



AEROSPACE INFORMATION REPORT

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Guidelines for Design of Digital Fiber Optic Link Loss Budget Methodology

RATIONALE

This document was originally published as AS5603, "Digital Fiber Optic Link Loss Budget Methodology for Aerospace Platforms". A revised standard, AS5603A, will be released in the future, providing the specification details for a fiber optic link budget in a form that is more suitable for use as an industry standard. This new document, AIR6113, is intended to archive the information that existed in the original AS5603 document.

AIR6113 has been reaffirmed to comply with the SAE Five-Year Review policy.

INTRODUCTION

This SAE document provides specific process and procedure based on broadly accepted engineering practices for the establishment of link loss power budgets in aerospace digital fiber optic systems. The underlying purpose is to improve the process of aerospace digital fiber optic link architecture, specification, and interface developments by promoting a standard terminology and methodology across the industry. A communication facilitation tool such as this streamlines the development of system requirements, establishes high-level confidence in predicted performance, and communicates to component suppliers the quality and quantity of test data needed to support high performance fiber optic links.

1. SCOPE

This document draws from, summarizes, and explains existing broadly accepted engineering best practices.

This document defines the process and procedure for application of various best practice methods.

This document is specifically intended as a standard for the engineering practice of development and execution of a link loss power budget for a general aerospace system related digital fiber optic link.

It is not intended to specify the values associated with specific categories or implementations of digital fiber optic links.

This document is intended to address both existing digital fiber optic link technology and accommodate new and emerging technologies.

The proper application of various calculation methods is provided to determine link loss power budget(s), that depend on differing requirements on aerospace programs.

A list of parameters is provided as guidance for aerospace fiber optics applications along with a check list to help assure that appropriate parameters and impairments have been accounted for in the link budget.

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1.1 Approach

The general approach of this document is to outline existing industry best practices for link budget analysis, including specific reference to MIL-STD-2052A [Ref. 22]. Additionally, reference is made to existing component and link test procedures, test data, and best practices commonly used to support the link loss power budget. Where industry best practices are not well established, appropriate alternative methods are described.

1.2 Data Basis and Methodology

Link loss power budgets are ultimately tied to component test and qualification data. The quality, quantity and pedigree of component test and qualification results that exist can impact the approach and methodology used for development of a link loss power budget. Accuracy of statistical methods depends on the quality of the statistical data available. Furthermore, technology maturity of a component can affect the methodology used. As such, various link loss budget methodologies are discussed with reference to the quality of data available. Additionally, the Technology Readiness Level (TRL) [Refs. 2,3] of components is discussed along with the influence it can have on link budget analysis.

A range of possible cases of component maturity and corresponding data exists. For example, flight qualified components may exist, without a large statistical database to help 'quantify' probability and confidence. Similarly, high quality and quantity statistical data may exist for some components, but these components may not have been through system flight-testing. Often, commercial components exist with minimum specifications and thus are neither flight qualified nor have a statistical database to draw on for analysis. These different cases suggest different approaches or at least different confidence and possibly margin associated with the link budget analysis.

Various analysis methods exist for establishing and analyzing link budgets (discussed in Section 4). As mentioned previously, the quality of the link budget analysis, and the resulting allocations, are dependent on the quality of the component loss and performance test data that are utilized. This translates directly to the confidence in predicted system performance. While different approaches provide differing levels of accuracy, they also may drive the component testing that is performed. In some cases, system developments must take on the burden of additional component testing to generate the quality of test data needed and to avoid even more costly over-design margin.

1.3 Link Loss Power Budget Background and Overview

The Power Budgeting is a part of the Systems Engineering Process. It is not an isolated analysis. It must be a consistent part of the overall systems engineering approach. This standard provides the different analyses as a tool for the customers and the link designers to evaluate the fiber technologies in meeting the fiber optics system's application intent/purpose.

The Figure 1 diagram provides a visual relationship of systems engineering process and power budgeting. The key emphasis is that an understanding of the relationships between the different considerations and their effects on each other and on the power budget is critical. These tools provide a means to either evaluate the current fiber link performance in certain environmental conditions (operational conditions, maintenance concept, etc.) or could be used to set performance requirements based on critical fiber link application needs. They serve as metrics to better understand how the link design will perform for the life of the system from beginning of life, installation, and end of life.

Link loss power budgets generally begin with the light source (laser or Light Emitting Diode, LED) output power, P , and extend through a power at the input to the receivers, R . The source power level is typically limited by the available appropriate products. The power level available from a source must account for environmental variations and end-of-life (EOL) degradation at a minimum.

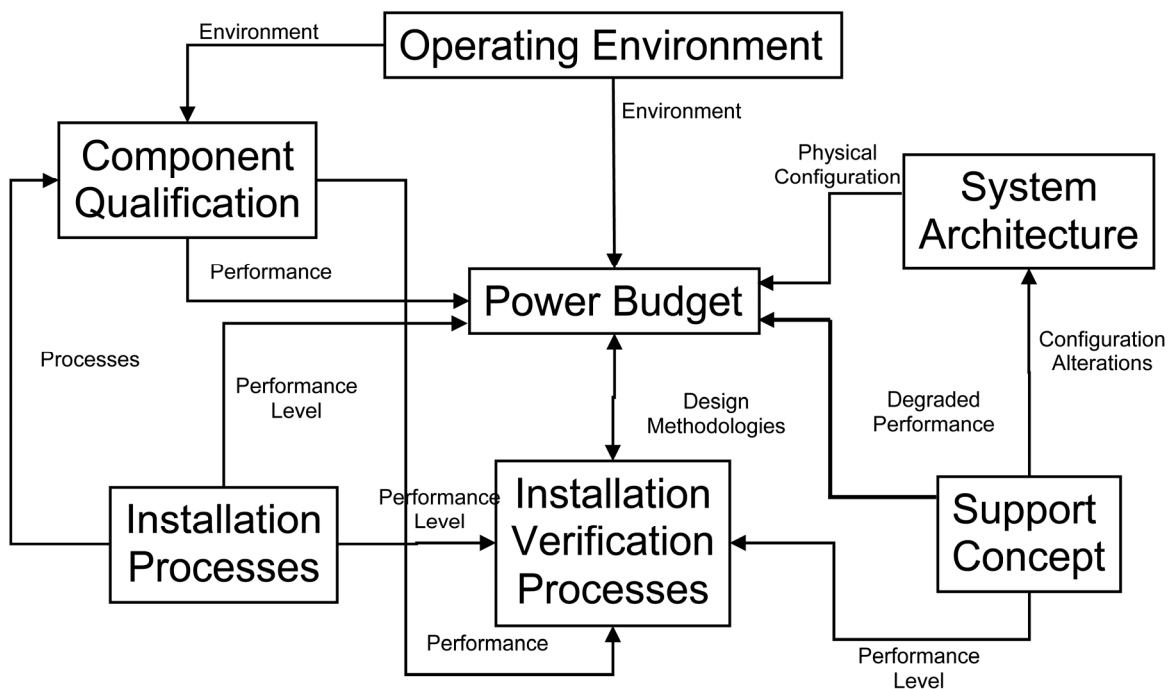


FIGURE 1 - SYSTEMS ENGINEERING PROCESS AND POWER BUDGETING

The required optical signal power at the receiver end of the link must be established by defining a required sensitivity referenced to some measure of performance, such as required link Bit Error Ratio (BER). There are other important receiver parameters related to the input signal such as dynamic range and clock timing jitter tolerance which must be included in performance analysis. Receiver sensitivity, however, is the driving limitation of most digital fiber optic links and corresponding link loss power budgets, and can be defined to incorporate many other receiver related effects and signal impairments.

In between the optical transmitter source and the receiver are the transport and distribution media and elements for the link. This includes the fiber, connectors, and all the passive and active components that make up the link. Each of these elements has a loss, L , associated with it that makes up the overall link loss. In addition to link loss, there are other impacts or adjustments, L_a , that contribute to degradation of link performance. A list and definition of these parameters is provided in the following major section.

In addition to the standard adjustments applied to loss in aerospace links, newer technologies can bring additional adjustments or complexities. Several technologies used primarily in the long haul terrestrial domain are starting to be considered for aerospace fiber optic data and communications links. Optical amplification and wavelength division multiplexing (WDM) are two such technologies. They both are primarily used with single mode optical fiber, which is now being considered more seriously for aerospace environments, partly because it provides access to these new technologies. Forward error correction (FEC) and electronic dispersion compensation (EDC) are two more technologies of import. They are well suited for direct application to multimode fiber links as well as single mode. These two technologies enhance the effective sensitivity of receivers and can often be treated as an adjustment to receiver sensitivity in a link loss budget. In general, these technologies bring additional complications to link loss budget analysis.

Optical amplifiers complicate standard single mode link loss techniques in several ways. Link loss, L , may be compensated for by link gain, G , but at a cost of increased noise. This increase in noise degrades the performance of a receiver at a given input optical signal power. For links with optical gain, optical loss becomes secondary to the resulting optical signal to noise ratio (OSNR). Implications of this for the link loss budget will be discussed in more detail in following sections. The implications are applicable to single mode or multimode. However, in multimode format the mode dependent spontaneous noise is sufficiently detrimental that no successful multimode optical amplifier products are currently in use. This is thus considered only a single-mode technology.

For WDM based links, link budgets must be viewed on a wavelength basis. Performance of many optical components varies with wavelength, and thus there is a spectral loss penalty. This can be addressed in several ways, such as by maintaining a spectral loss penalty for each component or by providing a budget at multiple wavelengths. While WDM has been predominantly a single mode technology, Coarse WDM (CWDM) is gaining popularity and being examined for multimode aerospace applications.

The growing applicability of these originally single-mode technologies, in addition to other advancements in technologies, methodologies, and standards, is part of the motivation for the creation of this document. As such, an attempt is made to both pull together the known industry best practices and incorporate implications of newer technologies to aerospace fiber optic digital links.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

Applicable and reference documents are listed in the References section of this report.

3. DEFINITIONS OF GENERAL FIBER OPTIC LINK TERMS AND PARAMETERS WITH RELEVANT UNITS

The following listed parameters and terms, with associated definitions and explanations, are most relevant to the formulation of a link loss budget. Definitions for fiber optic terms used in this standard are in accordance with ANSI/TIA-440-B-2004, "Fiber Optic Terminology" [Ref. 3], except where specifically defined. Some terminology defined in ANSI/TIA-440-B-2004 is further explained here with specific emphasis on link budget relevance or impact. This list of parameters is intended to help assure common standard terminology and to be a reminder of parameters of most importance. It is intended to be thorough, though there is no claim that it is comprehensive.

3.1 Definition of General Fiber Optic Link Terms

3.1.1 Link I/O Terminology Definitions and Units

Input/Output (I/O) includes transmitters and receivers in addition to optical modulators and amplifiers, since they are often lumped with transmitter and receiver I/O devices.

Power is specified in Watts or dBm. The dBm, and corresponding dB fractional loss, is most typical since loss budgets are comprised of cascaded products of power losses, which become sums of losses in logarithmic dB representation. Units are highlighted by '[unit]' designator brackets, e.g., [dB].

3.1.1.1 BER: Bit Error Ratio (or Rate) is that measure of bit errors per total bits transmitted at some specified point in the link. BER is often measured with a pseudo random bit pattern generator prior to the transmitter and an error analyzer at the receiver. A receiver's optical average power sensitivity is defined at a particular BER. Many standards exist, but $BER = 10^{-10}$ and $BER = 10^{-12}$ are typical specified values for modern telecommunications links that support data links (e.g., ITU-T G.957, G.826).

