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Fix the Nonlinear Effect and Dispersion in Optical-interleave Division Multiple Access System for Long Distance

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Abstract

Objectives: Nonlinear effect and dispersion are the main factors to degrade the performance of Optical-Interleave Division Multiple Access (O-IDMA) system for long distance. The objective of this paper is to reduce these effects and improve the performance of the system. **Methods/Statistical Analysis:** Solitons have been utilized as the pulses of transmitting signals in place of Gaussian pulse, to reduce nonlinear effect and recent interleaving mechanisms are applied to decide the optimum in the O-IDMA system. MATLAB is used for simulation. **Findings:** The simulation results demonstrate that Solitons are the optimum solution for nonlinear effect and Group Velocity Dispersion (GVD) while the prime interleaving mechanism is optimized for user separation in the O-IDMA system. **Applications/Improvements:** The performance of the O-IDMA system is improved significantly and system support more no. of users and high data rate transmission.

Keywords: GVD, Gaussian pulse, Interleavers, O-IDMA Scheme, Solitons

1. Introduction

In the present communication world, for wired communication, the optical fiber is frequently employed for achieving high spectral efficiency for long distance communication. Now-a-days, for efficient utilization of bandwidth, CDMA scheme is frequently used with optical fiber based communication system[1,2].

Till now, the CDMA scheme has been the most popular alternative of design engineers due to better bandwidth efficiency than its counterparts including Frequency-Division Multiple-Access (FDMA) and Time-Division Multiple-Access (TDMA) schemes. The performance of Optical-CDMA (O-CDMA) scheme is predominately limited by multiple access interference (MAI) and inter-symbol interference (ISI) in addition to other constraints. The solution of CDMA constraints is to utilize the alternate mechanism familiar as Interleave-Division Multiple-Access (IDMA) scheme[3] in which most of above specified problems do not subsist due to the implementation of user-specific interleavers having modest cross-correlation amongst them[3–6]. The comparison between CDMA and IDMA schemes have been exhibited[6,7] and deduced that user-specific interleavers may anticipate better orthogonality and emerge least interference between each other in the channel.

The optical communication inherits the advantage high spectral efficiency; however, its performance is limited by the nonlinear effect when communication is established with Gaussian pulse[8,9]. The Group Velocity Dispersion (GVD) phenomenon causes most of the transmitted pulse to get broadened in time as they propagate through an optical fiber. Nevertheless, a distinct form of the pulse shape known as Solitons yields the advantage of nonlinear effects in silica, especially Self-Phase Modulation (SPM) deducing from the Kerr nonlinearity, to bridle the pulse-broadening effects of GVD phenomena.

In reality, Solitons is a very narrow pulse with high peak

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power. In an optical fiber, Soliton pulses are originated by counter leveling the effect of dispersion by the self-phase modulation[8,10]. The Solitons can conserve its shape and velocity during transmitting along the fiber because it is very stable. Due to this incentive, Solitons do not broaden in optical fiber after thousands of kilometres[11].

In this paper, the communication process in the O-IDMA system has been implemented with Solitons replacing Gaussian pulse. The transmission of a Gaussian pulse is not a very good idea since it broadens with distance and degrades the system by increasing the Bit Error Rate (BER)[9]. The Solitons based O-IDMA system is duly simulated in MATLAB platform which can provide a very effective solution. Solitons can be used for the transmission of the very high bit rate in optical system with very less error rate. The objective of this paper is to amplify the completion of the O-IDMA system by rectifying the nonlinear effect and Group Velocity Dispersion phenomena. The completion of the proposed system is rightly contrasted with the Gaussian pulse based O-IDMA system.

2. Optical-IDMA Scheme

In proposed optical fiber based communication system, the recent multiple-access scheme based on interleaving mechanism is utilized for high spectral efficiency, modest receiver complexity and enhanced performance[12–15]. The scheme, in which the interleavers are used to scatter the user's data to discriminate various users, is known as IDMA scheme.

