# PERFORMANCE ANALYSIS OF OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING TRANSMISSION SYSTEMS

A Dissertation Submitted in partial fulfilment of the requirements for the award of the degree of

**Masters of Engineering**
**In**
**Electronics and Communication Engineering**

Submitted by
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# CERTIFICATE

I, Manbir Kaur Brar, hereby declare that the work which is being presented in the dissertation entitled, **"PERFORMANCE ANALYSIS OF OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING TRANSMISSION SYSTEMS"** by me in partial fulfillment of the requirement for the award of degree of M.E in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler**, Senior Professor, ECED.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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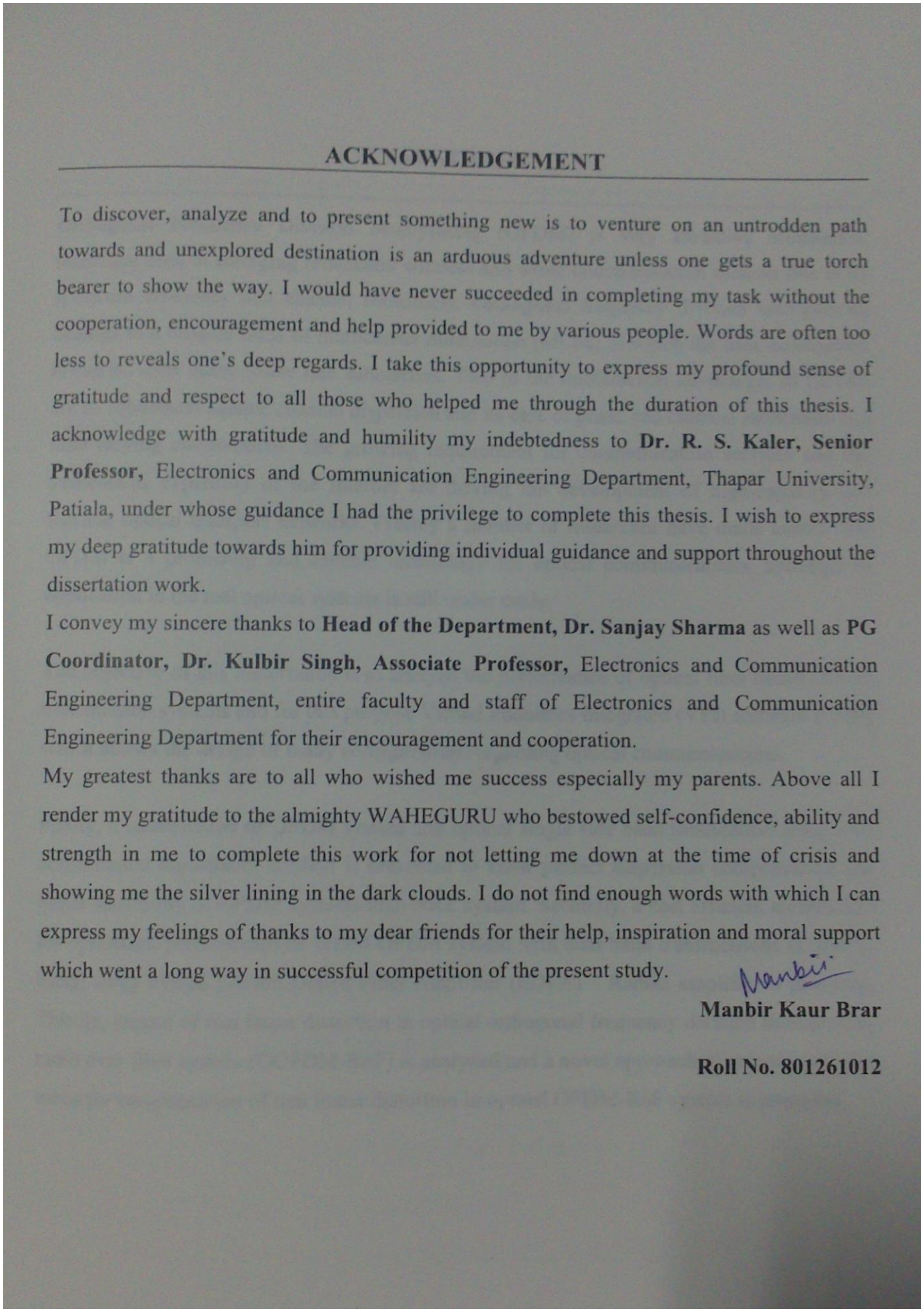

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# ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is very attractive modulation technique used in emerging broadband wireless and wired communication systems due to its spectrum efficiency and channel robustness. Orthogonal frequency division multiplexing belongs to a broader class of multicarrier modulation (MCM) in which the data information is carried over many lower rate subcarriers. Two of the fundamental advantages of OFDM are its robustness against channel dispersion and its ease of phase and channel estimation in a time-varying environment. The growing requirement for communication services and the tremendous expansion of the Internet are driving the development of high-capacity and flexible optical transport networks. Freshly a number of researches have made known that OFDM is a promising and capable technology for optical communications, although its application in the real optical systems is still under study.

The objective of this dissertation is to analyze the performance of optical fiber based OFDM transmission systems and for this purpose Virtual Photonics Integrated (VPI) software is used which allows the design of many configurations regarding optical communications.

Firstly, a combination of OFDM system and optical single side band modulation along with constellation adjustment method is presented to show perfect dispersion compensation and better sensitivity of OFDM systems than NRZ system. Secondly, a cost efficient architecture for optimized performance of WDM OFDM system with dual band transmissions (C and L-band) using hybrid Erbium Doped Fiber Amplifier (EDFA) – Raman amplifier is proposed. Thirdly, impact of non linear distortion in optical orthogonal frequency division multiplexing radio over fiber system (OOFDM-RoF) is analyzed and a novel approach of insertion of pilot tones for compensation of non linear distortion in optical OFDM-RoF system is proposed.

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# LIST OF ABBREVIATIONS

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| | |
|---|---|
| ADC | Analog to Digital Converter |
| AFC | Adaptive Frequency Correction |
| BER | Bit Error Rate |
| CCDF | Complementary Cumulative Distribution Function |
| CD | Chromatic Dispersion |
| CE-OFDM | Constant Envelope Orthogonal Frequency Division Multiplexing |
| CFDM | Coded Frequency Division Multiplexing |
| CO-OFDM | Coherent Optical Orthogonal Frequency Division Multiplexing |
| CO | Central Office |
| CP | Cyclic Prefix |
| CSR | Carrier to Sideband Ratio |
| CTB | Composite Triple Beat |
| CW | Continuous Wave |
| DAC | Digital to Analog Convertor |
| DCF | Dispersion Compensating Fiber |
| DDO-OFDM | Direct Detection Optical Orthogonal Frequency Division Multiplexing |
| DFT | Discrete Fourier Transform |
| DMT | Discrete Multi Tone |
| DTT | Digital Terrestrial Television |
| DRA | Distributed Raman Amplification |
| EDC | Electronic Dispersion Compensation |
| EDFA | Erbium Doped Fiber Amplifier |
| EDFA | Erbium Doped Fiber Amplifier |
| EVM | Error Vector Magnitude |
| FDM | Frequency Division Multiplexing |
| FEC | Forward Error Correction |
| FFT | Fast Fourier Transform |
| ICI | Inter Carrier Interference |
| IDFT | Inverse Discrete Fourier Transform |

| | |
|---|---|
| ISI | Inter Symbol Interference |
| IFFT | Inverse Fast Fourier Transform |
| IMD | Inter Modulation Distortion |
| IM/DD | Intensity Modulated/ Direct Detection |
| LAN | Local Area Network |
| LM-DD | Linearly Mapped Direct Detection |
| LS | Least Sequence |
| MCM | Multi Carrier Modulation |
| MZM | Mach Zehnder Modulator |
| NLD | Non Linear Distortion |
| NLM-DD | Non Linearly Mapped Direct Detection |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OOFDM | Optical Orthogonal Frequency Division Multiplexing |
| OSNR | Optical Signal to Noise Ratio |
| OSSB | Optical Single Side Band Modulation |
| PAPR | Peak to Average Power Ratio |
| PCF | Partial Carrier Filling |
| PD | Photo Detector |
| PLL | Phase Locked Loop |
| PMD | Polarization Mode Dispersion |
| PSK | Phase Shift Keying |
| PTS | Partial Transmit Sequence |
| QAM | Quadrature Amplitude Modulation |
| Rof | Radio over Frequency |
| ROP | Received Optical Power |
| ROF | Radio Over Frequency |
| RS | Remote Site |
| SCM | Single Carrier Modulation |
| SOA | Semiconductor Optical Amplifier |
| SLM | Selective Mapping |

# CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION:

Orthogonal Frequency Division Multiplexing is a very attractive modulation and multiplexing technique that is used in broadband wireless and wired communication system due to its spectrum efficiency and channel robustness. Orthogonal frequency division multiplexing belongs to a broader class of multicarrier modulation (MCM) carrying the data information over many lower rate subcarriers. OFDM, a modulation as well as multiplexing technique is the origin of several telecommunications standards counting digital terrestrial television (DTT), wireless local area networks, and digital radio broadcasting. OFDM is even the source of nearly all DSL standards, and within this situation OFDM is generally known as discrete multitone (DMT).

Regardless of the benefits offered by OFDM and its prevalent usage in wireless communications, it has been considered for optical communications during the last years. The growing requirement for communication services and the tremendous expansion of the Internet are driving the development of high-capacity and flexible optical transport networks. In recent times, many researches started to pay more interest to apply the OFDM technique with multi-carrier modulation (MCM), instead of single carrier modulation (SCM) in optical fiber communication [1-2] due to its ability to reduce the effect of selective fading, chromatic dispersion and decrease Inter-symbol Interference (ISI).

Optical orthogonal frequency division multiplexing (O-OFDM) has gained much interest in recent years as it is developed for longer distance and has capability to equalize chromatic dispersion (CD) and polarization mode dispersion (PMD) efficiently. OFDM technique has been applied so it can be utilized in wavelength division multiplexing (WDM) system [3].

To attain a high spectral efficiency and achieve simple channel equalization, OFDM takes benefit of the Fast Fourier Transform (FFT). Optical OFDM has become one of the most capable technologies that are used for designing bit rate and bandwidth variable transponders for spectral efficient optical networks. O-OFDM with phase modulation and coherent detection is also the future for suitable spectral efficient key, robust against system nonlinearities, and for transmission in elastic networks [4].

## 1.2 HISTORICAL PERSPECTIVE OF OFDM:

In1966, Chang first introduced the concept of OFDM in a seminal paper [1]. The plan was soon analyzed by Saltzberg in 1967, and in fact "OFDM" is first appeared in his separate patent in 1970 [2]. The proposal to create the orthogonal signals using an FFT came in 1969 [5]. In 1980, the cyclic prefix (CP) was proposed [6].

For practical wireless applications, OFDM began to be considered in the mid 1980s. A paper on OFDM for mobile communications is published by Cimini of Bell Labs in 1985 [7]. In 1987, the use of OFDM for radio broadcasting is considered and the significance of combining forward error correction (FEC) with OFDM is also noted by Lassalle and Alard [8]. Due to this relationship, OFDM is known as Coded OFDM (C-OFDM). The field of OFDM had long been developed as a peripheral interest in military application. OFDM is now the basis of many telecommunications standards and is even the origin of nearly all DSL standards, and within this situation OFDM is generally known as discrete multitone (DMT).

The summary of theoretical basis and practical application of OFDM across a range of communication systems is shown in figure 1.1.

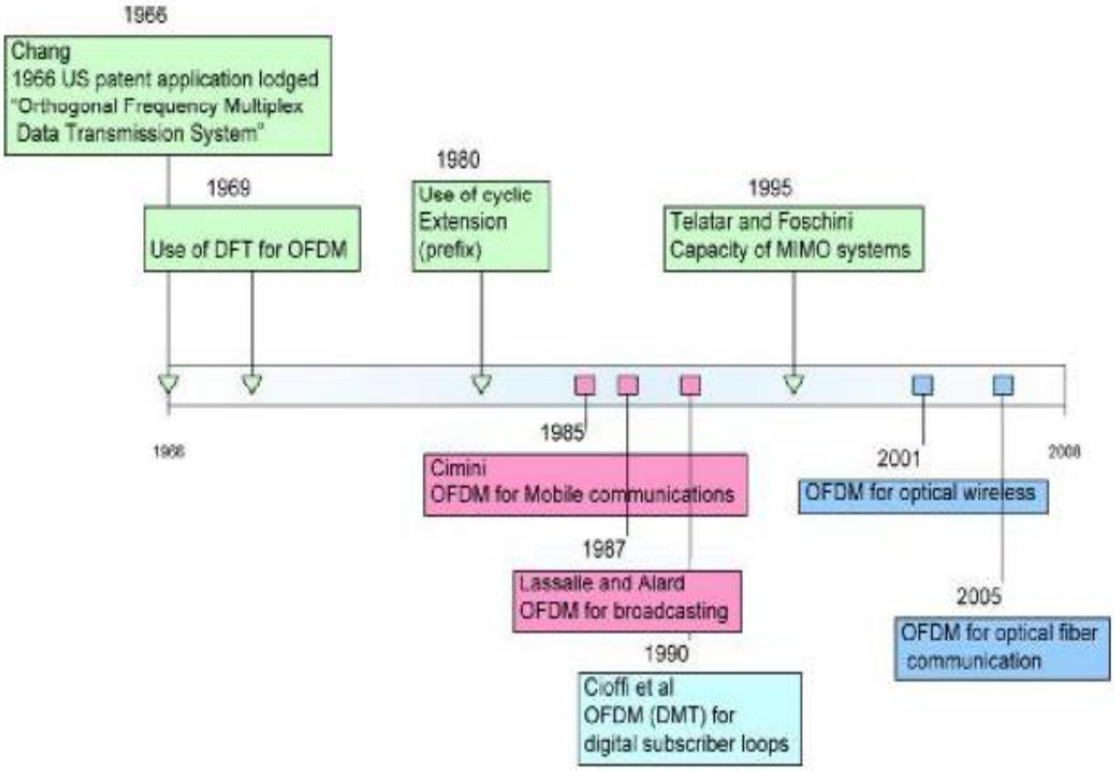


Fig. 1.1 Historical development and practical implementation of OFDM.

OFDM in optical communications has grown dramatically in recent years, and a rising number of papers on the theoretical and practical performance of optical OFDM in many systems including optical wireless are present [9, 10]. In the late 2000s, optical OFDM has been investigated for long-haul transmission. Two major research directions came into account, i.e. direct-detection optical OFDM (DDO-OFDM) and coherent optical OFDM (CO-OFDM). DDO-OFDM is suitable for low-cost short reach applications and CO-OFDM that aims to achieve high spectral efficiency and receiver sensitivity.

Table 1.1 progress of optical OFDM (O-OFDM) in recent years.

| | |
|---|---|
| 1996 | Pan and Green, OFDM for CATV [11] |
| 2001 | Kahn, OFDM in direct modulation (DD) systems [12]<br>Dixon et al., OFDM over multimode fiber [13] |
| 2005 | Jolley et al., experiment of 10 Gb s$^{-1}$ optical OFDM over MMF [14]<br>Lowery and Armstrong, power-efficient optical OFDM in DD systems [15] |
| 2006 | Lowery and Armstrong [16], and Djordjevic and Vasic [11], long-haul direct-detection optical OFDM (DDO-OFDM)<br>Shieh and Athaudage, long-haul coherent optical OFDM (CO-OFDM) [17] |
| 2007 | Shieh et al. [17], 8Gb s$^{-1}$ CO-OFDM transmission over 1,000 km |
| 2008 | Yang et al. [18], Jansen et al. [19], Yamada et al. [19], >100 Gb s$^{-1}$ per single channel CO-OFDM transmission over 1,000 km |
| 2009 | Ma et al. [14], Dischler et al. [15], Chandrasekhar et al. [19], >1Tb s$^{-1}$ CO-OFDM long-haul transmission |

## 1.3 OFDM BASICS:

In Frequency Division Multiplexing (FDM), the transmitted signal is split into a set of individual signals, known as subcarriers which are in the frequency domain. Then every subcarrier is modulated using a conventional modulation format, and later they are jointly combined to generate the FDM signal. Each of the subcarriers in FDM transmission is independently recovered by the receiver.

If the subcarrier signals accomplish the orthogonality condition then this result in overlapping of spectrum and hence spectral efficiency is improved. This technique is known as Orthogonal Frequency Division Multiplexing (OFDM).

Figure 1.2 reports the OFDM modulation schematically. Data with bit rate R is transmitted into N parallel channels, each one of them with separate frequencies. Over each channel, the total bit rate is spread in equal parts at rate R/N. In each channel the data will be mapped to represent an information symbol and then multiplied by its corresponding frequency. These parallel information symbols are summed to form one OFDM symbol. Thus the duration of each OFDM symbol is $T_s = \frac{N}{R}$.

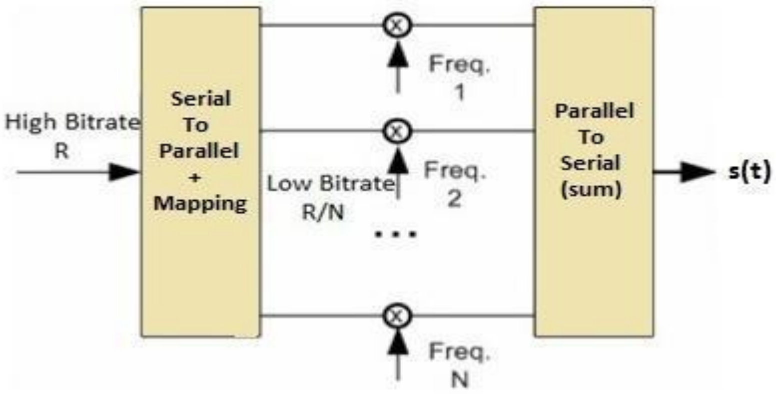


Fig. 1.2 Frequency division multiplex: Analogue transmitter

### 1.3.1 Concept of orthogonality:

Orthogonality is a property which allows multiple signals to be perfectly transmitted over a common channel and detected at the receiver without interference. OFDM signal in time domain is represented as:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{Nsc} c_{ki}\, S_k(t - iT_s) \tag{1.1}$$

$$S_k(t) = \prod(t) e^{j2\Pi f_k t} \tag{1.2}$$

$$\prod(t) = \begin{Bmatrix} 1, & (0 < t \leq T_s) \\ 0, & (t \leq 0, t > T_s) \end{Bmatrix} \tag{1.3}$$

where $c_{ki}$ is the i-th information symbol at k-th subcarrier , $S_k$ is the waveform for k-th subcarrier, $f_k$ is the subcarrier frequency, $Nsc$ is no. of subcarriers, $\prod(t)$ is pulse shaping function, $T_s$ is symbol period.

The frequency has to fulfill orthogonality condition:

$$f_k = k\frac{1}{T_s} \tag{1.4}$$

This indicates that to achieve orthogonality, each subcarrier must be separated from its neighbor by $\frac{1}{T_s}$. For couple of subcarriers this property can be explained by the under given expression:

$$\int_{-T/2}^{T/2} \cos\left(\frac{2\Pi nt}{T}\right)\cos\left(\frac{2\Pi mt}{T}\right)dt = 0, m \neq n \tag{1.5}$$

Over one period, the area under this product is zero in case of m and n be different natural numbers. The condition of orthogonality is accomplished for these waves and the frequencies of these waves are called harmonics.

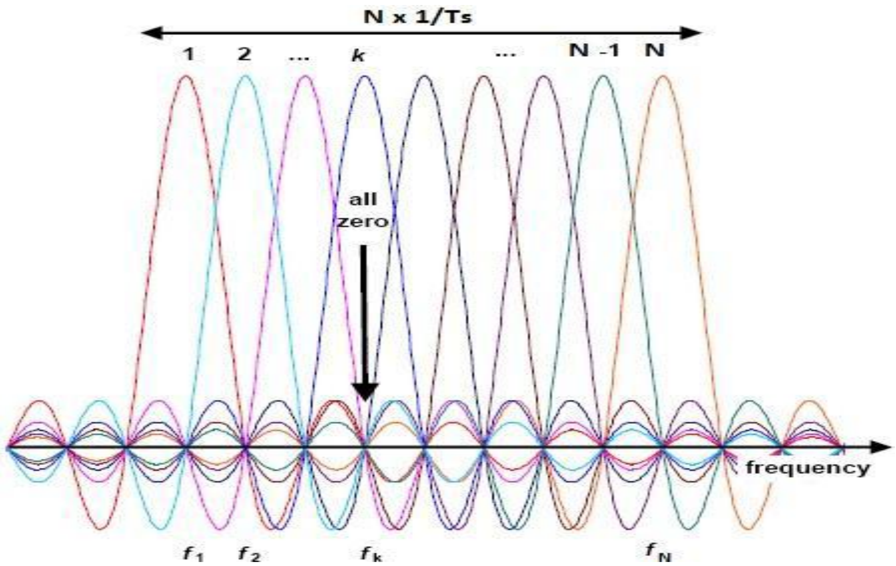


Fig. 1.3 Spectrum showing an OFDM symbol with overlapping subcarriers.

