Impact Analysis of PMD and GVD on the Performance of Optical Fiber Communication Employing OFDM - QAM Technique

Md Shahabul Alam, Md Abul Hossain

***Abstract*— In this paper the performance of optical fiber communication system is analytically investigated on account of fiber chromatic and polarization mode dispersion employing OFDM-QAM. The influence of the dispersions on the signal spectrum is determined as a function of fiber length, Bit rate and dispersion parameters for intensity modulation/ direct-direct (IM/DD) receiver. It is found that the bit error rate (BER) performance of the system is highly dependent on fiber length, bit rate and dispersion parameters. The power penalty suffered by the system is evaluated at BER=10^{-09} for single mode fiber operating at 1.55 µm wavelength. It is found that the proposed system performance mainly degrades due to dispersion when the system operates at higher bit rates.**

***Index Terms*— OFDM-QAM, communications system performance, group-velocity dispersion, polarization-mode dispersion, Chromatic dispersion, Bit Error Rates.**

I. INTRODUCTION

In recently optical fiber communication systems have radically changed the telecommunications industry and other communication systems by utilizing the optical bandwidth as well as power efficiently. The novel transmission systems have been developed in early years such as WDM, DWDM, OFDM and TDM. The main goal is that to fulfill the high bit rate demand with less power penalty. But these transmission systems suffer from much dispersion such as CD and PMD. These dispersions are important linear distortions that affect the performance of high speed optical fiber transmission systems. The CD and PMD effects can be describes in time domain as well as frequency domain. The modulations and multiplexing techniques are vastly used in communication systems to reduce the system bandwidth effectively. Though chromatic dispersion (CD) is not a limiting factor in subcarrier multiplexing (SCM) systems but polarization mode dispersion (PMD) has a great impact on SCM system with 10Gb/s capacity performance due to radiofrequency phase detection at receiver end and one had showed the significant of receiver sensitivity (BER) corresponding to received optical power level [1]. The impact of CD and PMD on differential phase-shift keying (DPSK) systems is also considerable. Reference [2] have analyzed binary differential phase-shift keying (2-DPSK) or quaternary DPSK (4-DPSK) with nonreturn-to-zero (NRZ) or return-to-zero (RZ) formats in relation to the impact of CD and PMD. Aside this also has been computed BER's and power penalties for these systems.

Manuscript received September, 2013.

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If one can considers only first-order PMD distortion, it has been provided the good approximation for the true power penalty than all orders of PMD for a given outage probability caused by PMD in a direct detection 10 Gbit/s NRZ system with 30ps of rise time and 27ps of polarization dispersion [3]. Because in the first-order approximation, the principal states of polarizations (PSP's) and the differential group delay (DGD) remain unchanged with frequency. However, higher-order PMD can cause additional distortion and degradation of the transmitted signal due to change the PSP's as well as DGD for larger change in frequency [4]. In addition, both PSPs and DGD vary with time making PMD a statistical process. The references [5] and [6] have showed the PMD impact on transmission beyond first-order as well as second-order respectively. The performance evaluation in terms of bit error probability of light wave communication systems with CD has cited in [7]. Dispersion effects in optical millimeter-wave systems also have drawn in [8] using self-heterodyne method. Both the single sideband subcarrier multiplexed (SSB-SCM) and double sideband subcarrier multiplexed (DSB-SCM) signals will show the similar sensitivity to PMD induced power fading. It has been experimentally investigated the PMD induced optical power fading penalty (~20 dB) as a function of DGD for DSB-SCM and SSB-SCM signals with an average DGD of -40 ps. And also have measured bit error rate corresponding to the received optical power for a 155 Mbit/s DSB-SCM and SSB-SCM binary-phase-shift-keyed (BPSK) signals at 7 GHz with and without first-order compensation [9].

