Impact of Optical Pulse Linear Chirp on the BER Performance of DS-OCDMA in Presence of Fiber Optic Dispersion.

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ABSTRACT

A theoretical analysis is presented to evaluate impact of optical pulse linear chirp on the bit-error-rate (BER) performance of direct sequence optical code division multiple access in presence of fiber optic dispersion. In our analysis, Gaussian-shaped optical orthogonal codes are employed as address sequence. Avalanche photodiode (APD) is used in an optical correlator receiver. The signal-to-noise power for the proposed system is evaluated with respect to APD short noise, bulk dark current, surface leakage current, thermal noise current, and multiuser access interference noises. The system BER performance is determined as a function of received signal power, number of simultaneous users, fiber length, and pulse linear chirp. The power penalty suffered by the system is evaluated at BER of 10^{-9}. The numerical results show that the BER performance of the proposed system is highly dependent on the number of simultaneous user, fiber length, and pulse linear chirp. It is found that, if the effect of second order and third order dispersion is considered, the proposed system performance (i.e., BER is degradation). Also, the pulse linear chirp has an important effect on the BER performance.

(Keywords: DS-OCDMA, chirp-Gaussian, pulse linear chirp, second order dispersion, SOD, third order dispersion, TOD)

INTRODUCTION

Optical code-division multiple-access (OCDMA) systems have attracted much attention in recent years [1-5]. This is due to the huge bandwidths offered by the optical links and the extra-high optical signal processing speed with the optical components. Optical CDMA is advantageous in that it makes channel assignment easier than in time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) systems. Thus, optical CDMA is an attractive option for future optical access networks. This technique allows several users to access the network asynchronously and simultaneously [2-3]. However, an OCDMA system is limited in capacity, since its performances are significantly reduced by Multiple Access Interference (MAI) [6-7]. The bit error probability is seriously degraded as the number of simultaneous user's increases. Moreover, future access systems require broadband transmission links that offer high-speed data rates. The increase of data rate and the spreading data technique used in CDMA, making light pulses shorter, must take into account the fiber dispersion effects [8] even for short optical fiber lengths (1 to 20 Km).

Until now, researchers of OCDMA mainly focused on direct-time spread OCDMA, spectral encoding–decoding, pulse position modulation OCDMA, asynchronous phase-encoding OCDMA [9], and frequency hopping (FH) OCDMA [10]. Most research to date on rectangular-shaped chip DS-OCDMA were carried out taking dispersion into account as reported in the literature so far [10-11]. It is expected that the dispersion-induced effect can be reduced significantly if a Gaussian-shaped chip is used in OCDMA instead of rectangular-shaped chip. Several studies have been performed on the fiber dispersion effect but, to the best of our knowledge, no results in an access context, especially for pulse linear chirp effect at high chip rate up to 100Gchip/s.

In this paper, an analytical approach is presented to know the impact of optical pulse linear chirp on the performance of DS-OCDMA in the presence of fiber optic second order dispersion (SOD) and third order dispersion (TOD). In our analysis, Gaussian-shaped optical orthogonal code (OOC) is used as the user address. Avalanche photodiode (APD) is used in an optical correlator receiver. The BER performance of the system is

determined as a function of fiber length, received signal power, number of simultaneous user, pulse linear chirp on account of receiver noises, and multiuser access interference (MAI). It is found that the BER performance of proposed system is severely degraded due to pulse linear chirp effect.

SYSTEM DESCRIPTION

The schematic configuration of the proposed system is shown in Figure 1. Here, we consider a incoherent, synchronous direct detection OCDMA system. In the transmitter, a user's binary data is modulated by Gaussian-shaped chip. A Gaussian-shaped optical orthogonal code sequence is impressed upon the binary data by the encoder. The composite signal is then transmitted through an optical fiber operating at 1550 nm. The loss of optical signal in the fiber is taken to be 0.2 dB/Km. At the receiving terminal, a particular user data is recovered by the correlation operation between composite received signal and a replica of the desired user's address code is carried out by an optical correlator receiver to achieve decoding. The decoding signal is incident on the APD. The output signal of APD is integrating throughout the bit period, then the threshold level is at the comparator for data recovery.

