
An OptifSIM Simulator for Optical Fiber Network

By

¹I. A. Zubairu, ¹Bajoga, B. G., ²M. Ajiya, ¹S. M. Sani, ²A. T. Salawudeen, ¹Tekanyi A. M. S.

¹Department of Communication Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.

²Department of Computer Engineering,
Bayero University, Kano, Nigeria.

¹Department of Communication Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.

Email: iazubairu@abu.edu.ng

ABSTRACT

This paper present an interactive Optical Fiber Simulator (OptifSim) for Optical Fiber Networking using MATLAB for user who have little or no programming knowledge of MATLAB. Attenuation of Optical Fibers limit the performance of optical communication systems and management of infrastructure which include fault localization. Thus, signal loss in the fiber optics and security vulnerability of the data poses a great concern. The OptiFSim also have the option to generate plots for easy interpretation and analysis. This paper will describe the use of OptiFSim for the analysis of some optical communication components to calculate most of the optical fiber related parameters such as attenuation loss, Rayleigh scattering, propagation constant and maximum attenuation allowed before a signal amplifier can be applied. This knowledge enable the network engineer in the design and know exactly where to place and amplifier for compensating the attenuation in the long distance network.

Key words: OptiFSim, MATLAB, Rayleigh scattering, Propagation Constant and Attenuation

INTRODUCTION

The World Wide Web based applications as well as integrated multimedia applications (voice/data/video) have fueled the need for higher bandwidth networks. These demands for higher bandwidth lead to greater investment in this area of research which in turn brought about rapid advances in microelectronics and optical networking technologies. The rapidly growing need for faster networks leads to the growth of 1.25 Gb/s wired baseband and 2 Gb/s wireless data have been successfully transmitted over the testbed (Abraha, 2012). To meet the demand for bandwidth, telecommunication operators are pushed to increase the per-channel data rate of Wavelength Division Multiplexing (WDM) systems based on 10 Gb/s channel rate deployment and recently, 224Gbs bidirectional speed over 3meters was achieved by University of Oxford researchers using infrared (IR) technology(Koenig et al., 2014). The material used in fibers is silica glass, or silicon oxide, which is one of the most abundant materials on earth with lower cost compared to other wired conductors. With the much higher information capacities, multiple channel routes using optic fibers can be compressed into much smaller cables, greatly reducing congestion in the overcrowded cable ducts(Nichols et al., 2002). This means that the use of fiber optic cables is one

of the most efficient data transmission medium, transferring Gbits of information in quick time. An optical fiber is a flexible filament of very clear glass capable of carrying information in the form of light. Optical fibers are waveguides that transmit, or propagate light in the ultraviolet, visible and infrared regions of the electromagnetic spectrum from one location to another. Optical fibers are hair-thin structures created by forming pre-forms, which are glass rods drawn into fine threads of glass protected by a plastic coating.

Fiber manufacturers use various vapor deposition processes to make the pre-forms. The fibers drawn from these pre-forms are then typically packaged into cable configurations, which are then placed into an operating environment for decades of reliable performance (Massa, 2000). The ability of any fiber optic system to transmit data ultimately depends on the optical power at the receiver.

This receiver power depends on two basic factors: how much power is launched into the fiber by the transmitter and how much is lost by attenuation in the optical fiber cable that connects the transmitter and receiver (Rath et al., 2017). The different angles of rays entering an optical fiber are called propagation modes. Different propagation modes have different speeds along the fiber. Only a finite set of modes can propagate along an optical fiber. If the radius of the optical fiber is small enough, then only one mode can propagate (that is single-mode fibers). Propagation in optical fibers is subject to pulse spreading, attenuation, and dispersion (Gawade & Mer, 2015).

These effects limit the transmission rate and usable length of a fiber. This is why optical fiber links sometimes require repeaters every 30 to 50 km. Research has shown that inline optical signal amplification is possible, that makes the receivers more sensitive, since such signals are weak and quickly overcome by noise, particularly thermal noise. An optical fiber consists of three concentric elements: core, cladding and the outer coating, is called protective jacket (plastic sheath). The core is usually made of glass or plastic. It is the light carrying portion of the fiber. The cladding surrounds the core. It is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber. Light is transmitted down the fiber and does not escape through the sides of the fiber (Ozer, Taner, Sadik and Recep, 2016). The jacket protects the fiber from external damage. The electromagnetic radiation is kept in the core by total internal reflection.

The optimal goal in building new communication lines is to effectively minimize attenuation, ensuring safety, reliability, and cost savings for the utility. To meet these challenges, the organizations need to switch to more integrated computer simulation the OptiFSim.

LITERATURE REVIEW

This sub section introduces review of fundamental concepts and similar works that are relevant to this study.

Overview of Fiber Optical Concepts

Fiber Losses

Optical fiber is an ideal medium that can be used to carry optical signals over long distances. There are different reasons for light losses which may occur during signal transmission of light signal inside the fiber or during the interconnection process of two fibers. Attenuation is one of the

most important parameters of an optical fiber and to a large extent, determines how far an optical signal can be delivered at a detectable power level. Signal attenuation in an optical fiber is defined as the decrease in light power during its propagation along an optical fiber. The following equation defines signal attenuation as a unit of length (Agrawal, 2001).

$$a = \frac{1}{L} \ln \left(\frac{P_1}{P_2} \right) \quad (1)$$

Where L is the fiber length expressed in kilometers, and the attenuation is expressed in db/km. The reduction of power of light wave as it travels down the optical fiber lead to the introduction of repeaters between the transmitter and the receiver. Several factors can cause attenuation, but it is generally categorized as either intrinsic or extrinsic. Intrinsic attenuation is caused by substances inherently present in the fiber (Absorption Loss, Rayleigh Scattering), whereas extrinsic attenuation is caused by external forces such as bending (Macro-bends, Micro-bends) (Laferrière & Li, 2001).

