Effect of Modulation Technique in Mach-Zehnder Modulator (MZM) in Optical OFDM system

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***Abstract*— This paper highlights the bit error rate (BER) performance of a radio-over-fiber system utilizing binary phase shift keying (BPSK), M-QAM, QPSK in the external modulator which is the Mach-Zehnder modulator (MZM). The results have been obtained from the RoF link over 8, 30, 60 90 and 120 km distance to study the effect of nonlinear dispersion and attenuation of signal and compare the results other modulation. Furthermore, the chromatic dispersion has no effect on MZM whereas it has distinct effect on OOK modulation scheme without optical dispersion compensation, the performances of different modulation schemes such as OOK, PPM and PAM are analyzed. Comparisons of transmission distance, transmission capacity, bandwidth efficiency in coherent optical orthogonal frequency division multiplexing (CO-OFDM) system are included. Simulation results are given using Matlab, Simulink and Optisystem software. The results also show the importance of upconverter to reduce the nonlinearity effect in the transmission channel.**

Keywords— Optical orthogonal frequency division multiplexing (O-OFDM), MZM, Modulation, Nonlinearity, Radio over fiber Introduction

I. Introduction

At present, there have been intensive studies on optical OFDM (O-OFDM) technologies in optical communication, and it is considered a promising technology for future ultra-high-speed optical transmission [1]. The RoF (Radio over Fiber) systems are compared in a novel way in terms of electrical signal-to-noise ratio (SNR) requirement, spectral efficiency and also signal bandwidth efficiency to the long distance optical fiber network. Optical wireless communication (OWC) has proven to be a capable applicant for medium range, high-speed data transmission with a potential to deliver several hundreds of Mbps data rate [2]. Optical OFDM (O-OFDM) transmission has established to be a strong carrier for high-speed data communication over the dispersive optical channel and it makes the outstanding error free transmission long huge data rate, so it could maximize the capacity of optical fiber transmission systems. In order to evaluate the system performance with different possibilities and performance of the O-OFDM system under the effect of spectra of OFDM subcarrier, requirement of Optical Signal to Noise Ratio (ONSR) [3] and bandwidth efficiency in optical channel, many research has done, which will explain in the next discussion.

In this paper, the effect of modulation technique in optical OFDM system transmitter nonlinearity will be observed and explained. A different modulation scheme that has an important role to reduce nonlinearity to optimize the system performance, which is a Mach - Zehnder modulator (MZM).

This paper is organized as follows: Section 2 presents OFDM and Coherent Optical OFDM, external and internal modulator from optical channel from where nonlinearity starts. Section3 highlights details of the problems of nonlinearity in optical up converter. The modulation technique analysis and its performance in optical channel explain in Section 4 and section 5 presented transmission performance evaluation tools. Finally, the conclusion of the paper is presented in Section 6.

II. Optical OFDM components

a) Optical OFDM

The application of OFDM to optical communications used surprisingly late and relatively compared with RF counterpart. However, the fundamental advantages of OFDM against optical channel dispersion was not recognized in optical communication until 2001, when OFDM to combat model model dispersion in Multimode fiber (MMF). A clear understanding of the unique optical channel or optical system make possible the most efficient design of the CO-OFDM system [4]. Wireless channel is in free space and it does not process any nonlinearity, but on the other hand, optical fiber signal fairly nonlinear. Some types of dispersion, Polarization dispersion and PLD effects make more complex than the wireless channel. OFDM plagued with high PAPR would not fit for the optical fiber with high nonlinearity.

