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A Comprehensive Review of QAM-OFDM Optical Networks

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Abstract—Orthogonal Frequency Division Multiplexing (OFDM) is a FDM scheme that has the ability to cope with harsh channel conditions without using complex equalization filters. With the introduction of guard band, OFDM offers better orthogonality for the transmission channels affected by high frequency attenuations in copper wire, frequency selective fading and Narrow-Band (NB) interference due to multipath propagation. Each subcarrier is modulated employing a digital modulation scheme such as Quadrature Amplitude Modulation (QAM) with lower symbol rate in order to achieve higher data rates in comparison to single carrier modulation scheme for the given bandwidth. We have studied QAM-OFDM based optical networks in order to obtain higher data rates with lower Bit Error Rate (BER). Variants of OFDM have also been discussed along with its advantages and limitations to achieve the desired optimum performance in the optical networks. This paper presents a detailed study of M-ary QAM OFDM schemes and methods used to overcome effects of Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI) with optimum utilization of system bandwidth.

Keywords—OFDM, ISI, ICI, QAM, Fast Fourier Transform (FFT), Inverse Fast Fourier Transform (IFFT), Discrete Fourier Transform (DFT), Peak to Average Power Ratio (PAPR), NB, Quality of Service (QoS), BER

I. INTRODUCTION

The data requirement for various services is increasing day by day. Therefore, to fulfill these needs we require effective utilization of communication resources i.e. available system bandwidth and transmission power. Digital modulation techniques facilitate optimum utilization of resources like enhancement of data rate, better noise immunity, reliable and secure communication etc[1][2].

The digital modulation techniques are classified on the basis of bandwidth compactness characteristics. The performance of every modulation method is evaluated by estimating the probability of error based on the assumption of presence/absence of Additive White Gaussian Noise (AWGN) [3]. The Modulation schemes which are capable of transmitting large number of bits per symbol at less error are having better immunity to noise and interference [4]. The different techniques available for digital modulation are ASK, FSK, PSK and QAM [5].

The OFDM is an efficient modulation technique which provides higher degree of throughput by sending a number of independent QAM-subcarriers simultaneously.

For designing of a robust system, appropriate OFDM parameters must be selected to avoid effects of ISI and ICI. OFDM is employed with MIMO for improving throughput of a system for a given bandwidth [6].

.The M-ary QAM is an attractive technique by which high data rates can be achieved without increasing bandwidth. QAM signal is formed with the combination of amplitude and phase modulation. QAM modulated data is represented in form of I and Q components. The BER performance of M-ary QAM degrades when higher level of QAM is used. Therefore the BER performance of 16-QAM is better than that of 64-QAM [7].

The paper is organized as follows. This paper presents a study of QAM-OFDM based optical networks. The OFDM technique is discussed in Section II. In Section III, FFT and IFFT are explained along with block diagram of the OFDM system followed by their mathematical analysis in Section IV. Section V defines the guard band implementation. The different variants of OFDM along with its applications are discussed in Section VI. A detailed study of M-ary QAM modulation technique is described in Section VII. Section VIII finally concludes the paper.

II. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (OFDM)

The OFDM is a process of encoding the digital data streams on multiple carriers. It is the modulation technique which provides higher data rates. OFDM consists of several subcarrier frequencies orthogonal (i.e. perpendicular) to each other. Orthogonality ensures that sub-carriers are spaced in a manner to have only partial overlap. Because the peak of each sub-carrier intersects at the zero crossing of other nearby sub-carrier. To evade interference in OFDM, guard bands are placed between multiple carriers. Spectrum of OFDM signal is shown in figure 1.

