ON OPTICAL POWER BUDGETS FOR FIBER OPTICS

Roxana-Mariana BEIU, Constantin D. STANESCU
Washington State University, "Politehnica" University of Bucharest

Abstract. After a brief historical retrospective of fiber optics, this paper presents the most important causes of optical losses occurring during communications. Telecommunication on fiber optics is widespread, ranging from global networks to desktop computers. Besides, the use and demand for optical fiber has been growing tremendously as there are a large number of other applications. The paper will continue by showing the influence of such losses on the overall optical power budget and discuss ways of dealing with them.

1. A BIT OF HISTORY

Optical communication systems date back to the 1790s, when the optical semaphore telegraph was discovered by French inventor Claude Chappe. In 1880, Alexander Graham Bell patented an optical telephone system, which he called the Photophone (which he realized experimentally).

All earlier fibers developed were bare and lacked any form of cladding, with total internal reflection occurring at the glass-air interface. In 1954, Dutch scientist Abraham Van Heel and British scientist Harold H. Hopkins separately wrote papers on imaging bundles. Hopkins reported on imaging bundles of unclad fibers. Stimulated by a conversation with the American optical physicist Brian O'Brien, Van Heel made the crucial innovation of cladding fiber-optic. He covered a bare fiber of glass (or plastic) with a transparent cladding of lower refractive index. This protected the total reflection surface from contamination and greatly reduced cross talk between fibers. By 1960, glass-clad fibers had attenuation of about 1 decibel (dB) per meter, which was enough for medical imaging, but much too high for communications.

By 1964, a critical specification was identified by Charles K. Kao for long-range communications: the 10 or 20 dB of light loss per kilometer standard. He also illustrated the need for a purer form of glass to help reduce light losses.

In the summer of 1970, one team of researchers began experimenting with fused silica, a material capable of extreme purity with a high melting point and a low refractive index. Researchers Robert Maurer, Donald Keck, and Peter Schultz invented fiber-optic wire or "optical waveguide fibers" which was capable of carrying 65,000 times more information than copper wire. Information carried by a pattern of light waves could be decoded at a destination even a thousand miles away. The team had solved the decibel-loss problem presented by Charles K. Kao. The team had developed a single mode fiber with loss of 17 dB/Km at 633 nm by doping titanium into the fiber core. In 1972 they discovered multimode germanium-doped fiber with a loss of 4 dB/Km and much greater strength than titanium-doped fiber.

After five years General Telephone and Electronics tested and deployed the world's first live telephone traffic through a fiber-optic system running at 6 Mbps, in Long Beach, California. They were soon followed by Bell in May 1977, with an optical telephone communication system installed in the downtown Chicago area, covering a distance of 1.5 miles (2.4 kilometers). Each optical-fiber pair carried the equivalent of 672 voice channels. Today more than 80% of the world's long-distance voice and data traffic is carried over optical-fiber cables [1].

2. OPTICAL FIBER LOSSES

Fiber-optic transmission offers the best option over both coaxial and free-space transmission. It has the ability to carry a signal from point A to point B without using the limited electromagnetic spectrum. Even more, it does not suffer from very limited bandwidth and data rate the way coaxial cable does.

Fiber-optic communication has many benefits over coaxial, as follows:

- immunity from electromagnetic noise;
- longer distance capability;
- lighter weight;
- higher signal quality;
- higher bandwidth, greater information capacity;
- lower cost;
- easier upgrade.

There are two basic types of fiber optic: multimode (MM) and single-mode (SM). MM fiber was used in the first commercially available fiber optic cable. Its core is much larger than that of SM, allowing hundreds of light rays (or modes) to move through the fiber simultaneously. SM, as its name suggests, allows a single ray. While this may suggest that MM would be superior, this is not the case. SM is better at retaining the fidelity of each light pulse over longer distances, therefore allowing more information to be transmitted. However, as SM has a smaller core, it is more difficult to couple light into it.

The standard way of sending an electrical signal through fiber optic requires a transmitter, which converts electrical signals into light, and a receiver, which works the other way around. The amount of light that is focused into the fiber optic cable is known as the launch or coupled power of the transmitter. As the fiber optic cable changes in diameter, the amount of light that is launched into it changes. The larger the fiber optic cable, the more light can be launched into it.