In a single mode fiber (SMF) communication systems, PMD causes a differential group delay (DGD) which is time varying between two polarization states. This PMD impact can be suppressed by fractionally spaced equalizer (FSE) as PMD is a linear effect with DGD. The FSE can compensate any arbitrary amount of CD and first-order PMD distortions in dually polarized coherent optical communication systems which have demonstrated in [10]. Also there have several solutions to diminish the effect of different PMD schemes have been illustrated based on electronic, optical and optoelectronic signal processing [11]-[14]. It has been experimentally demonstrated that a successful PMD distortion compensation in combination with CD distortion of 100km SMF at 10 Gbit/s by electronic equalisation in the receiver where more than 11 dB optical power penalty reduction have measured [15]. However, the CD limitation for various coherent light wave transmission systems is more severe than direct detection on-off keying (OOK) systems [16].

Since the PMD value of optical transmission line is identified as the average value of DGD and thus a PMD limit has to given for both power penalty and outage probability. The PMD compensator scheme has been fully described to overcome this PMD limit in [17]-[19]. The PMD equalizer has allowed excellent compensation for DGD's ranging between 0 and 1.7 bit durations in transmission systems with bit rates 10, 20 and 49 Gbit/s [20]. In this distributed equalizer, a pure first-order PMD compensator would have been inadequate due to higher order PMD. A combination of OFDM and optical single sideband modulation (OSSB) has been utilized to compensate CD distortion in ultra-long-haul 10 Gbit/s standard SMF links but it requires high power [21]. Reference [22] has demonstrated that OFDM using a simple direct-detection can post compensate for dispersion in over 320km of SMF at 20 Gbit/s. But the system performance is limited by the response of the arbitrary waveform generator (AWG) as well as optical amplifier. The optical single sideband (OSSB) modulation can adaptively compensate for CD dispersion high capacity long-haul WDM SMF system links including 40% spectral efficiency [23] without using a feedback path. Arthur James Lowery and Jean Armstrong [24] have proposed that the OFDM technique offers an excellent method of compensating for single mode as well as multipath dispersion in optical systems. OFDM can compensate for linear distortions like PMD and GVD, the reference [25] have computed a specific power penalty for GVD and first-order PMD considering a minimum number of subcarriers and cyclic prefix length where GVD is the dominant impairment because it requires large cyclic prefix length than PMD. So, a large fraction of the transmitted energy is required for sampling the large cyclic prefix which leads to more power penalty.

From the above studies it is seen that there are several papers on PMD and CD dispersions and the relevant solutions for dispersion compensation of optical fiber communication systems include OFDM system. However, there is only one paper concerning combined OFDM & QAM technique namely OFDM-QAM system have presented [26] for adaptive dispersion compensation of long haul optical fiber system operating at 1.55µm having dispersion coefficient 20 ps/nm/km for bit rate 64 Gbps. Although optical fiber provides enormous bandwidth, the system performance severally degrades due to dispersion. It is therefore very much important to investigate how an OFDM-QAM system is influenced in presence of dispersion, particularly, chromatic dispersion and polarization mode dispersion. Our system performance is evaluated at a bit error rate 10^{-9} for a single mode fiber operating at 1.55µm.

II. PROPOSED SYSTEM MODEL

OFDM is a multicarrier transmission system based on the principle of transmitting data by dividing the stream into several parallel bit streams. That is, data is transmitted over many parallel frequencies or subcarriers say n and each with a baud rate of of the total data rate, where m is the order of the m-QAM modulation of each subcarrier and each subcarrier should be more tolerable to propagation effects specially CD effect and this dispersion limit is inversely proportional to the square of the baud rate. As the orthogonal carrier provides more compact spectrum and thus dispersion effect will be less in OFDM-QAM system. The Fig. 1 shows the block diagram of OFDM-QAM system [26] which is consists of transmitter, transmitting medium and receiver. According to the system model, The data stream is first subdivided into a number of sub-streams and then converted the digital data into parallel data by using digital to analog converter (DAC) afterward each one has to be modulated by using a QAM technique over a separate carrier signal (called subcarrier) according to even and odd function. After that the adder have added the I-channel and Q-channel modulated data and thus we have got the QAM signal and each channel signal is modulated by sub-carriers which are orthogonal to each other and the frequency spacing between carriers is 1/T (where T is the symbol period. Finally the signals from all channels are multiplexed.

