Effect of Polarization Mode Dispersion on the BER Performance of Optical CDMA

Md. Jahedul Islam and Md. Rafiqul Islam
Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology
Khulna-9203, Bangladesh.
Email: {jahed_eee, islambit}@yahoo.com

Abstract—In this paper, impact of polarization mode dispersion (PMD) on the bit error rate (BER) performance of direct sequence optical code division multiple access with in-line optical amplifiers is analytically investigated. Intensity modulation direct detection technique is employed in optical correlator receiver. Optical orthogonal codes are used as address sequence. The system BER performance is determined in presence of PMD and different noises induced from receiver, optical amplifiers, and multiple access interference. The power penalty suffered by the system is evaluated at BER of $10^{-9}$. It is found that the BER performance of the proposed system degraded more at high chip rate, chirp parameter and long fiber length due to the effect of PMD. Further, the BER performance of the proposed system is studied in presence of PMD compensation with frequency advanced higher order PMD vectors. The results demonstrate that the system BER performance is improved significantly for a particular fiber length and third-order PMD compensation technique shows better performance compared to first-, and second-order compensations.

Index Terms—OCDMA, MAI, OOC, PMD, and BER Performance.

I. INTRODUCTION

The optical code division multiple access (OCDMA) has drawn significant attention in recent years because of its attractive features such as asynchronous multiple user access, privacy, and security in transmission [1-4]. In previous studies, extensive researches were carried out on intensity modulation and direct detection on-off keying OCDMA [5], pulse position modulation OCDMA [6], spectral-phase encoded OCDMA [4], phase-encoded OCDMA [7], frequency hopping (FH) OCDMA [8], and direct sequence (DS) OCDMA [9]. These studies were carried out [7-9] to evaluate the bit error rate (BER) performance of OCDMA considering only the effect of group velocity dispersion (GVD). It is well known that polarization mode dispersion (PMD) severely degrades the BER performance of optical fiber communication at high bit rate [10-19] due to differential group delay between two principal states of polarization which causes spreading and overlapping of bits. In case of OCDMA system, it is believed that the BER performance will degrade more by the PMD due to transmission of short duration chip. To best of our knowledge, there is no study on DS-OCDMA considering the effect of PMD.

In this paper, an analytical approach is presented to investigate the BER performance of DS-OCDMA with in-line cascaded optical amplifiers taking into account of PMD for a single mode fiber (SMF) operating at 1550 nm assuming that the GVD-induced effect is compensated. In our analysis, Gaussian-shaped optical orthogonal code (OOC) is used as user address. Avalanche photodiode (APD) is used in the optical correlator receiver. The BER performance of the proposed system is determined as a function of system parameters considering different noises associated with the system. It is found that the PMD-induced pulse shape broadening severely degrades the proposed system performance for long fiber length, high chip rate, and chirp parameter. Furthermore, the system performance is studied in presence of PMD compensation and significant improvement of the system performance is found by third-order PMD compensation with respect to first-, and second-order compensations.

II. SYSTEM DESCRIPTION

The schematic block diagram of the proposed OCDMA transmitter, transmission medium with in-line optical amplifier, and optical correlator receiver is shown in Figs.1 (a), (b), and (c), respectively. In the transmitter, user's data is encoded by unipolar signature sequence. The encoded signals of $N$ users are coupled using an $N$:1 coupler and transmitted through optical fiber transmission medium with $n$ sections and $N_{2}[N_{2} = (n-1)]$ in-line optical amplifiers. The gain of the amplifier is adjusted to compensate the loss of the optical signal in each fiber section. In the receiver, a particular user data is decoded by the correlation operation using an optical correlator receiver. The output signal is integrated throughout the data bit period, and then compared with a threshold level at the comparator for data recovery.

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III. THEORETICAL ANALYSIS

A. Pulse broadening due to PMD

The rms pulse width broadening due to the PMD is given by [15]

\[ \sigma^2 = \sigma_0^2 + \frac{1}{4}[\langle \Omega^2 \rangle > -(s, \langle \Omega \rangle)^2 ] \]

(1)

where \( \Omega \) and \( s \) are the input PMD vector and input state of polarization (SOP), respectively. \( \sigma_0 \) is the initial rms pulse width defined as

\[ \sigma_0^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} |f(t)|^2 dt \]

(2)

The bracket, \( \langle \rangle \) denotes frequency average such that

\[ \langle \Omega \rangle = \int_{-\infty}^{\infty} \Omega |F(\omega)|^2 d\omega \]

