Analysis of Fiber Loss Mechanisms in Communication System to Simulate Different Attenuation

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Authors’ contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

ABSTRACT

The fiber optic communication system can transmit data at a rate of 10 GB/S or more, over a maximum possible distance with less attenuation. In this research a low loss optical fiber has been simulated. The simulation is done by MATLAB Software. This research deals with different loss mechanisms in optical fiber communication. A number of mechanisms are responsible for the signal attenuation within optical fibers. As the optical signal propagates over long stretch of fiber, it becomes attenuated because of absorption, scattering, fiber bends by material impurities, and other effects. The absorption loss at 1310 nm wavelength of light is significantly very low. It is also observed that the scattering loss decreases as the wavelength of light increases and the same case for bending loss; for link loss the fiber attenuation is increased gradually with the increasing fiber distance. In this research it is shown that the attenuation for multimode fiber is greater than single mode fiber at wavelength 1550 nm, attenuation level for 1550 nm wavelength is lower than
1310 nm wavelength. It is also shown that there are great attenuation between glass and plastic optical fiber and large attenuation between plastic and Plastic Clad Silica optical fiber. Different fiber types and their properties such as attenuation or loss are also observed. The performance improvement of the proposed different loss, such as absorption loss, rayleigh scattering, bending loss, link loss for different wavelength and different material within the various loss mechanisms in fiber optic communication is shown through simulations.

Keywords: Optical fibers; communication system; attenuation; wavelength; loss mechanisms.

1. INTRODUCTION

In the communication age, it has been highly desirable technologies for networks of higher capacities at lower costs. Recent advances in data processing capabilities brought about by the development of high speed and high-density integrated circuits have surpassed existing data transmission capabilities. The use of large amount of copper wires is becoming less desirable for transferring information. The size, weight, bandwidth limitations, and cost of metal conductors have forced scientists and engineers to investigate other means of data handling. Among the several alternatives, fiber optics is one of the most important and cost effective solutions for the communication [1]. Optical fibers are used most often as a means to transmit light between the two ends of the fiber and find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths (data rates) than wire cables. Fibers are used instead of metal wires because signals travel along them with lesser amounts of loss; in addition, fibers are also immune to electromagnetic interference, a problem from which metal wires suffer excessively. Fibers are also used for illumination, and are wrapped in bundles so that they may be used to carry images, thus allowing viewing in confined spaces [2]. In this system, many users communicate at the same time due to high bandwidth easily. In the present scenario, optical communication supports 300 THz bandwidth [3]. Fiber optics offers potential advantages in size, weight, bandwidth (i.e.1013 to 1014Hz), resistance to electromagnetic interference (EMI) and nuclear radiation, and cost when compared with metallic conductors [4]. Fiber optics can also provide reliable data transmission capabilities over the expected life of the system. However, during information transmission in optical fiber communication it faced several attenuations, which reduce the performance of the system. The aim of this study is to analysis the different loss mechanisms in optical fiber technology.

2. MATERIALS AND METHODS

2.1 General Communication System and Optical Communication System

Optical fibers are extremely thin strands of ultrapure glass designed to transmit light from a transmitter to a receiver. These light signals represent electrical signals that include video, audio, or data information in any combination [5]. Fiber optic communication has revolutionized the telecommunications industry Using fiber optic cable, optical communications have enabled telecommunications links to be made over much greater distances and with much lower levels of loss in the transmission medium and possibly most important of all, fiber optical communications has enabled much higher data rates to be accommodated [6]. As a result of these advantages, fiber optic communications systems are widely employed for applications ranging from major telecommunications backbone infrastructure to Ethernet systems, broadband distribution, and general data networking [7]. Fiber-optic communication systems transmit information from one place to another by sending light through an optical fiber. The light forms a carrier signal that is modulated to carry information. On the other hand a general communication system consists of transmitter, encoder, channel, decoder, and receiver. There are huge similarity within a general communication and a optical fiber communication system [8].

2.2 The General Communication System Model

Fig. 1 shows the block diagram of a general communication system in which different functional elements are represented by blocks.

2.3 Optical Fiber Communication System Model

Fig. 2 shows the block diagram of optical fiber communication system model.
Core: This is the physical medium that transports optical data signals from an attached light source to a receiving device. The core is a single continuous strand of glass or plastic that's measured in microns (µ) by the size of its outer diameter. The three multimode sizes most commonly available are 50, 62.5, and 100 microns. Single-mode cores are generally less than 9 microns.

Cladding: This is the thin layer that surrounds the fiber core and serves as a boundary that contains the light waves refraction.