Intrinsic Attenuation

Intrinsic attenuation results from materials inherent to the fiber. It is caused by impurities in the glass during the manufacturing process. As precise as manufacturing is, there is no way to eliminate all impurities. When a light signal hits an impurity in the fiber, one of two things occurs: It scatters or it is absorbed. Intrinsic loss can be further characterized by two components which include material absorption and rayleigh scattering.

Absorption Loss

Light travels best in clear substances. Impurities such as metal particles or moisture in the fiber can block some of the light energy, it absorb the light and dissipate it in the form of heat energy, which caused absorption loss (Lathief, 2014). The solution is to use ultra-pure glass and dopant chemicals to minimize impurities, and to eliminate loss at the water peak wavelength during the process of fiber manufacturing, absorption loss is as shown in Figure 1.

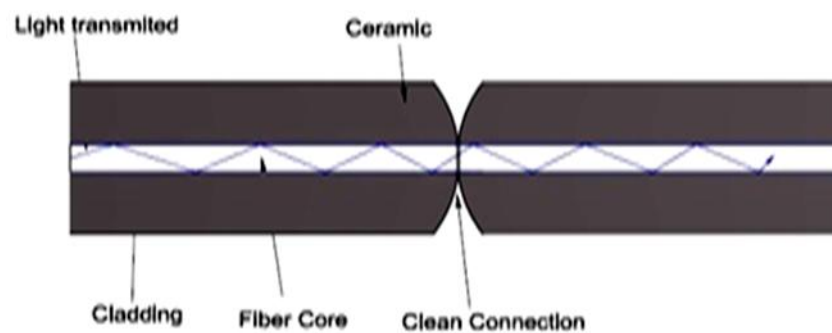


Figure 1: Absorption Loss In An Optical Fiber (Keiser, 2014).

Rayleigh scattering

The most common source of attenuation in optical fibers occurs when light scatters in different directions by Rayleigh scattering. It is the loss of the optical signal due to the molecular imperfections or the lack of optical purity in the fiber and from the basic structure of the fiber.

Scattering is cumulative, meaning that the further the light travels through a medium, the more likely the light is going to scatter. Figure 2 shows an example of Light scattered during transmission in an optical fiber.

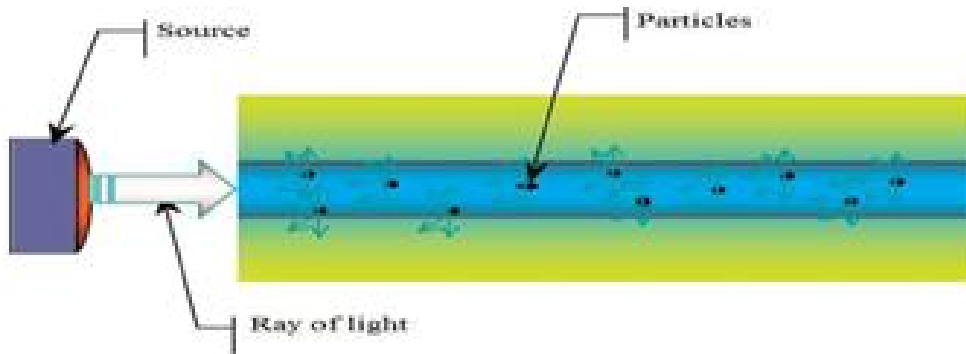


Figure 2: Schematic representation of Rayleigh-backscattering(Keiser, 2014).

The attenuation coefficient due to Rayleigh scattering in (pure) fused silica is given by approximate equation (2) (Bailey & Wright, 2006; Keiser, 2000).

$$R(\lambda) = \alpha_0 \left(\frac{\lambda_0}{\lambda}\right)^4 \quad (2)$$

where, R - Rayleigh scattering, λ - wavelength of fiber in micrometer, α_0 - attenuation coefficient $\alpha_0 = 1.7 \text{ dB/km}$ at $\lambda_0 = 0.85 \mu\text{m}$. Rayleigh scattering can also be expressed as in equation (3)

$$\alpha_R = \frac{C}{\lambda^4} \quad (3)$$

where the constant C is in the range $0.7\text{--}0.9 \text{ (dB/km)}\text{-}\mu\text{m}^4$, depending on the constituents of the fiber core. These values of C correspond to $R = 0.12\text{--}0.16 \text{ dB/km}$ at $\lambda = 1.55 \mu\text{m}$.

Extrinsic Attenuation

Extrinsic attenuation can be caused by two external mechanisms: macro bending or micro bending. Both cause a reduction of optical power. If a bend is imposed on an optical fiber, strain is placed on the fiber along the region that is bent. The bending strain affects the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out, and loss occurs (Arumugam, 2001). Again there are two external mechanisms of extrinsic attenuation, which are:

- i. Macro-bends
- ii. Micro-bends

Macro-bends: This describes the bending of the fiber optic cable in a tight radius. Macro bending of an optical fiber is the attenuation associated with bending or wrapping the fiber. Light can "leak out" of a fiber when the fiber is bent, when as the bend becomes more acute, more light leaks out. The bend curvature creates an angle that is too sharp for the light to be reflected back into the core, and some of it escapes through the fiber cladding, causing optical loss. This optical

power loss increases rapidly as the radius is decreased to an inch or less (Ramaswami, Sivarajan, & Sasaki, 2010). Different fiber optic cables have different specifications on how much the cable can be bent without affecting the stated performance or loss. Figure 3 shows an example of bending radii of an optical fiber. A macro bend is a large-scale bend that is visible, and the loss is generally reversible after bends are corrected. To prevent macro bends, all optical fiber has a minimum bend radius specification that should not be exceeded. This is a restriction on how much bend a fiber can withstand before experiencing problems in optical performance or mechanical reliability.

