

Reduction of Micro-Bending Losses in Fiber Optic Communication System

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ABSTRACT

It is known that optical fiber link is the hub of 21st Century telecommunications as such; maximizing its throughput to reduce losses along the transmission channel is of great importance. This work describes the systematic marginal reduction of refractive index of Parabolic Multimode fiber optic cable in order to optimize the throughput of optical fiber communication system. In this work, an optical approach was employed to compensate for the mechanically induced anomaly (micro-bends) or external pressure on the optical communication channel. From the result obtained, a 10% reduction in the micro-bend losses was achieved. Further attempt to reduce the losses increased the refractive index of the fiber clad to be greater than that of the core. This implies that, rather than reduce the channel loss due to micro-bends, the losses were increased.

The significance of this study is tailored to the fact that the result will aid in the determination of the exact value of the marginal refractive index that will ensure effective throughput maximization.

(Keywords: throughput, micro-bend, refractive index, fiber channel, optical losses, fiber clad, fiber core)

INTRODUCTION

Fiber optic communication has not only become the fastest communication channel, it has also become the most efficient. The massive deployment of this medium of communication network has given rise to some operational limitations due to the issues associated with manner in which the installations are being made. This prevalent problem has driven Scientists and Engineers to research ways to optimizing this communication network thereby handling these drawbacks.

This study considers the effective reduction of micro-bending losses as a means to maximize the

throughput of fiber optic communication links through the Marginal Reduction of Refractive Index of the optical signal across the loop. It considers micro-bending which occurs as a result of joining varying sizes of optical cables. This gives rise to power loss along the joining that exist over the fiber length, thereby inducing power losses and compromising the throughput of the fiber optic communication link.

A four channel Wave Division Multiplexing (WDM) fiber optic communication link was used as the premise to implement the study. The optisystem simulation was used to present the scenario of joining fiber cable lines along the channel. The study adopts a generalized approach for single mode fiber optic communication as a premise for analysis and simulation.

STATEMENT OF PROBLEM

Due to the global rise in the demand for data, fiber optic communication has in recent years emerged as the hope for effective and efficient mode of communication. Unfortunately, this mode of communication is not without drawbacks. In the course of this research work, marginal reduction of refractive index have been adopted to limit attenuation along the transmission channel which usually occur as a result of absorption of the optical signal by the fiber cladding due to refraction. Ensuring that the optical signal travels along the channel through the core gives maximized throughput of fiber optic communication network.

The Marginal Reduction in Refractive Index of the optical signal along the channel in this work will be constantly adjusted after every kilometer through a total of 15km length of transmission link to obtain a perfect propagation of the optical signal through the core of the fiber channel irrespective of the mechanically induced micro-

bends or fiber splicing along its length. This in the end will lead to maximizing the throughput of the fiber optic communication network.

REVIEW OF RELATED WORKS

Most digital data transmitted in the recent times are propagated by optical fibers. Thus, there is need to increase the information-carrying capacity of these fiber optic telecommunication links to match the huge traffic of data running through them. This process, hence, warrants an improvement in the throughput of the already existing link. To effectively maximize throughput in fiber optic communication links, it is necessary to have detailed information on fiber optics, laws governing their behavior (refraction and reflection laws), fiber optics design and how they are implemented in real life scenarios/situations. These details will form a strong premise on which the optisystem simulation was performed.

Smink and Tjihuis have made research efforts to compute the bending losses of modes in optical fibers in order to maximize the throughput of fiber optic communication links. Their approach was more tilted to macro bending in fiber optics and was based on a full vectorial analysis of the bent fiber. For this analysis, they were able to distinguish between field solutions inside and outside the fiber. For the interior region, a coupled system of ordinary differential equations is integrated numerically from the known regular solutions at the center to the boundary. For the exterior region, triple integrals involving products of modified Bessel functions with large, complex order and argument arise. They were able to show correctly computed bending losses of a step-index, single-mode fiber for various radii of curvature (Smink, et al., 2005).

Arthur H. Vartanian has also made research efforts to investigate the effect of pseudo-random transverse microscopic corrugations on the attenuation of the fundamental hybrid mode in curved graded-index mono-mode fibers. His work has paved way for more research efforts towards general formulation of micro-bending loss in local toroidal co-ordinates thereby improving the throughput of fiber communication links. Theoretical results of the wavelength dependence on excess micro-bending loss for two power spectral density functions along with their respective optimized statistical fiber parameters

were investigated and shown in his study findings (Vartanian, 1999).

An experiment-based evaluation method for estimating micro-bend studies has been put forward by Petermann. His theory depended on the geometry of the micro-bends. He demonstrated his method by predicting the excess losses in two precision-wound spools of fiber. He was able to completely estimate the bend losses by modeling the micro-inflammations in the fiber core using the Gaussian model, considering two major parameters which were the Gaussian standard deviation and the peak amplitude of the Gaussian node (Petermann, 1976).

Nacer-Eddine carried out a study on Chemical etching of concave cone fiber ends for core fiber alignment. In his bid to estimate the loss at a joining point of two fibers from cable to cable, he adopted a simple logarithmic power ratio equation to predict the loss. His equation can be used to estimate the loss at a node due to differences in core sizes (Nacer-Eddine, 2005).

$$\sigma = 10 \log_{10} P_o / P_e$$

where;

P_o = Optical power emerging from length of fiber.

P_e = Optical power entering length of fiber.