(3)

\( f(t) \) and \( F(\omega) \) are the initial pulse amplitude and its Fourier transform, respectively. It should be noted that (1) includes all higher order PMD effects and does not depend on the pulse shape. If we define an expected rms broadening \( b \) as

\[ b^2 = E\left\{ \frac{\sigma^2}{\sigma_0^2} \right\} = 1 + \frac{1}{4\sigma_0^2} [E\langle \Omega^2 \rangle > - E\langle (s, \langle \Omega \rangle)^2 \rangle] \]

(4)

where \( E\{\} \) denotes expectation value. From (4), the unchirp broadening factor due to the PMD is given by [15]

\[ b_{UC}^2 = 1 + \frac{1}{4\sigma_0^2} \left[ E\{\Delta \sigma^2\} - \frac{1}{3} \int_{-\infty}^{\infty} G(\omega_1 - \omega_2) \frac{F(\omega_1)^2 F(\omega_2)^2}{4\pi^2} d\omega_1 d\omega_2 \right] \]

(5)

where \( \Delta \sigma \) is the magnitude of the PMD vector \(|\Omega|\), referred to as the differential group delay (DGD). In deriving (5), the order of the frequency integration and averaging was changed, and the frequency correlation of the PMD vector is used, which is given by [16]

\[ E\{\Omega_j(\omega_1) \Omega_j(\omega_2)\} = \frac{1}{3} \delta(i-1) G(\omega_1 - \omega_2) \]

\[ 1 - \exp \left[ - \frac{E\{\Delta \sigma^2\}}{3} (\omega_1 - \omega_2)^2 \right] \]

(6)

For an intensity normalized unchirped Gaussian initial pulse, the broadening factor is calculated analytically and given by

\[ b_{UC}^2 = 1 + z - \frac{1}{2} \left[ \frac{1 + 4\pi z^2}{3} \right] - 1 \]

(7)

where \( z = \frac{\Delta \sigma^2}{\sigma_0^2} \).

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Fig. 1: Schematic block diagram of proposed OCDMA system (a) transmitter, (b) transmission medium with in-line optical amplifier, and (c) optical correlator receiver.
Also for an intensity normalized chirped Gaussian initial pulse, the broadening factor is calculated analytically and given by
\[ b_{\text{chirp}}^2 = 1 + z - \frac{1}{2(n + C^2)} \left[ 1 + \frac{4}{3} \left( 1 + C^2 \right)^2 \right] - 1 \] (8)
where
\[ z = E\{\Delta \sigma^2\} = \frac{D_{\text{PMD}}^2}{4\sigma^2_0} \cdot \frac{L}{n} \] (9)
Here \( L \) is the length of the fiber, \( D_{\text{PMD}} \) is the polarization mode dispersion coefficient and \( C \) is the chirp parameter. The frequency correlations between the higher order PMD vectors, which are defined as frequency derivatives of the PMD vector, can be derived by differentiating (6)
\[ E\{\Omega^{(v)}(\omega_1), \Omega^{(v)}(\omega_2)\} = \frac{d^{(v+1)}G}{d\omega_1 d\omega_2} \] (10)
which also gives us the expectation of the higher order PMD vector as a function of \( E\{\Delta \sigma^2\} \). In (10), \( \Omega^{(v)} \) is the \( v \)-th-frequency derivative of the PMD vector, that is, the \((v+1)\)-th-order PMD vector.

**B. PMD Compensation with frequency advanced higher-order PMD vectors**

In this section, a simple approach to higher-order PMD compensation is presented with frequency advanced higher-order PMD vectors. The idea is to use the frequency average of the higher order PMD vector of the fiber in emulating the compensation PMD vector. The compensation PMD vector will be in the form of
\[ \Omega_{c} = \omega + < \Omega^{(1)} > \omega + < \Omega^{(2)} > \left( \omega^2 / 2 \right) \ldots \] (11)
This compensation vector may not be a good approximation of the fiber PMD vector near the center frequency for large PMD values, but in terms of PMD compensation, it may be more effective. The performance of this approach is analyzed in the section IV.

