Fiber Optical Networks Revealed

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RuggedCom
Industrial Strength Networks

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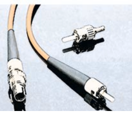
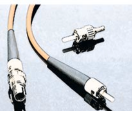


2.0 Overview

This document is aimed at operational managers and engineers tasked with creating, extending, or modernizing their existing communication structure to include Ethernet-based fiber optical technologies. The factors involved in designing, maintaining and understanding fiber optical networks will be addressed, in the hopes of making transitions toward new fiber optic installations smooth and efficient.

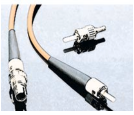


3.0 Introduction

Designing and implementing a fiber optical based communication network meant to replace or augment an existing communication network can be an intimidating task, but this does not have to be the case. With some basic knowledge in the key factors affecting communication standards and performance, one can easily lay the foundations for a reliable, "future-proof " installation.

It is important to note that published data by communications equipment manufacturers are typically 'worst-case' industry accepted quantities for link distances and speeds. Though these industry-accepted numbers are a good basis for estimating link distances and performance characteristics, performance and cost benefits can be realized through detailed measurements and planning.

With the help of this document, and the support of RuggedCom Inc. representatives, it is our hope that any future fiber optical installations will go smoothly and efficiently.



4.0 Fiber Optical Overview

Traditionally fiber optical cabling (fiber for short) has been associated with high-cost and high-priority installations where speed and long-distance performance were paramount. Today fiber has become a large player in not only the traditional 'long-haul' telecommunications markets, but also in local and wide area networks (LANs and WANs). With the rapid reduction in fiber costs (including installation, maintenance, and equipment cost), fiber optic implementations are quickly approaching that of copper-based twisted pair (Category 5 and higher) installations.

The rapid population of fiber optic-based networks on the industrial plant floor, in metropolitan networks, and connecting utility substations can be attributed to the following factors:

- Large bandwidth (high speed data carrying capability)
- Immunity to electromagnetic interference
- Lower long-term maintenance costs
- Increased security (resistance to eavesdropping)
- Future Proof (cable is compatible with current/future LAN/WAN standards)
- Lightweight cable
- Higher pull strength than typical copper cabling

5.0 Fiber Optic Components

5.1 Fiber Cabling Overview

To better understand fiber performance and operational specifics, we must first look to the fiber cable for a good basis of understanding.

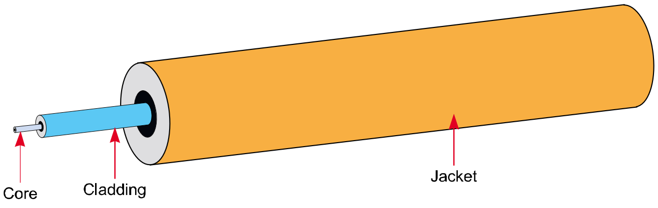
All fiber optic cables consist of three layers:

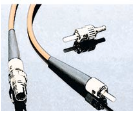
1. Core - An extremely thin single strand of glass or high quality plastic. This single strand is layer that carries the data.

2. Cladding - Another layer of glass with a slightly different index of refraction from the core. This slight difference can either allow light energy out from the core or keep the majority of energy within the core (via reflections).

3. Jacket - Usually the last outer layer of plastic intended to protect the core and the cladding. The composition of this layer greatly depends on the intended installation environment.

Fiber Optic Cable Construction





5.2 Fiber Optic Transceivers Overview

A fiber optic transceiver is simply a transmitter receiver pair. A transceiver is tasked with transmitting and receiving data (1's and 0's). A fiber optic transceiver accomplishes this task by either turning the light source on or off. There are two general categories of transceivers: LED transceivers and laser transceivers. LEDs are generally more cost effective and extremely reliable, but due to the nature of the technology are limited to shorter link distances and slower speeds. Lasers are generally higher in power and emit a signal of better quality resulting in longer link distances and are used for applications requiring greater speeds.

5.3 Multi-Mode Communication Links

Multi-mode communication links are generally the most common due to the low cost of fiber cabling and transceivers. When forming a multi-mode link, one must use multi-mode transceivers as well as multi-mode cabling.