Jin and Payne have also developed a numerical approach to investigate micro-bending induced loss. Their model was an analytical model for micro-bending in optical fibers with arbitrary refractive index profiles. In their model, random perturbations of the fiber core along the fiber axis were described by an analytical function whose power spectral density is derived from an exponential autocorrelation function.

They used the model together with the beam propagation method to investigate micro-bending loss for several different types of optical fibers, which include the traditional single-mode/multimode fibers as used in existing optical networks, and typical few-mode/ring-core fibers (FMF/RCF) with the potential for future ultra-high speed optical networks. The validity of their proposed model was demonstrated based on a comparison done between the micro-bending loss of a SMF computed using coupled mode theory and their own results. Simulation results

show the SMF and RCF supporting only one radial mode have nearly equal micro-bending loss, whilst the FMF and MMF have relatively low micro-bending loss. In addition, the micro-bending loss of the RCF is shown to be dependent on the ring core thickness (Jin and Payne, 2015).

From the above research on improving the quality of optical fiber communication while reducing its attenuation or losses, it can be seen especially from Petermann's work that the geometric integration of the successive micro-bending mechanically induced through Gaussian model cannot completely eradicate the losses due to the bending owing to the fact that the transmission channel distance may increase and this will lead to large analysis that may end up being ambiguous.

On the flip side, Optisystem tool make it possible to vary these parameters and allow the designer to choose a perfect value for the refractive index that will encourage the total internal reflection of the optical signal via the fiber channel.

RESEARCH METHODOLOGY

The method adopted in the case of the study include a dynamic optimization of every stage in the Fiber Optic Communication Network using the Optisystem Telecommunication tool, i.e. considering the principle of operation and adjusting some parameters of the transmitter end, Optical medium, and the receiving end for its optimized performance. Hence, this approach involves the slight modification of some parameters of each of the communication stage (sub-units) of the entire network as shown in the Figures 1 and 2.

The study considers the reduction of throughput in fiber optic communication links due to the anomaly of micro-bends occurring in the core of fiber cables and further presents an optical approach on how to reduce the effect (optical power losses and throughput reduction) of micro-bend anomaly and thereby improve the throughput of the fiber optic communication link.

In theory, micro-bending loss is a complex process that often requires some statistical methodology to characterize the loss behavior completely. Areas where these statistical approaches are employed are usually in estimating parameters such as the varying width

of the individual periodic bell-shaped inflammations along the fiber line using a standard deviation so as to fully describe the loss behavior.

Reduction in throughput of fiber networks results from but not limited to micro-bending due to the fiber curvature which causes repetitive coupling of energy between the guided modes and non-guided modes in the fiber. The existence of periodic "bell-shaped" micro-inflammations along the fiber is a good scenario that is perfectly explained by a Gaussian curve. The micro inflammations are periodically dispersed all over the fiber length, having varied periodic amplitudes and varying width. The standard deviation usually termed the Gaussian RMS variable controls the width of the "bell".

The resulting model presented in this section will be an optimization of the Petermann's model or concept. The Petermann model describes periodic, Gaussian-shaped micro-bends that are separated by a distance L by modeling the loss in dB/km as a function of fiber specifications and micro-bend geometry (Petermann, 1977). Thus, the model approach will be premised on parameters associated with the fiber specification and the micro-bend geometry.

From Petermann's concept, the approximate description of the micro-bending loss based on the fiber specification and the micro-bend Gaussian geometry is given:

$$\alpha = \frac{q}{m} \left[\frac{A^2 B^3}{(B^2 + \sigma^2)^{\frac{5}{2}}} + \frac{\sigma^2 B}{2(B^2 + \sigma^2)^{\frac{3}{2}}} \right] \exp \left[\frac{-A^2}{B^2 + \sigma^2} \right] \quad (1)$$

Where:

Q = Constant

K = Wave number

N = Refractive index of the core

α = Standard deviation parameter

A = Average half width at 1/e amplitude

The variable q defines the product of an experimentally derived constant and the square of the amplitude of the small Gaussian-like fluctuations in the radius of the core given by Y^2 . Thus, we can express q as:

$$Q = 13.644 Y^2$$

The variable m defines the product of the period (time interval between the Gaussian nodes) between the Gaussian fluctuations or micro-bends along the fiber line and the square of the spot size w . We have that:

$$m = L w^2 \quad (2)$$

This implies that a supposed reduction in L will imply more losses along the fiber line. When the variables q and m are replaced with their respective expressions the Petermann's equation to model the microbending loss anomaly becomes:-

$$\alpha = \frac{13.644Y^2}{Lw^2} \left[\frac{A^2 B^3 2(B^2 + \sigma^2)^{\frac{3}{2}} + \sigma^2 B (B^2 + \sigma^2)^{\frac{5}{2}}}{(B^2 + \sigma^2)^{\frac{5}{2}} 2(B^2 + \sigma^2)^{\frac{3}{2}}} \right] \exp \left[\frac{-A^2}{B^2 + \sigma^2} \right] \quad (3)$$

A = average half-width at the $1/e$ amplitude, as shown in Figure 1.

σ = Standard deviation parameter describing varying half-width values.

$$B = \frac{knw^2}{\sqrt{2}} \quad (4)$$

k = wave number, given by the expression:

$$k = \frac{2\pi}{\lambda} \quad (5)$$

n = refractive index of the core.

The approach employed to model the micro-bending reduction by optimization of the Petermann model is such that relates the anomaly of micro-bending (which is known to be externally induced) to the internal parameters that mirror the presence of these micro-bends.