SYSTEM ANALYSIS

Transmission equation

The Nonlinear Schrödinger Equation (NLSE) is used to mathematically describe varying pulse envelopes propagating in a medium with linear and nonlinear attributes. NLSE supports both linear and nonlinear effects, suitable for describing optical pulse propagation inside single-mode fiber. Numerical solution for NLSE can be obtained by applying split step Fourier method. Equation (1) represents the generalized form of NLSE for complex envelope $g(z,t)$. Equation (2) is the linear part of NLSE. It consists of SOD, TOD, and attenuation. Equation (3) is the nonlinear part of NLSE. β_2 and β_3 are the quadratic and cubic dispersion coefficient, α is the attenuation factor, and ν is the nonlinear coefficient.

$$\frac{dg}{dz} = -\frac{i\beta_2}{2}\frac{d^2g}{dt^2} + \frac{\beta_3}{6}\frac{d^3g}{dt^3} - \frac{\alpha}{2}g - i\nu|g|^2g \quad \text{(1)}$$

$$\frac{\partial g_L}{\partial z} = -\frac{i}{2}\beta_2\frac{\partial^2 g}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3 g}{\partial t^3} - \frac{\alpha}{2}g \quad \text{(2)}$$

$$\frac{\partial g_{NL}}{\partial z} = -i\nu|g|^2g \quad \text{(3)}$$

Chirp Gaussian pulse is used as a chip shape. In case of chirp Gaussian pulse, the incident field can be written as [12]:

$$g(0,t) = exp\left[-\frac{1+iC}{2}\cdot\left(\frac{t}{T_0}\right)^2\right] \quad \text{(4)}$$

Where T_0 is the initial pulse width and C is the optical pulse linear chirp. The Gaussian pulse is still keeps it shape for the Gaussian form in deliver process, after the distance of transmission L, the relation of the pulse width σ and initial pulse width $\sigma_0 = \left(T_0/\sqrt{2}\right)$ is given by [12]:

$$\frac{\sigma}{\sigma_0} = \left[\left(1 + \frac{C\beta_2 L}{2\sigma_0^2}\right)^2 + \left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1+C^2)^2\frac{1}{2}\left(\frac{\beta_3 L}{4\sigma_0^2}\right)^2\right]^{1/2} \quad \text{(5)}$$
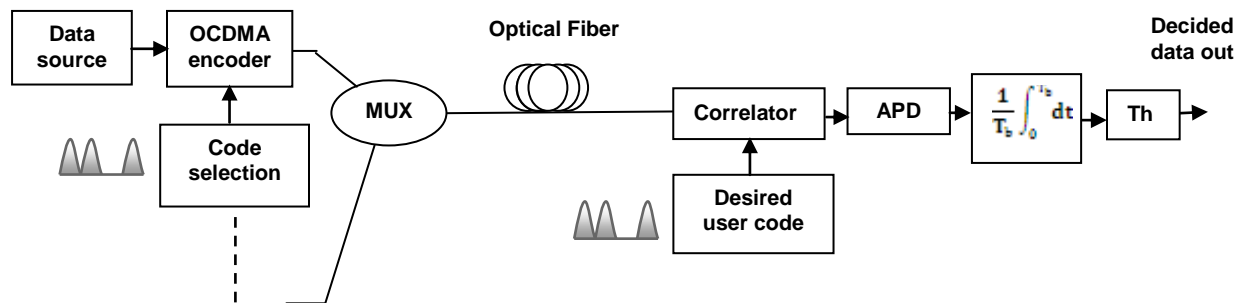

Figure 1: Schematic Configuration of Proposed DS-OCDMA System.