The application of IDMA in Optical domain plays a vital role in enhancing the accomplishment in terms of bit error rate (BER). The block diagram of O-IDMA transmitter and receiver system is introduced in Figures 1 and 2 respectively. O-IDMA can be used in many applications[16].

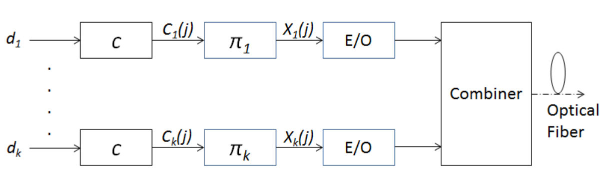

Figure 1. Block diagram of optical-IDMA transmitter.

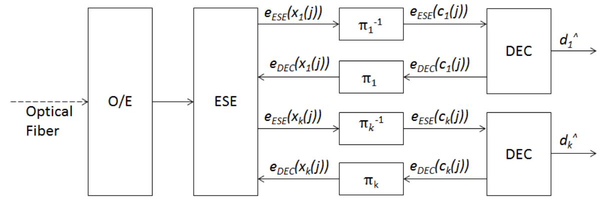

Figure 2. Block diagram of optical-IDMA receiver.

In the system, the coding rate c is acquired low for encoding the input data string d_k of user-k, to originate a coded string $\boldsymbol{c}_k=[c_k(1)\ldots..c_k(j)\ldots..c_k(J)]^T$. The frame length allied to user data is designated as J and the components in $\boldsymbol{c}_k$ are acknowledged as coded bits. The coded string$\boldsymbol{c}_k$ is implemented to particular interleaver π_k which erects $\boldsymbol{x}_k= [x_k(1)\ldots..x_k(j)\ldots..x_k(J)]^T$ data string by permuting rightly. The components in $\boldsymbol{x}_k$ are introduced as 'chips'[17,18].

The decisive concept of IDMA is to implement the user-specific interleavers $\{\pi_k\}$ for separating the user data strings and maintain the orthogonality condition. Conventionally, it is supposed that the random interleaving mechanismis followed by the interleavers to separate the users. The coded strings are scattered by interleavers and maintain the correlation property. Therefore, these strings have negligible correlation between each other and constructs Chip-By-Chip (CBC) detection process relatively facile and fast with smallest BER[17,19].

Succeeding the user-specific interleaver initiation, the mode locked laser (MLL) is rightly used to convert the electrical signal into optical signal for accomplishing specific optical transmitting pulses. The electric field of MLL is stated as[20]

$$E_{MLL} = e^{iwot} \sum_{k=0}^{k-1} e^{ik(\Delta w)t} \tag{1}$$

where, k and Δ w are designated as the number of modes and channel spacing between two consecutive modes in the Mode Locked Laser (MLL) system respectively.

Additionally, A on off keying (OOK) modulation is used to modulate the output of MLL system with interleaved data $x_k(j)$. OOK is the simplest form of Amplitude Shift Keying (ASK) where the carrier is absent during the transmission of a zero and it performs better to overcome the effect of inter symbol interference (ISI). The transmitting signal through the fiber is stated as:

$$E_{MLL}\, X_k(j) = X_k(j) e^{iwot} \sum_{k=0}^{k-1} e^{ik(\Delta w)t} \quad (2)$$

where, $x_k(j) \in (1,0)$

In Figure 1, the transmission channel is optical fiber, which is explained in the next section.

