The Performance Analysis Fiber Optic Dispersion on OFDM-QAM System

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***Abstract*—Performance of Orthogonal Frequency Division Multiplexing (OFDM) combined with Quadrature Amplitude Modulation (QAM) has been analyzed in presence of fiber optic dispersion. The influence of dispersion on the OFDM spectrum is investigated with fiber lengths, bit rates, no. of channels and source line-widths. The inter-channel interference occurs due to dispersion-induced broadening of OFDM spectrum. The power penalty suffered by the system is evaluated at bit error rate (BER) 1×10^{-9} for a single mode fiber operating at 1.55 μm. The results obtained from the OFDM–QAM system demonstrate that the influence of dispersion is lower in OFDM–QAM spectrum in comparison with single bit transmission with same bandwidth.**

Keywords-OFDM, QAM, ISI, BER, BRS

I. INTRODUCTION

In modern communication technology, efficient utilization of communication resources (bandwidth and power) is the key challenge to meet the high bit rate demand in future application. There are several approaches to reduce system bandwidth as well as transmission power in digital communication techniques [1]. Among them, advanced digital modulations and multiplexing techniques are widely used to reduce system bandwidth significantly. It is well known 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= 2^N 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 performance, bandwidth requirement is the higher than M-ary PSK. With the combination of M-ary PSK and M-ary ASK, 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*. It is well established that orthogonal frequency division multiplexing (OFDM) provides us more compact spectrum. Therefore with the combination of OFDM multiplexing and QAM modulation an efficient communication system can be obtained.

Optical fiber is a well known waveguide capable of propagating light wave in the range of near infrared [2]. The available bandwidth in optical carrier is in the order of 10^5 times than that of microwave link.

Therefore, if OFDM-QAM system is combined with optical fiber, the speed of data communication can be enhanced dramatically. Although optical fiber provides us enormous bandwidth, the system performance severally degrades due to dispersion. It is therefore very much important to investigate how a OFDM-QAM system is influenced with that of same bandwidth single bit transmission in presence of dispersion. The system performance will be evaluated at bit error rate 10^{-9} for a single mode fiber operating at $1.55\mu m$.

II. FIBER OPTIC TRANSMISSION SYSTEM

Optical fiber is a wave-guide, which propagates light wave having frequency range near infrared in the electromagnetic spectrum (1.7~0.8μm). The optical carrier frequency in the range 10^{13} to 10^{16} Hz. There are two basic types of fiber: Multimode and Single-mode. Multimode fiber has a larger core and therefore supports multiple light wave paths. Multimode fiber was the first type of fiber used for data networks and is usually abbreviated with the letters MMF. There are two diameters used with multimode fiber—62.5 micron and 50 micron. Both types have a 125-micron cladding. Multimode fiber is used for distances of typically less than 2 km because, with the support of multiple paths or modes, there is a greater chance that some light traveling down a certain path will arrive later than light traveling directly down the center of the core, causing the remote end to see fading in the light signal. Single-mode fiber (SMF) has a core that supports one path or mode by which light may travel. The core of an SMF is much smaller than the core of an MMF—8.3 or 7.1 microns versus 62.5 or 50 nm. 125 micron cladding surrounds both SMF cores. Lasers are the required light source for SMF, which means that although the cost of SMF is frequently less than that of MMF, the cost of the light source (laser) makes SMF installations costprohibitive for short distances. However, single-mode fiber can send high bit rate signals over long distances beyond 2 km.

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

- Transmitter
- Optical fiber
- Receiver

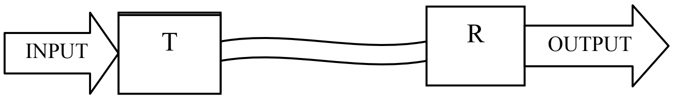

Figure 1. Optical fiber communication system.

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've used LASER sources. As it's 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.