The BER Performance Analysis

In this analysis, the effects of shot noise, surface leakage current, and thermal noise current associated with APD receiver are considered. Furthermore, we assume that all users have the same effective power at any receiver, the identical bit rate, and signal format. For an OCDMA system with N transmitter and receive pairs (users), the received signal $y_{out}(t)$ is the sum of N user's transmitted signals, which can be given by:

$$y_{out}(t) = P_r \sum_{n=1}^{N} \sum_{i=1}^{F} B_n A_n(i) \int_{\tau_n + iT_c}^{\tau_n + (i+1)T_c} g(t - \tau_n - iT_c) dt \qquad (6)$$

where P_r is the received pulse peak power, B_n is the nth user's binary data bit (either "1" or "0") with duration T_b at time t ($0 < t \le T_b$), $A_n(i)$ is the ith chip value (either "1" or "0") of the nth user address code with code length $F = \frac{T_b}{T_c}$, code weight W, and τ_n is the time delay associated with the nth user's signal.

Without loss of generality, we assume that user 1 is the desired user, all delays τ_n at the receiver are relative to the first user delay only (i.e., $\tau_1 = 0$. $g(t)$) is the Gaussian function with period T_c, and satisfies the normalization condition. All users are assumed chip synchronous, (i.e., $\tau_n = jT_c$, and $0 \le j < F$) is an integer. In that case, the MAI will be maximum and the BER will be an upper bound on the BER for the chip asynchronous case.

At the receiving terminal, the correlation operation between signal $y_{out}(t)$ and a replica of the desired user's address code is carried out by an optical correlator receiver to achive decoding. The decoding signal is incident on the APD. Output photocurrent X_1 sampled at time $t = T_b$ can be written as:

$$X_1 = I' + I'' + I_n \qquad (7)$$

Where I' is the desired user's signal current, I'' the interference signal current due to MAI, I_n the APD noise currents which includes shot noise current, bulk dark current, surface leakage current, and thermal noise current. We assume that the ($F, W, g(t)$) OOC's selected as user address codes. By the correlation definition of OOC's, each interference user can contribute at most one hit during the correlation time. If γ denotes the total number of hits from interference users, the probability density function of γ is given by:

$$P(\gamma) = \binom{N-1}{\gamma} K^{\gamma} \rho^{N-1-\gamma} \qquad (8)$$

where $K = W^2/2F$, $\rho = 1 - K$ and γ is an integer ($0 \le \gamma \le N - 1$). If code length F, code weight W and γ are given, the first two terms in equation (7) can be determined. We assume that the APD noise current has Gaussian nature. The output photocurrent X_1 can be regarded as a Gaussian random variable. Its average I_1 and variance σ_1^2 for bit "1" and "0" are determined as follows [13]. Since the received signal is multiplied by the user address code, i.e., (0,1) sequence. During the bit "1" interval of the desired signal, photons fall on the APD only during the W mark intervals and are totally blocked during the $F - W$ space intervals. During the W chip intervals of the desired signal, the total number of pulses (either marks or spaces) due to N users is WN.

Among these WN pulses, there are $W + \gamma$ mark pulses with power level $\sigma_d P_r$, and $WN-(W + \gamma)$ space pulses with power level $\sigma_d r P_r$. Here, σ_d includes the effect of SOD, TOD, and pulse linear chirp; and r is the extinction ratio of APD receiver. Therefore, for data bit "1" the average photocurrent I_1 and noise variance σ_1^2 are given by:

$$I_1 = M(R_0 P_t^l + I_{BD}) + I_{SL} \qquad (9)$$

$$\sigma_I^2 = 2eM^{2+x}(R_0 P_t^l + I_{BD})B_e + 2eI_{SL}B_e + \frac{4\kappa_B T}{R_L} \qquad (10)$$

where the exponent x varies between 0 and 1.0 depending on the APD material and structure, M the average APD gain, R_0 the unity gain responsiveness, e an electron charge, I_{BD} the average bulk dark current, which is multiplied by the avalanche gain, I_{SL} the average surface leakage current, which is not affected by avalanche gain, B_e the receiver electrical bandwidth, κ_B the Boltzmann's constant, T the receiver noise temperature, and R_L the receiver load resistor.