An OFDM symbol spectrum is shown in figure 1.3 which consists of overlapping subcarriers, where each subcarrier is separated from its neighbors by 1/Ts and is centered at $f_k$. So the condition of orthogonality is accomplished and a good spectral efficiency is attained.

Regardless of signal spectral overlapping, at the receiver the recovery of subcarriers is possible with no intercarrier interference (ICI) by using a bank of oscillators and low-pass filtering for each one subcarrier, as shown in figure 1.4.

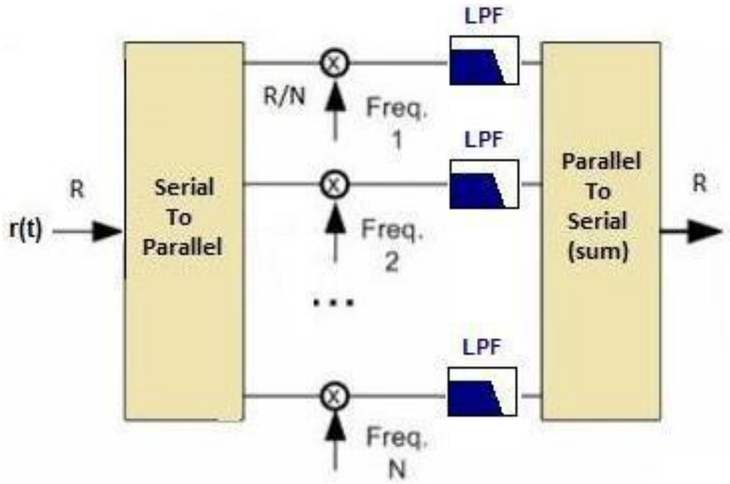


Fig. 1.4 Frequency division multiplex: Analogue receiver

## 1.4 OFDM SYSTEM DESCRIPTION:

The block diagram of OFDM transmission system is shown in figure 1.5. At the transmitter, digital data at the high rate is split into N parallel streams. Each stream uses some modulation scheme i.e. QAM, PSK, etc. and is mapped to a symbol stream. The symbols, using the inverse discrete Fourier transform (IDFT) are modulated to subcarriers. IDFT is an operation in which OFDM symbol is transformed from the frequency domain to time domain. A cyclic prefix is added to the OFDM symbol after the IDFT operation and then followed by digital-to-analog converter (DAC). The output of DAC is baseband signal which is transmitted after it is up-converted in frequency.

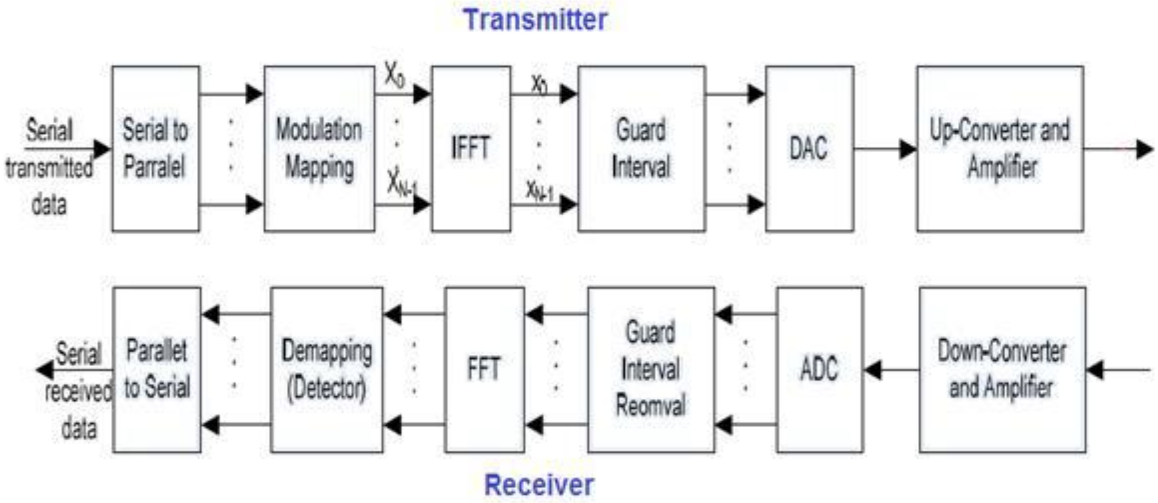


Fig. 1.5 Block diagram of basic OFDM system.

At the receiver, the signal is down-converted to baseband signal. Then using an analog-to-digital converter (ADC), the signal is converted from analog to digital. The samples are fed into the discrete Fourier transform (DFT) to be changed to frequency domain, after removing guard interval and data is detected finally as shown in figure 1.5.

### 1.4.1 Implementation of Discrete Fourier Transform:

Data are apportioned in the frequency domain, at the transmitter of an OFDM system, and the data is modulated into the time domain by using IFFT. If conjugate symmetry is imposed on the input data then the FFT output data are guaranteed to be real-valued. At the receiver, the original data is recovered by FFT which allows proficient implementation of modulation of data onto multiple carriers [20]. This similarity of the forward and inverse transform allows the same circuitry, with minor modifications for both modulation and demodulation in transceiver.

A large number of subcarriers are required in OFDM so that the transmission channel affects each subcarrier as a flat channel, which leads to a complex architecture of OFDM system involving many filters and oscillators. Weinsten and Ebert discovered that inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT) can be used for OFDM modulation and demodulation [21].

Let the symbol to be transmitted using OFDM be $\{X_n\}_{n=0}^{N-1}$. The modulated signal can be represented in time domain as:

$$x(t) = \sum_{n=0}^{N-1} X_n e^{j2\Pi f_n t} \qquad (1.6)$$

where $f_n = f_0 + n\Delta f$, n=0,1……N-1, and $T_s$ is symbol duration , and $\Delta f$ is sub channel spacing. $\Delta f$ is chosen to make N number of subcarriers orthogonal.

If, the time domain signal x (t) is sampled at the time interval of $T_{sa} = T_s/N$ then

$$x_k = x(kT_{sa}) = \sum_{n=0}^{N-1} X_n e^{j2\Pi f_{n}\frac{kT_s}{N}} \qquad (1.7)$$

If $f_0 = 0$ then $f_n . T_s = n$. Hence equation 1.7 becomes:

$$x_k = \sum_{n=0}^{N-1} X_n e^{j2\Pi\frac{kn}{N}} = \text{IDFT}\{X_n\} \qquad (1.8)$$

where IDFT denotes inverse Discrete Fourier Transform. IDFT is used to implement OFDM transmitter and similarly OFDM receiver can be implemented by DFT.

DFT and IDFT implementation of OFDM provides two important advantages, they are:

- The number of complex multiplications is reduced from $N^2$ to $N/2$, approximately linearly with the number of subcarriers $N$, due to efficient IFFT/FFT algorithm.
- When large numbers of subcarriers are required, IFFT/FFT implementation provides simple OFDM architecture without restoring much on complicated RF oscillators and filters.

### 1.4.2 Cyclic Prefix (C.P) for OFDM:

Along with modulation and demodulation of orthogonal subcarriers by IFFT and FFT, there is a need to compensate dispersive channel effects as polarization mode dispersion and chromatic dispersion. Therefore for each OFDM symbol, a guard time which is cyclically extended is introduced after the IFFT to eliminate ISI and ICI. This cyclic extension, also called insertion of cyclic prefix is one of the enabling techniques to null ISI and ICI between the OFDM symbols [22-23].

Let's assume two OFDM symbols that experience a dispersive channel along with a delay spread of td. Suppose each OFDM symbol includes two subcarriers represented by "fast subcarrier" as well as "slow subcarrier," with the fast delay spread and slow delay spread at td, respectively. Figure 1.6a shows the two subcarriers, "fast subcarrier" as well as "slow subcarrier" inside each OFDM symbol, are aligned upon the transmission. Figure 1.6b shows the same OFDM symbol with "fast subcarrier" as well as "slow subcarrier" upon the reception, where the "slow subcarrier" is delayed against the "fast subcarrier." by td. DFT window with a complete OFDM symbol is shown for the "fast subcarrier" and it is perceptible that the "slow subcarrier" has crossed the symbol boundary resulting in inter-symbol-interference (ISI) between neighboring OFDM symbols, due to channel dispersion. Additionally the orthogonality state for the subcarriers is lost, leading in an intercarrier-interference (ICI) penalty because the OFDM waveform is incomplete in the DFT window for "slow subcarrier."

Cyclic prefix was introduced to nullify ISI and ICI between the OFDM symbols [23]. Figure 1.6c shows, the waveform in the guard interval is the same copy of the waveform in the DFT window, with time-shifted through "ts" forward. Hence insertion of cyclic prefix is shown in figure 1.6c. Figure 1.6d shows the reception of OFDM signal with the guard interval.

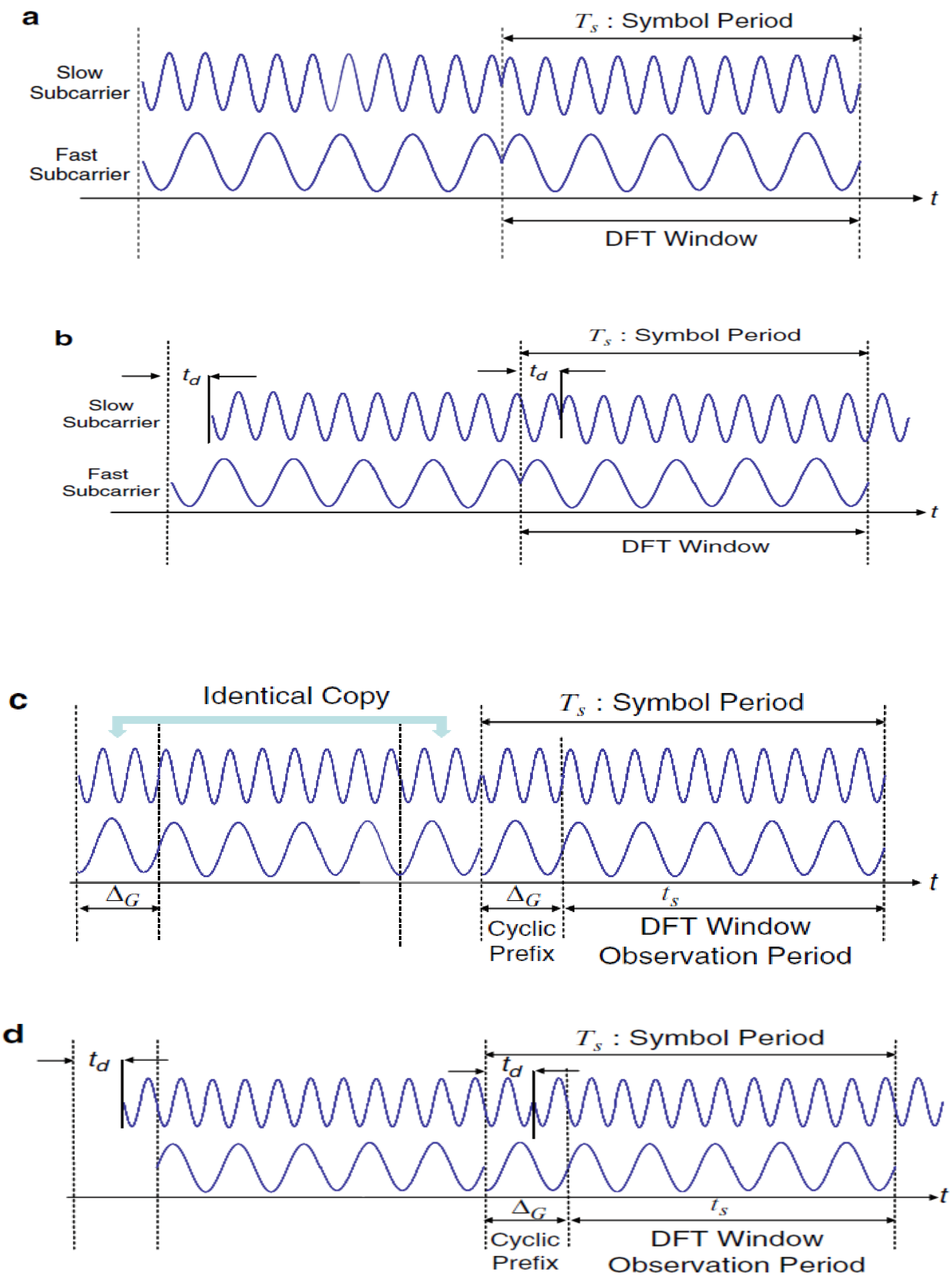


Fig. 1.6 OFDM signals (**a**) without Cyclic Prefix at the transmitter, (**b**) without Cyclic Prefix at the receiver, (**c**) with Cyclic Prefix at the transmitter (**d**) with Cyclic Prefix at the receiver.

Figure 1.7 shows one OFDM symbol that is composed of C.P as well as observation period. The frequency-domain information symbols will be recovered by the waveform contained by the observation period.

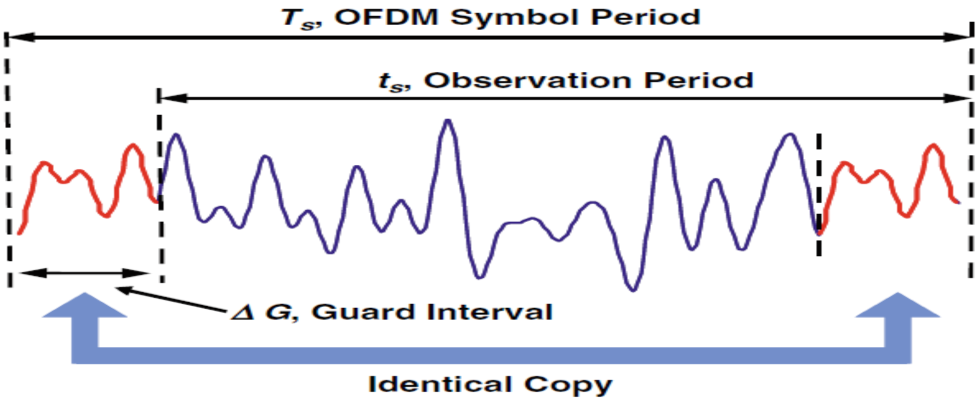


Fig. 1.7 Time-domain OFDM signal for one complete OFDM symbol.

### 1.4.3 Mapping and Demapping:

The transmitted data stream is converted into several parallel data streams; each one mapped on equivalent information symbols using complex modulation format (M-QAM or QPSK) for the subcarriers in one OFDM symbol.

In case of the 4-QAM modulation shown in figure 1.8, the serial data uses two bits to create each one of possible 4 complex-valued QAM symbols:

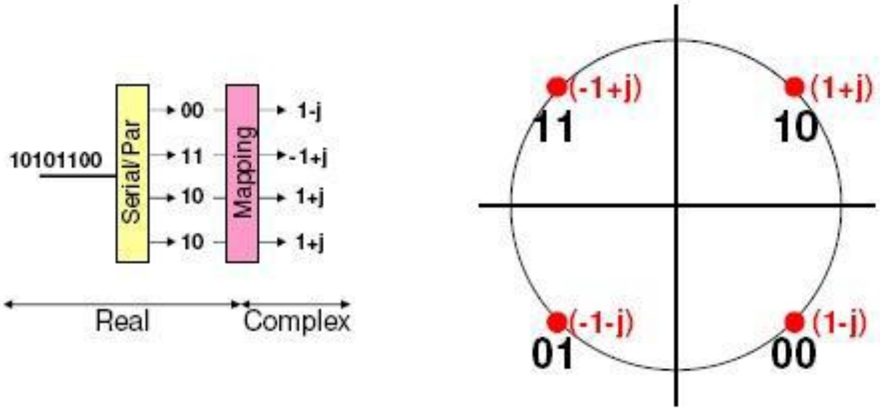


Fig. 1.8 4-QAM mapping.

At the receiver side, demapping of each one of complex-valued symbol takes place and the obtained sequence is serialized to acquire the actual bit stream. However as the data is not transmitted using an ideal channel, so before demapping a decision has to taken of which constellation point is to be received. This method is known as slicing shown in figure 1.9:

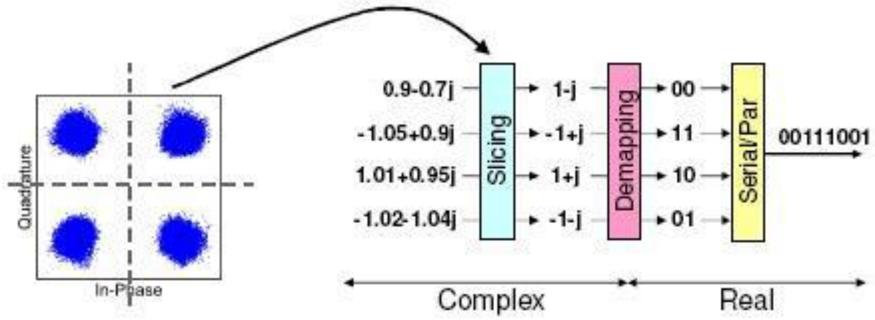


Fig. 1.9 4-QAM demapping and slicing.

### 1.5 Optical OFDM (O-OFDM):

Despite the use of OFDM in wireless communications, it has been applied towards optical communications recently. OFDM has newly received a lot of interest in the fiber-optic community. The main benefit of optical OFDM is that it can deal with virtually unlimited amount of ISI. ISI is caused by chromatic dispersion and polarization mode dispersion (PMD) in high-speed optical systems [24-25]. This chromatic dispersion and polarization dispersion is serious issue in long haul systems.

Table 1.2 comparisons between Wireless OFDM and O-OFDM.

| | Optical OFDM (O-OFDM) | Wireless OFDM |
|---|---|---|
| Mathematical Model | Continuous frequency domain<br>Dispersion | Multiple discrete time domain<br>Rayleigh fading |
| Speed | Average | Fast for mobile environment |
| Non Linearity | Important, Significant | None |
| Information carried | On optical intensity | On electrical field |
| Local oscillator | At receiver | At receiver |
| Polarity | Unipolar | Bipolar |

The basic concepts of optical OFDM are described in this section, as major characteristics of an optical channel, available optical modulation and demodulation techniques etc.

### 1.5.1 Optical channel: Chromatic Dispersion

Chromatic dispersion (C.D) is a type of distortion due to optical fiber design. It results to frequency dependence of the rate by which the phase of the wave propagates in space (optical phase velocity) and its result on the transmitted optical signal mostly scales quadratically through the data rate.

The frequency dependence of the phase mentioned could be simply recognized by a pulse that propagates through a single mode fiber in the frequency domain.

$$X_{out}(\omega) = X_{in}(\omega)e^{-j\beta(\omega)z} \tag{1.9}$$

where $X_{in}(\omega)$ corresponds to the Fourier transform (F.T) of the signal transmitted, $X_{out}(\omega)$ corresponds to the F.T of the signal received and β (ω) represents the phase constant of propagating mode.

Due to frequency dependence of phase β, the major restrictive effect measured in equation (1.9) would be C.D. Other phenomenon as nonlinearities or losses will not be considered, although their effects could be considered later.

The phase constant $e^{-j\beta(\omega)z}$ is linear dependent with frequency, in an ideal case. This means that every spectral components travel with the equal velocity and thus experience the same phase delay. The signal will be received with a constant delay but without any distortion.

But, the phase constant $e^{-j\beta(\omega)z}$ is nonlinear dependent with frequency, in a dispersive channel. The result is separate arrival times of the frequency components; the consequence is that at the reception side, the recovered signal would be different from transmitted signal.

### 1.5.2 Optical modulation techniques:

In order to transmit the electrical signal by the optical channel, there is major need of optical modulation which includes two types of a Mach-Zehnder modulator (MZM): the IQ MZM and the “standard” mode, and a directly modulated laser.

### 1) Intensity Modulation/ Direct Detection (Directly modulated laser):

In this case, an electrical signal by its bias current is used to directly modulate the laser diode. Figure 1.10 shows the typical curve of laser diode, which shows a linear-behavior region. The slope of this region is called slope efficiency. Besides this, the schematically diode laser is also shown in figure 1.10, where $P_0$ and $I_L$ refer to the optical power and bias current, respectively.

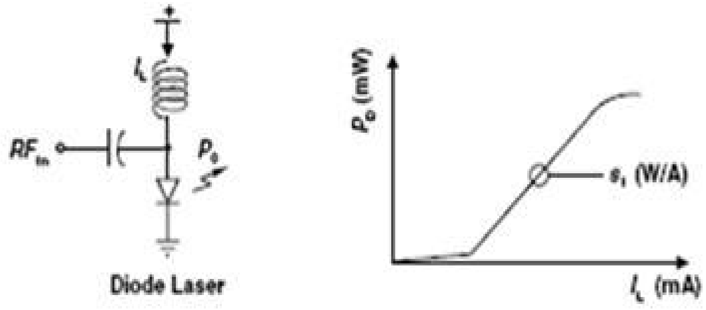


Fig. 1.10 Schematic and typical curve of laser diode.