**BII. First-Order Compensation**

In the first-order compensation, the total PMD vector is \( \Omega_{1s} = \Omega - < \Omega > \). The broadening factor calculated in the same way can be given by
\[
E\{< \Omega_{1s} >\} = E\{< \Omega^2 >\} - E\{< \Omega >^2\} = E\{\Delta \sigma^2\} - \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| G(\omega_1 - \omega_2) \right|^2 \left| F(\omega_1) \right|^2 \left| F(\omega_2) \right|^2 \frac{d\omega_1 d\omega_2}{4\pi^2} \] (12)
\[ b_{1s}^2 = 1 + z - \frac{2}{2(n + C^2)} \left[ 1 + \frac{4}{3} \left( 1 + C^2 \right)^2 \right] - 1 \] (13)

**BII. Second-Order Compensation**

Applying the idea to the second-order compensation, the total PMD vector becomes
\[ \Omega_{2s} = \Omega - < \Omega > - < \Omega^{(1)} > \omega \] . The broadening factor can be represented by
\[
E\{< \Omega_{2s} >\} = E\{< \Omega^3 >\} + E\{< \Omega^{(1)} >^2 \omega^2 > - 2 < \Omega < \Omega^{(1)} > \omega^2 >
- 2\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{dG}{d\omega_1} \left| F(\omega_1) \right|^2 \left| F(\omega_2) \right|^2 \frac{d\omega_1 d\omega_2}{4\pi^2} \] (14)
\[ b_{2s}^2 = b_{1s}^2 + \frac{2}{2(n + C^2)} \left[ 1 + \frac{4}{3} \left( 1 + C^2 \right)^2 \right] - 3(1 + \frac{4}{3} \left( 1 + C^2 \right)^2) \frac{1}{2} \] (15)

**III. Third-Order Compensation**

In the third-order compensation, the total PMD vector is \( \Omega_{3s} = \Omega - < \Omega > - < \Omega^{(1)} > \omega - < \Omega^{(2)} > \omega^2 / 2 \). The broadening factor is calculated as follows:
\[
E\{< \Omega_{3s} >\} = E\{< \Omega^4 >\} + E\{< \Omega^{(1)} >^3 \omega^3 > + E\{< \Omega^{(1)} >^2 \omega^2 > - 3 < \Omega^{(1)} > < \Omega^{(1)} > \omega^2 >
- 3\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{dG}{d\omega_1} \left| F(\omega_1) \right|^2 \left| F(\omega_2) \right|^2 \frac{d\omega_1 d\omega_2}{4\pi^2} \] (16)
\[ b_{3s}^2 = b_{2s}^2 + \frac{2}{2(n + C^2)} \left[ 1 + \frac{4}{3} \left( 1 + C^2 \right)^2 \right] - \frac{20}{3} + \frac{3}{4} \left( 1 + \frac{4}{3} \left( 1 + C^2 \right)^2 \right) \frac{1}{2} \] (18)

**C. The BER Calculation**

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 \( y_{\text{out}}(t) \) is the sum of \( N \) user’s transmitted signals, which can be given by
\[
y_{\text{out}}(t) = P_{\text{S}} \sum_{j=1}^{N} \sum_{i=1}^{\text{N}} B_i A_j \delta(i,j) \delta(t - t_i - t_f) dt \] (19)
where $P_b$ is the received pulse peak power, $B_i$ is the $i$-th user’s binary data bit (either “1” or “0”) with duration $T_b$, at time $t$ $(0 < t < T_b)$, $A_i(t)$ is the $i$-th chip value (either “1” or “0”) of the $i$-th user address code with code length $F$, code weight $W$, and $\alpha_i$ is the time delay associated with the $i$-th user’s signal. Without loss of generality, we assume that user 1 is the desired user, all delays $\alpha_i$ at the receiver are relative to the first user delay only, i.e., $\alpha_1 = 0$. $g(t)$ is the Gaussian function with period $T_c$, and satisfies the normalization condition. All users are assumed chip synchronous, i.e., $\alpha_i = nT_c$, and $0 \leq n < F$ is an integer. In that case, the multiple access interference (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 $Y_1$ sampled at time $t = T_b$ can be written as

$$Y_1 = \mu_1 + \mu' + \mu_n + \mu_a$$  \hspace{1cm} (20)

where $\mu_1$ is the desired user’s signal current, $\mu'$ is the interference signal current due to MAI, $\mu_n$ is the APD noise currents (shot noise current, bulk dark current, surface leakage current, and thermal noise current), and $\mu_a$ is the optical amplifier noise currents (signal spontaneuous beat noise and spontaneuous-spontaneous beat noise currents). 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 $\gamma$ denotes the total number of hits from interference users, the probability density function of $\gamma$ is given by