3.1.1.2 Dynamic Range [dB]: Dynamic Range typically refers to the power range ratio, measured in [dB], of the transmitter, receiver, or system over which specified performance is met. It is usually limited by receiver sensitivity on the low end, and maximum transmitter output or receiver saturation on the high end. A valid link's power budget must fall within the dynamic range, and the margin is the measure of how far from the limits the link is.

- 3.1.1.3 Electromagnetic Interference (EMI) Disruption of Receiver: A fiber optic receiver includes an optical detector, which typically produces relatively low current levels before amplification. Therefore, this is a circuit point susceptible to EMI disruption. A common source of such corruption is the conducted interference resulting from a co-located transmitter. EMI impact is sometimes accounted for by adding link margin since it is often quite unpredictable. It can usually be nearly eliminated with robust receiver packaging design.
- 3.1.1.4 Excess Noise Figure [dB]: Excess noise can come from a number of sources, such as reflections, or Optical Return Loss [Ref. 3], feedback into the laser, Relative Intensity Noise (RIN), amplified spontaneous emission (ASE), etc. These all directly impact the Signal-Noise Ratio (SNR). Accurate link budget analysis should include these losses, allocate margin to them, or verify that they are negligible.
- 3.1.1.5 External Modulation: External modulation consists of the modulation of Continuous Wave (CW) light through an external device such as an electro-optic modulator or an electro-absorption modulator.
- 3.1.1.6 Extinction Ratio (or Modulation Depth): The ratio of power on ($P_{\max}$) to power off ($P_{\min}$), $ER = P_{\max}/P_{\min}$, often measured in [dB], or $ER = 10\log_{10}(P_{\max}/P_{\min})$. Residual light existing in the off state contributes to zero level noise. Modulation depth of the laser can directly impact Bit Error Rate (BER) performance independent of link loss. Modulation depth is typically included in the analysis of the digital receiver 'Q' factor [Ref. 4] or SNR. Section 4.3.1 provides a discussion and quantitative definition of modulation depth and discusses the impact it has. It can be represented as a power penalty [dB].
- 3.1.1.7 Inter-Symbol Interference (ISI): Inter-symbol Interference results from the value in a particular bit interval being a function of previous bits as well as the current bit sent. In fiber optic systems this is usually the result of bandwidth limitations due to either fiber dispersion or transceiver limitations that "smear" the signal into subsequent intervals. It can also result from multiple reflections due to such things as connector interfaces. ISI can be represented as a power penalty in [dB] in a link budget.
- 3.1.1.8 Noise Sources [Ref. 5]
- Photon Noise, or Photo-electron Noise (Shot Noise): Photon/photo-electron noise is associated with the quantized statistical nature of the generation and detection of light. The generation of 'coherent' light (photon noise) is Poisson distributed, and the detection (photo-electron) statistics follow the generation statistics. This noise forms a fundamental limit on light even for an idealized 'noiseless' receiver, and is limited by twice the electron charge times the mean signal photo-electron current, $2e(i_{\text{sig}})$, which is equal to the statistical variance per bandwidth of the mean photo-electron level.
 - Relative Intensity Noise (RIN) [Ref. 3]: RIN is proportional to the light intensity, usually from relaxation oscillations in the transmitter laser gain, or reflections. Often listed with respect to bandwidth over which it occurs, since it may vary across the spectral band.
 - Johnson (Thermal, or Nyquist) Noise: Johnson noise is classic Boltzman thermal-based circuit white noise, a fundamental circuit limit, and is given by the four times the Boltzman constant times absolute temperature divided by the effective shunt resistance, $4k_B T/R$.
 - Avalanche Gain Noise: Avalanche gain noise is expressed as an excess noise factor in Avalanche Photo-Diodes (APDs) due to the random nature of the electron avalanche process. The factor varies with avalanche technologies and parameters, but is generally expressed as a factor greater than one times the photo-electron variance that reflects the uncertainty of the gain value.
 - Amplified Spontaneous Emission (ASE) Noise: ASE is usually a dominant noise in optically amplified receivers (signal spontaneous beat component), and results in a best case 3 dB Noise Figure. ASE is Bose-Einstein distributed, and thus noisier than the fundamental shot noise. The dominant noise is often the beat noise between the signal and the ASE, which is a convolved distribution and roughly given by four times the product of the photo-electron current from the signal and the ASE, or beat noise, $4(i_{\text{sig}})i_{\text{ase}}$
 - Dark Current Noise: Can be a contributor on biased photo-diodes due to tunneling, especially for noise occurring during zero bits, and can be treated by adding to the photo-electron current, $2e(i_{\text{sig}} + i_{\text{dark}})$

- g. Transistor Noise: The transistors used in the receiver electronics generate noise that can sometimes dominate the noise statistics.
- h. Mode Partition Noise (MPN) [Ref. 3]: MPN is the noise due to the random exchange of optical power between two or more laser modes. When a laser has significant mode partitioning, the longitudinal side modes will cause interference at the receiver because the different side modes propagate with different velocities, particularly in multimode fibers.
- i. Modal Noise [Ref. 3]: Modal noise is the result of optical losses and phase variations as the result of dynamic mode distribution. This is really a transient modal effect that can generate errors in the receiver, and appear as a receiver noise. Synonym: Speckle Noise. This often results from system vibration impacts on connection interfaces in multimode systems.

3.1.1.9 Optical Amplifiers [Refs. 3,6]: An optical amplifier is a device that amplifies an optical signal without employing O/E and E/O conversions. Amplifiers may be placed just after the transmitter (power booster), at a distance between the transmitter and the receiver (in-line amplifier), or just before the receiver (preamplifier). Gain and Noise Figure are the two most important link budget related parameters associated with amplifiers. These both must be specified over a given optical spectrum since both parameters vary over the amplifier's optical spectrum.

- a. Gain [dB]: Gain is signal power magnification at output versus input power. Noise is correspondingly amplified and the signal further degraded. The additional degradation is quantified in the Noise Figure. Gain has some variation with polarization, called Polarization Dependent Gain (PDG) [Ref. 3] that should be accounted for in link budgets.
- b. Noise Figure, NF [dB] : Noise Figure is a signal degradation term and is the ratio of the signal-to-noise into an amplifier over the signal-to-noise out of an amplifier. The theoretical minimum in optical amplifiers is 3 [dB], more typically they are in the 4 to 7 [dB] range. The noise figure is typically dominated by the amplified spontaneous emission (ASE) optical noise output by the laser gain optical amplifier and is directly impacted by the insertion loss of coupling the input signal fiber into the amplifying gain.

3.1.1.10 Power Penalties [dB]: Power penalties are a method to quantify performance impacts in terms of a dB loss. They are assessed if not accounted for at the transmitter level or in the receiver sensitivity to take into account effects caused by use of a device with non-ideal values of extinction ratio, jitter, pulse rise times and fall times, optical return loss, insertion loss, distortion, dispersion or other impacts that, when small, can be compensated by increased optical power level, but are not strictly losses.

3.1.1.11 Q, or Receiver Q-Factor [Ref. 4]: The received signal quality factor 'Q' may be approximately defined as the difference in the mean photo-detection current level between a '1' (or mark) and a '0', (or space), at the decision point in time, divided by the sum of the noise currents of a '1' and '0', which are characterized by the respective standard deviations. This may be expressed mathematically as [Refs. 4,7,8],

$$Q = \frac{\langle i(1) \rangle - \langle i(0) \rangle}{\sigma(1) + \sigma(0)} \approx \frac{\langle i(1) \rangle}{\sigma(1) + \sigma(0)}, \quad (\text{Eq. 1})$$

Physically this represents the mean eye diagram opening at the decision point in time divided by the noise current variance of the opening, at the decision point.

3.1.1.12 Receiver (Rx) [Ref. 3]

- a. Sensitivity [Watts] or [dBm]: The minimum acceptable value of received average power needed to achieve an acceptable BER or performance as specified by a similar quantitative means. It is possible to define an "effective sensitivity" which accounts for a variety of penalties and enhancements. It is preferred to specify sensitivity as an end-of-life value, meaning the sensitivity at the end of the receiver's life.

- b. Environmental Impacts on Sensitivity: Environmental impacts are sometimes listed as a power penalty in [dB]. This includes both operationally occurring conditions, such as temperature, humidity, vibration, etc., as well as maintenance induced, such as contamination, fiber bending, etc. Long term environment contributes to EOL degradation and is used in testing to stress the receiver in order to accelerate life for EOL assessment.
- c. Additional Adjustments to Sensitivity: Detector area, fiber size effects, optical subassembly alignment, and receiver test set-up can all contribute power penalties if sensitivity is not specified at pigtail test point.
- d. Saturation: Saturation occurs when light exceeds a level such that the photocurrent no longer scales linearly with optical power and the recovery time back to dark current level increases.
- e. Clock Timing Jitter Tolerance: Timing errors, that is, deviations from the optimal clock, can be both static and dynamic and the dynamic errors are referred to as jitter. This is sometimes assessed as a jitter power penalty and sometimes included in receiver sensitivity, depending on how the receiver is tested. Similar to dispersion, if jitter exceeds a certain limit it cannot be compensated with power, or the power penalties become infinite.
- f. Electronic Dispersion Compensation (EDC): Electronic dispersion compensation is an adaptive dispersion impairment technique that can be electronically implemented within the receiver. Such techniques are most commonly based upon classic analog feed-forward and decision feed-back equalization techniques.
- g. Forward Error Correction (FEC): Forward Error Correction is an electronic impairment compensation technique that utilizes repeated bits in the transmitted format overhead along with post detection algorithms, such as Reed-Solomon, to correct erroneous bits and provide significantly enhanced effective receiver sensitivity.

3.1.1.13 Signal-to-Noise Ratio, S/N Ratio, or SNR in [dB]: The SNR is the ratio of the total signal power to the total noise power. SNR is a measure of signal quality relevant to signal 'Q' and to receiver BER, both of which are calculable in terms of SNR.

3.1.1.14 Test Points Measured: This is a precise description of where optical and electrical measurements will be made for consistency.

3.1.1.15 Transmitter (Tx) [Ref. 3]

- a. Power [Watts] or [dBm]
 - 1. Average Power: As used in this document, average power is the amount of optical power that would be registered by a low-frequency optical power meter. That is, it will be half of the modulated optical power plus all of the CW power, when modulated at a nominal 50% duty cycle.
 - 2. Peak Power: This is highest instantaneous optical power, including both the CW optical power and the maximum modulated optical power.
- b. Launch Conditions: The optical condition of the coupling of laser light output to optical fiber is described by the Launch Conditions. This includes more than just the percentage of light that is captured by the fiber, sometimes expressed as insertion loss [dB]. It includes the distribution of modes of the fiber that are excited as well as any polarization of the light occurring in this coupling. Related issues are: Launch Angle, Launch Numerical Aperture, Launch Spot, and Launch Fiber [Ref. 3]. Standardized launch conditions have been specified (Mode Distribution, Overfill Launch condition, Under-fill Launch, etc.)
- c. End of Life (EOL) Transmitter Power: The amount of optical power (average or peak) that exists at the end of a source's specified life.
- d. Environmental Impacts on Power: Environmental impacts are sometimes listed as a power penalty in [dB]. This includes both naturally occurring conditions, such as temperature, humidity, vibration, etc., as well as man-made conditions, such as contamination, fiber bending, etc.