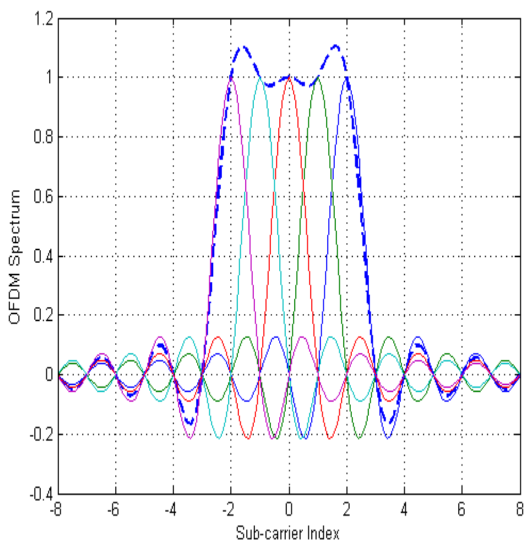

Figure 1. Spectrum of OFDM Signal

OFDM uses IFFT function for modulation or multiplexing and FFT function for demodulation or de-multiplexing. It is used in optical transmission system to overcome Chromatic Dispersion (CD) and PMD. In OFDM a data stream is distributed into various NB channels at different frequencies in order to eliminate ISI and also mitigate the effects of ICI. OFDM is also used to convert high rate serial data stream into multiple parallel streams of low data rate. Thereby it provides compact spectrum. Hence, the bandwidth requirement of OFDM system is much less than that of conventional FDM system for same data transmission rates [8].

III. FOURIER TRANSFORM (FT)

Fourier Transform basically converts time domain signal into frequency domain signal. There are different versions of FT used based on application of the network. In the traditional FT boundless time/frequency domain continuous signals are transmitted. To make signal processing simpler, signals are sampled in traditional transform. Sampling of infinite spectrum signals results in aliasing, whereas processing of boundless time signals results in storage memory problems.

To cope with these issues, signal processing units mostly exploit DFT which is a variant of traditional transform used to sample signals in time as well as frequency domains. In DFT, the time domain waveform must repeat continuously, which results in the frequency spectrum also to repeat continuously in the frequency domain.

FFT and IFFT

FFT and IFFT are fast algorithms that efficiently compute the DFT and IDFT and are widely used in many digital signal processing applications. OFDM systems rely on the IFFT at the transmitter side for an efficient implementation of the signal modulation and FFT at the receiver side for efficient demodulation [9]. The FFT/IFFT implementations need optimization in order to attain the required throughput with minimum power consumption and area penalty. The requirement of larger FFT size for system realization is a limitation of OFDM. The FFT size is directly proportional to PAPR. So, larger size of FFT leads to higher PAPR ratio. Due to high PAPR, nonlinear distortion affects the OFDM system[10]. The block diagram showing a FFT-based OFDM system is given in figure 2.

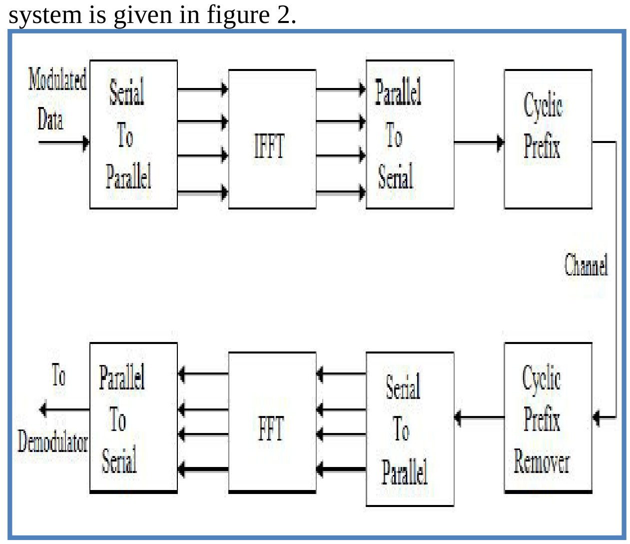

Figure 2. Block diagram of OFDM System

At transmitter, the signal is represented in frequency domain. This sampled digital signal enables the discrete Fourier spectrum to exist only for discrete frequencies. Each OFDM carrier matches to at least one of the discrete Fourier spectrum component. The input serial data is converted into parallel data to form n bits complex number. These n symbol represents the signal constellation for the given subcarrier M-QAM, i.e. 16-QAM, 32-QAM and so on. These complex numbers are modulated using IFFT and thereafter converted back to serial data for transmission [11]. Guard bands are placed between multiple carriers to evade effects of ISI. At the receiver, cyclic prefix is removed and with the help of FFT cyclic time is converted into frequency spectrum.

