Effect of Optical Pulse Shape on the Performance of OCDMA in Presence of GVD and Pulse Linear Chirp

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Abstract*—In this paper, the effect of optical pulse shape on the performance of direct sequence optical code division multiple access in presence of fiber group velocity dispersion (GVD) and pulse linear chirp is analyzed. In our analysis, chirp-Gaussian shape and chirp-Hyperbolic-Secant shape 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 on account of 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, pulse linear chirp, and pulse-shape. 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, pulse linear chirp, and pulse-shape. It is found that, if the effect of GVD is considered, the proposed system performance i.e., BER is degraded. The BER performance of the proposed system also aggravated due to presence of pulse linear chirp. It is also found that the proposed system suffers minimum penalty when chirp-Hyperbolic-Secant shape optical pulse is used instead of chirp-Gaussian shape pulse.

Keywords-OCDMA, chirp-Gaussian pulse, chirp-Hyperbolic-Secant, GVD, and pulse linear chirp.

I. INTRODUCTION

The optical code-division multiple-access (OCDMA) system is an attractive scheme for all optical networks [1-2]. In an OCDMA system, all users can asynchronously access the network in a very flexible manner without any timing devices and optical electrical conversion. It is convenient to exploit the very broad bandwidth of optical fiber and implement the very high speed communication system in the future. It is expected that the chip rate of all-optical networks adopting OCDMA technique can reach up to more than 100Gchip/s and therefore, the OCDMA system will be a promising candidate for the next generation of all-optical networks, especially the access network [3]. Until now, researches on OCDMA mainly focused on direct time spread OCDMA, spectral encoding–decoding, pulse position modulation OCDMA, asynchronous phase-encoding OCDMA [4], and frequency hopping (FH) OCDMA [5]. Most of previous researches on rectangular-shaped chip DS-OCDMA are carried out taking into account of dispersion as reported so far [5-6]. 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 Hyperbolic-Secant shaped chip at high chip rate up to 100Gchip/s.

In this paper, an analytical approach is presented to know the impact of optical pulse shape on the performance of OCDMA in presence of group velocity dispersion (GVD) and pulse linear chirp. In our analysis, chirp-Gaussian-shaped and chirp-Hyperbolic-Secant 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, pulse-shape 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. It is found that the proposed system suffers minimum penalty when chirp-Hyperbolic-Secant shaped optical pulse is used; and combined effect of GVD and pulse linear chirp present.

II. SYSTEM DESCRIPTION

The scheme of an OCDMA communication system basing on unipolar sequence is shown in Fig. 1. In Fig. 1, the optical encoder and decoder are fulfilled by optical delay lines [7]. At the transmitter, when the data source is “0”; no light is emitted and the output of the optical encoder is none. When the data is “1”; an ultrashort optical pulse is sent into the optical encoder and splitted into several ultrashort optical pulses which experience different time delays respectively according to the address code. This direct time spread optical signal is sent to the receiver through the optical fiber network. At the receiver, the decoder assembles the desired time spread optical signal and exports an optical pulse to optical threshold device. So the data is recovered.

In this paper, we consider the initial optical pulse as chirp-Gaussian and chirp-Hyperbolic-Secant model. We also consider normal single mode fiber operating at 1550nm as transmission medium. The loss of optical signal in the fiber is taken to be 0.2 dB/Km. APD is used in the system receiver.

III. SYSTEM ANALYSIS

A. *Transmission Equation*

The Nonlinear Schrödinger Equation (NLSE) is used to mathematically describe varying pulse envelope 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 second order dispersion, and attenuation. Equation (3) is the nonlinear part of NLSE. β_2 is the quadratic dispersion coefficient, a is the attenuation factor, and v is the nonlinear coefficient.

