In Presence of FWM, Optical Fiber Communication Performance Analysis with OFDM-QAM

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Abstract: The theoretical performance of optical fiber communication based on orthogonal frequency division multiplexing (OFDM) system along with quadrature amplitude modulation (QAM) has been analyzed in the presence of four-wave mixing (FWM). The influence of dispersion and FWM induced crosstalk on the OFDM spectrum is investigated with different fiber lengths, bit rates, number of channels, number of optical amplifiers and their gains and source line widths. The optical non linearity in a single-mode fiber imposes a fundamental limitation on the capacity of orthogonal frequency-division multiplexed (OFDM) system. The receiver sensitivity degradation is determined at number of bit error rate 10-9 for direct detection P-i-N receiver with number of OFDM channel, symbols and other system impairments associated with the proposed system. It is found that, FWM-induced crosstalk in presence of GVD severely degrades the system performance when the fiber input powers a large and/or the channel spacing is too small. The theoretical results obtained from the proposed system demonstrate that the system having 32 OFDM channels suffer power penalty of 0.51 dB due to the combined influence of FWM for fiber length 50 km and bit rate 2.5Gb/s. The power penalty is found to be 2.09 dB for the same number of channels and fiber length at bit rate 5Gb/s. Simultaneously our results also demonstrate the system performance severely degrades when number of OFDM channels exceed over 16, the BER performance degrades due to presence of FWM crosstalk .

Keyword- Quadrature Amplitude Modulation, Four Wave Mixing, Orthogonal Frequency Division Multiplexing, Group Velocity Dispersion, Bit Error Rate, Time Division Multiplexing.

I. INTRODUCTION

The major challenge of modem communication system to meet the high bit rate demand in various applications is effective and efficient utilization of communication resources (power and bandwidth). To reduce system bandwidth as well as transmission power in digital communication technique, several approaches are available. Among them, advanced digital modulations and multiplexing techniques are widely used [1]. It is well established that M-ary modulation techniques have the property of reducing bandwidth by the order of N, where N is the number of bits used to form a symbol.

In M-ary modulations, a large number of symbols that is, (M=2N symbols) are modulated with the M carriers which are closely separated either by M-phases or M-frequencies or M-magnitudes. The transmission power as well as system performance mainly depend on the modulation types. It has been shown in previous study [1] that the probability of inter symbol interference is more in case of M-ary phase shift keying (PSK) compare to that of M-ary frequency shift keying (FSK). Although M-ary FSK gives better

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performance, bandwidth requirement is higher than M-ary PSK. With the combination of M-ary PSK and M-ary QASK, an efficient modulation technique has been developed known as M-ary quadrature amplitude modulation (QAM) in which probability of inters symbol interference is lower than M-ary PSK.

The orthogonality nature of frequencies is used in orthogonal frequency division multiplexing (OFDM) which provides more compact spectrum. Therefore the combination of OFDM multiplexing with QAM modulation can give an effective communication system. There are a series of transmission medium available in digital communication, optical fiber is well known waveguide in which the light wave can be propagated in the near infrared range. The available bandwidth in optical carrier is in the order of 105 times than that of microwave link [2]. Therefore, by combining OFDM-QAM system with optical fiber, the data communication speed can be extended dynamically.

Though the fiber transmission allows an enhanced bandwidth, the system performance degrades severely by dispersion and fiber nonlinearity such as Four Wave Mixing (FWM) crosstalk, Cross-Phase Modulation (XPM) etc (widely known as Kerr Affect) [3]. So it is essential to optimize the OFDM-QAM system by evaluating its performance under dispersion and non-linear crosstalk.

A wide range of experiments have been done on the basis of optical fiber communication to achieve faster data rate. The fiber optic communication system containing semiconductor LASER amplifiers have investigated theoretically and experimentally in the previous study [4]. The effect of chromatic dispersion on BER performance on OFDM system has been analyzed with 4 Gb/s optical pre-amplifier. The channel capacity of CO-OFDM system limited by FWM has been analyzed and compared for QAM and PSK modulation formats. Here the effect of FWM has been analyzed for a channel capacity of 128 and fiber length of 5.80 Km [5]. Also the experimental results of the effect of chromatic dispersion on OFDM system has carried out for transmission through 100 Km fiber at 1550 nm with a bit rate of 5~9 Gb/s [6].

It is seen in previous studies, considerable works have been accomplished on optical fiber transmission and OFDM system on the influence of either dispersion or FWM crosstalk. No significant work has done that contains the effects of both chromatic dispersion and FWM on OFDM-QAM system. So, our objective is to investigate the system performance under the influence of both dispersion and FWM crosstalk on a 32 charnel OFDM-QAM coherent system.

II. TRANSMISSION AND RECEPTION THROUGH OPTICAL FIBER

Optical fiber signal transmission system mainly consists of three basic components. These are:

- Transmitter
- Optical Fiber
- Receiver

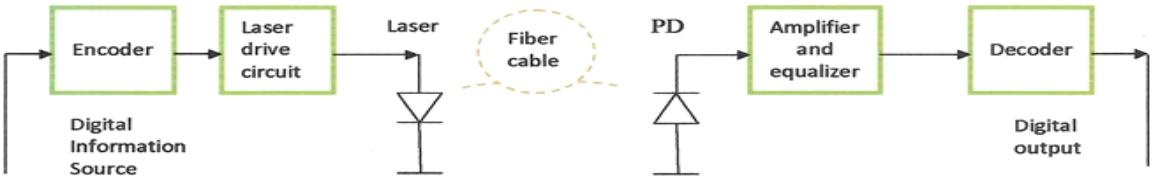

Figure-1: Optical Fiber Communication System

In the transmitter there is Optical sources which are used to convert electrical energy into optical energy. There are mainly three types of Optical sources

• Wideband Sources (Incandescent Lamp)
• Incoherent Sources (LED)
• Coherent Sources (LASER).

In our proposed system we have used LASER sources. As it is a coherent source of light, light energy is not dispersed. The material used in optical fiber is Silica. When signals pass through the Silica Fiber, signal is dispersed due to dependence of wave speed on its frequency.

At the receiver there are optical detectors which are used to detect optical signals. There are different types of photo detectors, such as

• Photomultiplier Tubes.
• Vacuum Photodiodes
• P-N Photodiode
• P-I-N Photodiode
• Avalanche Photodiode

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III. System Model

- **Transmitter:**

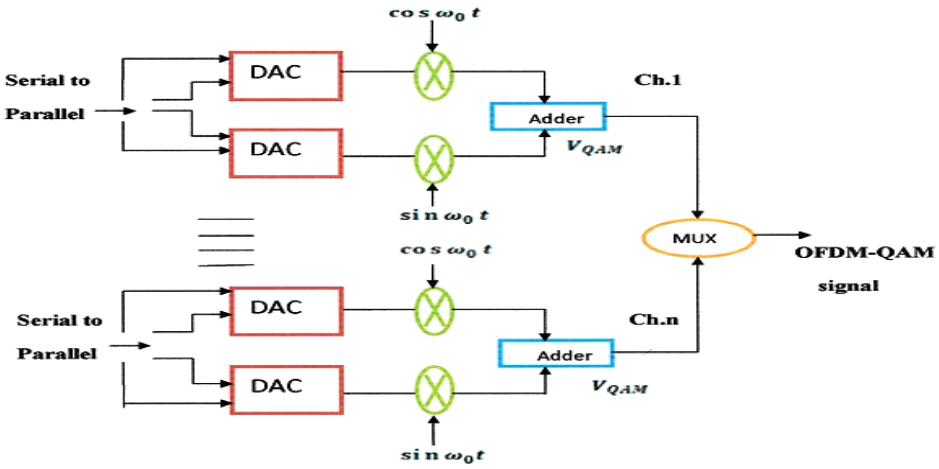

Figure-2: Transmitter for generation of OFDM-QAM signal.

