Improvement of BER Performance in DS-OCDMA System using Chirped Pulses under GVD regime

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***Abstract*—This paper studies the effect of the probability of bit error using various chirped optical pulses on direct sequence optical code division multiple access (DS-OCDMA) system under group velocity dispersion (GVD) regime. Here, the Gaussian, Hyperbolic-secant and super-Gaussian shaped chirped pulses are used as optical orthogonal codes (OCCs), and they are employed as address sequence on OCMDA system. We have experimentally analysed the BER performance in terms of mentioned chirped pulses with standard single mode optical fiber, and the outputs are compared with the BER results when dispersion shifted fiber (DSF) is used. Finally, it is demonstrated that a significant improvement of BER performance is possible by the use of standard single mode optical fiber with proper chirped pulses under GVD regime.**

Keywords—DS-OCDMA system, GVD regime, Chirped Gaussian pulse, Chirped Hyperbolic-secant pulse, Chirped super-Gaussian pulse.

I. INTRODUCTION

Optical CDMA system is a promising technology for next generation all-optical networks, especially the access network [3]-[5]. Due to the inherent features, like asynchronous flexibility, decentralized networking, secured communication and effective bandwidth utilization [4], OCDMA has become an attractive research arena. Though OCDMA offers an enormous data throughput for all network users, the performance of the system is badly affected by the multiple access interference (MAI) [8]. As the number of simultaneous user increase the error performance in OCDMA system seriously degrade due to MAI. Many researches have been targeted to increase the error performance by considering alternative coding and modulation techniques [6]-[10]. Reference [9] shows the BER improvement based on a modified double weight code and a NAND subtraction technique. Authors of [10] indicate a better BER result using spectral direct decoding detection technique.

Chirp effects on fiber optics communication have been investigated from many angles. The chirp effects on fiber optics communication on various dispersive regimes are discussed in [11]-[17]. In [12], the impact of chromatic dispersion (CD) on BER performance in OCDMA system is studied; whereas to mitigate the CD and polarization mode dispersion (PMD) effect by using chirped pulses is analysed in [13]. Moreover, Effects of chirped optical pulse to enhance BER result on OCDMA system is partially discussed in [16], [17]. However, to our best knowledge, there is no article that rigorously evident any error performance improvement using mentioned chirped pulses compared to mostly used DSF medium.

The rest of the paper is organised as follows: section II presents the methodology in which the experimental model is described. Section III covers the mathematical explanation of broadening factor for each of the targeted chirped pulses under GVD effect. In section IV, the probability of bit error in OCDMA system in terms of mathematical equations is evaluated. The experimental results with MATLAB simulation is presented in section V. Finally, section VI contains the concluding part.

II. METHODOLOGY

When pulses propagate through physical optical fiber, the width of pulses become broadens which is called dispersion. The main reason of dispersion is modulation chirp which is an inevitable for optical sources. In this experiment, we use opposite-valued chirped optical pulses which minimize the mean chirp effect, results the reduction of dispersion effect. And, the whole effect is measured in terms of BER performance in OCDMA system.

In our analysis, we consider intensity modulation and direct detection (IMDD) OCDMA system. OOC is employed as address sequence codes with fixed code length and code weight, and avalanche photodiode (APD) is selected as the system receiver. The effects of APD receiver, like shot noise, bulk dark current, surface leakage current, thermal noise current, are considered. But, the loss of system devices is neglected. The systems performance is evaluated under the assumption of constant optical signal power at receiver. As a transmission medium we consider standard single model fiber (SMF) operating at 1550 nm wavelength with linear dispersive characteristics at |20| ps/km.nm dispersion coefficient. We also consider single mode DSF medium with zero dispersion at 1550 nm wavelength. The whole experiment is performed under the consideration of only second order GVD effect on optical pulse propagation.