IV. MATHEMATICAL ANALYSIS

Mathematically, In OFDM the Carrier signal is given as:

$$c(t) = \frac{1}{N}\sum_{n=0}^{N-1} A_c(t)\, e^{j[\omega_c t+\phi_c t]} \qquad \ldots(1)$$

Where, t is the symbol duration period, A_c represents amplitude of carrier. OFDM consists of several subcarrier so, the complex signal $c_s(t)$ is given as:

$$c_s(t) = \frac{1}{N}\sum_{n=0}^{N-1} A_n(t)\, e^{j[\omega_n t+\phi_n t]} \qquad \ldots(2)$$

Where, $\omega_n = \omega_0 + n\Delta\omega$

The variables A_c(t)andf_c (t) have fixed values which are carrier frequency dependent and hence:

$$\phi_n(t) = \phi_n,\ A_n(t) = A_n$$

On sampling the signal at frequency of 1/T, we get:

$$c_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n\, e^{j[(\omega_0+\mathrm{n}\Delta\omega)\mathrm{kT}+\phi_n]} \qquad \ldots(3)$$

Now, by limiting time we have:

$$t = NT$$

Let w_0=0 in eqn.3, $c_s(kT)$given as:

$$c_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n\, e^{j\phi_n} e^{j(\mathrm{n}\Delta\omega)\mathrm{kT}} \qquad \ldots(4)$$

Now we compare eqn.4 with general IFT equation:

$$g(kT) = \frac{1}{N}\sum_{n=0}^{N-1} G\left(\frac{n}{NT}\right) e^{\mathrm{j}2\pi nk/N} \qquad \ldots(5)$$

In eq.4 the fn. $A_n e^{j\phi_n}$ is signal in sampled frequency domain and $c(kT)$represents signal in time domain. Eq. 4 is equal to Eq. 5 when:

$$\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{NT} = \frac{1}{r} \qquad \ldots(6)$$

Eq. 6 must be satisfied to maintain orthogonality between multiple sub-carriers. In order to define OFDM signal with the help of FT events.

The N-point DFT is given as:

$$X_p = \sum_{n=0}^{N-1} x_p\,[n] e^{-j\left(\frac{2\pi}{N}\right)kn} \qquad \ldots(7)$$

And the N-point IDFT is given as:

$$x_p = \sum_{n=0}^{N-1} X_p\,[k] e^{-j\left(\frac{2\pi}{N}\right)kn} \qquad \ldots(8)$$

The natural effect of this method allows producing carriers which are orthogonal in nature.

For data sequence$(d_1, d_2, - - - d_{N-1})$, where each d_n is a complex number $d_n = a_n + jb_n$, $(a_{n,} b_n = \pm 1\ for\ QPSK, a_{n,} b_n = \pm 1, \pm 3\ for\ 16-QAM)$.

$$D_k = \sum_{n=0}^{N-1} d_n\, e^{-j\left(\frac{2\pi nk}{N}\right)} = \sum_{n=0}^{N-1} d_n\, e^{-j2\pi/f_n t_k} \quad \ldots(9)$$

Where k=0, 1, 2, - - - -, N-1

Here, $f_n = \frac{n}{ND\,(T)}$, $t_k = kD$(t).

Whereas D(t) is symbol duration of the serial data sequence d_n. The real part of Vector D is given as:

$$\mathrm{Y_k} = \mathrm{Re(D_k)} = \sum_{\mathrm{n=0}}^{\mathrm{N-1}} [(\,\mathrm{a_n}\cos(2\pi \mathrm{f_n}\,\mathrm{t_k}) + \mathrm{b_n}\sin(2\pi\mathrm{f_n}\,\mathrm{t_k})] \qquad \ldots(10)$$

, where k=0, 1, 2, - - - -, N-1

When these elements are applied to a LPF with an intervals D(t), the signal obtained almost approximates the FDM signal. The time domain representation is given as:

$$y(t) = \sum_{n=0}^{N-1} [(\,a_n\cos(2\pi f_n\, t_k) + b_n \sin(2\pi f_n\, t_k)] \quad ,\ 0 \le \mathrm{t} \le \mathrm{N}\Delta\mathrm{t} \ldots(11)$$

V. IMPLEMENTATION OF GUARD BAND

The sub-carriers are separated by FFT at the receiver end in the absence of interference induced in transmission channel. But, in real practice this condition is not possible. Because the OFDM spectrum is not a band limited $\mathrm{sinc}(f)$ function.Each sub channel leaks energy into the adjacent channels due to multipath interferences resulting in ISI. By increasing the symbol duration/ number of carriers, the distortions can be reduced. However, implementation is difficult in terms of Doppler shift, stability of carrier, latency and FFT size. Therefore, a guard band is added after each sub-carrier which prevents overlapping with other sub-carriers.

The introduction of longer guard band eliminates the effect of ISI and multipath delay. The total symbol duration is given as

$$T_{tot} = T_g + T$$

Where, T_g and T represents guard band and symbol interval respectively. In ideal conditions it must follow $T_g \leq T/4$.

