paragraphs and tables referenced in this example can be found in Section 5 of this standard.

30.2 Example. The example herein demonstrates the selection and application of equations used to evaluate the SAFENET topology shown in figure 22 and described in 30.2.1. The topology and component specifications have been provided by a system design team as a proposed tactical shipboard network. Is the proposed system viable under worst case conditions?

30.2.1 System specifications.

a. Fiber specifications:

Type:	single mode
Size:	8.3/125 μm
Attenuation:	1.0 dB/km @ 1300 nm ± 20 nm, max
Dispersion Slope at Zero Dispersion Wavelength:	0.1 $ps/nm^2 \cdot km$

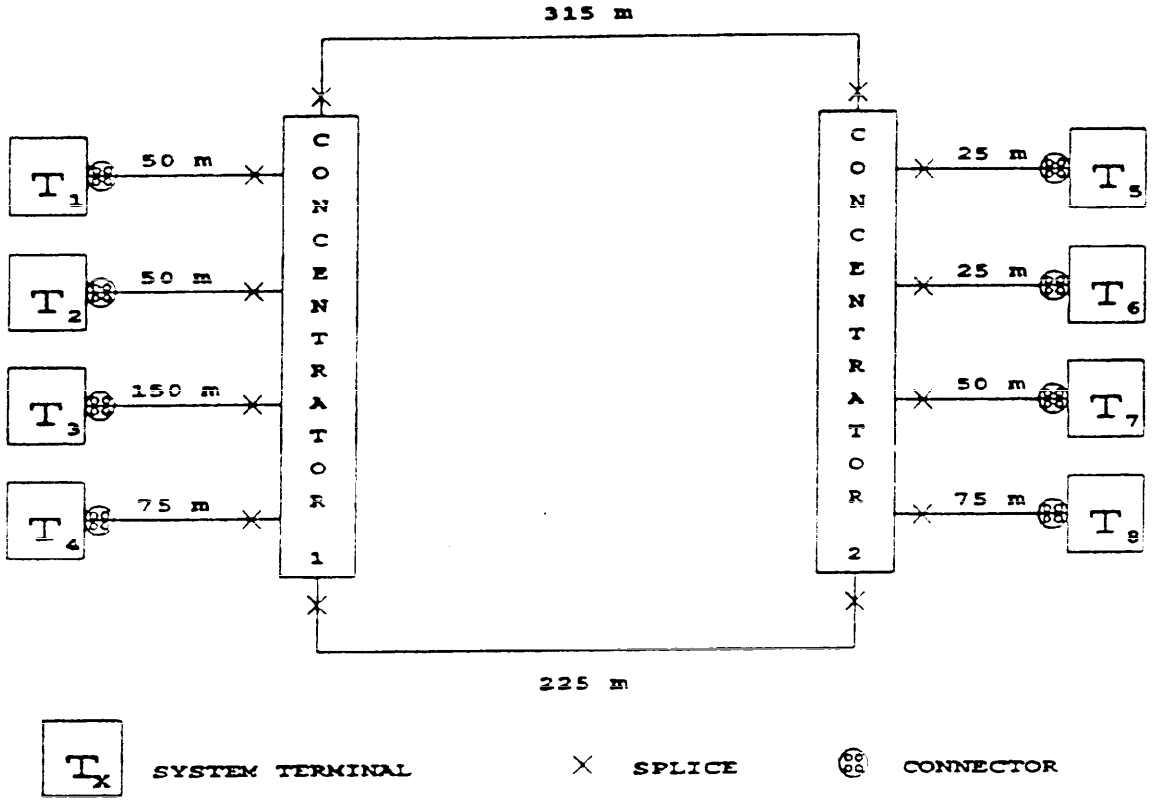

FIGURE 22. Single mode SAFENET topology.

Fiber Zero Dispersion Wavelength:	1311 nm

b. **Transmitter specifications:**

Source Type:	Semiconductor laser diode (LD)
Center Wavelength:	1300 nm ± 10 nm
Spectral Width:	1.25 nm RMS
Optical Output Power:	-3 dBm, min @ 1300 nm into 8.3/125 µm fiber over the rated lifetime
Rated Rise Time:	0.5 ns, max

c. **Receiver specifications:**

Detector Type:	Positive-Intrinsic-Negative (PIN) Diode
Sensitivity:	-36 dBm, min for BER of 10^{-9} over the rated lifetime
Maximum Input Power:	-12 dBm
Rated Rise Time:	2 ns, max

d. SAFENET specifications:

Concentrators:	See transmitter and receiver above
Splice Loss:	0.6 dB, max
Connector Loss:	1.0 dB, max

30.2.2 Design evaluation. The design evaluation illustrated in this example assumes a worst case scenario, aging included in the transmitter/receiver specifications, and calculates the environmental margin.