Coating: This is a layer of plastic that surrounds the core and cladding to reinforce and protect the fiber core. Coatings are measured in microns and can range from 250 to 900 microns.

Strengthening fibers: These components help protect the core against crushing forces and excessive tension during installation.

Cable jacket: This is the outer layer of any cable. Most fiber optic cables have an orange jacket, although some types can have black or yellow jackets [9].

Fig. 1. The general communication system

Fig. 2. The optical fiber communication system
2.5 Types of Optical Fiber

Classification of fibers:

- **All glass fibers**
- **All plastic fibers**
- **Glass core with plastic cladding fibers**
- **Polymer clad silica fibers**

3. THE BASIC PRINCIPLE OF OPTICAL FIBER COMMUNICATION

The basic principle of optical fiber in the transmission of an optical signal is **total internal reflection**. The law of refraction, which is generally known as Snell's law, governs the behavior of light-rays as they propagate across a sharp interface between two transparent dielectric media. The law of refraction states that the incident ray, the refracted ray, and the normal to the interface, all lie in the same plane. Furthermore,

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2, \]

Where \( \theta_1 \) is the angle subtended between the incident ray and the normal to the interface, and \( \theta_2 \) is the angle subtended between the refracted ray and the normal to the interface. The quantities \( n_1 \) and \( n_2 \) are termed the **refractive indices** of media 1 and 2, respectively.

An important extension of Snell's law is the concept of Total Internal Reflection and the critical angle [10].

**Conditions for Total Internal Reflection**

(a) The refractive index \( n_1 \) of the core must always be greater than the refractive index \( n_2 \) of the cladding.

(b) The angle of incidence \( i \) must be greater than critical angle \( C \), it can be defined as when light travels from a more optically dense material [larger index of refraction] to a less dense material the angle of refraction is larger than the incident angle. Fig. 4 shows total internal reflection & critical angle.

3.1 Optical Fiber Communications Loss Mechanisms

Attenuation is a general term that refers to any reduction in the strength of a signal. Attenuation occurs with any type of signal, whether digital or analog [11]. Sometimes called loss, attenuation is a natural consequence of signal transmission over long distances. The Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic units of the decibel [12]. The decibel, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power \( P_i \) into a fiber to the output (received) optical power \( P_o \) [13].

Number of decibels (dB) = 10 log \( P_i/P_o \)

3.1.1 Absorption losses

Absorption is a major cause of signal loss in an optical fiber. Absorption is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat. The equation of absorption losses is:

\[ \alpha_{\text{absorp}} = 7.81 \times 10^{11} \times \exp(48.48/\lambda) \]  

(3.1)

3.1.2 Scattering losses

Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. During manufacturing, regions of higher and lower molecular density areas, relative to the average density of the fiber, are created. Light traveling through the fiber interacts with the density areas, then partially scattered in all directions.

**Rayleigh scattering**: In commercial fibers operating between 700-nm and 1600-nm
wavelength, the main source of loss is called Rayleigh scattering. Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions occurs when the size of the density fluctuation (fiber defect) is less than one-tenth of the operating wavelength of light. Loss caused by Rayleigh scattering is proportional to the fourth power of the wavelength \((1/\lambda^4)\). As the wavelength increases, the loss caused by Rayleigh scattering decreases.

The equation of Rayleigh scattering is:

\[
\gamma_R = \frac{8n^3}{3\pi^2} n_0^2 p^2 \beta \kappa T_F \tag{3.2}
\]

Where,

- \(\gamma_R\) is the Rayleigh scattering coefficient.
- \(\lambda\) is the optical wavelength.
- \(n\) is the refractive index of the medium.
- \(p\) is the average photo elastic coefficient.
- \(\beta\) is the isothermal compressibility at a fictive temperature \(T_F\), and \(K\) is Boltzmann’s constant.

The fictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature. Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber \(L\) following the relation.

\[
L = \exp (-\gamma_R L) \tag{3.3}
\]

Where \(L\) is the length of the fiber

\[
\text{Attenuation} = 10 \log \left( \frac{1}{L_{\text{km}}} \right) \tag{3.4}
\]

**Mie scattering:** If the size of the defect is greater than one-tenth of the wavelength of light, the scattering mechanism is called Mie scattering. Mie scattering, caused by these large defects in the fiber core, scatters light out of the fiber core.

### 3.1.3 Bending Loss

Bending the fiber also causes attenuation. Bending loss is classified according to the bend radius of curvature: micro bend loss or macro bend loss.

### 3.1.4 Microbend losses

Microbend small microscopic bends of the fiber axis that occur mainly when a fiber is cabled.