b) Coherent and Direct Detection Optical OFDM design

There are two types of OFDM for long haul application that is needed for dispersion management for optical communication. Direct detection (DD-OFDM) Coherent optical OFDM (CO-OFDM) represents the ultimate performance in receiver performance, spectral efficiency, robustness against dispersion, but it is very complex to design as a whole system. CO-OFDM was 1st proposed by William Shieh and et.al [4] with the concept of multiple-input multiple-output (MIMO) OFDM and experimentally it was 1000 km standard single-mode fiber transmission over 8 GB/s and more than 4100 km SSMF transmission at 20 GB/s by Jansen et.al. Yahama et.al proposed no-guard interval CO-OFDM where in the system optical subcarriers without requiring a cyclic prefix. This system needed linearity in RF-to-optical (RTO) up converter and optical to RF converter. Furthermore, this system has five basic functional blocks such as (1) OFDM transmitter (RF), (2) RF to Optical up converter, (3) Optical channel, (4) Optical to RF down converter and (5) OFDM receiver(RF) [4]. If we consider a linear optical channel where without fiber nonlinearity even though, it is a big challenge to implement to obtain linear up converter and also down converter. Coherent detection uses a six port 90 degrees optical hybrid and a pair of balance photo detectors and the main objective of coherent detection are (1) to recover I and Q component linearly of the incoming signal (2) to suppress the noise. Using six port 90 degree optical hybrids for signal detection and analysis in RF domain. The purpose of the four output ports of the 90 degree optical is to generate phase angle for I and Q components and 180 degree phase shift for balance detection.

In the CO-OFDM systems, N number of OFDM subcarriers are transmitted in each OFDM symbol period of T_s. So the total symbol rate R will be in CO-OFDM systems

$R = N_{sc} / Ts$

The bandwidth of the OFDM system used at all to denote the boundary of each wavelength channel [5]. The OFDM bandwidth, B_{OFDM} is thus given by

$$B_{OFDM} = \frac{2}{T_S} + \frac{N_{SC} - 1}{T_S} \qquad (1)$$

Where the observation period or symbol period is T_s and assuming a large number of subcarriers used, so the bandwidth efficiency of OFDM can be measured

$$\eta = 2\frac{R}{B_{OFDM}} = 2\alpha, \alpha = \frac{t_s}{T_S} \qquad (2)$$

c) External modulator and Direct modulator

In the optical transmission radio over fiber modulation technique can be divided into two important groups that are Direct modulator and external modulator (Mach-Zenhnder Modulator) [6] and direct modulation which is called as intensity modulator. MZM is used to modulate the phase angle of the optical carrier and this modulator preferred due to direct modulation is perfect for low-priced transmitters [7]. Two types of external modulators are commonly used- one is MZM and another is electro absorption modulator (EAM). The MZM planar waveguide structure deposited on the substrate [8]. Let $V_1(t)$ and $V_2(t)$ upper and lower electrode which drives the electrical signal. If output of electrical field $E_{out}(t)$ and related input electrical signal E_{in} then

$$E_{out} = \frac{1}{2}[\exp(j\frac{\pi}{V_\pi}V_1(t)) + \exp(j\frac{\pi}{V_\pi}V_2(t))] \qquad (3)$$

Where is differential drive voltage (V_1-V_2 = V_π) a possible modulation format that we can use in MZM including OOK with a zero / nonzero chirp, binary phase shift keying (BPSK), quaternary phase shift keying (QPSK) and differential QPSK.

d) Optical Amplifier

An optical amplifier is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. There is a general form an OA in Fig.1 and the signal is amplified with pumping inside its architecture. The purpose of OA (optical amplifier) is to restore the signal power level that reduces due to losses during propagation, without any optical to electrical conversion. The main ingredient is the optical gain realized through the amplifier pumping (electrical to optical) to achieve the population inversion. The amplifier factor G is defined in [3] as the ration of amplifier output P_{out} to input P_{in} powers, $G = P_{out}/P_{in}$. Amplifier factor can be determined

$$g(\omega) = \frac{g_0}{1 + (\omega + \omega_0)^{2T_2^2}} \qquad (4)$$

Where g is the gain coefficient, g_0 is the gain pick value, ω_0 is automatic transition frequency, P is the incident signal power and P_s is saturation power. We can define another optical amplifier parameter, the output saturation power, as being the optical power at which the gain G is reduced to $G_0/2$ (3 dB down)

$$P_{out}^{sat} = \frac{G_0 \ln 2}{G_0 - 2} P_S \approx (\ln 2) P_2 \qquad (5)$$

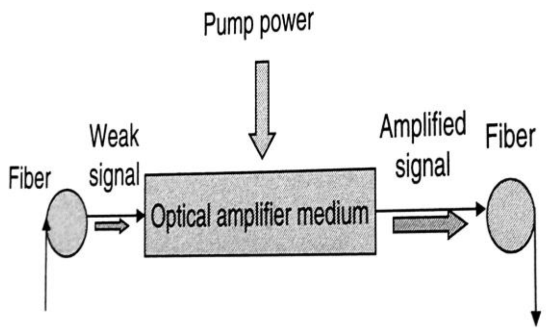

Fig. 1 Optical amplifier principal [2]