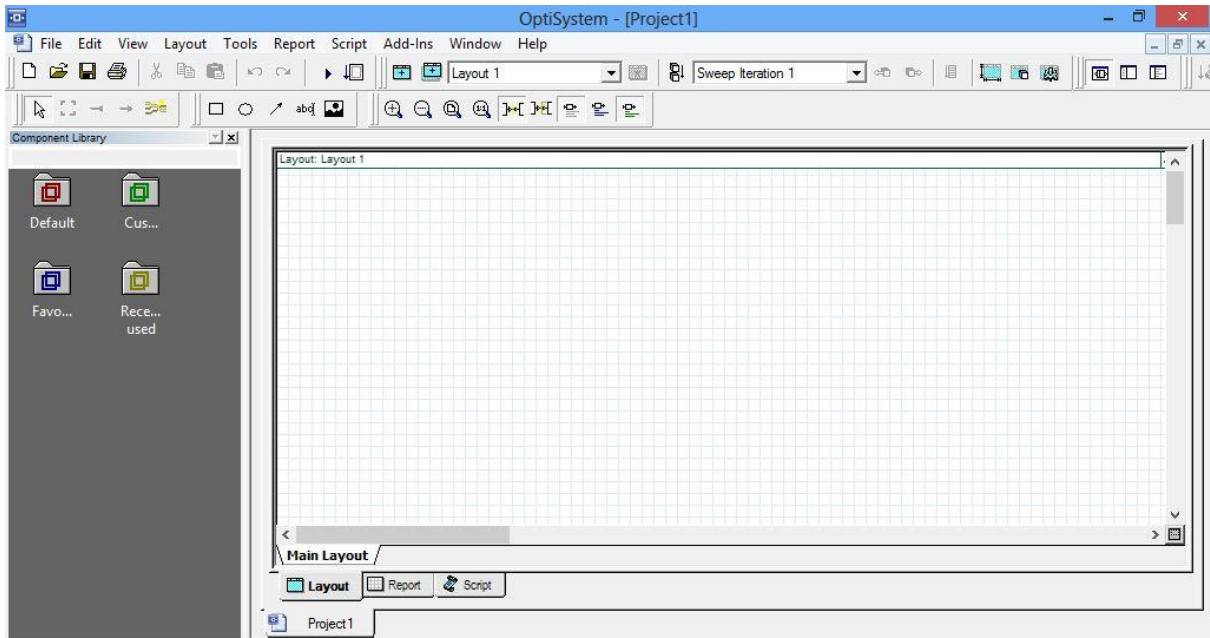
Since micro-bends will occur as a result of non-uniform external pressure along the fiber line, a best fit internal parameter that internally expresses the magnitude of external non-uniform pressures along the optical fiber line is the fluctuation or variation in peak amplitudes of the Gaussian curves used to estimate these micro-bends. This means that there will be high amplitude points internally along areas on the fiber line where there are higher mechanical pressures from external sources.

This concept negates the purely theoretical approach adopted by the Petermann model as it assumes ideal geometry (i.e., constant peak amplitude, which means equal external pressures along the fiber line), since the possibility of equal peak amplitudes is not realistic enough to precisely investigate the losses due to micro-bending. Thus, the contribution to the overall loss due to micro-bending (by different sections on the fiber cable line) is never equal since different points on the fiber line suffer varying magnitudes of perturbations and different lateral pressures, implying varying amplitudes.

This proposed optimized model will exclude the assumption of constant magnitude of micro-inflammation along the fiber line. It will thus take into cognizance the varying contribution to overall loss by different sections of the optical fiber experiencing the anomaly of micro-bend, as a result of varying lateral pressures along the fiber line. This is implemented by expressing varying peak amplitudes of different micro-bends existing in the core of the fiber as a function of the standard deviation and taking the summation of the resulting function.

THE OPTISYSTEM SIMULATION

The simulation for this work is designed over the Optisystem telecommunication application tool. The Optisystem simulation is divided into three different stages. However, a four channel WDM network is used to implement all two stages of the different scenarios that contribute to the overall effect of micro-bending. A progressive component library stepwise process for the simulation is presented: *Designing the optical transmitter for 4 channel WDM optical fiber communication system in Optisystem environment.*



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Figure 1: Optisystem Environment.