$$P(\gamma) = \binom{N-1}{\gamma} p^\gamma q^{N-1-\gamma}$$  \hspace{1cm} (21)

where $p = W^2/2F$, $q = 1 - p$ and $\gamma$ is an integer $(0 \leq \gamma \leq N-1)$. If code length $F$, code weight $W$ and $\gamma$ are given, the first two terms in (20) can be determined. We assume that the noise currents have Gaussian distribution. The output photocurrent $Y_1$ can be regarded as a Gaussian random variable. Its average $I_1$, and $I_0$ and variance $\sigma^2_1$, and $\sigma^2_0$ for bit “1”, and “0”, respectively. Since the received signal is multiplied by the user address code, i.e., (0,1) sequence. For 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 $\sigma_b P_R$, and $WN - (W + \gamma)$ space pulses with power level $\sigma_b eP_R$. Here, $\sigma_b$ include the effect of PMD, and $\varepsilon$ is the extinction ratio of APD. Therefore, for data bit “1” the average photocurrent $I_1$ and noise variance $\sigma^2_1$ are given by

$$I_1 = M \left[ R_0 G P_1^a + I_{BD} \right] + I_{SL}$$  \hspace{1cm} (22)

$$\sigma^2_1 = 2e^\varepsilon M^2 \left[ R_0 G P_1^a + I_{BD} \right] b_0 + 2e^\varepsilon \sigma_b eP_R + \frac{4\kappa B T}{R_L} b_0 + \left( I_{SL} L \right)^2 \frac{b_0 (2b_0 - b_1)}{2b_0}$$  \hspace{1cm} (23)

where the exponent $x$ varies between 0 and 1.0 depending on the APD material and structure, $M$ is the average APD gain, $R_0$ is the unity gain responsivity, $\varepsilon$ is the electron charge, $I_{BD}$ is the average bulk dark current, which is multiplied by the avalanche gain, $I_{SL}$ is the average surface leakage current, which is not affected by avalanche gain, $b_0$ is the receiver electrical bandwidth, $\kappa_B$ is the Boltzmann’s constant, $T$ is the receiver noise temperature, and $R_L$ is the receiver load resistor.

$$P_1 = (W + \gamma) \sigma_b P_R + (WN - W - \gamma) \sigma_b eP_R$$  \hspace{1cm} (24)

$$I_{SP} = N_A N_{SP} (G - 1) b_0$$  \hspace{1cm} (25)

$$I_0^1 = \frac{2e^\varepsilon eP_R}{h \nu (\varepsilon + 1)}$$  \hspace{1cm} (26)

where $N_{SP}$ is the spontaneous emission factor, $N_A$ is the number of optical amplifier, $G$ is the gain of optical amplifier. $\sigma_b (= 1/b)$ is the ratio of initial rms pulse width $\sigma_0$ to output rms pulse width $\sigma$. For data bit “0”, the average photocurrent $I_0$ and noise variance $\sigma^2_0$ of $Y_1$ can be determined in the same way as for data bit “1”. In this case, $I_0$ and $\sigma^2_0$ can be written as

$$I_0 = M \left[ R_0 G P_1^0 + I_{BD} \right] + I_{SL}$$  \hspace{1cm} (27)

$$\sigma^2_0 = 2e^\varepsilon M^2 \left[ R_0 G P_1^0 + I_{BD} \right] b_0 + 2e^\varepsilon \sigma_b eP_R + \frac{4\kappa B T}{R_L} b_0 + \left( I_{SL} L \right)^2 \frac{b_0 (2b_0 - b_1)}{2b_0}$$  \hspace{1cm} (28)

where $P_1^0 = \gamma \sigma_b P_R + (WN - \gamma) \sigma_b eP_R$  \hspace{1cm} (29)

$$I_0^0 = \frac{2e^\varepsilon eP_R}{h \nu (\varepsilon + 1)}$$  \hspace{1cm} (30)