The OFDM signal is then modulated by laser light wave which is a coherent source of light and finally we have got the desired OFDM-QAM signal and then this signal passed through Optical Fiber Link. Optical modulator converts the electrical energy into optical energy. When the signal passes through the fiber, due to different group velocities of different signal they will arrive at different times. For digital modulation of the carrier, this results in dispersion. The dispersion effect also depends on fiber length, laser line width, bit rate of the fiber input signal and the number of channel used to send the signal. As a result ICI occurs due to the broadening of OFDM channel signal. In case of high bit rate signal the dispersion effect limit the bit rate of the signal, as a result the signal cannot be send through the long length fiber. The photo detector converts the optical energy into electrical energy. The photo detector detects the OFDM signal which is modulated by laser light wave.

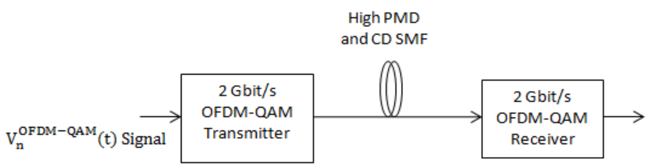

Fig.1 Simplified version of proposed system model

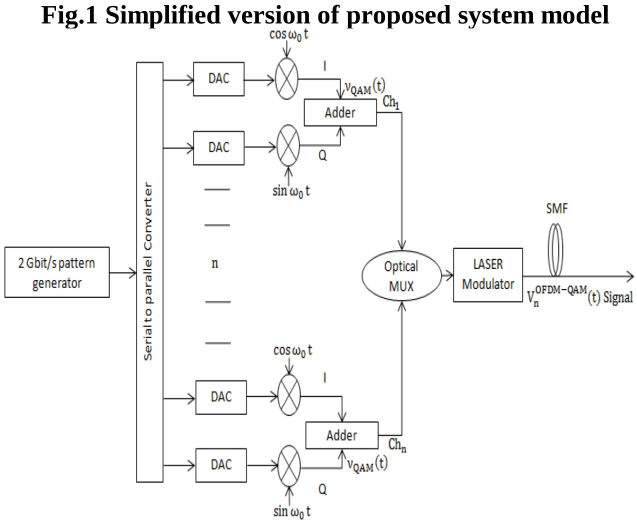

Fig.2 Transmitter for generation of OFDM-QAM signal.

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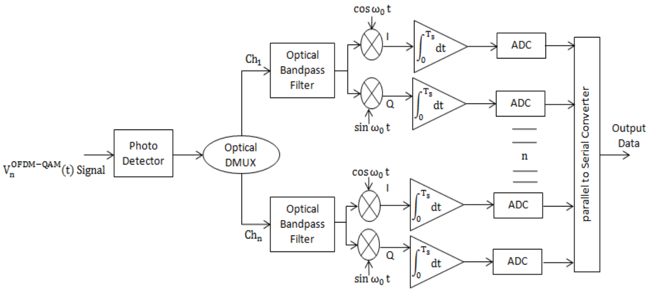

Fig.3 Receiver for reception of OFDM-QAM signal.

In the receiver, OFDM-QAM signal is detected by using OFDM-QAM detector and all the subcarriers are demodulated. For recovering each channel signal optical band pass filter are used specially cosine filters as like [26]. The cut off frequency of each signal is determined from OFDM-QAM signal. However, there are some noises exist such as shot noise, thermal noise and so on. And for removing these noises, each channel signal is filtered by low pass filter. The analog to digital converter (ADC) converts the incoming analog signal to digital signal. Lastly, The OFDM-QAM values are de-mapped into binary values, and finally a parallel to serial converter converts the binary values to serial and sends out the information bits with high rate, which is exactly replica of the original binary bit streams at the transmitter.