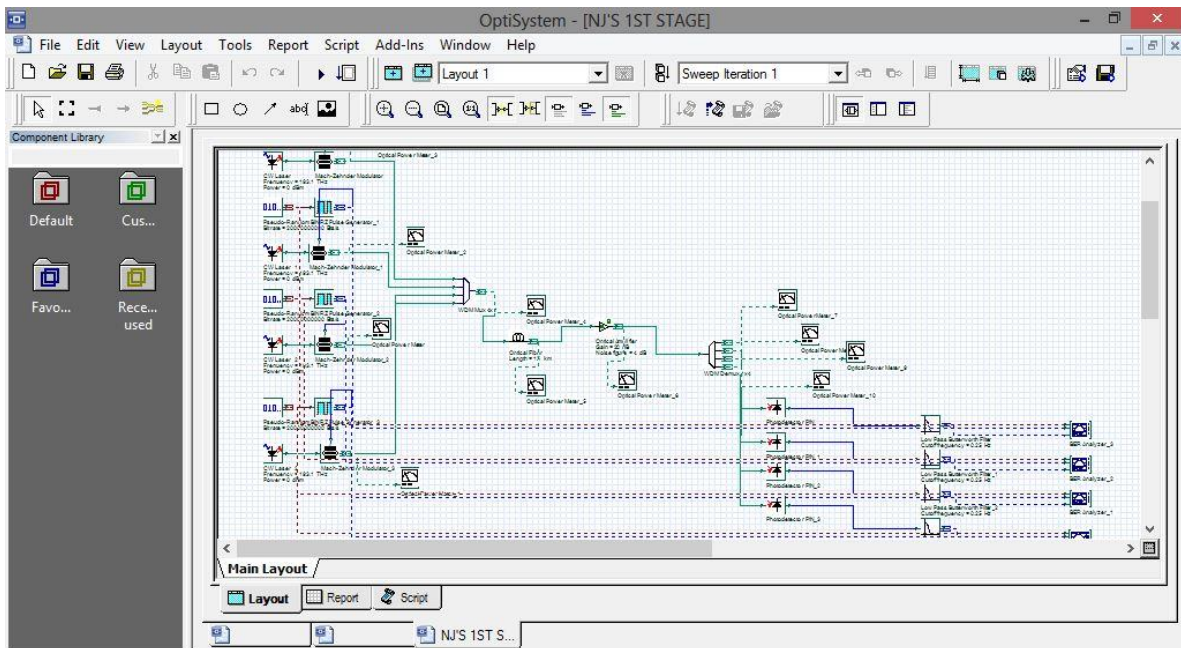


Figure 2: Ideal Four Channel WDM Network without Losses.

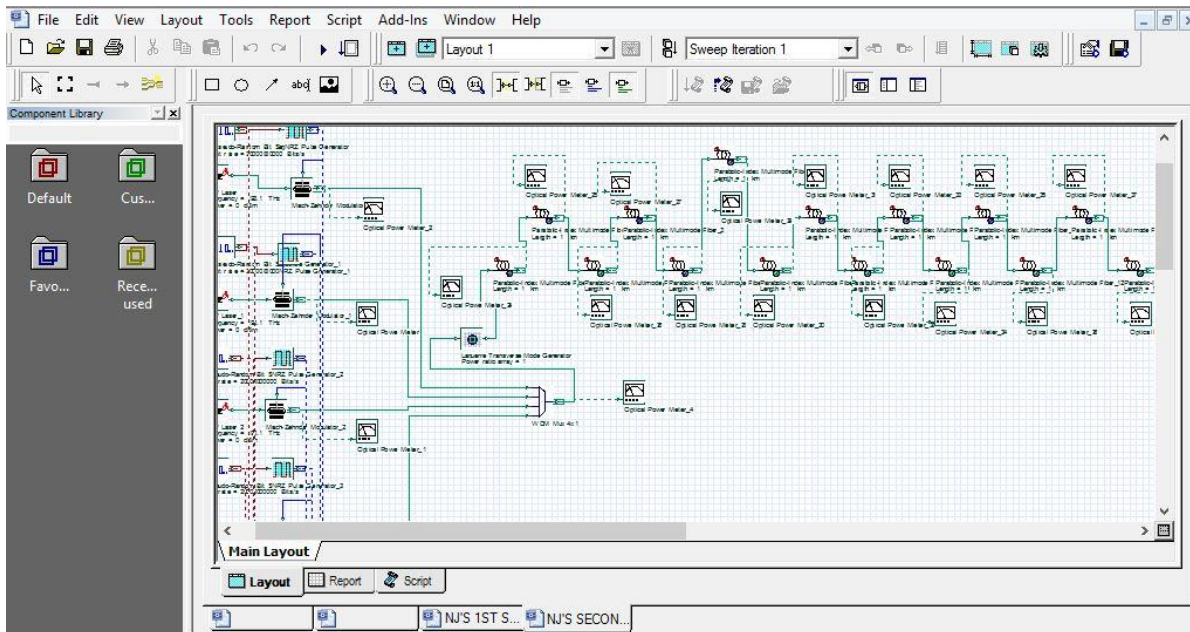


Figure 3: Four Channel WDM Network with Micro-bend Losses.

RESULTS AND DISCUSSIONS

This study makes efforts to maximize the throughput of fiber optic cable lines by employing an optical approach in mitigating the mechanical factors affecting throughput.

Results from power loss observations in 4 channel WDM system simulated as an ideal case will be compared with the results from the simulation (with losses), being the simulation stage where the micro-bending scenario is implemented in Optisystem simulation environment. The difference in loss values presented by the optical power meters in dB/Km equals the loss margin induced by reason of the micro-bending anomaly.

Table 1: Parameters used in the Simulation Tool.

S/N	Parameter	WDM Configured
1	Q Factor	20db
2	BER	1.63
3	Jitter	0.086(ns)
4	Optical output after fiber	10.84db

Where Optical Power after fiber transmission = 10.84db.

The Optisystem power meter results shown by the ideal 4 channel WDM optical fiber

telecommunications network simulated in this study is presented in Table 2. The results show that the losses occurring over the 15Km length of fiber is majorly due to attenuation increase as a function of fiber length since there are no fiber joining simulated throughout the entire 15Km of fiber length.

Table 2: First Simulated Result of the Ideal 4 Channel WDM Optical Network Simulation.