Several types of optical amplifier are used such as a Semiconductor optical amplifier (SOA), fiber Raman amplifiers, rare-earth-doped fiber amplifiers (EDFA operates at 1500nm and praseodymium- doped operating at 1300nm).

e) Effect on system of modulation format

Modulation technique is one of the most significant processes for optical communication system. Digital modulation techniques can directly affect to OSNR and improve the system performance [9] We can categorize Radio over fiber modulation method into two groups: direct modulator and external modulator and direct modulator is called intensity modulation and external modulator known as a Mach - Zehnder Modulator (MZM). A. Bahrami et.al investigated in [9] the BER performance of RoF system using BPSK into MZM over various distances, such as 8, 30, 60,90, 120km of a single mode fiber and he compared the performance between external modulation and direct modulation techniques in Fig.2

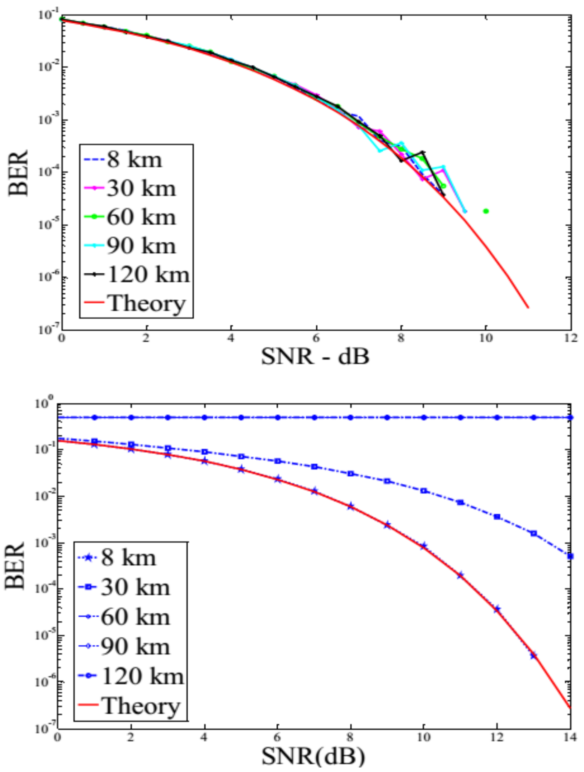

Fig. 2. Above: MZM modulation at carrier frequency of 5 GHz. Bottom: OOK modulation performance [9]

The method of intensity modulation- direct detection (IM-DD) is used for unipolar non-return to zero (NZR) format in order to modulate the laser source. The generated bits are transmitted through a transmitter filter *p(t)* and amplitude pulse response duration T_b.

$$s(t) = A\sum_{-\alpha}^{\alpha} b_i p(t - iT_b) \qquad (6)$$

Where *A* is the amplitude of the signal and T_b is the duration of one bit, when the bit is *'0'* then there is no signal transmitted through the optical channel and when the bit is *'1'* signal is generated. The well define electro-optical characteristic at a minimum exhibit point in MZM system is

$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{\sqrt{\alpha_I}} \sin\left(\frac{u(t)\pi}{2U_\pi}\right) \qquad (7)$$

Where E_{in} is input and E_{out} is output electric field, α_I is insertion loss >=1, *u(t)* is the electric voltage in time *t* and U_π is the hulf wave switching voltage. For different modulation scheme optical channel power can loss that is called modulation excess loss and it can be presented

$$\alpha_E = \frac{P_{in}/\alpha_I}{P_{out}} \qquad (8)$$

To study the effect of MZM nonlinearity on system performance at [6] the optical signal-to-noise ratio (OSNR) required to reach a bit error rate (BER) of 10^{-3} by simulation with linear external modulators. Then the OSNR penalty is defined by