III. PULSE PROPAGATION EQUATION

The propagation of optical pulses inside single-mode fiber (pulse width > 5 ps) can be written in terms of nonlinear Schrodinger equation for a complex envelope $U(z, T)$ as [1]

$$\frac{\partial U}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 U}{\partial T^2} - \frac{\alpha}{2}U - i\gamma|U|^2 U \quad (1)$$

The three terms on the right-hand side of (1) govern, respectively, the effects of fiber dispersion, losses, and nonlinearity on pulses propagating inside optical fibers. In this analysis we consider only the effect of GVD on optical pulse propagation in a linear dispersive medium; hence (1) can be represented as

$$\frac{\partial U}{\partial z} = -i\frac{\beta_2}{2}\frac{\partial^2 U}{\partial T^2} \quad (2)$$

Equation (2) can be solved by using the Fourier-transform method. If $\tilde{U}(z, \omega)$ is the Fourier transform of $U(z, T)$ then the general solution of (2) is [1]

$$U(z,T) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{U}(0,\omega) exp\left(\frac{i}{2}\beta_2\omega^2 z - i\omega T\right) d\omega \quad (3)$$

Where, $\tilde{U}(0, \omega)$ is the Fourier transform of the incident field at $z=0$ and is obtaining as

$$\tilde{U}(0,\omega) = \int_{-\infty}^{\infty} U(0,T) exp\ (i\omega T) dT \quad (4)$$

Now, if the propagating pulse is a chirped Gaussian pulse which is emitted by directly modulated semiconductor laser, then the incident field can be written as [1]

$$U(z,T) = \frac{T_0}{[T_0^2 - i\beta_2 z(1+iC)]^{1/2}} exp\left(-\frac{(1+iC)T^2}{2[T_0^2 - i\beta_2 z(1+iC)]}\right) \quad (5)$$

However, chirped Gaussian pulse maintains its Gaussian shape during on propagation. The width of T_1 after propagating a distance z is related to the initial width T_0 as [1]

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{C\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2 z}{T_0^2}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

Although pulse emitted from many lasers can be approximated by a Gaussian shape. But, some other pulses particularly the hyperbolic-secant pulse shape that occurs naturally in the context of optical solitons and emitted from some mode-locked lasers is also can be considered. In terms of Hyperbolic-Secant Pulses (6) can be approximated as [1],

$$\frac{T_1}{T_0} = \left[\left(1 + \frac{C\beta_2 z}{T_0^2}\right)^2 + \left(\frac{2\beta_2 z}{\pi T_0^2}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

Moreover, pulse emitted by directly modulated semiconductor lasers is relatively steeper leading and trailing compared to Gaussian pulse. Hence, a super-Gaussian shape is more likely to be used to model the effects of the pulse broadening and the pulse broadening factor can be written as [1]

$$\frac{T_1}{T_0} = \left[1 + \frac{\gamma(1/2m)}{\gamma(3/2m)}\frac{C\beta_2 z}{T_0^2} + m^2(1 + C^2)\frac{\gamma\left(2 - \frac{1}{2m}\right)}{\gamma(3/2m)}\left(\frac{\beta_2 z}{T_0^2}\right)^2\right]^{\frac{1}{2}} \quad (8)$$

Where, m governs the degree of edge sharpness. For m=1, (6) and (8) will be identical. For larger value of m, the pulse becomes square shaped with sharper leading and trailing edges.

IV. BER PERFORMANCE ANALYSIS ON DS-OCDMA SYSTEM

Let we assume an OCDMA system with N simultaneous users where all users have the same effective power at any receiver with the identical bit rate and signal format. For an OCDMA system with N simultaneous users, the received signal $y(t)$ is the sum of N user's transmitted signals, which can be written as [18]

$$y(t) = P_r \sum_{n=1}^{N}\sum_{i=1}^{F} B_n A_n(i) \int_{\tau_n + iT_c}^{\tau_n + iT_c + T_c} g(t - \tau_n - iT_c) dt \quad (9)$$

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 K, 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., $\tau_n = 0$. $g(t)$ 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 maximal and the BER will be an upper bound on the BER for the chip asynchronous case.

Now at receiving terminal, the correlation operation between received signal $y(t)$ and a replica of the desired user's address code is executed by optical correlator to achieve decoding. The decoding signal is incident on the APD receiver, the output current Y_1 sampled at time $t = T_b$ can be written as [18]

$$Y_1 = X_1 + I_1 + I_n \quad (10)$$

Where, X_1 is the desired user's signal current, I_1 is interference signal current offered by MAI, and I_n is the APD noise current that includes shot noise current, bulk dark current, surface leakage current and thermal noise current. We assume that the (F, K, $g(t)$) OOCs are selected as user address codes. By the correlation definition of OOCs, each interference user can contribute at most one hit during the correlation time. If v is an integer ($0 \le v \le N\text{–}1$) denotes the total number of hits from interference users, the probability density function of v is given by [18]