Cable length (Km)	Attenuation due to fiber length (dB/Km)	Power loss before fiber transmission	Power loss due to 15km fiber transmission	Total Power loss over 15Km
15Km	0.2db/Km	4.263db	3db	7.263db

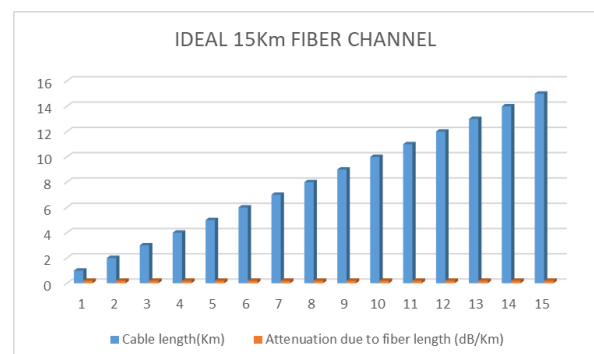


Figure 4: Ideal 4 Channel WDM Optical Network Simulation.

Table 2 presents Optisystem results for losses in the 4 channel WDM optical link designed to implement the scenario of micro-bend losses due to joining.

Tables 1 and 2 show similarities in the values for optical output after the fiber transmission as this study only considers power input and output before and after the fiber transmission section. Table 3 presents Optisystem results for losses in the 4 channel WDM optical link designed to implement the scenario of micro-bend losses due to joining.

From Table1, total micro-bend loss due to joining occurring across the 15Km length of fiber is 4.636/15Km of fiber length. This shows that the contribution to loss due to micro-bend over the 15Km of fiber length is 1.636db above the attenuation due to length of the fiber. This means that every 1km of fiber length along the joining nodes experiences micro-bends losses and offer at least 50percent of power loss that attenuation due to length of fiber offers.

Table 3: Tabulated Outcome for Micro-bending Loss due to Joining over a 15km Fiber.

Fiber length (km)	Micro-bend loss (M_L) (dB/km)	Attenuation due to fiber length (A_L) (dB/km)	Loss/Km due to fiber length and joining ($L_{f+j} = (M_L) + (A_L)$)
1 st	0.200	0.2	0.400
2 nd	0.468	0.2	0.668
3 rd	0.443	0.2	0.643
4 th	0.310	0.2	0.510
5 th	0.135	0.2	0.335
6 th	0.202	0.2	0.402
7 th	0.130	0.2	0.330
8 th	0.265	0.2	0.465
9 th	0.472	0.2	0.672
10 th	0.338	0.2	0.538
11 th	0.200	0.2	0.400
12 th	0.253	0.2	0.453
13 th	0.284	0.2	0.484
14 th	0.646	0.2	0.846
15 th	1.381	0.2	1.581
Total fiber length= 15km	Total loss over 15km due to joining = 5.727dB/15km	Attenuation due to 15km fiber length= 3dB/15km	Total Loss due to fiber length and joining = 8.727dB/15km

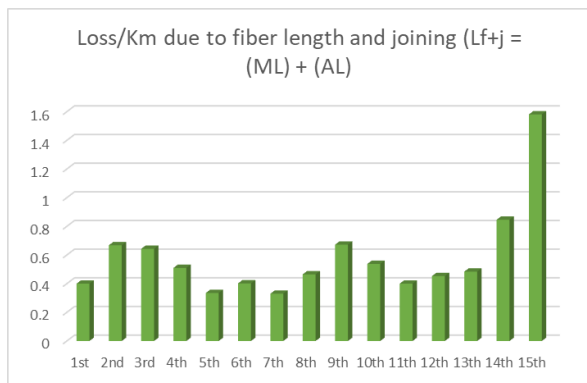
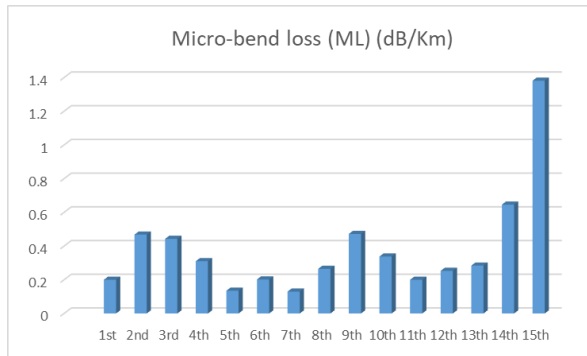


Figure 5: Micro-bending Loss and Micro-bending Loss due to Joining.

From Table 2, if we add the loss before fiber transmission (which is constant for all 4 channel WDM simulated stages presented in the study) given as 4.263db to the loss due to 15km fiber transmission given as 8.727dB, we have a total loss of 12.99db.

Also, from Table 3, total micro-bend loss due to joining occurring across the 15km length of fiber is 5.727/15km of fiber length. This shows that the contribution to loss due to micro-bend over the 15km of fiber length is 5.727dB above the attenuation due to length of the fiber. As is observed from Table 2, the smallest node existing along the 15km length with joining offers at least 0.2db loss, which is the constant value for attenuation due to loss as is found in our study.

On comparing Tables 1 and 2, the total losses presented in Table 3 is given as 12.99db, while the total losses from ideal case simulation as presented in Table1 is given as 7.263db/15km. Thus, the joining existing along the 15km length has offered an additional micro-bend loss of 5.727db. This means that the presence of micro-bend nearly doubles the losses in the ideal case 4

channels WDM simulation. A good way to implement the varying standard deviation of Gaussian nodes in Optisystem is to express σ as function of insertion loss. If σ is expressed in the light of the insertion loss at the node, then we can successfully imply varying standard deviation values from the Optisystem simulation. From table 2, the standard deviation is thus obtained by the simple equation

$$\sigma = 10 \log_{10} P_o / P_e$$

P_o = Optical power emerging from 1km progressive length of fiber.