$$\gamma_p = \gamma_r - \gamma_0 \qquad (9)$$

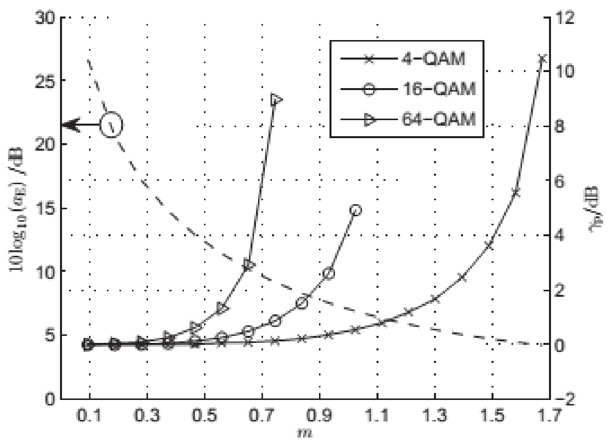

Fig.3 OSNR penalty γ_p due to MZM nonlinearity for different modulation orders (solid lines) and EL_{aE} (dashed line) [6].

In the quasi-linear region OSNR penalty is negligible as the driving signal of the MZM characteristic, but it shows a steep rise when m (modulation order) is further increased. Compared to 4-QAM and more higher modulation orders are obviously more sensitive to nonlinearities: for an allowable OSNR penalty of 2 dB, modulation index (m) must be below 0.6 for 64-QAM and 0.9 for 16-QAM.

In OOK modulation, information bits are converted into some code pulse as Non Return to Zero (NRZ), Return to Zero (RZ) and Manchester. Taissir et.al measured the system performance, which was BER analysis in terms of bandwidth efficiency and power requirements using On-Off keying (OOK), Pulse position Modulation (PPM) and Pulse

Amplitude Modulaton (PAM) in [9]. The error probability of OOK-NRZ in optical data can be expressed as a function of OSNR

$$BER_{NRZ-ook} = \frac{1}{2} erfc(\frac{1}{2\sqrt{2}} \sqrt{SNR} \qquad (10)$$

And the bandwidth requirement for NRZ-OOK is equal to bit rate. i.e. "B_{req} =R_b"[8]. BER for L-PPM can be expressed as

$$BER_{ppm} = \frac{1}{2} erfc(\frac{1}{2\sqrt{2}} \sqrt{SNR \frac{L}{2} \log_2 L} \qquad (11)$$

Where L is the possible position code for optical bits ransmission and the bit rate

$$R_b = B_{req} \frac{\log_2 L}{L} \qquad (12)$$

When the massage information is coded in the amplitude of a series of pulse BER of PAM can be expressed as

$$BER_{PAM} = \frac{1}{2} erfc(\frac{\sqrt{SNR \log_2 M}}{2\sqrt{2(M-1)}} \qquad (13)$$

Where *M* is the possible pulse amplitudes code for each bit of information and bit rate is R_b=$B_{req}\log_2 M$. Here PPM is power efficient because it requires high bandwidth with numbers of data bits in low power requirements. On the other hand, PAM requires increasing in the power to transmit huge numbers of data then bandwidth was decreased.

f) DPD Algorithm to mitigate Nonlinearity

Digital predistortion (DPD) technique can provide flexible, efficient and economical linearize optical modulator. It has been extensively used in wireless OFDM system to recompense the nonlinearities of electrical to power amplifiers [3]. OFDM signal is very sensitive for optical modulator because of its nonlinearities. Yuan Bao et.al [3] proposed pre-distortion algorithm to linearize the optical signal from modulator including electro-absorption modulated lasers (EML) and Mach Zehnder modulators (MZM) [10]. An optical modulator for OFDM transmitter implemented to compensate nonlinearities by high power amplifier in wireless system. However, this DPD algorithm only discusses about the MZM and recently, OFDM based direct modulated passive optical network (LTE, Wimax, UWB) employing a DPD algorithm to linearize the modulator.

A DPD algorithm is used to recompense for the nonlinearity of the EML. Generally, DPD algorithm for the linearization of EML consists of two steps in [11]. Firstly, nonlinear transfer function of EML is estimated by comparing the input and output optical OFDM signal of EML. Then, digital predistortion algorithm, that has the inverse transfer function of the nonlinear transfer. EML, is applied to the input optical OFDM signal.

