Performance analysis of a spectrally efficient QAM coherent OFDM optical link

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Coherent detection is a promising technique to compensate for the linear and non linear impairments of an optical communication link. Coherent optical receivers followed by Digital Signal Processing (DSP) facilitate in demodulating advanced modulation formats like Quadrature Amplitude Modulation (QAM), providing an effective solution to upgrade optical backbone network. Orthogonal Frequency Division Modulation (OFDM) is being widely studied to implement scalable, dispersion compensated high speed optical networks. This work aims to design and analyze a spectrally efficient QAM OFDM optical network. In order to further boost the system capacity dual polarized signal has been investigated.

(Received September 20, 2017; accepted June 7, 2018)

Keywords: Coherent detection, CO-OFDM, Dispersion compensation, DSP, Spectral efficiency

1. Introduction

An important design objective of a long-haul optical fiber system is to achieve maximum throughput over longer distances without signal regeneration. Recently a lot of work has been done in the field of optical communication to increase its capacity and to make it more dynamic and robust [1]. The capacity of an optical system does not keep increasing indefinitely with increase in signal power, but has a theoretical upper limit called Shannon limit. The non linear impairments become prominent as power of the signal increases, thus limiting the system capacity [2]. It is very important to maximize the Spectral efficiency and minimize the average energy transmitted per bit.

The concept of coherent optical communication was actively being pursued in mid 1980s but the practical deployment did not happen as it had very complex mechanism for phase and polarization management. Coherent communication made a big comeback 20 years later with the advances in Digital Signal Processing (DSP) techniques and application specific integrated circuits [3]. The most advanced optical communication systems employ coherent detection with DSP to flexibly compensate linear as well as non linear impairments present in the fiber. Using DSP makes it very easy to delay, split, amplify, and manipulate the signal without affecting the signal quality [4]. Phase and polarization management which was the main limitation to implement coherent receiver can be managed well using DSP. Multilevel modulation formats such as Quadrature Phase Shift Keying (QPSK) or Quadrature Amplitude Modulation (QAM) can be used in coherent systems thus increasing the Spectral efficiency up to several b/s/Hz [5].

The amount of individual bit streams that can be packed onto a single transmission medium determine a system's aggregate capacity. Capacity-constrained systems, such as long-haul fiber-optic transport employ the most advanced multiplexing techniques [6]. Quadrature carrier systems like M-ary Shift Keying (MSK) and QPSK increase the bandwidth efficiency but only at the expense of either the bit error probability or the transmitter power. For more than 4 symbols, M-ary QAM requires less average power than M-ary PSK for a specified probability of error. The rectangular shape of M-ary QAM constellation allows more distance between message points as compared to the circular constellation of M-ary PSK. Due to this, QAM has a two dimensional constellation and improved detection error probability. Two separate data symbols are simultaneously sent over the same carrier, one on the in-phase part and the other on the quadrature part. Hence out of the various advanced modulation techniques being studied, QAM-16 is a promising technology that offers a good compromise between various limiting effects and enables high-speed, high-capacity long-haul optical networking.

OFDM is a Multi-Carrier Transmission Technique (MCT) where a data stream is carried with many lower-rate subcarrier tones. Coherent (CO)-OFDM combines the advantages of coherent detection as well as OFDM modulation techniques and thus posses many merits that are critical for future high-speed fiber transmission systems. The advantages include effective mitigation of Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD), high optical Spectral Efficiency and reduced electrical bandwidth requirement. Hence, this work aims to exploit the advantages of QAM along with CO-OFDM.

2. Coherent optical detection

The detection methods used in optical links are non-coherent, differentially coherent and coherent detection. In non-coherent detection, the decision variables are computed by the receiver from the measurement of signal energy. It allows signals to encode only one Degree of Freedom (DOF) per polarization per carrier, reducing spectral efficiency and power efficiency. Further, the loss of phase information during detection is an irreversible transformation that prevents full equalization of linear channel impairments by linear filters [7].