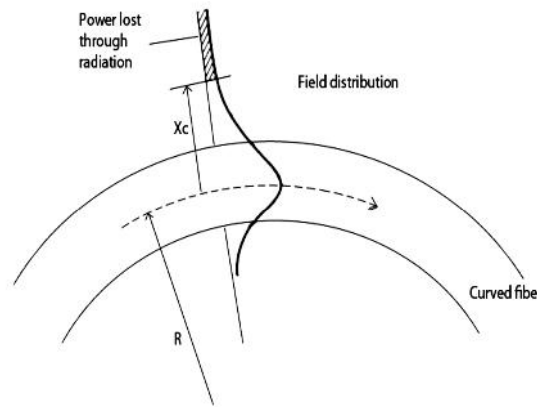


Figure 3: Bending Radii of an Optical Fiber(Keiser, 2014).

For a single mode fiber of length L , the bend loss can be calculated using the equation (4) (Ramaswami et al., 2010)

$$L_s = 10l\alpha_{-1} (e^{-2\alpha}) = 8.686 \alpha \quad (4)$$

Where α is a bending loss coefficient which is determined by the fiber structure, bending radius and input wavelength of light. When the bending reaches a critical radius of curvature (R_c), then loss due to bending can be neglected, and R_c is defined as (5) (Marcuse, Menyuk, & Wai, 1997)

$$R_c = \frac{3n_2\lambda}{4\pi(N.A)^2} \quad (5)$$

Where R_c is the critical radius of bending, n_2 is the refractive index of the cladding, $N.A$ is the numerical aperture of the fiber and λ is the wavelength. The empirical formula defining macro bending attenuation required the attenuation to be in dB. This can be achieved using equation (6)(Pal & Gupta, 2014)

$$\text{Attenuation per unit length} \left(\frac{d}{m}\right) = \frac{A}{\pi \frac{D}{2}} \quad (6)$$

Where A is the attenuation (dB) caused by a half-loop bend with a diameter D (m). If the fiber is curved around a corner, different portions of the same mode must travel at different speeds to maintain the integrity of the mode. However, for portions of the mode traveling through the “outside” of the curve, a small enough radius of curvature will require that this portion of the mode travel essentially faster than light speed (Saeid, 2012). Under these conditions, the mode integrity cannot be maintained and the energy radiates away from the fiber structure, thus contributing to a

reduction in the optical power transmitted by the fiber. In general, the amount of attenuation increases exponentially with decreasing radius of curvature. For larger radii, the losses are typically very small, particularly compared with losses associated with the material phenomena described above. However, beyond a threshold radius, the losses become much larger. Given the increase in modal field intensity distribution near the cladding for higher order propagating modes, macro bending losses are more likely to affect these modes.

REVIEW OF SIMILAR WORKS

Biebuma and Omijeh, (2013) presented Geographic Information System (GIS) as an invaluable tool in path loss schemeing. It shows how GIS can reveal features through its visualization capabilities. A program was written in Visual Basic for Applications (VBA) to automatically compute the path loss using Cost 231 Hata Scheme, and display it spatially on an administrative map and satellite imagery (Land Use/Land Cover) using ArcMap 9.0 Application. The results obtained were tested to be consistent with results of previous study done in Southern Nigeria. Thus, the integration of GIS into existing path loss analysis applications is recommended for fast, accurate and exciting results brought about by the ability to visualize the terrain and other great features. However, this scheme will not work because it did not consider Proximity, Network and Overlay which can further simplify the work of the telecommunications engineer.

Kumar and Bhatt, (2013) proposed a new method of prevention oriented network planning concept aimed at increasing all-optical network security in an economically more viable way. Current approach uses a system known as Remote Fiber Monitoring System (RFMS). RFMS allows an operator to remotely monitor the condition of a fiber cable by using Optical Time Domain Reflectometer (OTDR). The requirements to place OTDR permanently for continuous monitoring force the line owners to place a high investment to the system. The result shows that SDH Line Systems with 140 Mb/s and 565 Mb/s line systems currently deployed in backbone networks are replaced by STM-16 (2.4 Gb/s). However, the permanent placement of OTDR tends to leads to cost implication which results to saturation of the OTDR, hence, false result recorded in the system.

Nasir et al., (2015) presented study of different loss mechanisms within the single mode fiber (SMF) in optical fiber communication. A simulation was carried out to determine the losses in fiber optics cable. The result shows that Brillouin threshold occurs at an optical power level of around 80mW whilst the Raman threshold is approximately seventeen times larger. It is therefore apparent that the losses introduced by non-linear scattering may be avoided by use of a suitable optical signal level. It is also noted that the threshold optical powers for both these scattering mechanisms may be increase by suitable adjustment of the others parameters in loss mechanisms. The authors suggested that the effect of different bending and bending losses with different Wavelengths should also be simulated.