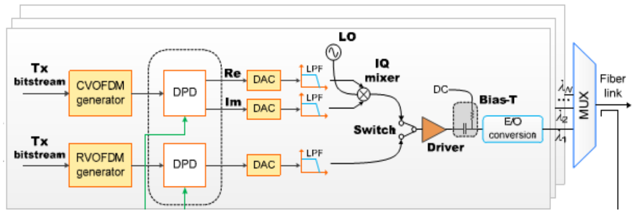

Fig.4 The structure of the O-OFDM transmitter with DPD algorithm [5]

A tunable optical filter (TOF) is employed to select the channel which needs to be monitored if it is a WDM system. The feedback signal will pass through down-conversion circuits if the signal is up-converted. The baseband signal is filtered out by LPFs and then digitized by an analog-to-digital converters (ADCs) [3].

III. Nonlinear effect of Up-converter in O-OFDM system

The nonlinearity is of vital importance characteristic of MZM of CO-OFDM RTO up-converter which has a great effect on the system performance. In the direct up conversion architecture in Fig. 5, the optical transmitter uses an optical I/Q modulator which comprises two MZMs to up convert the real or imaginary parts and in the down-conversion parts [2], the OFDM optical receiver uses two pairs of balanced receivers and an optical 90^0 hybrid to perform the optical I/Q detection

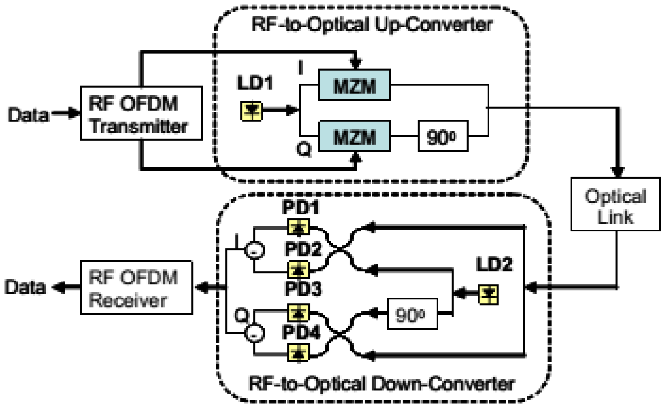

Fig.5 A CO-OFDM system with up and down converter [7].

OFDM requires no interference orthogonality between subcarriers, and it is more sensitive to the frequency and phase noise which may interfere with its orthogonality. Another obstacle is the co-channel interference caused by RF due to two devices simultaneously transmits using the same frequency[12]. Several techniques have been proposed to mitigate the interferences and to observe the improvement in BER performance. Therefore, Mach-Sender modulator has highly nonlinear electrical to optical power transfer characteristics which restricts the OFDM signal to occupy a narrow dynamic range in the most linear region of the power transfer equation.

$$P_0 = P_{in}.k[1+\cos(\pi \frac{V_{RF} - V_{Bias}}{V_\pi})] \qquad (14)$$

Here P_o is the optical power output and is the optical power input. The RoF links normally tolerate from a limited linear dynamic range because of it's nonlinear distortion characterestics of the optical transmitter, either the laser diode or the Mach-Zehnder modulator (MZM).To overcome this limitation sometimes baseband OFDM signal is clipped and clipped peaks are widowed before putting the up-converted OFDM signal on the optical carrier using MZM. Bharath Umasankar et.al did an experiment to identify an adaptive modulation technique to mitigate nonlinear optical noise in optical OFDM systems in [10].

IV. Modulation Technique in O-OFDM

OFDM is used to transmit digital data over a long distance and there are different modulation technique used in the external modulator such as MZM and also internal modulator. Amirtha Vijina.V.J et.al measured the performance between different modulation technique in [13]. QAM is a combination of two amplitude-modulated signals into a single channel consisting of two carriers, each having same frequency but different in phase by 90º. M-QAM where M value 16 and 64 into Mach-Zehnder interferometric modulator in terms of measuring BER performance varying the length of fiber. Nonlinear distortion of OFDM signals caused by Mach-Zehnder electro optical modulator in the stage of radio over fiber transmission investigated by Peter Horvath et.al [10]

