Integration of Coherent Optical OFDM with WDM

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ABSTRACT

This paper proposes a system design that integrates CO-OFDM with WDM to reach a data rate of 400 Gbits/s over 1000 Km Single Mode Fiber (SMF). The 400 Gbits/s signal is generated by multiplexing eight OFDM with 50 Gbits/s for each OFDM. We present the performance of CO- OFDM WDM back to back design by measuring the BER and the OSNR (Optical Signal to Noise Ratio) and the constellation diagram of each user. We will also show the performance of CO-OFDM WDM for 1000 Km SMF by measuring the BER and the OSNR of different WDM channels and studying the constellation diagram of each user.

Keywords: OFDM, CO-OFDM, WDM, OSNR, BER, IFFT, QAM, DCF.

1. INTRODUCTION

The need for high data rates has led the increased interest in Orthogonal Frequency Division Multiplexing (OFDM) in optical communication [1]. OFDM is intended to be used as the modulation technique in the next generation broadband wireless networks because it supports increased robustness with respect to narrowband interference and frequency selective fading [2]. Also, OFDM has the ability to deal with the delay spread of the multi-path. The principle of operation of OFDM is that it divides high data rate streams into lower data rate streams. Then, the entire low data rate stream is transmitted at the same time over a number of sub-carriers. Because of this the duration of symbol is increased [2]. Therefore, the amount of dispersion generated from delay spread of the multi-path will be reduced significantly.

As mentioned before, OFDM uses a number of subcarriers to send parallel low data rate streams. The sub-carriers of the OFDM can be modulated by using different types of modulation, such as Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK) [3]. After that, the subcarriers are carried over a high frequency carrier (e.g. 7.5 GHz). The Fast Fourier Transform (FFT) and the Inverse Fast Fourier Transform (IFFT) are very effective algorithms that can be use in the OFDM transceivers. These effective algorithms prove that OFDM has higher scalability above the data rate and the channel dispersion [3].

In optical fiber communication systems, OFDM has received great attention as an effective modulation technique to overcome different restrictions in the optical fiber transmission systems, such as relative intensity noise, modal dispersion, , chromatic dispersion (CD), polarization mode dispersion (PMD) [4].Coherent optical OFDM (CO-OFDM) has emerged as an efficient technique for high data rates beyond 100 Gbps. CO-OFDM integrate the advantages of OFDM modulation technique and coherent detection technique and have many benefits that are crucial for the future of high-speed fiber optic transmission systems [4].

One of the main advantages of using CO-OFDM in the optical fiber communication system is its ability to reduce the effect of the chromatic dispersion (CD) and the polarization mode dispersion (PMD) [5]. Also, it can give high spectral efficiency because the OFDM subcarriers spectra are incompletely overlapped. Moreover, the electrical bandwidth of the CO-OFDM transceiver can be considerably reduced by using direct up/down conversion. These features are greatly appealing for designing high-speed circuits. CO-OFDM is a technology that has a great potential for getting high speed data rates in today’s transmission systems [5].

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Theoretical principles for OFDM:

The OFDM modulation technique is used in this design to modulate the electrical signal. A multi carrier modulation (MCM) signal at transmitter side can be described as follow [5][6]:

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

$$s_k(t) = \Pi(t) e^{2\pi j f_k t} \tag{1.2}$$

$$\Pi(t) = \begin{Bmatrix} 1, 0 < t \le T_s \\ 0, otherwise \end{Bmatrix} \tag{1.3}$$