In the transmitter, at first serial data stream is then converted into parallel data. Then the digital data is converted into analog data by using digital to analog convener (DAC). At the output of (DAC), we get the even data and odd data which are modulated by using quadrature amplitude modulation technique i.e. QAM technique. Then these are added together and as a result we get the QAM signal. After that each channel signal is modulated by sub-carriers which are orthogonal to each other i.e. the frequency spacing between carriers is $\frac{1}{T}$, where T, be the symbol period. The signals from different channels are then multiplexed and at the output of the MUX we get the OFDM-QAM signal.

- **Signal Transmission**

The OFDM signal is then modulated by laser light wave which is a coherent source of light and then 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 sent 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.

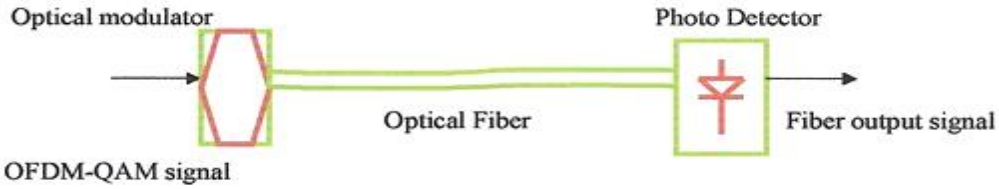

Figure-3: Transmitting medium for OFDM-QAM signal.

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- **Receiver**

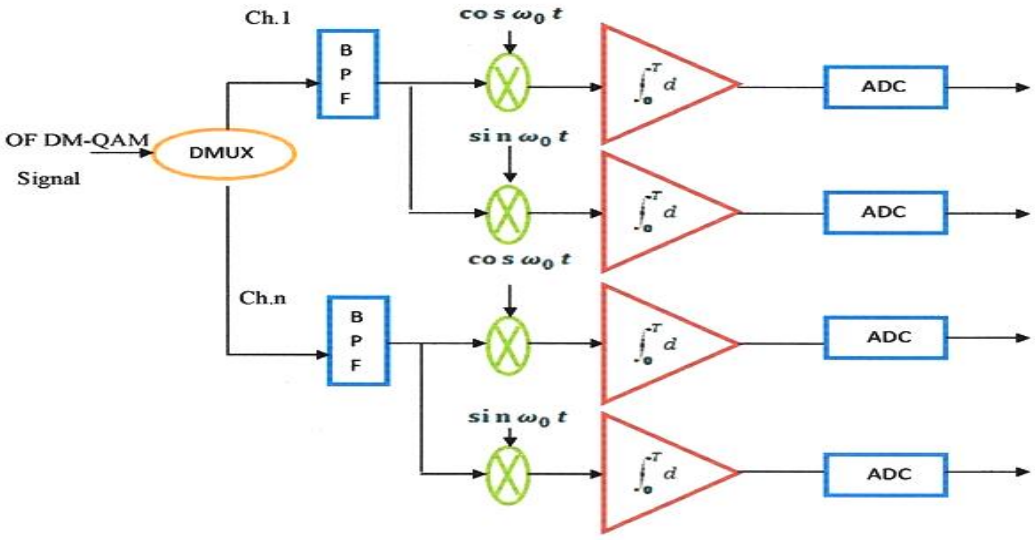

Figure-4: Receiver for reception of OFDM_QAM signal.

The receiver picks up the OFDM-QAM signal, which is then demultiplexed. To regain the each channel signal filters are used. Here we have used cosine filter. The cut off frequency to regain each signal is determined from the OFDM-QAM signal. When the signals from each channel are separated then there remain some noises such as shot noise, thermal noise etc. To remove these noise each channel signal is filtered by a low pass filter. And at Last we get a noise free output signal. This returns parallel streams, each of which is converted to a binary stream using an appropriate symbol detector. These streams are then re-combined into a serial stream, which is an estimate of the original binary stream at the transmitter.

IV. Generation of OFDM-QAM signal

The baseband signals are the first modulated by using M-ary QAM modulation technique. A detailed description of M-ary QAM can be found in [1] where we can find the expression for QAM symbol.

The 32-QAM signal is given by:

$$v_{QAM(t)} = k_1 a u_1(t) + k_2 a u_2(t) \ldots\ldots\ldots \quad (1)$$

IN which k_1 and k_2 are each equal to ± 1 or ± 3. Since we have that

$u_1(t) = \sqrt{\left(\frac{2}{T_s}\right)} cos\omega_o t$ and that $u_2(t) = \sqrt{\left(\frac{2}{T_s}\right)} sin\omega_o t$ and a = $\sqrt{0.1E_s}$. We can write Eq(1) as

$$v_{QAM} = k_1\sqrt{0.2\left(\frac{E_s}{T_s}\right)} \cos\omega_o t + k_2\sqrt{0.2\left(\frac{E_s}{T_s}\right)} \sin\omega_o t \ldots\ldots \quad (2)$$

And since $\frac{E_s}{T_s} = P_s$ we have for OFDM-QAM signal,

$$v_n^{OFDM-QAM}(t) = \sum_{n=1}^{M}[(k_1)\sqrt{0.2P_s} cos\omega_o t + k_2\sqrt{0.2P_s} sin\omega_o t] \ldots\ldots \quad (3)$$

A QAM signal for 4 bit symbol $b_k+_3b_k+_2b_k+_1b_k$ from which 2 bit represent by $A_e(t)$ modulates the balance modulator whose input carrier is the even function $\sqrt{P_s} cos\omega_o t$ and A_o (t) modulates the modulator with odd-function carrier. The transmitted signal is then

$$v_n^{OFDM-QAM}(t) = \sum_{n=1}^{M}[A_e(t)\sqrt{P_s} cos\omega_o t + A_o(t)\sqrt{P_s} sin\omega_o t] \ldots\ldots\ldots \quad (4)$$

Comparing Eq. 3 with Eq. 4

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A_ε, $A_0 \pm \sqrt{0.2}$ Or $\pm 3\sqrt{0.2}$

For orthogonal sub carrier the carrier spacing between each channel is 1/T.

$v_n^{OFDM-QAM}(t)$ is the time domain signal.

Here, we have used 32-QAM and to transmit the OFDM-QAM signal, 32 channels have been used. The carrier frequency for 1st channel is 1GHz. The sampling period of the carrier is 3.921×10^{-12} sec, where the no. of sample is 256.

For 1st channel,

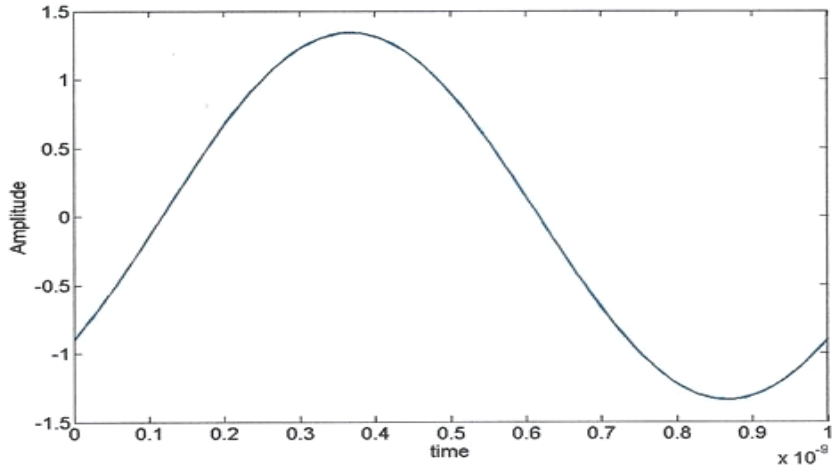

Figure-5: Time domain signal for 1st channel having carrier frequency 1GHz.