Multi-mode fiber cable is generally specified as two numbers such as 62.5/125µm or 50/125µm. This implies a core size of 62.5µm in diameter and a cladding size of 125µm. 62.5/125µm cabling is generally the most popular, followed by 50/125µm. For historical reasons 62.5/125µm cabling has a large install base, but generally 50/125µm cabling is recommended for all new installations to allow for an upgrade path to gigabit (and beyond) speeds.

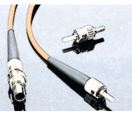
Multi-mode is called such because the light used to transmit the data actually travels multiple paths within the core. The fiber cable is designed with a core/cladding index difference to keep the majority of light energy within the fiber so that it 'bounces' around. At the other end of the fiber, a data signal is composed of both the light that took straight paths through the center of the core as well as the light beams that 'bounced' around. This phenomenon is called modal dispersion and is the primary characteristic that limits multi-mode link distances.

5.4 Single-Mode Communication Links

Single-mode communication links are less common than multi-mode links, but are quickly gaining ground when longer link distances (> 3 km) are required. When constructing a single-mode link, one must use single-mode transceivers with single-mode cabling.

Single-mode fiber is also specified as two numbers such as 9/125 µm. This implies a core of just 9µm, and a cladding 125µm in diameter. 9/125µm Cabling is generally the most common, followed by 8/125µm.

Single-mode cabling is typically slightly more expensive that the multi-mode counterparts, but can reach distances up to 10 or 20 times farther. The whole idea behind a single-mode link path is that light carrying the data travels a single path. Light energy that strays away from the center path leave the core and become trapped in the cladding due the properties of single-mode cabling. Because almost all the light received at the opposite end travels approximately the same path, modal dispersion (or timing jitter) is no longer a factor. The primary distance-limiting factor for single-mode links is signal power (or amplitude).



5.5 Standard Wavelengths

Fiber optic transceivers generally use four wavelengths (analogous to colours) of light. The following is a table for reference only, as links should be designed with fiber standards in mind as opposed to wavelengths of light.

Fiber Optic Wavelengths

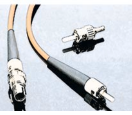
Wavelength	Mode	Usage
850nm	Multi-mode	10Base-FL, 100Base-SX, 1000Base-SX
1300nm	Multi-mode	100Base-FX, FDDI, ATM/OC-3
1310nm	Single-mode	10Base-FL, 100Base-FX, 1000Base-LX
1550nm	Single-mode	High-performance long-haul networks, Wave Division Multiplexing (WDM) networks

6.0 Fiber Optic Standards

The Institute of Electrical and Electronic Engineers (IEEE) is one of the most widely recognized standards body in the world. The IEEE has had a large involvement developing electrical and communications standards including fiber optic communications. The following table lists several of the industry accepted IEEE fiber optic standards:

IEEE Fiber Optic Standards

Standard	Cable Type	Data Rate (Mbps)	Distance
10Base-FL	Multi-mode 62.5/125 or 50/125	10	2 km
	Single-mode 9/125 or 8/125		15 km
100Base-FX	Multi-mode 62.5/125 or 50/125	100	2 km
	Single-mode 9/125 or 8/125		15 km
100Base-SX	Multi-mode 62.5/125 or 50/125	100	300 m
1000Base-LX	Multi-mode 62.5/125 or 50/125	1000	550 m
	Single-mode 9/125 or 8/125		5 km
1000Base-SX	Multi-mode 62.5/125	1000	220 m
	Multi-mode 50/125		550 m
1000Base-LH	Single-mode 8/125	1000	70 km



7.0 Fiber Optic Equipment - Terms and Specifications

This section is designed to give the reader a brief introduction to some of the common industry terms used to plan and design a fiber optical communication system. Knowing these key terms will help you define the limits of your system.

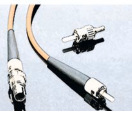
Optical Output Power: A measure of the amplitude of light energy as it leaves the fiber optic transmitter. This term is required in order to calculate the Optical Budget described below. This figure is measured in decibels relative to 1mW (dBm).

Receiver Sensitivity: A figure that describes the minimum amount of light energy required to properly detect a received light waveform. This figure is also measured in decibels relative to 1mW (dBm).

Receiver Saturation: Is indicative of the maximum received input power allowed before the receiver is saturated and therefore cannot receive data. This property is of an important concern when you have very short distances between two pieces of communicating equipment. This figure is stated in decibels relative to 1mW (dBm).