P_e = Optical power entering 1km length of fiber.

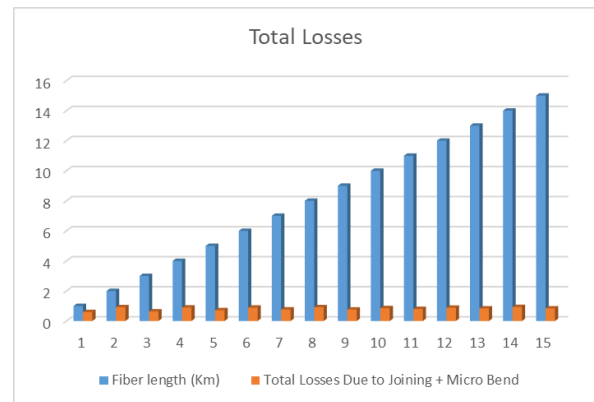


Figure 6: Chart for Showing Micro-bending Loss due to Joining.

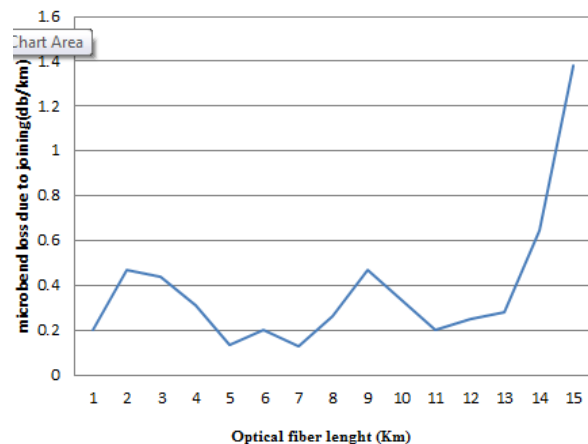


Figure 7: Micro-bending Loss due to Joining.

Figure 8 illustrates a non-uniform progression for the micro-bending loss due to joining along the fiber. This is due to non-uniform joining modes of fiber

core along the fiber length as described in the Optisystem simulation.

These slight differences in core size offer a hike in the micro-bend loss for every new or succeeding fiber length. Thus, from figure 8, a higher micro-bend loss is observed for points where the difference in core size (due to miss-match) is higher. This difference in core size models the progressive value for our peak amplitude values and Gaussian standard deviation values.

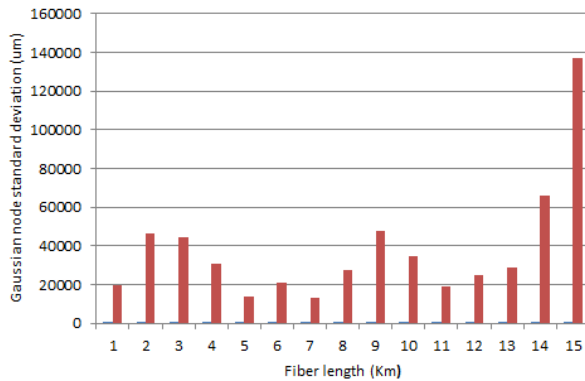


Figure 8: Illustration of Magnitude of Gaussian Nodes over 15km of Fiber Length.

There is huge similarity between the graphical illustrations presented in Figures 8 and Figure 9 as shown above. This is largely expected because the behavior (rise and fall) of micro-bend losses induced will be exactly replicated by the Gaussian nodes or micro-inflammations happening throughout the fiber line. Thus, for every point on the fiber line where there is a node of high standard deviation value as well as peak amplitude, the loss contribution for that point is expected to be higher. This is clearly portrayed in the agreement between Figure 8 and Figure 9.

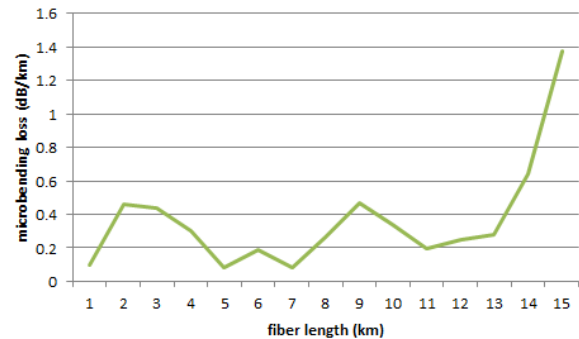


Figure 9: Graphical Illustration of Reduced Micro-bend Losses over 15km of Fiber Length.

Table 4: Tabulated Outcome for Reduced Micro-bending Loss due to Joining over 15km of Fiber Length (Table of Maximized Throughput of the Communication Channel).