Ozer et al., (2016) developed a geographic information system (GIS)-based novel fiber network monitoring with capabilities for both detailed digital schemeing and central monitoring of Fiber optics Network (FONs). The system can perform scheduled measurements and dispatch alarms if any fault or degradation is detected in the concerned FON. The system is designed to be operational on a CMS and CMUs that are connected to the transmission control protocol/Internet protocol (TCP/IP)-based network. The GIS server module is deployed on the CMS to store and

manage geographical data. Application software modules operate on a Java 2 platform Enterprise Edition (J2EE)-based application server. GIS operations are managed by the programming interface of the web application development framework (ADF). The developed system can be used for planning, scheming, and monitoring of pipelines, railways, power line networks, and transportation networks, where management of GIS-based inventory items is densely employed. However, the system is not cost effective since OTDR must be connected to all channel at all time to carry out all measurement and also APD receiver can saturate if the OTDR receives high power, resulting in a transient in which the APD does not work properly. However, the APD receiver gets saturated, if the OTDR receives high power, thereby resulting in a transient in which the APD does not work properly

METHODOLOGY

The step by step processes used in the development of the interactive Optical Fiber Simulator (OptiFSim) is presented. In this research, an interactive software which will enable an essay simulation of some optical fiber parameters were developed. The developed software has three basic features. These features include input parameters, output parameters and the graph showing the attenuation with respect to the length of the optical fiber. The flowchart for the programming the OptiFSim software is given in Figure 4

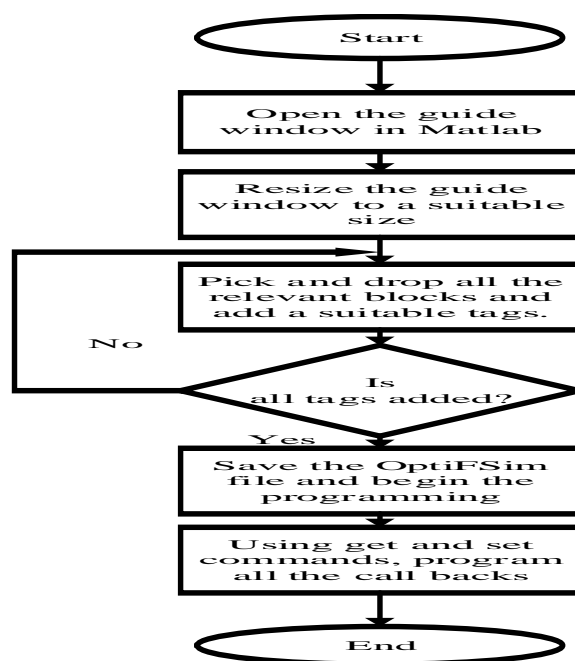


Figure 4: The Flowchart of OptiFSim Development

From the OptiFSim programming flowchart given in Figure 3.19, the MATLAB software is initiated and the GUI window is opened by typing the command guide in the MATLAB command window. The GUI window is resized appropriately and all the relevant control block are selected from the control dropdown menu. Tags were attached to each control block and the callback for each block were programmed appropriately using get or set command. The get command is to accept

an input from the user (keyboard) while the set command is to pass an output to the user (screen). The snippet of the developed OptiFSim software is shown in Figure 5.

INPUT PARAMETERS

From Figure 5, it can be observed that, the input parameters of the OptiFSim software includes the number of connectors, number of splice, attenuation of one optical connector, system margin, attenuation of optical cables, maximum optical length attenuation of one splice, wave length index of the core, diameter of the core and index of cladding. In the output parameter option are the maximum allowable attenuation, normalized propagation constant and total attenuation are displayed. The flow of simulation on the OptiFSim is given in Figure 6.