III. Dispersion and Its Effects

Dispersion is a phenomenon that causes the separation of a wave into spectral components with different wavelengths, due to the dependence of the wave's speed on its wavelength. Dispersion mechanism within the fiber causes broadening of transmitted light pulses as they travel along the channel. As a result, each broadened pulse overlaps with its neighbors and eventually becomes indistinguishable at the receiver input. This effect is known as inter symbol interference (ISI**)**. Dispersion is a process where an optical signal is degraded due to the fact that different wavelengths move at different velocities through the fiber. The light pulses moving through the fiber become spread out while traveling across the fiber. The spreading of pulses makes it difficult to detect the beginning and end of a pulse, which can cause bit errors and limits the fiber's total bandwidth capacity. The higher a fiber's dispersion, the less data a fiber can transport reliably. There are two major causes of dispersion: modal and chromatic. Effect of dispersion through optical fiber communication depends on the fiber length & laser line width. The effect of dispersion can be explained by the following Figure 2 & Figure 3.

1 0 1 1

Figure 2. Signal at the input of the fiber.

Here we can see that when signal passes through the fiber due to dispersion, in the output signal there is no zero level and each spectra overlap with other, so it becomes difficult to detect the original signal.

Three separate dispersion mechanisms exist in a fiber. These are

i. Intermodal dispersion.
ii. Material or chromatic dispersion, and
iii. Waveguide dispersion.

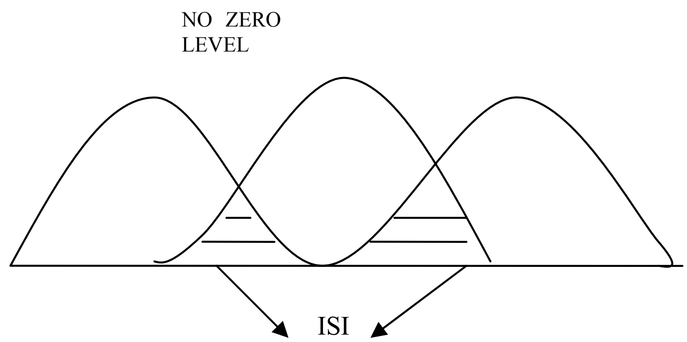

Figure 3. Signal at the output of the fiber.

A. *Intermodal Dispersion*

Modal dispersion mainly occurs in multimode fiber. Different fiber modes or paths travel at different speeds. The cause of modal dispersion is multiple or different optical paths within the fiber. Dispersion increases with the length of the fiber segment. Using single-mode fiber helps to eliminate the multiple paths within a fiber segment and decreases modal dispersion.

B. *Material Dispersion*

Material dispersion originates from the frequency or wavelength dependent response of the atoms/molecules of a material to electromagnetic waves. All media are dispersive and the only non-dispersive medium is vacuum [5]. The source of material dispersion can be examined from an understanding of the atomic nature of matter and the frequency dependent aspect of that nature [5]. Material dispersion occurs because atoms absorb and re-radiate electromagnetic radiation more efficiently as the frequency approaches a certain characteristic frequency for that particular atom called the resonance frequency [5].

Chromatic dispersion or light spreading occurs because different colors of light travel at different speeds. In general, the shorter the wavelength, the faster it travels within the fiber.

Lasers today are not able to produce one single pure frequency or wavelength of light. So as light travels down the fiber, dispersion or spreading occurs. Dispersion increases with the length of the fiber segment. Problems occur when either end of the fiber cannot detect the beginning or end of a data transmission, thereby introducing errors, which can effect data transmission rates and connectivity. Fiber containing tightly controlled chromatic dispersion characteristics and narrow spectral width lasers can help reduce chromatic dispersion [6].

C. Waveguide Dispersion

Waveguide dispersion occurs because waveguide geometry variably affects the velocity of different frequencies of light. More technically, waveguide dispersion is caused by the variation in the index of refraction due to the confinement of light an optical mode [5]. Waveguide dispersion is a function of the material parameters of the waveguide such as the normalized core-cladding index difference,

$$\Delta = (n_{core} - n_{cladding}) / n_{core}$$

and geometrical parameters such as the core size, *a* [5, 6]. The index in a waveguide is known as an effective index, *neff,* because of the portion of the index change caused by propagation in a confined medium. Confinement is best described by a quantity known as the V parameter, which is a function of both the material and geometry of the waveguide. The V parameter is given by Equation (1)

$$V(\lambda) = \frac{2\pi}{\lambda} a (n^2_{core} - n^2_{cladding})^{1/2} \approx \frac{2\pi}{\lambda} a n_{core} \sqrt{2\Delta} \quad (1)$$

