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Soliton: Gateway to Future Optical Communication

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Abstract— Soliton in fiber optic is a good solution to achieve the benefits of optical fiber without many of its limitations like the use of more repeaters or amplifiers in case of long haul communication. This work considered three particular long haul systems (Three segments of SEA-ME-WE 4 sub marine cable Networks) and shown the difference between the signal response in case of fiber optics with Gaussian pulse and with Soliton pulse. The parameters considered for this purpose are- pulse broadening ratio, phase displacement, attenuation and number of amplifiers used. By simulation, both the pulses were transmitted through optical amplifiers and analyzed their performances to show that the performances with Soliton pulse are better than the performances with Gaussian pulse over the long haul fiber optics communication.

Index Terms—Soliton Pulse, Gaussian Pulse, Non Linear Schrödinger Equation (NLSE), Optical Amplifier, Repeater, EDFA, WDM, Pump Power, Pass Gain, Phase Displacement, Attenuation, Dispersion, Pulse Broadening Ratio.

I. INTRODUCTION

The emergence of Soliton pulse has come to being because of better performances in all the necessary aspects of performance when compared to Gaussian pulse. Hence, the motivation behind this work has been to illustrate that Soliton pulse in long haul communication outperforms Gaussian pulse in the same condition. It has been observed that in an optical communication system when Gaussian pulse is used for signal transmission through a non-linear channel, dispersion occurs with the transmitted signal. In order to avoid Inter-Signal Interference, Soliton pulse is used. Soliton is a kind of pulse for which dispersion is cancelled out by its self phase modulation, so it can maintain its shape for long distance transmission [1][5]. For a long haul communication system; after a certain distance, the Soliton pulse also gets attenuated even if it is not dispersed. So, implementation of the amplifiers is needed in the transmission channel to boost up the power level of the Soliton pulse [4]. Thus, the number of amplifiers used for a long haul communication is a good indication of which pulse produces better performance for the system. Here the usage of Soliton pulse is more effective in comparison to usage of Gaussian pulse as it ensures reduced number of amplifiers. Also, the signal here is transmitted through an all-optical environment. So, it uses optical amplifier, which is a better choice over optoelectronic amplifier because of its less processing time which will be discussed in the results section. Moreover Gaussian pulse and Soliton pulse's comparison for dispersion, pulse broadening ratio and phase shift are illustrated in the result analysis section. In this paper, split step Fourier method has been used to solve nonlinear Schrödinger equation because of greater computation speed and increased accuracy [10].

II. MATHEMATICAL MODEL

A. Theoretical Analysis:

The mathematical description of Soliton employs the nonlinear Schrödinger (NLS) equation which is satisfied by the pulse envelope $A(z, t)$ in the presence of GVD and SPM. This equation can be written as:

$$\frac{\partial A}{\partial z} + i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = i \gamma |A|^2 A - \frac{\alpha}{2} A \quad (1)$$

Where, α = fiber losses, β_2 and β_3 are the second- and third-order dispersion effects respectively. The nonlinear parameter,

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

Here the nonlinear-index coefficient n_2 , the optical wavelength λ , and the effective core area A_{eff} . To discuss the Soliton solutions of Equation (1) as simply as possible, consider $\alpha = 0$ and $\beta_3 = 0$. It is useful to write this equation in a normalized form by introducing

$$\tau = \frac{t}{T_0}, \xi = \frac{z}{L_D}, U = \frac{A}{\sqrt{P_0}}$$

The normalized form:

$$i \frac{\partial U}{\partial \xi} - \frac{s}{2} \frac{\partial^2 U}{\partial \tau^2} + i N^2 |U|^2 U = 0 \quad (2)$$

Where, T_0 = Pulse width

P_0 = Pulse width

$L_D = \frac{T_0^2}{|\beta_2|}$ Is the dispersion length

$S = +1$ when β_2 is positive (for normal GVD)

$S = -1$ when β_2 is negative (for anomalous GVD)