The receiver takes the light that comes out of the fiber optic cable and also converts it into a standard electrical signal. Because of the light transfers occurring between the connectors and the fiber optic, and even due to fiber optic itself, the value of the input power will be decreased. The difference between the amount of light that is launched into the fiber optic cable and the amount of light necessary to give a usable signal into the receiver is known as the *link power budget*. An important step when we set up a fiber optic link is to know the losses of the optical signal transmission. The following effects can lead to losses in electromeagnetic energy propagating in fibers: material absorption, material scattering, waveguide scattering due to form-inhomogeneities, mode losses due to fiber bending and cladding losses [2].

Material-Absorption

Absorption losses are largely due to impurities in glass material from residual foreign atomic substances and hydrogen/oxygen molecules. Lastly, there are attenuation maxima in small band wavelength regions. The fundamental attenuated wavelength (highest absorption) is due to $(OH)^-$ ions. In quartz this is at $\lambda \cong 2.7\ \mu m$. In the spectral region below this wavelength, there are other absorption bands at 1.38 μm, 1.24 μm, 950 nm and 720 nm. Between these wavelength bands there are “windows” of minimal attenuation. These spectral regions are at 850 nm (1st windows), at 1300 nm (2nd window), at 1550 nm (3rd window) and at 1650 nm (4th window) – see figure 1.

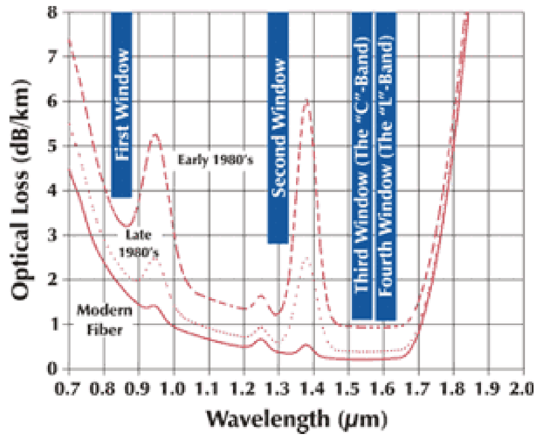


Fig. 1. Fiber optics communication windows [3].

Attempting to transmit short wavelength light in quartz fibers (ie., UV light) can lead to a damaging mechanism referred to as *solarization*. In quartz there are absorption centers where anions (negativly charged ions) are replaced by an electron. These electrons can be excited, potentially at resonance. These regions in the crystal are also called color centers, because the normally color neutral crystals (i.e. NaCl) become characteristically discolored.

Table 1 shows a few transmission media, their attenuation characteristics, and the maximum spacing allowed between repeaters. These values are mostly theoretical. Special coaxial cable systems exist with repeaters spacing of 12 kilometers. There exist systems capable of operating at very high speed (a few megabits per second) over telephone twisted pairs for distances of four to six kilometers without repeaters. The technology is called ADSL (Asymmetric Digital Subscriber Line) or VDSL (Very fast Digital Subscriber Line). This technology makes use of very sophisticated digital signal processing to detect the last bit per second from a very difficult medium. Nevertheless, the advantage of fiber transmission is obvious.

Tab.1 Different material's attenuations and their repeaters spacing [1]

Material	**Attenuation [dB/Km]**	**Repeaters spacing [Km]**
Coaxial cable	25	1.5
Telephone twisted Pair	12…18	2…3
Window glass	5	7
Silica	0.18…1	50…150
Improved silica	0.16	250
Halide	0.01	3500

Material Scattering

One crucial scattering mechanism is *Rayleigh Scattering*. This is due to high density gradients (short compared to the wavelength) which alter the index of refraction and cause scattering. The intensity of the scattered light is proportional to $1/l^4$. This effect evidences itself in, among other things, strong reverse scattering. Another scattering mechanism is *Mie Scattering*, which mainly results in forward scattering. This mechanism comes from material inhomogeneities in larger wavelength spectrums. *Stimulated Raman Scattering* and *Stimulated Brillouin Scattering* are non-linear radiation induced effects, which exceed intensity thresholds. Transmitting laser light alone can exceed these threshold values.

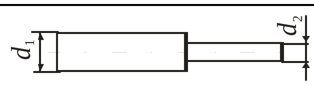
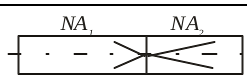
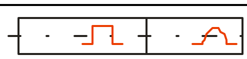
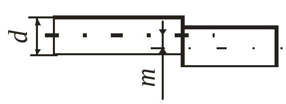
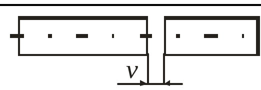
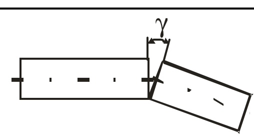
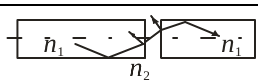
Light Guide Specific Scattering Mechanisms

The so called intrinsic fiber characteristics can also cause energy loss. Some of these effects are: changes in core diameter, difference in refractive indices, index profile effects, mode coupling (double mechanisms) and scattered radiation in the cladding glass. Radiation losses exist due to the conversion of core modes to non-propagating modes (cladding modes). This results in a reduction in the carrying modes. Extrinsic causes for loss mechanisms come from such things as mechanical influences, (micro and macrobending).

