ENHANCING SIGNAL QUALITY IN RADIO OVER FIBER LINKS HAVING THE LENGTH OF (100-200) KM

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Abstract - In this paper, we build 3 calculating models of radio over fiber links having length of (100km - 200km) corresponding to the three positions of optical amplifier (EDFA) located on the link: at the end of link (PA), at the beginning of link (BA) and in the middle of link (LA). We then examine dominant noises that influence on signal quality, determine signal power, calculate signal-to-noise ratio (*SNR*) and Bit Error Rate (*BER*) at the receiver in each calculating model. Next, we compare and evaluate *BER* based on investigating the main parameters such as EDFA's gain, optical signal power launched to the fiber and transmission length. After that, an algorithm chart is built to calculate and determine the value of EDFA's gain, EDFA's position on the link so that the *BER* at the receiver will still lie in the given range of values ($10^{-14} \leq BER \leq 10^{-12}$) corresponding to different transmission lengths. These results can be used as the reference documents in designing, operating and exploiting RoF links.

Key words - Radio over Fiber; *SNR*; *BER*; Boost Amplifier; Line Amplifier; Pre Amplifier; ASE noise.

1. Introduction

Optical fiber communication systems (OFCS) have been grown rapidly thanks to their large bandwidth and small loss of transmission medium. Therefore, integrating radio communications in optical fibers is a leading solution in order to improve capacity and transmission distance. Radio over Fiber Technique (RoF) is considered to be not only the platform for wireless broadband access networks in the future but also the solution of combining wireless and wire communications to exploit advantages of both systems. There are variety of mobile networks and very large capacity, very high quality of fiber optic system. RoF application in intensity modulation-direct detection (IM-DD) fiber optic communication systems gets high economic efficiency thanks to simplicity in modulation-demodulation method. In addition, the coherent receiver will be used in this system to enhance its sensitivity. When transmission length is required larger than that of Coherent fiber optical link, EDF amplifier can be installed to compensate power loss in transmission link. It ensures that BER is smaller or equal to given BER. Depending on the location of EDFA on the link, three kinds of configurations are named as follows, when EDFA is located at the end of link (at receiver) we have PA (Pre Amplifier) configuration; when EDFA is at the beginning of link (at transmitter) we call BA (Boost Amplifier) configuration and when EDFA is in the middle of link we have LA (Line Amplifier) configuration. Each configuration has its own advantages and disadvantages and certain applications. Besides that, EDFA's gain as well as its different position on the link also impact on signal quality. The reason is both signal power and noise power change versus two these parameters and transmission link, this can be observed through the changing of SNR and BER. Thus, the problem is that with a given transmission length we need to determine essential parameters to achieve BER lying in a given range. The rest of paper is organized as follows. In section 2 and 3, we propose calculating models, then, show calculation of equation signal power, dominant different noises, SNR at receiver in PA, BA, LA configurations. In section 4, comparing and evaluating BER in these configurations are carried out. Section 5, we build algorithm chart to determine essential parameters such as EDFA Gain, position of EDFA on the link for keeping BER value lying in given range (10-14≤BER≤10-12) corresponding to different lengths. In this section, we simulate and draw graphs of the present system performance and discuss it by using MatLab-based program Section 6 will be the conclusion.