Pulse-like Solitons are found only in the case of anomalous dispersion. Order of Soliton pulse,

$$N^2 = \gamma P_0 L_D = \gamma P_0 \frac{T_0^2}{|\beta_2|} \quad (3)$$

Considering $s = -1$ (anomalous GVD) and introducing $u = NU$ as a renormalized amplitude and writing the NLS equation in its canonical form with no free parameter as

$$i \frac{\partial u}{\partial \xi} + \frac{1}{2} \frac{\partial^2 u}{\partial \tau^2} + |u|^2 u = 0 \quad (4)$$

The main result of the above equation can be summarized as follows. When an input pulse having an initial amplitude $u(0, \tau) = N \operatorname{sech}(\tau)$ is launched into the fiber, its shape

remains unchanged during propagation when $N = 1$. It is the property of fundamental Soliton which makes it an ideal candidate for optical communication. In essence, the effects of fiber dispersion are exactly compensated by fiber non-linearity when the input pulse has a 'sech' shape and its width, order and peak power are related by

$$N^2 = \gamma P_0 L_D = \gamma P_0 \frac{T_0^2}{|\beta_2|} [1,6,7,11].$$

B. Split Step Fourier Method:

The split step Fourier method is a pseudo-spectral numerical method. It is used to solve partial differential equations such as the nonlinear Schrödinger equation. For this method, the entire length of the fiber is divided into small step sizes of length, h , thus solving the nonlinear Schrödinger equation by splitting it into two halves. One half is the linear part, or also known as dispersive part and the other half is the nonlinear part ranging from z to $z+h$ [2, 10].

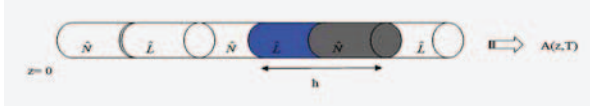


Figure 2.1. Split step Fourier method [7]

Initially each part is solved individually. All of these are then combined together to obtain the aggregate output of the traversed pulse. First using the Fast Fourier Transforms, It solves the linear dispersive part, in the Fourier domain. Then it uses Inverse Fourier transforms to the time domain. Here it is applied to solve the equation for the non linear term. Then all the parts are combined. This process is repeated over the entire span of the fiber to approximate non linear pulse propagation. Below are the equations with description. The value of 'h' is chosen for $\phi_{\max} = \gamma |A_p|^2 h$, where $\phi_{\max} = 0.05$ rad and $A_p =$ peak power of $A(z, t)$; $\phi_{\max} =$ maximum phase shift [2,5,8,10]. In the following part the solution of the generalized Schrödinger equation is described using this method.

$$\frac{\partial A}{\partial z} = \left(-\frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} - \frac{\alpha}{2} A \right) + i\gamma |A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - A T_R \frac{\partial}{\partial T} |A|^2$$

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N}) A$$

The linear part (dispersive part) and the nonlinear part are separated.

Linear part:

$$\hat{D} = -\frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} - \frac{\alpha}{2} A$$

Nonlinear part:

$$\hat{N} = i\gamma |A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R \frac{\partial}{\partial T} |A|^2$$

For the linear part $\exp(h\hat{D})$ the solution is done in the Fourier domain using the identity $\frac{\partial}{\partial T} = i\omega$. Here ω is simply a numerical sequence of digits in the Fourier domain. As a result the calculation that would otherwise be complicated in

the time domain due to computation of the differential terms is mitigated in the Fourier domain [2,5].

$$\text{Linear solution: } \exp(h\hat{D}) \xleftrightarrow{FT} \exp[h\hat{D}(i\omega)]$$

And

$$A(z, t) \xleftrightarrow{FT} A(z, \omega - \omega_0) \quad (5)$$

$$\text{Nonlinear part solution: } F^T [\exp(h\hat{D}(i\omega)) \times A(z, \omega - \omega_0)]$$

C. Simulation Layout:

In the mathematical model at first a Gaussian pulse has been generated based on mathematical equations,

$$u_1(0, \tau) = A_0 \exp(-(1+iC)(\tau^2)/2t_0^2) \quad (6)$$

which is generally being used now-a-days for optical communication. Then the dispersion of the signal has been checked with respect to distance travelled. Secondly, a Soliton pulse is produced using some mathematical equations and check its dispersion too.