3.1.2 Loss [Ref. 3] Terminology Definitions and Units

3.1.2.1 Attenuation [Ref. 3]: Attenuation is optical power loss per unit length of fiber and is typically dominated by Rayleigh Scattering from core dopants, imperfections in the core boundary, and absorption. Link budgets may need to use EOL values, particularly if radiation exposure is anticipated in the environment.

3.1.2.2 Cabling Losses

- a. Cable Loss [dB/m]: This is the attenuation that occurs within the cable due to manufacturing and is generally a linear function of length, usually given in dB/m. It varies from one cable to another and is therefore best described statistically, in terms of a mean loss and a variance to that mean. Note that cable loss is wavelength-dependent.
- b. Installation Losses [dB]: Installation losses are additional losses in the installed cable due to routing, clamping, cable bending, etc. In aerospace platforms Harness Loss is often a significant component.

3.1.2.3 Connector Insertion Loss (Terminus Insertion Loss, see also 'Insertion Loss') [dB]: This loss is any attenuation that occurs as the result of the fiber-to-fiber interface at a connector. Lack of cleanliness of the end-face is the overwhelmingly most common source of loss. In addition to cleanliness there are six main fundamental sources of connector loss: lateral misalignment, angular misalignment, end separation, surface finish, Fresnel loss, and intrinsic fiber loss. Within intrinsic fiber losses there are five primary sources of losses due to fiber properties: different core diameters, different Numerical Apertures (N.A.), core eccentricity, core ellipticity, and different core designs (e.g., matched clad step index versus depressed clad) [Ref. 3].

- a. EOL Connector Loss: EOL connector loss is lifetime degradation from maintenance (mate/demate and cleaning) and environment (i.e., vibe, temp, shock, etc.); often an estimate based on testing [dB].
- b. Environmental Impacts [dB]
 1. Salt, Fog, Oil, Dust, Dirt, etc.: In general, excessive fiber terminus end-face contamination is a problem that must be accounted for in real systems, particularly ones that are exposed for maintenance.
 2. Shock and Vibration: Shock and vibration are often temporary transient losses but will cause long-term permanent degradation that impacts link performance over life and can produce excessive fiber terminus end-face damage. Thus there are temporary losses in [dB] that are sometimes correlated with other losses if the system suffers transient and separate permanent losses [dB] that can count against EOL performance.
 3. Fiber Pistoning: Fiber pistoning is a terminus or connector phenomenon that can result from environmental stress or terminus wear. It results when the fiber sinks into, or sometimes protrudes from, the ferrule end face.
- c. Fiber Mismatch Loss: Fiber mismatch loss is additional intrinsic loss that results from fibers of different construction being mated. For example, a larger-core fiber connected to a smaller-core fiber, a mismatch of the angular acceptance (Numerical Aperture or N.A.), or a change in the index profile or optical mode profile will all result in an optical loss.

3.1.2.4 Coupling Ratio/Loss (C_R [%], C_L [dB]) [Ref. 3]: The ratio/loss of optical power from one output port to the total output power, where the ratio is a fractional % and the loss is typically listed in [dB]. For example, for a 1x2 coupler with output powers P_{o1} and P_{o2} , either output P_{oi} may be given as:

$$CL[dB] = 10 \log_{10} (P_{oi} / (P_{o1} + P_{o2})) \quad (\text{Eq. 2})$$

3.1.2.5 Excess Loss [dB]: Excess loss is a loss typically associated with a device that is in excess of the fundamental loss limited by physics. For example, a 3 dB splitter may output power in the two legs that is 4 dB down from the input. In this case the splitter has 1 dB of excess loss on each branch.

3.1.2.6 Extraneous Point Losses [dB]

- a. Bend loss: Bend loss is insertion loss due to bends, often due to the fiber routing and is often a significant contributor to cable and installation loss.
- b. Splice Loss: Splice loss is a loss incurred from a fusion or mechanical splice connection. The loss can be much larger when non-identical fibers are spliced.

3.1.2.7 Insertion Loss [dB] [Ref. 3]: The insertion loss is the additional loss added to a fiber optic system by inserting a piece of optical equipment into that system. Insertion loss is generally measured in [dB]. The ratio of incident (input) optical power to the transmitted (output) optical power, where P_i is the power input and P_o is the power output:

$$L_{IL}[dB] = 10 \log_{10} (P_i / P_o) \quad (\text{Eq. 3})$$

- a. Correlated Insertion Losses: Correlated losses are individual losses that are physically related such that their means and standard deviations add linearly in a statistical sum of losses; most statistical loss analysis assumes uncorrelated losses that sum in a vectorial or Root Sum Square (RSS) manner.

3.1.2.8 Margin (Loss Margin): The Margin is a factor purposely added to a link loss budget to provide a needed or desired confidence to the baseline predicted performance over its intended life. It can be used to account for:

- An expected system degradation of performance over time, if not accounted for in the component data;
- A level of uncertainty for things that cannot be accurately quantified;
- An unknown loss that may occur, such as a soft failure or environmental degradation;
- A flight safety factor above some minimum performance level, due to the flight critical aspects of the link;
- A mission essential factor above some minimum performance level due to mission critical aspects of the link.

3.1.2.9 Modal Loss [dB] (i.e., Mode Selective Loss (Also see related Modal Distortion, Modal Noise): In multimode fiber systems, modal loss depends on modal distribution. It can lead to transient losses (see Modal Noise [Ref. 3]) due to modal distribution change and can lead to inter-symbol interference or pulse distortion due to modal dependence in laser modulation. Static and dynamic mode partitioning, and mode dependent loss can cause power penalties due to pulse distortion, which may be dynamic in nature.

3.1.2.10 Mode Reduction/Injection Losses: For mode reduction/injection losses, some modes launched into the fiber may be attenuated, reducing optical power transmitted through the fiber.

3.1.2.11 Modal Noise: Modal noise is "Noise" generated in an optical fiber system by the combination of mode dependent optical losses and fluctuation in the distribution of optical energy among the guided modes or in the relative phases of the guided modes. This is really a transient modal loss that can generate errors in the receiver and not a receiver noise. This often results from system vibration impacts on connection interfaces in multimode systems.

- 3.1.2.12 Reflectance [Ref. 3]: Reflectance, R , is the ratio of the reflected power, P_r , to the incident power P_i , at a reflection point or interface, or from a component. It is most often used in the broader optics industry as a surface characterization metric referenced to free space propagation [Ref. 5], but is also used for characterization of guided wave light power reflection phenomena, such as in a fiber. Reflectance can be expressed as a ratio, in percent, or in [dB]:

$$R_{ref}[dB] = 10 \log_{10}(P_r / P_i) \quad (\text{Eq. 4})$$

NOTE: This will be negative since the ratio is less than unity and since no minus is used in the formula. This is in contrast to Return Loss RL.

- 3.1.2.13 Return Loss (RL) [dB] [Ref. 3]: The more common parameter measured to determine reflected power is Return Loss, RL, which is the negative of reflectance, defined as:

$$RL[dB] = -10 \log_{10}(P_r / P_i) \quad (\text{Eq. 5})$$

- 3.1.2.14 Transient Insertion Loss [dB]: Transient losses are momentary losses that impact performance but may disappear when the system returns to its unperturbed condition. They may be periodic, systematic, or random. Transient losses can be correlated or uncorrelated with other loss sites in a link. Transient losses are typically difficult to model and need sufficient transient condition test data for analysis.

- 3.1.2.15 Wavelength Penalty [dB]: Wavelength penalty is a penalty assessed against performance for signals at a spectral region of low device performance if the component specification does not cover the worst case wavelength span. Different devices may have different spectral dependence.

3.1.3 Components (Typical to Fiber Optic Link)

- a. Attenuators: An attenuator is a passive device for reducing the amplitude of a signal without appreciably distorting the waveform. A Variable Optical Attenuator (VOA) is an attenuator with variable attenuation levels.
- b. Fusion Splice: A fusion splice is a thermally fused optical fiber connection. They are typically less susceptible to environment effects than mechanical splices.
- c. Mechanical Splice [Ref. 3]: A mechanical splice is an optical fiber junction accomplished by fixtures or materials, rather than by thermal fusion. The prepared fiber is held in a mechanical fixture to high precision and is aligned by the fixture to high precision with its mating fiber. It sometimes has index matching material, gel or fluid to reduce loss and reflections. Mechanical splices are typically more susceptible to environment effects than fusion splices.
- d. Optical Filters [Ref. 3]: An optical filter is a component or element that selectively passes (transmits) or attenuates (blocks) a range of wavelengths.
- e. Optical Isolators [Ref. 3]: An optical isolator is a component used to extinguish reflected and unwanted light, within a given optical wavelength range, from a down stream element or interface, based on magneto-optical rotary effects. The level of light suppression is typically given in terms of [dB].
- f. Optical Switch [Ref. 3]: An optical switch is a device to change the path of the optical signal. It results often in insertion loss [dB] and return loss [dB].
- g. Splitter (Coupler/Star Coupler, Combiner, Power Splitter): Splitters are optical devices that combine or split power from one or more optical fibers and route the power into one or more fiber outputs (see Modal Loss, Mode Selective Splitting ratio)

3.1.4 Additional Performance Considerations

- a. Crosstalk/Channel Interference (in WDM Design) [Ref. 3]: Crosstalk is any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired coupling of modulated energy in another circuit or channel. Crosstalk is typically quantified as:

$$X_T[dB] = 10 \log_{10}(P_d / P_o) \quad (\text{Eq. 6})$$

where X_T is crosstalk in [dB], P_o is the received optical power, and P_d is the undesired power in the disturbed fiber at the corresponding received location.

- b. Chromatic Dispersion, or Dispersion (D)[ps/nm-km][Ref. 3]: Chromatic dispersion is a term used to describe the chromatic or wavelength dependence of the refractive index. Signal distortion in an optical fiber is caused by several dispersive mechanisms which include at least waveguide dispersion and material dispersion. In addition, the signal suffers degradation from multimode “distortion”, which is often (erroneously) referred to as multimode “dispersion”.
- c. Effective Modal Bandwidth (EMB)[MHz-km] Speed/Bandwidth, Bandwidth Length Product [Refs. 3,9]: The EMB product is the range of frequencies for which a fiber optic wave-guide or terminal device can transmit data or information over a given length. The dominant mechanism for limitation of bandwidth in multimode fibers is Modal Distortion. EMB can be used to assess a receiver power penalty in that the effective modulated power decreases to half the input value under certain mode-fill conditions when the signal bandwidth distance product equals the EMB.
- d. Modal Distortion (Intra-modal Distortion, or Multimode Dispersion) [Refs. 3,9]: Modal distortion is a mode dependent difference in net propagation velocity causing a pulse made up of multiple modes to spread spatially, or distort, along its propagation direction.
- e. Polarization Effects (Sources, Fiber, Detector, etc.) [Ref. 3]: Many devices are sensitive to polarization of the propagating light and have Polarization Dependent Loss (PDL), in addition to Polarization Mode Dispersion (PMD) [Refs. 3,10]. Various propagation modes can have polarization states that are not strictly vertical or horizontal, and take on different well known field patterns [Ref. 11]. PDL is often covered in budgets by max and min limits for a component, since it is likely in a system that all states of polarization will exist at some time. Since multimode links have a variety of polarization states and modes, PDL and also PMD are typically incorporated in mode dependent losses and distortions.