At the receiver, the optical detectors PIN or Avalanche Photo Detector[21] (APD) are rightly utilized for efficient detection of specific chips[22]. A wide bandwidth and acute response time are the essential parameter to retain by the optical detector for accomplishing high bit-rate of a system. The electrical output per optical input of the detector is measured in term of Responsivity. If the photo-current (mA) is characterized by I_p and average light power (mW) is characterized by P_o then the responsivity is

$$R = \frac{I_p}{P_0} \quad (3)$$

Additionally, the Quantum efficiency is measured by the ratio of radiative recombination to the total recombination (i.e. Summation of radiative and non-radiative recombination)

$$\eta = \frac{I_p\, h\, c}{q\, p_0\, \lambda} \quad (4)$$

The Poisson distribution is introduced to calculate the probability of photons which can be absorbed by an incident optical field of the detector over a chip interval T_c. If the received laser power is characterized by P_0, the photon absorption rate λ_s is stated as

$$\lambda_s = \frac{\eta P_0}{hf} \quad (5)$$

where, η denotes the quantum efficiency, f denotes the optical frequency, q denotes the charge of the electron and h is Planck's constant.

The output of the detector is the input of an iterative receiver which comprises an elementary signal estimator (ESE), de-interleavers, interleavers and decoders (DECs)[17,23] with *a* posteriori probability (APP). The generated output of an ESE and DECs can be formulated in terms of extrinsic log-likelihood ratios (LLRs) of $\{x_k(j)\}$ as,

$$e_{ESE}(x_k(j)) \equiv \log\left(P_r\left(x_k(j) = +1\right)\right) - \log(P_r(x_k(j) = -1)) \quad (6)$$

This is the expression to calculate the extrinsic *a posteriori* Log-Likelihood Ratios (LLRs) of user k produced by the decoder.

The received signal *r(j)* has the signal component and noise sample *n(j)* at the ESE. If channel coefficient is characterized by h_k for user k, the received signal is stated as

$$r(j) = \boldsymbol{h}_k x_k(j) + n(j) \quad (7)$$

For a particular user k, the equation (7) can be modified as[3]

$$r(j) = \boldsymbol{h}_k x_k(j) + \xi_k(j) \quad (8)$$

where, $\xi_k(j)$ denotes the distortion in the received signal including interference and additive noise. The $\xi_k(j)$ can be stated as

$$\xi_k(j) = \sum_{k' \neq k} \boldsymbol{h}_{k'} x_{k'}(j) + n(j) \quad (9a)$$

$$\xi_k(j) \equiv r(j) - \boldsymbol{h}_k x_k(j) \quad (9b)$$

The detection of information from received signal is finished by chip by chip (CBC) algorithms. The listing of the CBC algorithm using the initialization $e_{DEC}(x_k(j)) = 0$, $\forall\, k, j$, is introduced as[3]

$$E(x_k(j)) = \tanh\left(e_{DEC}\left(\frac{x_k(j)}{2}\right)\right) \quad (10a)$$

$$var(x_k(j)) = 1 - (E(x_k(j)))^2 \quad (10b)$$

$$E(\xi(j)) = \sum_{k' \neq k} h_{k'} E(x'(j)) \quad (10c)$$

$$var(\xi_k(j)) = \sum_{k' \neq k} |h_{k'}|^2\, var(x_k(j)) + \sigma^2 \quad (10d)$$

$$e_{ESE}(x_k(j)) = \frac{2hk}{\mathrm{var}(\xi_k(j))}(r(j) - E(\xi_k(j))) \quad (10e)$$

After the APP decoding process, further operations are performed in the DECs for generating the LLRs $\{e_{DEC}(x_k(j)), \forall k, j\}$. Now, again the iterations are repeated back to (10a) for the next iteration, if required.

With a count of iterations in the receiver, the accuracy of the decoded data increases, however, it also increases the mathematical complexity and high power requirement at the receiver side. It has been perceived with numerous simulations that count of 15 iterations in the receiver section, is sufficient for recovery of any user-specific data. The BER vs. number of iterations are shown in Figure 6 and explanation is in result and discussion section.