This is mainly the simple way to transmit information via fiber (optical fiber), based upon bias current variations of a laser diode beyond a certain threshold. These bias current variations ($I_m$) are responsible for the proportional output optical power variations, that can be detected at the receiver end by a PIN diode, which carries the reverse process and sent information signal is recovered as:

$$P_{out} = P_0(1 + m.s(t)) \tag{1.10}$$

where s(t) is information signal, m is modulation index and $P_0$ is power associated to laser bias, m is given by:

$$m = \frac{I_m}{I_0} \tag{1.11}$$

The total received intensity is given by:

$$I_R(t) = RGP_0(1 + m.s(t)) \tag{1.12}$$

where R is responsivity of PIN diode, $I_R(t)$ is total received intensity and G is different gains of the amplifier devices.

Figure 1.11 shows an electrical signal s (t) is modulated over an optical carrier. During the stage of emission, the electrical signal is converted into the optical signal (E/O) and at the reception stage vice versa i.e. (O/E) takes place. This type of transmission is called Intensity Modulation / Direct Detection (IM/DD).

Fig. 1.11 Schematic Intensity Modulation and Direct Detection.

### 2) Standard Mach- Zehnder Modulator (MZM):

The direct modulation of a laser (IM/DD) is inexpensive as well as can easily adapt to less cost applications for moderate transmission rates or distances. On the other hand, for applications related to long distance links or high data rates, external modulation is a good result.

The main external modulator is Mach-Zehnder modulator (MZM) that modulates the light generated by laser working in continuous wave (C.W) mode. The MZM has usually a DC bias input and an RF input, as shown in figure 1.12.

The optical power at the MZM output depends upon the phase difference of the two arms of the modulator (MZM) that can be altered by varying the bias of the modulator (MZM):

$$P_{out}(t) = P_{in}(t).d(t) = P_{in}(t)cos^2[\Delta\phi(t)] \qquad (1.13)$$

$$\Delta\phi(t) = \frac{\Delta\phi_1(t) - \Delta\phi_1(t))}{2} \qquad (1.14)$$

where d(t) is the power transfer function of MZM and $\Delta\phi_1(t)$ and $\Delta\phi_1(t)$ are the phase changes in each arm of MZM.

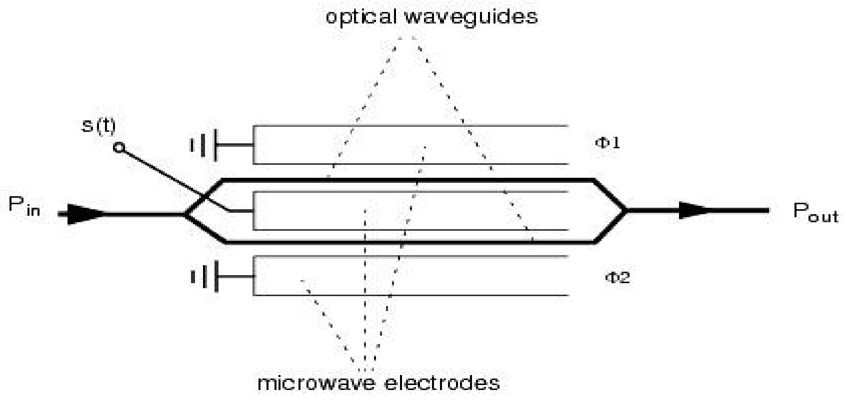


Fig. 1.12 Mach- Zehnder modulator (MZM)

The schematic of Intensity Modulation and transfer function of MZM is shown in figure 1.13, where the bias point is located in the linear zone of transfer function so to acquire a relationship of linear intensity-to-optical power (IM). This point is known as the quadrature point.

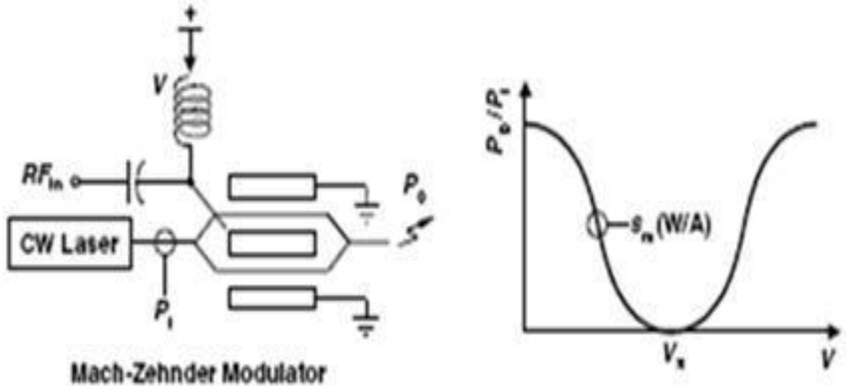


Fig. 1.13 IM with Mach-Zehnder modulator

The phase of two arms of MZM is shifted by varying the bias of the MZM. Hence by setting the bias of Mach-Zehnder modulator (MZM) to the null point, the Optical Field Modulation mode can be determined. The transfer functions of the optical field and of optical intensity are represented in figure 1.14.

The signal created by a MZM is called “double sideband”, whether the MZM is biased in null point or quadrature. This duplicated sideband entails some disadvantages for O-OFDM system and can be removed by the use of optical filters.

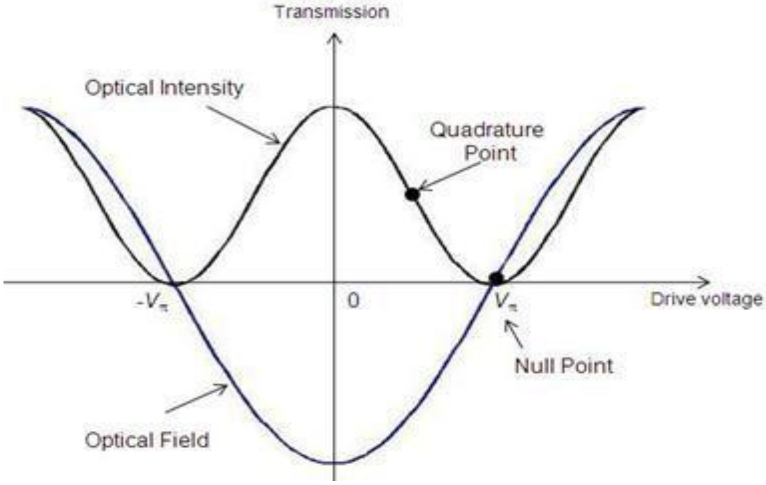


Fig. 1.14 Transfer function of optical field and optical intensity.

### 3) IQ Mach-Zehnder Modulator:

The IQ Mach-Zehnder modulator (MZM) mainly consists of two null-biased Mach-Zehnder modulators (MZM) with a $90^0$ phase difference between them as shown in figure 1.15, with one RF input for each one section of the OFDM signal (I and Q).

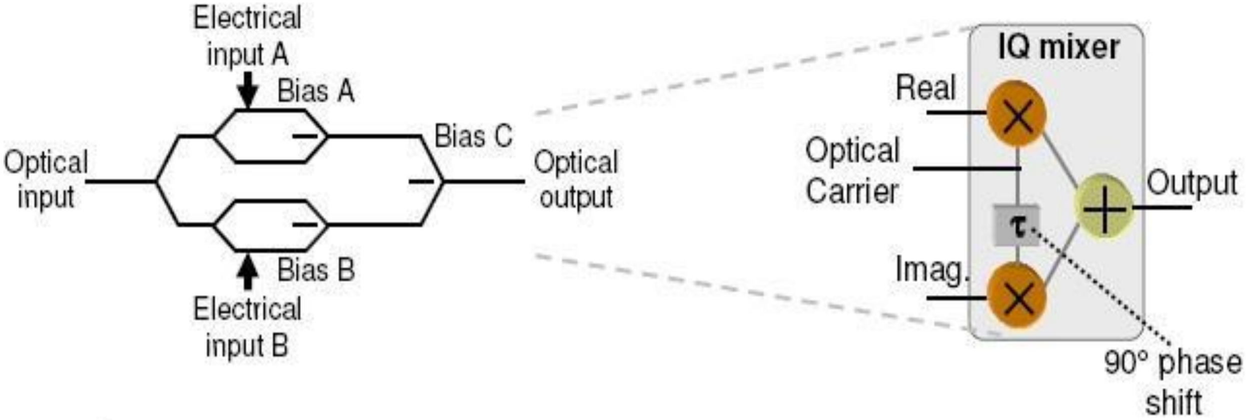


Fig. 1.15 IQ Mach-Zehnder modulator

The electrical field envelope of the optical modulated signal is relative to the information signal when IQ MZ modulator in its bias null-point is used. The main drawback of IQ MZ modulation is that it has three bias voltages which required to be correctly adjusted. The problems associated by the double sideband spectrums could be removed for a complex OFDM signal which results in single optical sideband.

### 1.5.3 Flavors of Optical OFDM (O-OFDM Detection):

The two main categories of optical OFDM are Direct detection and Coherent detection. Over the last two decades direct detection had the stronghold for optical communications, while the latest growth in forward-looking research has distinctly pointed to the trend that the coherent detection is the future of optical communications.

**Direct detection-**

DDO-OFDM has much extra variants in comparison to the CO-OFDM. Direct-detection OFDM is suitable for cost effective short reach applications and the common trait for DDO-OFDM is that the direct detection is used at the receiver. According to how optical OFDM signal is being generated, DDO-OFDM is classified into two categories: (1) linearly mapped DDO-OFDM (LM-DDO-OFDM), in which the optical OFDM spectrum display a replica of baseband OFDM

(2) nonlinearly mapped DDOOFDM (NLM-DDO-OFDM), in which the optical OFDM spectrum is not a replica of baseband OFDM [26]. The first report of the DDO-OFDM [27] shows that DDO-OFDM takes benefit of the OFDM signal which is more immune in CATV network to the impulse clipping noise. Other example is the single-side-band OFDM for long-haul transmission which has been proposed by Lowery et al. and Djordjevic et al. [28, 29].

**Coherent detection-**

CO-OFDM requires the maximum complexity in transceiver design but also represents the vital performance in spectral efficiency, receiver sensitivity, and robustness against polarization dispersion. The basic principle of CO-OFDM is to attain high spectral efficiency as a result of overlapping subcarrier spectrum however avoiding the interference by using signal set orthogonality and coherent detection. Superior performance of CO-OFDM makes it brilliant candidate for long haul transmissions. In CO-OFDM systems, the local oscillator is used, as the optical carrier is generated locally by laser. Hence less transmitted power i.e. optical power is required in CO-OFDM in comparison to DDO-OFDM, although it is extra sensitive to the phase noise.

The main advantages arising from the combination of OFDM with coherent optical communications are multifold: first is high spectral and computation efficiency, second is that the CO-OFDM is robust against polarization mode dispersion and chromatic dispersion, third is CO-OFDM offers high receiver sensitivity, fourth is less DSP complexity and less oversampling factor.

### 1.5.4 Coherent optical OFDM (CO-OFDM) system:

The conceptual diagram of a coherent optical system (CO-OFDM) is shown in figure 1.10. It contains five essential functional blocks: 1) RF-OFDM signal transmitter, 2) RF to optical (RTO) upconverter, 3) Optical fiber links, 4) optical to RF (OTR) downconverter, 5) RF-OFDM receiver.

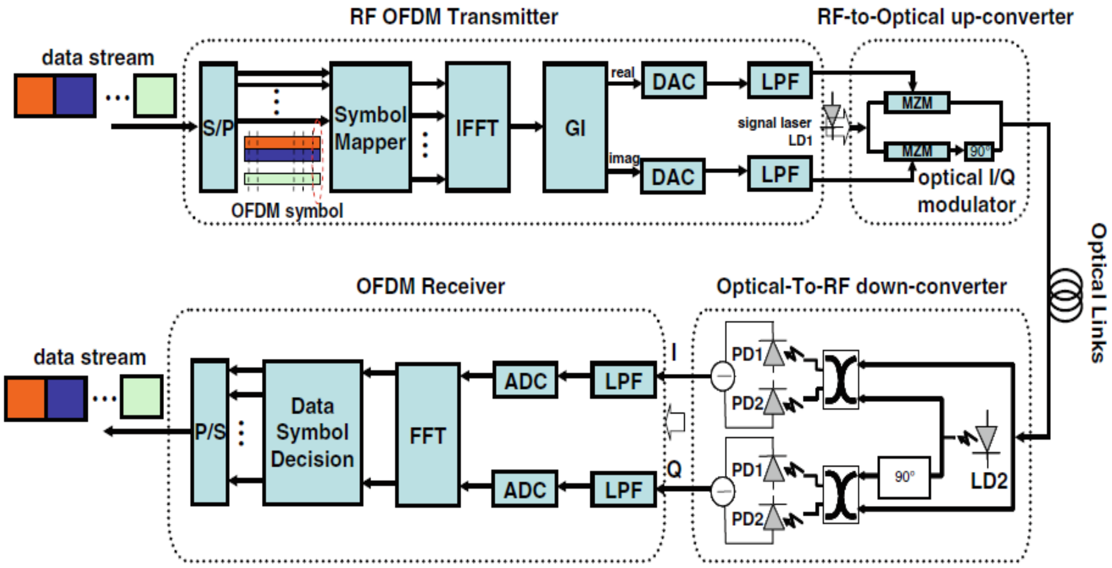


Fig. 1.16 Block diagram of a coherent optical OFDM (CO-OFDM) system.

In RF OFDM transmitter, the data stream is divided into many parallel branches, also called “serial-to-parallel” (S/P) conversion. The number of various multiple branches is of same number as that of loaded subcarrier, together with the pilot subcarriers. Then the converted signal is mapped onto modulation formats, as quadrature amplitude modulation (QAM), phase-shift keying (PSK) etc. The mapped signal from frequency domain is converted by IFFT block into the time domain. The information is carried by two-dimensional complex signal. The insertion of cyclic prefix is used to remove channel dispersion (ISI, ICI). Digital-to-analog converters (DACs) change the time-domain digital signal to analog signal. The alias sideband signal is removed by the use of low-pass filters. At the transmitter, the effect of the anti-aliasing filter is shown in figure 1.11.

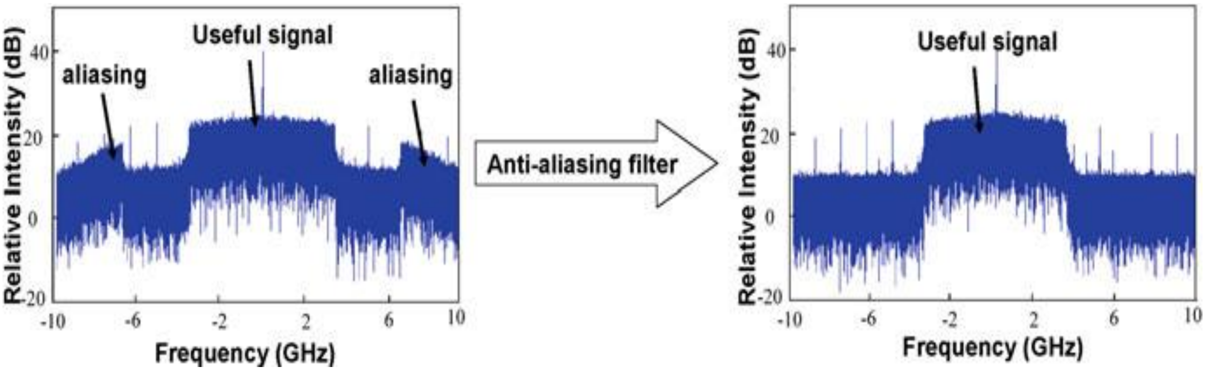


Fig. 1.17 Effect of anti-aliasing filter.

At the RF to optical (RTO) upconverter, the baseband OFDM signal $S_B(t)$ is up converted to optical domain by means of an optical I/Q modulator that comprises of two Mach–Zehnder modulators along with optical phase shifter of 90°. The up-converted OFDM signal within optical domain is represented by:

$$E(t) = e^{(j\omega_{LD1}t+\phi_{LD1})}S_B(t); \quad (1.15)$$

where $\phi_{LD1}$ and $\omega_{LD1}$ are the phase and frequency of the laser at the transmitter, respectively. The optical signal E (t) with impulse response of h (t) is launched into the fiber link. The received optical signal becomes:

$$E'(t) = e^{(j\omega_{LD1}t+\phi_{LD1})}\, S_B(t)\Theta\, h(t); \quad (1.16)$$

where Θ denotes the convolution operation.

At the OTR down converter, the optical signal E' (t) is received and is mixed with a local laser at a phase of $\phi_{LD1}$ and frequency of $\omega_{LD1}$.

Assume that there is phase and frequency difference between transmitter and receiver lasers and is given by:

$$\Delta\phi = \phi_{LD1} - \phi_{LD2} \quad (1.17)$$

$$\Delta\omega = \omega_{LD1} - \omega_{LD2}; \quad (1.18)$$

Then the received RF OFDM signal can be expressed as

$$r(t) = e^{(j\Delta\omega t+\Delta\phi)}S_B(t)\ \Theta\ h(t); \quad (1.19)$$

In RF OFDM receiver, the inverse procedures are carried out as analog to digital (A/D) conversion, FFT, Parallel to serial (P/S) conversion and digital data is obtained.

## 1.6 ADVANTAGES OF OPTICAL OFDM:

Optical OFDM has several advantages and some of the advantages are shown below:

1. A large amount of data can be transmitted and at receiver simple equalizer is used to detect that data.
2. Robust against intersymbol interference (ISI), intercarrier interference (ICI), chromatic dispersion. Cyclic prefix is used to nullify ICI and ISI.
3. Optical OFDM, without complex equalization can easily adjust to severe channel conditions.
4. Efficient implementation by means of FFT.
5. Low sensitivity to time synchronization errors.
6. Capable of power overloading and dynamic bit.
7. Ease of dynamic channel estimation.
8. Extra resistance to fading.
9. High bandwidth (spectral) efficiency since carrier spacing is reduced as the subcarriers in optical OFDM is orthogonal and overlaps with each other. Hence results in high spectral efficiency as shown in figure 1.18.

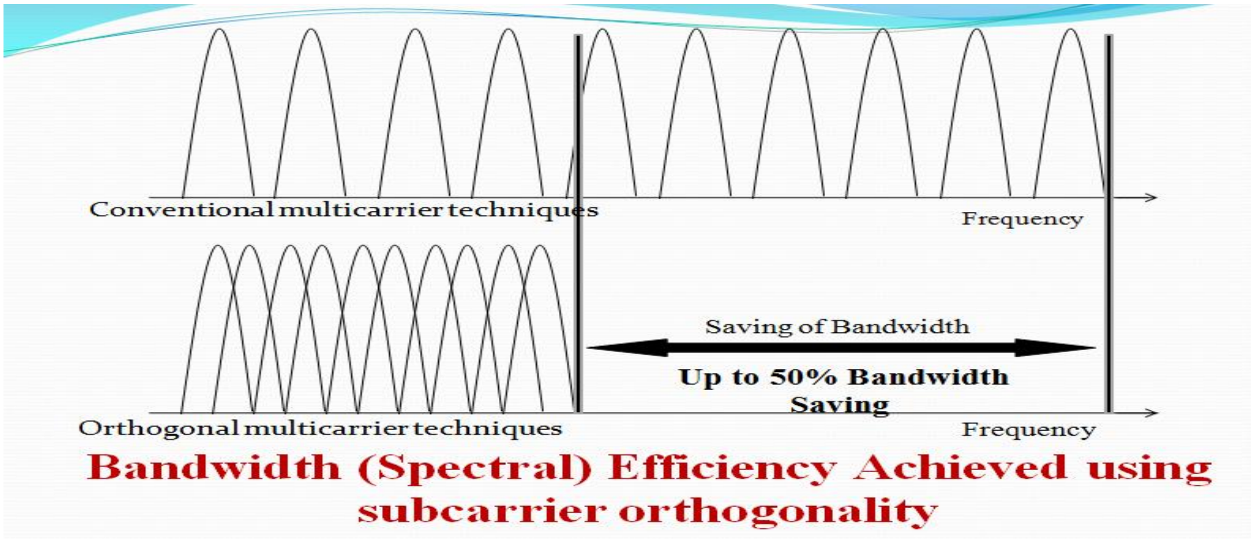


Fig. 1.18 High bandwidth efficiency achieved due to orthogonal subcarriers.