Currently the most advanced detection method is coherent detection, where the receiver computes decision variables based on the recovery of the full electric field, which contains both amplitude and phase information. It allows the greatest flexibility in modulation formats, as the information can be encoded in amplitude and phase, or alternatively in both in-phase (I) and Quadrature (Q) components of a carrier. The receiver must have the knowledge of the carrier phase, as the received signal is demodulated by a Local Oscillator (LO) that serves as an absolute phase reference.

3. Principles of OFDM

In Multi Carrier Modulation (MCM) for designing the filters and oscillators cost-effectively, the channel spacing has to be multiple of the symbol rate. This requires excessive bandwidth and reduces the spectral efficiency of MCM. OFDM on the other hand, employs overlapped yet orthogonal signal set and the frequencies are spaced at multiple of inverse of the symbol rate. These orthogonal subcarrier sets can be recovered with the matched filters without any Inter-Carrier Interference (ICI) in spite of the strong signal spectral overlapping. The origin of orthogonality is the simple correlation between any two subcarriers [8].

A signal s(t) transmitted in a Multi-Carrier Modulation scheme can be written as

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{N_{SC}} c_{ki} s_k(t - iT_s) \qquad (1)$$

$$S_k(t) = \Pi(t) \exp(j2\pi f_k t) \qquad (2)$$

where

$S_k(t)$ represents the kth subcarrier of the OFDM

f_k represents the k^{th} frequency of the subcarrier

T_s represents the symbol period

c_{ki} is the i^{th} information symbol at the k^{th} subcarrier

$$\Pi = \{1, for\ 0 < t \leq T\_S\ \}$$

The correlation between any two subcarriers in an OFDM symbol can be represented as

$$\delta_{kl} = \frac{1}{T_s} \int_0^{T_s} S_k S_l^* dt$$

$$= \frac{1}{T_S} \int_0^{T_S} \exp(j2\pi(f_k - f_l)t) dt$$

$$= \exp(j\pi(f_k - f_l)T_S) \frac{\sin(\pi(f_k - f_l)T_S)}{\pi(f_k - f_l)T_S} \qquad (3)$$

The two subcarriers become orthogonal to each other if they satisfy the following condition

$$f_k - f_l = m \frac{1}{T_S} \qquad (4)$$

where m must be a positive integer. As OFDM uses partially overlapped spectrum of the subcarriers it provides higher Spectral efficiency as compared to the traditional MCM techniques. Also if the subcarrier frequencies are spaced at a multiple of inverse of the symbol period, the signal can be recovered back without any ICI.

CO-OFDM is implemented by optical I-Q modulation in conjunction with coherent detection. It shows higher performance in terms of bandwidth efficiency and receiver sensitivity. A generic CO-OFDM system is shown in Fig. 1, it has five basic functional blocks: OFDM transmitter, in RF-to-optical (RTO) up-converter, optical link, optical to RF (OTR) down converter, and OFDM receiver. The coherent system provides OFDM linearity in RTO up-conversion and OTR down-conversion. OFDM brings coherent system computation efficiency and ease of channel and phase estimation. Due to its superior scalability with the bit rate of the transmission systems, CO-OFDM is well-positioned to be an attractive choice of modulation format for the next generation of 100 Gbit/s transmissions [9].

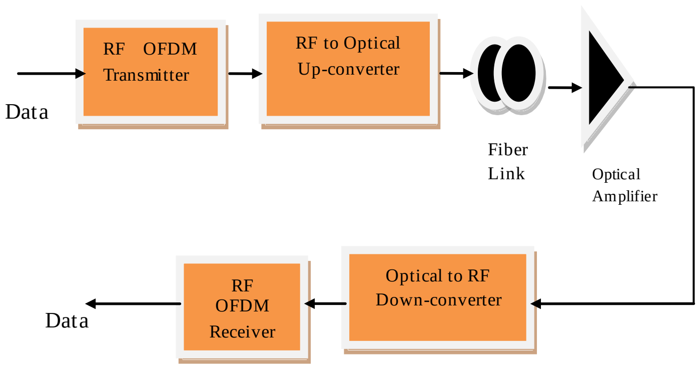


Fig. 1. A generic Coherent OFDM network

In CO-OFDM in each symbol period T_S, N_{SC} number of symbol carriers are transmitted thus giving symbol period $R = N_{SC}/T_S$. Bandwidth of the OFDM signal is given by [8]