3.1.5 Statistical and Analysis Terms

- a. Confidence Interval: A confidence interval is the interval (a,b) within which the estimate value X will lie with a probability $\Pr(a \leq X \leq b)$, and is associated with the confidence level $C(a,b)$. It is sometimes called a ‘q-percent’ confidence interval since what is often desired is the determination of the interval over which X can be found with q-percent confidence.
- b. Confidence Level $C(a,b)$: Confidence Level $C(a,b)$ is the probability percent (q-percent) that the random variable X could be found in the confidence interval bounded by a and b . This may be expressed as $C(a,b) = 100\Pr(a \leq X \leq b)$, or the percent probability of finding the variable in that range.

This can also be expressed in terms of the CDF (or cumulative distribution function), defined below as,

$$C(a,b) = 100(F_X(b) - F_X(a)) \quad (\text{Eq. 7})$$

- c. Confidence Limits (a,b): The confidence limits are the bounds ‘a,b’ on the confidence interval. They are often expressed in terms of plus and minus a factor times the standard deviation of a population, about the mean of the population. For example $a = \bar{X} - \kappa\sigma$, $b = \bar{X} + \kappa\sigma$.

- d. Cumulative Distribution Function [Ref. 12] (CDF): The CDF, $F_X(x)$, is defined for a continuous random variable X . The CDF is defined such that if X is a random variable and x is any allowed value of X , then $F_X(x)$ is the probability that the observed random variable, X , is less than or equal to the allowed value x . Thus, $F_X(x) = \Pr(X \leq x)$. Another way to define it is the fraction of values in the population less than or equal to x . It is the integral of the probability density

function, or $F_X(x) = \int_{-\infty}^x f(u) du = \Pr(X \leq x)$.

- e. Probability Function, $\Pr(X)$: The probability reflects the possibility of the value X occurring in a given population or the relative frequency in which X may be selected from a population normalized to 1, (100% probability). The probability can occur under many different constraints and conditions.
- f. Probability Density Function [Ref. 12] ($pdf(x)$), often represented as $f(x)$: The fraction of the population of values that can be found in the interval dx , where $f(x) = dF_X(x)/dx$, or the derivative of the Cumulative Distribution Function. Thus $f(x)dx$ is the probability of the random variable X existing in the range of possible variables x between x and $x+dx$, or $\Pr(x < X \leq x+dx)$.

- g. Mean: The mean $\bar{X}$ is the statistical average of a population or sample of a population of a random variable X . It is a point estimate (a single value) that reflects the most central effective value of a population. The term effective value is used since there may not be an actual value X in the population with the mean value. For a continuous variable, the

mean is $\bar{X} = \int_{-\infty}^{\infty} xf_x(x) dx$ and for a sampled variable of N samples the mean is $\hat{m} = \frac{\sum_{i=1}^N x_i}{N}$.

- h. Standard Deviation, σ : The standard deviation represents the magnitude of the randomness or spread of a sample or population of data. It is determined by the square root of the sample or population mathematical variance, that is,

$\sigma = \sqrt{\overline{(X - \bar{X})^2}}$, where X is a continuous random variable and $\bar{X}$ is the mean of random variable.

- i. Variance: Variance is the square of the standard deviation for a continuous variable and for a sampled variable may be represented in terms of the true standard deviation by dividing by the number of samples, $Var(\hat{m}) = \frac{\sigma^2}{N}$.

TABLE 1 - DEFINITION OF PARAMETERS AND SYMBOLS USED IN EQUATIONS

Symbol	Definition
A_j	Optical loss adjustments or corrections that are necessary for the chosen optical element
A_k	Optical gain adjustments or corrections that are necessary for the chosen optical element
A_P	Optical power adjustments or corrections that are necessary for the chosen optical source element
A_R	Optical sensitivity adjustments or corrections that are necessary for the chosen optical receiver element
A_{WC}	The sum of all the worst case adjustments to the link loss budget including the sum of the power penalties associated with the specific system design including environmental effects and aging factors.
B_μ	The optical link loss power budget defined by input power to receiver
B_{WC}	The worst case optical link loss power budget including environmental effects and aging factors
C	Confidence level; an indicator that represents how certain a value will be above (or below) the selected value of the optical loss budget margin.
C	Confidence level; an indicator that represents how certain a value will be above (or below) the selected value of the optical loss budget margin.
ER	The extinction ratio
f_j	Distribution of optical loss for the j th optical element chosen at random
f_k	Distribution of optical gain for the k th optical element chosen at random
f_P	Distribution of optical power for the optical source element chosen at random
f_R	Distribution of optical sensitivity for the optical receiver element chosen at random
G	The total optical gain for the specified digital optical link.
G_i	Distribution of optical gain for the chosen optical element in a link
I_N	Noise current
I_S	Signal current
L	The total optical power loss for the specified digital optical link.
La_{ER}	Loss adjustment due to Extinction Ratio
La	The sum of the means of all the adjustments to the link loss (effective loss) including power penalties associated with dispersion, distortion and other impacts associated with specific system designs (see list of parameters and definitions). Power penalties may also be accounted for in the transmitter power, P and the receiver sensitivity, R. Care must be taken not to double count a power penalty; that is in both La and R or P.
L_C	Connector loss
L_{C_μ}	The sum of the mean connector loss.
L_{WC}	The sum of the worst case connector losses including environmental effects and aging factors.
L_{f_μ}	The mean of the fiber loss (can include fiber bend, routing, harness and cable)

Symbol	Definition
L_{fWC}	The worst case loss of the fiber including the sum of the worst case bend and clamping losses including environmental effects and aging factors.
L_i	Total distribution of optical loss per optical element in a link
L_{IL}	Insertion loss
L_{μ}	The mean loss of the optical link.
LS_{μ}	The sum of the mean splice loss.
LS_{WC}	The sum of the worst case splice losses including environmental effects and aging factors.
$L_{T\mu}$	The mean of the transient (temporary environmental) loss.
L_{TWC}	The worst case optical fiber transient loss including environmental effects and aging factors..
$\bar{M}$	The average (or mean) of the interim optical loss budget margin values, M_i
M_{ACT}	Actual optical loss budget margin calculated by the budgeting method
$M_{ACT \kappa}$	The actual optical link loss margin calculated at confidence factor κ .
M_i	Interim optical loss budget margin
$M_{Numerical}$	Calculated total optical loss budget margin
M_{REQ}	Optical loss budget margin design requirement
$M_{SAT,numerical}$	Calculated total optical loss budget saturation margin
M_{WC}	The worst case intrinsic optical link loss margin.
P	The total optical power of the source for the specified digital optical link.
P_i	Total distribution of optical power per optical source element in a link
P_{μ}	The mean optical source power
P_{max}	The maximum optical output level that produces a Logic '1'
P_{min}	The minimum optical output level that produces a Logic '0'
$P_{mod,avg}$	Total average modulated optical power in the link
$P_{tot,avg}$	Average total power output in the link measured by an averaging meter
P_{WC}	The worst case optical source power including environmental effects and aging factors
R	The total optical receiver sensitivity of the destination of the specified digital optical link.
R_i	Total distribution of optical sensitivity per optical receiver element in a link
R_{μ}	The mean optical receiver sensitivity in terms of power.
R_{WC}	The worst case optical receiver sensitivity including environmental effects and aging factors.
κ	The multiplier factor associated with a given confidence level
σ	The standard deviation of the optical link
σ_a	The RMS sum of the standard deviations of all the adjustments to the link loss budget including power penalties associated with specific system designs and the allowance for future upgrading.
σ_C	The RMS sum of the standard deviations of the connector loss.

Symbol	Definition
σ_F	The standard deviations of the fiber including expected bend loss.
σ_P	The standard deviation of the power output by the transmitter
σ_R	The standard deviation of the receiver sensitivity
σ_S	The RMS sum of the standard deviations of the splice loss.
σ_T	The standard deviation of the transient loss.

4. CALCULATION METHODS

This section discusses the primary methodology for calculation of the link budget.

4.1 Basic Notional Method

This subsection is only intended to give a common overview of, and introduction to, the method of calculating optical link budgets. It describes the steps to prepare, the basic concept of calculating a budget, and a generalized success criteria of a budget. For more specific details on implementing and calculating an optical link budget see the following sections depending on the methodology under consideration.

In Figure 2, an example digital fiber optic link is shown. This link is comprised of a transmitter, a receiver, and a number of optical elements connecting the two end points. When a link like this will be implemented in an aerospace platform, it should be checked for functionality over the appropriate environmental conditions. This check is referred to as an optical link loss budget.

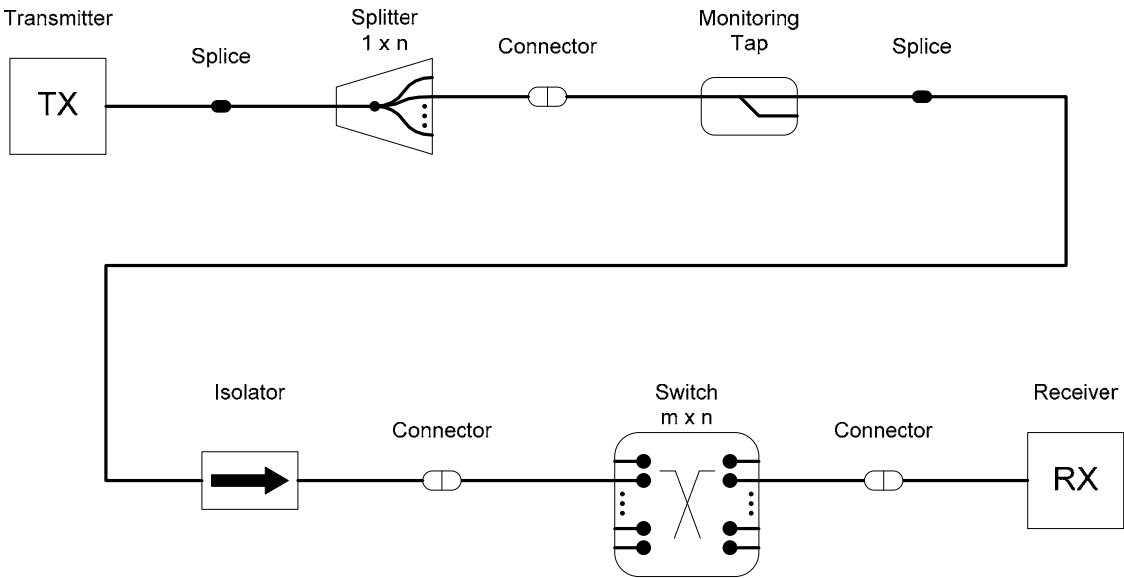


FIGURE 2 - AN EXAMPLE DIGITAL FIBER OPTIC LINK

Before calculating an optical link loss budget, several items must be agreed upon between the customer and an entity designing and/or building the optical system. These details would be something negotiated and written up in a contract between the parties.

The first of these items is the required margin, M_{REQ} , of the optical system. This parameter reflects an additional amount of optical power in the link set aside to accommodate unknown and unexpected losses. This parameter is similar to the “safety margin” described in MIL-STD-2052A. However, MIL-STD-2052A only specifies two values for that parameter whereas today’s more complex fiber optic technology requires greater flexibility. Hence, the value of M_{REQ} will depend heavily on reliability needed, data on the components available, and which quantities have or have not been characterized or measured. Assigning a value to M_{REQ} that is too small when there is a lack of data on system components and system effects may result in an optical system that does not achieve the needed reliability and performance. Assigning a value to M_{REQ} that is too large when the components and system effects are well characterized may result in an optical system drastically overbuilt and costly for the needed reliability and performance. In the extreme, a large M_{REQ} value may also saturate optical receivers, negatively affecting the reliability and performance of the optical system. Because of this possibility of saturation, some systems should include a check against $M_{REQ(SAT)}$, the required saturation margin. Note that $M_{REQ(SAT)}$ may be different from M_{REQ} .