30.2.2.1 Bandwidth and rise time calculations. Since transmitters and receivers are located in the system terminals and the concentrators, the maximum cable length in this topology is 315 meters. The shortest path is 25 meters between concentrator 2 and T5, T6 and T7. Starting with Equation (7) and the minimum transmitter wavelength the source centroid wavelength for a laser source is

$$\lambda_c = 1300-10 = 1290\ nm$$

From Equations (5) and (6), the fiber dispersion and the dispersion slope at the fiber optic transmitter centroid wavelength are

$$D = \frac{1x10^{-13}}{4}1290\left[1-\left(\frac{1311}{1290}\right)^4\right] = -2.15x10^{-12}\ s/(nm\text{-}km)$$

$$S = \frac{1x10^{-13}}{4}\left[1+3\left(\frac{1311}{1290}\right)^4\right] = 1.05x10^{-13}\ s/(nm^2\text{-}km)$$

The system's minimum bandwidth will occur in the link with the longest length of cable. For this example, L_c equals 315 meters. The rise times associated with the first and second order chromatic dispersion for this link are given by Equations (3) and (4) to be

$$t_{cd1} = (2.6)(1.25)(-2.15x10^{-12})(0.315) = -2.2x10^{-12}\ s$$

$$t_{cd2} = 1.4\left(1.05x10^{-13} + \frac{2(-2.15x10^{-12})}{1290}\right)(1.25)^2(0.315) = 7.0x10^{-14}\ s$$

Note that Equation (2) for cable modal bandwidth does not apply for single mode systems. From Equation (12), by excluding the receiver and the fiber modal distortion terms, the transmitter/cable exit bandwidth is

$$BW_{ex(-3)} = \left[\left(\frac{0.5x10^{-9}}{0.29}\right)^2 + \left(\frac{-2.2x10^{-12}}{0.34}\right)^2 + \left(\frac{7.0x10^{-14}}{0.25}\right)^2\right]^{-1/2} = 580x10^6\ Hz$$

Also from Equation (12), the total optical link -3dB bandwidth is calculated to be

$$BW_{T(-3)} = \left[\left(\frac{0.5x10^{-9}}{0.29}\right)^2 + \left(\frac{-2.2x10^{-12}}{0.34}\right)^2 + \left(\frac{7.0x10^{-14}}{0.25}\right)^2 + \left(\frac{2x10^{-9}}{0.36}\right)^2\right]^{-1/2} = 172x10^6\ Hz$$

To satisfy the conditions of Equation (13), the total optical link -3dB bandwidth must be equal to or greater than 70% of the optical baud. SAFENET utilizes a 4B/5B coding format and a 100 Mbps electrical line bit rate. With E equal to 5/4 from table VI, the optical line baud is thus

$$baud = 5/4(100x10^6) = 125x10^6\ baud$$

After substituting, Equation (13) becomes

$$BW_{T(-3)} \geq 0.7(125x10^6) \geq 88x10^6\ Hz$$

This condition is satisfied.

30.2.2.2 Loss budget calculation. This is a tactical link and it has been decided to calculate the environmental margin neglecting radiation effects, so only a 3 dB safety margin (M) shall be used in the loss budget equation. This path includes two splices and one cable. Jumper cables are internal to the transmitter and receiver and are considered to be negligible (l_{JC}, μ_{JC}, and $\lambda_{JC} = 0$). The mean environmental margin (μ_E) as calculated from Equation (18) is

APPENDIX C

$$\mu_g = 0.318(1.35+0) + 2(0.16+0) = 0.75\ dB$$

Adjustments, A, include a 0.75 dB dispersion power penalty and 0.001 dB mode partition noise penalty calculated from Equations (20) and (21) as follows

$$P_D = 1.42\left[\frac{125x10^6}{172x10^6}\right]^2 = 0.75\ dB$$

$$P_{MPN} = 0.5\left[\frac{125x10^6}{580x10^6}\right]^4 = 0.001\ dB$$

A single mode optical cable does not have a transient loss. From information provided by the cable manufacturer, μ_λ was determined to be 0.06 dB/km. The loss budget equation, Equation (17), is

$$0 \le -3 -(-36) - 3 - 0 - 0.751 - 0.75 - (0.315)(1+0.06) - 2(0.6)$$

$$0 \le 26.9\ dB$$

The right hand side of the above equation is equal to 26.9 dB and the conditions represented in the loss budget equation are satisfied. Now, the shortest path length must be analyzed to ensure that the transmitter is not saturating the receiver. The shortest path length is 25 meters between concentrator 2 and T5, T6 or T7. This path includes one connector and one splice. From Equation (18), the maximum power available at the receiver would be

$$P_{Rmax} = -3 - 0.025(1.0) - 1(1.0) - 1(0.6) = -4.6\ dB$$

Since the maximum receiver input power is -12 dBm, the link transmitters will saturate the receivers and the link will not operate properly.

30.2.3 <u>Conclusions</u>. Because of the relatively high output power of the laser sources and the relatively low maximum input power of the receivers, attenuators may need to be placed in all of the short concentrator-to-terminal links. Further analysis on these shorter links is necessary to determine which will need attenuators and how much attenuation is required.

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3. DOCUMENT TITLE
FIBER OPTIC SYSTEMS DESIGN

4. NATURE OF CHANGE *(Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)*

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