2. Building calculating models

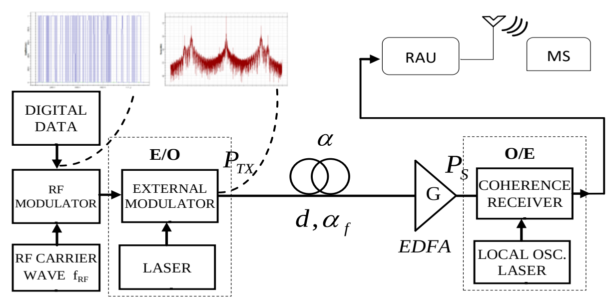

Figure 1. *Calculating model with EDFA at receiver (PA)*

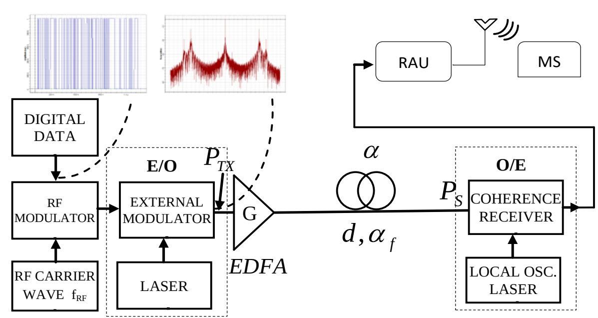

Figure 2. *Calculating model of link having EDFA at transmitter (BA)*

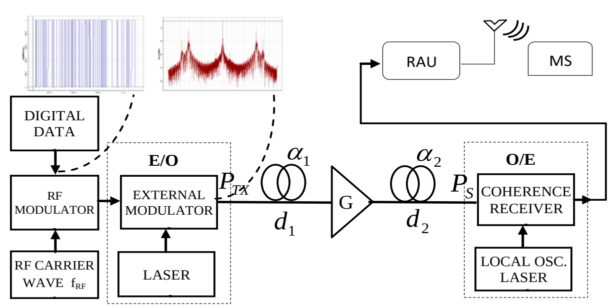

Figure 3. *Calculating model of link having EDFA in the middle (LA)*

3. Building calculating equations

Figure 1, 2 and 3 show calculating models of Radio over

Fiber (RoF) links, which have transmission length of (100-200)km, using EDFA and Coherence receiver corresponding to 3 cases of different EDFA's position. In Figure 1, EDFA is located at the end of link (PA), in Figure 2, it is at the beginning of link (BA) and in Figure 3, EDFA is in the middle of link (LA). In all 3 configurations, at the transmitter part, RF signal is ASK modulated by digital data then this RF signal modulates optial signal through external modulator. In the coherent receiver ASK demodulation method is used.

Firstly, we investigate and build calculating expressions of electrical signal, noise powers and signal-to-noise power ratio *SNR* at the output of the photodiode in PA configuration (Figure 1).

Electrical signal power at output of photodiode in ASK method is given as [1], [2]:

$$P_{signal} = \frac{1}{4} R_L I_P^2 = \frac{1}{4} R_L (2R\sqrt{P_S P_{LO}})^2 = R_L (\frac{\eta e}{h\nu})^2 P_S P_{LO} \quad (1)$$

Where $P_S = \alpha G P_{TX}$ is incident optical power at receiver; P_{TX} is optical power launched to fiber (at transmitter); P_{LO} is local oscillator optical power; G is EDFA's gain; $R_L[\Omega]$ is load resistor; R[A/W] is responsivity-optical-electrical conversion coefficient of photodiode. α is total loss in the link showed in Figure 1 and Figure 2.

$$\alpha = \alpha_f d + \alpha_{cn} n + \alpha_{sol} k \quad (2)$$

Where α_f, α_{cn}, α_f are 1-fiber km loss (loss of the silica-doped material), connector-unit loss and soldering-unit loss respectively; n is number of connectors; k number of solderings in the link. Total noise power at output of photodiode can be showed as follows [1], [2]:

$$\begin{aligned}\sigma_\Sigma^2 R_L &= (\sigma_{SH}^2 + \sigma_{S-ASE}^2 + \sigma_{LO-ASE}^2 + \sigma_{ASE-ASE}^2 + \sigma_{TH}^2) R_L \\ &= 2\frac{\eta e^2}{h\nu} B_e (P_{LO} + \alpha G P_{TX} + h\nu m_t n_{sp} (G-1) B_o R_L + \\ &+ 4\frac{(\eta e)^2}{h\nu} \alpha P_S n_{sp} G(G-1) B_e R_L + \\ &+ 4\frac{(\eta e)^2}{h\nu} P_{LO} n_{sp} (G-1) B_e R_L + \\ &+ 2(\eta e)^2 m_t n_{sp}^2 (G-1)^2 B_e R_L + 4KTB_e\end{aligned} \quad (3)$$

Where B_e is electrical bandwidth of receiver; B_o is optical filter bandwidth to reduce ASE of EDFA; T is absolute temperature, K is Boltzmann constant, $h\nu$ is photon energy; n_{sp} is spontaneous emission factor of EDFA; m_t is number orthogonal polarization modes. η is quantum efficiency; e electron charge.