$$B_{OFDM} = \frac{2}{T_S} + \frac{N_{SC} - 1}{t_S} \qquad (5)$$

where t_S is the observation period of DFT window. The spectral efficiency can be expressed as

$$\eta = 2 \frac{R}{B_{OFDM}} \qquad (6)$$

where R is the symbol rate, B_{OFDM} is the OFDM bandwidth and the factor of 2 represents the two polarization states of the fiber.

4. Digital signal processing in coherent detection

Earlier, Phase Locked Loop (PLL) was used for synchronizing the carrier, but its performance is limited when used with high speed optically modulated signals, hence it is being replaced by DSP unit. The DSP component makes it possible to perform many offline functions like carrier synchronization, dispersion compensation and polarization alignment. It performs the compensation of fiber impairments in digital domain and helps to recover the signal after coherent detection [10]. DSP is providing us with the suitable technology for building high speed coherent optical networks beyond 100G [11]. Employing DSP at the transmitter or receiver side makes the reception for advanced modulation formats simpler and also enables the impairments to be processed and compensated for in the digital domain [12].

The Universal DSP component available in OPTISYSTEM includes 12 functions and algorithms starting with a preprocessing stage (add noise to signal, DC blocking and normalization) followed by the signal recovery stage (Bessel Filter, Resampling, Quadrature Imbalance (QI) Compensation, CD Compensation, NL compensation, Timing recovery, Adaptive Equalizer, down sampling and carrier phase estimation). It uses the Gram-Schmidt orthogonalization procedure to correct for non orthogonalization in received signal. An all pass digital filter can be used to compensate for CD resulting from propagation over fiber. The dispersion compensating filter can be implemented in either the frequency domain or time domain. The slope of this function depends on the fiber characteristics and length. Dispersion compensation is achieved by filtering the incoming signal using a phase response opposite to that of the fiber. Dispersion compensation filtering can be done two ways: Finite Impulse Response (FIR) or Infinite Impulse Response (IIR). This component is mainly responsible in enhancing the performance of the link and depending on the transfer function in frequency domain or impulse response of finite impulse response filter desirable performance can be achieved.

In long haul transmission Reduced Guard Interval CO-OFDM signals, joint frame and frequency synchronization has been realized using Almouti Algorithm [13] and digital computation of Fractional Fourier Transform [14].

5. Measure of performance-error vector magnitude

Error Vector Magnitude (EVM) is a suitable standard for measuring performance of optical links limited by Additive White Gaussian Noise (AWGN) [15]. In literature, many researchers use the EVM values to compare the performance of different optical links employing higher order modulation formats.

EVM is a measure of the effective distance between the received symbol and its expected ideal position in the constellation diagram. The EVM of the received signal is calculated as

$$EVM = \frac{\sqrt{|S-[S_D]|^2}}{||S_D||^2} * 100\% \qquad (7)$$

where S represents the signal sequence and S_D is the decision of S. Thus EVM can be used in coherent optical links employing advanced modulation techniques like QAM to measure the system performance and evaluate the quality of received signal Also using the values of EVM we can dependably estimate the BER [16]. For a system employing M-ary modulation, EVM and BER for a 16-QAM vector signal can be expressed as

$$BER = \frac{3}{4} Q\left(\sqrt{\frac{1}{5EVM^2}}\right) \qquad (8)$$

where Q(.) is the Gaussian co-error function. In order to get optimum performance, the BER of the optical link should be less than 10^{-9} and EVM value should be less than 10%.