The second parameter is the confidence level, C , needed for meeting the M_{REQ} of the system. This parameter is typically expressed as a percentage. For example, the loss budget may be 97.7% confident that the margin is met. The confidence level is not used directly at this stage but may affect the values or distributions used. There may be a trade off in negotiating the value of C and M_{REQ} . For example, a system with a low M_{REQ} may need a high C to compensate while a system with a large M_{REQ} may have a lower value of C .

The next item to determine is the method to calculate the optical power of the source in the optical link. This is represented by the parameter, P , and discussed further in 4.3.1.

The next item to determine is the method to calculate the sensitivity of the destination in the optical link. This is represented by the parameter, R , and discussed further in 4.3.2.

The next item is what optical losses will be included in the calculation. Note that in establishing a value for M_{REQ} , the types of losses accounted for in the loss budget should be considered as a trade off. This may be a direct trade-off or a more complex relation depending on the loss type and data available. For more loss types included, M_{REQ} should be decreased by an appropriate amount. All of these losses are generally represented by the parameter, L , and discussed further in 4.3.3. Table 2 summarizes the loss types that should be considered and negotiated in applying a budgeting method. Note that Table 2 only lists optical losses due to elements of the optical link and not environmental or system effects. These environmental and system effects are accounted for through adjustments that are described later. As research into optics and photonics continues, new component types may need to be added to Table 2. As a final reminder, Table 2 contains optical loss elements that should be considered in an optical link loss budget, not elements that are required.

TABLE 2 - OPTICAL LOSS ELEMENTS TO CONSIDER IN AN OPTICAL LINK LOSS BUDGET

Optical Loss Element	Symbol (if applicable)	Comment
Generic Element	L_i	The i th element of an optical link, a generic representation of any element on this list.
Connector	L_c	There may be a variety of connector types in an optical link.
Splice	L_s	
Fiber	L_f	Known losses in a fiber due to known fiber bends and routing. Temporary and unexpected losses accounted elsewhere.
Attenuator		
Optical Filter		Include multiplexing and demultiplexing elements
Optical Isolator		
Optical Switch		
Splitter / Coupler		Also referred to as combiner, star coupler, power splitter, and monitor tap.
Modulator		

Additionally, there may be some gain elements in the optical link. All of these optical gains are generally represented by the parameter, G , and discussed further in 4.3.4. Typically, the optical gains are called out separately from optical losses in order to highlight the adjustments that may need to be included in the optical link loss budget.

Lastly, there are additional penalties or adjustments, A , that should be taken into account for the optical link. These adjustments reflect a number of environmental effects on the system and system interaction between the elements in the optical link. The adjustments considered are ones that affect only the optical link and not any supporting electronics dealing with the resulting or generation of electrical signals. Depending on the budgeting method, these adjustments are used in different ways. For example, the adjustments may be added like an optical loss or they may alter the distribution used to represent an optical component. These adjustments and penalties are discussed further in 4.3.1 through 4.3.4. Table 3 summarizes the adjustments that should be considered and negotiated in applying a budgeting method. Note that in negotiating a value for M_{REQ} , the types of adjustments accounted for in the loss budget should be considered as a trade off. For more adjustments included, M_{REQ} should be lowered by an appropriate amount. As research into optics and photonics continues, new adjustments may need to be added to Table 3. As a final reminder, Table 3 contains adjustments that should be considered in an optical link loss budget, not elements that are required.

TABLE 3 - ADJUSTMENTS TO CONSIDER IN AN OPTIC LINK LOSS BUDGET

Adjustments	Concerns			
	Power (Source)	Sensitivity (Receiver)	Optical Losses	Gains
Altitude	X	X	X	X
Bend sensitivity			X	
Chromatic Dispersion	X	X	X	X
Clamp sensitivity			X	
Clock Timing Jitter Tolerance		X		
Contamination			X	
Crosstalk		X	X	X
Dynamic Modal Noise (non-vibration)		X	X	
EMI disruption	X	X		
End of Life	X	X	X	X
Extinction Ratio Penalty	X	X		
Fluids			X	
Fungus			X	
Humidity	X	X	X	X
Inter-Symbol Interference		X		
Launch Conditions	X			
Mate-Demate cycling			X	
Noise, ASE	X			X
Noise, RIN	X			
Noise, Shot		X		
Optical Reflections	X	X	X	X
Ozone			X	
Polarization Effects	X	X	X	X
Radiation	X	X	X	X
Rain			X	
Salt Fog			X	
Sand and Dust			X	
Shock	X	X	X	X
Sulfur Dioxide			X	
Temperature	X	X	X	X
Temporal Dispersion	X	X	X	X
Temporary Fiber Bends			X	
Terminus insert/remove cycling			X	
Thermal Shock	X	X	X	X
Tolerance of concentricity of coated fibers			X	
Transient Conditions	X	X	X	X
Vibration	X	X	X	X
Wavelength Penalty		X	X	X

Until an agreement has been reached on the items from Tables 2 and 3, completing one of the methods described in later sections may not satisfy the customer and the entity designing and/or building the optical system. These items are summarized in Table 4.

TABLE 4 - SUMMARY OF ITEMS THAT ARE REQUIRED BEFORE A BUDGETING METHOD IS APPLIED

Parameter	Action Needed
M_{REQ}	Agreement on the required margin for the specified digital optical link.
$M_{REQ(SAT)}$	(Optional) Agreement on the required saturation margin for the specified digital optical link.
C	Agreement on the required confidence that the specified digital optical link meets the required margin.
P	Agreement on the method to determine the optical power of the source for the specified digital optical link.
R	Agreement on the method to determine the sensitivity of the destination of the specified digital optical link.
L	Agreement on the optical loss elements included from Table 2 for the specified digital optical link.
G	Agreement on optical gains included for the specified digital optical link.
A	Agreement on the adjustments included from Table 3 for the specified digital optical link.

Once the items in Table 4 have been negotiated then an optical loss budget may be calculated. Generically, each budgeting method attempts to satisfy the following equation:

$$M_{ACT} = (P - R) - L + G \quad (\text{Eq. 8})$$

where M_{ACT} is the actual margin calculated by the budgeting method. Note that adjustments, A , are not included in this generic formula. This is because different methods may take those adjustments into account in different manners from simply adding a term to the equation to adjusting the distributions used for the individual elements. Also note that confidence, C , is not specifically called out in this generic formula. Each method may account for the required confidence in different ways. For example, one method may increase or decrease parameters based on how high the confidence is required and another method may require more iterative calculations.

Now that the actual margin of the optical link has been calculated, it may be determined if the optical link to be implemented will function over the appropriate environmental conditions for the aerospace platform. If M_{ACT} is less than M_{REQ} , the optical link does not meet the requirements of the design and must be redesigned to address the inadequacies. If M_{ACT} is greater than or equal to M_{REQ} , the optical link meets the goals of the design.

As an additional check, the optical link should be verified against saturation conditions where too much optical power reaches the receiver. Often this check is not performed because most of the degradations in an optical system reduce rather than increase the optical power available and the optical system does not approach the saturation limit of the receiver. Hence, it may be negotiated whether or not this check is performed. This check is similar to the one described above in that each budgeting method attempts to satisfy the following equation:

$$M_{SAT} = R_{SAT} - P_{\max} + L_{\min} - G_{\max} \quad (\text{Eq. 9})$$

where M_{SAT} is the actual saturation margin calculated by the budgeting method and R_{SAT} is the saturation value of the receiver. It is important to note that for this check the values of $P_{\max}$, $L_{\min}$ and $G_{\max}$ allow the maximum amount of light to reach the receiver. If M_{SAT} is less than the required saturation margin, $M_{REQ(SAT)}$, the optical link does not satisfy this check. If M_{SAT} is greater than or equal to $M_{REQ(SAT)}$, the optical link satisfies this check. Note that $M_{REQ(SAT)}$ may be different from M_{REQ} .

4.2 Data Required

The quality, quantity and pedigree of component test and qualification results that exist can impact the approach and methodology used for development of a link loss power budget.

4.2.1 Direct Data Collection

Direct data collection by the system or link designer is a good approach for systems that require high confidence. This is because the system conditions can be simulated most accurately in the testing, and few component manufacturers or suppliers test to aerospace qualification conditions. This, however, is the most expensive approach. A preferred approach is to have full statistical data supplied by the component suppliers that can be validated with limited testing for special conditions not previously tested, or simply to sample the population for secondary verification of supplied test results. It is more common, however that such data does not exist or is not made available by the component suppliers, or if it is available, it does not cover all environments of interest. As such, the system designers often require direct data collection. The data may be determined through measurements made on an appropriate sample size of the components and include appropriate environmental effects. These values should minimally include the statistical mean and standard deviation.

4.2.2 Manufacturer's Data

Manufacturer's, or component supplier's data, depending on the component supplied, may include attenuation, insertion loss, reflectance, output power, sensitivity, etc. The provided values shall be representative of current production and shall be measured in accordance with the specification for the component. These values should minimally include the statistical mean and standard deviation. Ideally they would include a histogram frequency plot as shown in Appendix A on Relevant Statistics along with a best fit distribution that could be used in a statistical analysis. Often information for these components evolves over the course of the program and refinements are made correspondingly due to special environmental conditions or new production lots, etc.

Vendors should also provide some justification behind the values including basis and measurement methods. It is recommended that manufacturers and suppliers at least use standard methods and procedures such as TIA/EIA-455 [Ref. 13] for environment and aging effects, in addition to generalized standard methods and procedures [Refs. 13,14,20,24,25] for all tests, with specific reference to the procedure used, in order to have a standard basis of measure. Aerospace platform environmental conditions often exceed both environment and the stress of aging simulated by the TIA/EIA-455 test conditions, and most platforms have platform-specific environment. These conditions and procedures, however, can often be extended to be representative. Some examples of standard environmental connector aging factor tests are:

Test Categories:

1. Initial IL (to establish baseline) (e.g., TIA/EIA-455-171, static test)
2. Durability (Mate-de-mate) (e.g., TIA/EIA-455-21A, 1,000, meas. Ea 25; max ave. inc. 0.1 dB, 0.2 sing. pt., -20dB RL)
3. Temperature Aging (e.g., 85 °C for 336 h, TIA/EIA-455-4B, max increase 0.2 dB ave. 0.3 dB single pt. dur; post 0.1, 0.2 dB)
4. Temperature Cycling (e.g., TIA/EIA-455-3A, -40 to 80 °C for 42 cycles.; max increase 0.2 dB ave., 0.3 dB single pt. dur; post 0.1, 0.2 dB)
5. Vibration (eg., MIL Random/Gunfire, x,y,z, or TIA/EIA-455-11B, post only 0.1, 0.2 dB, for MIL can monitor during with high bandwidth (HBW) power meter)
6. Shock (e.g., MIL landing, or Impact TIA/EIA-455-2C, post only 0.1, 0.2 dB, can monitor during with HBW power meter)
7. Humidity (e.g., 95 %RH @ 60 °C 336 h, TIA/EIA-455-5B, max inc. 0.1 dB ave. 0.2 dB sing. pt., -20dB RL dur; post 0.1, 0.2 dB)

8. Temperature Altitude (MIL only)

9. Salt Fog/SO₂ (MIL only)

Note that particularly active components should be tested under appropriate representative test protocol conditions using representative components (EAMs, VCSELS, Edge Emitters, etc.). Passive components (particularly multimode) such as connectors should be tested using representative fiber launch conditions, polarization, etc.