$$P(v) = \binom{N-1}{v} s^v t^{N-1-v} \quad (11)$$

Where, $s = K^2/2F$, $t=1\text{–}s$ and v is an integer ($0 \le v < N\text{–}1$). The output photocurrent Y_1 can be regarded as a Gaussian random variable by assuming that the APD noise current has Gaussian nature. Then it's average photocurrent μ_1 and noise variance σ_1^2 for bit "1" and "0" can be determined. Since the received signal is multiplied by the user address code sequence, (0, 1), during the bit "1" interval of the desired signal, photons fall on the APD only during the K mark intervals and are totally blocked during the $F–K$ space intervals. And during the K chip intervals of the desired signal, the total number of pulses (either marks or spaces) due to N users is KN. Among these KN pulses, there is $(K + v)$ mark pulses with power level $\epsilon_d P_r$, and $KN – (K + v)$ space pulses with power level $\epsilon_d \gamma_e P_r$, where ϵ_d represents the effect of GVD and pulse linear chirp, and γ_e is the Extinction ratio of APD receiver. Therefore, for the data bit "1" μ_1 and σ_1^2 are given by [18]

$$\mu_1 = M(R_0 P_t^1 + I_{BD}) + I_{SL} \tag{12}$$

$$\sigma_1^2 = 2eM^{2+x}(R_0 P_t^1 + I_{BD})B_e + 2eI_{SL}B_e + \frac{4K_BT}{R_L}B_e \tag{13}$$

Where, x is the excess noise index that varies between 0 to1.0 depending on APD, M is the average APD gain, R_0 is unity gain responsivity, e is electron charge. I_{BD} and I_{SL} are the average bulk dark current and surface leakage current, respectively. B_e represents the receiver electrical bandwidth, K_B is Boltzmann's constant, T is receiver noise temperature, R_L is Receiver load resistor and

$$P_t^1 = (K+v)\epsilon_d P_r + (KN-K-v)\epsilon_d \gamma_e P_r \tag{14}$$

$$\epsilon_d = \frac{\sigma_0}{\sigma} = \frac{T_0}{T} \tag{15}$$

The average photocurrent μ_0 and noise variance σ_0^2 of Y_1 can also be determined for data bit "0" in the same way as for data bit "1". In this case, μ_0, σ_0^2 and P_t^0 can be written as

$$\mu_0 = M(R_0 P_t^0 + I_{BD}) + I_{SL} \tag{16}$$

$$\sigma_0^2 = 2eM^{2+x}(R_0 P_t^0 + I_{BD})B_e + 2eI_{SL}B_e + \frac{4K_BT}{R_L}B_e \tag{17}$$

$$P_t^0 = v\epsilon_d P_r + (KN-v)\epsilon_d \gamma_e P_r \tag{18}$$

For the desired user's data bit "1" or "0", the conditional probability density function of the output photocurrent Y_1 can be expressed as

$$P_{Y1}\left(\frac{y}{v}, bit\ 1\right) = \frac{1}{\sigma_1\sqrt{2\pi}} exp\left[\frac{-(y-\mu_1)^2}{2\sigma_1^2}\right] \tag{19}$$

$$P_{Y1}\left(\frac{y}{v}, bit\ 0\right) = \frac{1}{\sigma_0\sqrt{2\pi}} exp\left[\frac{-(y-\mu_0)^2}{2\sigma_0^2}\right] \tag{20}$$

For a given threshold level Th, the probability of error for bit "1"and "0" are calculated by [18]

$$P_e^{(1)}(v) = \int_0^{Th} P_{Y1}\left(\frac{y}{v}, bit\ 1\right) dy = \frac{1}{2} erfc\left[\frac{\mu_1 - Th}{\sigma_1\sqrt{2}}\right] \tag{21}$$

$$P_e^{(0)}(v) = \int_{Th}^{\propto} P_{Y1}\left(\frac{y}{v}, bit\ 0\right) dy = \frac{1}{2} erfc\left[\frac{Th - \mu_0}{\sigma_0\sqrt{2}}\right] \tag{22}$$