$$u_2(0, \tau) = N \text{sech}(\tau/t_0) \quad (7)$$

Firstly some basic parameters are provided and the Gaussian and Soliton pulses are generated based on theoretical equations (For Gaussian $P_0 = 1$ mW, Peak amplitude $A_0 = \sqrt{P_0}$, Pulse Width $t_0 = 125$ ps, Chirping Factor $C = -0.5$, $\tau = dt/t_0$; For Soliton $P_0 = 0.64$ mW, Soliton Order $N = 1$, Pulse Width $t_0 = 125$ ps, $\tau = dt/t_0$). Secondly the pulse is travelled through a nonlinear channel; this channel has attenuation and nonlinearity parameters so the pulse is attenuated in both cases though the pulse is dispersed more in case of Gaussian rather than Soliton pulse (Attenuation $\alpha = 0.16$ dB/km, Nonlinearity Factor, $\gamma = 0.003$ /W/m, Propagation distance $h = 1000/L_D$, $L_D =$ Dispersion Length). Thirdly the pulse is amplified using EDFA optical amplifier. EDFA is not only the commonly used amplifier in optical communication but also inexpensive. Finally the results are analysed and compared based on four parameters which are: attenuation, pulse broadening ration, dispersion and phase shift.

III. LONG HAUL COMMUNICATION

In optical communication, according to the distance between the source and the destination, the communication channel can be classified into few types:

Short haul: When the distance is less than few kilometers.

Long haul: Communication channel's length must be in the range of few hundreds of kilometers.

Ultra-long haul: For an ultra-long haul channel, the length should be around thousand kilometres (approximately 3000 km). "SEA-ME-WE 4 (South East Asia-Middle East-West Europe 4)" is an optical fiber submarine communication cable which provides the internet backbone between South East Asia and West Europe via Middle East and Indian subcontinent. It's total length is approximately 20,000 km. It is divided into four segments which are illustrated in figure 3.1:



Figure 3.1. Geographical scenario of SEA-ME-WE 4 with segments [12]

We have considered three different parts of the SEA-ME-WE 4 system between the following landing points [12] for practical scenario analysis:

- Cox's bazaar to Tuas
- Cox's bazaar to Satun
- Cox's bazaar to Chennai

IV. RECEIVER SENSITIVITY

The sensitivity for a digital optical receiver can be defined as the minimum number of photons (or the corresponding optical energy) per bit necessary. This is done to make sure that the rate of error (BER) is smaller than a prescribed rate (e.g., 10^{-9}). Sometimes randomness of the number of photoelectrons detected during each bit, as well as the receiver circuit itself will lead to errors occurring. So, an average of at least 10 photons per bit is required. This ensures that BER is $\leq 10^{-9}$. This signifies that bit "1" should carry an average of at least 20 photons, since bit "0" carries no photons. When other form of noise is present, then there is requirement for a larger number of photons. Sensitivity of \bar{n}_0 photons means an optical energy $h\nu\bar{n}_0$ per bit and an optical power $P_r = (h\nu\bar{n}_0)/(1/B_0)$,

$$P_r = h\nu\bar{n}_0 B_0 \quad (5)$$

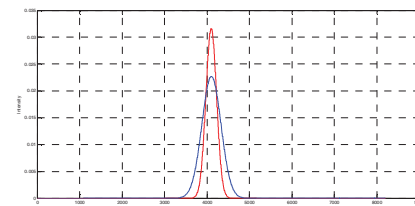
It is proportional to the bit rate B_0 . With the increase in bit rate, a higher optical power is required to maintain the number of photons/bit constant. In case of circuit noise being important, the receiver sensitivity depends on the receiver bandwidth B_0 . To avoid complexity the receiver sensitivity is assumed to be independent of B_0 in the following analysis [13].