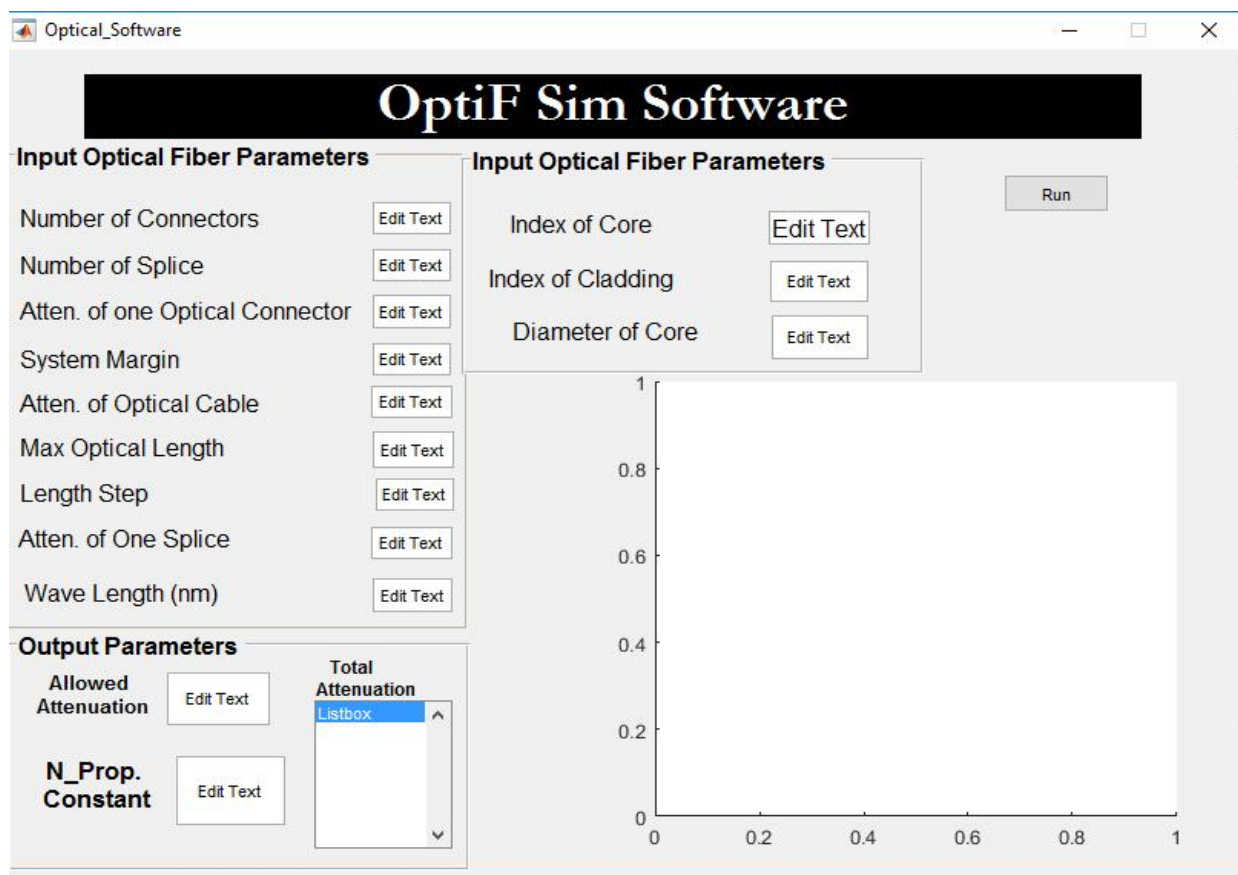


Figure 5: OptifSIM Software

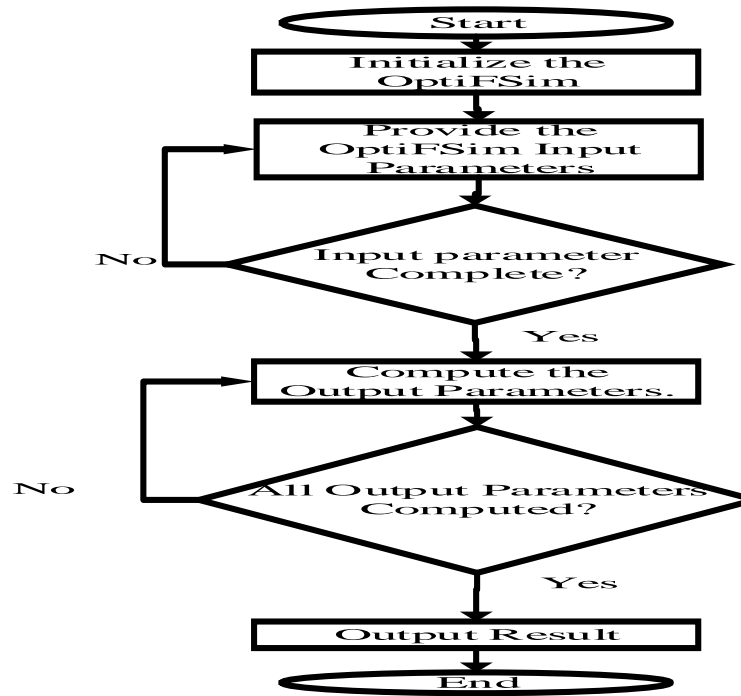


Figure 6: OptiFSim Simulation Flowchart

Figure 6 shows the flow for simulating with the OptiFSim software. In the OptiFSim, all the optical fiber input parameters are provided. Simulation is performed and the output parameter is generated. From the generated output parameters, a plot of attenuation loss is displayed and results shown.

LOSSES AND FITTING PARAMETERS

Beyond a threshold radius, the losses become much larger. Given the increase in modal field intensity distribution near the cladding for higher order propagating modes, macro bending losses are more likely to affect these modes.

The macro bended fiber is schemed as a curved dielectric slab surrounded by an infinite cladding, and then by this approach a closed form of solution might be obtained. Different approaches have been employed for evaluation of the macro bending loss. Macro bending loss coefficient (2α) (dB/km) which has been proposed by Marcuse, according to the mode coupling theory is presented as equation (7) (Marcuse, 1977)

$$2\alpha = \sqrt{\pi\delta^2}L_c \left(\frac{2n_1K}{b} \Delta\right) - \sum_s e. \left\{ \left| (\beta_y - \beta_{1s}) \frac{L_c}{2} \right|^2 \frac{J_0^2(J_{1s} \frac{a}{b})}{J_u(J_{us})} e. \left(\frac{-2a^2}{w^2}\right) \right\} \quad (7)$$

which usually is considered in step index optical fibers, uses Bessel function of zero and first order (J_0, J_1) and also the root of Bessel function (J_{0s}, J_{1s}), with boundary conditions $J_0(J_{0s}) = 0, J_1(J_{1s}) = 0$. (Tsao & Cheng, 2000) have modified equation (2.17) for 2α , and they considered other

parameters like number of wrapping turns (N), and curve fitting function (F), and also Vnumber, and the suggested formula is as follows (8):

$$2\alpha = 2FN \left[4\sqrt{\pi\delta^2} \frac{1}{\Lambda_c} \left(\frac{n_1 K \Delta}{b} \right)^2 - \sum_s J_1^2 \left(J_{1s} \frac{b}{a} \right) V^{-2} \right] \quad (8)$$

Where Λ_c is the spatial perturbation wavelength, and is defined as

$$\Lambda_c = 2R \quad (9)$$

Where R is the radius of curvature of the bend, and for loss they used the following equation:

$$L_R = \eta_R \exp(\eta_R R) \quad (10)$$

Where η_R , η_R are fitting parameters, and for $\lambda = 1550$ nm, their values are given as 70 and 0.5 respectively (Marcuse, 1977). The η_R , η_R are functions of bending radius or wavelength only. The researcher also proposed a linear relationship between losses and number of turns as in equation (2.21) (Marcuse, 1977)

$$L_N = \eta_N N \quad (11)$$

Where L_N is the loss due to the number of wrapping turns (N), η_N is constant, which has 0.01 value and N is number of turns.