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

$$P_e(v) = \frac{1}{2}\left[P_e^{(1)}(v) + P_e^{(0)}(v)\right] \tag{23}$$

Here, it is assumed that the bit "1" and "0" have the identical probability. To make the above expression achieves minimum value; an optimum threshold level can be obtained,

$$Th = \frac{\mu_1\sigma_0 + \mu_0\sigma_1}{\sigma_0 + \sigma_1} \tag{24}$$

The total probability of error P_e per bit is given by [18]

$$P_e = \sum_{v=0}^{N-1} P_e(v)\binom{N-1}{v} s^v t^{N-1-v} \tag{25}$$

V. MATLAB SIMULATION

In this analysis, the chirp effect on various pulses is analysed in terms of probability of bit error. Throughout the experiment, it is assumed that the InGaAs APD is selected as the system receiver, and the specification of APD as follows: mean gain 20, excess noise index 0.7, extensive ratio 0.05, bulk dark current 2 nA, and surface leakage current 10 nA, and receiver load resistance 1000 Ω. OOC address code is used with code length 409 and code weight 4. All the simulation is done at 1550 nm wavelength as operating frequency, and it is assumed that the GVD for standard single mode fiber at 1550 nm is -20 ps/km. Since the GVD parameter β_2 is negative at 1550 nm wavelength, the chirped value is chosen as positive throughout the experiment. It is also assumed that there is no GVD effect for dispersion shifted fiber at 1550 nm wavelength. The whole analysis is performed with chip rate 40 Gbps. Since our main purpose to analyse only chirp effect under GVD regime, the transmission distance is considered within the fiber dispersion length, L_D.

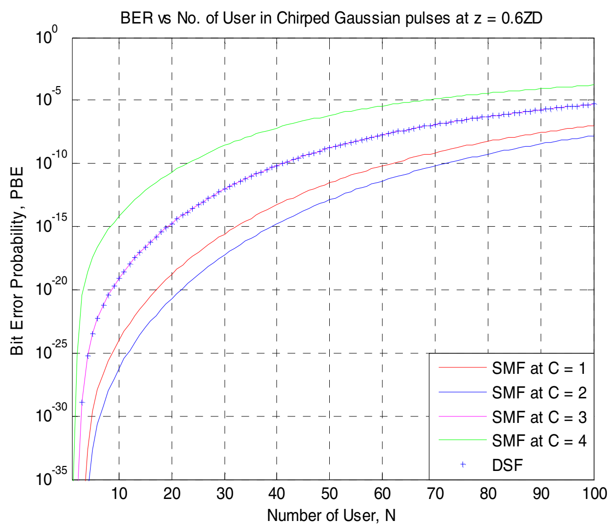

Fig. 1. Chirp effects on Gaussian pulse at z = 0.6L_D with 40 Gbps chip rate.

Fig. 1 demonstrates the chirp effect on Gaussian pulses with distance z = 0.6L_D. It is observed that the use of standard single mode fiber with appropriate chirp value the BER performance in OCDMA is much better than the BER performance compared to dispersion shifted fiber. In this setup it is shown that in case of DSF the BER for 40 simultaneous users is equal to the BER for standard SMF when 70 users simultaneously used the system with chirp value C equal 1. However for different chirp value the system performance is different and after a certain value any additional chirp definitely will degrade the BER.

Fig. 2 depicts the same result when hyperbolic-secant pulse is used to transmit bit at distance $z = 0.6L_D$. Here, it is found that the BER performance is much better in case of hyperbolic-secant pulse compare to Gaussian pulse. In case of super-Gaussian pulse it is also found that the use of standard SMF instead of DSF enhance BER performance of OCDMA system with appropriate chirp value, though the effect is much lower than the rest two pulses. Fig. 3 shows the chirp effect on super-Gaussian pulses (at m = 2) when the transmission distance $z = 0.3L_D$.

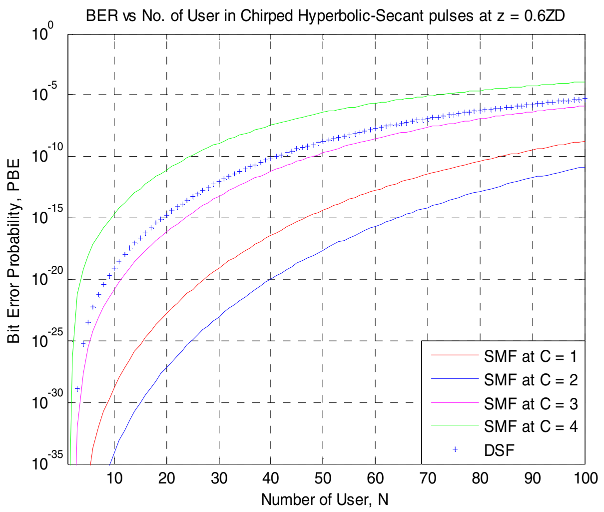

Fig. 2. Chirp effects on Hyperbolic-secant pulse at $z = 0.6L_D$ with 40 Gbps chip rate.