Although, the throughput of OFDM system decreases by inserting guard band. The merits of inserting guard interval are:

- Reduces ISI
- Provides robustness

VI. VARIANTS OF OFDM AND ITS APPLICATIONS

The different variants of OFDM and their relative applications are described as follows [12].

- **OFDMA:** This OFDM access technology with multiple access capabilities is used for cellular communication applications. Multiple access is implemented in OFDMA by assigning subsets of subcarriers to individual users. This enables several users to transmit simultaneously at low data rates. OFDMA supports the desired QoS by assigning distinct sub-carriers to different users. OFDMA is also well-suited for other technologies such as MIMO and smart antennas [13]. He OFDMA spectrum is shown in figure 3.

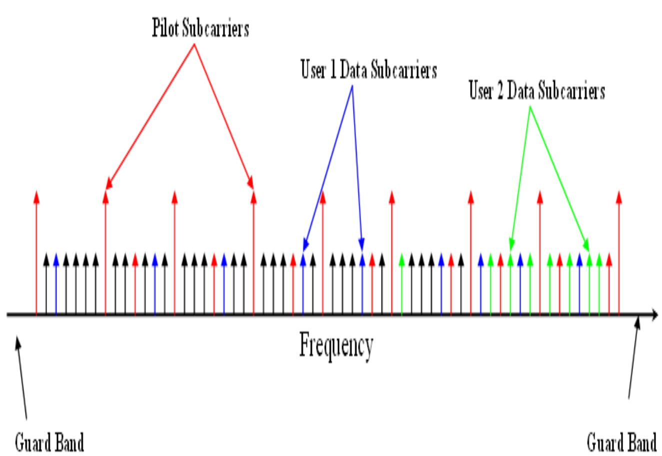

Figure 3.OFDMA Spectrum

- **Coded OFDM (COFDM):** In this modulation scheme that is best suited for terrestrial broadcasting channels. It has the capacity to cope with high level of multi-path propagation and uses a wide spread of delays between the received signals. COFDM is an innovative approach with a number of exciting features used in Digital Video Broadcasting - Terrestrial (DVB-T) and WLAN. It transforms blocks of thousands of modulated signal samples through IFFT into the frequency domain and also inserts guard intervals into the spectrum. COFDM has ability to deal with high levels of multi-path propagation and handles co-channel narrowband interference very well [14]. Hence, COFDM has been preferred for two broadcasting standards, namely:

  - Digital Audio Broadcasting (DAB): DAB was specifically built to handle the rigors of signal reception in moving cars - particularly the issue of multi-path reception which, in the above case, is time varying.
  - Digital Video Broadcasting - Terrestrial (DVB-T): DVB-T requires a higher capacity when compared with DAB. Multi-path tolerance is crucial due to the extensive usage of set-top television antennas.

  In order to accommodate the specific requirements of DAB and DVB-T, COFDM is used, with proper adjustments in parameters. The overall performance of COFDM with respect to multi-path propagation and interference can be achieved only by a sensible choice of parameters. A successful implementation also demands special attention on how the forward error-correction coding is used.

COFDM involves the modulation of data into a large number of carriers with the help of the FDM technique.

Fast Low Latency Access with Seamless Handoff – OFDM (Flash-OFDM): Flash-OFDM is a Flarion copyrighted technology, for mobile broadband data communications. It uses Internet Protocol over a packet-switched network. Speech services are implemented using VoIP. Flash-OFDM is used for wireless internet access through a PC with a suitable modem. Flash-OFDM also claims to be efficient than UMTS. The base station, supporting Flash-OFDM is called a Radio Router [15].

The main features of Flash-OFDM are:

1. Optimization for packet-switched data
2. Based on Internet Protocol
3. Provides low latency
4. Supports of user mobility
5. Supports FDD

- **Vector OFDM (VOFDM):** It is an open standard developed by CISCO to offer broadband wireless Internet services. It utilizes the idea of MIMO (Multiple Input Multiple Output) technology. VOFDM uses spatial diversity in wireless system to overcome effects of noise, interference and multipath fading. In VOFDM signal can be transmitted and received with the help of multiple antennas to reduce multipath fading effects. The idea of MIMO-VOFDM [16] is illustrated in fig.4.