V. OPTICAL AMPLIFICATION

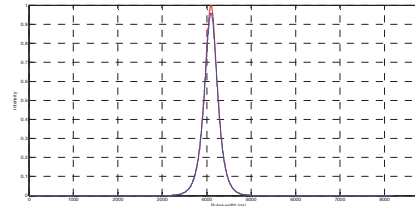
An optical amplifier normally signifies a device that is used to amplify the optical signal directly without ever changing it to electricity. The light itself is amplified. However, the move in optical systems from repeaters to amplifiers is a matter of great irony in the communication world. An optical communication system is mostly devoid of noise or signal interference [3]. There are several purposes an optical amplifier can serve in the design of fiber-optic communication systems. For long-haul systems the most important application mainly involves using amplifiers as in-line amplifiers. These can replace electronic regenerators. Cascading many optical amplifiers in the form of a periodic chain is also an option as long as the cumulative effects of fiber dispersion, fiber nonlinearity, and amplifier noise do not limit the system performance. Especially for WDM light wave systems, the use of optical amplifiers are attractive because all channels can be amplified simultaneously.

VI. RESULT ANALYSIS AND COMPARISON BETWEEN GAUSSIAN PULSE AND SOLITON PULSE FOR LONG HAUL COMMUNICATION

Two different signals have been transmitted, one is a Gaussian pulse with power 1mW, and another is a Soliton pulse whose signal power is 0.64 mW. Both signals were transmitted for the same distance. Here assuming fiber loss $\alpha=0.16$ dB/km and nonlinearity factor $\gamma=0.003$ $W^{-1}m^{-1}$. This part shows the results without EDFA amplifications.



(a)



(b)

Figure 5.1. (a) Comparison between transmitted Gaussian pulse and dispersed Gaussian pulse, (b) Comparison between transmitted Soliton pulse and dispersed Soliton pulse.

From Figure 5.1 (a) & (b) this is clearly visible that the red one is transmitted pulse and blue one is dispersed pulse after propagating 520 km which is the dispersion length for Soliton pulse. These figures show that in case of Gaussian pulse the intensity is lower than Soliton pulse; as a result it disperses and attenuates more than Soliton pulse.

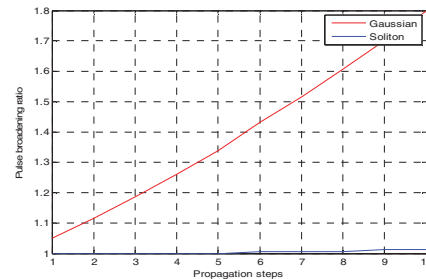


Figure 5.2. Comparison of Pulse broadening ratio with respect to propagation steps in case of Gaussian and Soliton pulse.

The above Figure 5.2 shows the comparisons between pulse broadening ratio of Gaussian and Soliton pulse. This clearly shows that Gaussian pulse is more broadening than Soliton pulse with respect to distance.

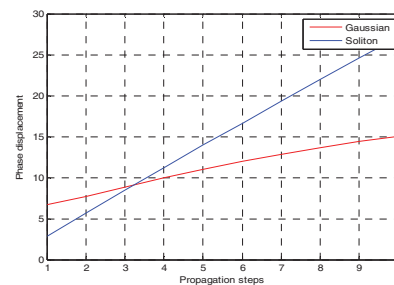


Figure 5.3. Comparison of Phase displacement with respect to steps in case of Gaussian and Soliton pulse.

In Figure 5.3, it is shown that Soliton pulse has higher phase displacement than Gaussian whether Figure 5.4 (a) & Figure 5.4 (b) shows that Soliton has less attenuation than Gaussian pulse.