### 3.1.5 Macrobend losses

Macrobend losses are observed when a fiber bends’s radius of curvature is large compared to the fiber diameter [12].

The equation for macrobend loss is:

\[
L_b (\text{dB/km}) = A \exp \left( \frac{m_1(2.748-m_2)^3}{\lambda_c} \right) \quad \frac{1}{2} \tag{3.5}
\]

Here \(A=60\pi(N/\lambda_c^2)^\Delta^3 R \star \lambda_c^3\) \tag{3.6}

\[
m_1=0.705(\Delta^3)R \tag{3.7}
\]

\[
m_2=0.996/\lambda_c \tag{3.8}
\]

### 3.1.6 Link Losses

Fiber link loss is the difference of the signal recorded in a link. The link loss budget is used to verify that the signals maximum

![Fig. 4. Total internal reflection & critical angle](image-url)
signal loss within the required operating levels of the transmitter and the receiver [14]. The receivers operating levels are determined by the receiver’s sensitivity in comparison to its dynamic range.

For fiber optic link, channel attenuation or link loss is obtained from the expression

\[ \alpha T = nC + cJ + L\alpha + M \]  

(3.9)

where,

- \( n \) is the number of connectors,
- \( C \) the attenuation for one optical connector (dB),
- \( c \) the number of splices in elementary cable section,
- \( J \) the attenuation for one splice (dB),
- \( M \) the system margin (patch cords, cable bend, unpredictable optical attenuation events, and so on, should be considered around 3dB),
- \( \alpha \) the attenuation for optical cable (dB/km) and
- \( L \) the total length of the optical cable.

3.1.7 Optical fiber Coupling Loss

Fiber-to-fiber connection loss is affected by intrinsic and extrinsic coupling losses. Intrinsic coupling losses are caused by inherent fiber characteristics. Extrinsic coupling losses are caused by jointing techniques [15].

4. LOSS CALCULATION OF FIBER OPTIC

As we know the absorption loss in optical fiber caused by imperfection in atomic structure in fiber material. From equation 3.1 we get the graph 5 of absorption losses. Calculating 3.2 equation we get the attenuation Table 1 for different wavelength and Table 2 for 100 to 900 optical fiber length. Using 3.2 equation we got the Figs. 6, 7, 8. We got bending loss Fig. 9 using equation 3.5. Calculating equation 3.9 we get the link losses from Table 3 for wavelength 1550 and 1310 nm. Table 4 exhibits Commonly accepted loss values for singe mode and multimode fiber link losses. Table 5 shows Comparison of fiber losses of Multi-Mode & Single Mode Glass, Plastic, PCS. Data were collected from online sources [16].

Using equation 3.9 we got the Figs. 10, 11, 12, 13, 14, 15, 16, 17 for different wavelength, fiber mode and materials. Spontaneous emission of the erbium is a noise source, so the amplification comes at the expense of reduced SNR [17]. Optical fibers and laser light medical devices, instruments, and techniques have been developed that have helped modernize medicine [18]. The wave meter development will boost optical and quantum sensing technology, enhancing the performance of next generation sensors and the information-carrying capacity of fiber-optic communication networks [19].

Table 1. Rayleigh scattering of optical fiber communication for different wavelength

| Wave length \( \lambda \) (m) | Rayleigh scattering coefficient | Transmission loss | Attenuation for Rayleigh scattering\((dB^{-km})\) |
|-----------------------------|--------------------------------|------------------|---------------------------------|
| 0.50                        | \(3.023 \times 10^{-3}\)       | 0.048            | 13.13                           |
| 0.565                       | \(1.85 \times 10^{-3}\)       | 0.156            | 8.05                            |
| 0.63                        | \(1.199 \times 10^{-3}\)      | 0.301            | 5.20                            |
| 0.695                       | \(8.099 \times 10^{-4}\)      | 0.444            | 3.5                             |
| 0.76                        | \(5.66 \times 10^{-4}\)       | 0.567            | 2.45                            |
| 0.825                       | \(4.07 \times 10^{-4}\)       | 0.665            | 1.77                            |
| 0.89                        | \(3.01 \times 10^{-4}\)       | 0.739            | 1.30                            |
| 0.955                       | \(2.27 \times 10^{-4}\)       | 0.796            | 0.98                            |
| 1.02                        | \(1.745 \times 10^{-4}\)      | 0.839            | 0.75                            |
| 1.085                       | \(1.36 \times 10^{-4}\)       | 0.872            | 0.59                            |