The subcarrier is denoted by s_k and c_k represents the information of kth subcarriers. N stands for the subcarriers number. The subcarrier frequency is represented by f_k . The symbol period is dented by T_s and $\Pi(t)$ represents the function of the pulse shaping. The mth sample of $s(t)$with sampling period of T_s/N can be described as [5][6]:

$$s_m = \sum_{k=1}^{N} c_k \cdot e^{j2\pi f_k (m-1) T_s/N} \tag{1.4}$$

In the OFDM system, a number of subcarriers frequencies are selected, where all subcarriers are orthogonal to each other. To maintain the orthogonality in the OFDM subcarriers, the following equation should be satisfied [6]:

$$f_k = \frac{(k-1)}{T_s} \tag{1.5}$$

By substituting the value of f_k in Eq.1.4, we get the following equation [6]:

$$s_m = \sum_{k=1}^{N} c_k \cdot e^{j2\pi (m-1)(k-1)/N} \tag{1.6}$$

It is noticed that s_k is the Inverse Fourier Transform (IFT) of the input signal c_k. The recovered signal $\hat{c}k$ can be defined as the Fourier transform of $\hat{s}k$, which is the received signal [6].

$$\hat{c}_k = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} \widehat{s_m} \cdot e^{-j2\pi (m-1)(k-1)/N} \tag{1.7}$$

It is clear that from Eq.1.6 the OFDM signal is consisting of a summation of many subcarriers. Subsequently, OFDM signal will have high peak to average power ratio (PAPR) compared to single carrier (SC) signals [6].

$$PAPR = \frac{max\{|s(t)|^2\}}{E\{|s(t)|^2\}}, t \in [0, T_s] \tag{1.8}$$

2. SYSTEM DESIGN

This paper concentrates on the integration between CO-OFDM and WDM to reach high data rates (400 Gbps). Figure 1 shows the conceptual system design of the system. The design consists of three main parts: CO-OFDM transmitter, optical fiber link, and CO-OFDM receiver. Wavelength Division Multiplexing (WDM) is used to support the high data rate with eight channels spaced at 50 GHz to support eight OFDM signals each with 50 Gbps to reach 400 Gbps data rate.

OptiSystem V.11 simulation tool is used to fully design, implement, and study the system. Some important parameters are shown in Table 1, which must be taken into consideration to make the system work properly and to get the right results [7].

Table 1: Simulation Global Parameters

Global Parameters	
Sequence length	**16384 Bits**
Samples per bit	**8**
Number of samples	**131072**