By similar way we get time domain signal for different channel. The carrier frequency of the 32nd channel is 32 GHz and time period for 32nd carrier is 32×10^{-9} sec. The time domain signal for the channel will be just like the figure bellow:

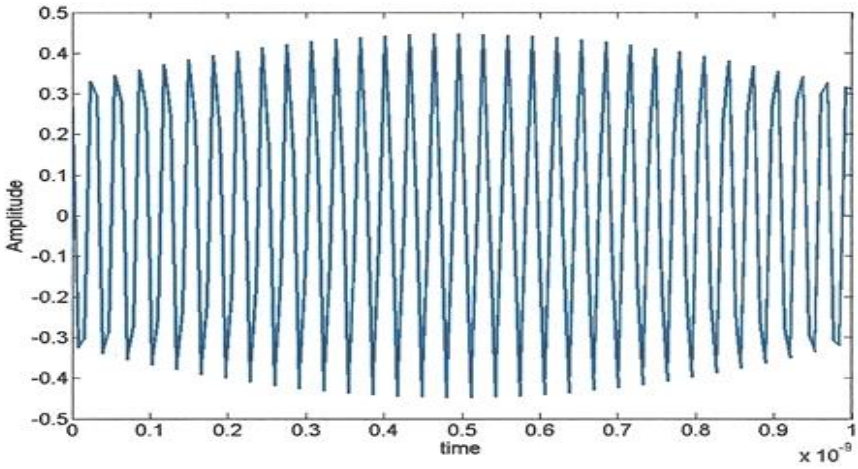

Figure-6: Time domain for 32nd channel having carrier frequency 32 GHz

After Fourier transformation of the domain signal we get the frequency domain signal. [7].

$$v(f) = FFT[v_n^{OFDM-QAM}(t)] \quad \ldots\ldots\ldots\

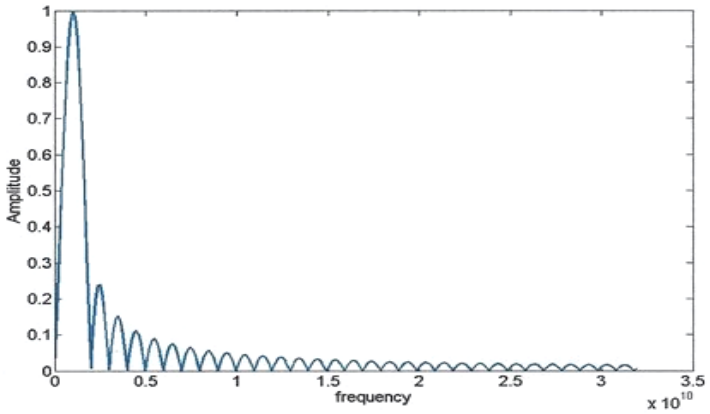

Figure-7: Frequency domain spectrum for 1st channel having bandwidth 2 GHz

Similarly, we get frequency domain signal for different channel, Frequency domain signal for 32nd channel is just like the figure below:

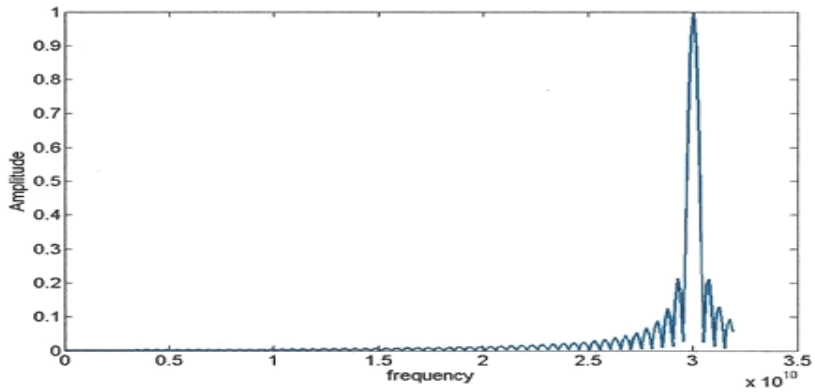

Figure-8: Frequency domain spectrum for 32nd channel having bandwidth 2 GHz.

After IFFT of the summation of frequency domain signal for each channel we get the OFDM-QAM signal by taking the time domain what will be just like the figure below:

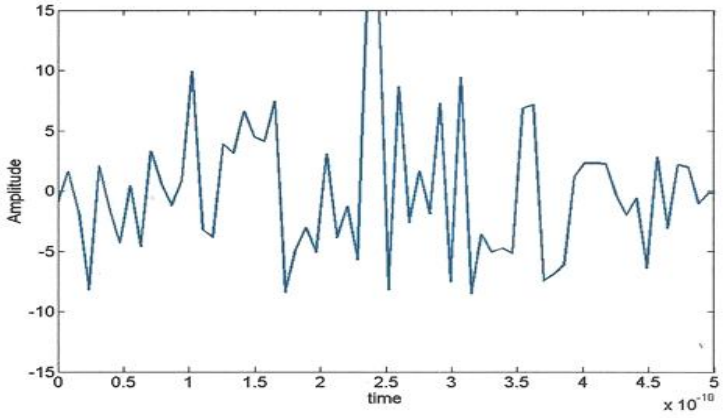

Figure-9: Single sideband 32 channel OFDM-QAM signal spectrum.

V. TRANSMISSION OF OFDM-QAM SIGNAL

In the way of propagation through the fiber, the OFDM-QAM signal is distorted due to dispersion. The transfer function of single mode is given by [3].

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$$H(f) = \left(\frac{if}{f_2}\right)^{-\frac{1}{2}} exp\left[-\frac{\left(\frac{f}{f_1}\right)^2}{2\left(1+\frac{if}{f_2}\right)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where the parameter f_1 and f_2 are given by:

$$f_1 = (2\pi\beta_2 L\sigma_\omega)^{-1} = (2\pi|D|L\sigma_\lambda)^{-1} \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

$$f_2 = (2\pi\beta_3 L\sigma_\omega)^{-1} = \left[2\pi\left(S + \frac{2|D|}{\lambda}\right)L\sigma_\lambda^2\right]^{-1} \ldots\ldots\ldots\ldots \quad (8)$$

Where, $\sigma_\lambda$is the source line width and D and S are the 2nd and 3rd order dispersion parameter respectively.
The impulse response of the fiber transfer function is, $h(t) = F^1[H(f)]$.
Optical fiber transfer function spectrum is given below:

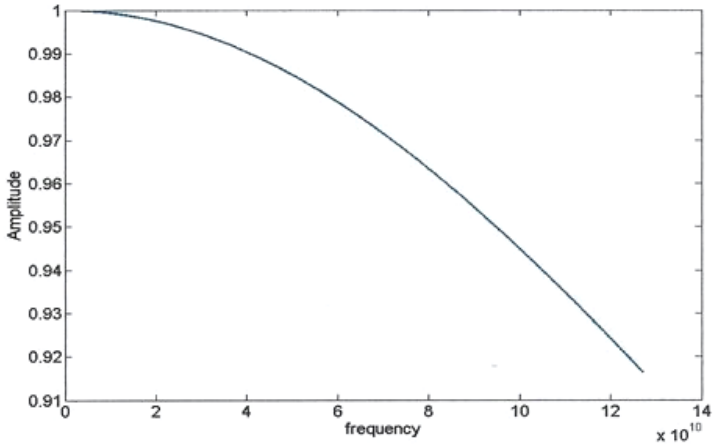

Figure-10: Optical fiber transfer function spectrum with fiber length, L=50Km and LASER linewidt, $\sigma_\lambda = 2\ nm, D = 15\ ps\ /nm.km, S = 0.$