Table 2. Rayleigh scattering for wavelength 0.50 and fiber length 100 to 900 m is given

| Fiber length (m) | Rayleigh scattering coefficient | Transmission loss | Attenuation for Rayleigh scattering\((dB^{-km})\) |
|-----------------|---------------------------------|------------------|---------------------------------|
| 100             | \(3.023 \times 10^{-3}\)       | 0.7391           | 1.3131                          |
| 300             | \(3.023 \times 10^{-3}\)       | 0.4037           | 3.9393                          |
| 500             | \(3.023 \times 10^{-3}\)       | 0.2205           | 6.5655                          |
| 700             | \(3.023 \times 10^{-3}\)       | 0.1205           | 9.1917                          |
| 900             | \(3.023 \times 10^{-3}\)       | 0.0658           | 11.8179                         |
Table 3. Calculated values for channel attenuation for $\lambda=1550$ nm and 1310 nm

| Supportable distance (m) | $9\,\mu$m channel attenuation in (dB) | $9\,\mu$m channel attenuation (dB) |
|--------------------------|--------------------------------------|-----------------------------------|
| 20                       | 2.5444                               | 2.5470                            |
| 40                       | 2.5488                               | 2.5540                            |
| 60                       | 2.5532                               | 2.5610                            |
| 80                       | 2.5576                               | 2.5680                            |
| 100                      | 2.5620                               | 2.5750                            |
| 150                      | 2.5730                               | 2.5925                            |
| 200                      | 2.5840                               | 2.6100                            |
| 250                      | 2.5950                               | 2.6275                            |
| 300                      | 2.6060                               | 2.6450                            |
| 350                      | 2.6170                               | 2.6625                            |
| 500                      | 2.6500                               | 2.7150                            |
| 860                      | 2.7292                               | 2.8410                            |
| 550                      | 2.6610                               | 2.7325                            |
| 800                      | 2.7160                               | 2.8200                            |
| 880                      | 2.7336                               | 2.8480                            |

Table 4. Commonly accepted link loss for single mode and multimode fiber

| Fiber type               | Wave length | Fiber attenuation dB/km | Connector loss in dB | Splice loss in dB |
|--------------------------|-------------|-------------------------|----------------------|-------------------|
| Multimode 50/125 μm      | 850 nm      | 2.40                    | 0.50                 | 0.10              |
| Multimode 62.5/125 μm    | 850 nm      | 0.70                    | 0.50                 | 0.10              |
| Multimode 62.5/125 μm    | 1300 nm     | 3.0                     | 0.50                 | 0.10              |
| Single mode 9 μm         | 1310 nm     | 0.35                    | 0.50                 | 0.10              |
| Singe mode 9 μm          | 1550 nm     | 0.22                    | 0.50                 | 0.10              |

Fig. 5. Absorption loss (dB/km) Vs Wavelength nm
Fig. 6. Rayleigh scattering for wave length 0.80 µm

Fig. 7. Rayleigh scattering for different wavelength
Fig. 8. Rayleigh scattering for fiber length 100 to 900 m

Fig. 9. Bending loss (dB/km) Vs radius of curvature
Fig. 10. Link loss for wavelength 850 nm and fiber length 20 m to 880 m

Fig. 11. Link loss for wavelength 850 nm and 1300 nm fiber length 10 m to 880 m
Fig. 12. Link loss for wavelength 1550 nm and 1310 nm fiber length 10 m to 880m

Fig. 13. Link loss for wavelength 1310 nm multi-mode & single mode glass fiber
Fig. 14. Link loss for wavelength 1550 nm multi-mode fiber & single mode glass fiber

Fig. 15. Link loss for wavelength 650 nm plastic multi-mode fiber
Table 5. Commonly accepted link loss values for Glass, Plastic and PCS

| Mode       | Material | Refractive Index Profile | \( \lambda \) nm | Diameter \( \mu m \) | Attenuation \( \text{db/km} \) | Connector Loss in dB | Splice Loss in dB |
|------------|----------|--------------------------|------------------|-----------------|------------------|---------------------|------------------|
| Multi-mode | Glass    | Graded                   | 1310             | 62.5/125        | 0.9              | 0.50                | 0.10             |
| Single mode| Glass    | Step                     | 1310             | 9.3/125         | 0.5              | 0.50                | 0.10             |
| Multi-mode | Glass    | Graded                   | 1550             | 85/125          | 0.4              | 0.50                | 0.10             |
| Single mode| Glass    | Step                     | 1550             | 8.1/125         | 0.2              | 0.50                | 0.10             |
| Multi-mode | Plastic  | Step                     | 650              | 485/500         | 240              | 0.50                | 0.10             |
| Multi-mode | Plastic  | Step                     | 650              | 775/750         | 230              | 0.50                | 0.10             |
| Multi-mode | Plastic  | Step                     | 650              | 980/1000        | 220              | 0.50                | 0.10             |
| Multi-mode | PCS      | Step                     | 790              | 200/350         | 10               | 0.50                | 0.10             |