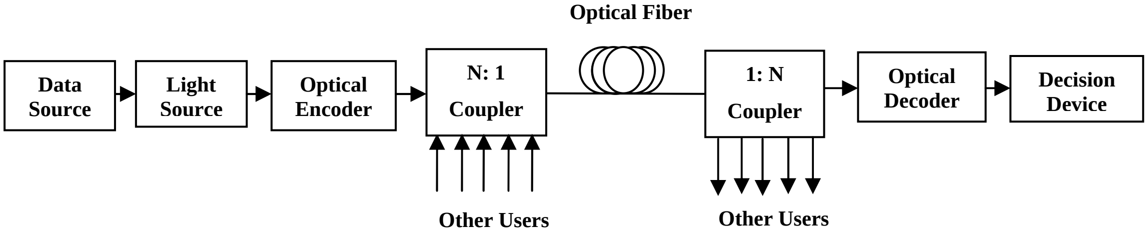

Fig. 1: Schematic diagram of an OCDMA system

$$\frac{dg}{dz} = -\frac{i\beta_2}{2}\frac{d^2 g}{dt^2} - \frac{a}{2}g - iv|g|^2 g \tag{1}$$

$$\frac{\partial g_L}{\partial z} = -\frac{i}{2}\beta_2\frac{\partial^2 g}{\partial t^2} - \frac{a}{2}g \tag{2}$$

$$\frac{\partial g_{NL}}{\partial z} = -iv|g|^2 g \tag{3}$$

Two types of pulses were used in this analysis, chirp-Gaussian pulse and chirp-Hyperbolic-Secant pulse as a chip shape. In case of chirp-Gaussian pulses, the incident field can be written as [8]

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

Where T_0 is the initial pulse width, and C is the pulse linear chirp. The Gaussian pulse is still keeps it shape for the Gaussian form in deliver process, after the distance of transmission z, the relation of the pulse width σ and initial pulse width $\sigma_0 = \left(T_0/\sqrt{2}\right)$ is given by [8]

$$\frac{\sigma}{\sigma_0} = \left[\left(1+\frac{C\beta_2 z}{2\sigma_0^2}\right)^2 + \left(\frac{\beta_2 z}{2\sigma_0^2}\right)^2\right]^{1/2} \tag{5}$$

Where β_2 is the average GVD of the transmitting fiber. In case of chirp-Hyperbolic-Secant pulse, the incident field can be written as [8]

$$g(0,t) = \operatorname{sec}h\left(\frac{t}{T_0}\right)\exp\left(-\frac{iCt^2}{2T_0}\right) \tag{6}$$

The Hyperbolic-Secant pulse is still keep its shape for the Hyperbolic-Secant form in deliver process, after the distance of transmission z, the relation of the pulse width σ and initial pulse width $\sigma_0 = \left(\pi/\sqrt{12}\right)T_0$ is given by [8]

$$\frac{\sigma}{\sigma_0} = \left[\left(1+\frac{\pi^2 C\beta_2 z}{12\sigma_0^2}\right)^2 + \left(\frac{\pi\beta_2 z}{6\sigma_0^2}\right)^2\right]^{1/2} \tag{7}$$

A. *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 receiver pairs (users), the received signal $y_{out}(t)$ is the sum of N user's transmitted signals, which can be given by

$$y_{out}(t) = P_r\sum_{n=1}^{N}\sum_{i=1}^{F} B_n A_n(i)\int_{\tau_n+iT_c}^{\tau_n+(i+1)T_c} g\left(t-\tau_n-iT_c\right)dt \tag{8}$$

where P_r is the received pulse peak power, B_n is the n-th 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 i-th chip value (either "1" or "0") of the n-th user address code with code length $F = T_b/T_c$, code weight W, and τ_n is the time delay associated with the n-th 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 achieve decoding. The decoding signal is incident on the APD. Output photocurrent X_1 sampled at time $t = T_b$ can be written as

$$X_1 = I' + I'' + I_n \tag{9}$$

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

$$P(\gamma) = \binom{N-1}{\gamma} K^{\gamma} \rho^{N-1-\gamma} \tag{10}$$

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 (9) 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 ${\sigma_1}^2$ for bit "1" and "0" are determined as follows [9-10]. 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 effects of GVD, 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 ${\sigma_1}^2$ are given by

$$I_1 = M\left(R_0 P_t^1 + I_{BD}\right) + I_{SL} \tag{11}$$

$${\sigma_1}^2 = 2eM^{2+x}\left(R_0 P_t^1 + I_{BD}\right)B_e + 2eI_{SL}B_e + \frac{4\kappa_B T}{R_L} \tag{12}$$