In most of these schemes one can see the effect of refractive index of the fiber (core and clad) and their differences (Δ), which are important physical parameters. It is claimed (Zendehnam, Mirzaei, & Farashiani, 2010), that oscillation of macro bending loss appears for sufficiently strong curvature, when R is smaller than the threshold value of bending radius (R_{th}) which is given by equation (12)

$$R_T = 2K^2 n_2^2 \frac{b}{\gamma^2} \quad (12)$$

Where $k = \frac{2\pi}{\lambda}$, n_2 is the refractive index of the clad, $\gamma = [\beta_0^2 - k^2 n_2^2]^{1/2}$, where β_0 is the complex propagation constant and $b = (x^2 + y^2)^{1/2}$

Loss budget calculation is also important for proper implementation of this research work. Loss budget includes fiber attenuation (length) of feeder, distribution and drop, splicing loss, adopter loss, splitter loss, connector and engineering safety loss. The power received at the Optical Network Termination (ONT) side at the receiver premises is calculated using equation (13):

$$\Sigma(\text{Power input}) = \Sigma(\text{Power output of all branch}) \quad (13)$$

Power received = Power transmitted - loss.

Estimating the Attenuation on the Optical Link (total attenuation (TA) of an elementary cable section can be summarized by the equation as shown in equation (14).

$$TA = n \times C + c \times J + L \times a + M \quad (14)$$

where: n—number of connectors, C—attenuation for one optical connector (dB), c—number of splices in elementary cable section, J—attenuation for one splice (dB), M—system margin (patch cords, cable bend, unpredictable optical attenuation events, and so on, should be

considered around 3dB), a —attenuation for optical cable (dB/Km), L —total length of the optical cable

SIMULATION RESULT ON OptiFSim SOFTWARE

The developed software was used to simulate and determine the total attenuation of a typical optical fiber input parameter scenario. The OptiFSim has an option to display the maximum attenuation allowed for a particular length of fiber optical cables. In the simulation scenario, the input parameter were set as shown in Figure 7.

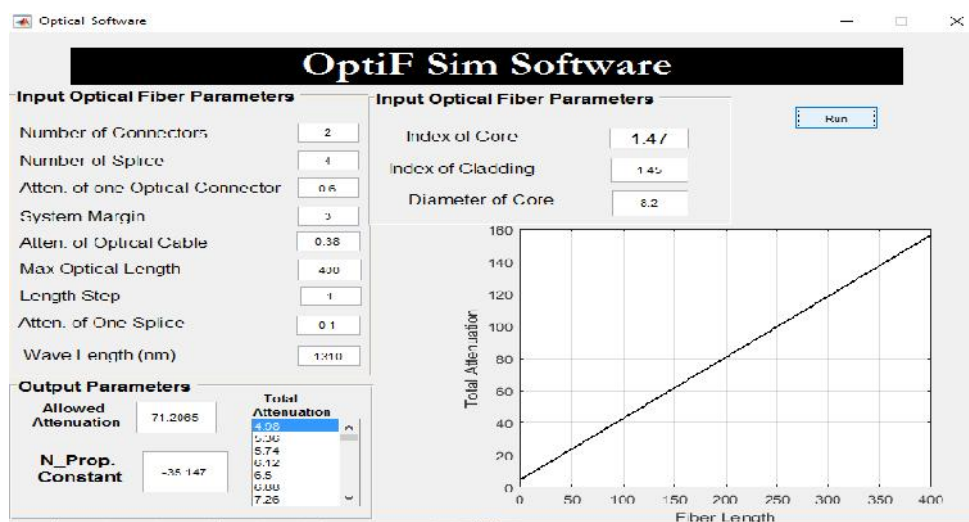


Figure 7: Simulation with the Optical Software

From Figure 4.16, it can be observed that OptiFSim software have the option to display output parameter. In the output parameters the minimum attenuation allowed for a particular length of optical fiber is displayed and the normalized propagation constant and the attenuation of the optical fiber for a specified length interval is also computed and displayed. The OptiFSim also have the option to display the plot of attenuation computed over the entire length of the optical fiber.

Rayleigh Scattering of Optical Fiber

The Rayleigh scattering of the optical fiber which serves as a dominant mode for optical loss was determined. The Rayleigh scattering was plotted for a total wavelength of $1.6\mu\text{m}$ considering the three attenuation wavelength windows. Starting from $1.5\mu\text{m}$, the Rayleigh scattering was determined at a 10 step size of wavelength (i.e, starting from 1.5, 1.6) using equation 2.13. The Rayleigh scattering loss only depends on the operating wavelength. Lower Rayleigh scattering loss occurs when the operating wavelength is above $1.5\mu\text{m}$. This is given in Figure 8.