It is also a recommendation of this standard that component suppliers work with the system designers in attempt to provide as much additional relevant test data as possible. This is considered a high value added by many system designers in the selection of a given component.

4.3 Calculation of Parameters

4.3.1 Power

The following subsection describes the method for calculating the parameters associated with power, P .

4.3.1.1 Modulated Power:

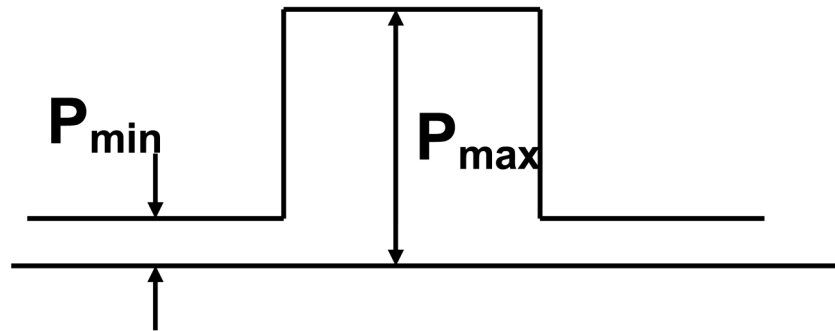


FIGURE 3 - OPTICAL PULSE SHOWING MODULATION AND PEDESTAL

Figure 3 is a representation of the laser output power for a fiber optic link. When a logic state corresponding to maximum laser output (for example, a logic '1') occurs, the laser is driven to produce an output power of P_{max} . Note, however, that the opposite binary logic state (for example, logic '0') does not drive the laser output power to zero.

Instead, most lasers are driven to an output power somewhat above zero, in order to meet threshold requirements. Many LED sources are also driven to some low, but not zero, output power for the low logic state. In Figure 3 this is labeled as P_{min} .

The modulated power is therefore given as $P_{max} - P_{min}$, not P_{max} .

4.3.1.2 Average Power: The output power that transceiver manufacturers often list on their data sheets is the average power. For a data stream that consists of 50% logic '1's and 50% logic '0's, this would mean that the Figure 3 waveform will produce a reading of $\frac{1}{2}P_{max} + \frac{1}{2}P_{min}$.

4.3.1.3 Extinction Ratio: When the output power is measured as an average power, special care must be taken to determine the actual modulated power, since this is the only power that conveys information. One measure of this relation between average power and modulated power is the Extinction Ratio.

Extinction Ratio is given by the ratio:

$$er = \frac{P_{max}}{P_{min}}$$

The ratio is often expressed in dB or:

$$ER = 10 \log \left(\frac{P_{\max}}{P_{\min}} \right) \quad (\text{Eq. 11})$$

It is important not to confuse this parameter, in dB, with the power penalty that results from the Extinction Ratio, also expressed in dB.

Now, the average *total* power measured (for example, by a slowly reacting power meter) is:

$$P_{\text{tot,avg}} = \frac{1}{2} (P_{\max} + P_{\min}) \quad (\text{Eq. 12})$$

(assuming probability of 1's and probability of 0's are both 0.5).

However, the average *modulated* power is given by:

$$P_{\text{mod,avg}} = \frac{1}{2} (P_{\max} - P_{\min}) \quad (\text{Eq. 13})$$

If the average total power of Equation 12 is used in the link budget without consideration of the fact that this is not the modulated power needed to transfer information, then the amount of modulated power from the laser will be overstated.

The resulting power penalty, in dB, is then given by:

$$\text{Penalty}(ER) = 10 \log \left(\frac{(P_{\max} + P_{\min})}{(P_{\max} - P_{\min})} \right) \quad (\text{Eq. 14})$$

This penalty must be included in the link budget if the transmitter power is measured for average power (either in the data sheet or in actual power measurements) and the receiver is specified for modulated input power. It is common practice to allocate this penalty to the receiver in the form of a degraded sensitivity value. There are a number of ways of varying model sophistication to do this including a direct addition of the above penalty. The most reliable way is to test the system receivers for sensitivity with a degraded ER and use this value for the receiver sensitivity. The transmitter is then specified to maintain the tested ER or better, and no additional penalty is required. It is recommended, for the case of receiver sensitivity, that manufacturers should include extinction ratio impacts by performing sensitivity measurements with a degraded extinction ratio, and state the values used in the measurements.

- 4.3.1.4 Source Penalties (RIN, Pulse Distortion, Spontaneous Emission): Although receiver noise typically dominates noise statistics, in some applications noise and other less-than-ideal source effects can affect the link budget as well. These include Relative Intensity Noise (RIN), pulse distortion, and Amplified Spontaneous Emission (ASE). The following is a very brief description of each phenomenon. For more complete descriptions, consult [Refs. 6 and 15] in the Applicable Documents section of this standard.

RIN is the variation in source (usually laser) intensity. This variation can be thought of as a noise component and therefore affects the link's SNR and, therefore, link budget. RIN is seldom a limitation in modern optical digital link systems (although it can be a limitation in RF analog links) due to the quality of modern diode lasers. It is always good to verify the RIN value for a given laser to assure there is no issue.

Pulse Distortion is any modification of the pulse from its idealized shape. For example, all sources have a finite rise and fall time. In particular, if the rise time is significantly different from the fall time, the result can be increased jitter in the link and, therefore, degraded link performance [Ref. 16].

ASE can be a significant source of noise in optical amplifiers. Spontaneous emissions occur in any optical medium, although usually at very low levels. In an amplifier, the Amplified Spontaneous Emissions at a particular wavelength will become mixed with a signal at that wavelength and produce an amplitude-multiplied noise source. This is discussed more in 4.3.4.

In addition to source penalties there are source modulation enhancements. Most of these can be characterized by what is usually termed signal modulation format. The most basic format is Non-return to Zero (NRZ), or Amplitude Shift Keyed (ASK). As data rate increases and chromatic dispersion becomes a limiting factor for long transmission links, more robust or exotic signal formats become desirable. Simple return-to-zero (RZ) improves on polarization mode dispersion (PMD) and non-linear optical mixing in long haul systems at a cost of twice the modulation bandwidth. There are chirped versions of NRZ and RZ (CRZ), and carrier suppressed RZ (CSRZ) to address dispersion and nonlinearities. More exotic formats follow, such as duo-binary (three level decisions) and single side-band (SSB) techniques. Finally, techniques used in co-axial and microwave transmission can be applied in the optical domain that offer significant bandwidth efficiency such as Differential and Differential Quadrature Phase Shift Keying (DPSK, DQPSK), which require a balanced detector at the receiver.

The impact of these formats varies, but in general they change the effective sensitivity of the receiver and sometimes the design of the receiver. In terms of the link budget, it is important to understand what signal format is intended for the system so that receiver sensitivity is specified for and tested to the appropriate format.

4.3.2 Receiver Sensitivity

Receiver sensitivity is a dominating parameter in determining a link budget. Sensitivity is generally set by the electrical noise within the receiver. It is usually referenced to a given Bit Error Ratio (BER) required by the system to meet the signal quality demands of the system that the link supports. Common sources of receiver noise that limit this performance are detector noise and preamplifier noise. This noise is normally given in dB relative to 1 mW (dBm).

With that information, the type of distribution (Gaussian or otherwise), and the required BER for a given signal format, the required signal level at the receiver (that is, the mean corresponding to the logic '1' or logic '0' states) can be determined.

An example will illustrate this procedure. A receiver exhibits 1 μ A rms of noise current at the preamplifier input (detector output). For this example, the random distribution created by the noise is Gaussian. For a responsivity of 0.5 A/W this would correspond to 2 μ W or -27 dBm.

In this example, the link is to maintain a BER of less than 10^{-12} , which corresponds to an SNR of approximately 7 (see Appendix D). Observe that this is defined as the ratio of μ to σ . Observe further that μ is the 0-to-peak amplitude. To determine the full peak-to-peak detector current needed we double this number and therefore the required signal amplitude is:

$$I_s(I_n = 1 \mu A, BER = 10^{-12}) = 14 \mu A. \quad (\text{Eq. 15})$$

For a detector with responsivity of 0.5 A/W, this means that at least 28 μ W optical power is needed during the logic '1' states. Since the transmitter's output power is usually specified as an average power, this is 14 μ W average at the detector. This can also be represented as -18.5 dBm. Thus the receiver sensitivity for this example is -18.5 dBm.

Note that such an average power specification assumes that all of the optical power is modulated (Extinction Ratio = ∞). Since the Extinction Ratio is finite, this must be taken into account, along with all of the losses between transmitter and receiver, when specifying the transmitter output.

- 4.3.2.1 Receiver Penalties: There are many potential receiver penalties. If not accounted for in the base receiver sensitivity they must be explicitly added in the budget as a receiver penalty or a loss adjustment. There is no universally accepted way to account for these since it depends on how the receiver sensitivity is specified or measured.

Extinction Ratio is one prevalent penalty since no transmitter has infinite extinction ratio. It is readily accounted for using the relationship given above, if not accounted for in the base sensitivity measurement. Additional sources of loss, such as receiver variations due to End of Life, vibration, and temperature, as well as losses due to any connectors and splices between the receiver input connector and the detector, may be included as penalties, if not accounted for in the base sensitivity.

One of the most important of these additional sources of penalty is the effect of fiber bandwidth limitation due to dispersion. Such bandwidth limitations can be the result of modal, chromatic, or polarization-dependent dispersion.

Modal distortion can impact even short link lengths in multimode links, particularly as the data rate increases. Distortion analysis should be performed to assess any possible impacts on the link budget. It can be assessed as a link power penalty; however, it is not necessarily a fully recoverable loss, compensated for by increasing power. Analysis should take into consideration the modal distribution injected by the laser or LED into the fiber link. Any link testing performed should use representative lasers that span the maximum and minimum mode filling range expected. Modal distortion in multimode fibers is usually characterized in terms of a 'bandwidth-length product' in [MHz-km], or similar. Standard test configurations are used for this characterization and are done by overfilled launch (OFL) conditions or Restricted Mode Launch (RML) conditions. [Refs. 17,18,19 and 27]

The result of such bandwidth limitations is a condition known as Intersymbol Interference (ISI) and is shown in Figure 4.

In addition to the more common dispersive ISI effects just described, multi-path reflections can cause interference between bits. In this case, a delayed version of the signal arrives at the receiver and interferes with the main signal being received.

For the dispersive effects illustrated in Figure 4, it is possible to make some prediction of performance degradation due to ISI based on the fiber manufacturer's published numbers. For example, the Effective Modal Bandwidth product for a multimode fiber might be 500 MHz-km. If the link length is, say, 50 meters, then a bandwidth of 10 GHz is a reasonable expectation. For a 20 Gbps serial transmission rate the eye would definitely begin to close. This effect is largely driven by the multimode modal population that exists in the fiber. It is difficult to fully quantify due to the large number of modes that can exist. In addition, the modes are unstable and change with any environmental change. The exact effect this has on BER and the resulting power penalty to be included in the link budget is difficult to quantify exactly but an estimate can be made [Ref. 15].

The method of assessing ISI described in the previous paragraph has several shortcomings. First, the manufacturer's bandwidth-distance product measurement is highly dependent on the launch conditions (modal population). If the launch conditions for a particular application are significantly different, the actual number may be much different. Second, as mentioned, it is difficult to assess the exact effect this bandwidth reduction has on the BER.