$$P_t^1 = (W + \gamma)\sigma_d P_r + (WN - W - \gamma)\sigma_d r P_r \tag{11}$$

$$\sigma_d = \frac{\sigma_0}{\sigma} \tag{12}$$

For data bit "0", the average photocurrent I_0 and noise variance σ_0^2 of X_1 can be determined in the same way as for data bit "1". In this case, I_0 and σ_0^2 can be written as:

$$I_0 = M(R_0 P_t^0 + I_{BD}) + I_{SL} \tag{13}$$

$$\sigma_0^2 = 2eM^{2+x}(R_0 P_t^0 + I_{BD})B_e + 2eI_{SL}B_e + \frac{4\kappa_B T}{R_L}B_e \tag{14}$$

Where,

$$P_t^0 = \gamma\sigma_d P_r + (WN - \gamma)\sigma_d r P_r \tag{15}$$

For the desired user's data bit "1" or "0", the conditional probability density function of the output photocurrent X_1 can be expressed as:

$$P_{X_1}(I|\gamma, 1) = \frac{1}{\sigma_1\sqrt{2\pi}}\exp\frac{-(I-I_1)^2}{2\sigma_1^2} \tag{16}$$

$$P_{X_1}(I|\gamma, 0) = \frac{1}{\sigma_0\sqrt{2\pi}}\exp\frac{-(I-I_0)^2}{2\sigma_0^2} \tag{17}$$

For a given threshold level Th, the probability of error for bit "1" and "0" are calculated by:

$$P_e^{(1)}(\gamma) = \int_0^{Th} P_{X_1}(I|\gamma, 1)\,dI = \frac{1}{2}\text{erfc}(\frac{I_1-Th}{\sigma_1\sqrt{2}}) \tag{18}$$

$$P_e^{(0)}(\gamma) = \int_{Th}^{\infty} P_{X_1}(I|\gamma, 0)\,dI = \frac{1}{2}\text{erfc}(\frac{Th-I_0}{\sigma_0\sqrt{2}}) \tag{19}$$

The probability of error per bit, depended on the threshold level Th, is defined as:

$$P_e(\gamma) = \frac{1}{2}[P_e^{(1)}(\gamma) + P_e^{(0)}(\gamma)] \tag{20}$$

The threshold level Th, is defined as:

$$Th = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \tag{21}$$

Here, we assume that the bit "1" and "0" have the identical probability. The total probability of error P_e per bit is given by:

$$P_e = \sum_{\gamma=0}^{N-1} P_e(\gamma)\binom{N-1}{\gamma}K^{\gamma}\rho^{N-1-\gamma} \tag{22}$$

RESULTS AND DISCUSSION

Following the analytical formulations the BER performance for the proposed system is evaluated with the combined effect of SOD and TOD in presence of pulse linear chirp. In the numerical calculation, we assume that the InGaAs APD is selected at the system receiver, its primary parameters are taken as follows: mean gain M = 20, excess noise index x = 0.7, bulk dark current I_{BD}= 2 nA, surface leakage current I_{SL} = 10 nA. Other parameter are receiver load resistor R_L=1000 Ω, extinction ratio r =0.05.