Equations (1) and (3) lead to electrical *SNR* at output of photodiode as follows

$$SNR_{PA} = \frac{P_{signal}}{\sigma_\Sigma^2 R_L} = \frac{R_L (\frac{\eta e}{h\nu})^2 \alpha G P_{TX} P_{LO}}{\sigma_\Sigma^2 R_L} \quad (4)$$

Therefore, Signal-to-Noise power ratio (*SNR*) at the output of the photodiode in PA is given as in eq.(5).

$$SNR_{PA} = \frac{\left(\frac{\eta e}{h\nu}\right)^2 \alpha P_{TX} P_{LO} G}{\{2\frac{\eta e^2}{h\nu} B_e (P_{LO} + \alpha G P_{TX} + h\nu m_t n_{sp} (G-1) B_o) + 4\frac{(\eta e)^2}{h\nu} P_{LO} n_{sp} (G-1) B_e + 4\frac{(\eta e)^2}{h\nu} \alpha P_{TX} n_{sp} G(G-1) B_e + 2(\eta e)^2 m_t n_{sp}^2 (G-1)^2 B_e B_o + \frac{4KTB_e}{R_L}\}}$$

Similarly, SNR at the output of the photodiode in BA and LA configurations can be showed as in eq.(6); eq.(7) respectively

$$SNR_{BA} = \frac{\left(\frac{\eta e}{h\nu}\right)^2 \alpha P_{TX} P_{LO} G}{\{2\frac{\eta e^2}{h\nu} B_e (P_{LO} + \alpha G P_{TX} + h\nu m_t n_{sp} \alpha (G-1) B_o) + 4\frac{(\eta e)^2}{h\nu} \alpha P_{LO} n_{sp} (G-1) B_e + 4\frac{(\eta e)^2}{h\nu} \alpha^2 P_{TX} n_{sp} G(G-1) B_e + 2(\eta e)^2 m_t n_{sp}^2 \alpha^2 (G-1)^2 B_e B_o + \frac{4KTB_e}{R_L}\}}$$

$$SNR_{LA} = \frac{\left(\frac{\eta e}{h\nu}\right)^2 \alpha P_{TX} P_{LO} G}{\{2\frac{\eta e^2}{h\nu} B_e (P_{LO} + \alpha G P_{TX} + h\nu m_t n_{sp} \alpha_2 (G-1) B_o) + 4\frac{(\eta e)^2}{h\nu} \alpha_2 P_{LO} n_{sp} (G-1) B_e + 4\frac{(\eta e)^2}{h\nu} \alpha \alpha_2 P_{TX} n_{sp} G(G-1) B_e + 2(\eta e)^2 m_t n_{sp}^2 \alpha_2^2 (G-1)^2 B_e B_o + \frac{4KTB_e}{R_L}\}}$$

In this eq.(6), α_2 is total loss calculated from EDFA to receiver corresponding to span length d_2 showed as in Figure 3.

The bit error rate (*BER*) is related to *SNR* in ASK method is given as [1],

$$BER = 0{,}5\{1 - erf\lfloor 0{,}3535(SNR)^{1/2} \rfloor\} \quad (8)$$

In addition, based on reference [4], loss of the silica -doped material (mentioned in eq. 2) can be written as

$$\alpha_f = \alpha_I + \alpha_S + \alpha_{UV} + \alpha_{IR} \text{ [dB/km]} \quad (9)$$

Where $\alpha_I \approx 0.003$ [dB/km] is the intrinsic loss which is the part of loss fiber, $\alpha_S \approx \left(\frac{0.75 + 66\Delta}{\lambda^4}\right)\left(\frac{T}{T_0}\right)$ where T is ambient temperature, and T_0 is a room temperature, Δ and λ are the relative refractive index difference, optical wavelength respectively. The absorption losses α_{UV} and α_{IR} are given as

$$\alpha_{UV} = 1.1.10^{-4} \omega_{ge}.e^{4.9\lambda} \text{[dB/km]} \quad (10.a)$$

$$\alpha_{IR} = \left(7.10^{-5}.e^{-24/\lambda}\right)^2 \text{[dB/km]} \quad (10.b)$$

Where ω_{ge} is the weight percentage of Ge and is showed as

$$\omega_{ge} = 213.27x - 594x^2 + 2400x^3 - 4695x^4 \quad (10.c)$$

Where x is the mole fraction.