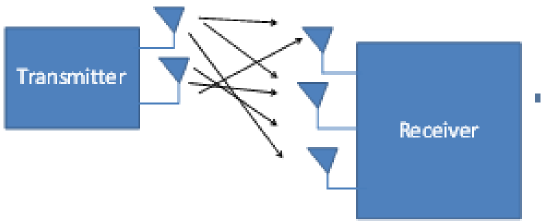

Figure 4. MIMO VOFDM

Merits of VOFDM:

- System's Frame Error Rate (FER) decreases
- No requirement of equalizer
- Removes Narrowband Interference

- **Wideband OFDM (W-OFDM):**

W-OFDM is basically based on IEEE standard 802.11a. It utilizes spreading FEC code to convert signal into DSSS code. W-OFDM has the ability to recover symbols even when few carriers are not present. WOFDM's efficiency and noise tolerance offers both the best of spread spectrum and NB systems. In order to compensate the noise and multipath fading spread spectrum system uses excessive bandwidth whereas, narrowband technology is more affected by multipath propagation.

The main features of WOFDM are:

- By using signal randomizer the need for linear radio frequency power amplifiers is reduced.
- Channel estimation to deal with effects of high PAPR and multipath fading
- Minimizes adjacent network interference by employing low power multipoint RF networks

Besides the limitations of PAPR and carrier frequencies offset and drift due to leakage of the DFT. OFDM offers following merits:

1. Efficient use of the spectrum with the help of overlapping subcarriers.
2. Resistant to frequency selective fading.
3. By adding cyclic prefix it eliminates effects of ISI and ICI
4. Use adaptive equalization techniques with single carrier systems.
5. Use of FFT to employ the modulation and IFFT to employ demodulation functions.
6. Immune from co-channel interference and parasitic noise.

Applications of OFDM:

1. Digital Broadcasting: Digital Broadcasting Audio (DAB) and Digital Broadcasting Video (DVB) standards are based on 16-QAM-OFDM and 64- QAM-OFDM.
2. Wireless networks: QAM-OFDM is used for implementation of many Wireless networks like Wi-Max, Wi-Fi, LTE, wireless ATM transmission, HIPERLAN/2, IOE(Internet of everything) etc.
3. OFDM like signaling in broadband satellite transmission (each signal carry multiple OFDM subcarriers)
4. Power line communication: For high speed data transmission BPL (Broadband over power lines) are used. Same transmission lines are used to transmit data services and electricity with the help of BPL lines.

VII. M-ary QAM

M-ary QAM is an efficient modulation technique which has less probability of ISI as compared to other digital modulation techniques. It is the combination of M-ary PSK and ASK. This modulation technique has the property of reducing system bandwidth requirement by order of N [17].Figure 5 shows a simple block diagram of M-ary QAM transmitter. To generate QAM signal two sinusoids that are 90 degree out of phase with each other are used. These sinusoids are called Quadrature carriers and referred as “I” (In-Phase) and “Q” (Quadrature-Phase) components. The polarity of signal is decided by I-bit and Q-bit at output of level converters and C-bit is used to decide the magnitude of signal.

The I and Q components are represented as:

$$I = A\cos(\phi) \text{ and } Q = A\sin(\phi)$$

The Carrier signal is given as

$$A\cos(2\Pi ft + \phi) = I\cos(2\Pi ft) - Q\sin(2\Pi ft)$$

where f represents carrier frequency.

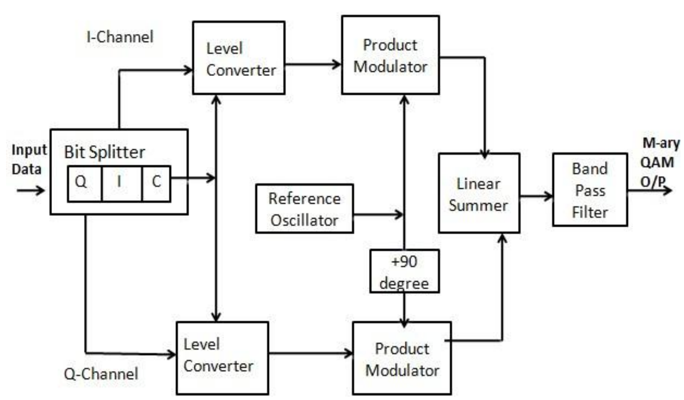

Figure 5. M-ary QAM transmitter

The transmitted signal in QAM is given as:

$$V_{QAM} = \sum_{-\infty}^{\infty}[V_c\,[n].\,h(t-nT_s)\cos(2\Pi ft) - V_s\,[n].\,h_t(t - nT_s)\sin(2\Pi ft)]$$

where $V_C\,[n]$ and $V_s\,[n]$ are the voltages apply to cosine and sine wave n^{th} symbol.