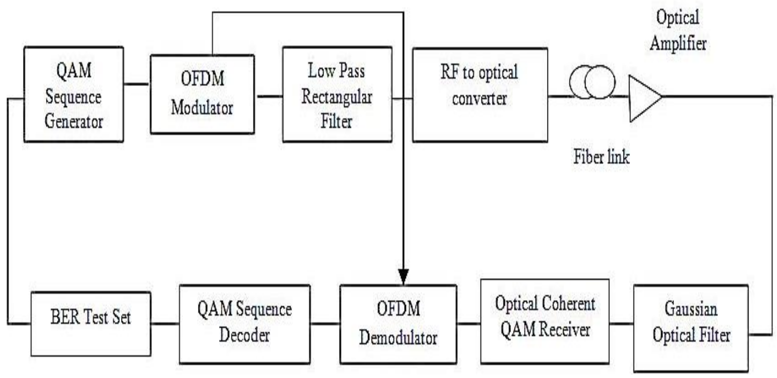


Fig. 2. Simulation setup of Coherent M-ary QAM-OFDM optic link

6. Simulation setup and results

The simulations for this work have been done using the tool OPTISYSTEM by Optiwave, the designed link is shown in Fig. 2. At the transmitter both modulation and multiplexing are achieved digitally using an Inverse Fast Fourier Transform (IFFT). The symbol rate employed is 10 Bd and bits are generated at the rate of 40 Gbps for QAM-16 and 50 Gbps for QAM-32. The QAM sequence generator provides square shape constellation with 4 bits/symbol for QAM-16 and 5 bits/symbol for QAM-32. This sequence is modulated by OFDM modulator having a maximum of 128 subcarriers out of which 80 subcarriers are being used. It uses symbol extension as cyclic prefix to mitigate inter symbol interference. A Continuous Wave Distributed Feedback (CW DFB) Laser and two Mach-Zehnder modulators are used to up-convert from the RF to the optical domain. CW DFB is centered at frequency of 193.1 THz, emits power of 10 dBm and has 0.1 MHz linewidth.

The signal is then propagated through a Standard Single Mode Fiber (SSMF) having attenuation of 0.2 dB/Km and dispersion value of 16.75 ps/nm/km. As the signal travels through the fiber it becomes degraded due to linear and impairments in the fiber. Non linear impairments become significant when the power in the signal is increased in order to increase the system capacity. A coherent QAM receiver based on homodyne detection is used to down-convert the data to the RF domain. The connection between the OFDM modulator and demodulator depicts the training sequences used for synchronization and channel estimation. The BER test set generates a sequence which is given as input to the QAM sequence generator, after the sequence passes through the entire link it is compared with the initial sequence to calculate BER.

The system parameters used for the simulation study are given in Table 1. The symbol rate employed is 10 Bd and the bit rates used are 40 Gbps and 50 Gbps for QAM-16 and QAM-32 schemes respectively. The simulations have been carried out using the tool OPTISYSTEM.

Table 1. Simulation Parameters of Coherent M-ary QAM OOFDM link

Simulation Parameters			
Global Parameters	(a)	Bit rate	40 Gbps
	(b)	Symbol rate	10 Baud
	(c)	Sequence length	32768
	(d)	Samples per bit	1
	(e)	Number of samples	32768
QAM-16 Sequence Generator	(a)	Bits per symbol	4
	(b)	Constellation type	Square
	(c)	Gray code	True
OFDM Modulator	(a)	Max possible subcarriers	128
	(b)	Cyclic prefix	Symbol Extension
	(c)	No of prefix points	10
	(d)	Average OFDM power	15 dBm
	(e)	No of subcarriers used per port	80
	(f)	Subcarrier location	25-104
CW-DFB Laser	(a)	Frequency	193.1 THz
	(b)	Power	10 dBm
	(c)	Linewidth	0.1 MHz
Single Mode Fiber	(a)	Attenuation Coefficient	0.2 dB/km
	(b)	Dispersion Coeff. (D)	16.75 ps $nm^{-1}km^{-1}$
	(c)	Dispersion Enabled	GVD,TOD
	(d)	Birefringence type	Stochastic
	(e)	PMD Coeff. (D_p)	0.05 $ps/km^{1/2}$
	(f)	Model Type	Scalar
	(g)	NL effect Enabled	SPM
	(h)	A_{eff}	80 μm^2
	(i)	n_2	26 x 10^{-21} m^2/W
CO-OFDM Receiver	(a)	Power	10 dB
OFDM Demodulator	(a)	No. of prefix points	10
	(b)	No. of training Symbols	10
BER Test Set	(a)	Bit Rate	Bit Rate*(80/120)
	(b)	No. of pilot symbols	6