In order to reduce dispersion that influences on signal in the link dispersion compensation using fiber (DCF) is used as expression: $D_1L_1+D_2L_2=0$, where L_1 and L_2 are SMF span length (with dispersion D_1) and DCF span length (with dispersion D_2) ($L_1+L_2=d$). In general cases, L_1 is chosen much larger than L_2; here we choose $L_1=10L_2$; Then $D_2=-10D_1=-10\times18$ps/(km.nm)=-180ps/(km.nm).

4. Comparing and evaluating BER in 3 configurations

Table 1 indicates the values of main parameters of investigated link using EDFA in 3 configurations PA, BA and LA. They are selected based on [1], [2], [4] and recommendation data.

Parameter	***Definition***	***Value and unit***
P_{LO}	Optical Oscillator power	-5dBm ≤P_{LO}≤ +5dBm
P_{TX}	Optical power launched to Fiber	-5dBm ≤P_{TX}≤ +5dBm
L	Fiber link length	100km ≤ L ≤ 200km
R_L	Load resistor of photodiode	50Ω
G	EDFA's Gain	10dB ≤ G ≤ 40dB
Rb	Bit rate	1 Gbit/s
α_f	1 km fiber loss	0.21dB/km
α_{sol}	soldering-unit loss	0.1 dB/unit
α_{cn}	connector-unit loss	0.5 dB/unit
BER	Bit Error Rate	(10^{-14}≤ BER ≤ 10^{-12})
T_o	Reference temperature	300K
T	Absolute temperature	300K ≤ T ≤ 340K
x	Mole fraction of gernanium	0.1 ≤ x ≤ 0.3

In this paper, EDFA investigated links have transmission length of (100km-200km). As mentioned in section 2, the effectiveness of 3 configurations that is showed by *SNR* and *BER* achieved at the receiver depends on many factors, such as transmission length, maximum optical power launched to the fiber (Pinfiber), EDFA's gain and noise characteristic of EDFA. Therefore, in order to have an objective evaluation, the configurations PA, BA, LA should be chosen in optimal conditions of their own before being compared. Several of these conditions are shown as follows: in BA and LA configurations with Bit rate (Rb) is approximately to several Gb/s Pinfiber ≤ 20dBm [1] (after it is amplified by EDFA) to reduce optical-fiber nonlinear phenomena that can degrade system characteristics and badly influence on signal quality. Initially, we select optical power at transmitter P_{TX} =0dBm, G = 20 dB for three configurations in order that the receiver in PA operates in beat noise conditions and avoid nonlinear phenomena in BA and LA, then we will change the value of P_{TX}, G in 3 configurations to investigate system characteristics corresponding different lengths.

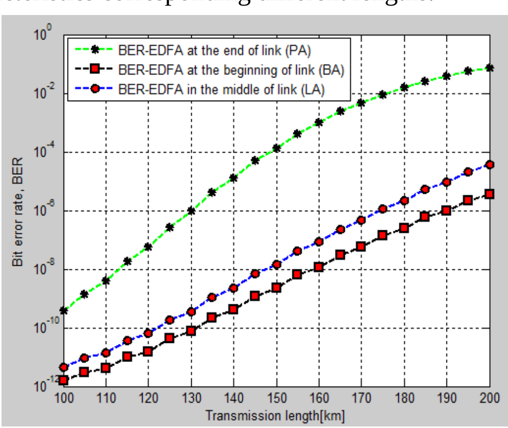

Figure 4. *BER vs. transmission length in 3 configurations with G=20dB; P_{LO}=10dBm; P_{TX}=0dBm*