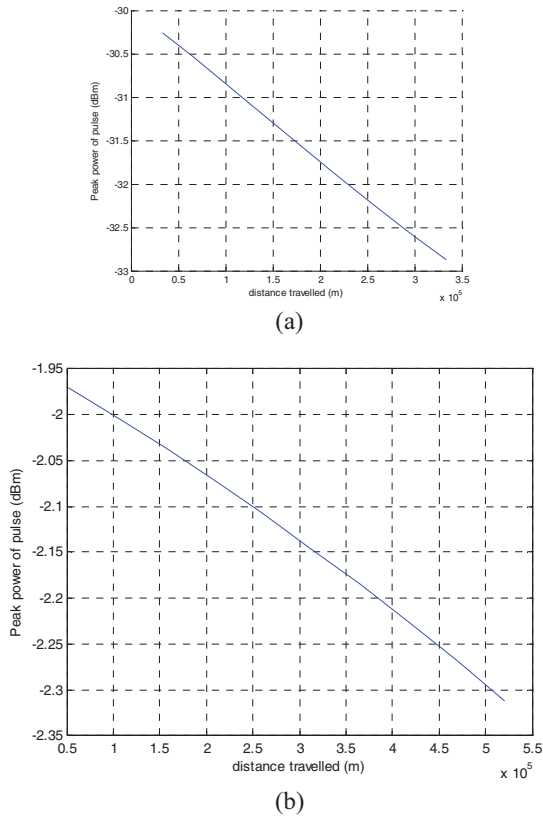


Figure 5.4. (a) Comparison of power attenuation of Gaussian pulse with respect to distance, (b) Comparison of power attenuation of Soliton pulse with respect to distance

The peak power attenuation of Gaussian pulse after propagating 330 km is around 2.62 dB whereas in case of Soliton pulse the attenuation for propagation distance of 520 km is 0.342 dB. So the Gaussian pulse gives around 2.27 dB more peak power attenuation than Soliton pulse. Here the optimum length and pump power of optical amplifier is chosen from another simulation result. Figure 5.5 (a) shows that at 1550 nm wavelength, to achieve 1.80 dB single pass gain in case of Gaussian pulse the required pump power is 6 mW where the length of the optical amplifier is 1.00 m. Whereas in Figure 5.5 (b) at 1550 nm wavelength, to achieve 1.08 dB single pass gain in case of Gaussian pulse, the required pump power is around 5.5 mw where the length of the optical amplifier is 1.00 m, the spacing between amplifier is $L_A \ll L_D$ [6,9].

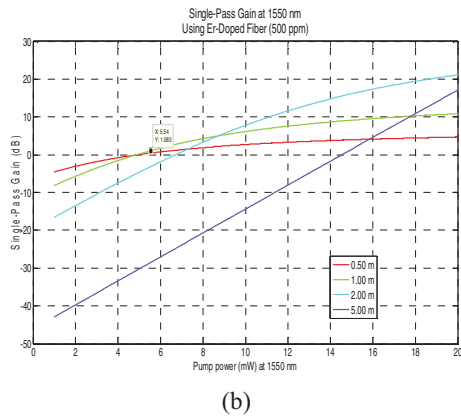
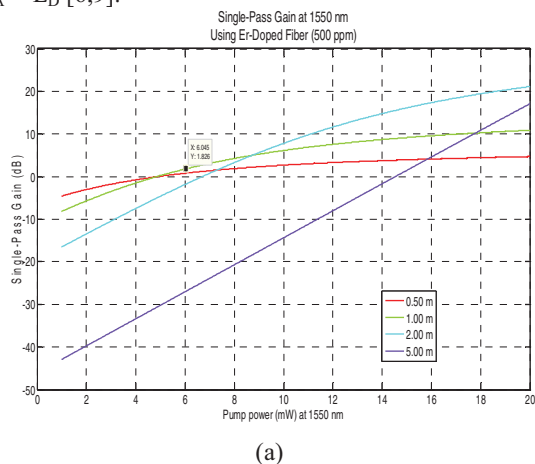


Figure 5.5. (a) Relation between pump power, Single pass gain 1.82 dB and length of optical amplifier at 1550 nm wavelength for Gaussian pulse (b) Relation between pump power, Single pass gain 1.083 dB and length of optical amplifier at 1550 nm wavelength for Soliton pulse

However for a fixed wave length and different length of the amplifier the pump power and gain is varied which is showed in this simulation result.

Now after EDFA optical amplification the scenario of Gaussian and Soliton pulse is shown in Figure 5.6 (a) & (b).