10. **Tolerance to linear impairments -** Alike coherent detection QPSK, OFDM can compensate to linear impairments in the electrical field. This is one of the advantages of OFDM, which enables a better tolerance towards PMD and dispersion.
11. **Oversampling -** One of the important advantages of OFDM is that oversampling can be realized using unmodulated subcarriers. This can be seen in figure 1.19 where the

electrical spectrum of an arbitrary waveform generator is shown. The Nyquist frequency is 5 GHz and sampling rate of the AWG is 10 GHz. In this case, Oversampling is realized by only modulating 190 subcarriers out of the 256 subcarriers. An oversampling factor of 1.34 is realized due to the 66 unmodulated subcarriers. Because of this oversampling, ~2.5 GHz spectral gap is present in between the aliasing products and the OFDM signal. A low pass filter can be used to eliminate the aliasing products.

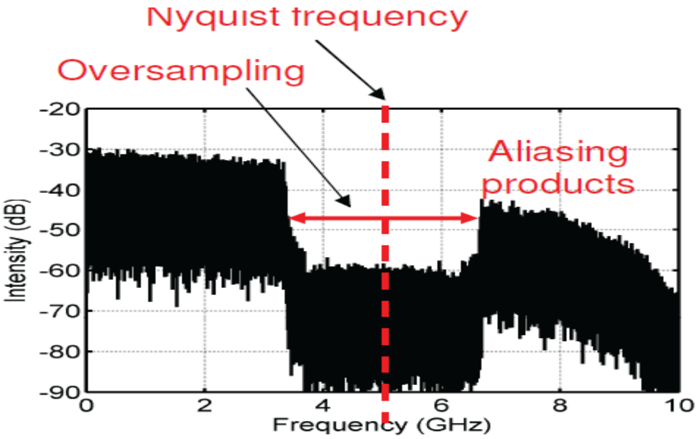


Fig. 1.19 Electrical spectrum of an OFDM signal that is generated by an AWG.

## 1.7 DISADVANTAGES OF OFDM:

On the other hand, OFDM offers some disadvantages. The complexity is one of the effective disadvantages of OFDM, where OFDM is a multicarrier modulation (MCM) that is more complicated in comparison to single-carrier modulation and along with this more linear power amplifier is required by OFDM.

Some of the disadvantages of OFDM are shown below:

1. **Peak to Average Power Ratio (PAPR):**

One of the major drawbacks of the OFDM modulation format is high peak to average power ratio (PAPR). An OFDM signal is created by addition of a number of independent subcarriers. This can result in a high peak to average power ratio (PAPR) as soon as all the subcarriers are added coherently, shown in figure 1.20 high peak at time (t=0.23).

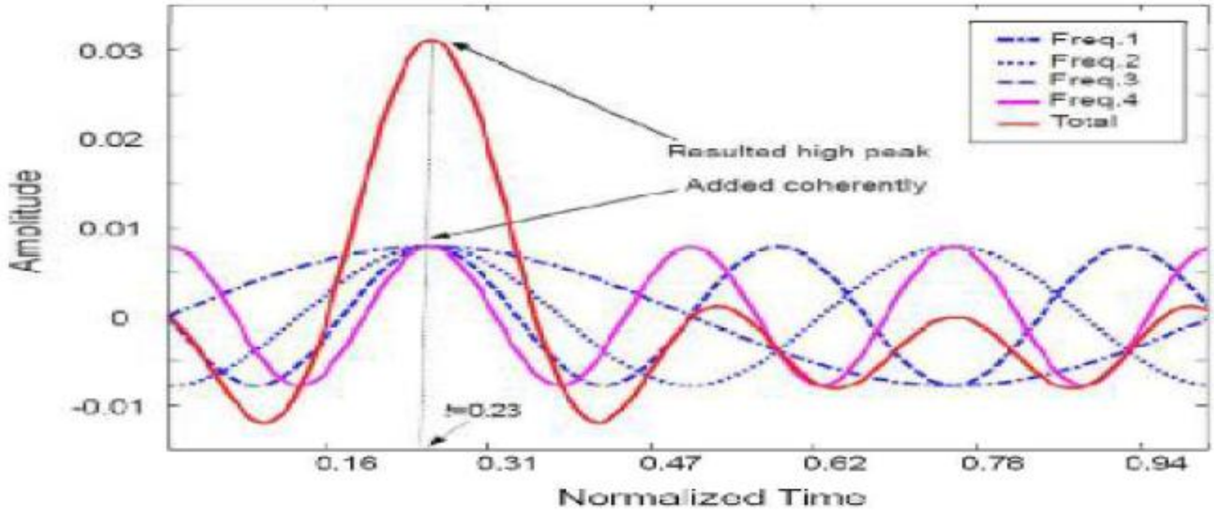


Fig. 1.20 High peak on OFDM system.

In the RF systems, the main problem lies at the transmitter end in the power amplifiers, at which the amplifier gain will saturate on large input power. The power amplifier needs to be operated at “back-off” regime at which the signal power is lesser in comparison to the amplifier saturation power, so to avoid comparatively “peaky” OFDM signal. But for the power amplifier, this needs an excess high saturation power that certainly leads to low power efficiency.

The optical power amplifier (Erbium-doped-amplifier) is perfectly linear in spite of its input signal power in the optical systems, because of its slow response time. Even then the PAPR poses a challenge for fiber optical communications because of the fiber nonlinearity [30-31].

The transmitted time domain waveform used for an OFDM symbol can be written as follows [25]

$$s(t) = \sum_{k=1}^{N_{SC}} C_k . e^{j2\Pi f_k t}, f_k = \frac{k-1}{T_s} \qquad (1.20)$$

For the OFDM signal, PAPR can be defined as:

$$PAPR = \frac{\max\{|s(t)|^2\}}{E\{|s(t)|^2\}}, t \in [0, T_s] \qquad (1.21)$$

Suppose we use M-PSK encoding for simplicity, where $|C_k| = 1$. So by setting $C_k = 1$ and t = 0 in equation 1.20, the maximum theoretical of PAPR in dB is $10log_{10}(N_{SC})$ and hence, with 256 subcarriers in OFDM systems the theoretical maximum PAPR is 24 dB that is very high.

An improved method to characterize the PAPR is by using the complementary cumulative distribution function (CCDF) of PAPR, where $P_c$ the probability that Peak to Average Power Ratio (PAPR) exceeds a particular value of $\zeta_p$ can be expressed as:

$$P_c = P_r[PAPR > \zeta_p] \tag{1.22}$$

CCDF with changeable number of subcarriers is shown in figure 1.21. Suppose QPSK encoding is used for each of the subcarriers. It can be noticed that regardless of the theoretical maximum PAPR of 24 dB intended for the 256 number of subcarriers OFDM systems, for more possible probability regimes, such as a complementary cumulative distribution function (CCDF) of $10^{-3}$, PAPR is about 11.3 dB that is less in comparable to the maximum value of 24 dB. But still PAPR of 11.3 dB is very high, so some type of PAPR reduction must be used. It is also noticed that the PAPR increases slightly of an OFDM signal with the increase in number of subcarriers. For example, PAPR increases by 1.6 dB when the subcarrier number increases to 256 from 32.

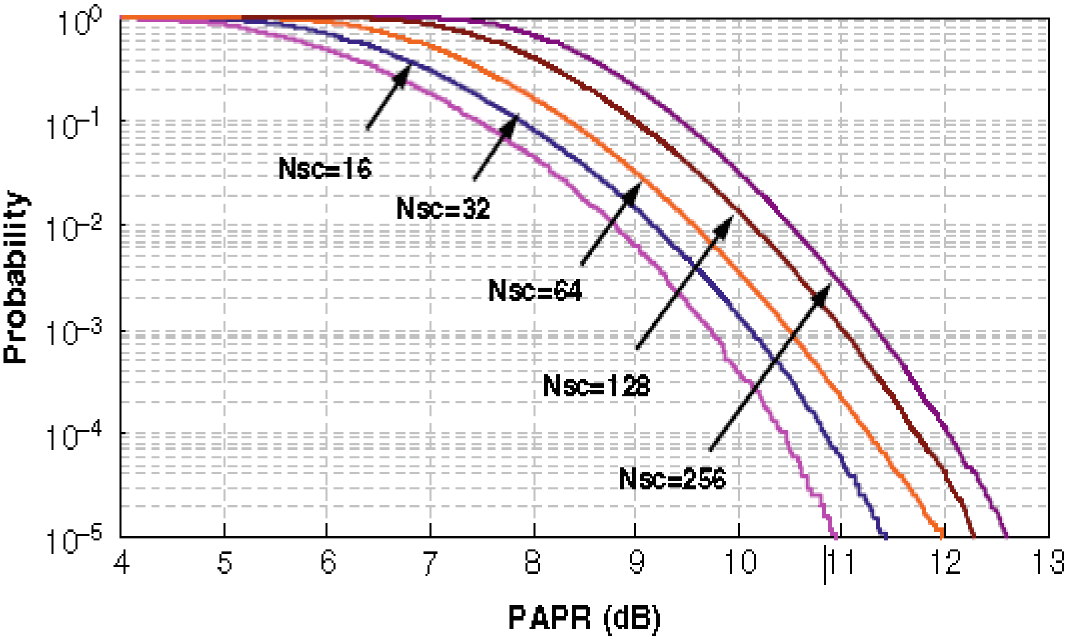


Fig. 1.21 CCDF for the PAPR of OFDM signal with changeable number of subcarriers.

The two popular approaches adopted for PAPR reduction are:

1) PAPR reduction with signal distortion: This approach uses hard clipping the OFDM signal [32-34]. The result of clipping is out-of band distortion and increased BER. Repeated filtering can be used to mitigate the out-of-band distortion [34].

2) PAPR reduction without signal distortion: The idea of this approach is mapping the original waveform into a set of new waveforms which shows a PAPR lesser than the desired value, mostly with a little bandwidth reduction. This includes selection mapping (SLM) [35, 36], and optimization approaches (PTS) [37, 38].

2. **Phase Noise and Frequency Offset Sensitivity:**

The two major disadvantages of OFDM are phase noise and frequency offset sensitivity which leads to intercarrier interference (ICI) due to its long symbol length in comparison to that of the single carrier. Frequency offset sensitivity can be removed through frequency compensation and estimation [25].

This frequency offset is generally compensated by use of adaptive frequency correction (AFC), and also the phase noise sensitivity is mainly resolved by the careful and proper RF local oscillator design that will satisfy the necessary phase noise specification [25].

3. **Time offset error:**

The type of error is caused through the wrong recognition of the OFDM symbol boundary at the receiver end, introducing intersymbol interference (ISI) and intercarrier interference (ICI). The addition of the cyclic prefix (CP) makes OFDM much more robust towards time offset errors. The time offset may fluctuate over an interval which is equal to the CP length without causing ISI or ICI.

The purpose of time synchronization is the estimation of the symbol boundary lines, hence an uncorrupted section of the OFDM symbol that is received is capable to be sampled for FFT.

## 1.8 OPTICAL OFDM – RADIO OVER FIBER (OOFDM-ROF) SYSTEM:

In OOFDM–RoF system, OFDM modulation technique is included into Radio over Fiber (RoF) system. This system includes the advantages of both, as OFDM can allocate the data over huge numbers of subcarriers which are spaced out at particular frequencies with overlapping bands, and on the other hand RoF systems can make use of the optical network's high capacity all along the mobility of wireless networks.

Hence OOFDM-RoF system can be used for long haul as well as short distance transmissions at high data rates. This system enhances the system flexibility without increasing system's cost as well as complexity.

### 1.8.1 General concept of Radio over Fiber (RoF) system:

Earlier RoF systems were generally used to transfer microwave signals, and also to attain mobility functions within the central office (CO). That is, microwave modulated signals need to be made available at the input side of the RoF system, which are later transported over a distance toward the Remote Site (RS) in form of optical signals. Hence the microwave signals are regenerated at the Remote Site (RS) and then radiated using antennas. A common RoF architecture is shown in figure 1.22.

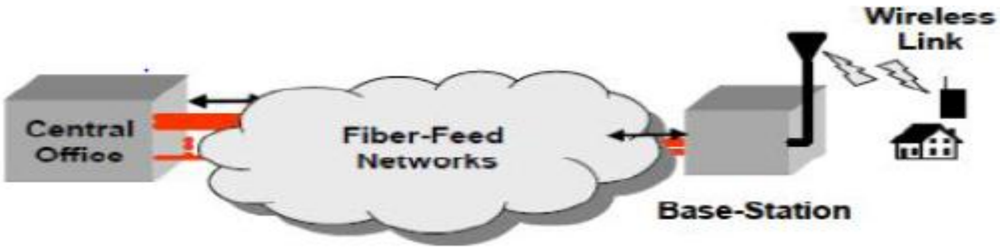


Fig. 1.22 Common RoF system concept.

### 1.8.2 Radio over Fiber (RoF) communication system architecture:

The general architecture of Radio over Fiber (RoF) communication system is shown in figure 1.23 that shows a RF signal (modulated by digital or analog modulation techniques) and later is transported by an analog optic fiber link. The RF signal might be modulated IF, baseband data, or the actual RF signal that need to be distributed. The optical source in the transmitter is modulated by RF signal. The optical signal produced is launched to the optical fiber. An optical receiver is required the other end of the fiber, to convert the optical signal back into the RF signal [39, 40].

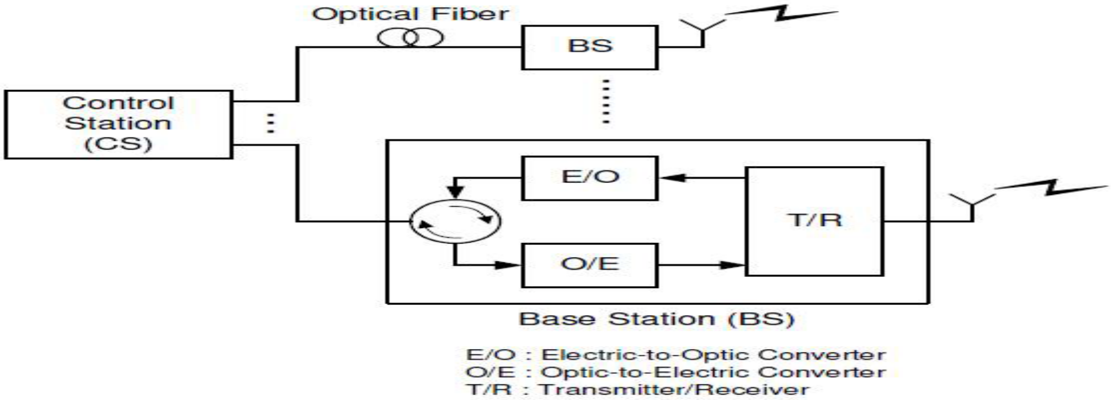


Fig. 1.23 Architecture of RoF communication system.

### 1.8.3 The OOFDM-RoF system model:

The block diagram of OFDM-RoF system is shown in figure 1.24. The digital data is divided into parallel streams of data through OFDM transmitter, and then this divided data is carried via fiber optical link. Along with this continuous wave (CW) laser emits a train of short pulses or continuous beam of a laser. In the Mach- Zehnder modulator (MZM) (external modulator) continuous wave light commencing from CW laser is combined with the electrical signal from the OFDM transmitter. Then these two waves are modulated by Mach-Zehnder modulator (MZM) that is sent through optical fiber.

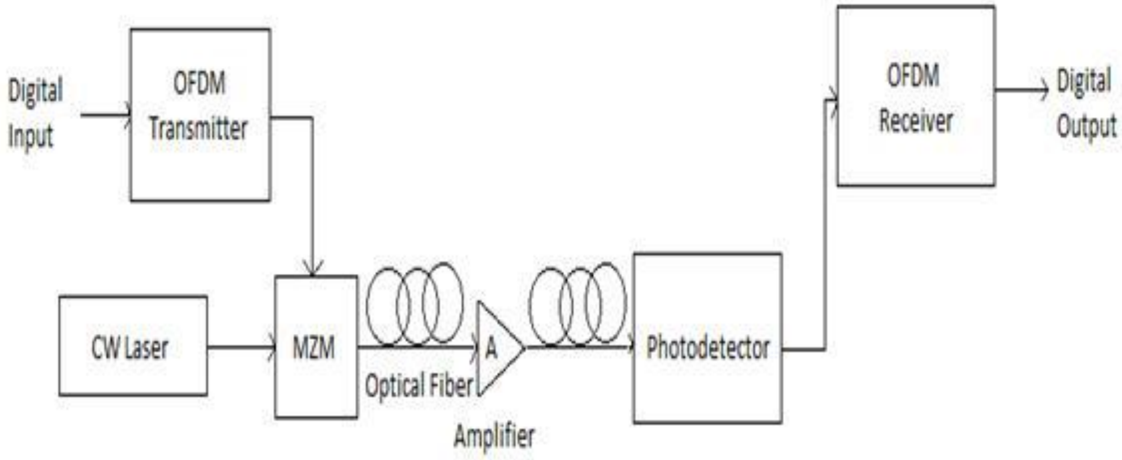


Fig.1.24 Block diagram of OOFDM-RoF system.

At the receiver end, the data is first received by photodetector (P.D) which converts the arriving photonic stream back into electron stream, thus the optical signals are converted back to electrical signals. In the OFDM receiver, the signal then recombines again to get back the original data.

## 1.9 OBJECTIVE OF DISSERTATION:

1. To present a novel scheme for compensation of chromatic dispersion in long haul transmission system.
2. To propose a cost efficient architecture for optimized performance of WDM OFDM system with dual band transmission.
3. To present a novel approach for compensating the impact of non linear distortion in OOFDM-RoF system.

## 1.10 ORGANIZATION OF DISSERTATION:

Chapter 2 includes the literature survey regarding the topic of the dissertation. In order to begin with the dissertation, the first step is to study the papers related that have been previously published by researchers. Literature review helps to perform this work easily.

Chapter 3 presents a scheme for compensation of chromatic dispersion in long haul transmission system by combining orthogonal frequency division multiplexing with (OSSB) optical single sideband modulation, so at the receiver the optical phase distortion can be mapped to electrical phase that can be compensated by equalization along with constellation adjustment method.

Chapter 4 presents a cost efficient architecture for optimized performance of WDM OFDM system with dual band transmission using hybrid Erbium Doped Fiber Amplifier (EDFA) – Raman amplifier.

Chapter 5 presents a novel approach for compensation of non linear distortion in OOFDM-RoF system using two pilot tones in fiber optical OFDM transmission.

Chapter 6 includes the Conclusion, Recommendation and Future Prospect of the work.

# CHAPTER 2

# LITERATURE SURVEY

Optical OFDM has gained much interest in recent years as depicted in this chapter. In recent times, many researchers started to pay more interest to apply OFDM technique with multi carrier modulation (MCM) in optical fiber communication. The literature survey of optical OFDM systems by various researchers in past years is shown below:

**Arthur James Lowery *et al*.** [3] demonstrated the feasibility of architecture to show an arrangement of orthogonal frequency division multiplexing (OFDM) along with optical single sideband modulation that compensates the chromatic dispersion in WDM systems. The authors studied using numerical simulations, the effects of fiber dispersion, WDM channel number and spacing, and input power for each channel on the received $Q$ and summarized these effects as a set of design rules.

**Michela Svaluto Moreolo *et al*.** [4] presented the Optical OFDM as one of the promising technique meant for designing bit rate as well for bandwidth variable transponders as key enablers of future flexible, elastic, and spectral efficient networks. The authors offered a cost-effective O-OFDM system with variable bit rate using less complexity DSP with Peak to Average Power Ratio (PAPR) reduction capabilities. O-OFDM using coherent detection and phase modulation was also proposed as appropriate spectral efficient way, robust against nonlinearities, in elastic networks.

**Z. Bo, L. Yinghua, Z. Jinling, Y. Biao** [40] demonstrated that the nonlinear distortion in Orthogonal Frequency-Division Multiplexing signals (OFDM) signals is caused due to semiconductor laser in a Radio-over- Fiber (RoF) link. The authors mathematically derived the expression for in-band noise due to nonlinear distortion (NLD), and then studied the relation of optical modulation index with carrier-to-noise ratio.

**R.S Kaler *et al*.** [41] demonstrated the gain-flattened L-band using a hybrid erbium-doped fiber amplifier (EDFA) and distributed Raman amplifier (DRA) (EDFA) for 160×10-Gb/s DWDM system at an interval of 25 GHz. The authors showed that the output signal power obtained was of the highest value (>8.9dBm) for hybrid EDFA-DRA at reduced channel spacing.

**Yannis Benlachtar *et al*.** [42] analyzed the use of OFDM to enhance the capacity of MMF based optical interconnects intended for data center applications. The authors presented a solution for intermodal dispersion of the MMF as well as for modulation bandwidth drawbacks of the lasers that is responsible for frequency-dependent attenuation. Adaptively modulated OFDM was reviewed, and new results using simulations was presented for assessing the capacity of these links for lengths equal to 300 m, assuming graded-index MMF at 850nm wavelength.

**Boonaue Pirom *et al*.** [43] analyzed mathematically the phase distortion of O-OFDM signal which is due to Kerr effect and fiber dispersion. The results were verified using OptiSys 5.0 software and were compared with the mathematical results and both the results were in a good agreement.

**R.S Kaler *et al***. [44] demonstrated that in case of SMF the second and third order dispersion has minimum impact on intensity and frequency on optical system.