5. RESULTS AND DISCUSSION

Simulation process is being performed to design the fiber using MATLAB software in this research. The study is being made to focus on the analysis of different types of fiber losses and their graphical representations. In simulation process, it is observed that the absorption loss increases as the wavelength of light increases. The absorption loss at 1310 nm wavelength of light is 0.661 µdB/km and 1550 nm wavelength of light 0.020dB/km respectively. It is clear from Fig. 5 the absorption loss at 1310 nm wavelength of light is significantly very low (0.661 µdB/km). For larger wavelengths, infrared absorption starts to increase. From Table 1 it is shown that for average length of 0.50m, 0.565m, 0.63m, 0.69m, 0.76m, 0.825m, 0.89m, 0.955m, 1.02m, 1.085m, 1.15m the scattering losses in \((dB^{-km})\) are accordingly 13.13, 8.05, 5.20, 3.5, 2.45, 1.77, 1.30, 0.98, 0.75, 0.59, and 0.46. So it is clear, the scattering loss decrease as the wavelength of light increases.

Fig. 6 shows that the Rayleigh scattering loss for 0.80 \( \mu m \) the scattering loss is 2.1665 dB/km. From Table 3 the scattering loss for 1310nm wavelength of light is 0.002846 dB/km and 1550nm wavelength of light is 0.0027336 dB/km respectively. So its exhibits that 1550 wavelength is better than 1310 wavelength for optical fiber communication. For short wavelengths, Rayleigh scattering of in homogeneities becomes important and towards UV wavelengths electronic absorption starts to kick in. For using 1550 nm region, it can be avoided the need for repeaters. Generally, performance and cost increase as wavelength increases. In case of bending loss,
the loss decrease as the wavelength of light increases. In case of link loss increasing fiber distance the fiber attenuation increase gradually. Figs. 10-12 shows that the attenuation increases in respect of fiber length. Fig. 14 provides attenuation for multimode and single mode fiber at wavelength 1550 nm that can be shown the attenuation for multimode fiber is greater than single mode fiber. Comparing the attenuation level for 1310 nm at Fig. 13 and 1550 nm at Fig. 14; it shows that attenuation level for 1550 nm wavelength is lower than 1310 nm wavelength. Fig. 15 shows that attenuation level for plastic multimode fiber. Fig. 16 shows that there are great attenuation between glass and plastic optical fiber. Fig. 17 shows that there are large attenuation between plastic and Plastic Clad Silica (PCS) optical fiber.

Loss of Rayleigh scattering be reduced by increasing the operating wavelength. The Rayleigh scattering, link loss only depends on the operating wavelength. So if we use the operating wavelength above the 2μm [20], the lower Rayleigh scattering and link loss attenuation can be reduced by increasing the operating wavelength in SMF [21].

6. CONCLUSION

This research contributed to the state-of-the-art in losses for fiber-optic communication systems. The main motivation of this work was to study simulation of optical fiber communication systems due to attenuation. Various kinds of components are the major factor that degrades the performance of transmission for short and long distance optical communication systems. The studies of attenuation are very limited as far as the significance of higher order attenuation terms is concerned. It is clear from the Fig. 5 that the absorption loss at 1310 nm wavelength of light is highly very low. The absorption loss can be highly minimized by making the core of optical fiber made of ultra pure low loss glasses. If we use single mode silica core fiber with attenuation in the range 0.15 to 0.17 dB/km at 1550 nm then losses should be minimized. We can use Polymer optical fiber instead of silica which is readily available with attenuation around 200dB/km at 650 nm, and losses of 50dB/km are possible, depending on the core composition and operating wavelength. Polymer has numerous advantages over glass. It is pliable, easier to terminate, polish, and connect as well, which can reduce the cost of installation and maintenance. So, the choice of a particular fiber cable, wavelengths, modes, fibers length will depend on the designer’s ability to assess the system loss budget and the overall attenuation. In case of scattering and bending loss, the loss decrease as the wavelength of light increases. It has been seen from the link loss graphs that it is related with the fiber distances. When fiber distances increase fiber attenuation increase inversely when fiber distances decrease the fiber attenuation also decreases. The main aim of the
A contribution is to develop such an optical fiber communication system which is lossless and very rapid than the previous one. This is our main target in future to developing optical fiber in such a pattern.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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