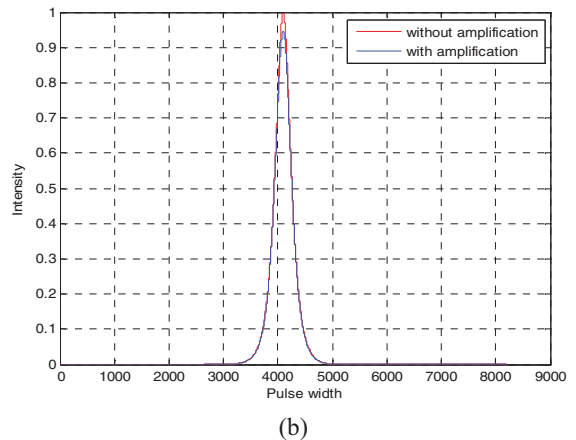
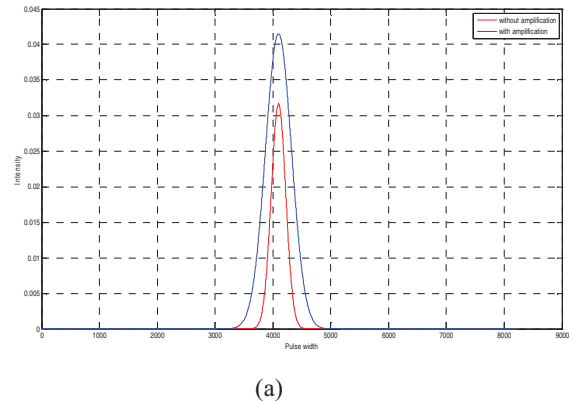


Figure 5.6. (a) Comparison between transmitted Gaussian pulse and dispersed Gaussian pulse.(b) Comparison between transmitted Soliton pulse and dispersed Soliton pulse.

Figure 5.6. (a) & (b) show that Gaussian pulse cannot manage dispersion like Soliton pulse, so after amplification the peak power of the pulse is increased in both cases though the Gaussian pulse is dispersed more than Soliton pulse. The pulse broadening ratio after EDFA amplification in case of Gaussian and Soliton pulse is shown in Figure 5.7.

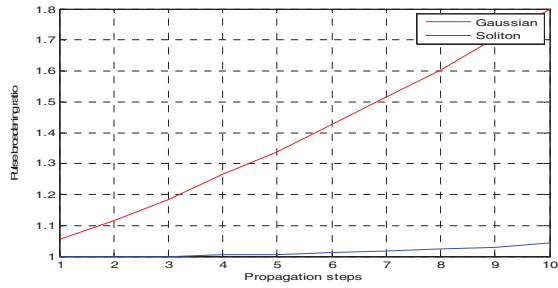


Figure 5.7. Comparison of Pulse broadening ratio with respect to propagation steps in case of Gaussian and Soliton pulse with EDFA amplification. From above figure, this is clearly visible that Soliton pulse still has lesser pulse broadening ratio than Gaussian pulse with EDFA amplification. The Phase displacement of Gaussian and Soliton pulse remains the same as before after amplification which is shown in Figure 5.8.

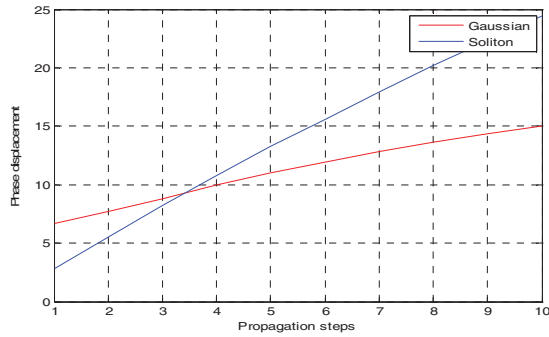


Figure 5.8. Comparison of Phase displacement with respect to steps after EDFA amplification in case of Gaussian and Soliton pulse. However the EDFA amplification results for Gaussian and Soliton pulses are shown in Figure 5.9.(a) & (b).