The performance of these systems has been analyzed in terms of BER, Error Vector Magnitude (EVM) and constellation diagrams. A series of simulations were performed, in the first one the BER performance of a single polarization QAM-16 OFDM link with DD was studied. In the second simulation keeping other parameters constant performance of coherent detector followed by Universal DSP and decision component (no OFDM) was analyzed by varying length of SSMF. The universal DSP component performs digital domain impairment compensation to aid in recovering the incoming transmission signal after coherent detection. The Decision component processes the I and Q electrical signal channels and performs a decision on each received symbol based on normalized threshold settings.

The Figs. 3-7 summarize the BER and EVM values obtained for different link designs and variation in fiber length. A DD QAM-16 link gives errorless transmission up to 20 km only. Whereas a QAM-16 modulated signal when detected with coherent detector followed by a universal DSP element increases the SSMF length to 150 km for EVM=9.64%. In coherent detection the receiver can extract any information which is embedded in either phase and/or frequency; this makes the receiver much more sensitive than Direct Detection (DD). Employing OFDM at the coherent detector further increases the transmission length to 250 km for EVM of 10.16%. Subsequently QAM-16 OFDM coherent detection link performance was compared for single and Dual Polarization (DP) configurations.

With single polarization in each QAM-16 signal 1baud is made up of 4 bits whereas after DP in each QAM-16 signal each baud consists of 8 bits, thus DP QAM doubles the data rate of the optical link and adds additional degree of freedom. This increased channel capacity is at the cost of slightly increased BER and EVM values. To further increase the system capacity a single polarization QAM-32 OFDM link was simulated. Each DP QAM-64 signal carries 16 bits in each baud as compared with 8 bits in each baud for SP QAM-64 signal. But as we move to higher order modulation formats like QAM-64 it results in a large increase in the transmitter and receiver complexity.

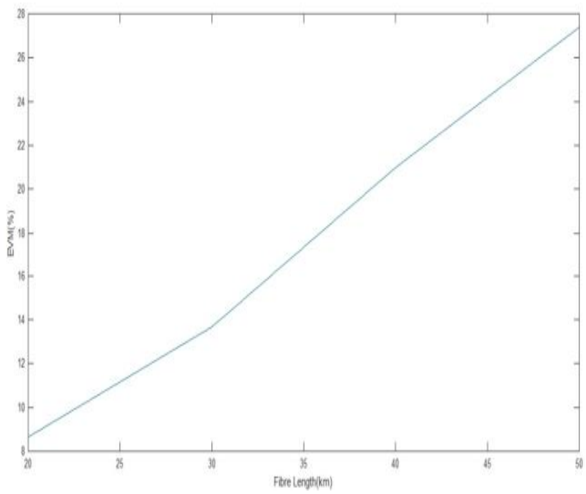


Fig. 3. EVM vs. Fiber Length for a QAM-16 Single Polarization DD OFDM

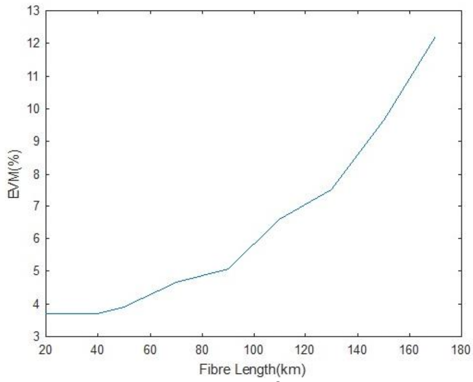


Fig. 4. EVM vs. Fiber Length for a QAM-16 link with Coherent Detection and universal DSP (no OFDM)