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 responsivity, 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.

$$P_t^1 = (W + \gamma)\sigma_d P_r + (WN - W - \gamma)\sigma_d r P_r \tag{13}$$

$$\sigma_d = \frac{\sigma_0}{\sigma} \tag{14}$$

For data bit "0", the average photocurrent I_0 and noise variance ${\sigma_0}^2$ of X_1 can be determined in the same way as for data bit "1". In this case, I_0 and ${\sigma_0}^2$ can be written as

$$I_0 = M\left(R_0 P_t^0 + I_{BD}\right) + I_{SL} \tag{15}$$

$${\sigma_0}^2 = 2eM^{2+x}\left(R_0 P_t^0 + I_{BD}\right)B_e + 2eI_{SL}B_e + \frac{4\kappa_B T}{R_L} B_e \tag{16}$$

Where

$$P_t^0 = \gamma\sigma_d P_r + (WN - \gamma)\sigma_d r P_r \tag{17}$$

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

$$P_{X_1}(I|\gamma,1) = \frac{1}{\sigma_1\sqrt{2\pi}} \exp\left[\frac{-(I - I_1)^2}{2\sigma_1^2}\right] \tag{18}$$

$$P_{X_1}(I|\gamma,0) = \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left[\frac{-(I - I_0)^2}{2\sigma_0^2}\right] \tag{19}$$

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

$$P_e^{(1)}(\gamma) = \int_0^{Th} P_{X_1}(I|\gamma,1)dI = \frac{1}{2} erfc\left(\frac{I_1 - Th}{\sigma_1\sqrt{2}}\right) \tag{20}$$

$$P_e^{(0)}(\gamma) = \int_{Th}^{\infty} P_{X_1}(I|\gamma,0)dI = \frac{1}{2} erfc\left(\frac{Th - I_0}{\sigma_0\sqrt{2}}\right) \tag{21}$$

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

$$P_e(\gamma) = \frac{1}{2}\left[P_e^{(1)}(\gamma) + P_e^{(0)}(\gamma)\right] \tag{22}$$

The threshold level Th, is defined as

$$Th = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \tag{23}$$

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

$$P_e = \sum_{\gamma=0}^{N-1} P_e(\gamma) \binom{N-1}{\gamma} K^{\gamma} \rho^{N-1-\gamma} \tag{24}$$

IV. RESULTS AND DISCUSSION

Following the analytical formulations the BER performance for the proposed system is evaluated with the combined effect of GVD and 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. Fig. 2 depicts the plot of BER versus number of simultaneous users. The result are obtained for Gaussian-shape pulse and Hyperbolic-shape pulse 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, pulse linear chirp, and pulse-shape. 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. It also shows that the BER performance of proposed system improves for Hyperbolic-Secant shape optical pulse. Fig. 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 30Km. It can be interred that, with the transmission distance of optical pulse along fiber increasing, the pulse broadening becomes more serious. So, the BER performance of the proposed system degraded. It also found that the BER performance of proposed system degraded if Gaussian shaped pulse is used instead of Hyperbolic-Secant shaped pulse.

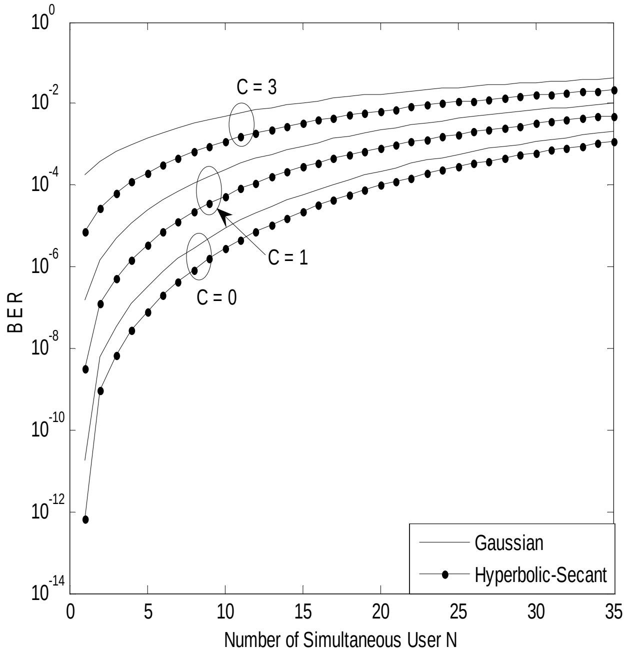

Fig. 2: Plot of BER versus number of simultaneous users with different value of pulse linear chirp, C when chip rate = 100 Gchip/s, and fiber length= 10Km.