3. Nonlinear Effects and Solitons in Channel of O-IDMA System

For long distance optical fiber based communication network, the non-linear distortion is quite crucial parameter in addition to the dispersion mechanism which causes the optical signal pulse to get broadens as they propagate along a fiber. If these pulses propagate adequate far distance, they are eventually bound to get overlapped with the neighboring pulses, thereby creating errors in the receiver output. Hence, the signal distortion ultimately becomes responsible for limiting the information carrying capacity of a fiber.

In general, optical network distances are counted in terms of ~100 km to 5000 km of range, hence for better performance of the O-IDMA system, it is necessary that optical channel should not introduce significant degradation in the signal. However, as the signal transmits through the fiber, the pulses disperse and their peak powers reduce. Therefore, for compensating such loss in power generally optical amplifiers, Erbium Doped Fiber Amplifiers (EDFA) are utilized in the transmission line. These amplifiers are capable of amplifying the loss of the signal power of the propagating signals, but unfortunately are also responsible for adding Amplified Spontaneous Noise (ASN) to the signal, which results in increment of overall BER.

For enhancing the performance of the O-IDMA system, the Solitons are implemented in place of the Gaussian pulse with transmitting signal since Solitons do not disperse due to nonlinear effects.

All optical pulses are monochromatic since it excites a spectrum of frequencies. The spectral spread of an optical source $\Delta\nu$, which emits power in a wavelength band $\Delta\lambda$, is presented by the relation

$$|\Delta\nu| = \left(\frac{c}{\lambda^2}\right)|\Delta\lambda| \tag{11}$$

In actual optical fiber based communication system, for high intensity optical excitations, a communicating pulse is adversely affected by Group Velocity Dispersion (GVD) phenomena and the Kerr nonlinearity. In addition to it, when a high intensity optical pulse is coupled to a fiber, the optical power of the pulse modulates the refractive index due to optical excitation. This originates the phase fluctuations in the propagating wave, thereby initiating a chirping effect on the pulse as demonstrated in Figure 3. This results in difference of instantaneous optical frequency from its initial value ν_0 across the pulse. It happens due to intensity dependent phase fluctuations, resulting in various phase shifts for different parts of pulses. This effect is known as frequency chirping.

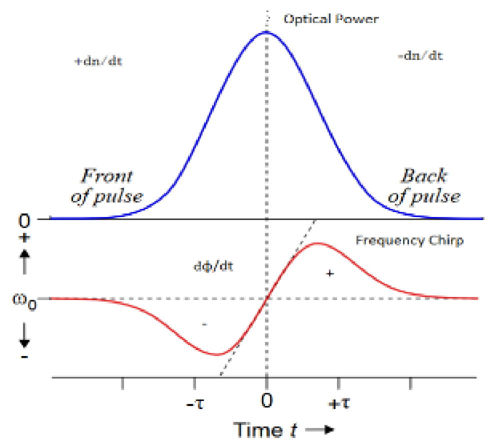

Figure 3. Spectral broadening of pulse due to self-phase modulation.

During the event of frequency chirping, the rising edge of pulse encounters a red shift in the direction of higher frequencies, while the trailing edge of the pulse encounters a blue shift in the direction of lower frequencies. Since the degree of chirping depends on the transmitted power, SPM effects more asserted for higher intensity pulses[8,24].

When the high intensity pulse transverses a medium with a positive GVD parameter for the elemental frequencies, the leading part of the pulse is shifted in the direction of the lower frequency band, so that the speed of data transmission in such particular portion increases. Conversely, in the trailing half, the frequency perceives the increment resulting in the decrement of speed in particular portion which causes the trailing edge to be additionally delayed. Hence, in addition to a spectral change with distance, the energy in the center of the pulse is dispersed to either side, and the pulse eventually takes on a rectangular wave shape. These effects will severely limit high-speed, long distance transmission if the system is operated in this condition[24].

On the other hand, during the transmission of narrow high intensity pulse with a negative GVD parameter for the elemental frequencies, GVD prevents the chirp production due to SPM. Now, due to GVD the lower frequencies of the pulse are retarded in the front end and higher frequencies of the pulse are advanced at the back, which further results in no change in shape and spectrum of high intensity sharply peaked Solitons pulse.