**Houshou Chen *et al*.** [45] proposed a PAPR reduction technique for 16-QAM OFDM systems and BPSK OFDM systems. The algorithms were designed to use a scrambling subcode for controlling PAPR and a correction subcode for controlling error. The authors obtained PAPR reduction in a BPSK OFDM system by combining the SLM method along with the binary cyclic codes, and also achieved the PAPR reduction in a 16-QAM OFDM system, by combining the SLM along with block coded modulation. The signal received of the modified SLM able to be decoded without the requirement of explicit side information.

**Pooria varahram *et al*.** [46] presented a small complexity Partial Transmit Sequence (PTS) scheme with applying a new phase sequence because Partial Transmit Sequence (PTS) is the most important techniques used for reducing the PAPR in OFDM systems. The proposed scheme needs half of the IFFT operations, contrasting to the conventional PTS that requires several IFFT operations. Simulation results were examined by the authors with QPSK modulation and power amplifier and OFDM signal with memory effects.

**Lilong Liu *et al*.** [47] proposed a new approach for compensating C.D and adjusted the phase/amplitude by making use of pilot tones in optical OFDM transmission. This novel approach makes use of the chromatic dispersion fiber properties by using less pilot tones. The simulations showed a major improvement in terms of the bit error rate penalty of the optical OFDM signal, compared with one-reference-symbol methods and the conventional least-square (LS) linear interpolation methods.

**Hadrien Louchet *et al*.** [48] proposed a novel architecture based upon the optical heterodyne detection and the OFDM modulation that needs no optical or electrical phase-locked-loop (PLL). The authors compared the system performances a data-rate of 100-Gb/s with DQPSK system.

**Jair A. L. Silva *et al*.** [49] proposed a new PAPR reduction method based on constant envelope OFDM (CE-OFDM) approach using 2.66 GHz signal bandwidth, 16-quadrature amplitude modulation (16-QAM), in order to reduce induced fiber nonlinearities in the direct detection OOFDM (DDO-OFDM) systems. Simulation results showed the proposed DDO-CE-OFDM system outperforms DDO-OFDM systems since it increases the nonlinearity tolerance in fiber links lacking dispersion compensation. The BER of the proposed scheme was decreased by a factor of 1000 when compared with conventional DDO-OFDM systems, for a span of 960 km of SSMF with 10 dBm of input optical power.

**Jie Pan and Chi-Hao Cheng** [50] demonstrated the nonlinear electrical equalizer based upon the Volterra model able to compensate fiber nonlinear distortion in PSK or OOK optical communication system. Though, the Volterra model based electrical equalizer’s implementation complexity prohibits its use in real-life CO-OFDM system. The authors further demonstrated the number of kernels of a Volterra model based electrical equalizer be able to reduced by means of the modified Gram-Schmidt method using reorthogonalization techniques. The performance of the electrical equalizer based upon “full” Volterra model is comparable to the electrical equalizer based upon “sparse” Volterra model.

**Jie Pan and Chi-Hao Cheng** [51] demonstrated that both equalizers and predistorters can be used for compensation of nonlinear distortion in CO-OFDM system. The authors investigated the performance between the electrical pth-order inverse Volterra equalizers and predistorters, using CO-OFDM system as a test system. The main difference that arises between the equalizer and the predistorter is that the predistorter is used to regulate the input power; hence, the performance of coherent optical OFDM (CO-OFDM) system using a predistorter is independent for a large range of laser launch power.

**Guoying Zhanget *et al*.** [52] presented that based on optical orthogonal frequency division (OOFDM) technique, new elastic optical network architecture, with scalability in spectrum allocation and immense flexibility and data rate accommodation could be built for supporting various services and rapid Internet traffic growth in the future. The authors presented a comprehensive survey on OOFDM technologies, including the essential principles of OFDM, together with O-OFDM technologies, with the architectures of OFDM based elastic core optical networks.

**S. Hussin *et al*.** [53] analyzed the performance of coherent optical OFDM (CO-OFDM), direct detection optical OFDM (DDO-OFDM), and self coherent optical OFDM (SCO-OFDM). The authors first reviewed the theoretical basics of O-OFDM and the differences among the three systems (CO-OFDM, DDO-OFDM, SCO-OFDM) and later, the comparison is made among the received optical power (ROP) on the system performance for these O-OFDM systems.

**C. Lim *et al*.** [54] investigated the optimal carrier-to-sideband ratio (CSR), meant for enhancing the transmission performance of a modulated millimeter (mm) wave signal in a wireless-fiber system through theory, experiment, and simulation and also presented an analytical model to show the performance enhancement resulting due to optical carrier-to-sideband ratio (CSR) variations. The authors showed the model is capable of analyzing the systems incorporating quaternary phase-shift keyed and binary phase-shift keyed modulation formats, and later quantified the optical carrier-to-sideband ratio (CSR) of a point-to-point radio- fiber link and established the improved performance of the fiber-wireless links when the optical signal is transmitted at 0 dB optimum CSR.

**Hongchun Bao and William Shieh** [55] presented the theoretical base for coherent optical OFDM (CO OFDM) systems in direct down/up conversion architecture. The authors demonstrated the system performance during simulation for WDM systems along with coherent optical OFDM (CO-OFDM) including the effect of fiber nonlinearity. The results showed that the Q system of WDM channels at 10 Gbps over 13 dB used for a transmission upto 4800 km of SSMF without compensation of dispersion. The authors also presented partial carrier filling (PCF) technique so to improve the non-linearity performance. The Q system of the WDM channels at 10 Gbps with a filling factor of 50 % showed improved results from 15.1 dB to 16.8 dB for a transmission upto 3200 km of SSMF with no dispersion compensation.

**W. H. Chen *et al*.** [56] presented a closed-form study to predict Mach-Zehnder modulator (MZM)-induced composite triple beat (CTB), in addition to linear-fiber-dispersion-induced composite second-order (CSO) and CTB distortions in order to understand the limitation of multiple narrow single-sideband subcarrier-multiplexed (SSB/SCM) signals. For combining SSB/SCM with DWDM systems, numerical and analytical tools that are not forced by any modulation frequencies and wavelength spacing were used to examine cross-phase modulation-induced crosstalk. The authors also studied a number of multichannel SCM/SSB/DWDM systems with 10 or 20 Gb/s per wavelength transport capacity, with 25, 50, and 100 GHz, wavelength spacing to realize the limitations of fundamental transmission.

**Naresh Kumar *et al*.** [57] presented the analysis of 10 Gbit/s optical OFDM Radio over Fiber (OOFDM-RoF) transmissions links using 4 QAM modulation with 50 km of distance and showed the superior performance after usage of square root module (SQRT) in comparison to without SQRT system.

**Inbal Kashany- Mizrahi *et al*.** [58] proposed a low cost optical OFDM (O-OFDM) based upon adaptive direct modulation SOA(semiconductor optical amplifier) since the low cost O-OFDM has huge potential for the next generation passive optical networks and optical access networks, due to its high spectral efficiency as well as high flexibility in bandwidth manipulation. The authors analyzed the adaptive current loading techniques for PAPR reduction. Simulations showed BER improvement for the proposed adaptive techniques.

**J. Zhao *et al*.** [59] showed that insertion of pilot tones along with frequency intervals, inversely proportional to the index of subcarrier exhibits superior dispersion estimation performance in comparison to the equal spacing design in fast OFDM (F-OFDM). The authors demonstrated a 20-Gbit/s, 4 ASK F-OFDM system without optical dispersion compensation with 840-km transmission and showed that a single F-OFDM symbol using six pilot tones be capable of achieving near-optimal estimation performance.

**Reginaldo B. Nunes *et al*.** [60] experimentally investigated a reduction technique for peak-to-average power ratio (PAPR) based upon a constant envelope OFDM approach (CE-OFDM) within direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM) systems. The results showed 6.37 dB performance increase in terms of error vector magnitude (EVM) among 5 Gbps DDO-CE-OFDM system at optical injection power of 5 dBm over 40 km of uncompensated SSMF, in comparison to conventional DDO-OFDM.

Table 2.1 literature survey of optical OFDM systems in past few years.

| **Type** | **Authors** | **Work Done** | **Results** |
|---|---|---|---|
| PAPR reduction | Michela Svaluto Moreolo *et al*. [4] | A cost-effective O-OFDM system with variable bit rate using less complexity DSP with PAPR reduction. | Spectral efficient way, robust against nonlinearities. |
| PAPR reduction | Houshou Chen *et al*. [45] | PAPR reduction technique for 16-QAM OFDM by combining the SLM with block coded modulation and also for BPSK OFDM by combining the SLM with binary cyclic codes. | The algorithms were designed to use a scrambling subcode for controlling PAPR and a correction subcode for controlling error. |
| PAPR reduction | Pooria varahram *et al*. [46] | Presented a small complexity PTS scheme, for reducing the PAPR in OFDM systems along with a new phase sequence. | Results were examined with QPSK modulation, and power amplifier and OFDM signal with memory effects. |
| PAPR reduction | Jair A. L. Silva *et al*. [49] | PAPR reduction method based on constant envelope OFDM approach using 2.66 GHz signal bandwidth, 16-QAM, in order to reduce induced fiber nonlinearities in the direct detection OOFDM systems. | The proposed system outperforms DDO-OFDM system. BER of the proposed scheme was decreased by a factor of 1000 when compared with conventional DDO-OFDM system. |

|  |  |  |  |
|---|---|---|---|
| PAPR reduction | Reginaldo B. Nunes *et al*. [60] | PAPR reduction scheme based on CE-OFDM approach within DDO-OFDM systems. | 6.37 dB performance increase in EVM among 5 Gbps DDO-CE-OFDM systems in comparison to conventional DDO-OFDM. |
| Dispersion Compensation | Arthur James Lowery *et al*. [3] | Architecture to show an arrangement of OFDM along with optical single sideband modulation that compensates the chromatic dispersion in WDM systems. | The effects of fiber dispersion, WDM channel number and spacing, and input power for each channel on the received Q. |
| Dispersion Compensation | Boonaue Pirom *et al*. [43] | Analyzed mathematically the phase distortion of O-OFDM signal which is due to Kerr effect and fiber dispersion. | The results using OptiSys 5.0 software were in a good agreement with the mathematical results. |
| Dispersion Compensation | Lilong Liu *et al*. [47] | Make use of pilot tones in optical OFDM transmission to compensate chromatic dispersion. | An improvement in BER penalty of the O-OFDM signal compared with one-reference-symbol and the conventional least-square (LS) linear interpolation methods. |
| Dispersion Compensation | Hadrien Louchet *et al*. [48] | A novel architecture based upon the optical heterodyne detection and the OFDM | The system performances at a data-rate of 100-Gb/s |

| | | | |
|---|---|---|---|
| | | modulation that needs no optical or electrical phase-locked-loop (PLL). | were compared with DQPSK system. |
| Dispersion Compensation | J. Zhao *et al*. [59] | Insertion of pilot tones along with frequency intervals, inversely proportional to the index of subcarrier in OFDM system. | Superior dispersion estimation performance in comparison to the equal spacing design in fast OFDM. |
| Radio over fiber link | Z. Bo, L. Yinghua *et al*. [40] | Nonlinear distortion in OFDM signals is caused due to semiconductor laser in a Radio-over- Fiber (RoF) link. | Derived expression for in-band noise due to NLD, and then studied the relation of optical modulation index with carrier-to-noise ratio. |
| Radio over fiber link | C. Lim *et al*. [54] | Investigated the optimal CSR, meant for enhancing the transmission performance of a modulated millimeter wave signal in a wireless-fiber system through theory, experiment, and simulation and also presented an analytical model to show the performance enhancement due to CSR variations. | The improved performance of the fiber-wireless links when the optical signal is transmitted at 0 dB optimum CSR. |
| Radio over fiber link | Naresh Kumar *et al*. [57] | The analysis of 10 Gbit/s OOFDM-RoF transmissions using 4 QAM modulation with 50 km distance | Superior performance after usage of SQRT than without SQRT system. |

# CHAPTER 3

# A NOVEL SCHEME FOR COMPENSATION OF CHROMATIC DISPERSION IN LONG HAUL TRANSMISSION SYSTEM

Chromatic dispersion in long-haul transmission system can be compensated using combination of OFDM and optical single sideband modulation and phase/amplitude residual dispersions left can be further adjusted by constellation adjustment method. Design rules for 800-4000 km optical OFDM systems are provided. OFDM has better sensitivity than NRZ (Non Return to Zero) and do not need a reverse feedback path for compensation. The investigation using simulation shows the perfect dispersion compensation, received optical spectrum and superior BER v/s OSNR of OFDM systems than NRZ system. NRZ system requires 1 dB better OSNR than 4 QAM OFDM system and also requires 0.5 dB better OSNR than 4 PSK-OFDM system for $BER = 10^{-3}$.

## 3.1 INTRODUCTION:

Orthogonal frequency division multiplexing (OFDM) due to its spectral efficiency has fascinated interest in recent years for the idea to be applied in optical domain for high-speed optical fiber transmission. OFDM plays a major part in the modem telecommunications for both wired and wireless communications. It has been established that optical OFDM is a capable technique of noticeably raising the spectral efficiency in high-speed optical fiber channel, while improving the polarisation mode dispersion (PMD) tolerance [26].

Electronic dispersion compensation [62, 63] is a substitute to the optical dispersion compensation techniques as Bragg gratings, DCF (dispersion compensating fiber), and optical resonators. EDC is a method for mitigating the effects of chromatic dispersion. EDC reduces system capital cost as it eliminates optical dispersion compensators as well as it reduces total optical loss, amplification requirements. EDC also reduces the system operating cost as it simplify deployment and operation and also enables dynamic and remote network reconfiguration. EDC lies in three categories i.e. Post compensation (Compensation at receiver), Pre distortion (Compensation at transmitter), use of electronic processing to adjust transmitted waveform. Orthogonal Frequency Division Multiplexing falls in third category and is flexible to multipath propagation and phase distortion.

A.J. Lowery et al. has previously showed that if non-linearities are not considered then chromatic dispersion can be compensated for infinite distance, by combination of optical OFDM with optical single side band (OSSB) modulation [3] but when non-linearities are considered transmission over 4000 km is possible. However, for the fiber optical channels with huge subcarrier number and wide bandwidth, the optical OFDM signals are still sensitive to the phase rotation resulted from the chromatic dispersion that can be compensated using constellation adjustment.

This chapter shows that the chromatic dispersion in long-haul transmission system can be compensated using combination of OFDM and optical single sideband modulation, so at the receiver the optical phase distortion can be mapped to electrical phase that can be compensated by equalization and some phase/amplitude residual dispersion will remain and can be adjusted by using constellation adjustment method.

This chapter is structured as follows: section 3.2 includes logical model and description of constellation rotation method, section 3.3 includes system description, section 3.4 includes the results, and section 3.5 concludes the chapter.

## 3.2 LOGICAL MODEL:

The phase dispersion of the Orthogonal Frequency Division Multiplexing signal as a result of Chromatic Dispersion can be represented as:

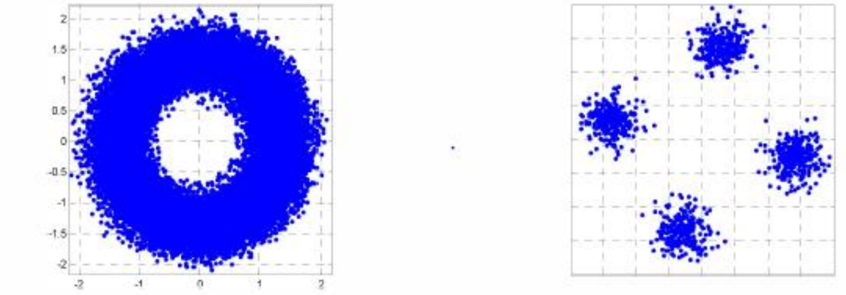
$$\Phi_d(f) = \prod . c . D_t . (f/f_{LD}) \tag{3.1}$$

Here $D_t$ is the total Chromatic Dispersion used for the full fiber length in ps/pm, $f_{LD}$ and $f$ are the frequencies of the laser carrier and subcarriers respectively, c is the speed of light.

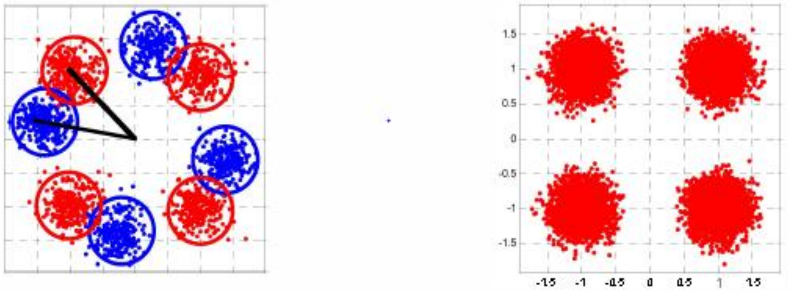
Due to Chromatic Dispersion phase rotation occurs about the origin so doughnut shape is observed in constellation diagram as shown in figure 3.1 (a) for (QAM) OFDM signals. Phase dispersion should be compensated to correctly demodulate the received signal and this can be done using several methods. One of the common ways is the combination of OFDM and optical single sideband modulation [3] as a result, at the receiver the optical phase distortion can be mapped to electrical phase that can be compensated by equalization but still some residual dispersion remains that can be adjusted using constellation adjustment method, as discussed below [47].

1) Rotate the phase dispersion $-\phi_m$for all the subcarriers.
2) Divide the constellation points into quadrants according to the subcarrier modulation format.
3) For each quadrant, calculate the center of the points, and the difference between the phase/amplitude and the theoretical constellation positions.
4) For each quadrant, make adjustment to all subcarriers, to compensate the phase/amplitude discrepancies.

Take QAM OFDM signals as an example, Fig. 3.l (b) shows one of the Chromatic Dispersion compensated subcarrier, where the phases are compensated by $-\phi_m$ . The residual rotation is still visible in Fig. 3.1 (b), which is compensated as well by the constellation adjustment, as shown in Fig. 3.l (c). Fig. 3.l (d) shows the constellation of all compensated subcarriers.



(a) All subcarriers, before CD compensation; (b) One subcarrier, CD compensated, no constellation



(c) One subcarrier, CD compensated, and constellation adjusted; (d) All subcarriers, CD compensated, and constellation adjusted.

Fig. 3.1 Constellation of: (a) all subcarriers before chromatic dispersion compensation (b) one subcarrier, CD compensation, no constellation adjusted (c) one subcarrier, CD compensated; constellation adjusted (d) all subcarriers after chromatic dispersion compensation.

### 3.3 SYSTEM DESCRIPTION:

Fig 3.2 shows the spectral optical OFDM system.The system consists of the following subsystems:

a) OFDM Electrical Transmitter:

Data at 10 Gb/s is offered and is modulated using 4-PSK modulation. The number of subcarriers is 64.These modulators provide the inputs of inverse fast Fourier transform. An interpolated waveform with well controlled spectrum is obtained by zero padding of IFFT inputs; this can be obtained through analog filters later than D/A converters. OFDM sidebands are relocated from the optical carrier through modulating them on a 7.5GHz RF subcarrier as to offer RF sideband from 5 to 10 GHz thus the practical optical filters are able to be used for sideband as well as carrier suppression.

b) Optical modulator and filter:

Mach-Zehnder modulators (MZM) could be used as an optical modulator in optical-OFDM systems. By using an optical filter the lower optical sideband is removed, after modulation. The optical carrier is suppressed and so, the receiver sensitivity is improved. When optical carrier power is equal to the power of OFDM sideband, then the result is best receiver sensitivity [3].