III. GENERATION OF OFDM-QAM SIGNAL

The base band signals are first modulated by using M-ary QAM modulation technique. A detailed description of M-ary QAM can be found in [l] where we can find the expression for QAM symbol.

$$V_n^{OFDM-QAM}(t) = \sum (A_e(t)\sqrt{P_s}\cos n\omega_0 t + A_0(t)\sqrt{P_s}\sin \omega_0 t) \qquad (1)$$

Where $A_e, A_0 = \pm\sqrt{0.2} or \pm 3\sqrt{0.2}$

For orthogonal sub carrier the carrier spacing between each channel is $1/T$. The equation (1) is the time domain signal. Here used 16-QAM symbols. Each symbol consists of four bit having the bit period of $T=5\times10^{-10}$ sec. Thus symbol period is $T_s=4\times T=2\times10^{-10}$sec. To transmit the OFDM-QAM signal, 16 different carriers have been used. The carrier frequency for 1st channel is 1GHz. The sampling period of the carrier is 7.8125×10^{-12} sec, where the number of the sample is 128.

The dispersion-induced distortion on OFDM-QAM spectrum can be analyzed by means of fiber transfer function [11]. The transfer function of single mode fiber is given by

$$H(\omega) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{\frac{j\omega\tau}{2}} & 0 \\ 0 & e^{\frac{-j\omega\tau}{2}} \end{bmatrix} \times \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \times e^{-j\frac{1}{2}\beta_2 L_{fiber}\omega^2} \qquad (2)$$

Where β_2 is the fibers GVD parameter, L_{fiber} is the fiber length, θ is the angle between the reference polarizations and the principal state of polarization (PSP) of the fiber, and τ is the differential group delay (DGD) between the PSP.

The fiber GVD parameter β_2 is given by $\beta_2 = (-(D(\lambda)\lambda^2)/2\pi c$, Where D (λ) is the fiber CD parameter, L is the fiber length, and λ is the wavelength. At a wavelength λ=1.55μm in standard, D (λ) is the order of 17ps/nm/km [12].

The impulse response of the fiber transfer function is, $h(t)=F^1\ [H(f)]$ (3)

The optical signal at the output of the fiber can be obtained as follows:

$P_r(f)=v(f)\times H(f)$ (4)

The influence of dispersion on the normalized power spectral density of the OFDM-QAM spectrum can be obtained by (5):

$$I_{avg} = \frac{1}{f}\left[\int_0^f P(f)df\right] \qquad (5)$$

Where $P(f)$ is the normalized power spectral density.

The ratio of the signal power to noise power is called SNR. In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise. The higher the ratio, the less obtrusive the background noise is. "Signal-to-noise ratio" is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange.

The SNR is given by $SNR=S/N_{total}$ (6)

Where S is the signal power and is given by $S=[I(t)]^2$ and $I(t)=I_{avg}RPA_{PMD}$

Here I_{avg} is the average power of the normalized signal.

R is the responsivity and varies from 0.80-0.90A/w

P is the input power in watt.

A_{PMD} is the constant factor by which the electrical signal at output is decreased.

$$A_{PMD} = \cos\left[(\frac{\Delta\theta}{2})\right] = \cos\left[(\frac{(\Delta\tau.\Delta\omega)}{2})\right] \qquad (7)$$

Here $\Delta\omega$ is the frequency separation between the carrier and the subcarrier is radians per second and the differential group delay of the fiber system is Δτ in seconds then Δθ is the angle separation of the state of polarization (SOP) between two frequency components [10].

The total noise power is $N_{total}=N_{shot}+N_{thermal}$ (8)

Here N_{shot} shot noise power spectral density and $N_{thermal}$ is thermal noise power.

The shot noise power is given by

$N_{shot}=2eI(t)B$ (9)

Here e is the charge of the electron and B is the bandwidth (80%of the Bit rate)

Thermal noise power is also given by

$N_{thermal}=4kTB/R_L$ (10)

Where k is the Boltzmann constant, T is the temperature (300K) and RL is the load resistance (1000Ω).

When the size of symbol is large PSK signaling is rather inefficient. For both M-ASK and M-PSK, the penalty in carrier to noise (CNR) for increasing the data rate by one bit (i.e., for increasing M by a factor 2) is approximately 6dB for M large. Alternate signal constellations, using a combination of multiple phases and multiple amplitudes, (APK), have been suggested to reduce this penalty [9].