Fiber length (Km)	Reduced Micro-bend loss (dB/km)	Micro-bend loss from 4 channelWDM (dB/Km)	Constant Attenuation due to fiber length (dB/Km)	Loss margin (dB/km)	Petermann experimentally observed quantity A(μm)	$\sigma(\mu m)$	$B = \frac{knw^2}{\sqrt{2}} \mu m$ Ref wavelength =1550nm.	Spot size or beam radius.w(μm)	Fiber Refractive index n
1	0.094	0.200	0.2	0.105262	1050	20074	18.56	4.87	1.4451
2	0.463	0.468	0.2	0.004059	1050	46729	18.05	4.87	1.4051
3	0.439	0.443	0.2	0.003053	1050	44470	17.54	4.87	1.3651
4	0.303	0.310	0.2	0.006672	1050	30834	17.02	4.87	1.3251
5	0.080	0.135	0.2	0.054348	1050	14086	16.51	4.87	1.2851
6	0.189	0.202	0.2	0.012962	1050	21112	15.99	4.87	1.2451
7	0.085	0.130	0.2	0.044932	1050	13111	15.48	4.87	1.2051
8	0.260	0.265	0.2	0.004149	1050	27404	14.97	4.87	1.1651
9	0.470	0.472	0.2	0.000672	1050	47845	14.45	4.87	1.1251
10	0.336	0.338	0.2	0.001562	1050	34471	13.94	4.87	1.0851
11	0.192	0.200	0.2	0.007793	1050	19305	13.42	4.87	1.0451
12	0.249	0.253	0.2	0.003192	1050	24933	12.98	4.87	1.0051
13	0.282	0.284	0.2	0.00183	1050	28843	12.40	4.87	0.9651
14	0.640	0.646	0.2	0.000136	1050	65785	11.88	4.87	0.9251
15	1.372	1.381	0.2	1.34E-05	1050	1372890	11.37	4.87	0.8851

The improved Petermann equation is used to obtain the loss margin, i.e. by how many decibels per kilometer the simulated loss will reduce. This approach is useful because it helps us to estimate the level of loss reduction that the selected progressive marginal change in fiber refractive index will offer. This loss margin when obtained from the improved (maximized) Petermann equation is subtracted from the simulated micro-bending loss to obtain the actual reduced micro-bend loss with specific reference to the simulated scenario.

From Table 4, experimentally derived values such as for **A** (μm), spot size (**w**) are obtained from the Petermann experiment for micro-bend tests. The Gaussian standard deviation parameter (σ) estimates the entire Gaussian node (the Gaussian width and the Gaussian peak amplitude).

Figure 10 illustrates the graphical result for the reduction of losses due to micro-bending from the Optisystem simulation.

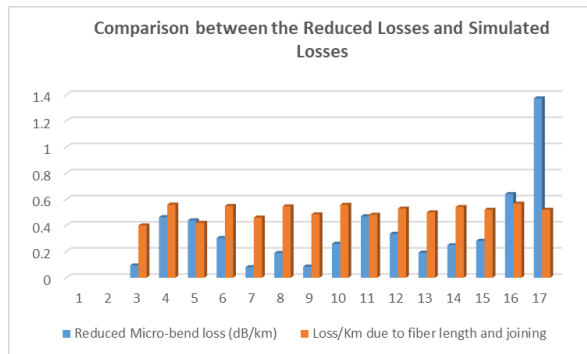


Figure 10: Graphical Comparison of Reduced Losses and Simulated Losses.

Figure 10 displays the actual micro-bending loss reduction by presenting a graphical outcome of the calculation done using the improved Petermann model to estimate the loss reduction margin that the progressive decremented change in refractive index will offer and further subtracting the loss reduction margin from the simulated losses.

Figures 11 and 12 show comparison between both results. In the end, there is successful reduction of the losses due to micro-bends as shown in Table 4.

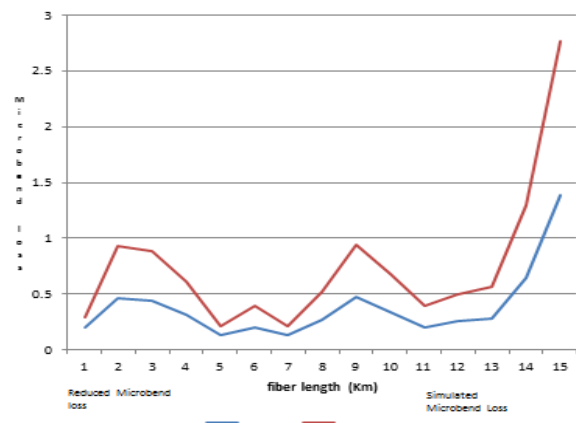


Figure 11: Graphical Comparison of Reduced Losses and Simulated Losses.

RESEARCH FINDING

The approach employed in reducing the micro-bend losses is associated with marginal trading on the refractive index of the optical fibers and the increasing speed effect of the optical signal as a result of this reduced index fibers.

This marginal trading concept permits (to an extent) a small change in refractive index so as to obtain a higher effect on the speed of the travelling optical signal in every new fiber length it enters through the core.

The approach adopted in this study which revolved around employing optical means to reduce or compensate for a mechanically induced anomaly such as micro-bend in optical fibers was only able to offer about 10 percent reduction of the micro-bending loss induced by reason of joining of the fiber cables.

The trade-offs parameters could not go beyond a loss margin of 10 percent. An attempt towards the reduction of fiber refractive index to further reduce the losses, by increasing the loss margin (offer Above 10 percent) between the scenarios considered will begin to induce a new challenge where the refractive index of the fiber clad begins to be higher than the core. This will in-turn bring about a huge power loss in the fiber.