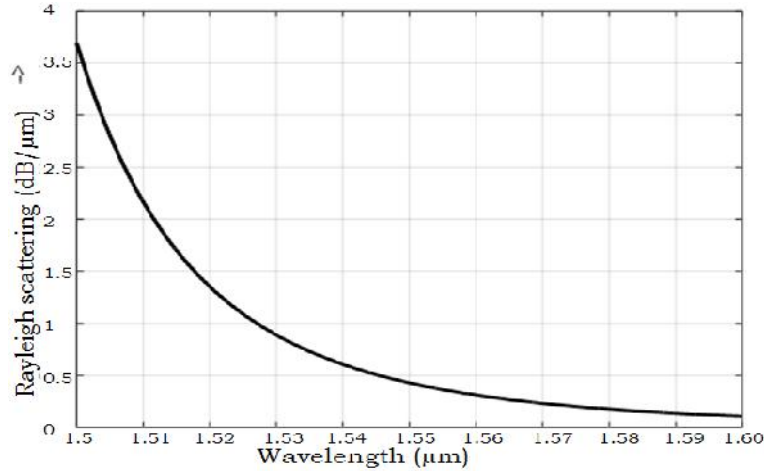


Figure 8: Optical Rayleigh scattering

From Figure 8, it can be observed that, the Rayleigh scattering is inversely proportional to the wavelength. The Rayleigh scattering was calculated for different value of wavelength starting from a wavelength of 1500μm in an interval of 10μm up to 1600μm. It can be observed that the Rayleigh scattering has it highest value when the wavelength is 1500μm. The value of the Rayleigh scattering reduces significantly all through the simulation until a minimum value of about 0.2dB/km is obtained. This minimum is obtained when the value of the wavelength is 1600μm. The equation (2.13) predicts the Rayleigh scattering loss to be 0.15dB/km at 1550μm wavelengths.

Propagation of Optical Fiber

The propagation constant of the optical fiber was also determined in order to further evaluate the characteristics of the optical fiber network of the selected study areas as shown in Figure 9.

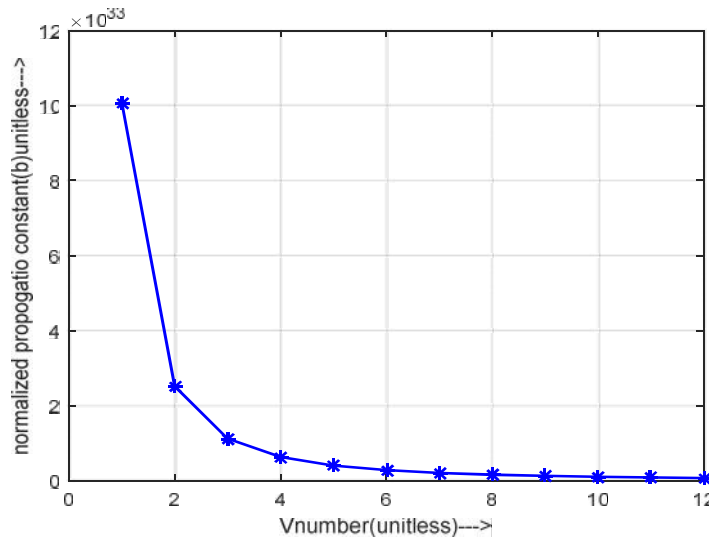


Figure 9: Normalized Propagation Constant

The simulation was carried out in MATLAB environment using equation 2.22 as shown in Figure 9, it is observed that, the normalized propagation constant reduces along the fiber optic as the length of the optical fiber increases. The propagation constant normalizes to an approximately constant value of 0.05 which occurred when the measurement point was increased to above 8. This indicates that the variation in the amplitude of the propagated information along the selected optical fiber region with respect to the phase remains approximately constant beginning from the stated point. The implication of this is that, nearly all the signal loss during transmission occurred at the early stage of the transmission process. The MATLAB program used to generate this plot is given in appendix D.

Optical Refractive Index against Radius

In this research, the simulation of refractive index of the propagated information along the optical fiber was implemented using equation 2.15 in MATLAB environment as shown in Figure 10.

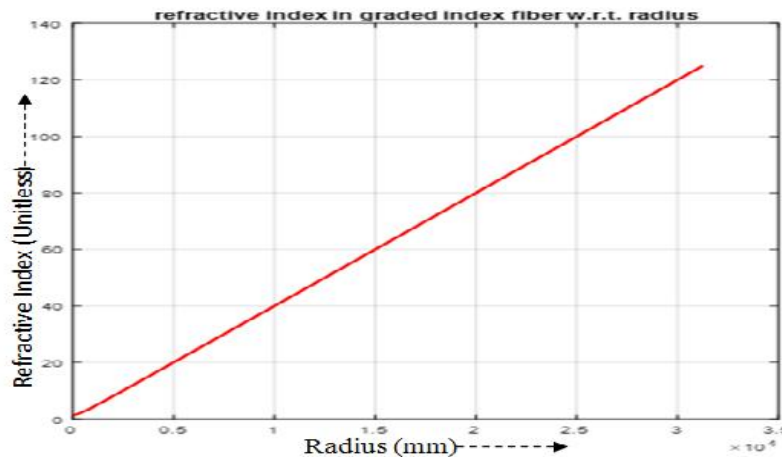


Figure 10: Optical Refractive Index against Radius

Figure 10 shows the plot of the refractive index against the radius in millimeter. From the Figure 10, it is observed that the refractive index of the optical fiber maintains a linearly increasing form with a constant slop.