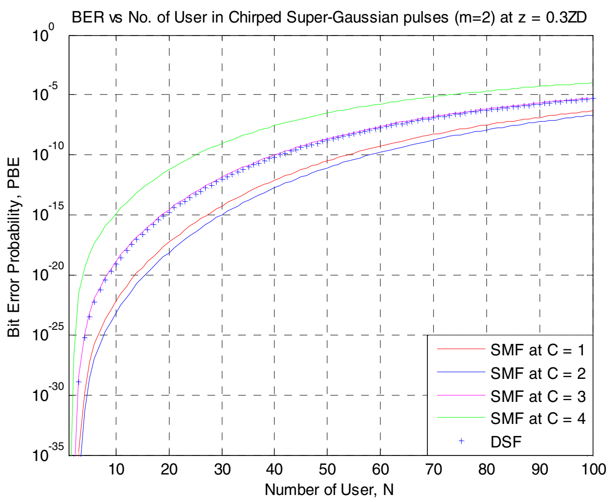

Fig. 3. Chirp effects on super-Gaussian pulse at $z = 0.3L_D$ with 40 Gbps chip rate.

The comparative performance of the all three chirped pulses is shown in fig. 4 and fig. 5 at $z = 0.8L_D$ and $z = 0.4L_D$, respectively. Here, it is evident that chirped Hyperbolic-secant pulse always contributes better BER result compare to rest two types of chirped pulse. It is also cleared that chirped super-Gaussian pulses contribute very limited BER improvement with a limited transmission distance. As the degree of steepness (m) increase both of the BER performance and transmission distance is decreased.

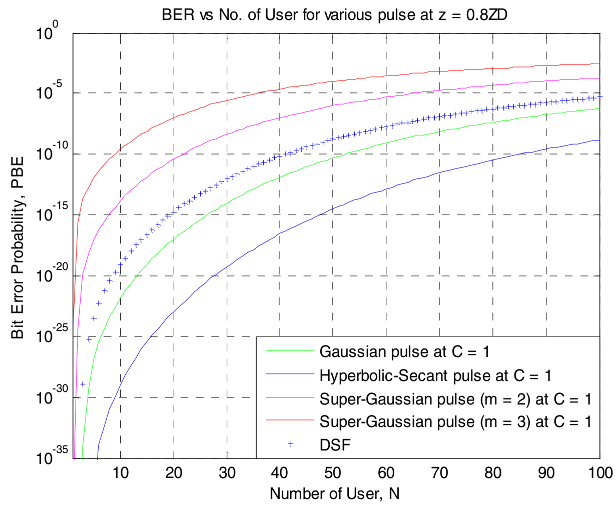

Fig. 4. Chirp effects on various pulses at $z = 0.8L_D$ with 40 Gbps chip rate & chirp equal 1.

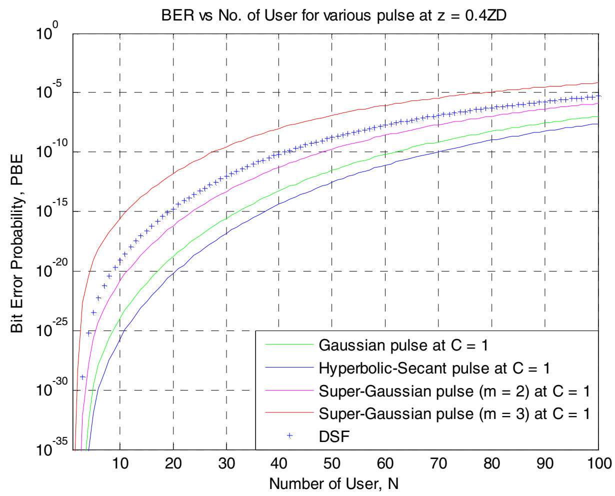

Fig. 5. Chirp effects on various pulses at $z = 0.4L_D$ with 40 Gbps chip rate & chirp equal 1.

However, to design a desirable OCDMA system with optimum BER performance the choice of appropriate chirp value is very crucial. Fig. 6 indicates the relationship between optimal chirp value and transmission distances in case of all three targeted pulses are used to transmit bit with optimal BER performance. Here, it is observed that the chirp value for optimal BER performance is exactly same for Gaussian and Hyperbolic-secant pulses regardless the transmission distance, but as transmission distance increase the chirp effect is oppositely decreased. While in case of super-Gaussian pulse, for optimal BER performance, the chirp value is much lower compared to other two pulses and as the degree of steepness

(m) is increased the value will be more lowered. Also, fig. 7 presents the optimum BER performance with respect to transmission distance for all three pulses.