Figure 4. shows relation between *BER* and transmission length with G=20dB; P_{LO}=10dBm; P_{TX}=0dBm for all 3 configurations in which EDFA is located in the center of the link ($\alpha_1=\alpha_2=\alpha/2$). We can see that if parameters G, P_{TX}, P_{LO} are constant, when transmission length increases, three *BER* characteristics become worse (*BER* increases). It can be explained as follows, from equations (5), (6), (7) when transmission length (d) increases losses (α) increase. This leads to *SNR* reduction and *BER* increase. We also can see that in case of parameters G, P_{LO}, P_{TX} are selected, the same in three configurations, signal powers at receiver are equally but noise powers in BA (eq.6), and in LA (eq.7) are smaller than that in PA (eq.5). It shows that in *BER* of PA is the worst, *BER* in LA is better and *BER* in BA is the best. That is because, in BA, EDFA is located at transmitter, in LA EDFA is in the middle of link. Therefore, ASE noise from EDFA output that impact at receiver is degraded by factor α and α_2 in BA and LA respectively ($\alpha \geq \alpha_2$).

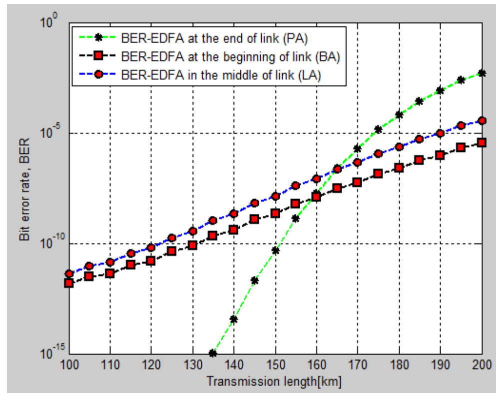

Figure 5. *BER vs. transmission length in 3 configurations with G=20dB; P_{LO}=10dBm; P_{TX} =0dBm for BA, LA and P_{TX} =5dBm for PA*

In order to enhance *BER* in PA configuration, we can increase P_{TX} as much as possible provided that it still keeps power launched to fiber not over threshold (≤20dBm) to avoid fiber nonlinear phenomena. This can be done because EDFA is located at receiver. Figure 5 presents *BER* graph versus transmission length in 3 configurations corresponding to P_{TX} =0dBm for BA, LA and PTX=5dBm for PA. Thanks to higher P_{TX}, *BER* in PA is better than two others in the length range of (100-160)km. Figure 6. shows relation between *BER* and transmission length with G=20dB; P_{LO}=10dBm; P_{TX} =0dBm for BA; P_{TX} =2dBm for LA; and P_{TX} =3dBm for PA. In that case, *BER* in LA is the best because P_{TX} is chosen higher than that in BA, at the same time ASE noise from EDFA output that causes at receiver is reduced by factor α_2 compared with that in PA.

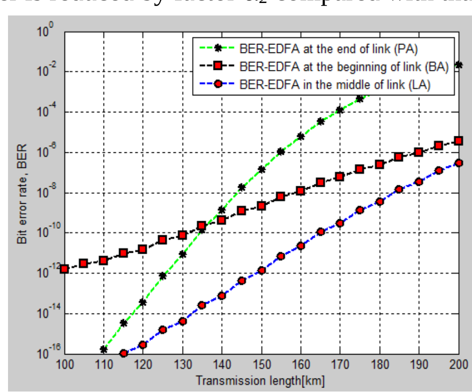

Figure 6. *BER vs. transmission length in 3 configurations with G=20dB; P_{TX}=0dBm for BA; P_{TX} =2dBm for LA; and P_{TX} =3dBm for PA;*

Through these investigations, we recognize that without optimizing parameters such as P_{TX}, EDFA's gain, EDFA's position in LA configuration..., we can not keep

BER value lying in allowed range when increasing transmission length because, beside the loss in the link, it is also influenced by many parameter values of EDFA as well as signal power at transmitter, total noise powers…