In a standardized optical fiber, it has been observed a point with no dispersion around 1310 nm wavelength. The GVD parameter is positive below 1310 nm and negative above 1310 nm wavelength. Therefore, the transmission of the signal in the form of Solitons must be in the range of the above 1310 nm wavelength.

For Solitons transmission, it is necessary to consider the Nonlinear Schrodinger (NLS) equation[25].

$$-j\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + N^2|u|^2 u - j\left(\frac{\alpha}{2}\right)u \qquad (12)$$

Here, $u(z, t)$denotes the pulse envelope function, N denotes an integer representing the order of the solutions, z denotes the communicating distance along the fiber, and α represents the loss of energy.

The propagating pulse $A(z,t)$ in the optical fiber can be expressed with the help of Nonlinear Schrodinger equation (NLS) and stated as

$$A_z = AL + AN \qquad (13)$$

The equation 13 is characterized as the nonlinear partial differential equation and expressed in terms of linear operator L and nonlinear operator N. The attenuation and dispersion[8] are the main parameters in optical fiber, which affect the accomplishment of the system. The Split step method is utilized to demonstrate the propagation of the pulse[8,24,25]

$$A_z = -\frac{\alpha}{2}A - i\frac{\beta}{2}A_n + i\gamma|A|^2 A \qquad (14)$$

The attenuation and dispersion are varied linearly. The attenuation can be stated as

$$\textbf{Attenuation} = e^{\frac{\alpha}{2}\times\frac{dz}{2}} \qquad (15)$$

The attenuation factor is designated by α and split-step distance is designated by dz. The dispersion is revealed as

$$Dispersion = e^{\left(\beta_1\frac{w}{2}+\beta_2\frac{w^2}{2}+\beta_3\frac{w^3}{2}\right)\times\frac{dz}{2}} \qquad (16)$$

In a single mode fiber, The Intermodal or modal dispersion is not present i.e. $\beta_1 = 0$.

$$\beta_2 = \frac{\lambda^2 \times D_1}{-2\pi c} \qquad (17)$$

$$\beta_3 = \frac{1}{(-2\pi c)^2}\left(D_3 + \frac{2D_2}{\lambda_{ref}}\right)\lambda_{ref^4} \qquad (18)$$

The symbol c denotes the velocity of light in free space.

The symbol D_2 denotes the second order dispersion and the symbol D_3 denotes third order dispersion.

The solution of equation (11) for fundamental Solitons is

$$u(z,t) = \mathrm{sech}(t) \times e^{\frac{jz}{2}} \qquad (19)$$

Here, the hyperbolic secant function is represented by *sech (t)*. This is the bell shaped pulse as presented in Figure 4.

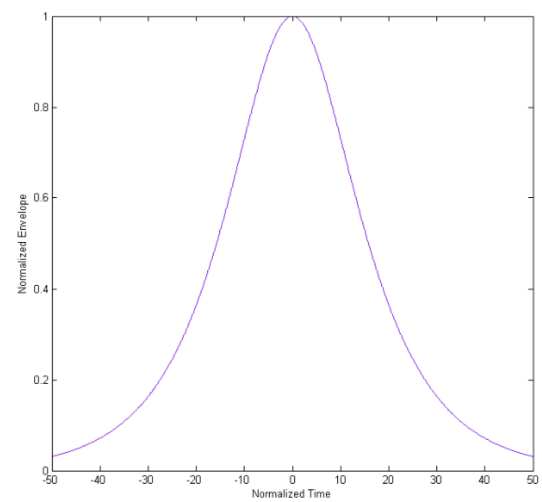

Figure 4. Hyperbolic secant function.