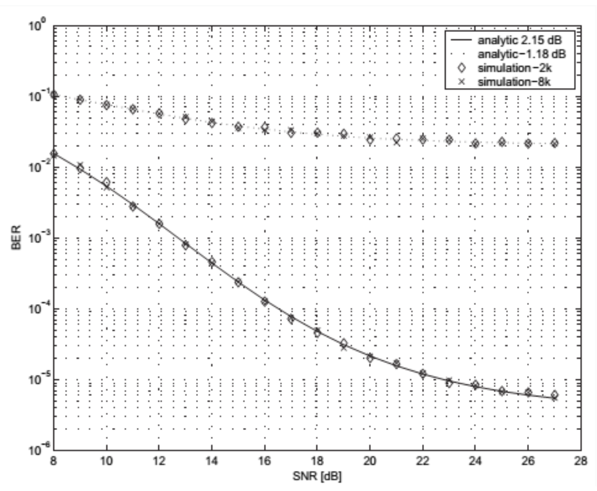

Fig.6 BER vs. SNR with QPSK modulation, 2048 and 8192 subcarriers with back-off 2.15 dB and -1.18 dB, respectively [12]

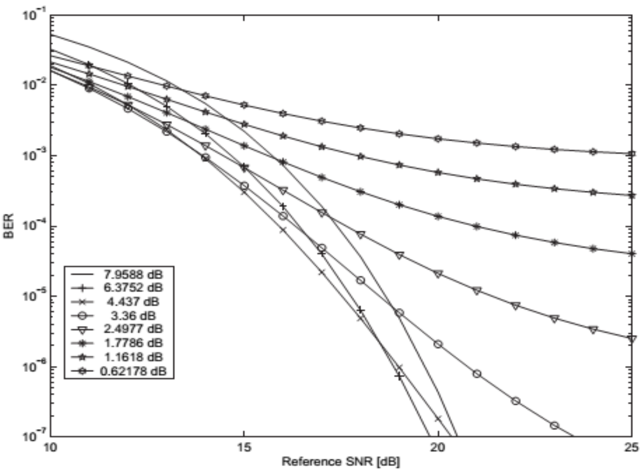

Fig.7 BER vs. SNR with QPSK modulation, parameter back up value.[10]

BER versus SNR values are shown in Figure 6, for two fixed back-off values and two different numbers of subcarriers. The agreement between simulation and analysis is more efficient. In addition, Fig.7 represents same curve using QPSK modulation in different back off values. Using On-Off Keying (OOK) and BPSK modulation, A.Bahrami et.al investigated external modulator as MZM's performance over the distance 8, 30, 60,90 and 120km of a single mode fiber (SMF) [7]. MZM modulates the phase of optical signals from an electrical signal. In fig.8, two electrical inputs xi (t) and xq(t) enters from the bottom of the device and optical carrier X_{LD} (t) and output signal E_R on right side.

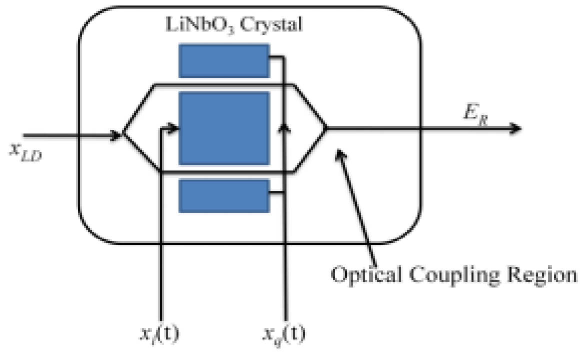

Fig.8 Mach Zehnder modulators[7]

The OOK modulation technique is subjected several dispersion of the optical carrier. From Fig.9, OOK modulation method has effect tremendously and especially at different distances.