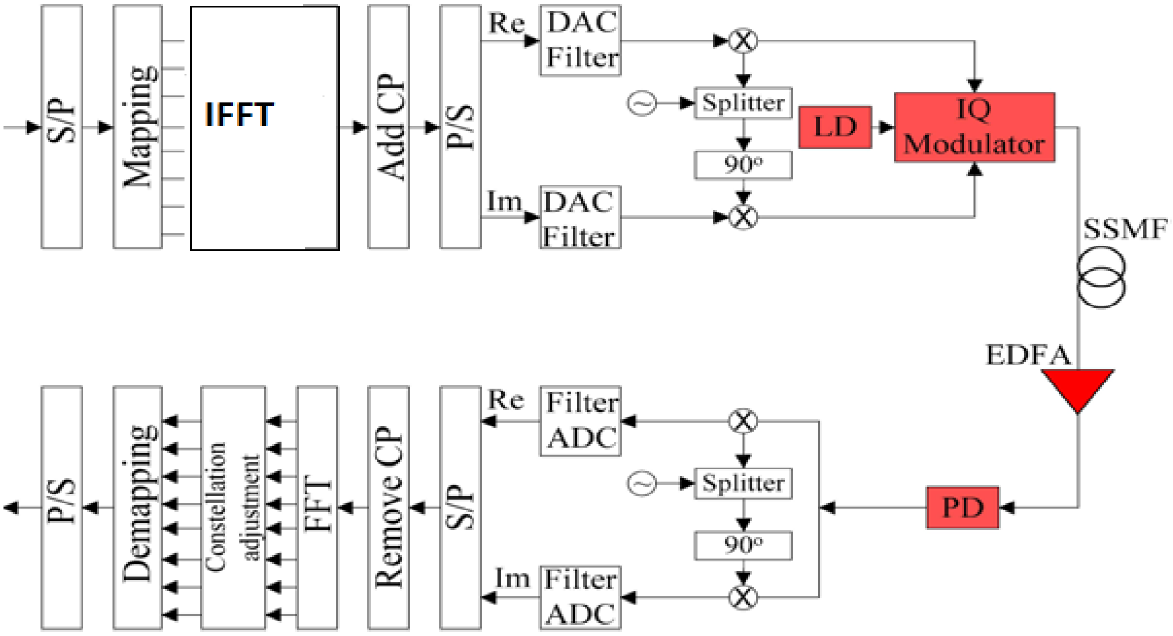


Fig. 3.2 The schematic optical OFDM transmission system.

c) Fiber link :

The fiber link consists of 100-km spans of S-SMF (standard single mode fiber) including an optical amplifier prior to each span. The amplifier increases the link distance, which is limited by fiber loss in an optical communication system. The length of fiber can be increased by increasing the number of loops. The amplifiers have a 6-dB noise figure and a 16-dB gain. The fiber has a loss of 0.2 dB/km, dispersion of 17 ps/nm/km, an effective area of 80 µ$\mathrm{m}^2$ and, a nonlinear coefficient of 2.6 × $10^{-20} m^2$ /W.

d) Receiver Model:

At the receiver, time-domain waveform which is proportional to the optical power is obtained using photodiode with 1 A/W responsivity. The photocurrent is converted into quadrature (Q) and inphase (I) components through mixing with $0^0$and $90^0$ phase of a 7.5 GHz LO (local oscillator). The inverse procedures are carried out i.e. S/P, remove cyclic prefix, and FFT, in order to get the OFDM signals. Once in frequency domain, every channel is equalized to remove for amplitude and phase distortions. This can simply achieved through a separate multiplication for every QAM channel. After that, constellation adjustments were carried out as mentioned in section 3.2, to eliminate residual phase dispersion. The $Q$ is extracted using the constellation. By assuming the Cartesian axes as the decision thresholds, the Q is represented as:

$$Q_{db} = 20.\log_{10}(q) \quad (3.2)$$

where, $q^2 = \frac{\mu_x^2}{\sigma_x^2} = \frac{\mu_y^2}{\sigma_y^2}$ (3.3)

with µ be mean value and $\sigma^2$ be variance as shown in fig 3.3. BER can be estimated using:

$$BER = 1/2 erfc(\frac{q}{\sqrt{2}}) \quad (3.4)$$

## 3.4 RESULTS:

Fig 3.3 illustrates a typical received constellation for 4 PSK modulations before and after chromatic dispersion compensation at the receiver. Before the equalizer, each constellation points form doughnut shape due to fiber chromatic dispersion. Phase dispersion is compensated after the equalization, due to combination of OFDM and OSSB modulation. But some residual phase dispersions are left, which is further adjusted by constellation rotation method as described in section 3.2, so all chromatic dispersion is compensated for all the subcarriers which is shown in figure 3.3. Hence Dispersion compensation is perfect.

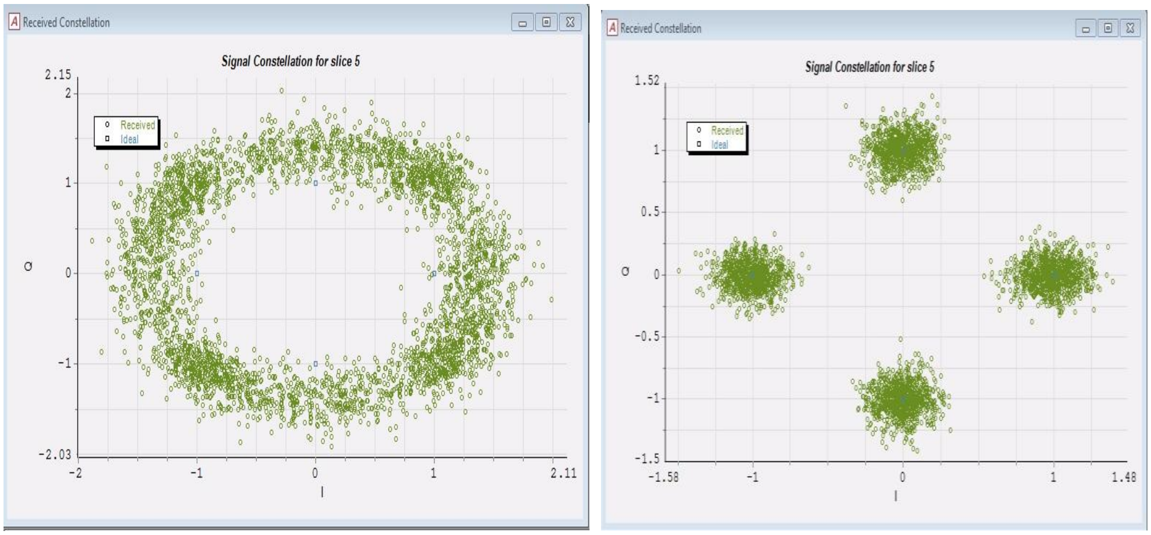


Fig. 3.3 Optical constellations before (left) and after (right) chromatic dispersion compensation for 4-PSK modulation.

A typical optical spectrum at the receiver just before the optical demultiplexer is shown in fig 3.4. The signal has propagated over a distance of 4000 km. Noise is included due to fiber nonlinearity and mix with the signals. The subcarriers are spaced very close (10-100MHz) in OFDM system, and the optical carriers suffer from amplitude and phase errors, which are compensated as shown in figure 3.3 above.

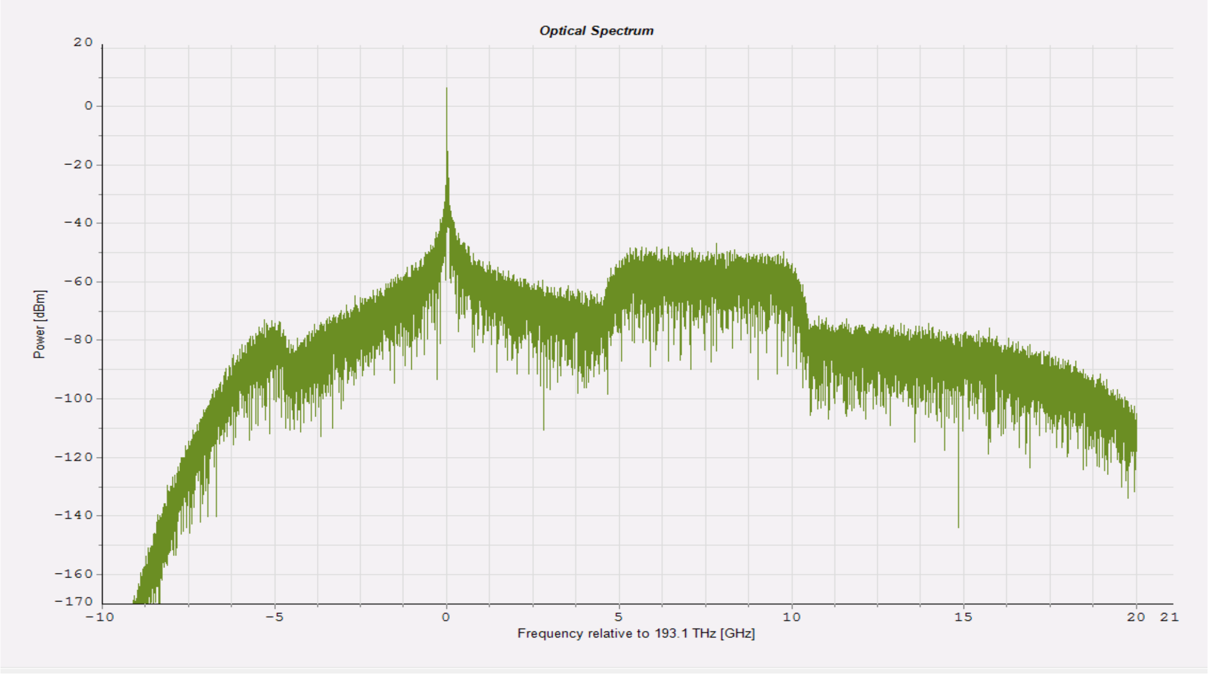


Fig. 3.4 Spectum after propogation through 4000 km of fiber.

The BERs of NRZ, 4 QAM-OFDM, 4 PSK-OFDM systems against the same OSNR was estimated. Before the receiver, the OFDM system uses a 10 GHz brickwall optical filter where as the NRZ system uses a 20 GHz brickwall optical filter, with NRZ transmitter to be a zero linewidth laser and NRZ receiver to be a 7.5 GHz fourth order Bessel filter.

Fig. 3.5 shows BER v/s OSNR, calculated over a bandwidth of 12.5-GHz. NRZ needs a 1-dB better OSNR than 4 QAM-OFDM and needs 0.5-dB better OSNR than 4 PSK-OFDM for BER = $10^{-3}$ . Therefore, OFDM systems showed superior BER in comparison to NRZ system.

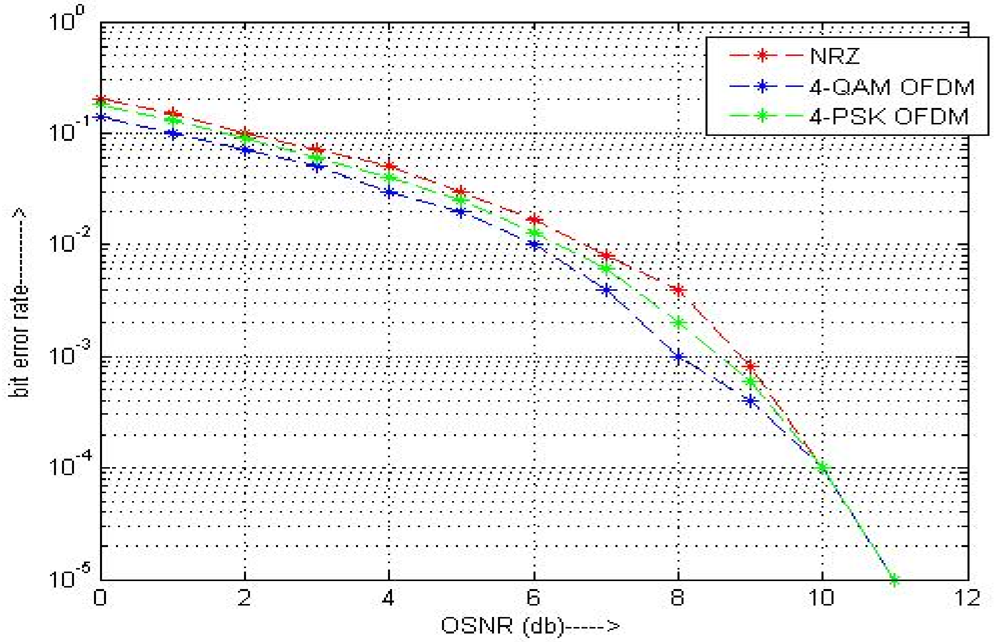


Fig. 3.5 BER v/s OSNR for OFDM and NRZ systems.

## 3.5 CONCLUSION:

OFDM is a most important technology so as to compensate phase and amplitude characteristics of a communication channel; hence it offers an adaptive and strong way of enhancing the performance of system. In this chapter, we presented a scheme to compensate chromatic dispersion i.e. phase and amplitude errors of OFDM signals by using a combination of OFDM and OSSB modulation and residual phase dispersions left are compensated using constellation adjustment method. Results have been investigated to show perfect dispersion compensation, received optical spectrum and better receiver sensitivity of OFDM system than NRZ system.

# CHAPTER 4

# DUAL BAND TRANSMISSION USING HYBRID EDFA- RAMAN AMPLIFIER FOR WDM OOFDM SYSTEM

In this chapter, the investigation shows that the multiplexing of 80 × 10 Gb/s C band and L band channels can be achieved in optical OFDM system using EDFA-Raman amplification. Raman amplification permits a better control of fiber nonlinearities. We have demonstrated the impact of hybrid Erbium Doped Fiber Amplifier-Distributed Raman Amplifier (EDFA-DRA) using dispersion compensating fiber on dual band transmission in WDM optical OFDM system. Power v/s fiber length, optical spectrum, and eye diagram are being analyzed using simulation results for hybrid EDFA-DRA module in OFDM system. The performance of proposed OFDM system is compared in terms BER v/s OSNR for 4 QAM and 16 QAM modulations using both C-band and L-band channels. Further, findings divulged that the proposed OFDM system with 4 QAM modulations showed superior BER in comparison to the 16 QAM modulations where 16 QAM modulated OFDM requires 8 dB better OSNR than 4 QAM modulated OFDM for same BER=$10^{-3}$.

## 4.1 INTRODUCTION:

Orthogonal Frequency Division Multiplexing is a very attractive multiplexing and modulation technique which is used in broadband wireless and wired communication system due to its spectrum efficiency and channel robustness. Regardless of the benefits provided by OFDM and its prevalent use in wireless communications, it has been considered for optical communications during the last years. Optical orthogonal frequency division multiplexing (O-OFDM) has gained much interest in recent years as it is developed for longer distance due to its ability to reduce the effect of selective fading, dispersion and decrease Inter-symbol Interference (ISI). OFDM technique has been applied so it can be utilized in wavelength division multiplexing system [3].

Fibers can be used in new wavelength ranges called bands as fiber optic networks are developed for longer distance, higher speeds, and wavelength division multiplexing. In this chapter, dual band transmissions i.e. combined C band and L band can be achieved in WDM optical OFDM system using hybrid EDFA-Raman amplification. The hybrid EDFA-Raman is a promising technology for future WDM multiterabit systems [41]. In fiber, nonlinear effects can be used for fiber measurement and among these effects, stimulated Raman scattering can be used for optical frequency conversion, generation, and for signal amplification [64-65]. Multiple channel signals can be simultaneously amplified by the use of Raman amplifier in WDM optical fiber communication system [66].

Some of the fundamental advantages of Raman amplification are, first Raman gain survive in every fiber that provides a cost effective means of upgrading from terminal ends. Second is non resonant gain which means over the entire transparency region of fiber ranging from 0.3 to 2 μm, gain is obtainable. Third is that the gain spectrum can be modified by pump wavelength adjustment.

Mohammed et al. [67] presented the performance limitation of EDFAs and theoretical analyzed EDFA-Raman hybrid optical amplifier. In single wavelength channel system, logical expression for Raman amplifiers for fiber low loss region is carried out [68]-[71]. M. S. Kao et al. [72] presented Analytical expression for N channel WDM system with Raman amplification. However general treatment of dual band transmission using hybrid EDFA-Raman amplification in WDM optical OFDM system is not studied yet, according to the best of our knowledge.

Multiplexing of C and L band channels is achieved in WDM optical OFDM system for the first time, by making use of dispersion compensating fiber along with hybrid EDFA/DRA module as Raman amplification permits a better control of fiber nonlinearities.

This chapter is organized as: Section 4.2 includes the analysis of the Raman amplification, Section 4.3 outlines system description, Section 4.4 reports the results of the system, and Section 4.5 draws the conclusion.

## 4.2 ANALYSIS:

Raman amplifiers use transmission fiber as gain medium and thus creating a lossless link and also reducing the overall noise figure. Raman amplification permits a better control of fiber nonlinearities. The on/off Raman gain can be defined as proportion of output signal powers with the pumps on and pumps off. The effective noise figure is defined as [73]:

$$\mathrm{NF_{eff}} = \frac{1}{\mathrm{G}_{\frac{\mathrm{on}}{\mathrm{off}}}}(\frac{2\mathrm{P_{ASE}}}{\mathrm{h}\nu\Delta\mu} + 1) \quad (4.1)$$

here $P_{ASE}$ is the forward ASE (Amplified Spontaneous Emission) noise output power for a frequency v in a bandwidth $\Delta\mu$ and h is the Planck constant.

BER estimation of proposed OFDM system:

In OFDM system, Q is extracted using the constellation. By supposing the Cartesian axes as the decision thresholds, the Q is represented as:

$$Q_{db} = 20.\log_{10}(q) \quad (4.2)$$

where, $q^2 = \frac{\mu_x^2}{\sigma_x^2} = \frac{\mu_y^2}{\sigma_y^2}$ with μ be mean value and $\sigma^2$ be variance.

BER can be approximated using [1]:

$$BER = 1/2erfc(\frac{q}{\sqrt{2}}) \quad (4.3)$$

For simulations using multiple WDM channels, $q^2$was averaged over all the channels before converting to Q (db).

## 4.3 SYSTEM DESCRIPTION:

Fig. 4.1 shows proposed WDM OFDM system with dual band transmission using hybrid EDFA-DRA module with dispersion compensating fiber. Different lasers are presenting data at 80 × 10 Gb/s, at different frequencies for C band and L band simultaneously, forming WDM channels and then are multiplexed to 100 km of standard single mode fiber (SSMF). Lasers at C band are operating at higher emission frequency than that of lasers at L band, and channel spacing is 100 GHz. Various WDM channels are obtained across frequency range from 187 to 191.6 THz for L-band and across frequency range from 191.6 to 195.9 THz for C-band channels. Along with this, two OFDM transmitters for both C and L bands will transmit data at 10 Gb/s using 4 QAM modulations and number of subcarriers is 64.

As shown in figure 4.2, various actions are carried in OFDM transmitter, digital data to be transmitted is converted by transmitter section, into a mapping of subcarrier amplitude and phase by using 4 QAM modulation followed with IFFT to convert data into time domain. The addition of a cyclic prefix solves both ISI and ICI.  After IFFT, and adding up C.P, the signals are modulated by MZM to the channel that comprises of 100 km of SSMF and a hybrid EDFA-DRA dispersion compensating module with a total of 10 spans. This module contains two pump lasers that perform Raman amplification in C and L bands and a DCF is adjusted for both C and L bands, as shown in figure below. C-band pump laser operate at 207 THz emission frequency and L-band pump laser operate at 201 THz emission frequency. EDFA provides additional amplification.

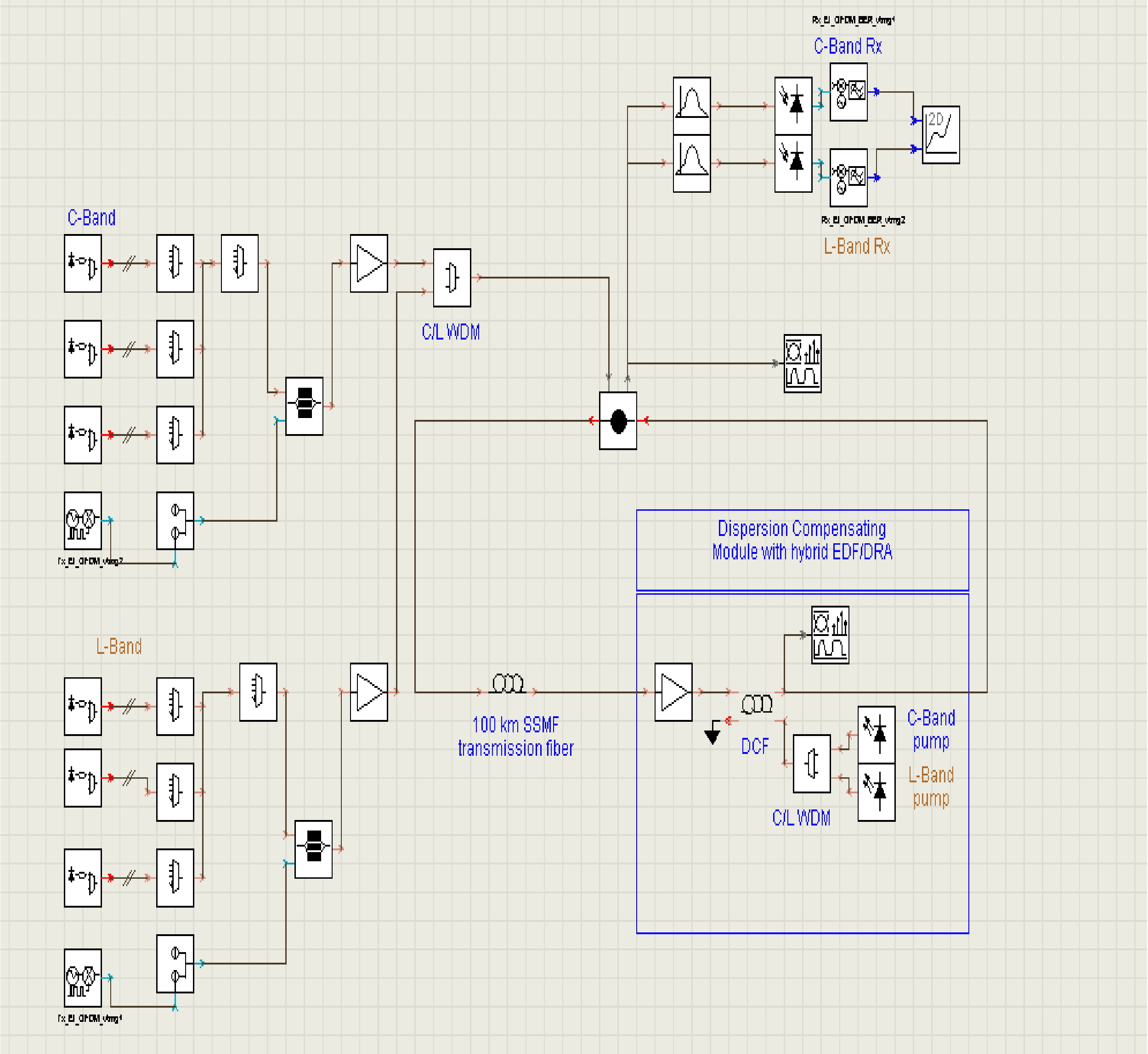


Fig. 4.1 Schematic WDM- optical OFDM system based on dual band transmission using hybrid EDFA-DRA dispersion compensating module.