Fiber Coupling Losses

Cleaved single fibers may be spliced. The splicing region can exhibit intrinsic (purely optical) and extrinsic (geometrical alignment) losses. Table 2 shows various configurations and transmission values for multimode fibers with cleaved terminations.

Tab.2 Fiber coupling losses [3]

 Variations of fibers diameters	$T=(d_2/d_1)^2$ $d_2 < d_1$
 Variation of numerical apertures.	$T=(NA_2/NA_1)$ $NA_2 \le NA_1$
 Variation of index of refraction profiles  Transversal misalignment (m).	$T=(g_2/g_1)\{(g_1+2)/(g_2+2)\}$ (g-profile parameter) $T=\{(2/\pi)\arccos(m/d)-(2m/\pi d)(1-(m/d)^2)^{1/2}\}$
 Axial gap (v).	$T=\{1-(v/d)\tan(\alpha_c)\}$ $\sin(\alpha_c)=NA$
 Angular misalignment (γ).	$T=\{1-(16/3\pi)(\sin(\gamma/2)/\sin(\alpha_c))\}$
 Surface reflections.	$T=\{1-(n_1-n_2)^2/(n_1+n_2)^2\}$

Besides the different types of attenuation, another reason of losses occurring into fiber optics is dispersion. When short pulses of light energy are launched into a fiber, the time behavior is strongly influenced by the fiber type, as well as the core and cladding materials. Transit time differences (see figure 2) will lead to limited bandwidth. In light transmission technology this effect is called dispersion [5].

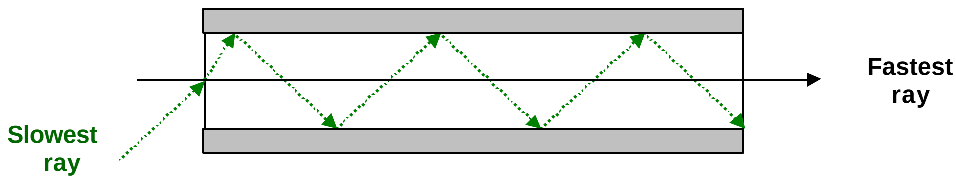


Fig. 2. The transit time differences between axis ray and nearby cladding rays

There are two basic types of dispersion:

- mode dispersion
- chromatic dispersion:
  - material dispersion
  - light guide dispersion

Mode dispersion comes from differing transit times for different modes due to differing optical paths (zig-zag patterns multiplied by the index of refraction). This happens only for multimode fibers. Single mode fibers propagate only one mode, which has only one path, and therefore no path difference or transit time difference. Gradient index fibers theoretically have the same optical path for all modes. Due to the decreasing index of refraction from the core to the cladding interface, light rays travel faster the closer they are to the interface. In this way, different modes travel on different spiral paths. Lower modes have a shorter path, as they propagate nearer the optical axis, but are also in a larger index material. Higher mode modes have a longer path length, but travel in lower index material. The product of "path length and index of refraction" is constant. Transit time differences are therefore greatly compensated by gradient index fibers.

Material Dispersion refers to the fact that the refractive indices of the core and cladding are wavelength dependent. This means that the differing wavelengths travel in the same medium with differing refractive indices. As the velocity in the medium is given by $v(l) = c/n(l)$ (c - speed of light in vacuum, n - refractive index of medium), it varies with varying wavelength (λ).

Light Guide Dispersion comes from the differing refractive indices between core and cladding, and their associated wavelength dependence, light in light guides travels with differing velocities. Together with material effects, a light guide will have spectral transit time variations. Careful material selection can limit transit time differences for specific wavelength regions [].

3. FIBER OPTIC LINK POWER AND LINK LOSS BUDGETS

The link power budget is the difference between the power launched into the fiber and the sensitivity (minimum amount of power required) of the receiver connected through the fiber optic cable.

Unlike the link power budget, the link loss budget is the total losses of any component of the link. In all cases, the link loss budget must be less than the link power budget. The total link power budget is the summation of the link loss budget and the safety margin - for future requirements and aging of the fiber optic system (see figure 2) [4].