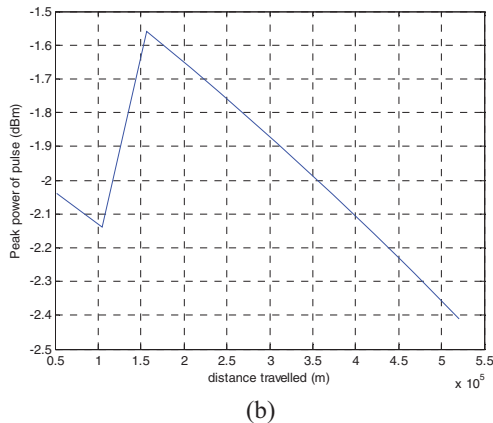
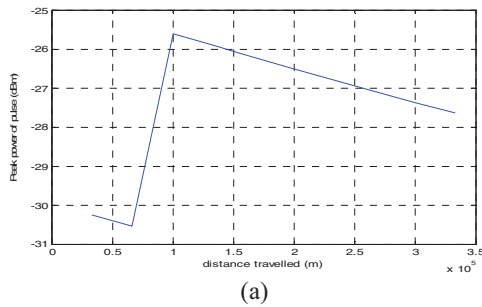


Figure 5.9. (a) Peak power of Gaussian pulse with EDFA amplification with respect to propagation distance. (b) Peak power of Soliton pulse with EDFA amplification with respect to propagation distance.

From the figure above, it is shown that in case of amplification, Gaussian pulse needs higher amplifier gain than Soliton pulse because of lower attenuation due to propagation distance. Moreover the mesh plots of Gaussian and Soliton pulse propagation without amplification and with EDFA amplifications are shown in Figure 5.10 (a), 5.10 (b) & 5.10 (c), 5.10 (d) respectively.

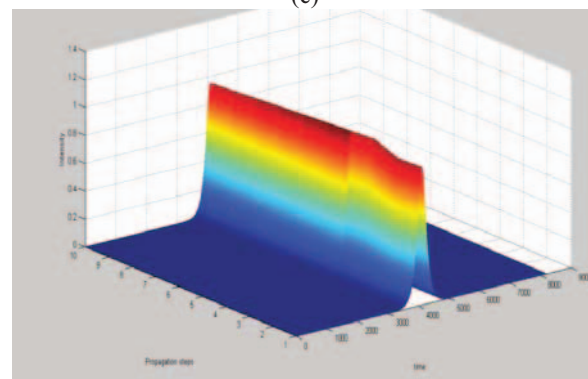
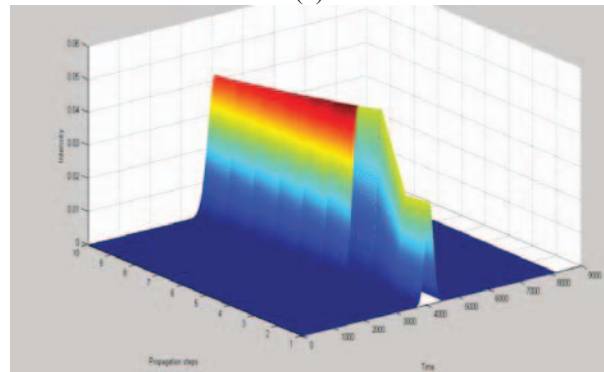
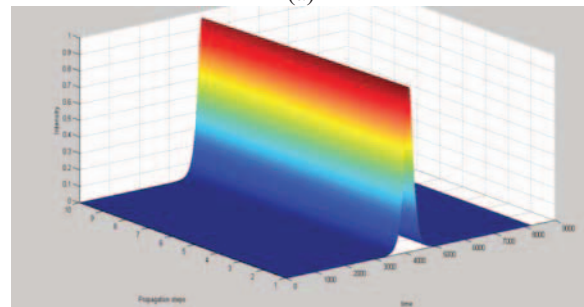
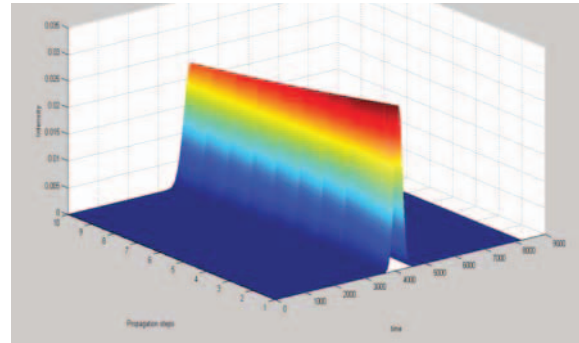