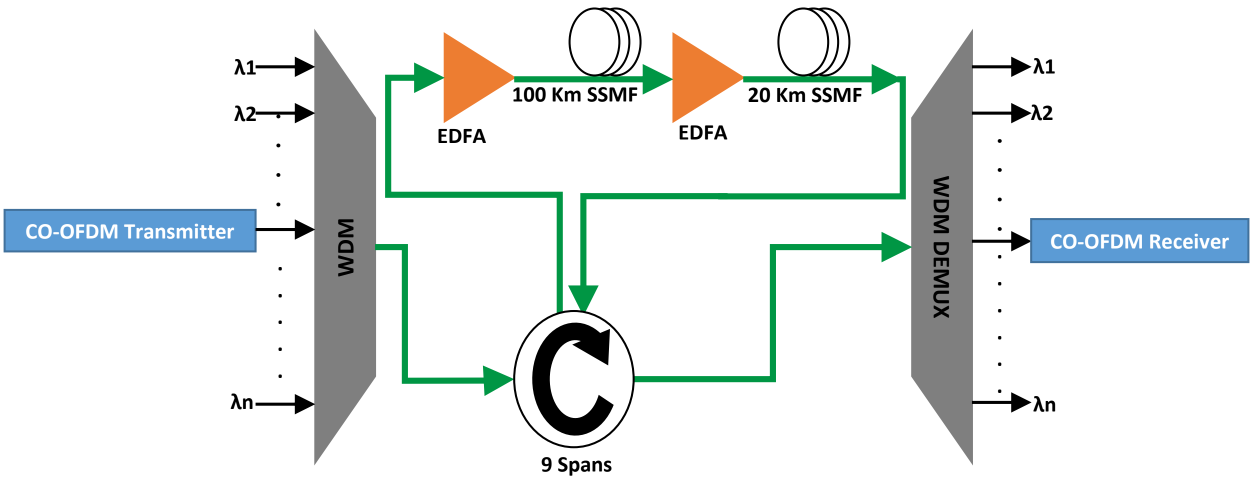

Figure 1: the conceptual system design of the system

2.1. CO-OFDM Transmitter

Figure 2 shows the design of CO-OFDM transmitter; the input signal is connected to a 4-QAM sequence generator and modulated by the OFDM modulator. The OFDM subcarrier is 512, the number of FFT points is 1024 and the guard interval is 1/8. The resulting signal from the OFDM modulator is transmitted to direct I/Q optical modulator, which consist of an optical power splitter, two Mach-Zehnder Modulators (MZMs) and a power combiner [8-10]. The laser source is connected to the power splitter and the output signals are fed to the two MZMs which are driven by the components of the OFDM. The resulting signals from the two MZMs are combined to be transmitted to the optical fiber link [11-12].

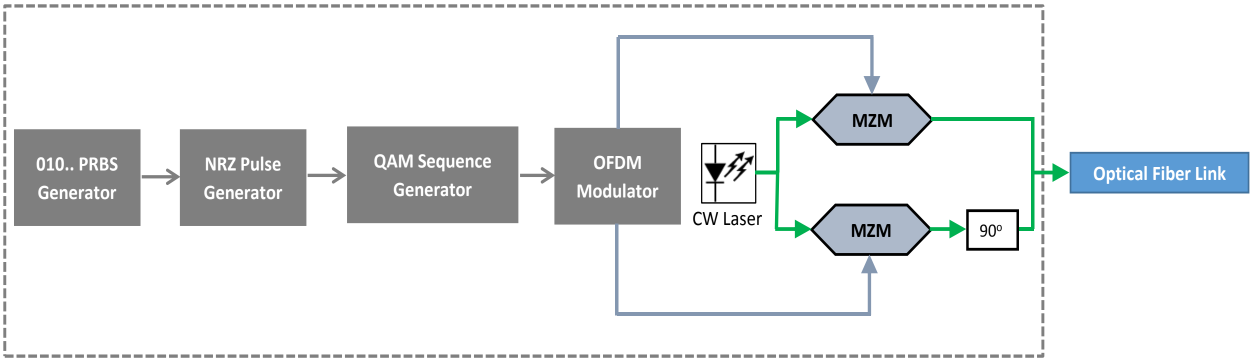

Figure 2: CO-COFDM transmitter.

2.2. Optical Fiber Link

Before the optical fiber, the eight OFDM signals are multiplexed using eight channels WDM and then launched to the optical fiber link. A multi-span optical fiber is used, which consist of 9-spans of 100 Km Single Mode Fiber (SMF), the SMF parameters are shown in Table 1. The dispersion of the fiber is compensated using DCF (Dispersion Compensation Fiber) of 20 Km in each span; Compensation parameters are shown in Table 2 [13] [14]. Two EDFAs are used in the fiber link to compensate the loss.

Table 2: SSMF Parameters

SSMF	
Dispersion	16 ps/nm/km
Dispersion Slope	0.08 ps/nm^2/km
PMD Coefficient	0.2 ps/km
Effective area	80 um^2
Nonlinearity Coefficient	2.6×10-20
Attenuation	0.2 dB/km

Table 3: Compensation Parameters

DCF	
Dispersion	-80 ps/nm/km
Dispersion Slope	-0.45 ps/nm^2/km
PMD Coefficient	0.2 ps/km
Effective area	30 um^2
Nonlinearity Coefficient	2.6×10-20
Attenuation	0.4 dB/km