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

$$P_r(f) = v(f) * H(f) \ldots\ldots\ldots\ldots \quad (9)$$

After passing the OFDM-QAM signal through the optical fiber which length is L=50Km. Fiber output OFDM-QAM spectrum are given below:

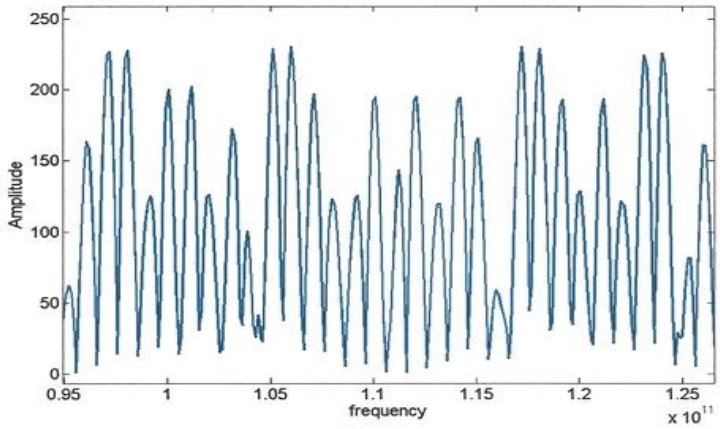

Figure-11: Optical fiber output for 32 channel OFDM-QAM spectrum with fiber length L=50Km and LASER linewidth $\sigma_\lambda = 2nm.$

From figure, it is seen that magnitude of the OFDM-QAM spectrum reduced due to the dispersion effect for the fiber length L=50Km.

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VI. Dispersion parameter

The dispersion parameter is obtained as,

$$I_{av} = \left[\int_0^{\infty} P_r^2(t)dt\right] \quad (10)$$

Where, $P_r(t)$, is the inverse Fourier transformation of the $P_r(f)$.

1. Input signal power and noise power

The receiver input signal is given by [7],

$$P_{in} = \frac{\left(\sqrt{2P_s}A_{av}(t)\right)^2}{2} \quad (11)$$

Where,
P_s= Signal power,
$A_{av}(t)$= Average no. of bit
Signal power has been obtained by:

$$S = (RGLI_{av}P_{in})^2 \quad (12)$$

Where,
R= Responsibility of the photodiode,
G= Gain of the optical amplifier,
L=Fiber loss,
Shot noise is given by:

$$N_{shot} = 2B_e e\eta_{out}\left(Gl_z\eta_{in} + I_{sp}\right) \quad (13)$$

Where,
e= Electronic charge,
B_e= Spectrum Bandwidth,
η_{out} = Amplifier output coupling efficiency
I_{sp}= PCE of spontaneous emission power
I_z= PCE of amplifier input power
η_{in} =Amplifier input coupling efficiency
L= Optical loss between amplifier and receiver
G= Optical gain
Thermal noise current has been obtained as [9]:

$$I_{th} = \frac{10^{-11}A}{\sqrt{H_z}} \quad (14)$$

So, thermal noise:

$$N_{th} = (I_{th})^2 * B_e \quad (15)$$

Signal-spontaneous beat noise

$$N_{s-sp} = \frac{4GI_z\eta_{in}\eta_{out}^2 I_{sp}L^2B_e}{B_0} \quad (16)$$

Where,
B_0= Optical bandwidth
Spontaneous-spontaneous beat noise

$$N_{sp-sp} = \frac{(I_{sp}\eta_{out}L)^2 B_e(2B_0 - B_e)}{B_0^2} \quad (17)$$

FWM noise is given by [4]:

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$$f_{jkl} = f_n = f_j + f_k - f_l, l \neq j.k \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

$$N_{FWM} = \sum_{jkl} \frac{4P^2\gamma^2 G_{jkl}^2}{\sigma^2 + \Delta\beta_{jkl}^2} X_{jkl} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

And

$$\Delta\beta_{jkl} = \frac{2\pi\lambda^2 D}{c(f_1 - f_l)(f_k - f_l)} \ldots\ldots\ldots\ldots\ldots \quad (20)$$

Where , G_{jkl}=1 for two-tone products and G_{jkl}=2 for three-tone products P is the optical power per RF channel and x_{jkl} represents a combined effect of the relative phase between the contribution waves and the statics of the data signals. γ is the nonlinear constant (typically $2W^{-1}km^{-1}$), α is the attenuation constant (0.2dB/km for preamplifier) and λ is defined as $1.5\mu m$.
Total noise given by:

$$N_{total} = N_{shot} + N_{s-sp} + N_{sp-sp} + N_{th} + N_{FWM} \ldots\ldots\ldots\ldots \quad (21)$$

2. Bit Error Rate (BER) calculation

The probability of error is given by [11]:

$$P_e(m) = \frac{2(m-1)}{m} erfc \sqrt{\frac{S}{2N_{total}}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

Where, m=$\sqrt{M}$ and M =2^k . This result is valid for k is even i.e. for M = 16, 4, 256 etc.
For k odd i.e. for M = 8, 32, 128 etc. P_e can be obtained as:

$$P_e(M) \approx \frac{4\sqrt{MN_{total}}}{\sqrt{6\pi S_{av}}} \exp\left[-\frac{3S_{av}}{2MN_{total}}\right] \ldots\ldots\ldots\ldots\ldots \quad (23)$$

The average power on each vector is $\frac{m^2 S}{12}$, m ≥ 1.
Now the BER is given by,

$$BER = \frac{P_e}{\log_2 M} \quad \ldots\ldots\ldots\ldots \quad (24)$$

BER spectrum is given below:

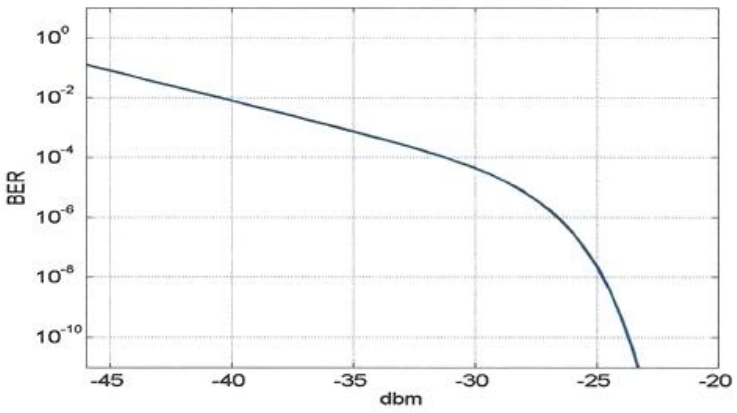

Figure-12: The bit error rate performance of 64Gb/s OFDM-QAM signal with fiber length L = 50km, source line with σ_λ = 2nmm.