Propagation in a waveguide is described by a quantity known as the normalized propagation constant, b, which is also a function of the material and geometry of the waveguide. This quantity is given in Equation (2)

$$b = \frac{n_{eff} - n_{cladding}}{n_{core} - n_{cladding}} \quad (2)$$

The contribution of the waveguide to the dispersion parameter depends on the confinement and propagation of the light in a waveguide and hence it is a function of both the V parameter and the normalized propagation constant, b. The waveguide dispersion can be calculated via knowledge of V and b via Equation (3).

$$D_W = -\frac{2\pi}{\lambda^2} \left[\frac{N^2_{G(cladding)}}{n_{cladding}\omega} \frac{V d^2(Vb)}{dV^2} + \frac{dN^2_{G(cladding)}}{d\omega} \frac{d(Vb)}{dV} \right] \quad (3)$$

In most cases the main effect of the waveguide dispersion in standard single mode fibers is a reduction in dispersion compared to dispersion in bulk [5]. In comparison to material dispersion the contribution of waveguide dispersion is quite small and in most standard single mode fibers it only shifts the zero dispersion wavelength from 1276 nm to 1310 nm [5]. This effect is illustrated in Figure 4:

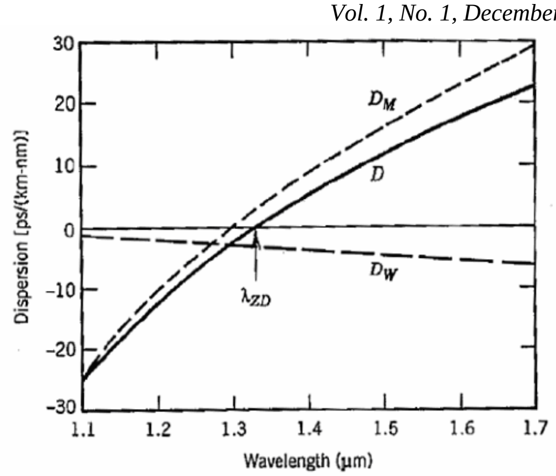

Figure 4. Contribution of both waveguide and material [12]

IV. MEASUREMENT OF THE DISPERSION PARAMETER

When light is confined in an optical fiber or waveguide the index is a property of both the material and the geometry of the waveguide. The waveguide geometry changes the refractive index via optical confinement by the waveguide structure. The refractive index is therefore a function of both the material and waveguide contributions. For this reason in a fiber or a waveguide the index is known as an effective index.

The relationship between the effective index and the first, second and higher order dispersion can be understood mathematically via a Taylor expansion:

$$n_{eff} = n_{eff}(\lambda_o) + (\lambda - \lambda_o)\frac{dn_{eff}}{d\lambda}\Big|_{\lambda_o} + (\lambda - \lambda_o)^2 \frac{d^2 n_{eff}}{d\lambda^2}\Big|_{\lambda_o} + (\lambda - \lambda_o)^3 \frac{d^3 n_{eff}}{d\lambda^3}\Big|_{\lambda_o} + \ldots \quad (4)$$

The first term in Equation (4) represents the linear portion of the effective index as a function of wavelength and shows how dispersion manifests itself in the wavelength dependence of the phase velocity for a wave inside a medium. The relationship between the first term and the phase velocity is described in Equation (5)

$$V_p(\lambda_o) = \frac{c}{n_{eff}(\lambda_o)} \quad (5)$$

The second term in Equation (5) is related to the group velocity of an optical pulse and represents the first order dispersion. The group velocity is the velocity that the envelope of an optical pulse propagates. It depends on a quantity known as the group index, *NG,* which is a function of both the index of refraction and the slope of the index of refraction at a particular wavelength. The group velocity relates to the second term via Equation (6), where c is the velocity of light in vacuum:

$$V_g(\lambda_o) = \frac{c}{N_G} = \frac{c}{n(\omega_o) + \omega_o \left.\frac{dn}{d\omega}\right|_{\omega_o}} = \frac{c}{n(\lambda_o) - \lambda_o \left.\frac{dn}{d\lambda}\right|_{\lambda_o}} \quad (6)$$