Optical Budget: Is term used to describe total amount of light energy amplitude available over a certain link path. The budget can be determined by subtracting the Receiver Sensitivity from the Optical Output Power. The optical budget serves as a useful estimation to determine if sufficient optical output power remains on the receiver side of an optical link. The use of the optical budget is described further on in this document.

Note: Some terms are described as an average (dBm Avg) while other terms are described as peak (dBm Peak). To convert from average to peak, add 3dBm. To convert from a peak measurement to average, subtract 3dBm.



8.0 Calculating Signal Losses and Maximum Distances

After a good primer on the basics of the fiber optical network components, one can now delve deeper and approach the questions of how an assembled network will work. To begin to look at link distances, one must first look at the factors associated with the optical signal degradation. Once the factors contributing to signal degradation are identified, we can move on to calculating signal losses, and finally verifying the theoretical design.

8.1 Factors Contributing to Signal Degradation

Below are the terms used to describe the primary factors contributing to optical signal degradation. All of these factors should be kept in mind when designing a fiber optic communication link:

Attenuation: Can be losses attributed to microscopic and macroscopic impurities in the fiber material and structure, which cause absorption and scattering of the light signal. Attenuation is a function of the wavelength, and the loss is usually stated in dB/km.

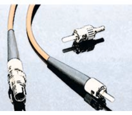
Modal Dispersion: Is only a factor in multi-mode communication links. Modal dispersion is the optical equivalent of timing jitter, where light signals of the same bit travel different paths along the fiber and cause an inability to accurately differentiate bits. Modal dispersion is a function of data rate.

Chromatic Dispersion: Is only a factor in high-speed (ie. Gigabit) single-mode communications links. Chromatic dispersion is the effect of having a wide spectrum of light as the single-mode light source, and as result have light rays of traveling at slightly different speeds due to differing wavelengths. The differences in light ray speeds result in the equivalent of timing jitter at the receiver.

Connectors: Mechanical connections can introduce dust, dirt, as well as normal wear to a light path that can obscure and block light. Typical loss attributed to one connector is 0.5dB.

Splices: Are the bonding of two fiber optic strands through polishing and a bonding agent. Average loss attributed to one splice is usually 0.1dB

Bending Losses: Are losses due to the bending of the fiber to less than the stated minimum bending radius and light energy is lost into the cladding. These losses can be avoided with proper system installation guidelines



8.1.1 Average Fiber Optical Losses

The following in Table 1 is provided as a tool for estimation only. All numbers listed are estimated averages, and actual losses should be measured and obtained from actual fiber optical cable specifications.

Average Fiber Optical Losses					
Wavelength and Mode	**Cable Size (μm)**	**Attenuation (per km)**	**Splice Attenuation (per splice)**	**Connector Attenuation (per connection)**	**Modal Bandwidth (MHz×km)**
850nm / MM	62.5/125	3 dB	0.1 dB	1.0 dB	160
1300nm / MM	62.5/125	1 dB	0.1 dB	1.0 dB	500
850nm / MM	50/125	3 dB	0.1 dB	1.0 dB	400
1300nm / MM	50/125	1 dB	0.1 dB	1.0 dB	500
1310nm / SM	9/125	0.3 dB	0.1 dB	1.0 dB	Infinite
1550nm / SM	9/125	0.2 dB	0.1 dB	1.0 dB	Infinite

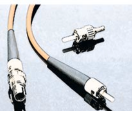
Table 1: Average fiber optical losses using common fiber optical cabling

8.2 Calculating Maximum Link Distance

When calculating signal losses and determining maximum link distances it is important to mention that full duplex (FDX) operation is necessary for all of the following calculations. If a fiber link is not a FDX link, then the distance is limited by protocol timing considerations that have to be taken into account. From this point on it is assumed that the communications link in question is a full-duplex link.