3. Reception of OFDM-QAM signal

At the receiver, the OFDM-QAM signal is demultiplexed. For example the separation of each channel signal cosine filter was and the transfer function is given by [8]. In cosine filter we get the sharp cut-off frequency.

$$|H_e(f)| = \begin{cases} 2T\cos\pi fT & for\ |f| < \frac{1}{2T} \\ 0 & \end{cases} \ldots\ldots\ldots\ldots \quad (25)$$

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H_e (f), the composite transfer function for the cascaded digital and rectangular filter. The duo binary equivalent H_e (f) is called a cosine filter. The corresponding impulse response h_e (t), found by taking the inverse Fourier transform of H_e (f) is,

$$h_e(t) = \sin c\left(\frac{1}{T}\right) + \sin c\left(\frac{t-T}{T}\right) \ldots\ldots\ldots\ldots \quad (26)$$

Cosine filter transfer function spectrum is given below:

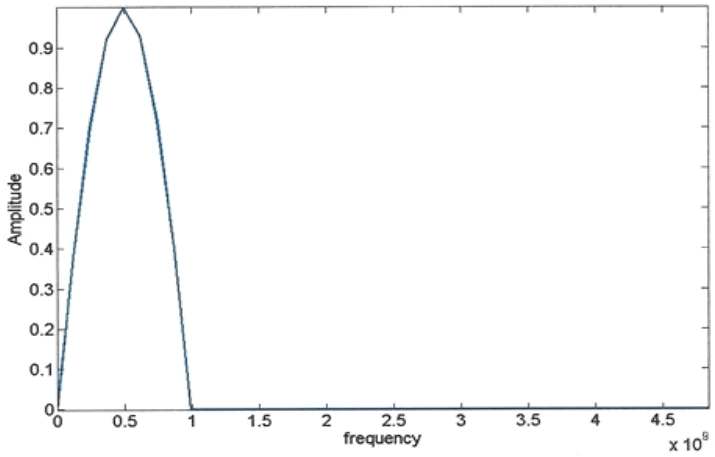

Figure-13: Cosine filter transfer function spectrum for band pass frequency 0-1GHz.

After filtration the signal becomes:

$$P_{rf}(f) = P_r(f) * H_e(f) \ldots\ldots\ldots \quad (27)$$

The output of the Cosine filter to extract the 1st channel signal will be just like the figure below:

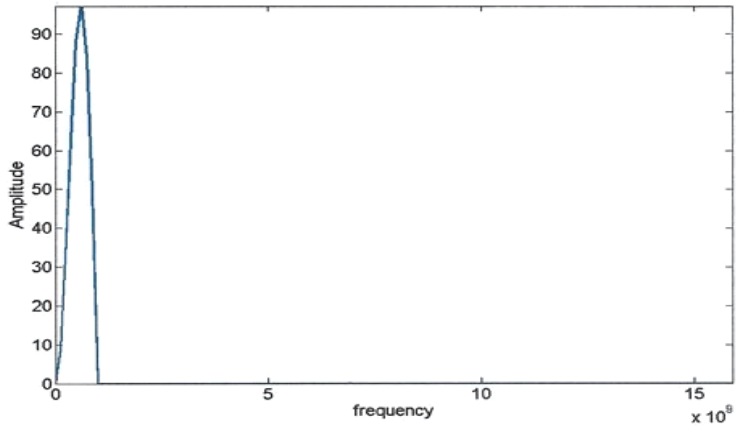

Figure-14: Filter output signal spectrum for the extraction of 1st channel signal.

Similarly, we can extract different channel signal.

VII. RESULTS AND DISCUSSION

Effect of dispersion on OFDM-QAM signal

When signals pass through the optical fiber due to fiber length, LASER linewidth it is broadened and as a result there occurs inter symbol interference (ISI). In an OFDM-QAM signal, the carriers are orthogonal to each other and that is why when the signals from different channels are multiplexed and allowed to pass through the fiber, the effect of dispersion in this system is less than other systems which is shown in figure-16 where the dispersion effect on OFDM-QAM system is evaluated with linewidth 2nm and bit rate at 2 Gb/S .

Effect of dispersion with LASER linewidth

Following the theoretical analysis, the performance results for an OFDM-QAM system in presence of dispersion are evaluated at a bit rate of 64 Gb/S, with different fiber length and LASER linewidth.

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The fiber used here is a single mode fiber whose 2nd order dispersion parameter D = 20 ps/nm.Km and 3rd order dispersion parameter, S is equal to zero. LASER linewidth, σ_λ was varied from 1~6 nm and calculated the average magnitude of the fiber output signal at the fiber length, L=50, 100, 150 Km. For the fiber length, L=50 Km and σ_λ =2 nm, the magnitude of the signal is 0.3668, so due to dispersion the magnitude of signal magnitude reduces to 63.32%.

For the same linewidth and fiber length, L=100 Km, the magnitude of the signal is 0.3554, so the effect of dispersion on the signal level is 64.46% and for fiber length, L=150 Km, the magnitude of the signal is 0.3508, so the effect of dispersion on the signal level is 64.92%.

In case of fiber length, L=50 Km, due to variation of LASER linewidth σ_λ from 2 nm to 3 nm, the magnitude of the signal level reduces from 0.2556 to 0.2548. So, due to increase in value of σ_λ, 1 nm, the effect of dispersion increases by an amount 0.08%. For L=150 Km, due to variation of LASER linewidth, σ_λ from 2 nm to 3 nm, the magnitude of the signal level reduces from 0.1776 to 0.1621. So, for the increase in value of σ_λ 1 nm, the effect of dispersion increases by an amount 1.55%.

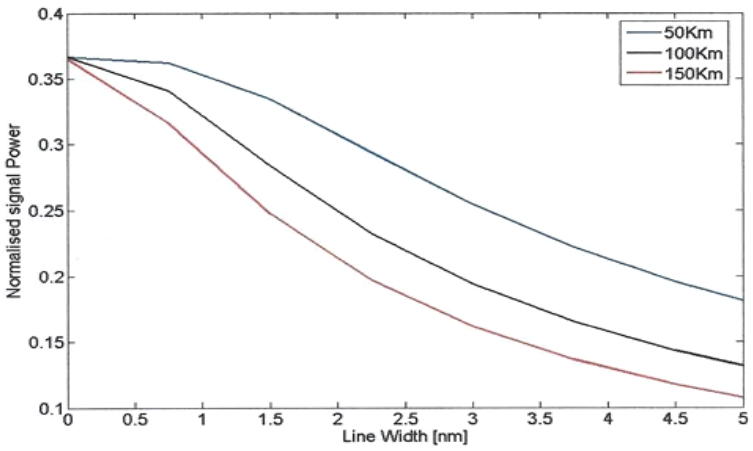

Figure-15: Effect of dispersion on OFDM-QAM signal due to variation of fiber length, L=50, 100, 150 Km and LASER linewidth, σ_λ = 1~5 nm at a bit rate of 64 Gb/S.

From the above results, it is seen that the values of dispersion effect are near to each other due to variation of fiber length, so we can let that within fiber length 60 Km, the effect of dispersion is constant. From here we may conclude that if we use OFDM technique combining with QAM technique within the fiber length 60 Km, the effect of dispersion remain constant but when the length increases from 60 Km, the dispersion effect increases. But in case of variation of LASER linewidth the effect of dispersion on OFDM-QAM signal magnitude is so severe than the variation of fiber length.

Effect of dispersion with fiber length

The dispersion effect is also analyzed with the variation of fiber length in terms of decrement of normalized power spectrum. The variation of fiber length from 30 Km to 300 Km is shown as follows:

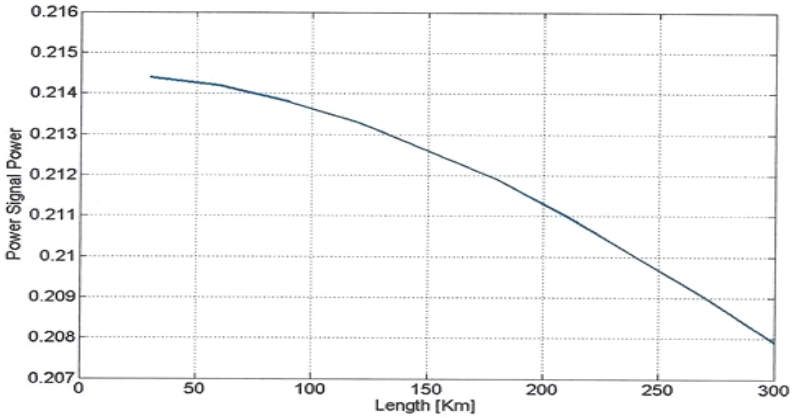

Figure-16: Effect of dispersion on OFDM-QAM signal at σ_λ= 2 nm and at a bit rate 2Gb/S.