The combined DR and EDF amplification is flatten by two optical filters at the receiver side. At the receiver, a time domain signal proportional to optical power is produced by photo diode and inverse procedures are carried for both C and L bands: S/P, remove cyclic prefix and FFT in OFDM receiver.

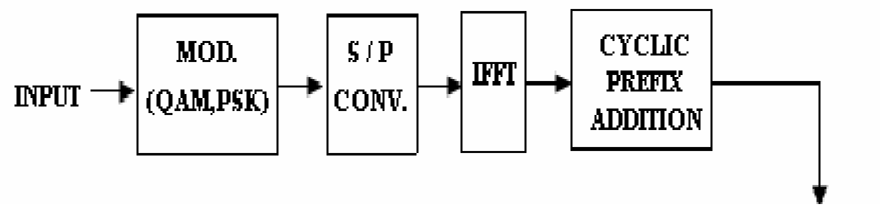


Fig. 4.2 Schematic OFDM transmitter system.

Table 4.1 shows the parameters of standard single mode fiber (SSMF) and table 4.2 shows the parameters of dispersion compensating fiber (DCF) used in the proposed wavelength division multiplexing - optical orthogonal frequency division multiplexing system.

Table 4.1 Parameters of SSMF (Standard Single Mode Fiber).

| **SSMF parameters** | **Value** |
|---|---|
| Length | 100 km |
| Attenuation | 0.2 dB/km |
| Dispersion | $16 \times 10^{-6}$ s/m$^2$ |
| Dispersion Slope | 80 s/m$^3$ |
| Core Area | $80\times10^{-12}$m$^2$ |

Table 4.2 Parameters of DCF (Dispersion Compensating Fiber).

| **DCF parameters** | **Value** |
|---|---|
| Length | 17.7 km |
| Attenuation | 0.5 dB/km |
| Dispersion | $-90\times10^{-6}$s/m$^2$ |
| Dispersion Slope | $-0.45\times10^{3}$s/m$^3$ |
| Core Area | $50\times10^{-12}$m$^2$ |
| Nonlinear effects | Raman scattering |

## 4.4 RESULTS:

Fig. 4.3 shows optical spectrum obtained at the receiver due to dual band transmission using hybrid EDFA-DRA dispersion compensating module in WDM OFDM system. For a WDM system formed by multiple carriers, where each channel is a band of OFDM subcarriers and an optical carrier as shown in figure below, these WDM channels will not affect one another because these WDM channels are likely to walk – off one another.

The signal has propagated over 100 km of SSMF and 17 km of hybrid EDFA-DRA dispersion compensating module with a total of 10 spans and noise is included in each optical amplifier and due to fiber non linearity, noise will mix with the signals. C and L band are simultaneously transmitted in OFDM system and optical spectrum due to dual band shows that optical carriers have very small amplitude variations, that indicates very small or no amplitude errors within the system.

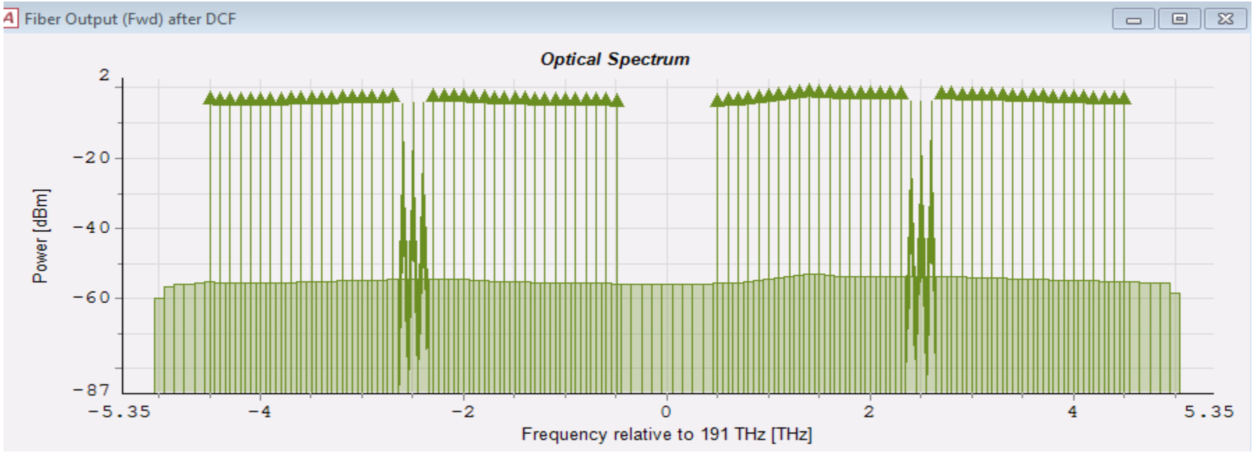


Fig. 4.3 Optical spectrum due to C and L band transmissions using hybrid EDFA-DRA module within in WDM OFDM system.

The power profile of the WDM signal due to dual band transmission in optical OFDM system is reported in figure 4.4. For both C- band and L- band transmissions in the OFDM system, power increases with the increase in emission frequency as shown in figure which will result in compensation of dispersion. Hence dispersion is removed using hybrid EDFA-DRA module with dual band transmission i.e. when C and L band channels are multiplexed at different frequencies and, then the power rises with increase in frequency and fiber length of DCF. This leads to improvement of system performance as chromatic dispersion which is due to single mode fiber is removed and effect of non-linearities and ISI is compensated as shown by eye pattern in figure 4.5, and figure 4.6 discussed below.

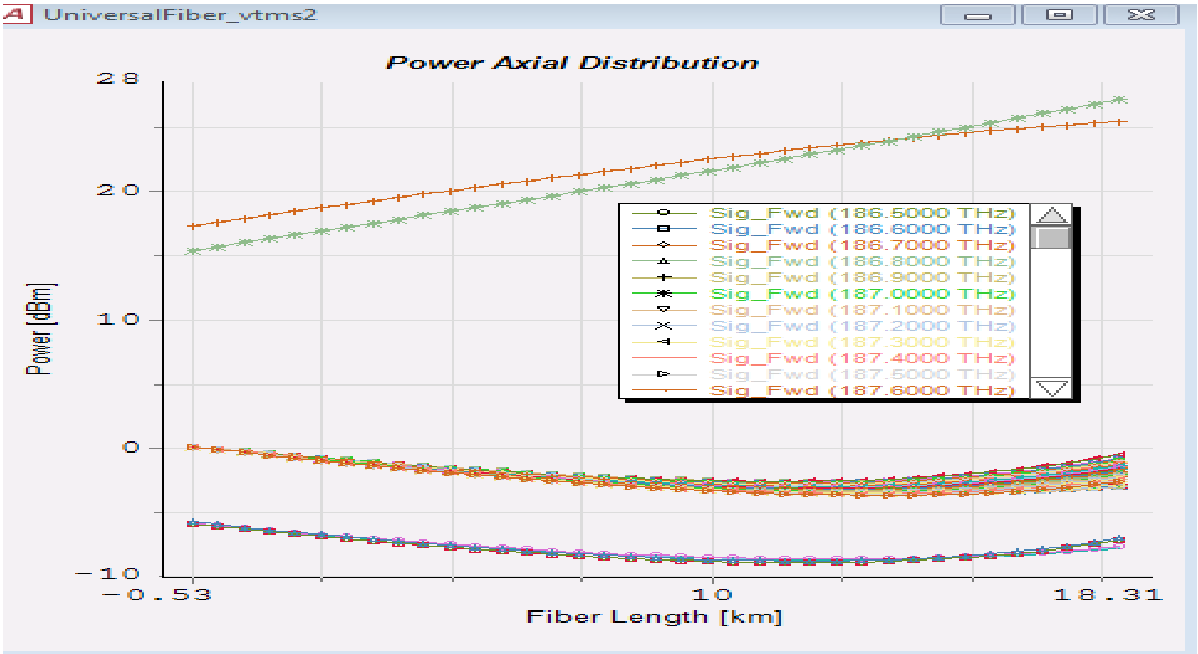


Fig. 4.4 Power axial distribution of hybrid EDFA-DRA dispersion compensating module due to dual band transmission in WDM OFDM system.

Eye pattern is a practical mode to study the intersymbol interference (ISI) and provides the information about the system performance. Eye pattern due to C and L band transmissions using hybrid EDFA-DRA module is reported in figure 4.5 and 4.6 respectively, for the case where the nonlinearities are switched on in the DCF.

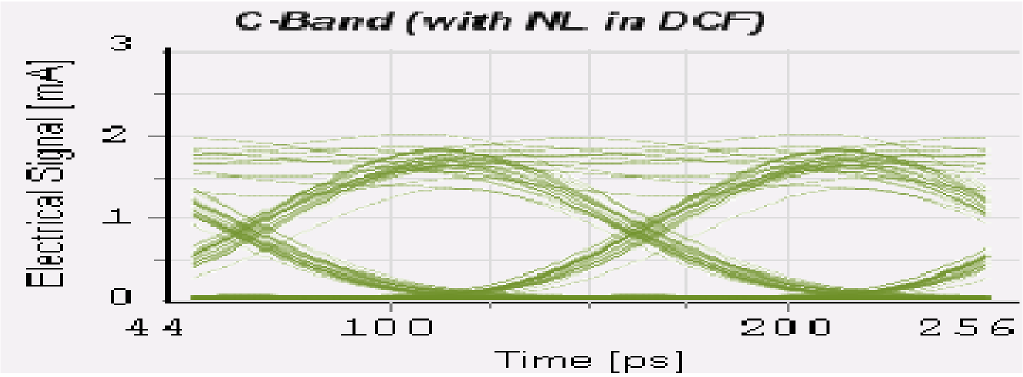


Fig. 4.5 Eye pattern due to C band channel using hybrid EDFA-DRA module in WDM OFDM system.

The interior region of the eye pattern, also called eye opening is wide and proper due to both C band channel using hybrid EDFA/DRA module, which indicates the effect of ISI is compensated properly. It is noticed that the fiber nonlinearities affect the L-band channel more than the C-band channel because of large input power of the channel into the DCF ensuing from the non-flat gain of DRA. The total distortion i.e. distortion at sampling rate and distortion of zero crossings is more in L band channel than the C band channel.

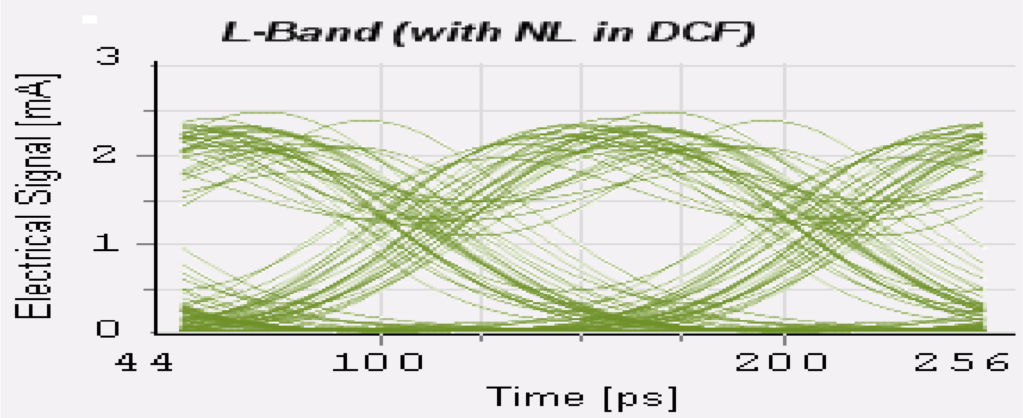


Fig. 4.6 Eye pattern due to L band channel using hybrid EDFA-DRA module in WDM OFDM system.

Figure 4.7 plots BER versus OSNR of proposed OFDM system for both 4 QAM and 16 QAM modulations. For BER=$10^{-3}$, 16 QAM modulated proposed OFDM system using both C and L-band channels requires 8 dB better OSNR than 4 QAM modulated proposed OFDM system using C and L-band channels, as shown in figure below. As M increases (M= 4 to M=16), B.W efficiency increases but BER decreases. Also it is noticed that the C-band channel shows superior BER performance than L-band channel for both 4 QAM and 16 QAM modulated OFDM system. L-band channel requires 0.6 dB better OSNR than C-band at BER=$10^{-3}$, for both 4 QAM and 16 QAM modulated OFDM system. Hence 4-QAM OFDM system with hybrid EDFA-DRA dispersion compensating module using dual C and L band transmissions shows superior BER in comparison to 16 QAM modulated proposed OFDM.

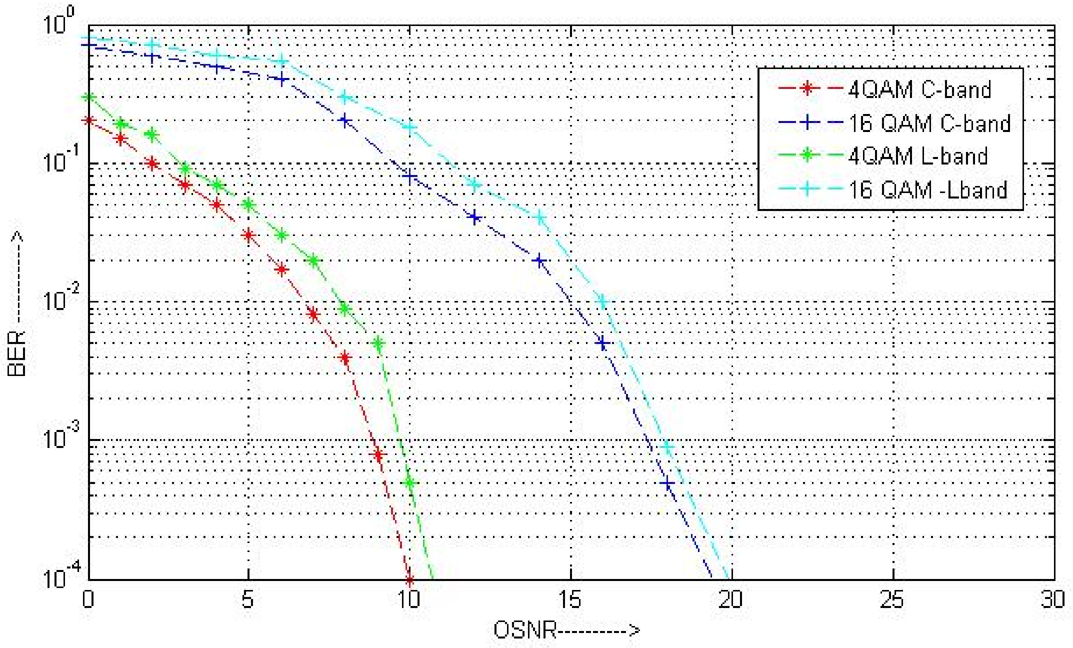


Fig. 4.7 BER v/s OSNR of 4 QAM and 16 QAM modulated proposed OFDM system.

## 4.5 CONCLUSION:

OFDM in optical fiber is a well established technology that offers an adaptive and robust method of increasing the performance of system because it could compensate all frequency dependant phase and amplitude characteristics of a communication channel. This chapter has shown dual C and L band transmissions using hybrid EDFA-DRA dispersion compensating module in WDM optical OFDM system. Raman amplification permits a better control of fiber nonlinearities, so distributed Raman amplifier (DRA) is used along with EDFA in order to improve the system efficiency by compensating the dispersion to a great extent. Result has been investigated against the power v/s fiber length, optical spectrum, and eye diagram of EDFA/DRA module for dual band transmission in OFDM system. Above proposed system was demonstrated by comparing the BER v/s OSNR for 4 QAM and 16 QAM modulations using both C-band and L-band channels. Further, findings divulged that the proposed OFDM system with 4 QAM modulations showed superior BER in comparison to the 16 QAM modulations where 16 QAM modulated OFDM requires 8 dB better OSNR than 4 QAM modulated OFDM for same BER=$10^{-3}$. This proposed system is cost efficient and enhances the system performance, which can be used for long haul transmissions.

# CHAPTER 5

# COMPENSATING THE IMPACT OF NONLINEAR DISTORTION USING TWO PILOT TONES IN OOFDM-ROF SYSTEM

This chapter presents that orthogonal frequency division multiplexing technique can be incorporated into radio over fiber (RoF) system and the investigation demonstrated that how optical OFDM- RoF system is affected by intermodulation distortion (IMD) resulting from non linear nature of optical link. This chapter provides a novel approach for compensation of IMD in OOFDM-RoF system by two pilot tones in optical OFDM transmission. One or several symbols have to be applied like pilot tones in conventional channel estimation methods. Five OFDM- QAM radio channels using 16 QAM modulation format directly modulates a laser, is demonstrated. Error vector magnitude (EVM) of center radio channel against 3rd IMD, the optical spectrum, constellation diagram are being analyzed using simulation results for OOFDM-RoF systems.

## 5.1 INTRODUCTION:

OOFDM- RoF system has fascinated considerable interest for the future gigabit broadband wireless and wired communication. In OOFDM–RoF system, OFDM modulation technique is included into Radio over Fiber (RoF) system. This system includes the advantages of both, as OFDM can allocate the data over huge numbers of subcarriers which are spaced out at particular frequencies with overlapping bands, and on the other hand RoF systems can make use of the optical network’s high capacity all along the mobility of wireless networks. Hence OOFDM-RoF system can be used for long haul as well as short distance transmissions at high data rates. This system enhances the system flexibility without increasing system’s cost as well as complexity.

The major issues raised through OFDM and RoF systems are large peak to average power ratio (PAPR) and the nonlinear distortion in form of intermodulation distortion (IMD) due to non linear nature of optical link [74-75]. IMD is the amplitude modulation of signal containing two or more frequencies in system with non linearities. OOFDM- RoF system suffers from IMD from inferior sensitivities due to limited optical modulation index (OMI) [75-76]. IMD can be further increased when multiple RF signal or frequency division

multiplexing signal drive optical modulator simultaneously. Inter Modulation Distortion (IMD) will reduce receiver sensitivity, dynamic range and thus RoF system performance.
Lilong Liu et al., uses the pilot tones for compensation of chromatic dispersion in optical OFDM systems [47]. But this channel estimation approach is presented for the first time in optical OFDM RoF systems to compensate IMD and correct amplitude/phase of OFDM signals by usage of two pilot tones, which will improve RoF system performance.

This chapter shows OFDM technique is incorporated into RoF system and laser is directly modulated by five OFDM – QAM radio channels, 2GHz carrier frequency each. The impact of NLD in OOFDM- RoF systems is studied by generating 2nd and 3rd order IMD by increasing either modulation index of laser or by increasing fiber length. A novel channel estimation approach is presented to compensate IMD and adjust phase/amplitude of OFDM signals by using two pilot tones, which will improve RoF system performance.

This chapter is organized as follows: Section 5.2 explains the logical description to compensate NLD, Section 5.3 outlines the system description of OOFDM- RoF system, Section 5.4 shows results and Section 5.5 shows the conclusion.

## 5.2 LOGICAL DESCRIPTION:

The phase/amplitude dispersion of OFDM signal can be expressed as [47]

$$\Phi_d(f) = \prod . c . D_t . \left(\frac{f}{f_{LD}}\right)^2 \qquad (5.1)$$

Here $D_t$ is the total dispersion for the full length of fiber in ps/pm, $f_{LD}$ and $f$ are the frequencies of the laser carrier and subcarriers respectively, c is the speed of light.
The phase/amplitude dispersion and IMD can be compensated by inserting pilot tones into symbol stream periodically in order to get the phase dispersion in each subcarrier for compensation. Let us consider two pilot tones on different subcarriers be indexed at p1 and p2, inserted in first symbol of frame then phase/amplitude dispersion of m-th subcarrier can be derived as:

$$\phi_m = \frac{m^2-p_2^2}{p_1^2-p_2^2} . \phi_{p1} + \frac{p_1^2-m^2}{p_1^2-p_2^2} . \phi_{p2} \qquad (5.2)$$

here $\phi_{p1}$and $\phi_{p2}$ are the two phases of the two pilot tones indexed at p1 and p2, respectively. The calculated phase values of equation (5.2) can be used to compensate NLD.