In order to determine the maximum link distance, one must consider three calculations required:

1. Determination of Power Budget
2. Maximum signal loss across communications link
3. Consider effects of Modal Dispersion (Bandwidth limitations)



8.2.1 Calculating Optical Power Budget

This section will show you how to calculate the typical optical power budget for a given transmitter and receiver pair. This is equivalent to calculating how much optical light power is available for losses in the link. The power budget is defined by the following equation:

Power Budget = (Output / Launch Power) - (Receiver Sensitivity)

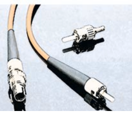
Suppose one had a 100BaseFX Multi-mode communications link with a maximum transmit power of -16dBm (average) and a minimum receiver sensitivity of -32dBm (average), then your power budget would be:

Power Budget = (-16dBm) - (-32dBm) = 16dB

Note that the units have changed from dBm (referenced to 1mW) to dB (unitless) since subtraction of logarithmic numbers is the equivalent of division of base 10 numbers. The next step of determining the maximum link distance is to determine sources of attenuation (ie. Power losses) using the following formula:

Net Optical Power Budget = (Power Budget) - (Power Losses)

The net optical power budget is indicative of the amount of optical power available above and beyond all losses and sources of attenuation. The next section details how to calculate power losses due to sources of attenuation in an example communication link.



8.2.2 Calculating Maximum Signal Loss

Calculating the signal loss is simply the sum of all the losses along a communications link. This involves adding up the number of splices, connections etc. and calculating the attenuation effects of the fiber cable itself. Loss can be concluded as:

Signal Loss (dB) = (Fiber attenuation) + (Splice attenuation) + (Connector attenuation)

Signal losses are summed losses in decibels (dB), and therefore can just be added. It is best to illustrate this with an example:

Suppose there is one particular multi-mode communications link that must first span 700m, then travel through a patch panel (two connectors mechanically mated together), followed by another 1200m of fiber containing one splice. This example is depicted in figure 1.

100FX Multimode Link Example

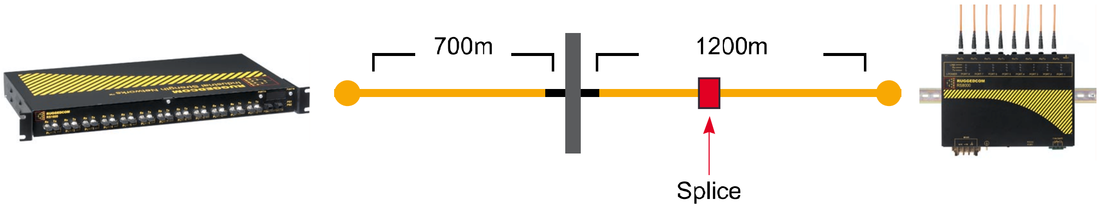


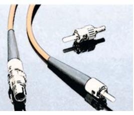
Figure 1: 100FX Multimode link example

To calculate the optical fiber losses one must consider all possible sources of attenuation and sum them together according to the following:

Optical Power Loss Calculation	
(length in km x Fiber Attenuation)	(0.7km+1.2km) x 1dB
(Splice Attenuation x Number of Splices)	1 x 0.1dB
(Connector Attenuation x Number of Connections)	3 x 1dB
Safety Margin	3dB
Total Optical Power Loss (Estimated)	8 dB

Table 2: Optical power loss calculation table for multimode link example

Note the 3dB of optical power attributed to a safety margin. Adding a safety margin allows one to take into account the inevitable degradation in fiber cabling, connectors, and aging effects of lasers and LEDs, and should be standard practice when planning communication links.



The optical power loss calculation should always be verified for once the system has been installed and properly terminated to avoid any unforeseen difficulties. This can be accomplished using an optical power meter that reads the level of light power received at the end of a fiber cable. More advanced methods of analysis such as Optical Time Domain Reflectometry (OTDR) can actually localize sources of loss along a fiber cable (ie splices, connectors, or damaged cable).

Once the optical power losses have been calculated, we must make a comparison with the available optical power budget.

In section 8.2.1 we calculated an available optical budget of 16dB, and in section 8.2.2 the total signal attenuation was calculated to be 8dB. By applying the Net Optical Power Budget formula:

Net Optical Power Budget = (Power Budget) - (Total Optical Power Loss)
= 16 dB - 8dB
= 8 dB

Since the net optical power budget is positive (ie. More power available than losses) we can conclude that there is sufficient optical power for this particular link. A negative power budget would imply that we do NOT have sufficient optical power given all the sources of attenuation in this particular link, and would therefore have to re-evaluate the system layout or limit link distance.