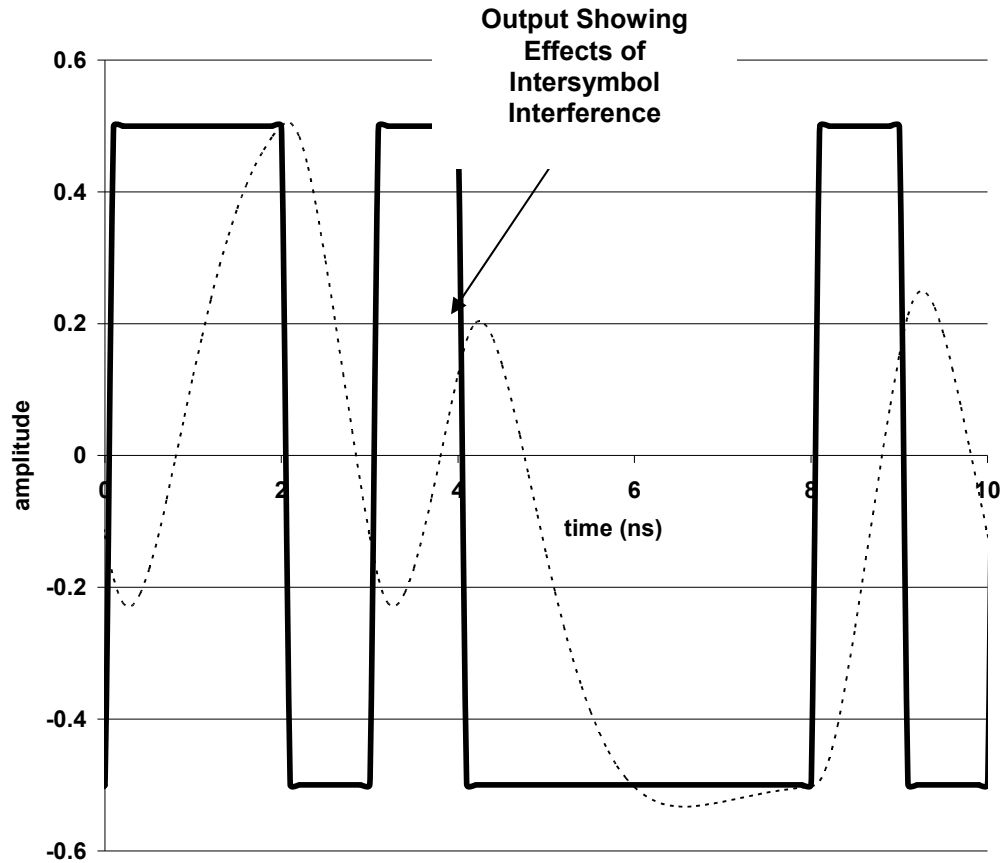


FIGURE 4 - OUTPUT WAVEFORM RESULTING FROM INTERSYMBOL INTERFERENCE

For these reasons, ISI effects on BER are often made as a measurement. From this a corresponding penalty to be included in the link budget can be derived. Note, however, that any such measurements should be made under controlled and realistic launch conditions.

If it is known that the injected signal is fully populating the mode volume of a multimode fiber an estimate of the penalty can be obtained from an overly simplistic model using a simple approximation for the power penalty at the receiver, in dB. This model is useful for initial budget estimates in that it may be conservative for a nominal mode population. It uses the effective modal bandwidth (EMB) of the fiber, the bit rate B_r , and the length of transmission ℓ , to estimate the power roll-off,

$$Penalty(EMB) = -5 \log_{10} \left(1 - \frac{3}{4} (B_r \ell / EMB)^2 \right). \quad (\text{Eq. 16})$$

In single mode fibers with chromatic dispersion D the results are more readily quantifiable. There have been several published relations for receiver power penalties associated with chromatic dispersion. One of the relationships for receiver power penalty in dB often referenced is [Ref. 15]:

$$Penalty(D) = -5 \log_{10} \left(1 - (4B_r \ell D \sigma_\lambda)^2 \right) \quad (\text{Eq. 17})$$

where B_r is the transmission bit rate, ℓ is the length transmitted, D is the dispersion coefficient of the fiber, and σ_λ is spectral linewidth of the transmitted signal, which can be the limiting factor for single mode fiber transmission.

Many other potential signal impairments can be estimated as power penalties against receiver sensitivity. An excellent discussion of these is presented in texts such as Ref. 15, and will not be discussed in detail here.

Care must be taken not only to account for all loss and penalty elements, but also to avoid counting loss penalties more than once. For example, many receiver manufacturers now account for end-of-life (EOL) degradation in the specified sensitivity, and test the receivers under 'stressed conditions'. It is important for receiver manufacturers to clearly specify the conditions under which receiver sensitivity applies and how it was tested, in order for the system designer to verify that it is appropriate for the intended environment. This includes the signal format or pseudo-random bit sequence that was used (i.e., $2^{23}-1$, etc.) in the testing.

Accurate construction of a link budget requires an in-depth understanding of what the specifications mean. Suppliers should work with the system designers to provide detailed insight into the test methods and what the values represent.

In addition to these receiver sensitivity penalties there are also receiver sensitivity enhancements. Adaptive techniques and forward error correction techniques can significantly 'adjust' the effective sensitivity level of a receiver in the direction of increased sensitivity. Adaptive thresholding is one technique to optimize the receiver threshold setting adaptively. Electronic dispersion compensation is an adaptive dispersion impairment technique that can be electronically implemented within the receiver. EDC techniques can significantly enhance the sensitivity of a given receiver, particularly one that has signal impairment due to chromatic, modal or even polarization mode dispersion.

Forward Error Correction [Ref. 28] is an electronic impairment compensation technique that utilizes repeated bits in the transmitted format overhead along with post detection algorithms to correct errored bits and provide significantly enhanced effective receiver sensitivity. FEC techniques can significantly enhance the sensitivity of a given receiver. For example, typical 10^{-12} BER requirements can be reduced to $<10^{-4}$ raw BER with FEC implementation. As such these techniques can be used to increase the margin in a link budget. As with any gain, however, there is typically a cost. For example FEC requires an increased transmission bit rate, and there is latency associated with the error correction algorithms. All these issues must be traded by the system designer in the selection of link components. The link loss budget is one tool that can assist in effectively making these trades.

4.3.3 Optical Loss

In between the optical transmitter source and the receiver are the fiber transport media and elements for the link. This includes the fiber, connectors, and all the passive and active components that make up the link. Each of these elements has a power loss, L , associated with them that make up the overall link loss. In multimode fiber links the location of a loss element may also be important for determination of its loss value L . An element near the transmission source may see higher loss numbers due to a potentially higher distribution of outer peripheral modes. As these modes are stripped off at loss interfaces (modal loss), equivalent loss elements down-stream may impart less loss to the link. Their loss value L should be appropriately reduced. This location dependent loss is another reason that testing in the intended configuration is important for verification of link performance values. Some of the losses are distributed and measured on a loss per unit length basis, such as fiber attenuation. This may vary with distance due to modal loss contributions, but can usually be accounted for on an averaged basis.

The total of all losses is summed over the path of the link for the link budget analysis. This total loss is typically the primary factor driving the link loss power budget. The loss values are usually obtained from component suppliers as a specified value. It is recommended that this data be supplied in a statistical format with reference to the test method used to obtain the data. When possible it is recommended to test the loss values in the intended configuration over the intended environment.

4.3.3.1 Optical Loss Penalties: There are a number of parameters that produce the effect of a loss, but are not strictly power losses, such as dispersion effects, finite modulation depth (extinction ratio ER), etc. These are often accounted for as optical loss penalties or power penalties. They may be accounted for in receiver sensitivity penalties, as discussed above. If not accounted for elsewhere in the budget, these terms may be rolled into a term ' L_a ' for Loss Adjustments discussed more in the worst case and statistical methods section.

4.3.3.2 Modal Loss: Modal loss is loss that depends on modal distribution in multimode fiber systems. It can vary with the distance down stream of the loss element, as discussed in the optical loss section above. It can also lead to transient losses due to temporal change in the modal distribution. This phenomena can, furthermore lead to pulse distortion due to modal dependence in laser modulation for multi-transverse mode lasers. Modal losses are incurred from connector coupling, splicing, or transmitter power injection when the element prior to the coupling interface supports more modes than the Equilibrium Mode Distribution (EMD) of the element or fiber following the coupling interface. This loss can also occur if the connector or interface element acts as a mode dependent loss element. This loss can be problematic in that it will change as the equilibrium mode distribution changes but is generally handled as a fixed loss value, or covered in the transient loss budget.

Modal noise is different from modal loss and is often accounted for in degraded receiver sensitivity. It is also sometimes accounted for in a separate transient budget since it often exhibits itself under transient conditions. This source of noise can result when a laser is launched into a multimode fiber. As a result of vibration, temperature variations, or other effects, the laser launch may change slightly so that the fiber modes change dynamically. Since the different fiber modes have different propagation delays through the fiber, the waveform will arrive at the receive end with a variation in amplitude and phase that can appear as a noise component in the receiver.

4.3.4 Optical Gains and Gain Penalties

Optical gain is currently applicable to only single mode fiber links, though experiments have shown some potential applicability to limited multimode transmission. It is included here for completeness and a belief that it will become more prevalent in the aerospace environment. If optical amplification exists in the link, then gain values, G , exist somewhere in the link that compensate some of the loss values (if not all). If gain exists then there is a gain penalty that results from the fact that gain elements have additional loss along with spontaneous emission noise. This is usually dealt with by a measure of the reduction in signal-to-noise caused by the amplifier. The term associated with the ratio of input to output signal to noise is noise factor, or noise figure, NF, if it is written in logarithmic terms (dB).

Optical gain can be utilized in a number of different ways in optical links. It can be used as a power booster at the initiation of the link (at the source), as an intermediate gain stage to compensate for loss in the middle of the link, or as a pre-amplifier just prior to the receiver to effectively enhance receiver sensitivity. In addition there may be a number of distributed amplifiers throughout the link. The treatment of each of these cases can vary. In particular, the way in which receiver sensitivity is impacted varies between these cases. A general block diagram that incorporates optical amplification is shown below with relevant parameters. This diagram illustrates the case of loss prior to the amplifier, loss after the amplifier, optical bandpass filtering required to filter extraneous spontaneous emission noise and other channels, and the photodiode-limiter elements of the optical digital receiver.

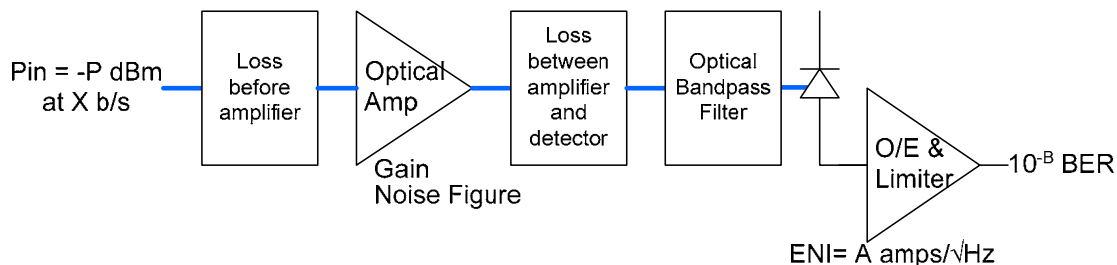


FIGURE 5 - ILLUSTRATION OF OPTICAL AMPLIFICATION IN FIBER OPTIC SYSTEM

It is not the intent of this document to provide a thorough review of these issues. A thorough discussion of amplifier impacts and analysis can be found in references such as Erbium Doped Fiber Amplifiers, E. Desurvire, Wiley Interscience (1994) [Ref. 6]. There are also a number of numerical modeling tools commercially available to perform receiver and even link analysis for any of the structures described above. It is the intent of this document to establish awareness of factors that impact link budget analysis, to describe a general procedure for inclusion of these impacts, and to provide reference to relevant literature when more detailed analysis is required.