Among the possible constellations, the quadrature amplitude modulation (QAM) has been found to be the most efficient and its signaling waveforms are

$$S_j(t) = A_j(a_0\cos\omega_0 t) + B_j(a_0\sin\omega_0 t), 0 \le t \le T \qquad (11)$$

j={1,2,3, ,m}, m=√ M

Since the QAM signal is equivalent to two separate orthogonal PAM signals on the quardature carriers, and coherent detection is used in the receiver.

The probability of correct decision is:

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$$P_c = (1 - P_e(m))^2$$

And

$$P_e = 1 - [1 - P_e(m)]^2 = 2P_e(m) - P_e^2(m) \cong 2P_e(m) \qquad (12)$$

The probability of error for QAM system can be given by

$P(m) = \frac{2(m-1)}{m} erfc\sqrt{\frac{E_0}{2n_0}}$ and m=√M ,with k even.

This result is valid for M=16, 64,256. For k odd, i.e. for M=8, 32,128, etc., a bound on P_e has been obtained as

$$P_e(M) \le 4erfc\sqrt{\frac{E_0}{2n_0}} \quad \text{for } k \ge 3 \qquad (13)$$

Since the average power on each vector is $\frac{m^2E_0}{12}, m >> 1$, the total power transmitted is the sum of the vector powers and the error rate is given by

$$P_e(M) \le 4erfc\sqrt{\frac{3E_{av}}{Mn_0}} \cong \frac{4\sqrt{Mn_0}}{\sqrt{6\pi E_{av}}} \exp\left[\frac{-3E_{av}}{2Mn_0}\right] \qquad (14)$$

Where $P_e(M)$ =symbol error, E_{av}=average energy, M=Number of symbols, n_0=noise power Spectral density

Now the bit error rate is given by

$$BER = \frac{P_e}{\log_2 M} \qquad (15)$$

IV. RESULTS AND DISCUSSION

The BER is evaluated for the proposed model for different fiber length, for different bit rate performance and for different differential group delay (DGD) by considering both the CD and PMD effect combined and separately. This BER performance is carried out for single mode fiber operating at 1.55µm. The dispersion coefficient of the fiber is considered as 17ps/nm/km. To evaluate the BER, signal to noise ratio (SNR) is evaluated in the presence of the receiver shot noise and thermal noise. The BER is evaluated for the BER=10^{-9}.

The base receiver sensitivity may be defined as the input power required to achieve BER=10^{-9} considering only the effect of the receiver noise. The additional signal power with respect to base receiver sensitivity may termed as power enalty at the BER=10^{-9} due to the effect of the various noise, dispersion and crosstalk power from the adjacent channel. The BER curve is obtained as a function of the received power.

The BER is evaluated corresponding to different fiber length from 10km to100km considering both the CD and PMD effect combined which is shown in Fig.4 and considering only the CD effect upon the channel which is shown in Fig.5. It is found that the BER of OFDM-QAM system is also increased with the increase of the fiber length. In this case the parameter τ of DGD of the polarization mode dispersion (PMD) remains constant.

The BER performance of the proposed system is evaluated for different fiber length in presence of CD, PMD, and CD+PMD. Fig.4 shows the plots of BER versus received signal power a function of fiber length while PMD parameters and bit rate were kept constant. It is found that BER degrades with fiber length and in order to have same BER receiver needs more power. This demonstrates that receiver sensitivity is highly dependent on fiber length due to dispersion induced pulse shape broadening.

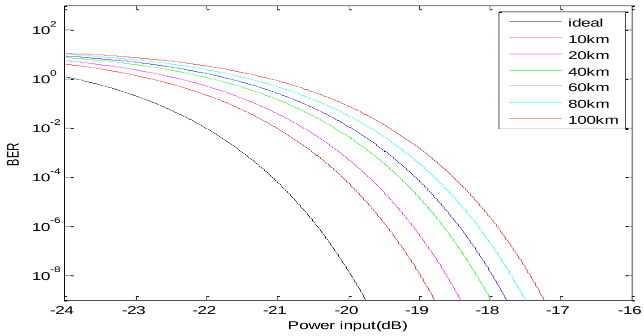

Fig.4 Both CD+PMD effect on the BER of the OFDM-QAM system due to variation of fiber length operating at 1.55µm having D=17ps/nm/km for bit rate 2Gb/s.