The third term in Equation (6) represents the variation in the group velocity as a function of wavelength. This variation in the group velocity is known as Group Velocity Dispersion (GVD), which is related to the third term via Equation (7), where λo is the particular wavelength for which the GVD is calculated and c is the speed of light in vacuum:

$$GVD(\lambda_o) = -\frac{\lambda_o^2}{2\pi c}\left[-\frac{\lambda_o}{c}\frac{d^2 n_{eff}}{d\lambda^2}\right] \quad (7)$$

The term in the brackets in Equation (7) is known as the dispersion parameter, D, which represents second order dispersion since it describes how the second derivative of the effective index varies with respect to wavelength:

$$D(\lambda_o) = -\frac{\lambda_o}{c}\left.\frac{d^2 n_{eff}}{d\lambda^2}\right|_{\lambda_o} \quad (8)$$

The dispersion parameter is important since it is related to pulse broadening which critically limits the bit rate of a communication system. Equation (9) shows how an increase in the dispersion parameter directly relates to an increase in pulse broadening:

$$\Delta T = D(\lambda_o) L \Delta\lambda \quad (9)$$

In Equation (9), Δλ is the range of wavelengths traveling through the medium and L is the length of the medium. The dispersion parameter, D(λo), which is related to pulse broadening, is the most significant parameter since it limits the bit rate of an optical communication system.

The dispersion parameter of a waveguide such as an optical fiber is given by the total dispersion due to both the material and waveguide contributions. The total dispersion is the combination of the material dispersion and the waveguide dispersion and thus the dispersion parameter of a waveguide is given by:

$$D = -\frac{2\pi c}{\lambda^2}\frac{d}{d\omega}\left(\frac{1}{V_G}\right) = D_M + D_W \quad (10)$$

The next two sections discuss the contributions that both material and waveguide dispersion make individually to the total dispersion.

V. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM is similar to the FDM except here the frequencies used by each channel are orthogonal to each other. In *OFDM*, FDM is achieved by assigning different *OFDM* sub-channels to different users.

If frequency f1 & f_n are such that for any integer n, an integer, the following holds,

$$f_n = n \times f1$$

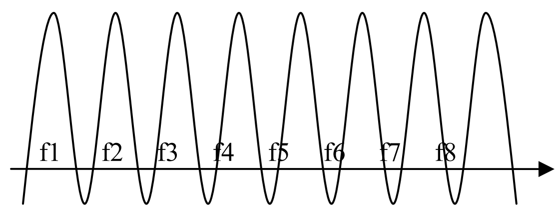

Figure 5. OFDM Techniques.

So that, f2 = 2f1
f3 = 3f1
……….
f8 = 8f1

All three of these are harmonics to f1, In this case, since these carriers are orthogonal to each other, when they added together, they do not interfere with each other. That means OFDM system provides zero cross-talk.

A. Causes of Choosing OFDM

In our proposed system, we've used *OFDM* . There are so many reasons for choosing this technique. These are:

▪ OFDM is done at a frequency of MHz range say 250 MHz & as the cut off frequency of Optical Fiber link lies between 10 GHz to 12 GHz. So we can send more signals through Optical Fiber link by using the OFDM technique**.**

▪ Signals can be transmitted at high bit rate through Optical Fiber link by using the *OFDM* technique.

▪ In *OFDM* different frequency components are multiplexed but each signal is a single frequency component. This characteristic of OFDM reduces dispersion.

▪ OFDMprovides a more compressed spectrum, which increases the spectral efficiency.

VI. RESULTS AND DISCUSSION

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.