The constellation diagram is useful to be considered in QAM. The constellation points are set in grids with identical horizontal and vertical spacing in QAM. The data used in QAM is basically binary which is arranged in power of 2 in grid points. So, the different M-ary QAM techniques are likely 4-QAM, 8-QAM, 16-QAM, 64-QAM, 128-QAM and so on. Figure 6 shows the constellation diagram of 4-QAM, 16-QAM & 64-QAM [18].

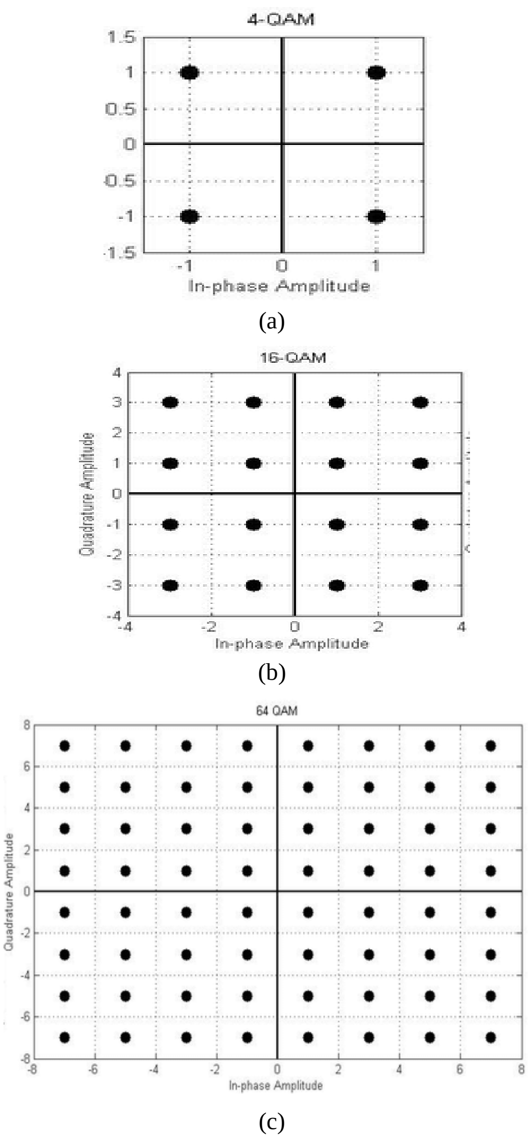

Figure 6. Constellation Diagram (a) 4 QAM (b) 16 QAM (c) 64 QAM

If the points in the constellation diagram are closer to each other, the transmitted signal is more susceptible to noise. Therefore, higher the order of constellation more the number of bits per symbol is transmitted. For higher order M-ary QAM BER decreases with increase in E_b/N_o. The advantages of QAM are efficient use of bandwidth, utilization of amplitude and phase variations. The QAM has several drawbacks such as more susceptibility to noise, power consumption by linear amplifiers for maintaining amplitude component.

Applications of QAM:

1.) In radio communication and data delivery applications

2.) Mostly used in domestic broadcast applications.

3.) Different versions of QAM are employed in wireless and cellular networks.

The QAM is combined with OFDM to complete modulation process. M-ary QAM takes M bit at a time and maps it to form 2^M complex values. The OFDM takes N sub-carriers and transmit them with the help of IFFT. Therefore the QAM-OFDM will optimally enhance data rates, provides better BER performance, mitigate high PAPR effects and compensate non-linearities.

There are some drawbacks of QAM-OFDM versions like depolarization during transmission, dispersion effects in received system, etc. which are considered while designing an optimum network.

VIII. CONCLUSION

This paper presents a detailed study of M-ary QAM and Orthogonal Frequency Division multiplexing technique. The mathematical algorithm (FFT and IFFT) used for implementation of OFDM are described along with the significance of Guard band Insertion. Different variants of OFDM viz OFDMA, COFDM, Flash-OFDM, VOFDM and WOFDM are also discussed. The M-ary QAM technique reduces the system bandwidth requirement. By using these 2 techniques in combination, the system performance can be enhanced in terms of dispersion, interferences, multipath fading, ICI and PAPR. This concept can be useful for researchers to further explore future optical networks.

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