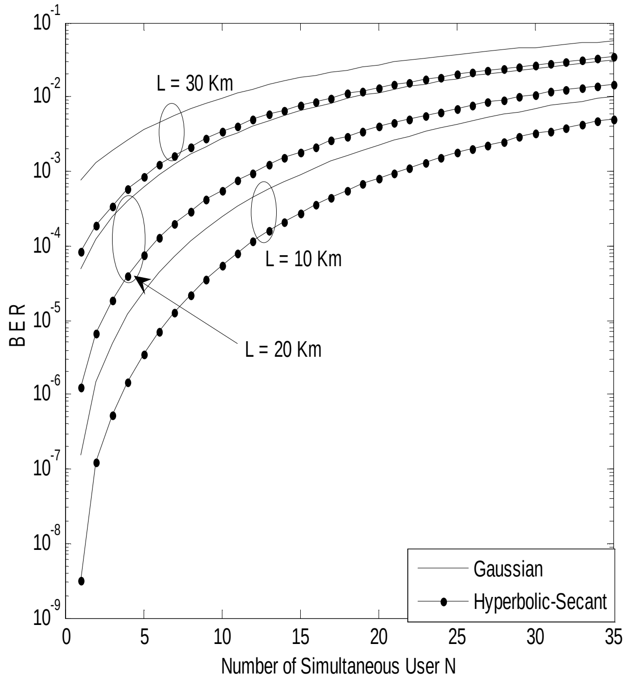

Fig. 3: Plot of BER versus number of simultaneous users with different fiber lengths when chip rate = 100 Gchip/s and pulse linear chirp C =1.

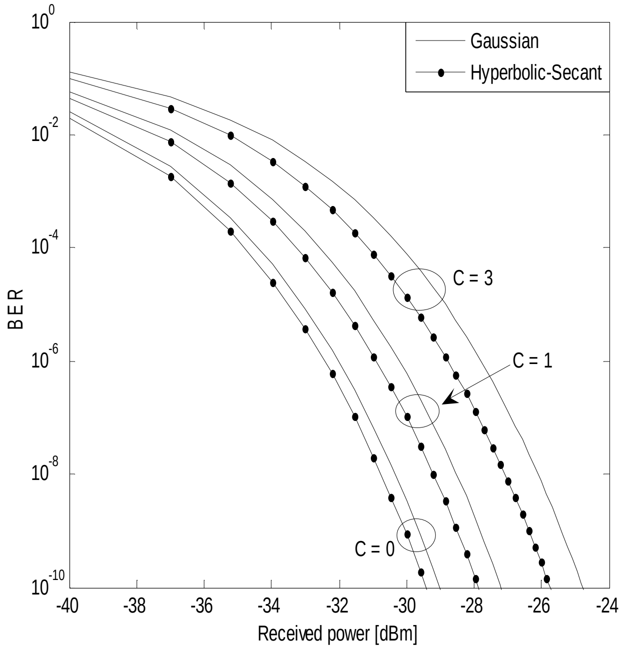

Fig. 4: Plot of BER versus received power with different value of C when chip rate = 100 Gchip/s, and fiber length= 10Km.