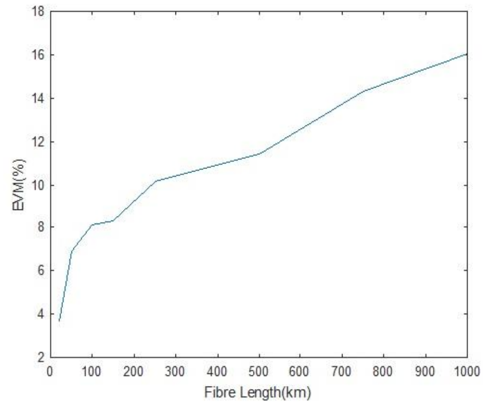


Fig. 5. EVM vs. Fiber Length for QAM-16 Single Polarization CO-OFDM

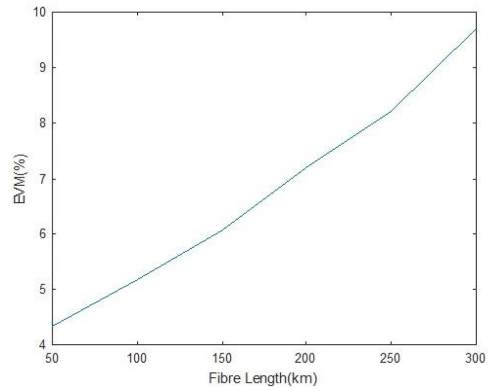


Fig. 6. EVM vs. Fiber Length for QAM-16 DP CO-OFDM

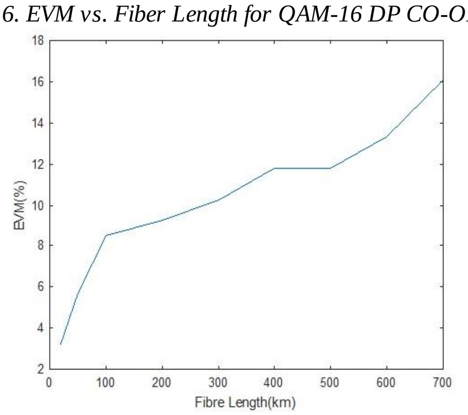
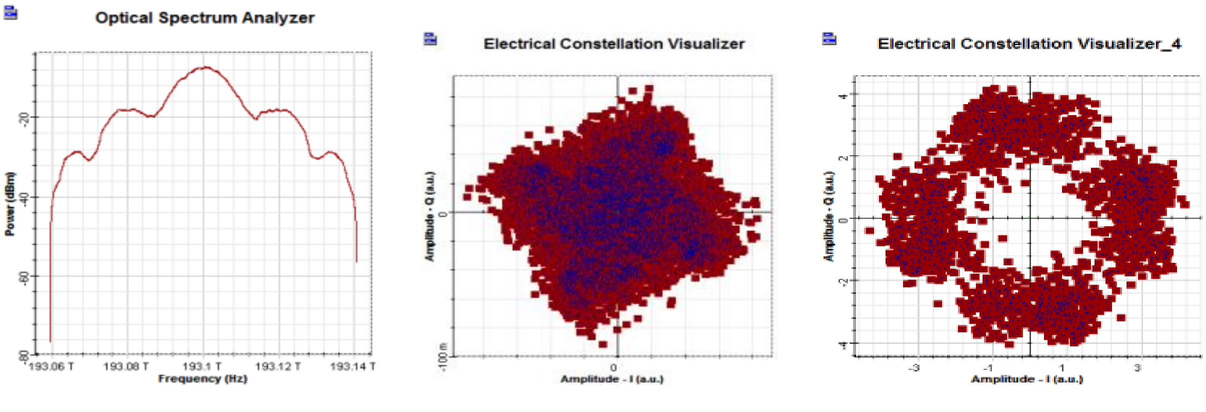