Gain, G , from optical amplifiers complicates the link loss budget because gain is not always static, and its value can depend on the optical power input to the amplifier along with the wavelength or wavelengths of the signal being amplified, not to mention the number of signals present if WDM exists. Gain, however, with the proper understanding of the parameters and conditions for which G applies, may often be treated as a simple additive term with the opposite sign of loss L , that is, $G = -L$.

Optical noise output from the amplifier can affect the receiver sensitivity in a number of ways. The Noise Figure associated with gain is the parameter most commonly used for optical link budget purposes. Noise figure is typically listed in dB and is the logarithmic form of the Noise Factor, F_o , or $NF = 10\log(F_o)$. The Noise Factor is simply the ratio of the Signal-to-Noise-Ratio (SNR_i) at the input to the amplifier (assumed to be shot noise limited) to Signal-to-Noise-Ratio (SNR_o) at the output of the amplifier. When the input SNR is shot noise limited it is at its fundamental limit since shot noise is the randomness in the detection of quantized coherent photon detection due to its fundamental Poisson distribution. Amplified Spontaneous Emission (ASE), however, follows Bose-Einstein statistics, which is noisier than Poisson Statistics. The signal-spontaneous beat noise falls between these two. In the end the generally accepted fundamental limit due to signal-ASE noise is a minimum 3 dB noise figure degradation due to the way noise figure has been defined.

One way to account for the additional optical noise generated by optical amplification within a link is to factor it into effective receiver sensitivity. Oversimplifications can sometimes be dangerous, and thus good numerical models are recommended to account for the effect on receiver sensitivity when optical amplification is present. A general rule of thumb, however, when the gain is optimized and receiver noise is dominated by the optical signal spontaneous emission noise, is that the receiver sensitivity is degraded by the noise figure value.

For example, a realistic noise figure for a well optimized optical amplifier might be 4 dB. This corresponds to a multiplication factor of 2.5. This means that the degradation in SNR through the amplifier is a factor of 2.5. This corresponds to a required signal power level of a factor of 2.5 more to receive the same quality SNR signal as would be required without the amplifier preceding the receiver. This is the gain penalty incurred for the gain produced in the system. This number can be folded into the effective receiver sensitivity. If the gain just precedes the receiver, however, so that it is acting as an optical pre-amplifier, then the effective sensitivity is often specified at the input of the amplifier receiver system. That would be just after the first loss block in the diagram above. This is termed an optically pre-amplified receiver.

If an amplifier in the link is used as an optical pre-amplifier, then the pre-amplified receiver effective sensitivity approach is simplest. This will typically give significantly enhanced receiver sensitivity. With adequate gain the receiver is optical noise limited by the pre-amplifier spontaneous emission-signal interference noise. There are many analytical approaches and numerical models available to calculate this new effective sensitivity level.

In the increasingly important case of optically amplified links, the optical signal to noise ratio, OSNR, often becomes the limiting performance factor at the receiver. In this case an OSNR link budget may be needed, in addition to the loss budget. The two are inherently related, as shown in the equation below. OSNR degradation, in dB, is proportional to loss, in dB, in each amplified span.

If multiple amplifiers exist in a link then the concept of noise figure becomes somewhat more complex. The definition of a noise figure assumes that the input SNR_i is shot noise limited. If the input signal to an amplifier has amplified spontaneous emission noise from a preceding amplifier, the noise figure corrupts this definition by providing additional noise at the input. This is addressed in many references such as [Ref. 6] and will not be discussed in detail here. At the risk of additional oversimplification, the linear addition of spontaneous emission noise may be approximated for estimation of noise degradation using the following rule-of-thumb for Optical Signal-to-Noise-Ratio (OSNR):

$$OSNR = 58 + Pch - NF - L - 10 \cdot \log(Na) - 10 \cdot \log(Br / 10Gb/s) \quad (\text{Eq. 18})$$

where Pch is the signal power per channel in dBm, L is the loss per span length between amplifiers in dB, Br is the signal bit rate in Giga-bits per second, NF is the noise figure in dB per amplifier, and Na is the number of identical amplifiers in the link. This is referenced to an approximate 0.1 nm spectral bandwidth. The 58 dB reference value is the OSNR due to a noise photon in dBm within the 0.1 nm spectral width. It correspondingly reflects the shot noise limited OSNR of a 0 dBm reference signal within the 0.1 nm spectral width.

For non-identical concatenated amplifiers, the additive nature of noise variance requires the OSNR from each amplifier to be summed according to the inverse sum rule:

$$\frac{1}{OSNR_{total}} = \sum_i \frac{1}{OSNR_i} \quad (\text{Eq. 19})$$

It is emphasized that a good numerical model is required to properly analyze receiver degradation due to amplifier noise injection. This rule-of-thumb is included for intuitive purposes. It is not recommended to use these 'rule-of-thumb' values in final link budgets without a thorough understanding of how the rules may apply.

While the OSNR represents a good method to track performance in an optically amplified link, it is not recommended to use OSNR degradation only as a final measure of performance for the fiber optic receiver. The OSNR may be equated to receiver Bit Error Ratio (BER), but only when OSNR is the dominant source driving the electrical SNR, since BER is set in the electrical domain by the receiver (see Appendix E). Even when OSNR drives the electrical SNR, the relationship between OSNR, SNR, Q and BER may be convoluted by a finite extinction ratio (ER). ITU-TO.201 [Ref. 28] and other standards and procedures documents [Refs. 13,14,15,23,24,25,26] provide detailed discussions of this and measurement methods. For purposes of the link budget, the most common performance reference is the receiver sensitivity at a given BER. As such it is expedient to convert all optical degradation to SNR to the electrical domain.

Experimental validation under system conditions is ultimately the preferred approach due to other complicating factors that can alter the effective noise figure of the amplifier, in addition to non-optical noise sources.

In addition to the above issues, other factors are important in amplifier performance. Amplifiers have a saturated output value that limits the gain and power output available. There is a corresponding input power at which the gain saturates to limit the output. These saturation limits are usually specified in terms of a 1 dB or 3 dB saturation point. That is, the output power or gain at the specified levels would be 1 or 3 dB higher if the saturation had not occurred. These issues must be accounted for in link budgets in order to understand what the limitations are to the gain and link performance.

Furthermore, the output of amplifiers is usually optically filtered. WDM signals are filtered to separate channels. Single channel systems are also filtered to reduce spontaneous emission noise and spontaneous emission power prior to input into a photo detector. The general rule for spontaneous emission is to filter to the point where pure spontaneous driven noise on the detector is small compared to the signal-spontaneous beat noise, but greater than twice the electrical filter bandwidth in order to avoid signal filtering impacts. Without filtering, a receiver may saturate on the broadband spontaneous emission power alone. A basic understanding of the filtering is required for any modeling of amplifier to receiver performance.

Amplifier suppliers will typically provide performance values appropriate for the link budget such as gain, noise figure, saturated power output, and spectral dependence. One additional consideration with amplifiers is to avoid saturating the receiver with the amplified signal. With high optical gain and output power it is easy to provide too much optical input power to the optical receivers. As stated above, knowledge of how the amplifier is implemented in the system, supported by noise and saturation analysis, is usually needed to fully understand the receiver sensitivity impacts, and thus to establish full confidence in link performance.

4.4 Worst Case Method

The worst case design method gives the least actual margin $M_{ACT|WC}$ as compared to the statistical design method or numerical method. As a result, the worst case method is viewed as the most conservative link loss power budget engineering approach to designing aerospace digital fiber optic links. 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.

When applying the worst case design method: (1) the worst case maximum loss value is used for the passive component losses, and a zero is used for the passive component loss standard deviation; (2) the minimum transmitter output power is used for the transmitter output power parameter; (3) the minimum receiver sensitivity is used for the receiver input power parameter, and a zero is used for the transmitter and receiver parameter standard deviations; (4) the worst case maximum system power penalty losses are used for the power penalty adjustment parameter.

Minimum transmitter output power is defined as the end-of-life output power assumed by the pre-agreed confidence level whereby all of the transmitters in the fiber optic system have output powers greater than or equal to the minimum transmitter output power value.

Minimum receiver sensitivity is defined as the end-of-life sensitivity assumed by the pre-agreed confidence level whereby all of the receivers in the fiber optic system have input power receiver sensitivity performance values that exceed the minimum receiver sensitivity. The worst case value shall combine the manufacturing, temperature, aging, extinction ratio, rise-fall time variations and other variations in a worst case fashion.

Before calculating the link loss power budget:

- a. Worst case power penalties (i.e., those described in 4.3.3) shall be determined and applied to the worst case performance values to define end-of-life (EOL) performance.
- b. Worst case added transient losses due to environmental effects (i.e., temperature, shock, humidity, vibration, nuclear, salt fog, rain, sand and dust, fluids, ozone, altitude, etc.) shall be applied to individual component worst case EOL performance values.
- c. Worst case added loss due to aging factors (i.e., connector damage due to mate-demate cycling, connector or splice damage due component material fatigue induced alignment shift, optical material attenuation, electronics performance degradations, optoelectronic device performance degradations, etc.) shall be applied to the individual passive and active component optoelectronic performance values to define end-of-life (EOL) component performance (some of this can be accounted for in the margin).

Performance values of active and passive components may or may not be fully applicable to the actual aerospace operational conditions. Therefore care must be taken to tailor the component values for the specific application.

In cases where component end-of-life performance exceeds component beginning of life performance, the minimum performance values are applied in the link loss power budget. In cases where component beginning-of-life performance exceeds end-of-life performance, the end-of-life performance values are applied in the link loss power budget.

4.4.1 Determination of Needed Worst-Case Values

The component manufacturers and/or the aircraft system supplier may provide appropriate production representative beginning-of-life and end-of-life performance values for all fiber-optic link components, or equivalent data. Depending on type and variety of components supplied, these values will include connector loss, splice loss, splitter loss, fiber attenuation loss, transmitter output power, receiver sensitivity, receiver saturation, transmitter and receiver power penalties, etc. The provided values may be representative of actual aircraft production parts, and may be measured in accordance with industry standards such as EIA/TIA, IEC, MIL, SAE, and representative signaling formats and protocols. In cases where no military or industry standard exists, an agreed upon test plan may be developed and implemented to obtain the needed values.

The system engineering defined bit error ratio maximum or equivalent may be applied to the receiver sensitivity value. Worst case component loss values may be verified by testing.

Table 2 (in the Basic Notional section) describes the component parameter value adjustments.

These adjustments may be defined as worst case source, sensitivity, loss and gains.

Worst case transmitter and receiver link loss power budget parameters such as transmitter output power, receiver sensitivity, receiver saturation, and link power penalties can be specified either at the optical reference plane discussed in Appendix C, or at the terminated end of the fiber attached to the transmitter and receiver.

The worst case transmitter output power link loss power budget parameter is given over the specified range of input circuit voltages and currents. Transmitter and receiver ambient temperature and vibration parameters are also incorporated in the worst case transmitter output power link loss power budget parameter and receiver sensitivity parameter. The transmitter's optical output waveform should comply with the system engineering optical transmission signaling specifications.