At 30 Km, the signal magnitude is 0.2144; at 150 Km the signal magnitude is 0.2126 at 300 Km the magnitude is 0.2079.

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It shows that, at smaller length, the signal is less affected by dispersion than the higher lengths. The combination of OFDM with QAM approves the signal to less deviate which is seen in previous figure since the dispersion at 60 Km is near about constant and then varies sharply with increase in fiber length.

BER performance

The base receiver sensitivity may be defined as the input power required to achieve a BER=10^{-9} considering only the effect of receiver noise. The additional signal power with respect to base receiver sensitivity (BRS) may be termed as power penalty at BER= 10^{-9} due to the effect of various noise, dispersion and crosstalk power from adjacent channels.

BER performance with LASER linewidth

The BER performance of OFDM-QAM system is shown in figure-17 in presence of fiber chromatic dispersion, FWM induced crosstalk, amplifier noise and other noises. The receiver sensitivity is defined as the optical power required achieving a BER of 10^{-9}.

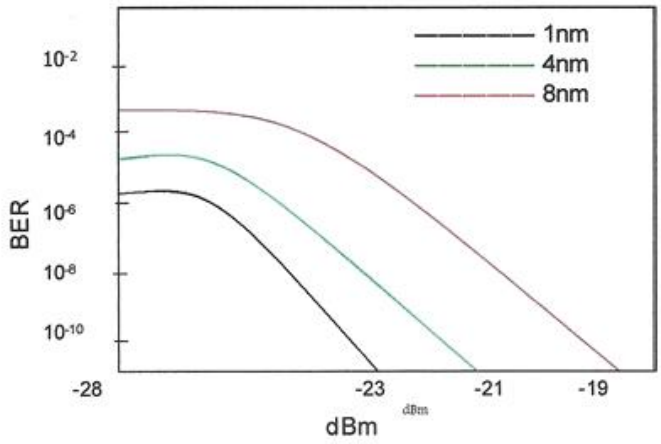

Figure-17: The BER performance with the LASER linewidth σ_λ at 1,4 and 8 nm for fiber length 50Km and bit rate 64 Gb/s

The results are given for different linewidth σ_λ of 1, 4 and 8 nm, fiber length of 50 Km and bit rate at 64 Gb/S. For LASER linewidth 1 nm, the receiver sensitivity is found to be -23.3dBm. As the linewidth increases, the bit error rate increases by giving decremented receiver sensitivity. For linewidth of 4 nm, the receiver sensitivity is found to be - 21.65dBm where for 8 nm, the sensitivity is found to be-18.9dBm.

From the above results, it is seen that, the increasing value of LASER linewidth causes the increment on the probability of error on the system performance. The receiver sensitivity decreases due to the incremental impact of chromatic dispersion and FWM induced crosstalk with incremental value of linewith on system BER performance.

BER performance with number of symbols

The BER performance of OFDM-QAM system has been analyzed for different number of symbols. The results are given for symbols of 8, 16 and 32 with fiber length of 50 Km, linewidth of 2 nm and bit rate at 2 Gb/S. The bit error probability is plotted along with the receiver sensitivity which is shown in figure

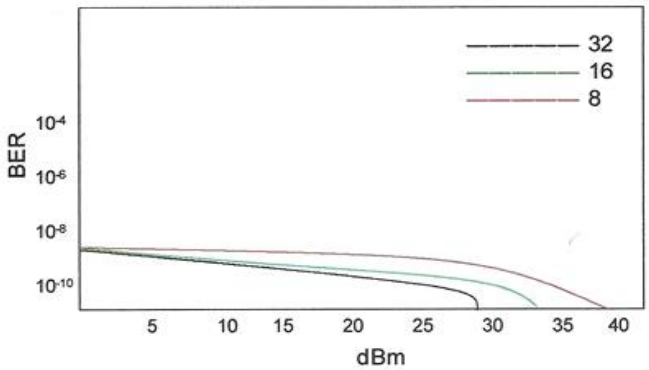

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Figure-18: The BER performance with number of symbol 8, 16 and 32 with fiber length of 50km, linewidth 2nm and bit rate 2Gb/s

It is shown that, at BER 10^{-9}, the sensitivity is -39 dBm for number of symbol 8 and for 32 the value is -29.2 dBm. Since both 8 and 32 constellations give odd number of k, the BER performance is degraded for 32 symbols. It is so due to the increase in number of symbols spacing between two adjacent symbols decreases resulting in inter symbol interference and degrades the receiver sensitivity of OFDM-QAM system.

From the above results, it is seen that, the receiver sensitivity decreases as the symbol rate increased in OFDM-QAM system. Though the 16 symbol system is quite efficient in accounting the BER performance but for high data rate system where larger number of symbols are needed, we need to rest aside this effect.

BER performance with fiber length and LASER linewidth

As the fiber length and LASER linewidth increases the probability of BER increases. As a result the power penalty to meet the base receiver sensitivity increases. If the fiber length lies between 1-75 Km the effect on BER performance of *OFDM-QAM* system is not so *severe* but when the fiber length increases from 75 Km, the effects becomes so severe. Here, the fiber length, L was varied from 30~300 Km and the LASER linewidth, σ_λ from 2~4 *nm* and calculated the value of power penalty at a bit rate 64 Gb/S. TABLE-1 shows these data.

TABLE-1: For BER performance with various linewidth σ_λ and fiber length L.

	Penalty(dB)	*Penalty(dB)*	*Penalty(dB)*
Length (Km)	For σ_λ = *2nm*	*For* σ_λ *= 3nm*	*For* σ_λ *= 4nm*
30	0.08	0.16	0.58
60	0.09	0.63	1.21
90	0.22	0.98	1.81
120	0.46	1.39	2.29
150	0.62	1.71	2.78
180	0.82	2.02	3.17
210	0.99	2.28	3.36
240	1.18	2.52	3.69
270	1.34	2.79	3.93
300	1.49	3.04	4.14

From the data of TABLE-1 the Figure-16 has been plotted. This shows the effects on BER performance of *OFDM-QAM* system due to variation of fiber length and LASER linewidth.

From TABLE-1 and figure -16 it is seen that, for fiber length, L=30 Km, due to increase in value of linewidth, σ_λ from 2 to 3 nm, the power penalty increases from 0.08 dB to 0.16 dB and due to increase in value of σ_λ from 3 to 4 nm, the increase in power penalty is from 0.16 dB to 0.58 dB. So, we can say that as the linewidth, σ_λ increases the power penalty increases.

At a constant linewidth, σ_λ =2 nm*;* when the fiber length, L increases the power penalty increases. For an increase in value of fiber length from 90~120 Km, there is an increase in power penalty of an amount of 0.24 dB.