A Solitons pulse has the phase shifts for nonlinear process is

$$d\Phi_{nonlin} = |u(t)|^2 dz = sech^2(t)dz \qquad (20)$$

And phase shifts for dispersion effect are

$$d\Phi_{disp} = \left(\frac{1}{2}\frac{\partial^2 u}{\partial t^2}\right)dz = \left[\frac{1}{2} - sech^2(t)\right]dz \qquad (21)$$

The sum of these two terms is a constant. Upon integration, sum simply produces a phase shift of z/2, which is common to the entire pulse. Since such a phase shift changes neither the temporal, nor the spectral shape of a pulse, the Solitons remains completely non dispersive in both the temporal and frequency domains.

4. Results and Discussion

The transmission of signals in the form of Gaussian pulse and Solitons in the optical fiber is shown in Figure 5. At z = 0 km it is observed that the shape of Solitons is very much similar to that of Gaussian pulse and can be easily transmitted in the optical fiber channel of the O-IDMA system.

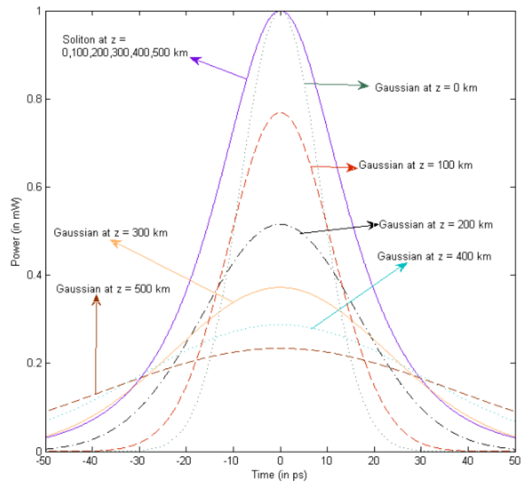

Figure 5. Effect of nonlinearities on the transmitting signals (Gaussian and Soliton) at Z=0,100,200,300,400& 500 km.

As the travelling distance z increases, (i.e. z = 0 to 500 km) the Gaussian pulse disperse due to nonlinear effect and Solitons has its original shape and power. It can be easily observed that Solitons has almost its original shape and power, but the Gaussian pulse disperses more and more as distance increases and the peak power is less than 0.2 m W. Therefore, Gaussian pulse could not maintain the required minimum power for transmission in optical fiber channel of the O-IDMA system.

Figure 6 shows the BER performance of the system with increment in the iterations of the receiver, for the O-IDMA system. It is observed from the simulations, that with increment in iterations, the BER performance gets decrement however, it demonstrates constant BER performance after 15 iterations.

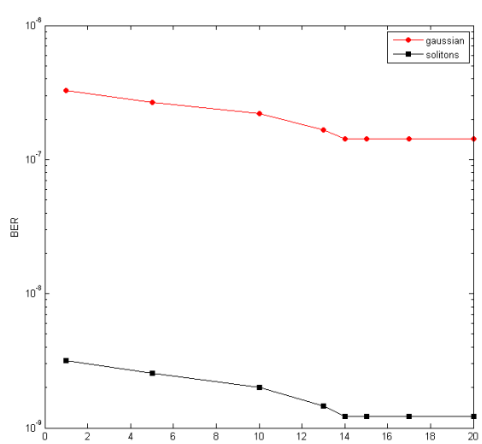

Figure 6. The BER vs. iterations for O-IDMA system.

For simulation purpose, a Prime interleaver mechanism is used since it gives the optimum performance due to better orthogonality between the interleavers and low complexity in the system[26]. The performance of the O-IDMA system using random, tree based and prime interleaver mechanism have been presented in Figure 7. The Figure 7 demonstrates that the prime interleaver mechanism is suitable for the O-IDMA system.