Figure 5.10. (a) Mesh plot of Gaussian pulse propagation without amplification, (b) Mesh plot of Soliton pulse propagation without amplification, (c) Mesh plot of Gaussian pulse propagation with EDFA amplification, (d) Mesh plot of Soliton pulse propagation with amplification

From the result analysis, this is clearly visible that Gaussian pulse has higher attenuation and pulse broadening ratio than Soliton pulse. These two parameters play vital roles in case of long haul optical communication. By amplification the pulse intensity can be amplified but the dispersion cannot be recovered without regenerator which is an expensive device as well.

At this point, a case scenario of SEA-ME-WE4 is considered for long haul submarine cable network along with all optical environments. Table I shows number of amplifiers required in case of long haul network between Cox's bazaar, Bangladesh and some different submarine cables landing stations connected by SEA-ME-WE 4 of data rate 8 Gbps where the bit duration is 125 us. By equation 4-1 the receiver sensitivity is -32.9 dBm. Here Gaussian pulse has dispersion length of 330 km and Soliton pulse has 520 km. This is achieved from simulation results considering $L_A \ll L_D$ for the whole network system.

TABLE I. COMPARATIVE RESULT OF NUMBER OF AMPLIFIER REQUIRED IN CASE OF LONG HAUL FIBER OPTIC NETWORK.

Network	Distance (km)	No. of amplifier required (Gaussian Pulse)	No. of amplifier required (Soliton Pulse)	Remarks
Cox's Bazar to Tuas, Singapore	4242	13	9	Gaussian pulse required 4 more amplifiers
Cox's Bazar to Satun, Thailand	3399	11	7	Gaussian pulse required 4 more amplifiers
Cox's Bazar to Chennai, India	2344	8	5	Gaussian pulse required 3 more amplifiers

So from the result analysis of Table I it is clearly visible that Gaussian pulse required more number of amplifiers/repeaters than Soliton pulse for same amount of receiver sensitivity (-32.9 dBm) and data rate (8 Gbps). The price of optical amplifier/repeater is very expensive hence Soliton pulse can provide more competent and cost effective solution for long haul fiber optic communication network.

VII. DISCUSSION

The results clearly show a superior performance for transmission with Soliton pulse in comparison to performance with Gaussian pulse. Considering all the parameters, Soliton comes out on top on each occasion thereby making it a clear decision that transmission with Soliton pulse is the way to move forward. And, since the devices and all other elements used in this system are of optical nature, the processing time will be a lot lesser, meaning faster transmission and better output level. So, all in all, this higher efficiency is ensured by using an optical system for transmission of Soliton pulse, which was the basic proposal. However, there were some limitations of this work. Those are listed below:

First of all, this research work does not include any hardware implementations. All of the work was based on simulation. In long haul communication, repeaters and amplifiers are used to make sure that signals do not get distorted and do not lose

amplitude respectively. In this research, all optical devices have been considered. However, during calculation, at no point repeaters were considered as a variable. The repeaters have only considered an optical device and not their impact on the communication system. Since, an all-optical system has been considered the processing time was lesser than for optoelectronic systems. Although there are lots of references that prove that statement, none of that has been shown in this study.

VIII. CONCLUSIONS

Considering all the results, it is clear that for long haul communication performances with Soliton pulse outweighs the Gaussian pulse. In case of non-linear channel, Soliton pulses show better results for all the key performance parameters. It has been found that the number of amplifiers required is less in the communication system using Soliton pulse rather than Gaussian pulse. It also minimizes the cost of the system installation also. All the three networks considered, have supported the proposed statement. Also, there is added consideration of an all-optical environment. This ensures better performance and faster results due to lesser processing time. Finally, all the observations indicate that Soliton pulse is the obvious choice for long haul communication through an all-optical environment.

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