Figure 2 depicts the plot of BER versus number of simultaneous users. The result are obtained for Gaussian-shaped chip with different values of pulse linear chirp, C when chip rate =100 Gchip/s, and fiber length= 10Km. It is found that the BER performance of the proposed system is strongly dependent on the number of simultaneous users, and C. The BER performance degrades with large number of users due to the effect of MAI for all values of C. It also found that the BER performance is aggravated with increasing the value of pulse linear chirp.
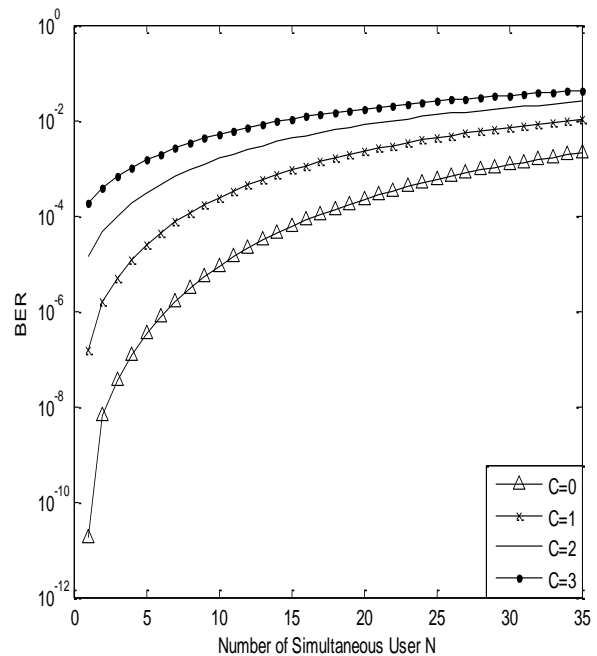

Figure 2: Plot of BER versus Number of Simultaneous users with Different Value of Pulse Linear Chirp, C when Chip Rate = 100 Gchip/s, Fiber Length= 10Km.

Figure 3 shows the BER versus number of simultaneous user curves plotted as a function of fiber lengths at constant pulse linear chirp, C=1. It is found that the BER increase with increase in fiber length from 10Km to 40Km. It can be interred that, with the transmission distance of optical pulse along fiber increasing, the pulse broadening becomes more serious. So, the proposed system BER performance becomes degradation.
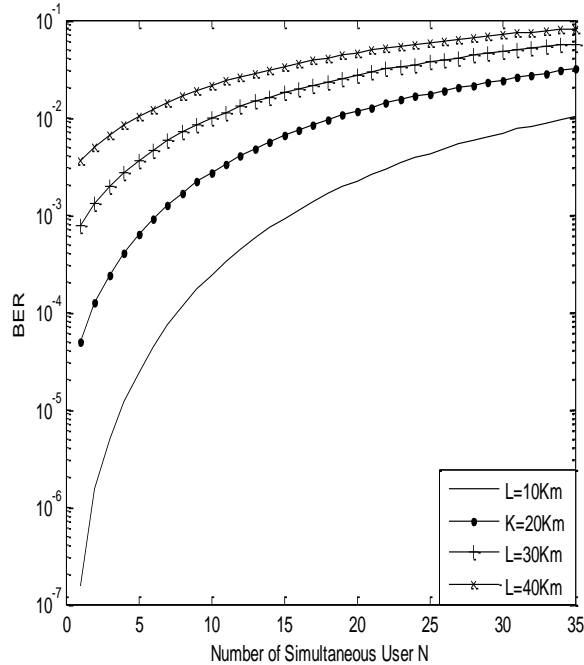
increased and hence the system BER performance is improved.

Figure 3: Plot of BER versus Number of Simultaneous Users with Different Fiber Lengths when Chip Rate = 100 Gchip/s and Pulse Linear Chirp C=1.
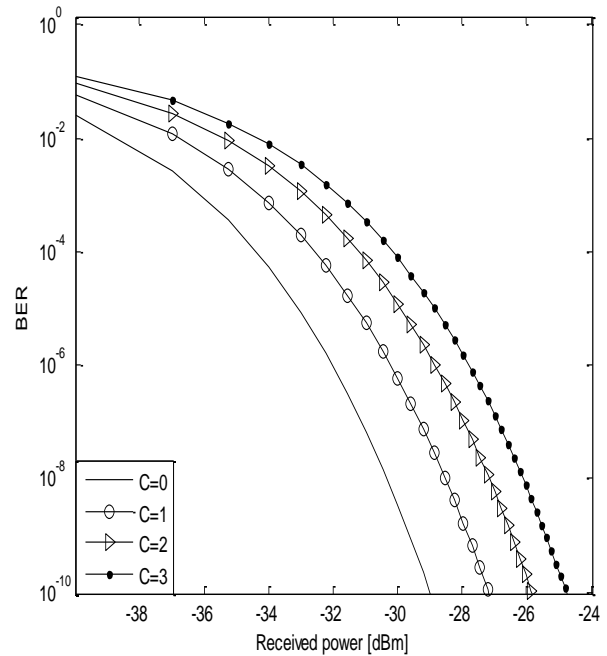