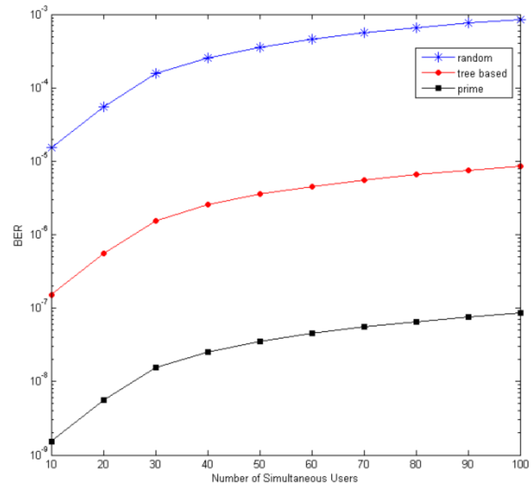

Figure 7. BER vs. no. of users for random, tree based and prime interleavers.

The parameters, used during the simulation, are chosen for optimum performance of the O-IDMA system. The opted length for spreading is 16 and the number of iteration is set to be 15. Responsivity of the detector is 0.65 and efficiency is 0.80. The data length for each user is opted to be same i.e. 4096 bits. The operating wavelength of the Optical fiber is 155nm with a maximum bit rate of 1 Gbps capacity and the transmitted signal contains 1mW power. The refractive index parameter[20] is $2.35*10^{-20}$ and this parameter is influenced by the intensity of light. The shapes of the transmitting pulses are Gaussian and Solitons while OOK modulation is used for pulse transmission. The number of users is 40 for all the simulations, where required except the Figure 7.

The BER performance of the O-IDMA system using Solitons and Gaussian pulse has been presented in Figure 8. It is observed that the BER of Gaussian pulse increases linearly with distance while BER of Solitons is almost constant.

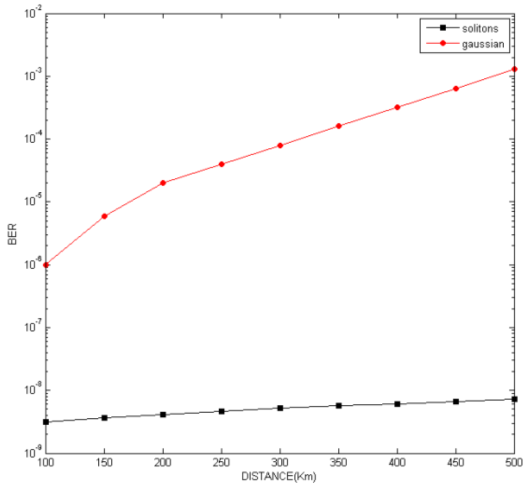

Figure 8. BER Performance of O-IDMA System with varying the transmitting distance of Optical Fiber for Gaussian and Solitons.

From the simulations, it is evident that Solitons has its original shape and maintain the power. The reason behind it is that the negative GVD prevents the generation of chirp due self-phase modulation in the narrow high intensity pulse for constituent frequency. The low frequencies in the front end of the pulse are retarded and the high frequencies at the back is advanced due to GVD. Therefore, no change observed in either its shape or in its spectrum of the high intensity sharply peaked Solitons during its transmission along the fiber[24] while the power of the Gaussian pulse decreases significantly. Therefore, Gaussian pulse has the major increment of BER performance as distance increases.

5. Conclusion

In this paper, the signal transmission in Gaussian pulse shape and Solitons have been simulated on the O-IDMA system. The simulation results demonstrate that propagation through Solitons can be easily implemented while it is similar to Gaussian pulse and suitable for the optical-IDMA system. The transmitted signal in Solitons shape did not disperse in the medium and maintain its original shape and signal strength.

The simulation results also confirm that Solitons ensure better BER and did not disperse due to GVD and nonlinear effect in O-IDMA communication system. The Gaussian pulse was not found to be suitable for long distance because it is highly dispersed due to GVD and nonlinear effects. It is also noted here that prime interleave mechanism may be preferred for separating the users because it provide better orthogonality amongst the users and produce better performance in the O-IDMA system.

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