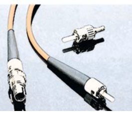
If this was a single-mode communication link, no more calculations would be necessary. We could have a high degree of confidence that this link would communicate reliably for years to come. While single-mode fiber optic links have essentially no bandwidth limitations, multi-mode fiber optic links must consider the effects of modal dispersion (bandwidth limits). Section 8.2.4 describes how to calculate available bandwidth.

8.2.3 Optical Saturation

There is a situation that can arise out of too much optical transmission power. Single mode fiber optical links are typically built with long distances (greater than 20km) in mind, and problems can arise when the same transmit power is used to communicate over a very short distance such as 10m. Receiver saturation describes the maximum power received before saturation takes place and data cannot be read due to excess optical power. To avoid optical saturation, one should check to ensure that receiver saturation levels are not exceeded by at least 3dB. Optical attenuators can be used to attenuate (lower) power levels when very short distances are involved.

8.2.4 Effect of Modal Dispersion (Maximum Bandwidth)

Multi-mode communications links are limited by an effect called modal dispersion. Since multimode fibers operate on the premise of a relatively large core, modes of light,



(light beams representing bits) begin to travel all at the same speed at the transmitter. As the light travels down the fiber, some modes take the shortest path through the center of the core, while other modes literally travel a longer and slower path due to fiber characteristics. As fiber lengths become longer, this phenomenon becomes more of a factor and causes light pulses to spread in time making the task of discerning bits difficult at the receiver causing data loss.

Because of the small core size of single-mode fibers as well as fiber cable characteristics, modal dispersion is not a factor for single-mode fiber optical links.

Therefore the maximum multimode link distance is limited by power as well as fiber bandwidth, whichever resulting calculation is less.

To calculate the maximum multimode distance, one must obtain the specifications for the fiber optical cable used in the application. The modal bandwidth should be stated for the given wavelength. Typical numbers are listed in Table 1. The formula for calculating maximum link distance due to data rate is as follows:

Maximum distance = (Modal Bandwidth of Fiber @ wavelength) / (Signal Rate)

Where the data rate is dependant on the actual fiber data rate. Fiber optical data rates are listed below and are standards dependant:

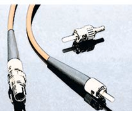
Fiber Optical Data Rates by Standard

Standard	Actual Signal Rate	Data Rate (Mbps)
10BaseFL	20MHz	10
100BaseFX, 100BaseSX	125Mhz	100
1000BaseSX, 1000BaseLX	1250Mhz	1000

For example, if one had a 100BaseFX (1300nm) multimode fiber optical link using cable that had a modal bandwidth of 500MHz·Km, we could use the following formula to determine maximum link distance:

Maximum distance = (500 MHz·Km) / (125Mhz) = 4km

From this we could conclude that if enough optical power was available, one could have a theoretical maximum link distance of 4km before data loss would begin to occur due to modal dispersion. It is good practice to not design for this limit, but rather to use it as a guideline for realizable link distances at least 20% less than this limit to account for aging and wear effects.



9.0 Conclusion

As the demands on the modern networks rise, speed, security and reliability become more of a necessity as opposed to a feature. Fiber optical networks can help deliver those requirements in harsher environments with additional benefits. As described in this guide, design of a fiber optical communications system can be done so smoothly through simple planning and evaluation. Contact RuggedCom associates if you have any questions or concerns regarding your particular system, whether upgrading an existing facility or building a new one up from the ground.

10.0 About RuggedCom Inc.

RuggedCom Inc. designs and manufacturers industrially hardened networking equipment including fiber optic Ethernet Switches, IP Routers, and Gateways suitable for the harsh environments of the electric power utility substation or industrial factory floor. Founded by people with strong backgrounds in utility and industrial automation and a passion for developing innovative technology, RuggedCom is well suited for providing the right solutions to address the needs of our customers.

RuggedCom can be reached at:

RuggedCom Inc.
30 Whitmore Road,
Woodbridge, Ontario, Canada
L4L 7Z4

Telephone: (905) 856-5288
Toll Free: (888) 264-0006
Fax: (905) 856-1995

Web: www.ruggedcom.com

Support: support@ruggedcom.com
Sales: sales@ruggedcom.com

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