Fig. 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}. Fig. 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 increased and hence the system BER performance is improved. It also shows that the BER performance of proposed system improves significantly when Hyperbolic-Secant shaped optical pulse is used. The power penalty suffered by the system is determined at BER of 10^{-9} and plotted in Fig. 6 with respect to number of simultaneous user for different pulse linear chirp in presence of GVD 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 penalties are increased 2.0 dB for C =1, and 4.40 dB for C =3 at number of simultaneous user 10. It also found in Fig. 6 that the proposed system suffers more penalties when Gaussian shaped pulse is considered. However, the power penalties are reduced 1.25dB at N =10 and 1dB at N =15 when Hyperbolic-Secant shaped optical pulse is considered in presence of both GVD and pulse linear chirp. Fig. 7 depicts the plot of power penalty versus fiber length for different pulse linear chirp in presence of GVD at chip rate 100Gchip/s, and number of simultaneous user 10. It is observed in Fig. 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. It is found that power penalties reduced 1.61dB (at L =35Km and N =10) and 1.80dB (at L =45Km and N =10) when Hyperbolic-Secant shape pulse is used instead of Gaussian shape pulse.

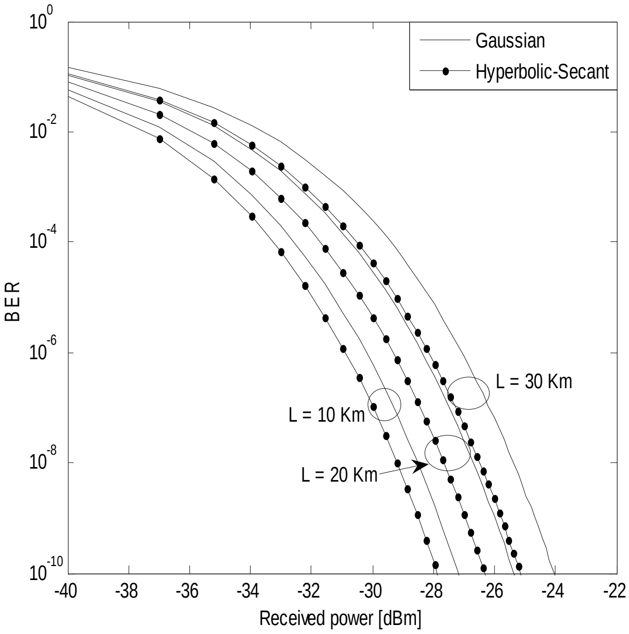

Fig. 5: Plot of BER versus received power for different fiber lengths when chip rate = 100 Gchip/s, pulse linear chirp C =1, and number of simultaneous user 10.

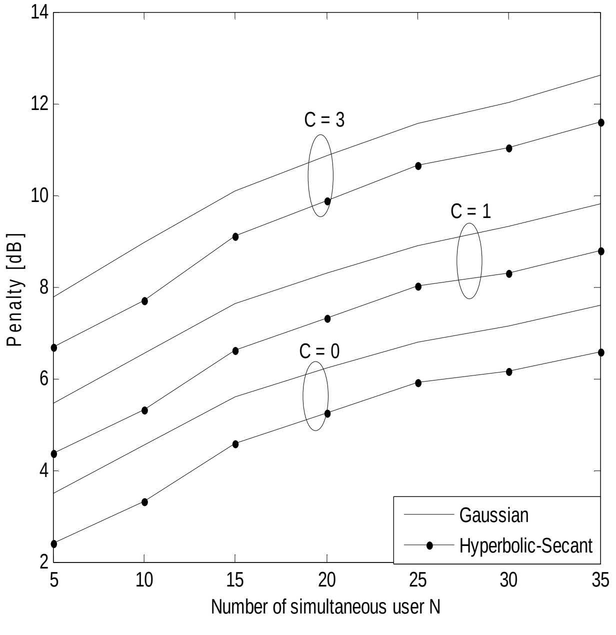

Fig. 6: Plot of power penalty versus number of simultaneous user for different pulse linear chirp in presence of GVD at chip rate 100Gchip/s, and fiber length=10Km.