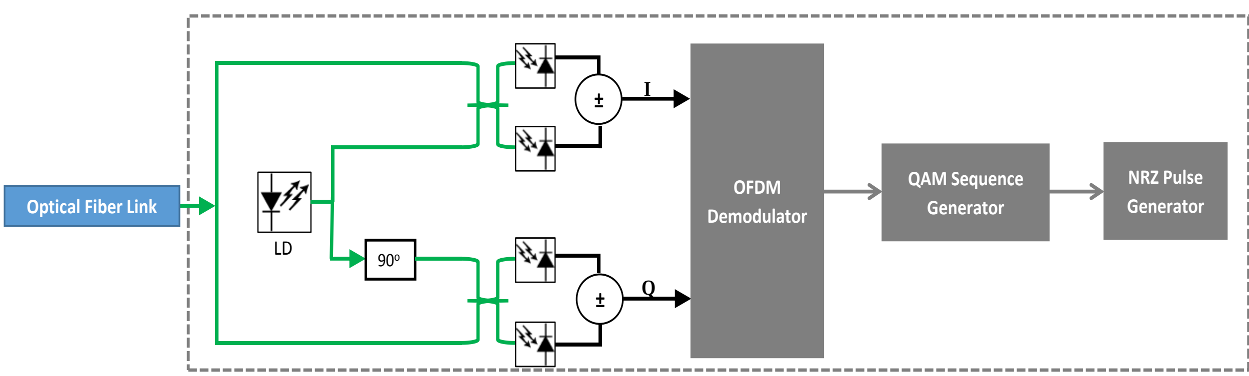

Figure 3: CO-OFDM Receiver.

2.3. CO-OFDM Receiver

Figure 3 shows the design of the CO-OFDM receiver which consists of four balanced PIN photodetectors and a local laser with a wavelength equal to the center of each band. Noise cancellation is performed by using the balanced detectors [15]. The output signal from the optical fiber link is received by the four balanced receivers to perform I/Q optical to electrical detection. The resulting signal is transmitted to OFDM demodulator to be demodulated and to remove the guard interval. After that, the resulting signal is transmitted to the by 4-QAM sequence generator [15][16].

3. RESULTS and DISCUSSION

The undistorted RF spectrum of CO-OFDM transmitter is shown in Figure 4. The power of RF is measured at -12 dBm. Figure 5 shows the RF spectrum of CO-OFDM receiver; the signal is spread over 1000 km SMF. The power of RF is decreased to -34 dBm, this degrades in the power occurred because of the attenuation increase due to the high increase of the fiber length. Figure 6 shows the eight OFDM spectrums after the WDM system. Eight WDM channels start at 193.05 THz up to 193.4 THz with channel space of 50 GHz.

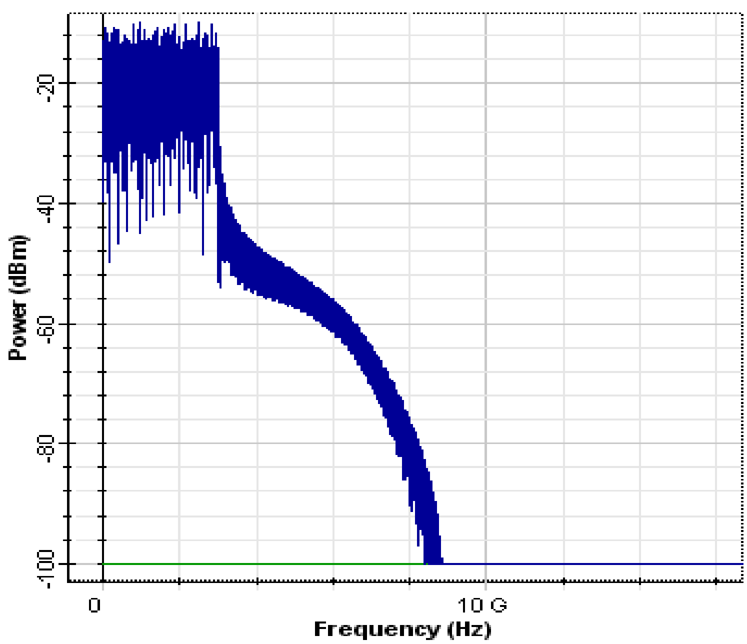

Figure 4: RF spectrum for CO-OFDM at the transmitter.

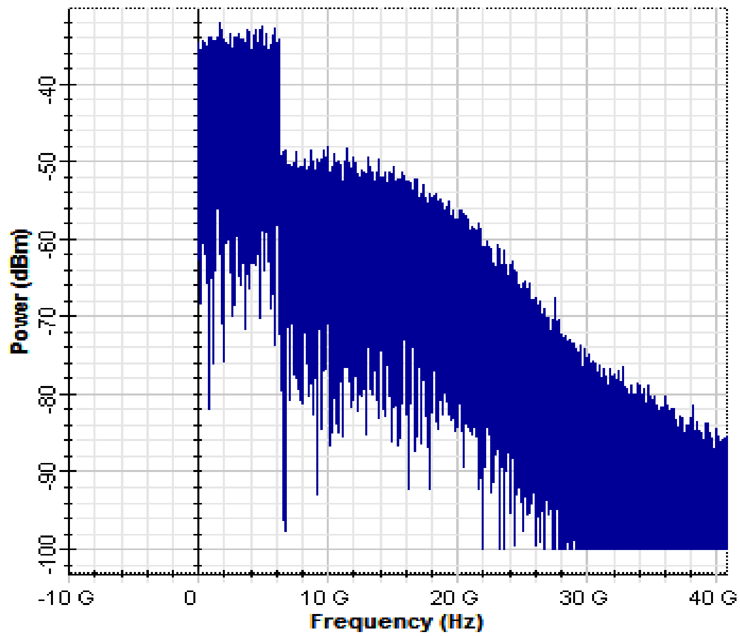

Figure 5: RF spectrum for CO-OFDM at the receiver.

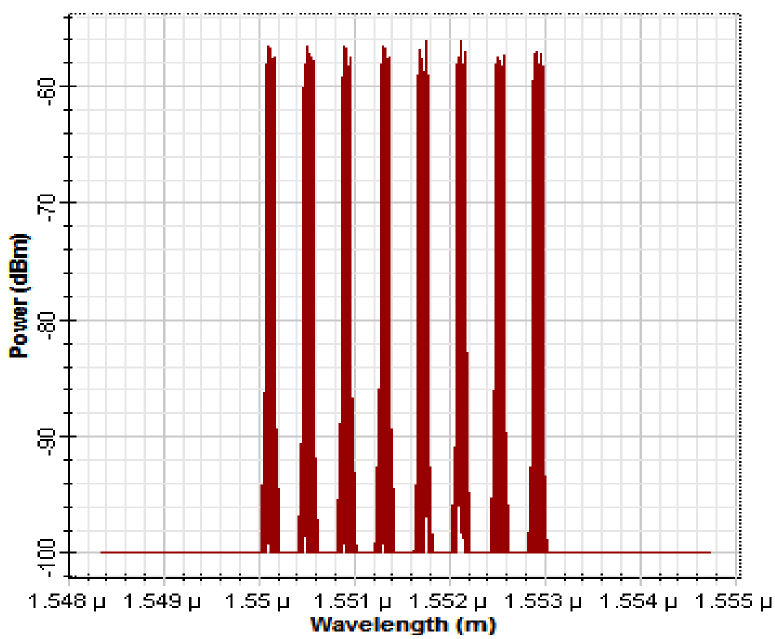

Figure 6: the spectrum of the 8 CO-OFDM signals after the WDM multiplexer.

The constellation diagram demonstrates a signal that is digitally modulated and displays it as a two-dimensional scatter diagram. The measurements of the constellation diagrams determine the effect of distortion and interference in a signal. In Figure 7, the transmitted signal is clearly shown by the electrical constellation diagram for 4-QAM digital modulator at the CO-OFDM transmitter.

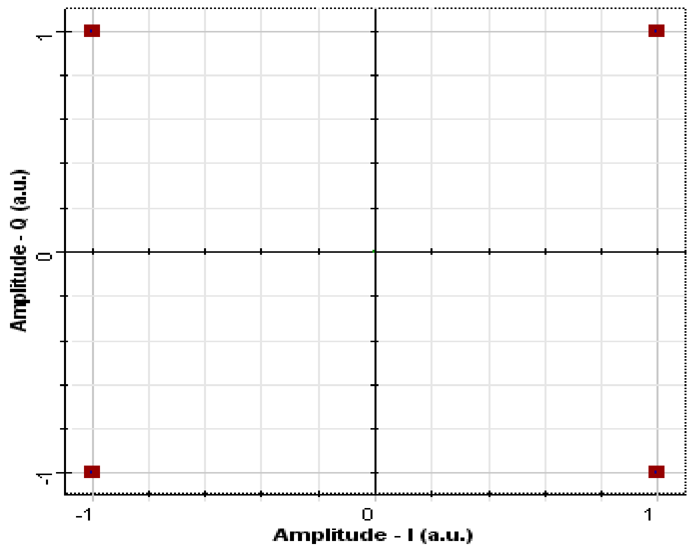

Figure 7: the constellation diagram at CO-OFDM transmitter

Figure 8 shows the constellation diagram of the back-to-back CO-OFDM system with no fiber in use; as can be seen from the figure the signal is delivered successfully. Figure 9 shows the constellation diagram of the system after 1000 Km SMF, as can be seen from the figure the signal is distorted when compared to Figure 8 B2B constellation diagram; this distortion of the signal occurred because of the chromatic dispersion and the nonlinear effects due to the increase of the data rate and the transmission distance. To overcome this problem Dispersion Compensation Fiber is used; Figure 10 show the constellation diagram of the system at the transmitter side after using the DCF to compensate the fiber dispersion.

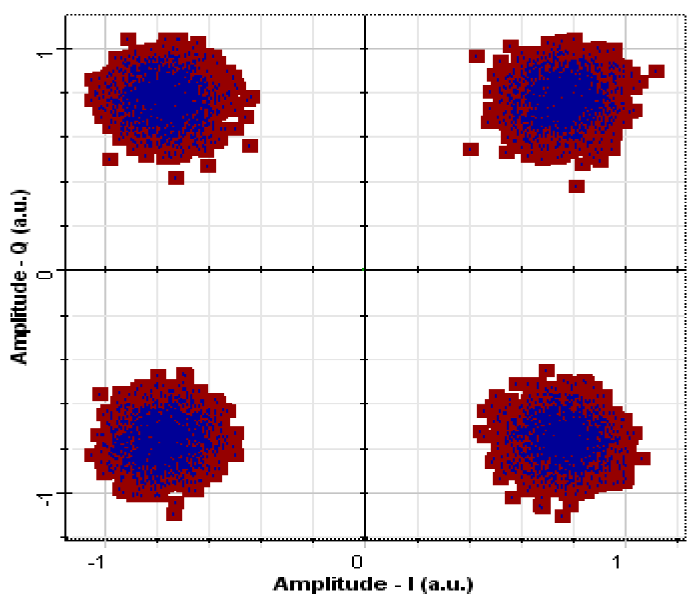

Figure 8: the constellation diagram of B2B CO-OFDM at receiver

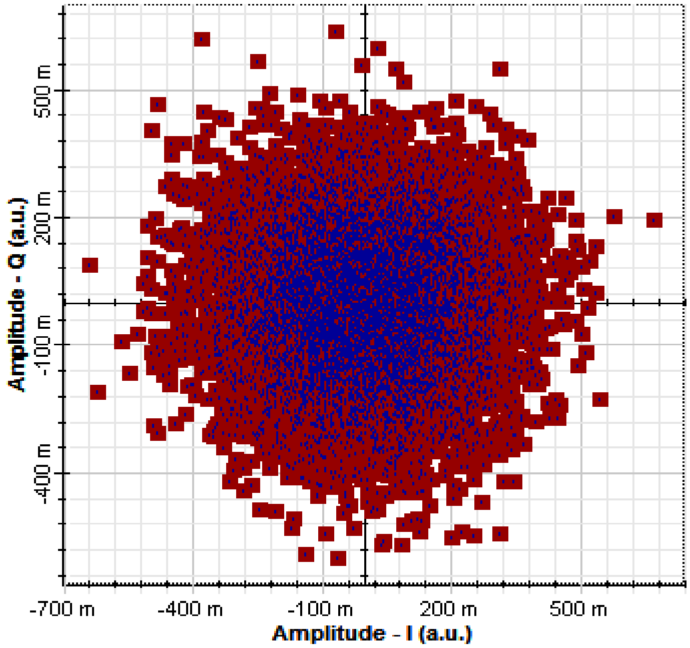

Figure 9: the constellation diagram of CO-OFDM at receiver after 1000 Km and before using DCF.

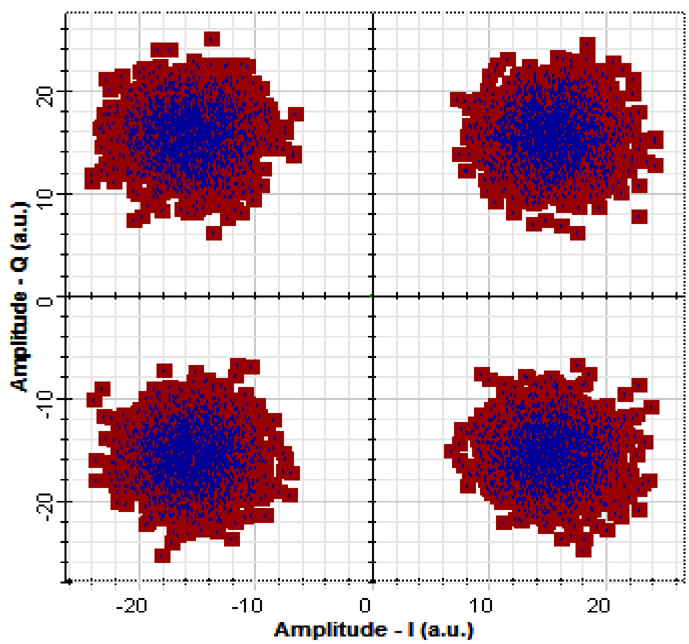

Figure 10: The constellation diagram of CO-OFDM at receiver after using DCF.

The high data rate long-haul system performance is studied by observing and analyzing the relationship of Bit Error Rate (BER) and transmission distance. Also, by studying the effect of the Optical signal to Noise Ratio (OSNR) on the system performance and the BER. Figure 11 displays the effect of the transmission distance on the BER. As can be seen in Figure 11, as the transmission distance increases the BER increases due to the increase of the fiber dispersion which will produce Intersymbol Interference that will affect the transmission of the signal.

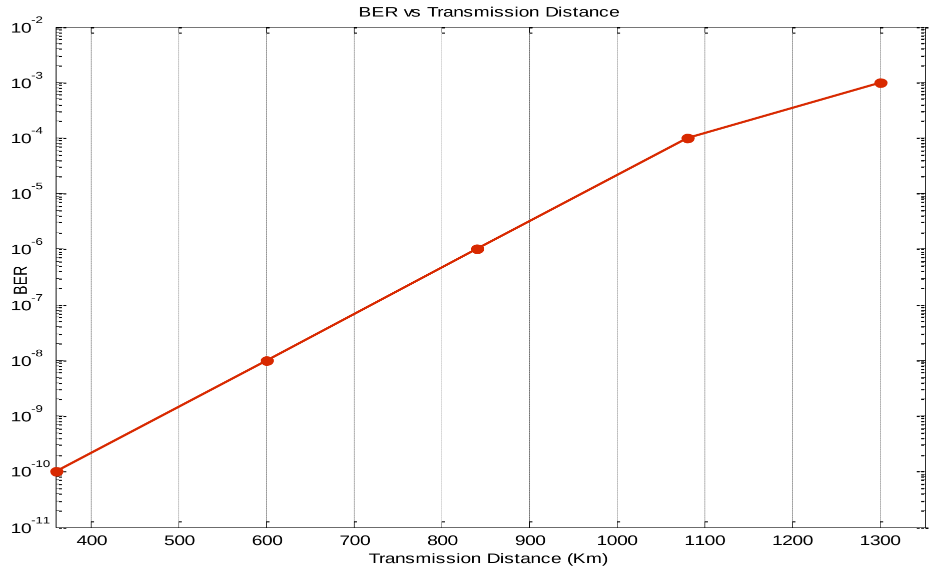

Figure 11: the relationship of BER and transmission distance

Figure 12 displays the effect of the OSNR on the BER of the system for the targeted transmission distance which is 1080 Km. As can be seen from Figure 12, increasing the OSNR will maintain BER less than 10^{-3}, however, increasing the OSNR should be limited because high OSNR will increase the nonlinear impairments on the system which will eventually affect the transmission of the signal and make it difficult to recover the original signal.

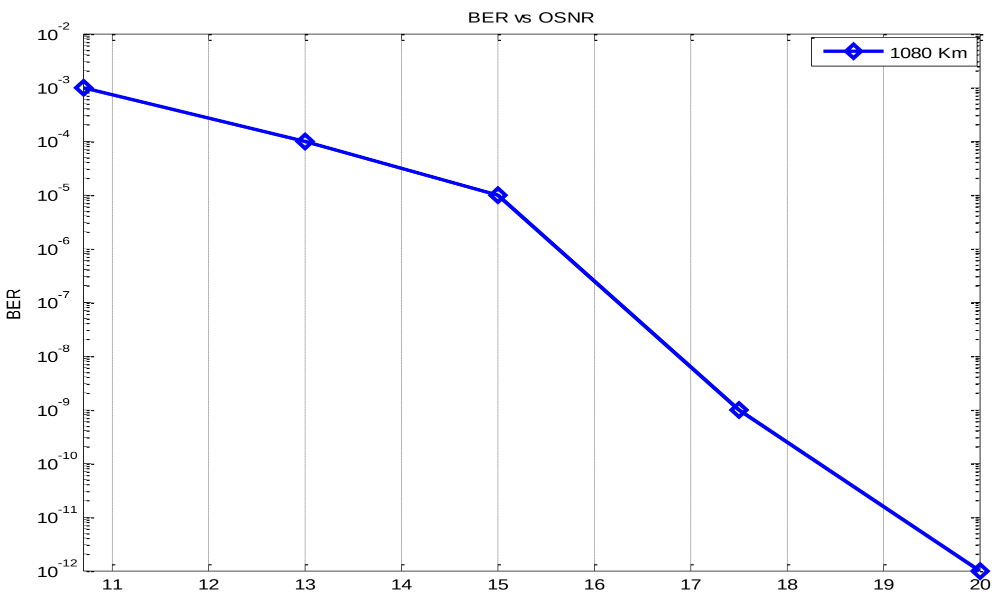

Figure 12: The relationship of BER and OSNR for 1080 Km

4. CONCLUSION

In this paper, the integration of the Coherent Optical OFDM with WDM has been studied and analyzed. The use of WDM helped to increase the capacity of the system and to reach a high data rate of 400 Gbits/s. The system was designed by eight channels spaced at 50 GHz to support eight OFDM signals each with 50 Gbps to reach 400 Gbps data rate. The proposed system gives clear results and the results proved that the system is reliable. The resulting data proved the effectiveness of the CO-OFDM-WDM system which can provide significantly high data rates. The results show that when increasing the fiber length the BER will increase and larger OSNR is required to keep the BER less than 10^{-3}. In the future study of the system, different modulation techniques, such as 16-QAM, and 64 QAM will be used to enhance system performance.

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