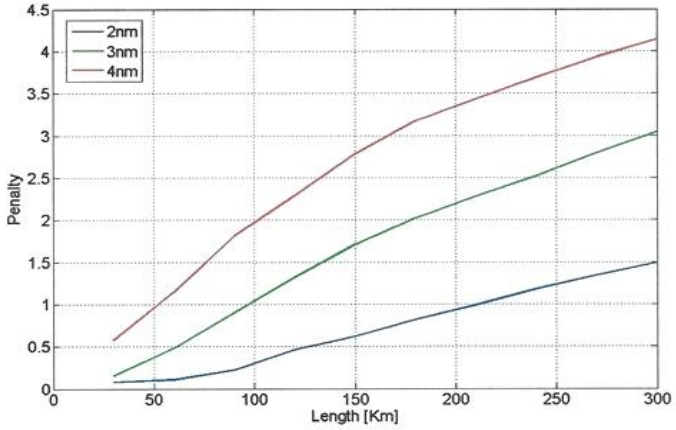

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Figure-19: Effect on BER performance of OFDM-QAM system due to variation of fiber length, L=30~300 Km and LASER linewidth, σ_λ =2~4 nm at a bit rate of 64 Gb/S.

The power penalty curve shows rapid variation from 60~120 Km due to the variation photocurrent factor. The photocurrent factor is sensitive to fiber length and channel capacity. At 75 Km, the factor magnitude is 0.3286 and at 150 Km, the magnitude is 0.2128. This variation is responsible for the rapid fluctuation of the penalty curve within the length 60~120 Km.

From the above results we can see that, the BER performance of OFDM- QAM signal degrades with the increase in value of fiber length and LASER linewidth. But this effect is not so distressing in case of short fiber length.

BER performance with bit rate

With the increase in bit rate, the speed of data communication increases but the probability of error increases i.e. BER increases and as a result, the power penalty increases. The performance of OFDM-QAM system has been analyzed with the variation of bit rate at LASER linewidth, σ_λ =2 nm and for the fiber length, L=50, 100 and 300 Km. TABLE-2 shows these data.

TABLE-2: For BER performance with various bit rate and fiber length L.

	Penalty(dB)	Penalty(dB)	Penalty(dB)
Bit rate (GHz)	L = 50Km	L = 100Km	L =300Km
2.0	0.00	0.09	0.26
2.5	0.51	0.60	0.79
3.0	0.92	1.01	1.18
3.5	1.28	138	1.53
4.0	1.59	1.69	1.84
4.5	1.86	1.95	2.12
5.0	2.09	2.16	2.32

According to the data of TABLE-2, figure-20 has been plotted. This shows the effect on power penalty due to variation of bit rate. As the bit rate increases, the power penalty increases.

At L=50 and bit rate =2.0 GHz, the power penalty is 0.00. For the increase in bit rate from 2.0 GHz to 2.5 GHz for the same fiber length the increase in power penalty is 0.51dB. When the bit rate increases from 4.5 GHz to 5.0 GHz, power penalty increases from 1.86 dB to 2.09 dB i.e. increase in power penalty is 0.23 dB.

For the fiber length, L=100 Km, BER performance of OFDM-QAM system due to variation of bit rate suffers more than for the fiber length, L=50 Km. Here, the lowest penalty required for the bit rate 2.00 GHz which is 0.09 dB. When the value of bit rate increases, the required power penalty increases and for the increase in bit rate from 4.5 GHz to 5.0 GHz, power penalty increases from 1.95 dB to 2.16 dB i.e. increases in power penalty is 0.21 dB.

BER performance of OFDM-QAM system due to variation of bit rate suffers more for the fiber length, L=300 Km. For the increase in bit rate from 2.0 GHz to 2.5 GHz, power penalty increases by an amount of 0.53 dB. When the bit rate increases from 4.5 GHz to 5.0 GHz, the power penalty increases from 2.12 to 2.32 dB i.e. increase in power penalty 0.2 dB.

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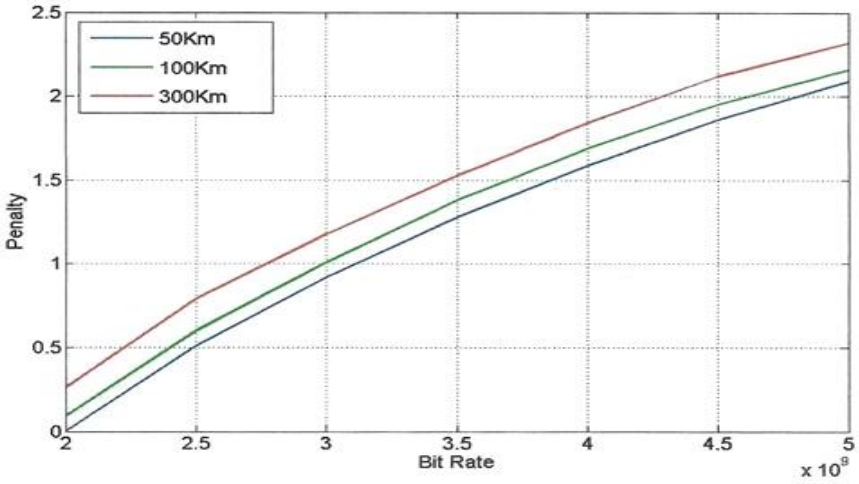

Figure-20: Effect on BER performance of OFDM-QAM system due to variation of bit rate for LASER linewidth, σ_λ =2 nm and for fiber length, L=50, 100, 300 Km.

From the above result, we can see that the BER performance of OFDM-QAM system suffers due to variation of bit rate. For short length fiber this effect is not as severe as long length fiber.

BER performance with number of channel

The BER performance of OFDM-QAM system also suffers with the variation of number of channel. As the number of channel increases, the probability of error increases and as a result the power penalty increases. In fact, when the number of channel increases, the signal spectrum becomes wider. As far we know, for a particular length and LASER linewidth, the fiber is restricted by certain cut off frequency. So, when the signal spectrum becomes so wider that the total signal cannot pass through the fiber then the signal becomes affected. The performance of OFDM-QAM system has been analyzed with the variation of bit rate at LASER linewidth, σ_λ =2 nm and for the fiber length, L=100, 300 and 400 Km. TABLE-3 shows these data.

TABLE-3: For BER performance with various numbers of channels with fiber length L.

	Penalty(dB)	Penalty(dB)	Penalty(dB)
No. of Channels	L = 100Km	L = 300Km	L =400Km
4	0.0057	0.01	0.016
8	0.0200	0.03	0.046
12	0.0420	0.06	0.086
16	0.1000	0.15	0.198
20	0.2500	0.35	0.145
24	0.4000	0.55	0.670
28	0.5500	0.75	0.880
32	0.7020	0.95	1.091

According to the data of TABLE-3, Figure-21 has been plotted. This shows the effect on power penalty due to variation of channels. As the channel increases, the power penalty increases.

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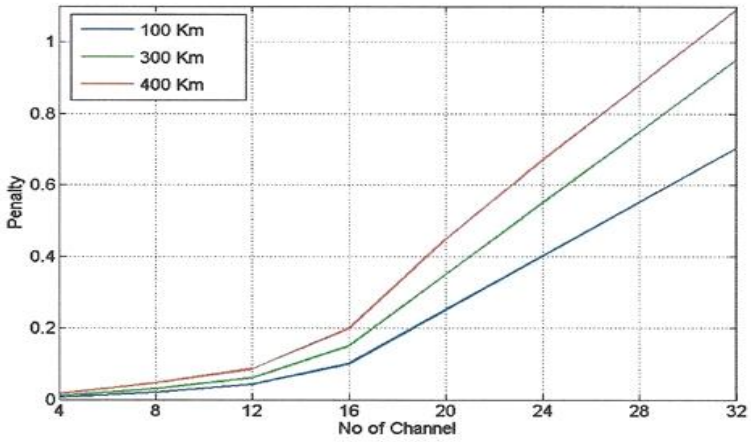

Figure-21: Effect on BER performance of OFDM-QAM signal due to variation of number of channel for LASER linewidth, σ_λ =2 nm and fiber length, L=100,300 and 400 Km.