A. With the fiber length and laser line-width

As the fiber length and LASER line width increases the probability of BER increases. If the fiber length lies between 1~100 Km the effect on BER performance of OFDM-QAM system is not so severe but when the fiber length increases from 100 Km, the effects becomes so severe. Here, the fiber length, L was varied from 30~300 Km and the LASER line-width, σ_λ from 2~ 4 nm and calculated the value of power penalty at a bit rate 64 Gb/S. This shows the effects on BER performance of OFDM-QAM system due to variation of fiber length and LASER line-width.

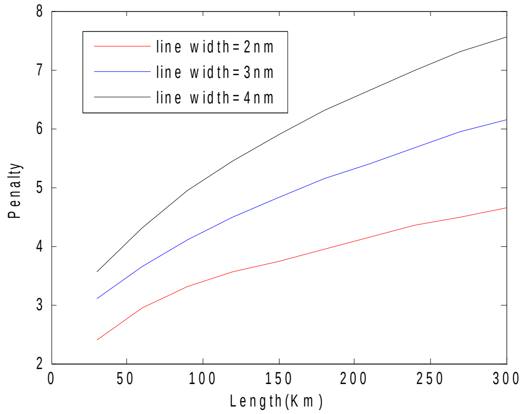

Figure 6. Effect on BER performance of OFDM-QAM system due to variation of fiber length L=30~300 Km and LASER line-width, σ_λ =2, 3, 4 nm at a bit rate of 64 Gb/S.

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 line-width. But this effect is not so distressing in case of short fiber length fiber.

B. *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 line-width, σ_λ =2 nm and for the fiber length, L=50, 100 and 300 Km.

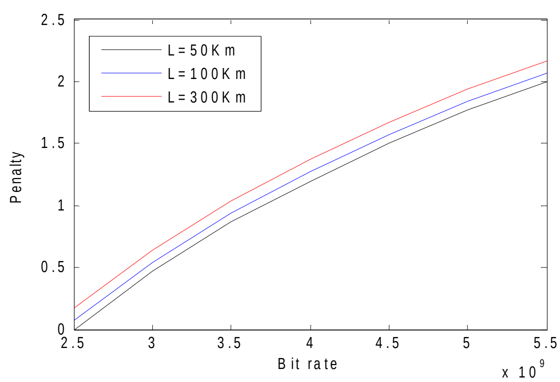

Figure 7. Effect on BER performance of OFDM-QAM system due to variation of bit rate for LASER line-width, σ_λ =2 nm and for fiber length, L=50,100,300 Km.

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.

C. *With the 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 no. of channel increases, the signal spectrum becomes wider.

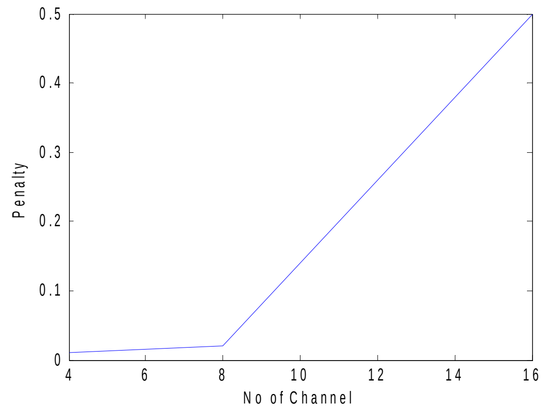

Figure 8 Effect on BER performance of OFDM-QAM signal due to variation of no. of channel for LASER linewidth, σ_λ =2 nm and fiber length, L=500 Km.

So, 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 no. of channel increases from these values, the effects becomes so extremely serious and can not be neglected.

VII. Comparision Between OFDM-QAM System and a Convensional System

To compare the performance of OFDM-QAM system with a conventional system, here a single bit signal has been chosen. The band width of this single bit signal is same as the OFDM-QAM signal but bit rate of OFDM-QAM signal is 4 times greater than the single bit signal. This signal has been allowed to pass through the same fiber that was used for the transmission OFDM-QAM signal.

A. *With Fiber Length*

When the fiber length increases the BER performance decades for all the system. The BER performance of both the OFDM-QAM signal and the single bit signal has been analyzed for LASER line width, σ_λ =2 nm and fiber length, L=30~300 Km.