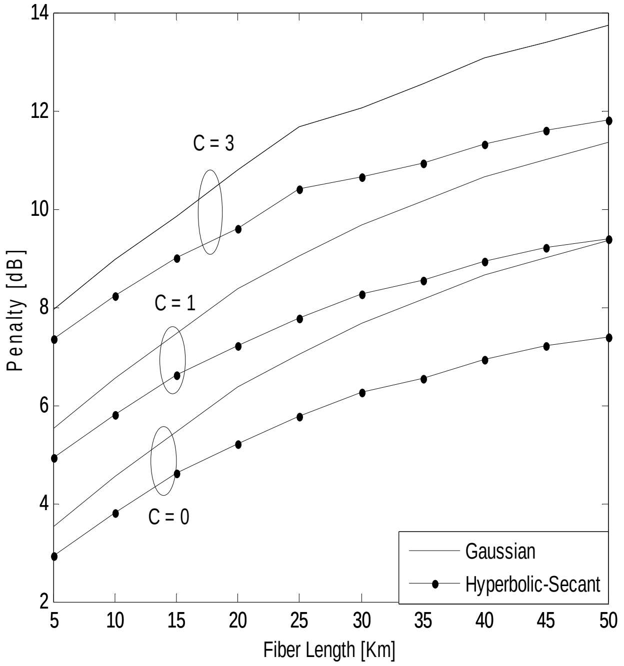

Fig. 7: Plot of power penalty versus fiber length for different pulse linear chirp in presence of GVD at chip rate 100Gchip/s, and number of simultaneous user 10.

V. CONCLUSION

This paper investigates the impact of optical pulse shape on the BER performance of OCDMA in presence of GVD and pulse linear chirp. The analysis is carried out by OOC's with chirp-Gaussian-shape and chirp-Hyperbolic-Secant shape chip. APD is used in the proposed system receiver. 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, pulse linear chirp, and pulse-shape. The results show that, on account of fiber GVD the proposed system BER performance is degraded. It found that the proposed system penalty is increased with increasing the value of pulse linear chirp. Also, the results show that the proposed system suffers minimum power penalty when Hyperbolic-Secant shape optical pulse is used instead of Gaussian shape pulse. The power penalty reduced 1.61dB for 35Km fiber length and 1.80dB for 45Km fiber length when Hyperbolic-Secant shape optical pulse is used at the number of simultaneous user 10.

REFERENCES

[1] V. K. Jain, "Performance evaluation of optical code division multiple access networks," Journal of Optical Communications, vol. 21, no. 3, pp. 110–115, 2000.

[2] J. Ratnam, "Optical CDMA in broadband communication: scope and applications," Journal of Optical Communications, vol. 23, no. 1, pp. 11–21, 2002.

[3] W. Huang, et al., "Coherent optical CDMA (OCDMA) systems used for high-capacity optical fiber networks-system description, OTDM comparison, and OCDMA/WDMA networking," Journal of Lightwave Technology, vol. 18, no. 6, pp. 765–778, 2000.

[4] M. Wehuna et al., "Performance analysis on phase-encoded OCDMA communication system," Journal of Lightwave Technology, vol. 20, no. 5, pp. 798–805, 2002.

[5] Chao Zuo, "The Impact of Group Velocity on Frequency-Hopping Optical Code Division Multiple System," Journal of Lightwave Technology, vol. 19, no. 10, pp. 1416-1419, 2001.

[6] S.P. Majumder, Afreen Azhari, and F.M. Abbou, "Impact of fiber chromatic dispersion on the BER performance of an optical CDMA IM/DD transmission system," IEEE photonics technology letters, vol. 17, no. 6, pp. 1340-1342, 2005.

[7] D. D. Sampson, W. T. Dove, and D. A. Jackson, "High bandwidth optical fiber delay line multichannel digital correlator," Applied Optics, vol. 32 , no. 21, pp. 3905–3916, 1993.

[8] Govind P. Agrawal, Nonlinear Fiber Optics, Third edition, Academic Press, An Imprint of Elsevier, 2001.

[9] Hyuck M. Kwon, "Optical Orthogonal Code-Division Multiple- Access System-Part I: APD Noise and Thermal Noise," IEEE transactions on communications, vol. 42, no. 7, pp. 2470-2478, 1994.

[10] Anand Srivastava, Subrat Kar, and V. K. Jain "Performance Evaluation of PIN+OA and Avalanche Photodiode Receivers in Optical CDMA Networks," Journal of Optical Communications, vol. 22, no. 2, pp. 67–73, 2001.

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