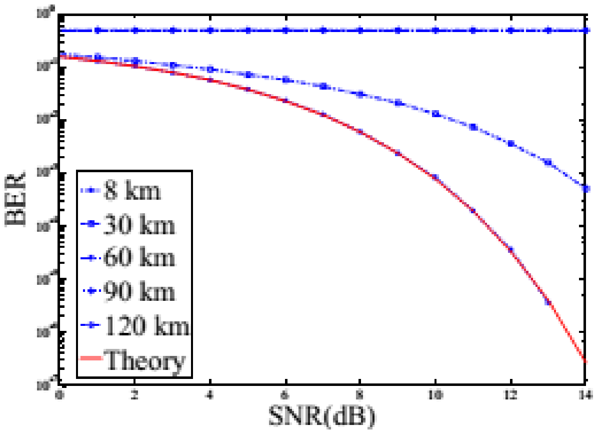

Fig.9 OOK Modulation in different distance[7]

Zhiyong Wang et.al analyzed the relationship between BER and OSNR in different modulation modes is shown in Fig.10. The conditions of the simulation are: the transmission rate is 10Gb/s, optical carrier is λ=1550nm, total subcarrier N= 128 and CP =N/8. Increase the OSNR to 10dB, the BER of the system will be 10^{-6}. In 4QAM, when the OSNR is 9dB, the BER of the system is 10^{-3}, and the OSNR is increased to 13dB, then the BER of the system is only 10^{-5}. In 8QAM, when the OSNR is increased from 10dB to 15dB, the BER of the system can be decreased from 10^{-2} to 10^{-4}. In 16QAM, the BER of the system is only 10^{-3} when the OSNR is increased to 15dB. OSNR is required in order to maintain the BER less than 10^{-3}, but due to the higher power launching into the fiber, the nonlinear effect of the fiber is increased, this makes the performance of the system worse.

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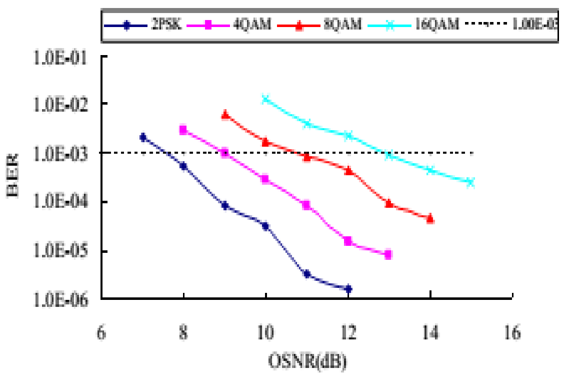

Fig.10 the simulation curves between BER and OSNR at several modulation schemes [7]

V. Performance Parameters in O-OFDM

The transmission quality of an optical channel can be estimated by using different tools such as SNR, Optical SNR (OSNR), Q-factor, eye opening penalty and BER. The OSNR defined as the ratio between the signal power and noise power. In optical systems, amplifier process ASE noise that accumulates along the transmission line and degrades the OSNR. Therefore, the OSNR can be defined as the received optical power and accumulated noise power. It is very common in optical communication to use the Q-factor [20] as a figure of merit instead of SNR. It is defined as

$$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0} \qquad (15)$$

Where I1 and I0 represents the average photo currents corresponding to one and zero and σ_1 and σ_0 are define standard deviations [2]. The total variance in the photocurrents

$$\sigma_{10}^2 = i_{sn10}^2 + i_{thermal10}^2 \qquad (16)$$

Where (i_{sn10}^2) is the variance corresponding to the short noise and $(i_{thermal10}^2)$ is the corresponding to the thermal noise. BER is the most important measuring tool in digital communication for quality assessment. The BER can be defined as

$$BER = P_r(0/1)P_r(1) + P_r(1/0)P_r(0) \qquad (17)$$

Where Pr(0|1) is the conditional probability of symbol 1 and Pr(1|0) is the conditional probability of symbol 0 [2]. As we know the complementary error function

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{-\alpha}^{+\alpha} e^{-x^2} dz \qquad (18)$$

So the obtain relation is

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \qquad (19)$$

Another important parameter is receiver sensitivity, it is defined as the minimum average received optical power

$P_R = (P_0+P_1)/2$, where P_i is average power required to operate at given BER. Each impairment causes the receiver sensitivity degradation, which is evaluated by power penalty.

VI. Conclusion

The objective of this study is to examine the role of the modulation scheme on system performance of coherent optical OFDM system and nonlinearity compensation technique for optical modulator using different modulation scheme and DPD algorithm [6]. The results illustrate that the performance of the system is degraded severely when the dispersion effect is taken into consideration in OOK cases over the selected fiber range. However, dispersion has almost no effect on MZM technique which provides OSSB modulation and is immune to chromatic dispersion over different fiber length.

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