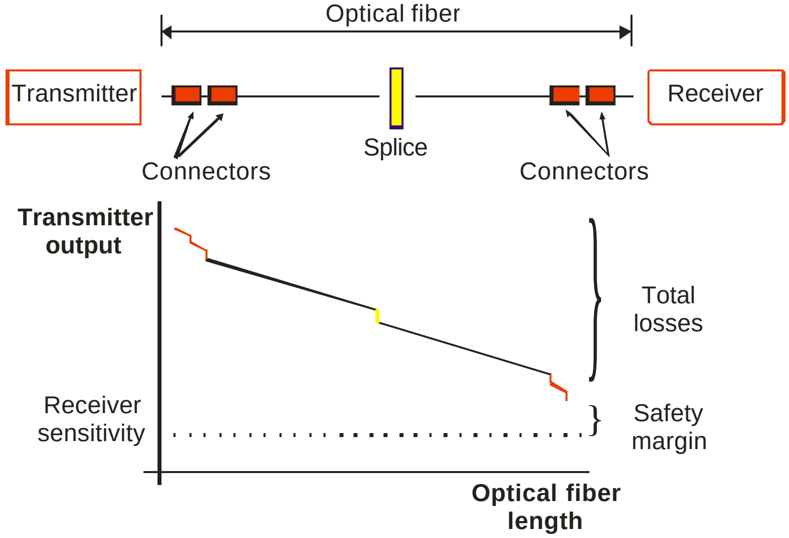


Fig. 2. Typical losses of a fiber optic communications system

To determine losses and maximum distances for a fiber optic communications, we had to identify the following variables [6]:

- losses from absorption and back reflection of the light caused by impurities in the glass; **attenuation** is a function of wavelength and needs to be specified or measured at the wavelength in use;
- the higher the data rate, the shorter the distance the signal can travel before **modal dispersion** creates an inability to accurately separate a "1" from a "0"; modal dispersion is only a concern with multi-mode cable and is directly proportional to the data rate;
- while single-mode fiber is not subject to modal dispersion, other **dispersion** effects cause pulse spreading and limit distance as a function of data rate. Chief among these is chromatic dispersion, where the broader spectrum of certain transmitter types can result in varying travel times for different parts of a light pulse (chromatic dispersion typically only starts to become a limiting factor at Gigabit speeds);
- although small and often insignificant, average **splice loss** is usually less than 0.1 dB (there is no perfect loss-less splice);
- like splices loss, there are **connector losses**; it is important to note that even the highest quality connectors can get dirty (dirt and dust can completely obscure a fiber lightwave and create huge losses). A 0.2 dB loss per connector is commonly the best case scenario assuming a cleaned and polished connector is used;
- it is common to add a couple dB of loss as a **design margin**. Allowing 3 dB of loss can take fiber aging, poor splices, temperature and humidity, etc., into account and ensure a solid system.

The amount of signal loss due to cable attenuation is just the attenuation per kilometer (at the signal wavelength) multiplied by the distance. To determine the maximum distance you can send a signal (leaving out the effects of dispersion), all you need to do is to add up all the sources of attenuation along the way and then compare it with the “link budget” [7].

Thus, if you have a transmitter of power - 10 dBm and a receiver that requires a signal of power - 20 dBm (minimum) then you have 10 dB of link power budget. So you might allow:

- 10 connectors at 0.2 dB per connector = 2 dB

- 2 km of cable at 2 dB per km (@1300 nm) = 4 dB
- contingency of (say) 3 dB for safety margin.

This leaves us with a total of 9 dB system loss. This is within our link budget and so we would expect such a system to have sufficient power. Dispersion is a different matter and may (or may not) provide a more restrictive limitation than the link budget.

The amount of power that we have to use up on the link and in connectors is determined by the characteristics of the components we select as transmitters and receivers [8].

4. CONCLUSIONS

This paper has briefly presented the many reasons for fiber optics losses when used in data transmission, including various forms of attenuation, dispersions, and scattering.

We have explained the notion of link power budget and link loss budget for fiber optics used in data transmission. An example has shown a simple view, as not taking into account all the possible losses. The main conclusion is that enhancing the reliability of communication of fiber optic systems can be done only through a careful selection and matching of all the subparts (transmitter, fiber optic, receiver, connectors).

The fiber optic should be matched to the application and verified that it satisfied the overall power budget. It should be stresses that the optimization of communication system based on fiber optics has quite a number of parameters. The only way to enhance on such system is to use a thorough engineering approach and tune it with the feed-back received from an economical analysis.

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