Figure 4: Plot of BER versus Received Power with Different Value of C when Chip Rate=100 Gchip/s, Fiber Length=10Km.

Figure 4 shows the plot of BER versus received power with different value of pulse linear chirp, C when chip rate=100 Gchip/s, fiber length= 10Km. It is found that higher received signal power is needed when C changes from 0 to 3 in order to maintain a BER of 10^{-9}.

Figure 5 depicts the plot of BER versus received power for different fiber lengths when chip rate =100 Gchip/s, and pulse linear chirp, C= 1. It is found that higher received signal power is needed with increasing fiber length in order to maintain a BER of 10^{-9}. At constant pulse linear chirp, the received signal power is decreased with increasing fiber length due to the effect of dispersion. For a particular value of fiber length, with the increase of received signal power, SNR is
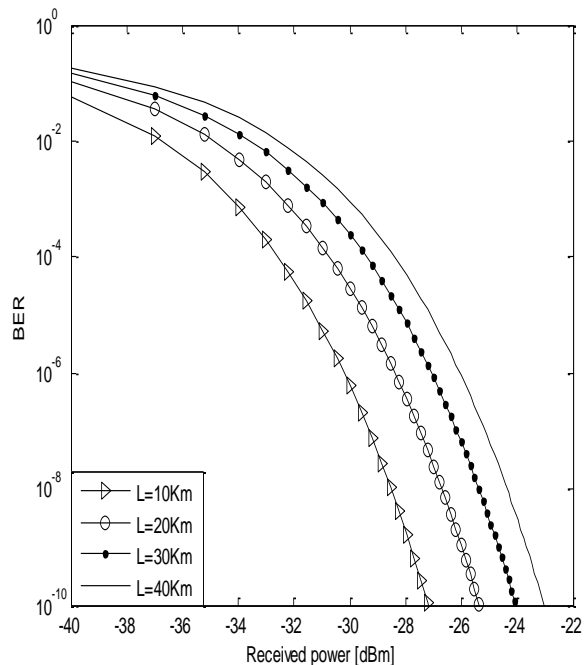

Figure 5: Plot of BER versus Received Power for Different Fiber Lengths when Chip Rate=100 Gchip/s, Pulse Linear Chirp C=1, and 10 Number of Simultaneous User.

The power penalty suffered by the system is determined at BER of 10^{-9} and plotted in Figure 6 with respect to number of simultaneous user for different pulse linear chirp in presence of SOD and TOD at chip rate 100Gchip/s, and fiber length=10Km. It is found that power penalty increased with increasing number of simultaneous user due to the effect of MAI. It also found that the proposed system penalty increase with increasing value of pulse linear chirp. The typical value of power penalty are increased 2.0 dB for C=1, and 3.36 dB for C=2 at number of simultaneous user 10.
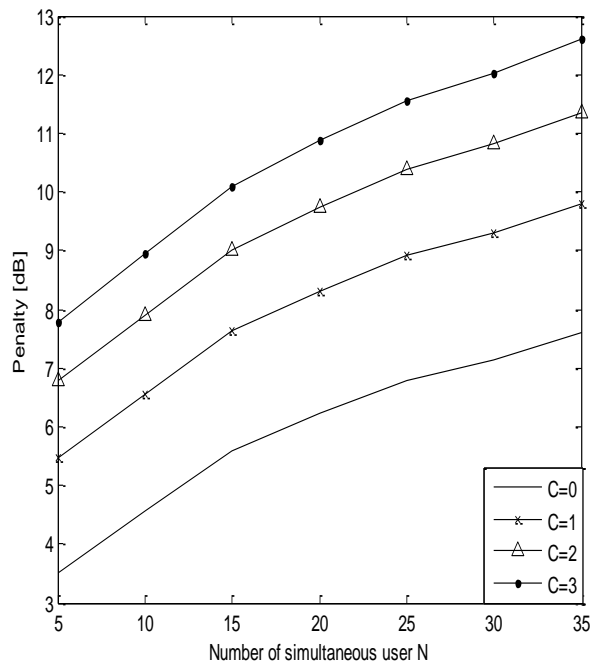