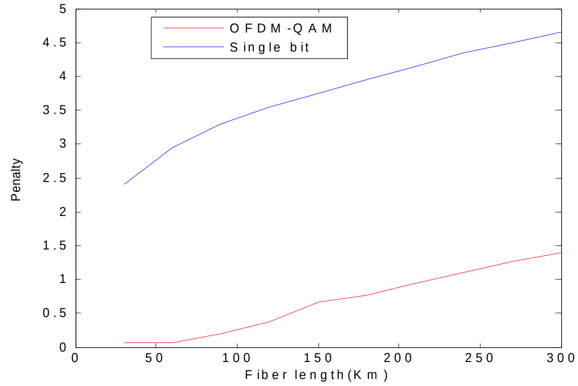

Figure 9. BER performance of OFDM-QAM system and a single bit system due to variation fiber length for LASER line-width, σ_λ=2 nm.

From the above result, we can say that the OFDM-QAM system provide more improved BER performance than a single bit system due to the variation of fiber length. And the power penalty required for a single bit system is 2 times greater than OFDM-QAM system.

B. *With Laser Line-width*

The BER performance also suffers not only with the variation of fiber length and but also with the variation of LASER line-width. When the LASER line-width increases, the power penalty required to achieve base receiver sensitivity increases. Both OFDM-QAM and single bit system has been analyzed for the fiber length, L=300 Km and LASER line-width, σ_λ was varied from 2~11 nm.

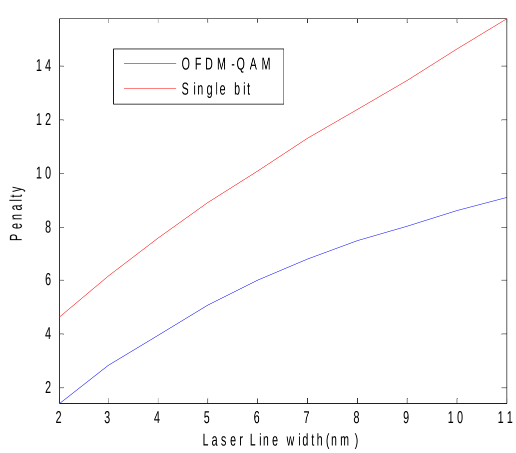

Figure 10. BER performance of OFDM-QAM system and a single bit system due to variation LASER line-width for fiber length, L=300Km.

From the above result, we can say that BER performance of OFDM-QAM system is more improved than the single bit signal for the variation of LASER line-width. The power penalty for single bit system is two times greater than the OFDM-QAM system.

VIII. Conclusion

The performance of OFDM-QAM system has been successfully evaluated .The increase of optical fiber length, source line-width causes the increase in dispersion effect of OFDM-QAM system. The BER performance of OFDM-QAM system has also been analyzed for various fiber length, LASER line-width, bit rate, number of channel.

For the single mode fiber having 2nd order dispersion parameter D=20 $pS/nm.Km$ and 3rd order dispersion parameter, S is equal to zero; the dispersion effects for the various fiber lengths i.e. for 20, 40, 60 Km are 49.50%, 49.51% and 49.53% respectively at LASER line-width σ_λ=2 nm. These values are very close to each other. 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 line-width.

So, it can be concluded that with the increase in fiber length and LASER line-width, the BER performance of OFDM-QAM falls.

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

So, the effect on BER performance of OFDM-QAM system for the no. of channel 4 and 8 can be neglected but when the no. of channel increases from these values, the effects becomes so extremely serious and can not be neglected.

To compare the performances of OFDM-QAM system with a conventional system, a single bit signal having the same bandwidth as the OFDM-QAM signal has been sent through the same fiber. With the variation of fiber length and LASER line-width, the BER performance of these two systems have been analyzed and obtained results have been compared.

Hence we can conclude that OFDM-QAM system has higher tolerance on the effect of fiber optic dispersion. It is two times less than that of a conventional system. The BER performance of OFDM-QAM system is more improved than that of a conventional system having the same bandwidth, though incase of OFDM-QAM the bit rate is four times greater than that of a conventional signal.

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