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

$$P_{Y_1} \left( I_{Y_1} \right) = \frac{1}{\sqrt{2\pi \tau^2_1}} \exp \left[ \frac{- (I_{Y_1} - \mu_1)^2}{2\tau^2_1} \right]$$  \hspace{1cm} (31)
For a given threshold level \( I_D \), the probability of errors for bit “1” and “0” are calculated by

\[
P_e^{(1)}(\gamma) = \int_{I_D}^{\infty} P_{Y_1}(I|\gamma) dI = \frac{1}{2} \text{erfc} \left( \frac{I_D - I_0}{\sqrt{2} \tau_0} \right)
\]

\[
P_e^{(0)}(\gamma) = \int_{0}^{I_D} P_{Y_1}(I|\gamma) dI = \frac{1}{2} \text{erfc} \left( \frac{I_0 - I_D}{\sqrt{2} \tau_0} \right)
\]

The probability of error per bit depends on the threshold level \( I_D \) and can be defined as

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

The threshold level \( I_D \) is given by

\[
I_D = \frac{\tau_0 I_1 + \tau_1 I_0}{\tau_0 + \tau_1}
\]

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

\[
P_e = \sum_{j=0}^{N-1} P_e(\gamma) \binom{N-1}{\gamma} p^\gamma q^{N-1-\gamma}
\]

IV. RESULTS AND DISCUSSION

Following the analytical formulations in the preceding section the BER performance of a DS-OCDMA system is evaluated in presence of PMD and PMD compensation technique. In the numerical calculation, InGaAs APD is selected in 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 parameters are receiver load resistor \( R_L=1000 \) \( \Omega \), extinction ratio \( \varepsilon = 0.05 \), spontaneous emission factor \( N_0 = 1.4 \), and the gain of each erbium doped fiber amplifier is adjusted to compensate the fiber attenuation in each fiber section. The parameters of the single mode fiber used for numerical computations are: chromatic dispersion coefficient \( D_c = 0 \) ps/(km.nm) assuming that GVD is compensated. The PMD co-efficient \( D_{PMD} = 0.5 \) ps/\( \sqrt{km} \) and fiber attenuation = 0.2dB/km are considered at wavelength \( \lambda = 1550 \) nm. Fig. 2 depicts the plot of BER versus number of simultaneous users for constant transmitted signal power. The results are evaluated for Gaussian-shaped chip with different values of fiber length \( L \) when chip rate = 80 Gchip/s. It is found that the BER performance of the proposed system is highly dependent on the number of simultaneous users as well as fiber length. The BER performance degrades with number of users due to the effect of MAI for all values of \( L \). It is also found that for a particular number of users, the BER performance is aggravated with increasing fiber length due to the effect of PMD. This is because the amount of birefringence increases with increasing fiber length. The BER performance is further plotted in Fig. 3 with respect to received power for different fiber lengths when chip rate = 80 Gchip/s, and number of simultaneous user = 10. It is found that the amount of received signal power increases with increasing fiber length in order to maintain a constant BER of 10\(^{-9}\), because the signal power to noise power ratio (SNR) goes below the base receiver sensitivity due to the effect of PMD. The power penalty suffered by the system is determined at BER of 10\(^{-9}\) and plotted in Fig. 4 with respect to the chip rate for different fiber lengths. The results are determined for the
It is found that the power penalty increases with increasing chip rate due to the effect of PMD. It can be depicted that, with increasing chip rate, the chip duration becomes very short, consequently, the possibility of interchip interference increases between the adjacent chips due to the differential group delay resulted from the PMD. The PMD-induced penalty is found to be almost negligible for chip rate lower than 10Gchip/s. However, it is evaluated to be 3.28dB when chip rate increases from 10Gchip/s to 80Gchip/s for the fiber length of 150km. It is also found in Fig. 4 that for a constant chip rate the system suffers more penalties with increasing fiber length. The PMD-induced penalty increases from 6.345dB to 9.117dB with increasing fiber length from 50km to 200km for a constant chip rate of 80Gchip/s. Fig. 5 shows the plot of power penalty verses number of simultaneous users for different chip rates when fiber length = 100km. It is found that the proposed system suffers more penalty with increasing number of users due to the effect of MAI. It is also found that for a particular number of users, the penalty increases with increasing chip rate due to interchip interference caused by PMD-induced broadening of short duration chips. To understand the influence of chirp (C) on the performance of OCDMA in presence of polarization mode dispersion, the system performance as a function of chirp parameter is determined. The results are shown in Fig. 6 with respect to chip rate where it is found that the system performance does not improve with chirp parameter.
It is presumed that the BER performance of the proposed OCDMA can be improved by the PMD compensation using a suitable compensation technique. Using the mathematical formulations presented in the previous section, the BER performance of the proposed system is further evaluated in presence of frequency advanced higher-order PMD compensation technique. The power penalty suffered by the system is determined at BER of $10^{-9}$ as a function of chip rate. Fig. 7 shows a comparison among the power penalties evaluated taking into account of PMD and different order of PMD compensation for fiber length 100km and number of user 10. It is found that the PMD-induced penalty is almost negligible below 30Gchip/s and increases sharply with increasing chip rate. This is because differential group delay between two principle states of polarization increases with increasing chip rate. The PMD-induced penalties are found to be compensated by 1.59dB, 2.13dB, and 2.25dB, using the first-, second-, and third-order PMD compensations, respectively. It is also found in Fig. 7 that there is a constant penalty (~5dB) at lower chip rate that can not be compensated, because this penalty is due to different noises for the proposed system.