Figure 6: Plot of Power Penalty versus Number of Simultaneous User for Different Pulse Linear Chirp in presence of SOD and TOD at Chip Rate 100Gchip/s, and Fiber Length=10Km.

Figure 7 depicts the plot of power penalty versus fiber length for different pulse linear chirp in presence of SOD and TOD at chip rate 100Gchip/s, and number of simultaneous user 10. It is observed in Figure 7 that the power penalty increased with increasing the fiber length due to the dispersion effect. The typical value of power penalties are 6.55 dB for fiber length L=10Km, and 8.38 dB for fiber length L=20Km at pulse linear chirp C=1.
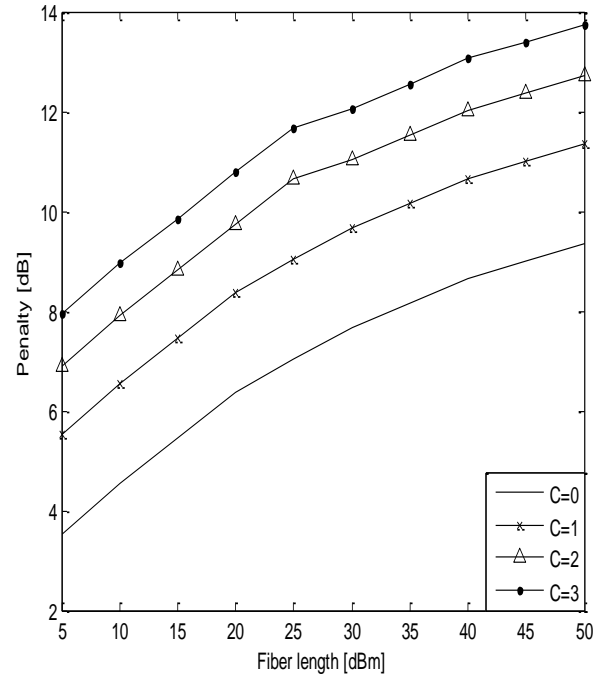

Figure 7: Plot of Power Penalty versus Fiber Length for Different Pulse Linear Chirp in Presence of SOD and TOD at Chip Rate 100Gchip/s, and Number of Simultaneous User= 10.

CONCLUSION

In this paper, the impact of optical pulse linear chirp on the BER performance of DS-OCDMA in the presence of fiber optic dispersion is analyzed. The analysis is carried out by OOC's with Gaussian-shaped chip. APD is used in the optical correlator receiver for optoelectronic conversion. The effect of receiver, and MAI noises are considered to evaluate the BER performance.

The power penalty suffered by the system at BER of 10^{-9} is determined as a function of fiber length, number of simultaneous user, and pulse linear chirp. The results show that, on account of fiber SOD and TOD, the proposed system BER performance is degradation. It also found that the proposed system penalty is increased with increase the value of pulse linear chirp. The power penalty increased 2.0 dB for C= 1 and 3.36 dB for C=2 when fiber length 10Km, and number of simultaneous user 10.

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