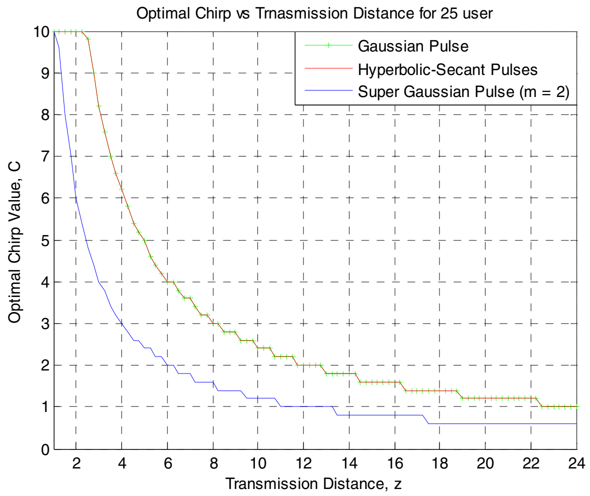

Fig. 6. Chirp values at optimal BER performance versus transmission distance at 40Gbps chip rate with 25 users.

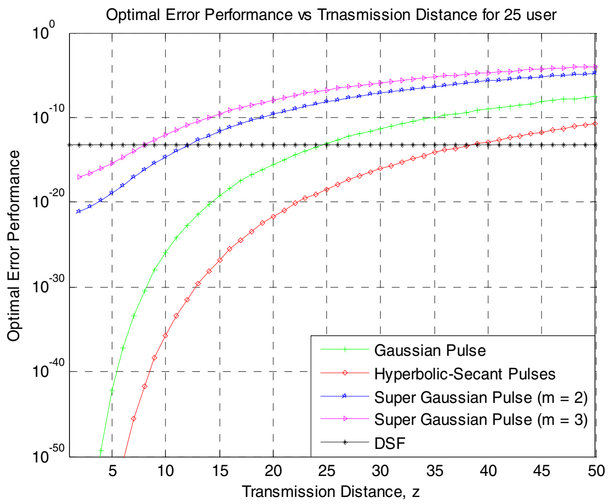

Fig. 7. Optimum BER performance versus transmission distance at 40Gbps chip rate with 25 users.

From fig. 7 it is shown that the optimal BER performance when chirped Hyperbolic-secant pulse is used to transmit bit is much better than other pulses, and the chirp effect still improve BER beyond the dispersion length, L_D (here, $L_D \approx$ 24.5 km). However, chirped Gaussian pulse also significantly enhance BER performance but limited within the dispersion length. Chirped super-Gaussian pulse also inhance the BER performance compared to DSF but the effect is limited within $L_D/2$ when m equal 2, $L_D/4$ when m is 3, and as the m increase the effect oppositely decease as well as the system become more distance bounded.

VI. CONCLUSION

In OCDMA system, maintains BER performance within a tolerable rang is very crucial since as the numbers of simultaneous users contribute the degradation of BER performance due to MAI effect which badly affects the system performance. Many researches have been done and ongoing to further enhance the BER performance with respect to proper code design and advance modulation techniques. In this analysis we propose the use of standard single mode fiber with proper choice of chirp effect in order to compensate the dispersion effect rather than the use of dispersion shifted fiber. We simulate our system with a variety of pulse shapes and find impressive improvement of BER performance in each case. We also evaluate the optimal choice of chirp value for all types of targeted pulses within the GVD length which implies the optimum design of OCDMA system with proper propagation pulse shape.

In this experiment we use zero dispersion effect for dispersion shifted fiber, but in practical case there might have some dispersion (approximately |2| ps/km). Moreover, the above simulation is applicable both of the anomalous-dispersion regime ($\beta_2 < 0$), and the normal-dispersion regime ($\beta_2 > 0$). In each case the chirp value should be selected properly to ensure $C\beta_2 < 0$. Here, our analysis is performed under anomalous dispersive regime (λ = 1550 nm), the GVD parameter β_2 is negative; hence we use positive chirp value to compensate the dispersion effect. Also, we analyse the system with chip rate 40 Gbps, but if higher chip is used then the dispersion length (L_D) will be shorter, and vice versa.

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