5. Building algorithm chart

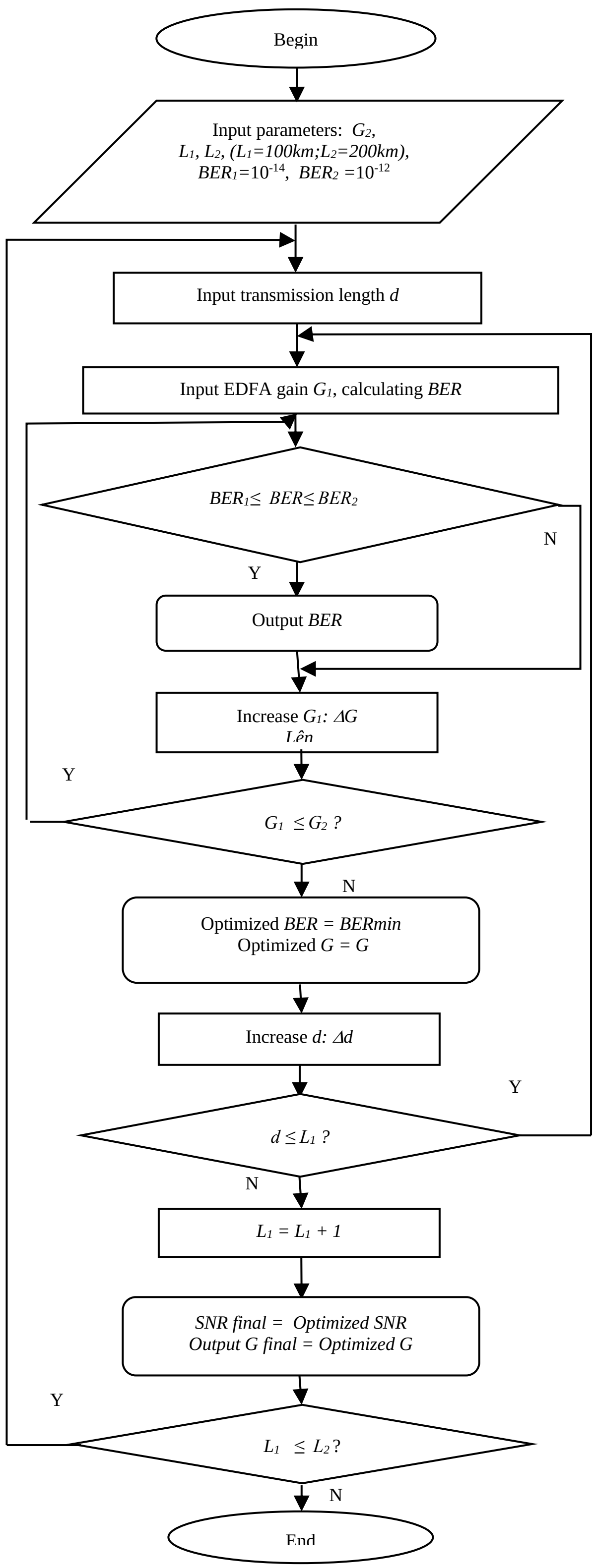

Figure 7. *Algorithm flow chart for optimizing parameters*

As mentioned in section 2, we arrange EDFA in the link to compensate fiber losses (especially in long haul link). However, from equations (5), (6) and (7) the position of EDFA in three configurations and its gain influence remarkably on *SNR* and *BER*, it means signal quality. The problem is that with a given transmission length in the range of (100km<*d*<200km), we need to determine EDFA's gain, EDFA's position on the link so that the *BER* at the receiver lying in the given range of values ($10^{-14} \leq BER \leq 10^{-12}$). In order to do that, we build an algorithm chart as in Figure 6. It can be explained in general as follows.

Step 1: Input parameters chosen from realistic values of link.

Step 2: Running nested loop corresponding to parameters *d* to determine set of distance values *d* [km] and EDFA gain values to get minimum of *BER* whose values lie between BER_1 and BER_2. Here, *optimized BER* of given transmission length is *BER min* and *optimized G* is *G* [dB].

Step 3: In loop in step 2, running other loop corresponding to parameters *G* to determine the set of EDFA's gain values to get minimum of *BER* corresponding to each value of *d* in step2. Both *SNR final* and *G final* are alternate maximum of *optimized SNR* and *optimized G*.

Step 4: Draw *SNR final*, *BER final*, and *G final* corresponding to different transmission lengths.