From figure -21, it is seen that when the no. of channel is 4, the BER performance of OFDM-QAM system can be considered as unaffected because here the power penalty is only 0.01 dB. But as the number of channel increases, the required power penalty to achieve base receiver sensitivity increases. When the number of channel is 16, the power penalty increases to 0.16 dB. But in case of no. of channel 32, the power penalty increases in a large amount i.e. 0.94 dB.

From the above results we can say that the effect on BER performance of OFDM-QAM system for the number of channel 4 and 8 can be neglected but when the number of channel increases from these values, the effects becomes so extremely serious and cannot be neglected.

Effect of FWM

The FWM induced crosstalk has higher dependency on channel capacity, fiber length and gain. As these factors increase considerably, crosstalk noise increases and degrades the system performance. The following analyzes the effect of FWM on BER and system SNR.

BER performance with FWM and without FWM

The error probability increases as the FWM induced crosstalk power increases basically with channel capacity and receiver gain.

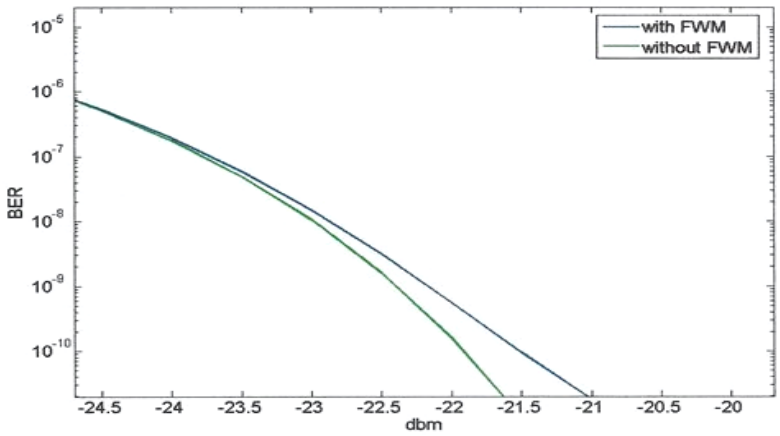

Figure-22: Effect of FWM on BER performance when the channel capacity is 32 fiber length of 50 Km and bit rate is 2 Gb/S.

The above figure shows the comparison of BER performance with and without considering FWM crosstalk. BER at 10^{-9} indicates the error probability is higher when we account the crosstalk effect. The system is oriented by the thermal noise but FWM has quite impact on system BER performance. The differentiate characteristics is defined as -0.5 dBm.

So, the BER performance of OFDM-QAM system degrades due to the presence of FWM crosstalk and it is higher for higher values of channel capacity and fiber length.

SNR characteristics

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The system SNR is oriented by thermal noise and FWM crosstalk noise mainly, but we have also accounted shot and spontaneous noises generated in amplifier. Though only the FWM crosstalk noise has rapid variation with channel capacity and fiber length, the system SNR is particularly observed under the influence of FWM crosstalk power variation.

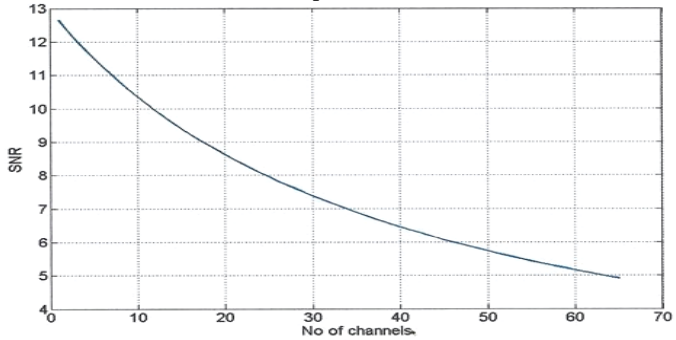

Figure-23: Effect of FWM on system SNR varying the channel capacity from 1~65, at a fiber length of 50 Km and bit rate of 2 Gb/S.

The above figure shows the system SNR along with channel capacity. At channel capacity of 8, the magnitude of SNR is 10.8, where at the capacity of 16, the magnitude is 9.238. For the channel capacity of 32, the SNR degrades to the magnitude at 7.175. So, from the above results we can say that the effect of FWM induced crosstalk on SNR performance of OFDM-QAM system for the number of channel 8 and 16 can be neglected but when the number of channel increases from these values, the effects becomes so extremely serious and can not be neglected.

4. Conclusion

The performance of OFDM-QAM system under the influence of dispersion and FWM have been successfully evaluated .The increase of optical fiber length, source linewidth causes the increase in dispersion effect of OFDM-QAM system. The FWM induced crosstalk affects the OFDM-QAM spectrum at receiver and has dependency on fiber length, number of RF channel and gain parameter. The BER performance of OFDM-QAM system has also been analyzed for various fiber length, bit rate, number of channel.

For the single mode fiber having 2^{nd} order dispersion parameter D=20 pS/nm.Km; the dispersion effects for the various fiber lengths i.e. for 50, 100, 150 Km are 63.32%, 64.46% and 64.92% respectively at LASER linewidth σ_λ=2nm. So the dispersion effect increases with the increase in fiber length for OFDM-QAM system.

So, it can be said that the effect of dispersion due to variation of fiber length on OFDM-QAM system is not so severe than that of variation of LASER linewidth.

For fiber length, L=30 Km, due to increase in value of linewidth, σ_λ from 2 to 3 nm, the power penalty increases from 0.08 dB to 0.16 dB and due to increase in value of σ_λ from 3 to 4 nm, the increase in power penalty is from 0.16 dB to 0.58 dB . So, increase in the linewidth, σ_λ causes increases in the power penalty.

At a constant linewidth, σ_λ =2nm, when the fiber length, L increases the power penalty increases, since the FWM induced crosstalk power and chromatic dispersion are highly dependent on fiber length. For an increase in value of fiber length from 90~120 Km, power penalty increases an amount 0.24 dB. The power penalty curve shows rapid variation from 60~120 Km due to the variation photocurrent factor. The photocurrent factor is sensitive to fiber length and channel capacity. At 75 Km, the factor magnitude is 0.3286 and at 150 Km, the magnitude is 0.2128. This variation is responsible for the rapid fluctuation of the penalty curve within the length 60~120 Km.

So, it can be concluded that with the increase in fiber length the BER performance of OFDM-QAM degrades.

In case of fiber length, L=50 Km, LASER linewidth, σ_λ =2nm when the bit rate increases from 2.5 GHz to 3.0 GHz, required power penalty increases from 0.51 dB to 0.92 dB. As the bit rate increases from this value, the power penalty increases more. When bit rate is 5 GHz, the power penalty is 2.09 dB.

Therefore, the increase in bit rate results more probability of error in bits and as a result power penalty increases more.

The BER performance of OFDM-QAM system has also been analyzed with the variation of number of channel. For the fiber length, L=300 Km, linewidth, σ_λ =2nm when the no. of channel is 8, the power penalty is only 0.03 dB. When the number of channel is 16, the power penalty is 0.15 dB. But in case of no. of channel 32, the power penalty increases in a large amount i.e. 0.95 dB.

So, the effect on BER performance of OFDM-QAM system for lower number of channel can be neglected but when the number of channel increases towards the higher values, the effects becomes so extremely serious and cannot be neglected.

The BER performance of OFDM-QAM system has analyzed under the influence of crosstalk power. The BER at $l0^{-9}$ shows when the system is free from FWM effect, the probability of error is less. The differentiate characteristics is defined as -0.5 dBm.

So, as the channel capacity is greater, the FWM crosstalk highly affects the system BER performance.

Therefore, the increasing effect of FWM induced crosstalk noise with channel capacity on system SNR degrades the system performance along with the other receiver and amplifier noises.

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