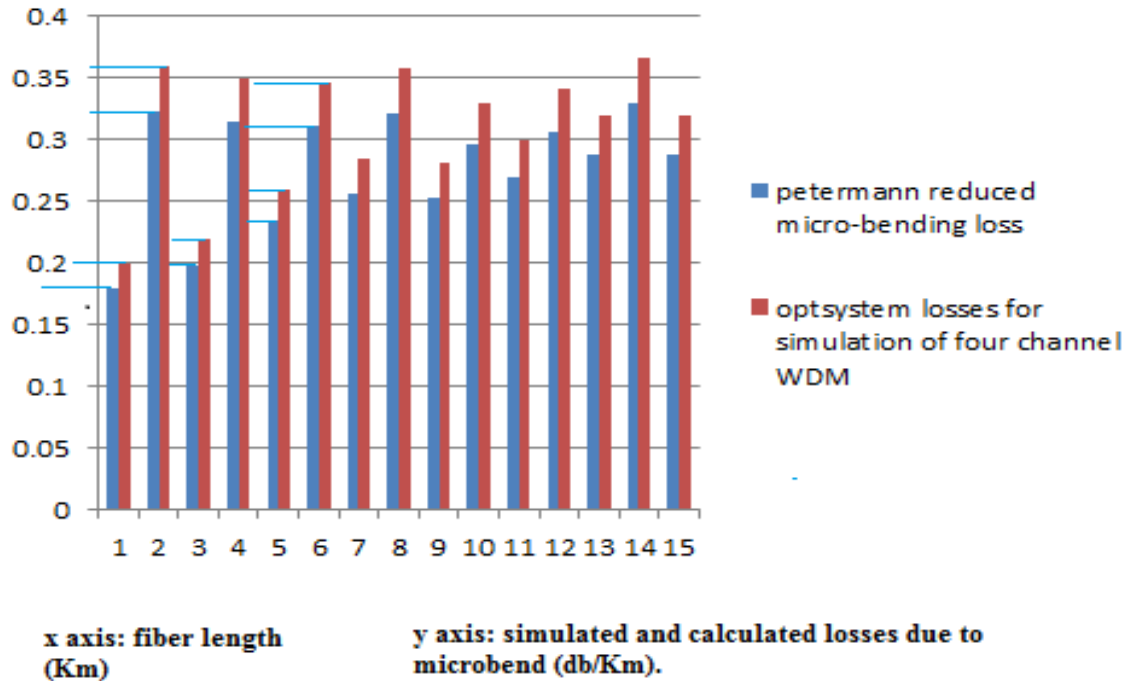


Figure 12: Graphical Illustration of Extent of Micro-bending Loss Reduction.

CONCLUSION

An optical approach towards throughput maximization in fiber cables by reduction of micro-bend losses has been presented in this work. Amongst several scenarios that foster the existence of micro-bends and give rise to optical power losses, the approach presented in this work has considered the most prominent scenarios for the existence of micro-bends in fiber optics which is in the joining of fiber cables.

The study employed the use of the Gaussian model of normal distribution to represent the scenario of the existence of micro-inflammation in the fiber optic cable lines termed as micro-bends. This approach is an improvement of the micro-bending loss estimation model presented by Petermann. The Petermann loss reduction model has been successfully improved to create a more accurate estimation of micro-bend losses based on a more realistic, less complex and practical approach. These improvements were done on the Petermann model with intentions to estimate the amplitude and width of Gaussian nodes as a function of the standard deviation of the Gaussian curve in other for a correct implementation in Optisystem simulation environment to be done.

A four channel WDM optical network was used as a premise for the work done in this study. The simulation done in the study was designed in two stages for effective implementation of the scenarios defined in the work scope. The first simulation stage is a four channel WDM network designed without any power losses due to either micro-bend losses from joining or external lateral pressures. The first stage simulation outputs will result for an ideal four channel WDM optical telecommunication network and will be used in this study as a reference for comparison of results in the subsequent simulation (i.e. the second stage). The second stage simulation in the study depicted the implementation of the event of micro-bending losses due to joining of fiber optic cable lines.

Finally, after the simulations, results were tabulated as shown in chapter four (table 4.3) to emphatically ascertain the exact value of the marginal refractive index that will ensure the effective maximization of the fiber optic communication link throughput [i.e. that will ensure that the optical signal travels through the fiber core (acceptance cone) without being refracted by the clad].

REFERENCES

1. Abdul, SK. and R.M. Sarwar. 2012. "An Efficient Wavelength Variation Approach for Bend Sensing in Single Mode & Multimode Mode Optical Fiber Sensors". *International Journal of Advanced Computer Research*.153.
2. Desurvire, E. 2008. "Design Optimization for Efficient Erbium-Doped Fiber Amplifiers". *Proceedings of World Academy of Science, Engineering and Technology*. V36.
3. Essiambre, R.J. 2012. "Capacity Trends and Limits of Optical Communication Networks". *Proc IEEE*. 100:1035–1055.
4. Jin, X., et al. 2015. "All-Optical Mode-Group Multiplexed Transmission over a Graded-Index Ring-Core Fiber with Single Radial Mode". Electrical Division, Department of Engineering, University of Cambridge: Cambridge, UK.
5. Petermann, K. 1976. "Theory of Microbending Loss in Fiber Communication Cable with Arbitrary Refractive Index Profile". *Arch. Electron Ubertr.* 30: 337.
6. Smink W. and G. Tjhuis. 2005. "Bending Loss in Optical Fibers—A Full-Wave Approach". *J. Opt. Soc. Am. B*. 24: 2610-2618.
7. Vartanian, A.H. 1990. "Theory of Microbending Loss in Curved Graded-Index Fiber Optic Communication Channel". Department of Electrical Engineering, McGill University: Montreal, Canada. Pg. 121-128.

SUGGESTED CITATION

Asianuba, I. and C. Nwabueze. 2020. "Reduction of Micro-Bending Losses in Fiber Optic Communication System". *Pacific Journal of Science and Technology*. 21(1):138-149.