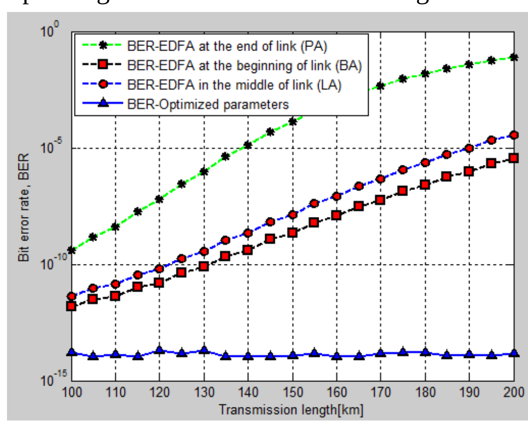

Figure 8. *BER vs. transmission length in 3 configurations and in LA configuration with optimized parameters to achieved* $10^{-14} \leq BER \leq 10^{-12}$

Figure 8, shows *BER* vs. transmission length in 3 configurations and especially in LA configuration with optimized parameters to achieved $10^{-14} \leq BER \leq 10^{-12}$. From this figure we can see that without optimizing parameters: EDFA's gain, EDFA's position 3 *BER* characteristics increase following transmission length and $BER \geq 10^{-12}$ (do not satisfy quality requirements of Fiber Optic Communication Systems). Thanks to applying algorithm flow chart for optimizing parameters, we keep the value of *BER* lying in allowed range $10^{-14} \leq BER \leq 10^{-12}$ although transmission length increases from 100 km to 200 km. It can be achieved because algorithm flow chart is combined synchronously in calculating EDFA's gain, EDFA's position, transmission length as well.

Figure 9, presents the relation between Optimized *SNR*, EDFA's Gain, EDFA's position and transmission length after optimizing parameters. We can see that when the length increases optimized *SNR* (*SNR max*) still lies in allowed range (corresponding to $10^{-14} \leq BER \leq 10^{-12}$. It can be explained as follows, thanks to algorithm chart, when length increases, we always find out appropriate parameters (EDFA's Gain, EDFA's position) to maintain *SNR* which is approximately to a constant value at the receiver.

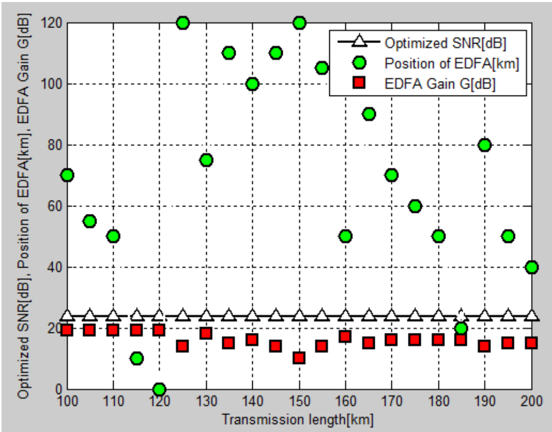

Figure 9. *Optimized SNR EDFA's Gain, EDFA's position vs. transmission length after optimizing parameters of the link*

Besides that, EDFA's gain, EDFA's position on the link corresponding to given transmission length to achieve Optimized *SNR* is also showed clearly in this figure. For example, from the result in Figure 9, with transmission length of 160 km, EDFA is located at position of 50 km (calculated from transmitter to EDFA) and EDFA's gain is about 19dB, then Optimized *SNR* achieves approximately 23dB. Similarly, with transmission length of 190 km, EDFA's position is 80 km (calculated from transmitter to EDFA) and EDFA's gain is about 16dB, corresponding to Optimized *SNR* of 22.8dB.

6. Conclusion

In this paper, we proposed calculating models of 3 configurations of RoF links (PA, BA and LA) using ASK method, EDFA on the link and Coherent receiver. After investigating and establishing *SNR* and *BER* equations related to many kinds of losses in the link, we built algorithm chart and found out essential parameters such as EDFA's Gain, EDFA's position to keep *BER* lying in allowed range ($10^{-14} \leq BER \leq 10^{-12}$) corresponding to transmission length increase from 100 km to 200 km. From graphs that show system performance such as *BER*, *SNR* versus transmission length we can see the effectiveness of optimization of essential parameters for enhancing signal quality in these links. These results can be used as the reference documents in designing, operating and exploiting RoF links.

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