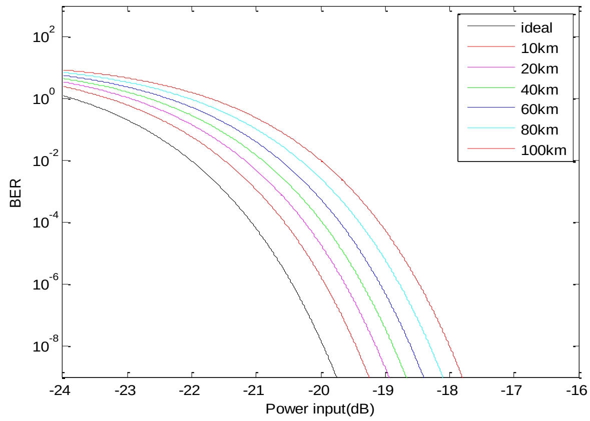

Fig.5 Only CD effect on the BER of the OFDM-QAM system due to variation of fiber length operating at 1.55µm having D=17ps/nm/km for bit rate 2Gb/s.

The power penalties required for the different length are calculated from the BER curve and is plotted against the different fiber length as shown in Fig.5. From the power penalty and length curve it is observed that with the increase of the fiber length the power penalty also increased due to the effect of the CD+PMD effect. The effect of CD also calculated by making DGD constant since there is no relation of DGD with length. The power penalty for the CD is lesser than that of the combined CD+PMD.

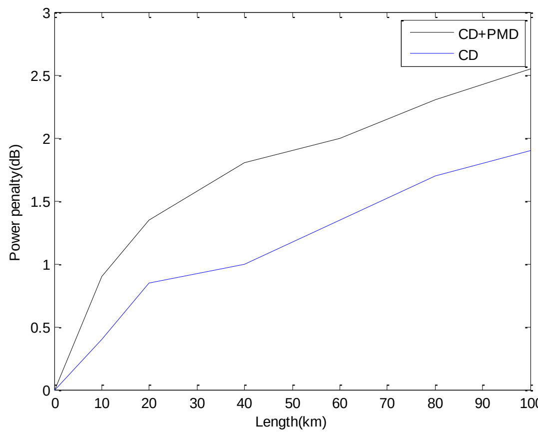

Fig.6 The effect on the power penalty of the OFDM-QAM system due to variation of length operating at 1.55µm having D=17ps/nm/km for bit rate 2Gb/s.

So from the obtained results it can be said that the BER performance of the OFDM-QAM system degrades with the increase in the optical fiber length and the degradation of the BER causes severe power penalty above the fiber length 100km.

The power penalty required for the different DGD are calculated from the BER curve and is plotted against the different DGD as shown in Fig.7. From the power penalty and length curve it is observed that with the increase of the DGD the power penalty also increased due to the effect of the CD+PMD effect. The effect of PMD also calculated by making optical fiber length constant in 10 km .From the curve it is observed that the power penalty required for both CD+PMD is larger than the only PMD effect. With more DGD more the power penalty required for the channel to transmit data with high bit rate.

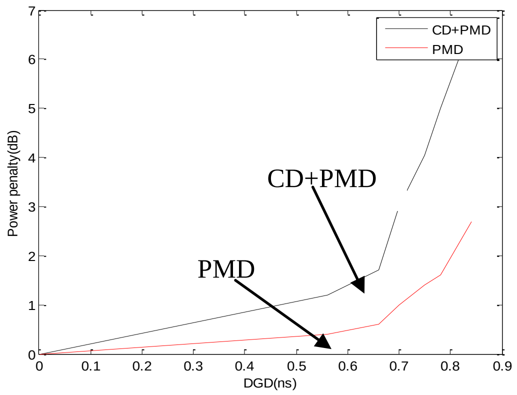

Fig.7 The effect on the power penalty of the OFDM-QAM system due to variation of fiber length operating at 1.55μm having D=17ps/nm/km for bit rate 2Gb/s.