To understand the performance of PMD compensation in terms of PMD co-efficient the system BER performance is further evaluated for 100km fiber length, 80Gchip/s and number of users 10. The results are shown in Fig. 8 where the compensation performance found to improve with increasing PMD co-efficient. The results indicate that, using the first-, second-, and third-order PMD compensations, it is possible to compensate PMD-induced penalties approximately 1.94dB, 2.92dB, and 3.24dB, respectively, for the PMD-coefficient 0.9 ps/√km. The results presented in Figs. 7 and 8 indicate that using the frequency advanced higher order PMD vectors it is not possible to have full compensation. The results also indicate that third-order PMD compensation gives better results than the first-, and second-order compensations. To understand the extent of effectiveness of the proposed compensation technique, the amount of PMD-induced compensated penalty is plotted in Fig. 9 with respect to fiber length. The results are evaluated at 80Gchip/s and number of user 10. It is found that the proposed compensation technique is suitable to compensate PMD-induced penalty up to 250km, 350km, and 400km fiber length for the first-, second-, and third-order PMD, respectively. After that the compensator performance is found to be degraded with fiber length due to the limitation of the proposed compensation technique.

V. CONCLUSION

The BER performance of the proposed DS-OCDMA system is evaluated in presence of PMD of a single mode fiber operating at 1550nm assuming that GVD is compensated. The results obtained in the present study demonstrate that the system BER performance degrades severely due to PMD at higher chip rate. The typical value of power penalty changes from 5.041dB to 7.44dB for increasing the chip rate from 10Gchip/s to 80Gchip/s when fiber length is 100km and number of user is 10. It is also found that the BER performance of the proposed system degrades due to PMD with increasing transmitting fiber length. The system suffers power penalty from 6.054dB to 8.399dB when fiber length is increased from 50km to 200km at chip rate of 70Gchip/s. The power penalty is found to increase from 5.244dB to 8.594dB when number of simultaneous user increases from 5 to 25 for the fiber length of 100km, and chip rate of 60Gchip/s. It is also found that the BER performance of the proposed system is degraded with chirp parameter. The typical value of power penalty increases 5.707dB to 7.841dB for increasing the chirp parameter from 0 to 3 at fiber length of 100km, and chip rate of 40Gchip/s. The BER
performance of the proposed system can be improved in presence of frequency advance higher-order PMD compensation technique. The PMD-induced penalty is reduced about 65%, 87%, and 92% using first-, second-, and third-order PMD compensation, respectively, at fiber length of 100 km, and chip rate 80 Gchip/s. The results obtained in the present study indicate that the proposed compensation technique is suitable for a particular fiber length.

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Md. Jahedul Islam received his B.Sc. and M.Sc. degrees in Electrical and Electronic Engineering from Khulna University of Engineering & Technology (KUET), Khulna, Bangladesh, in 2009, and 2011, respectively. He is currently working as a lecturer in the department of Electrical and Electronic Engineering, KUET, Khulna-9203, Bangladesh. His research interests include optical fiber communication, and free space optical communication.

Md. Rafiqul Islam received the B.Sc. degree in Electrical and Electronic Engineering from KUET, Khulna, Bangladesh, in 1991. He did M.Sc. degree in Electrical and Electronic Engineering from BUET, Dhaka, Bangladesh, in 1998. He did Dr. Engineering from Kyoto Institute of Technology, Japan, in 2004. He is currently working as a professor in the department of Electrical and Electronic Engineering, KUET, Khulna-9203, Bangladesh. His research interests include optical fiber communication, compound semiconductors, magnetic semiconductors, and optoelectronic devices. He has published more than 60 referred articles in international Journals/Conferences. He is a member of IEEE.