## 5.3 SYSTEM DESCRIPTION:

Fig 5.1 shows the optical OFDM- RoF system. The system shows a laser is directly modulated by five OFDM - QAM radio channels with 2 GHz-2.4 GHz carrier frequency, 100 MHz channel spacing using 16 QAM modulation format. Data at 5×40 Mb/s is presented to QAM modulator using 16 QAM modulation and data is split into parallel steams of data. The number of subcarriers is 64. Non Linear Distortion (NLD) in OOFDM – RoF system is compensated using channel estimation by inserting two pilot tones at high frequency indexes in one of the OFDM transmitter shown in figure 5.2. After Inverse Fast Fourier Transform as well as adding up C.P, the signals can be modulated directly by a laser to dispersion compensating fiber of length 100km. The fiber has a loss of 0.6 dB/km, dispersion of $16\times10^{-6}$s/m$^2$, an effective area of 80 μm$^2$ and, a nonlinear coefficient of $2.6 \times 10^{-20} m^2$ /W.

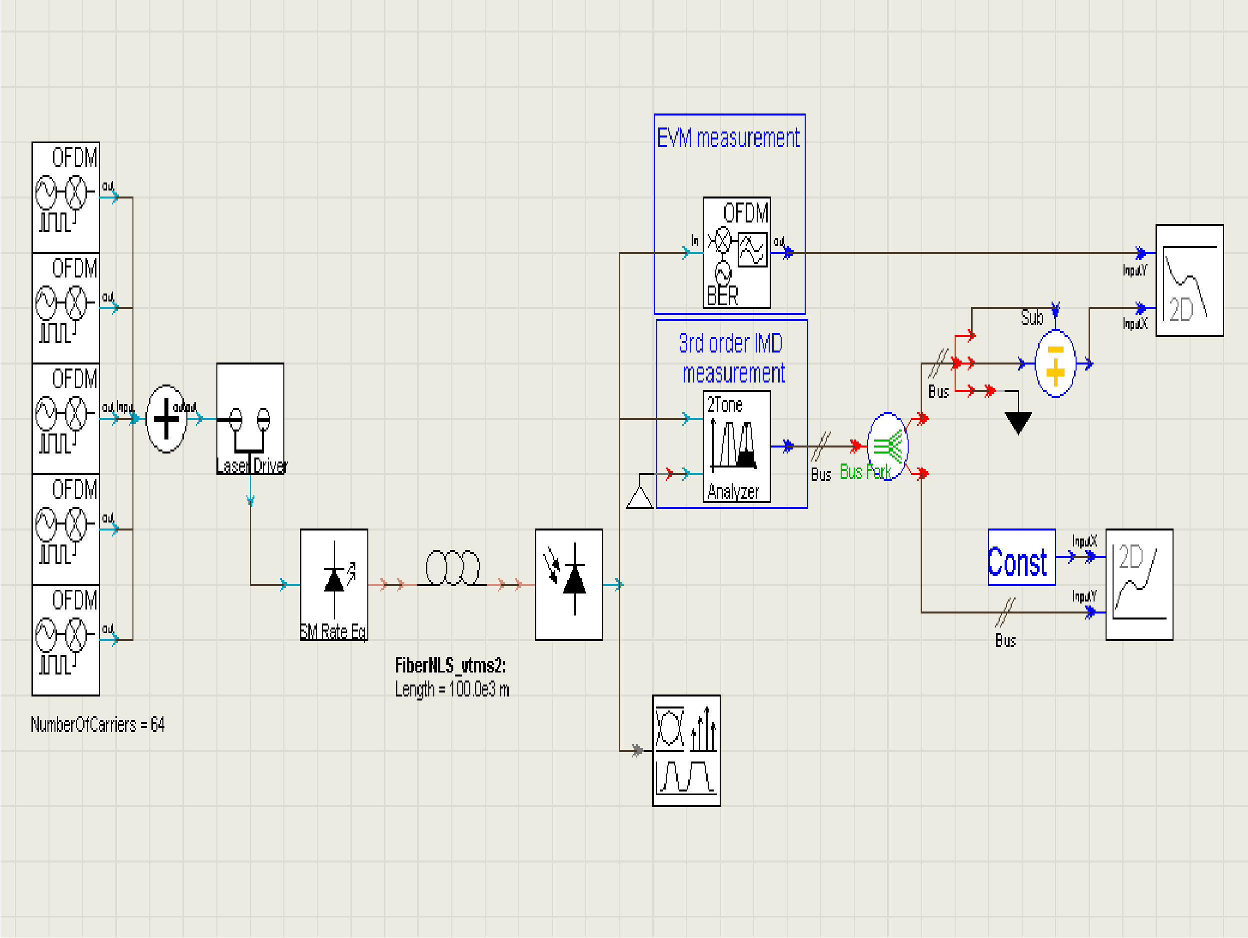


Fig. 5.1 The schematic optical OFDM RoF system.

At the receiver, a time domain waveform that is proportional to the power is produced by photodiode. The entire inverse procedures i.e. serial to parallel conversion, removal of cyclic prefix, FFT procedures are carried away in order to obtain OFDM signals. Inter modulation distortion (IMD) that is a NLD is generated by either increasing the modulation index of laser or fiber length. Two tone analyzer estimates the quality of analog signal and also calculates channel power, noise power, SNR and power of intermodulation distortion. In figure 5.1, two tone analyzer used at the receiver is used for measurement of 3rd order intermodulation distortion (IMD).

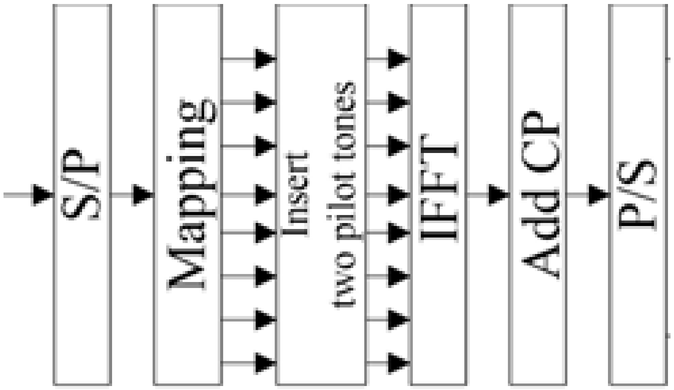


Fig. 5.2 The optical OFDM transmitter system to compensate Non Linear Distortion (NLD) using two pilot tones.

Table 5.1 shows the parameters of dispersion compensating fiber (DCF) used in the proposed optical orthogonal frequency division multiplexing-radio over fiber system.

| **DCF parameters** | **Value** |
|---|---|
| Length | 100 km |
| Attenuation | 0.6 dB/km |
| Dispersion | $16\times10^{-6}$s/m$^2$ |
| Dispersion Slope | 80 s/m$^2$ |
| Core Area | 80 μm$^2$ |

## 5.4 RESULTS:

Figure 5.3 illustrates 16 QAM constellation diagram after compensating NLD by using channel estimation approach by inserting two pilot tones within fiber OFDM transmission. This approach is used to mitigate equally fiber dispersion and as well as frequency response of various microwave components. All the constellation points are rotated around the origin, and the degree of rotation caused by fiber dispersion, is proportional to its frequency relative to optical carrier squared. Error signal is produced by subtracting expected phase from the received phase and the received signals can be corrected by this error signal. So constellation reduces to 16 distinct points indicating NLD is compensated. Hence dispersion compensation is perfect.

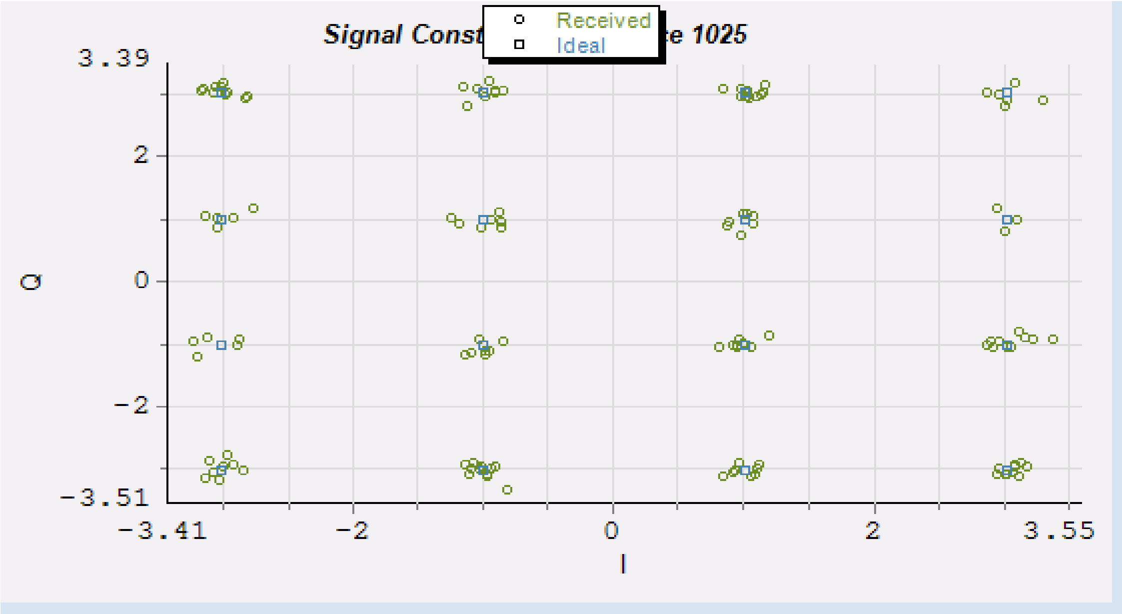


Fig. 5.3 Constellation diagram of 16 QAM after the equalization at receiver.

Figure 5.4 shows optical spectrum just before the optical demultiplexer at the receiver. The reason for the impact of NLD is that the fiber nonlinearity strongly affects the signal peaks. In OFDM system, all the subcarriers are closely spaced and due to fiber dispersion they will not walk off one another. There is a strong deviation in the amplitudes of the subcarriers that results in amplitude errors as shown in figure 5.4. This variation in the form of dispersion can be compensated using channel estimation technique by inserting two pilots as shown in figure 5.3.

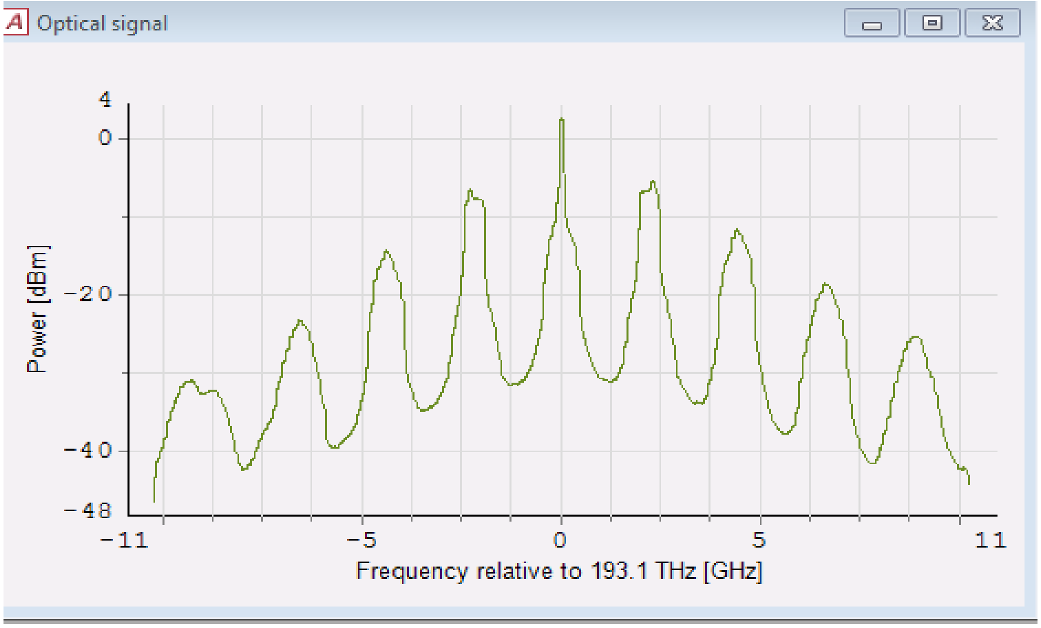


Fig. 5.4 Optical Spectrum just before the optical demultiplexer at the receiver.

A signal transmitted by a transmitter as well as received by the receiver would have all the constellation points at perfect locations but due to various imperfections that are due to non linearities is responsible for the actual constellation points to diverge from the perfect or ideal locations. EVM is a measure to calculate how faraway the points are as from the ideal locations. EVM is a measure to analyze the performance of digital radio receiver or transmitter.

Error Vector Magnitude (EVM) of central radio channel is displayed against 3rd order Intermodulation Distortion (IMD) as shown in figure 5.5. 3rd order IMD and EVM are related exponentially. With the increase in IMD, EVM shows exponential rise which indicates that the intermodulation distortion is responsible for the constellation points to diverge from the perfect or ideal locations.

However figure 5.3 shows perfect constellation diagram of 16 QAM OFDM system, indicating that intermodulation distortion (IMD) is compensated by the proposed approach used i.e. insertion of two pilots in optical OFDM transmission.

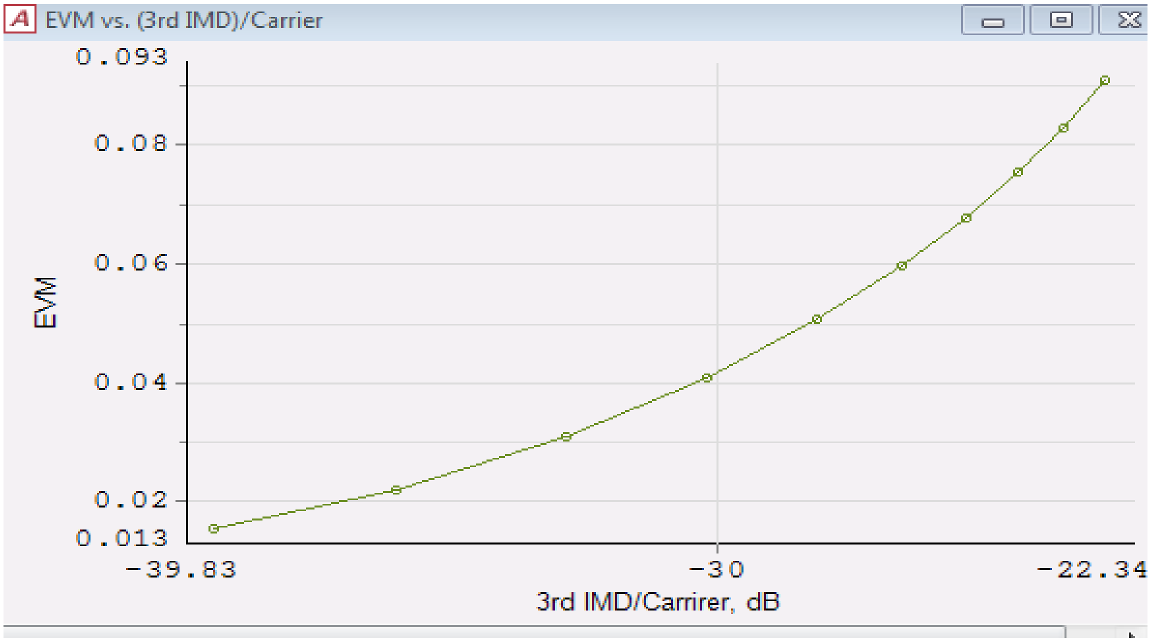


Fig. 5.5 Error Vector Magnitude (EVM) against 3$^{rd}$ IMD at the receiver.

## 5.5 CONCLUSION:

Incorporating optical OFDM all along with the RoF system is capable of both short distance as well as long distance transmissions. OOFDM-RoF can improve system flexibility, provides a very large coverage area with no increase in the complexity and cost of the system. This chapter showed the impact of NLD in OOFDM-RoF system, which is compensated using a novel approach of channel estimation by inserting two pilot tones in optical OFDM transmission. The simulation results showed error vector magnitude (EVM) of center radio channel against 3rd IMD, the optical spectrum, and perfect dispersion compensation of 16 QAM after inserting pilots, an approach for channel estimation.

# CHAPTER 6

# CONCLUSION, RECOMMENDATION AND FUTURE SCOPE

## 6.1 CONCLUSION AND RECOMMENDATION:

This chapter provides the summary of the research work done in this dissertation. First the conclusions have been made from this study, then the recommendations have been given on the basis of the conclusions and then the scope for the future research is discussed. The main results obtained in this thesis are concluded and summarized below:

1. OFDM is a most important technology so as to compensate phase and amplitude characteristics of a communication channel; hence it offers an adaptive as well as strong method of enhancing the performance of system. A novel scheme to compensate chromatic dispersion i.e. phase and amplitude errors of OFDM signals is proposed, by using a combination of OFDM and OSSB modulation and the residual amplitude/phase dispersions left are further compensated using constellation adjustment method. The analysis of simulation results showed perfect dispersion compensation, received optical spectrum and better receiver sensitivity of OFDM system than NRZ system. 4 QAM-OFDM system shows superior BER than NRZ, where NRZ system requires 1 dB superior OSNR than 4 QAM OFDM. Also 4 PSK-OFDM system shows superior BER than NRZ, where NRZ system requires 0.5 dB better OSNR than 4 PSK-OFDM systems.

   This proposed system is recommended for high speed and long haul transmissions. Dispersion management is recommended wherever the speed of data communication needs to be increased.
2. Dual C and L band transmissions using hybrid EDFA-DRA dispersion compensating module in WDM optical OFDM system is proposed. Raman amplification permits a better control of fiber nonlinearities, so distributed Raman amplifier (DRA) is used along with EDFA in order to improve the system efficiency by compensating the dispersion to a great extent. Results have been investigated against the power v/s fiber length, optical spectrum, and eye diagram of EDFA/DRA module for dual band transmission in OFDM system. The fiber nonlinearities affect the L-band channel

more than the C-band channel because of large input power of the channel into the DCF ensuing from the non-flat gain of DRA. BER v/s OSNR for 4 QAM and 16 QAM modulations using both C-band and L-band channels was compared. Further, findings divulged that the proposed OFDM system with 4 QAM modulations showed superior BER in comparison to the 16 QAM modulations where 16 QAM modulated OFDM requires 8 dB better OSNR than 4 QAM modulated OFDM for same BER=$10^{-3}$.

This proposed WDM OFDM system could prove to be cost efficient that enhances the system performance, and also could be used for long haul transmissions.

3. Incorporating optical OFDM all along with the RoF system is capable of both short distance as well as long distance transmissions. OOFDM-RoF can improve system flexibility, provides a very large coverage area with no increase in the complexity and cost of the system. The impact of non linear distortion (NLD) in OOFDM-RoF system is demonstrated, which is compensated using a novel approach of channel estimation by inserting two pilot tones in O-OFDM transmission system. The simulation results showed the optical spectrum and error vector magnitude (EVM) of center radio channel against 3rd IMD. With the increase in IMD, EVM shows exponential rise which indicates that the intermodulation distortion is responsible for the constellation points to diverge from the perfect or ideal locations. Further, findings divulged the perfect dispersion compensation of 16 QAM after inserting pilots, an approach for channel estimation.

   This proposed system is recommended for high speed short distance as well as long distance transmissions. OOFDM- RoF system has attracted considerable attention for future gigabit broadband wireless communication.

## 6.2 FUTURE SCOPE:

During the course of this dissertation, several avenues for continuation of this study became evident. The topics which were considered worthwhile are summarized below:

1. OFDM combined OSSB (Optical single side band) modulation; along with constellation adjustment can compensate chromatic dispersion over infinite distance when non linearities are not considered, but over 4000 km if non linearities are

considered. So, design rules for longer distance span (higher than 4000 km) can be implemented in future.

2. In this dissertation the polarization effects have not been taken into account. Simulation studies can be done for same architectures while taking into account the polarization effects.
3. We have used channel spacing of 100 GHz in this dissertation. This can be further reduced for more bandwidth utilization and some other techniques can be introduced for further network sharing.

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# LIST OF PUBLICATIONS:

[1] Manbir Brar, R. S. Kaler, “Chromatic Dispersion Compensation in Long-Haul Transmission Systems” Communicated to Optik- International journal for light and electron.

[2] Manbir Brar, R. S. Kaler, “Compensating the Impact of Nonlinear Distortion using two pilot tones in OOFDM-RoF System” Communicated to Optik- International journal for light and electron.

[3] Manbir Brar, R. S. Kaler, “Dual band transmission using hybrid EDFA- Raman Amplifier for WDM OOFDM system” Communicated to Optik- International journal for light and electron.