So from the obtained results it can be said that the BER performance of the OFDM-QAM system degrades with the increase in the DGD and the degradation of the BER causes severe power penalty.

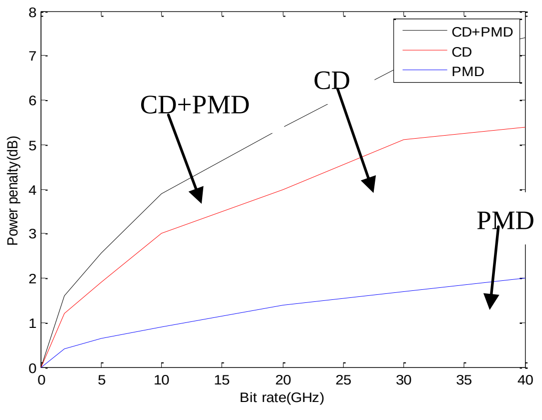

Fig.8 The effect on the power penalty of the OFDM-QAM system due to variation of bit rate operating at 1.55μm having D=17ps/nm/km.

The power penalty curve function of different bit rate is shown in Fig.8. From this figure it is observed that power penalty received for both CD and PMD combined is increase with the increase in the bit rate. Here length is constant at 10km and DGD parameter is also constant. By varying the bit rate only CD and PMD case for the power penalty also plotted. The power penalty only for the CD effect is also increased with the increase of the bit rate. Similarly the power penalty only for the PMD effect is also increased with the increase in bit rate.

So, it was found that BER performance degrades with the bit rate and in order to have the same BER the receiver needs more power. This demonstrates that receiver sensitivity is highly dependent on bit rate due to dispersion-induced pulse shape broadening.

V. CONCLUSION

In our research work, we have analyzed the performance of fiber optic OFDM-QAM system using optical single sideband (OSSB) modulation technique. OSSB is an effective method to reduce the impact of the fiber chromatic dispersion (CD) and increase bandwidth efficiency. For high data communication the CD and PMD both are effectively affect the system performance. Our main objectives of this work were to investigate this impact of CD and PMD combined and separately on our proposed system model (i.e. OFDM-QAM). For long distances it has been observed that there is a gradual degradation of the system performance.

We know that PMD is a serious problem that can limit data rates in a single mode optical fiber system causing the pulse broadening and separation of the PSP in the output of the fiber optic transmission medium. During fiber transmission both the carrier and subcarrier are decomposed into fast and slow PSP. Since the PMD is the differential arrival time of different polarization component of an input light pulse, transmitted by the optical fiber. This light pulse can always be decomposed into pairs of orthogonal polarization modes which propagate at different speed according to slow and fast axis which is the DGD measured in seconds and by varying these PMD parameters we have found the impact of PMD.

In our main research work we have analyzed the impact of the PMD by varying the bit rates and DGD on the OFDM-QAM system performance. It is found that as bit rates and DGD continue to increase the impact of the PMD on the OFDM-QAM system performance have been more pronounced. To find the impact of the CD and PMD we have analyzed the system performance at a BER=10^{-9} operating at 1.55μm and dispersion coefficient D=17ps/nm/km with the variation of the optical fiber length, bit rates and DGD. From the BER and power penalty curve it has been observed that both the CD and PMD cause the increasing amount of power penalty with the increase of the optical fiber length, bit rate and DGD.

In case of the only CD effect while the PMD effect is constant the BER and power penalty curve shows that it causes the rising of the power penalty with the increase of the optical fiber length and bit rate. Another case when considered only the PMD effect while making the CD effect constant, we found that with the continue increase of the bit rate and DGD the system performance degrades and suffered with power penalty.

It is therefore concluded that OFDM-QAM system has higher tolerance on the effect of fiber optic dispersion. This impact is less in OFDM-QAM system than the conventional system. The BER performance of the OFDM-QAM system is more improved than that of a conventional system having the same bandwidth, though in case of the OFDM-QAM bit rate is four times greater than that of a conventional signal.

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So our proposed OFDM-QAM model can be used for high speed data communication system significantly.

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