CONCLUSIONS

This research has presented an OptifSim Simulator for Optical Fiber Network of Ahmadu Bello University, Zaria. To efficiently carry out this, the spatial data of the fiber optics infrastructure of the university was collected. A number of MATLAB simulations were carried out in order to determine the performance of the fiber optics network of the selected study area. The Raleigh fading and propagation constant were calculated. Simulation showed that the propagation constant of fiber optics network normalized at approximately a constant value of 0.05 which occurred when the measurement point was increased above 8. This is an indication that, nearly all the signal loss during transmission occurred at the early stage of the transmission process. The research developed a scheme for determining the attenuation loss on a fiber optical cable over a distance before an amplifier is added. This research has developed a graphical user interface called the OptiFSim to

enable easy and friendly simulation of fiber optical networks. The analytical system schemeling of the fiber optics network design within the network data center of the selected study areas can be considered. The impact of the physical layer setting up light paths by employing appropriate schemes of the multi wavelength optical devices can be considered. Effects of various attack such signaling attack on the fiber optics network data transmission can also be considered. The developed OptiFSim software can be updated to incorporate several other optical parameters for improved analysis.

REFERENCES

- Abraha, S. T. (2012). Impulse Radio Ultra Wideband over Fiber Techniques for Broadband In-Building Network Application (Doctoral dissertation, Ph. D. thesis. Eindhoven: Tech. Univ. Eindhoven, <http://alexandria.tue.nl/extra2/735363.pdf>).
- Agrawal, G. P. (2002). Fiber-Optic Communications Systems, Third Edition. (Vol. 6). A John Wiley and Sons, INC.
- Arumugam, M. (2001). Optical fiber communication — An overview. Indian Academy of Sciences, 57, 851–859.
- Bailey, D. and Wright, E. (2006). Practical Fiber Optics, Delhi, Elsevier.
- Gawade, S. B., & Mer, S. B. (2015). Testing and Loss Measurement Techniques in Optical FIBER for Healthy Optical FIBER Communication, 10(3), 54–56. <https://doi.org/10.9790/2834-10315456>
- Keiser, G. (2014). Optical fiber communication. MGH International Editions, Singapore (second edi). Singapore: McGraw Hill, Inc. Retrieved from http://scilab.in/files/textbooks/ProfSenthikumar/Optical_Fiber_Communication.pdf
- Koenig, S., Antes, J., Lopez-Diaz, D., Schmogrow, R., Zwick, T., Koos, C., ... Kallfass, I. (2014). 20 Gbit/s Wireless Bridge at 220 GHz Connecting Two Fiber-Optic Links. Journal of Optical Communications and Networking, 6(1), 54. <https://doi.org/10.1364/JOCN.6.000054>
- Laferrière, J. R. T. S. W., & Li. (2001). Guide to Fiber Optic Measurement (Vol. 33).
- Lathief, K. A. (2014). Attenuation Measurement in Optical Fiber Communication, 1(4), 62–67.
- Nichols, J., Tech, V., Travis, T., Carolina, S., Yafchak, M. F., Nichols, J., & Tech, V. (2002). Optical Networking Cookbook.
- Massa, N. (2000). Telecommunication. Massachusetts: Springfield Technical Community College Springfield,.
- Marcuse, D., Menyuk, C. R., & Wai, P. K. A. (1997). Application of the Manakov-PMD equation to studies of signal propagation in optical fibers with randomly varying birefringence. Journal of Lightwave Technology, 15(9), 1735–1745. <https://doi.org/10.1109/50.622902>
- Marcuse D., (1977). Loss analysis of single-mode fiber splices', Bell Syst. Tech. J., 56(5), pp. 703–718.
- Ozer Koray AKDEM, Taner DURSUN₁, Sadık ARSLAN₁, Recep BENZER, M. A. A., & Sciences, C. (2016). A GIS-based novel active monitoring system for fiber networks. Turkish Journal of Electrical Engineering & Computer Sciences [Http://journal S . Tubi Tak.gov. Tr/elektrik/](http://journal.s.tubi.gov.tr/elektrik/) Research Article Turk, 247–261. <https://doi.org/10.3906/elk-1306-217>
- Pal, G. P., & Gupta, M. (2014). Signal degradation in optical fibers 1,2, 1(1), 15–19.
- Ramaswami, R., Sivarajan, K. N., & Sasaki, G. (2010). Optical Networks : A Practical Perspective Third Edition Solutions Manual for Instructors. United States of America: ELSEVIER Inc.

- Rath, P. S., Satyam, A., Jha, D. M., & Khalid, I. (2017). Performance Analysis of Long Fiber Optic Link using Fiber Bragg Grating for Dispersion Compensation. *International Journal of Engineering Science and Computing*, 7(4), 10279–10284. Retrieved from <http://ijesc.org>
- Saeid, S. H. (2012). Computer Simulation and Performance Evaluation of Single Mode Fiber Optics. *Proceedings of the World Congress on Engineering*, II, 1–6.
- Tsao, S., & Cheng, W. (2000). Defense Technical Information Center Compilation Part Notice Broadband Wavelength Division Multiplexing Fiber Sensor Systems.
- Rajive, R., Kumar N. S., Galen H. S. (2010). *Optical Networks, A practical Perspective*. Third edition, Morgan Kaufmann Publishers is an imprint of Elsevier. 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
- Zendehnam, A., Mirzaei, M., & Farashiani, A. (2010). Investigation of bending loss in a single-mode optical fibre, 74(4), 591–603.
<https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation>