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# Performance Analysis of Post Compensated Long Haul High Speed Coherent Optical OFDM System

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**ABSTRACT**

This paper addresses the performance analysis of OFDM transmission system based on coherent detection over high speed long haul optical links with high spectral efficiency modulation formats such as Quadrature Amplitude Modulation (QAM) as a mapping method prior to the OFDM multicarrier representation. Post compensation is used to compensate for phase noise effects. Coherent detection for signal transmitted at bit rate of 40 Gbps is successfully achieved up to distance of 3200km. Performance is analyzed in terms of Symbol Error Rate and Error Vector Magnitude by varying Optical Signal to Noise Ratio (OSNR) and varying the length of the fiber i.e transmission distance. Transmission performance is also observed through constellation diagrams at different transmission distances and different OSNRs.



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## 1. INTRODUCTION

As the daily need with respect to internet usage is growing at an astonishing rate owing to the increase in multimedia applications, it has become necessary to provide high data rates so as to run these applications effectively. Due to the enormous capacity provided by optical fiber communication systems, they have become the inseparable part of the modern day communications. More and More investigations are being carried out to fully exploit the huge bandwidth provided by optical fibers. Hence the current focus is on high throughput data transmission over long distance communication [1]. Several channel impairments such as inter and intra channel non linearities affect the system performance at these high speeds. This is the reason that novel advanced techniques in modulation and multiplexing, coding, signal processing etc are being explored by the scientists to provide high speed and long haul communication system. OFDM is a multi carrier modulation format in which the data is carried over a number of subcarriers. Hence a high data rate stream is converted into many low data rate streams which are transmitted in parallel. The individual carriers have narrow bandwidth whereas the composite signal has a wide bandwidth. OFDM has been rapidly deployed in RF-wireless systems as can be observed in various examples such as cell-networks and digital-audio and digital-video broadcasting. This large scale deployment of OFDM in RF wireless systems owes to its advantages that it is resilient to multipath propagation and phase distortion [2]. Similarly the advanced optical systems are required to implement the best combination of modulation and multiplexing technique to satisfy the ever increasing demand of bandwidth. Hence Optical OFDM is becoming the choice of researchers as a promising solution for high speed long haul communication. Optical OFDM receiver can be implemented using two configurations: Direct Detection and Coherent Detection. Coherent Receiver has number of advantages over direct detection. As the entire optical field is mapped into digital domain, therefore in addition to amplitude, the phase and the state of polarization of the signal is also detected. Due to this chromatic dispersion and PMD can be digitally compensated by inverting the linear optic channel. Advanced spectrally efficient modulation formats can be decoded efficiently using coherent reception. Further due to high power Local Oscillator, weak signal gets amplified resulting in improved receiver sensitivity. On the other hand coherent optical/electrical OFDM leads to addition of a phase chirp across the frame due to fiber dispersive effects. Hence Equalizing algorithms are required to remove this. Whereas Equalizer is not required in direct detection as the output is directly proportional to the absolute square of the field envelope [3].

CO-OFDM combines the advantages of 'coherent detection' and 'OFDM modulation' and posses many merits that are critical for future high-speed fiber transmission systems such as efficient estimation of chromatic dispersion and Polarization mode dispersion,high optical spectral efficiency,reduced electrical bandwidth requirement, signal processing in the form of Fast Fourier Transform (FFT)/Inverse Fast Fourier Transform (IFFT) [4]. Hence it can be concluded that the combination of coherent detection, DSP and spectrally efficient modulation format results in a system which fully utilizes the advantages of three approaches. In this paper all these three approaches are combined to transmit signal at data rate of 40 Gb/s using 4QAM as modulation format.

## 2. SIMULATION SET UP DETAILS

The complete simulation set up consists of Transmitter ,Channel and Receiver. Transmitter consists of PRBS Generator, OFDM coder, Dual Mach Zehnder IQ modulator. Data rate is 40Gbps. The top level block diagram of Optical OFDM system is as shown in the Figure 1. Serial data is converted into parallel form in the first stage of OFDM coder.QAM modulation is used as a mapping technique. QAM is a combination of Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK). QAM is preferred modulation format because of the greater distances between the adjacent points in IQ plane with the disadvantage that for QAM both amplitude and phase need to be detected. Different forms of QAM are 4 QAM,16 QAM, 64 QAM ………. And so on. As the order of QAM increases, the data points come closer to each other hence making them more vulnerable to noise. However using higher order QAM leads to increased spectral efficiency because more data transmission takes place in small bandwidth with a cost to pay that bit error rate will increase as the order of QAM increases if the signal transmission power remains same [5]. The system is investigated for 4QAM and 16QAM. 128 subcariers are used. Pilot carriers are also sent along with the transmitted data which aids in channel estmation. Channel estimation technique is used to estimate the response of channel to different conditions and different parameters [6]. Cyclic Prefix of value one eighth the symbol duration is added to avoid intercarrier interference. Transmitter Laser Linewidth and Local laser linewidth is chosen to be 10 kHz.

The first step inside the OFDM transmitter is the mapping of the input data bits onto the corresponding information symbols of the subcarriers within one OFDM symbol. After that Inverse Fast Fourier Transform (IFFT) is used to get the digital time domain signal s(t) [7].

$$s(t) = \sum_{-\infty}^{\infty} \sum_{k=1}^{k=N_{SC}} C_{ik}\, \pi(t - iT_s)\exp(j2\pi f_k(t - iT_s)$$

$$f_k = \frac{k-1}{t_s}$$

$$\pi(t) = \begin{cases} 1, (\Delta_G < t \le t_s \\ 0, (t \le -\Delta_G, t > t_s \end{cases}$$

where $C_{ik}$ is the $i^{th}$ information symbol at the $k^{th}$ subcarrier, $f_k$ is the frequency of the subcarrier, $N_{sc}$ is the number of OFDM subcarriers, $T_s$, $\Delta_G$, and $t_s$ are the OFDM symbol, period, guard interval length and observation period respectively. The base band OFDM signal s(t) is generated as:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-N_{sc}/_2+1}^{k=\frac{N_{SC}}{2}} C_{ik}\pi(t - iT_s)\exp(j2\pi f_k(t - iT_s)$$

The coded data modulates the optical signal through dual arm Mach Zehnder Modulator. The advantage of using Mach Zehnder external modulators is their smaller chirp, hence resulting in a narrower signal spectrum and resulting in a larger tolerance to uncompensated chromatic dispersion. But it has a disadvantage that it is the main source of non linearity also [8]. The modulated signal is passed through single mode fiber having attenuation of 0.2 dB/km and dispersion of 16 ps/nm/km. Erbium- doped fibre amplifiers (EDFAs) are used at regular intervals to amplify the optical signal propagating through a single mode fiber (SMF). A loop of length 200 km is taken. The loop consists of SMF, dispersion compensating fiber (DCF) and EDFA.At the receiver side all reverse operations are carried out. The steps involved are coherent heterodyne detection, serial to parallel conversion, FFT operation, cyclic prefix removal, channel estimation, equalization and finally parallel to serial conversion.Coherent heterodyne detection is used. Two identical optical coherent balanced detectors are used to detect the CO-OOFDM signal. They perform optical-to-electrical OFDM I/Q conversion. I/Q components of a locally generated carrier are mixed with the optical signal to obtain the electrical I/Q components. Each coherent detector consists of a pair of couplers and PIN detectors Coherent detection suffers from phase noise effects and Local Oscillator (LO) offset effects. RF-pilot tone based compensation is used to counteract these effects. For the correct demodulation of subcarriers at the receiever, perfect synchronization at the receiver is required so that the correct time of start and end of symbol duration can be determined.Synchronization is realized by inserting known OFDM symbols at regular intervals. These training symbols can find correlation between subsequent symbols. The training symbols are also used for channel equalization, which compensates for timing offset and the distortions of the transmission path (e.g. chromatic dispersion). The coefficients of the channel estimator are found by comparing the sent training symbol with the original symbol [9]. Let βm is the phase angle of transmitted pilot subcarrier and βm' be the phase angle of the received information symbol, Estimated phase drift is given by:

$$\theta = \frac{1}{N_{SC}} \sum_{n=1}^{N_{SC}} [\beta m - \beta m']$$

After estimating the phase drift the received information symbols are multiplied by exp (-j $\theta$).This multiplication removes the laser phase noise effect. After phase noise compensation, the Fast Fourier Transform (FFT) is taken to convert the signal back into the frequency domain. Finally, the symbols are demapped and converted from parallel to serial so that the further investigations can be carried out in terms of Symbol Error Rate (SER), Error Vector Magnitude, Q Factor etc.

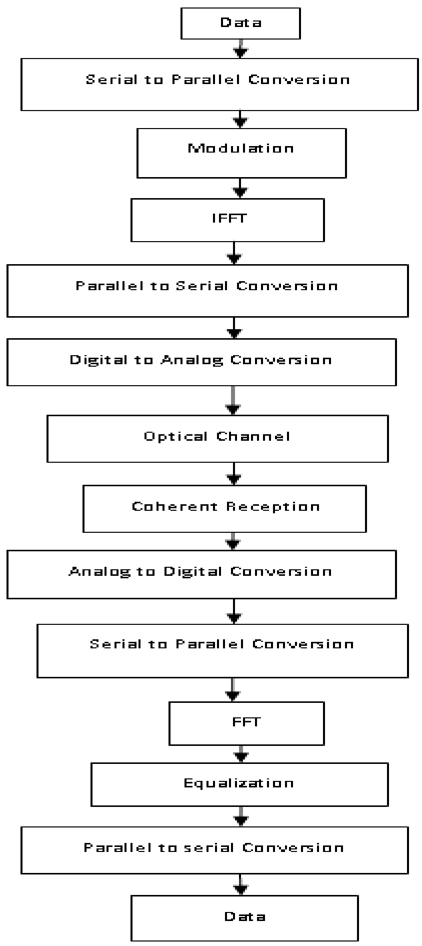



Figure 1. Block Diagram of Optical OFDM system

## 3. RESULTS AND ANALYSIS

The performance is investigated in terms of symbol error rate and error vector magnitude by plotting the graphs of BER and EVM against OSNR for various transmission distances .Graphs have been plotted for 4QAM and 16QAM. Constellation diagrams are also observed at OSNR of 25dB for both the modulation formats at various distances with and without compensation.

### 3.1. Results for 4QAM Modulation format

Figure 2 shows the graph of SER as OSNR is varied from 10dB to 40dB for distances of 800 km, 1600km, 2400 km and 3200 km for 4QAM. It can be observed from the graph that with the increase in OSNR, SER decreases and the system has shown acceptable performance for 3200 km distance. Even at OSNR=15 dB. It gives SER less than $10^{-3}$ which is a very good transmission reach.

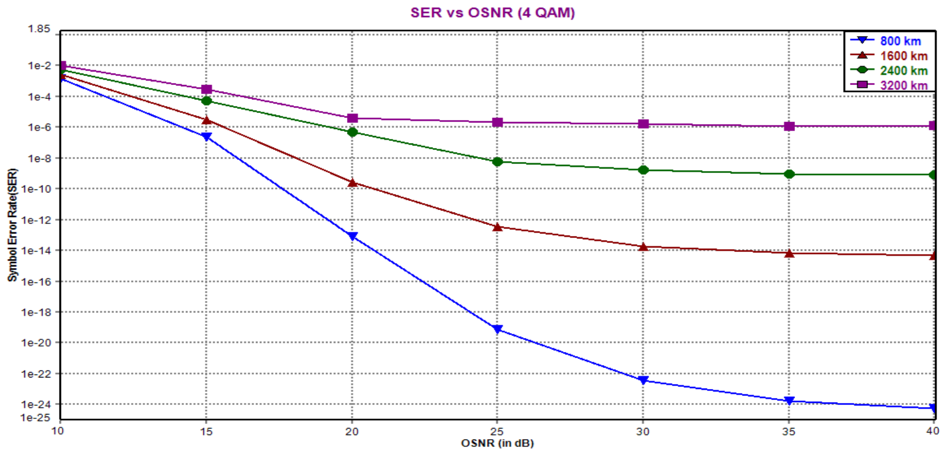



Figure 2. SER vs OSNR for various transmission distances (4 QAM)

This can also be observed through a graph shown in the Figure 3 in which SER is plotted against varying transmission distance for different OSNRs. On x axis distance is shown in terms of number of loops of fiber where each loop=200 km. Here also it is seen that at 15dB OSNR, signal can be sent upto 16 loops of fiber i.e 3200 km having SER<$10^{-3}$.

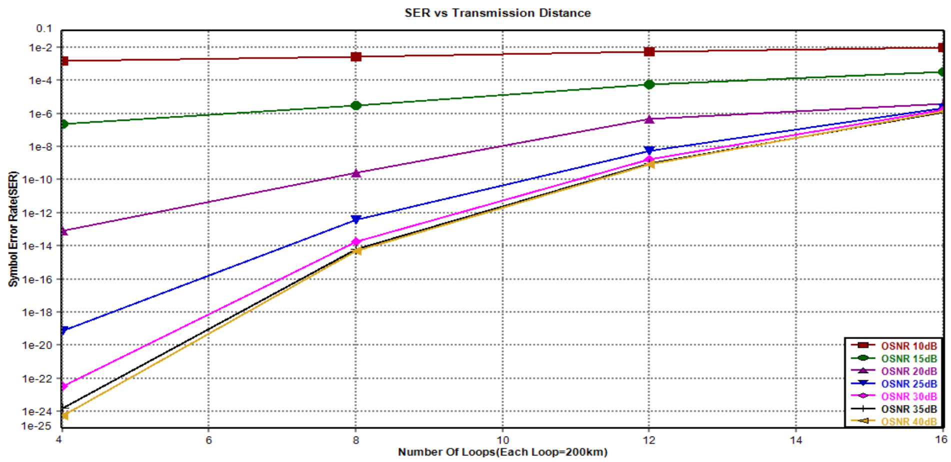



Figure 3. SER vs Transmission distance for various OSNRs (4 QAM)

Also the graphs are plotted for Error Vector magnitude (EVM) vs OSNR for varying transmission distances (Figure 4).

EVM (RMS) is defined as the difference between the received symbols and the ideal symbols normalized. It is given by:

$$EVM_{RMS} = \sqrt{\frac{\frac{1}{N}\sum_{r=1}^{N}[(I_r - \bar{I_r})]^2 + (Q_r + \overline{Q_r})^2}{\frac{1}{N}\sum_{r=1}^{N}({I_r}^2 + {Q_r}^2)}}$$

EVM value is indicative of the error between the received symbol and the sent symbol.From the graphs it is observed that with increase in OSNR, EVM decreases (Figure 4) and with increase in transmission distance EVM increases. These graphs also show efficient transmission up to 3200 km at OSNR=15 dB. The value of error vector magnitude is 0.28 at 3200 km distance (OSNR=15dB)

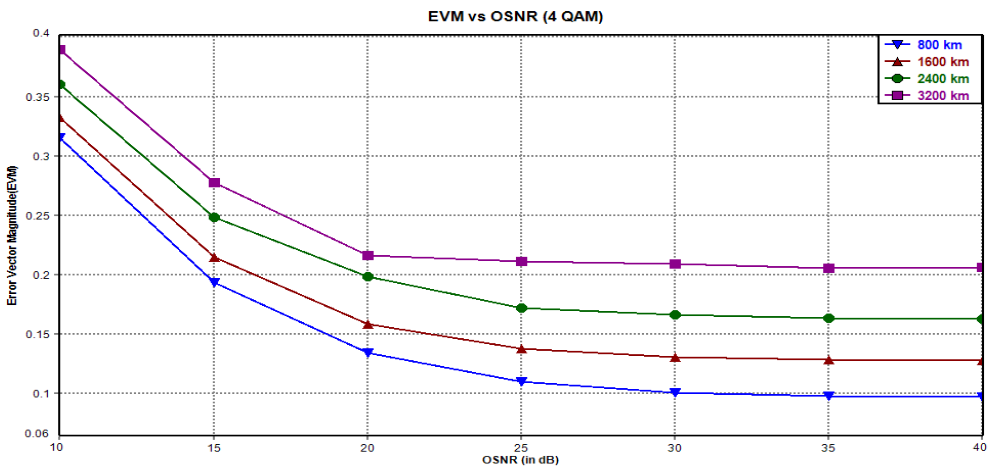
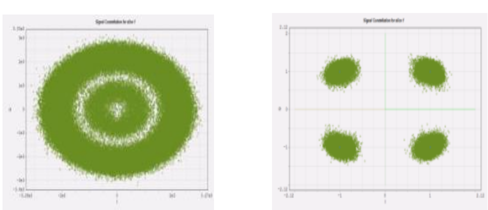
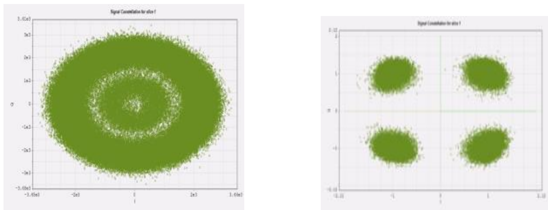


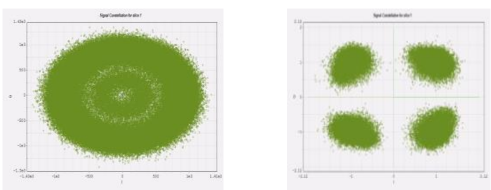

Figure 4. EVM vs OSNR for various transmission distances (4 QAM)



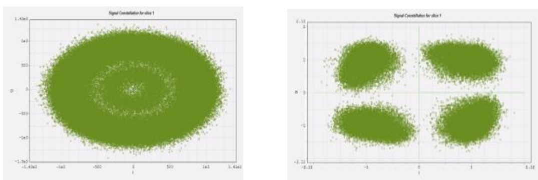
(a) Without Compensation (b) With Compensation
(i) after 800 km(OSNR=25dB)



(a) Without Compensation (b) With Compensation
(ii) after 1600 km(OSNR=25dB)



(a) Without Compensation (b) With Compensation
(iii) after 2400 km(OSNR=25dB)



(a) Without Compensation (b) With Compensation
(iv) after 3200 km(OSNR=25dB)

Figure 5. Constellation Diagrams (4QAM)

The interference and distortion present in the signal can be monitored through constellation diagram. Constellation Diagrams are also indicative of Error Vector Magnitude. Figure 5 (i), (ii), (iii) and (iv) shows the constellation diagram for 4 QAM obtained at the distances of 800 km, 1600 km, 2400 km and 3200 km for OSNR = 25dB. The constellation diagram at each distance mentioned has been shown for both the cases (a) without Compensation and (b) With Compensation. Without phase noise compensation, the constellation points are rotated and after phase noise compensation, the constellation points are within the boundaries of their level. It is also observed from the Figure 5 that as the distance increases, Constellation points become closer to each other which show the increase in distortion as transmission distance increases.

### 3.2. Results for 16 QAM Modulation format

All these results have been plotted for 16 QAM also. The advantage of 16 QAM modulation format is that now more number of bits can be transmitted now within symbol duration.But this advantage is at the cost of Increased OSNR penalty. Figure 6 shows the graph of SER against OSNR for 16QAM. The graph has been plotted for 800km, 1600 km, 2400 km and 3200 km transmission distances. As observed from the graph at 15 dB OSNR for 3200 km transmission distance, SER is now more than $10^{-3}$.Hence 15 dB OSNR is not sufficient for error free transmission without error control coding. To get SER less than $10^{-3}$, OSNR should be at least 20dB. So OSNR requirement is increased by nearly 5 -6dB as the order of QAM is raised from 4 to 16. As the modulation format is raised from 4 QAM to 16 QAM bandwidth efficiency is doubled. This also results in mean power $5d^2/2$ per symbol for 16 QAM as compared to $d^2/2$ for 4 QAM where d denotes the minimum Euclidian distance between two symbols. If it is approximated that Bit Error Rate depends only on minimum Euclidian distance when comparing the various modulation formats, nearly 7 dB higher signal to noise ratio is required as the level is raised from 4QAM to 16QAM [10].

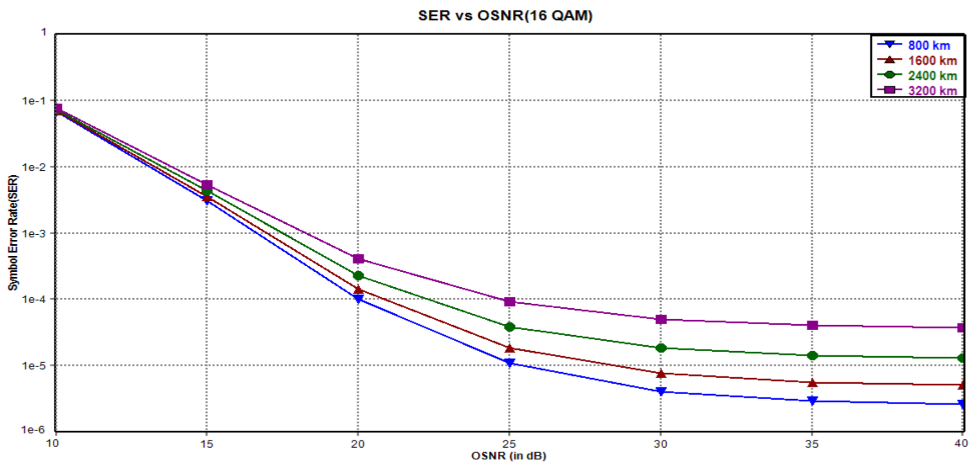



Figure 6. SER vs OSNR for various Transmission Distances (16 QAM)

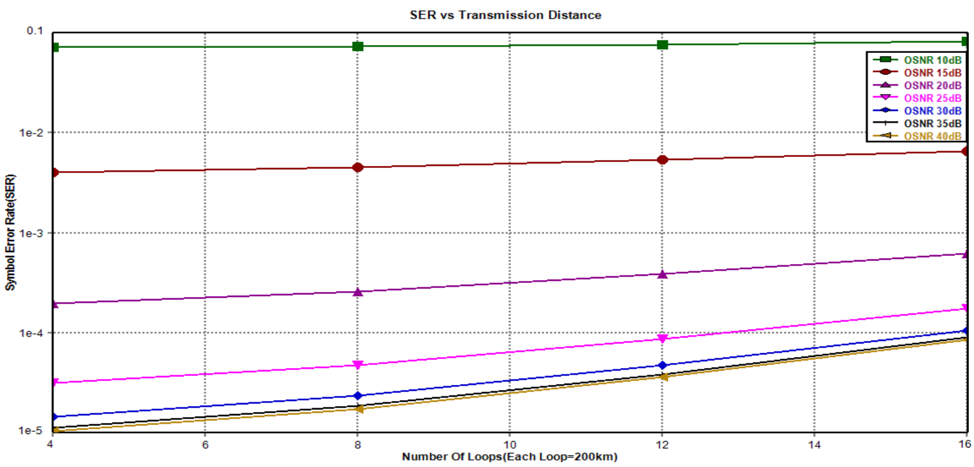



Figure 7. SER vs Transmission Distance for various OSNRs (16 QAM)

Figure 7 shows the plot of SER as transmission distance is varied from 800 km to 3200 km. The graphs have been plotted for different values of OSNR. Increase in transmission distance results in poor symbol error rate performance. Increase in OSNR improves the performance in terms of Symbol Error Rate.

Figure 8 shows the variation of EVM with OSNR for various transmission distances. The value of EVM varies from 0.24 at OSNR=10dB to 0.08 at OSNR=40dB for transmission distance of 3200 km whereas this variation is 0.4 at 10 dB to 0.23 at 40 dB for the same transmission distance for 4 QAM. EVM performance is better for 16 QAM because the received symbols are close to ideal ones in case of 16 QAM as compared to 4 QAM because the number of points are more in 16 QAM due to which the received symbol points are less scattered for 16 QAM as compared to 4 QAM.

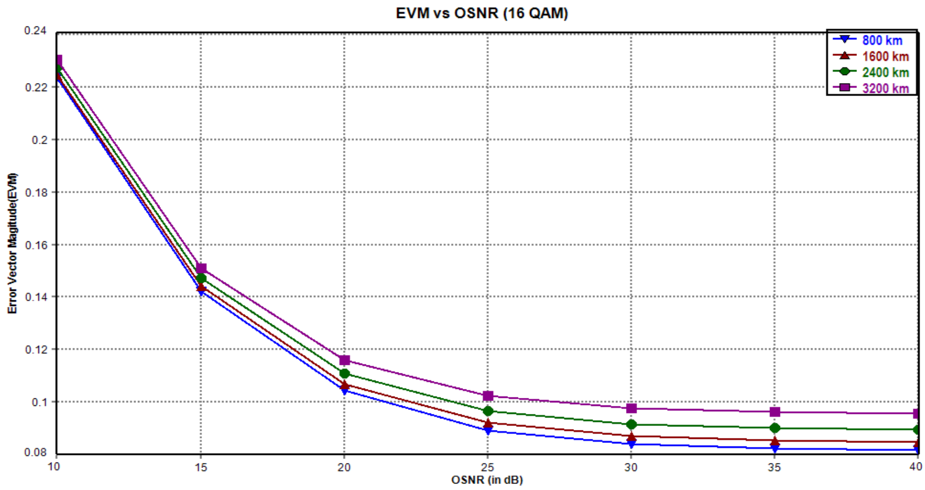
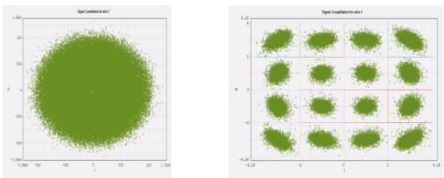
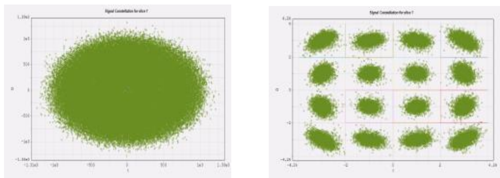



Figure 8. EVM vs OSNR for various Transmission Distances (16 QAM)

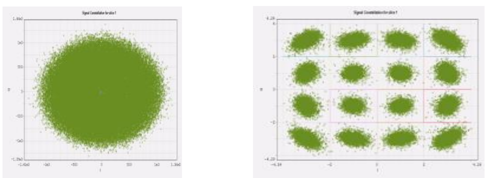
Figure 9 (i)-(iv) shows the constellation diagrams at 800 km, 1600 km, 2400 km and 3200 km for 16 QAM at OSNR=25 dB. Again the constellation diagrams are shown for both the cases i.e without post compensation and with post compensation. The constellation diagram depicts that the signals are received successfully at the mentioned distances at an OSNR of 25 dB.



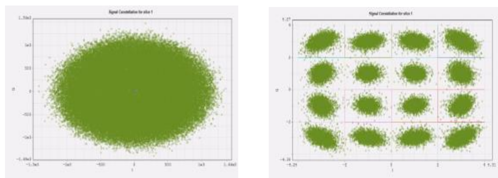
(a) Without Compensation (b) With Compensation
(i) after 800 km (OSNR=25dB)



(a) Without Compensation (b) With Compensation
(ii) after 1600 km (OSNR=25dB)



(c) Without Compensation (b) With Compensation
(iii) after 2400 km (OSNR=25dB)



(d) Without Compensation (b) With Compensation
(iv) after 3200 km (OSNR=25dB)

Figure 9. Constellation Diagrams (16 QAM)

### 3.3. Comparison of 4QAM and 16QAM Modulation Format

There is an OSNR penalty of nearly 6-7dB as the order of QAM increases at the each of the distances of 800 km, 1600 km, 2400 km and 3200 km, however spectral efficiency increases which is justified from theoretical background also. Comparing the graphs for 4 QAM and 16 QAM, the OSNR requirements for SER less than $10^{-3}$ are summarized in Table 1.

Table 1. OSNR Requirements for 4QAM and 16QAM (SER=$10^{-3}$)

| Transmission Distance in kms | OSNR Requirement in dB (4QAM) | OSNR Requirement in dB (16QAM) |
|---|---|---|
| 800 | 10 | 16.75 |
| 1600 | 10.5 | 17 |
| 2400 | 11.25 | 17.5 |
| 3200 | 12.25 | 18 |

This is also clear from Figure 10. In which graph has been plotted between Symbol Error Rate and OSNR for 4 QAM and 16QAM modulation format at a distance of 3200 km.

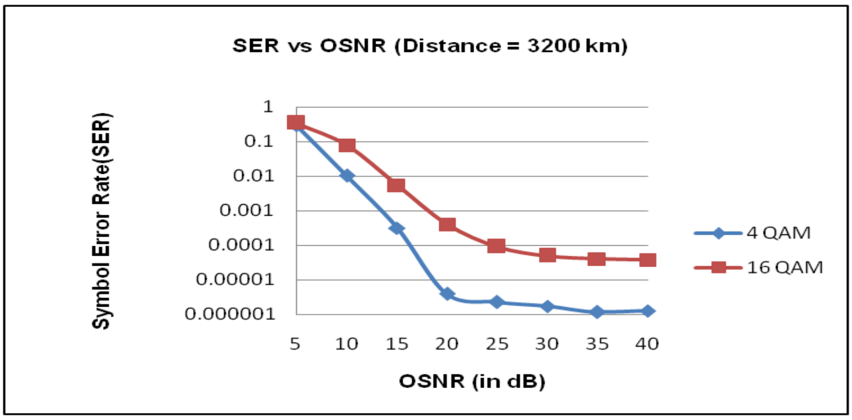



Figure 10. SER vs OSNR (at 3200 km distance)

Figure 11 shows the graph between OSNR and Error Vector Magnitude at a distance of 3200 km. It is observed that EVM is more in case of 4 QAM as compared to 16 QAM because 4 QAM constellation points are scattered more from their ideal positions as the number of possible decision regions are only four in case of 4 QAM whereas there are 16 distinct decision regions in 16 QAM. Hence EVM in case of 16 QAM is less.

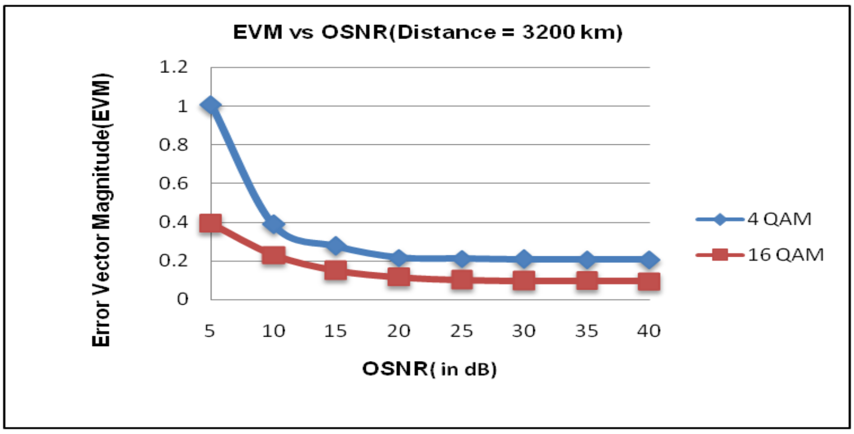



Figure 11. EVM vs OSNR(at 3200 km distance)

## 4. CONCLUSION

The behavior of Post Compensated CO OFDM system operated at 40 Gbps is investigated. 4 QAM and 16 QAM modulation formats are studied and their performance is investigated. Performance is analyzed by calculating the maximum transmission reach.Performance in terms of SER and EVM is investigated as OSNR is varied from 10dB to 40dB. 3200 km distance can be reached at 12.25 dB OSNR for SER$<10^{-3}$ for 4 QAM and at nearly 18dB OSNR for 16 QAM. Hence it is concluded that 6-7dB OSNR penalty results as the modulation format is raised from 4 QAM to 16 QAM.

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