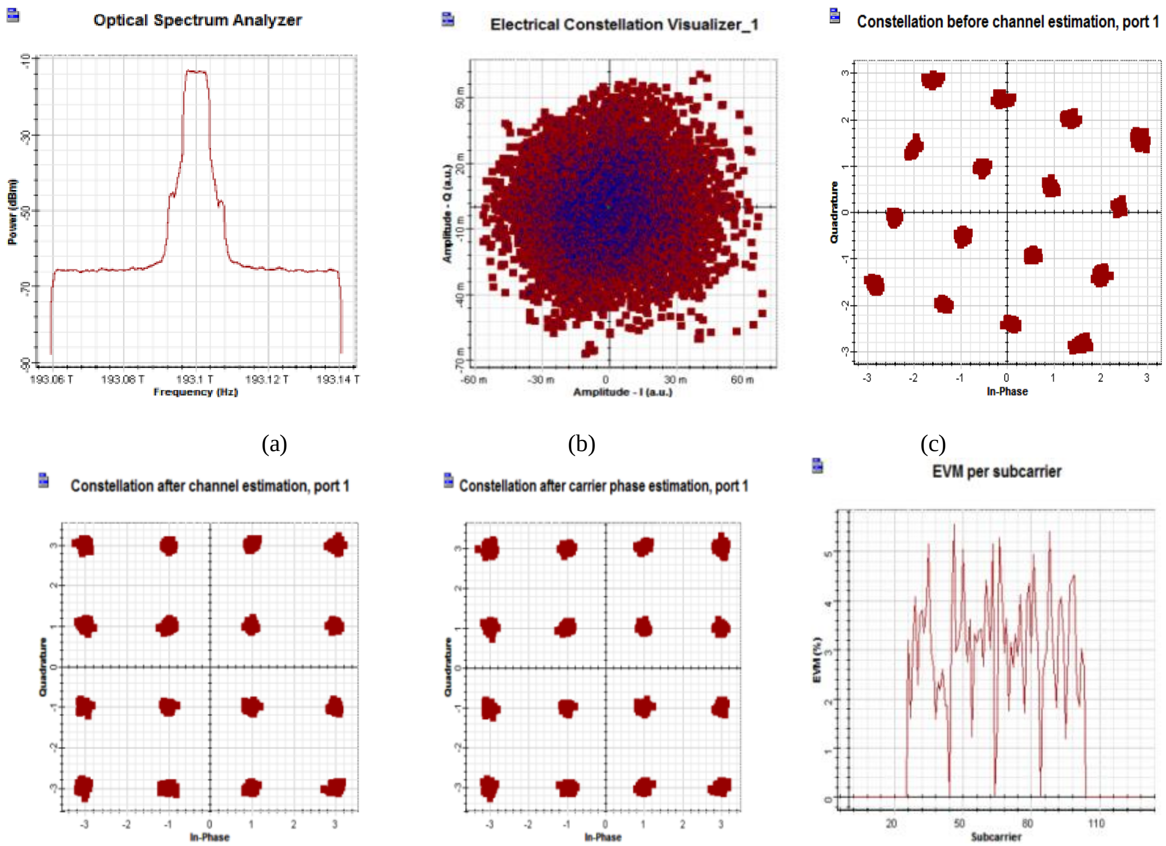
Fig. 7. EVM vs. Fiber Length for QAM-32 Single Polarization CO-OFDM

The performance of different M-ary optical links is also compared using constellation diagrams in Figs. 8-11. Fig. 8 illustrates how placing a DSP component after the coherent receiver aids in CD compensation in digital domain using filtering. As explained in section 4, DSP component includes an adaptive equalizer that compensates for any residual CD, polarization mode dispersion and reduces ISI. Due to frequency and phase offset there is rotation of constellation to compensate it frequency offset estimation is made by DSP component, also carrier phase estimation is done to compensate for any phase mismatch between the LO and the signal. The results obtained for a QAM-16 CO-OFDM link are shown in Fig. 9, the constellation rotation in Fig. 9(c) has been compensated in 9(d). Figs. 10 and 11 compare the coherent QAM-32 link performance with and without employing OFDM technique. It can be clearly seen that with OFDM the spacing between constellation points increases and hence the CD present in the optical fiber is compensated.



(a) (b) (c)

Fig. 8. QAM-16 coherent 20 km optical link (no OFDM) (a) Spectrum of input signal (b) Constellation at the output of coherent optical receiver (c) Constellation at the output of DSP component



(a) (b) (c)

(d) (e) (f)

Fig. 9. QAM-16 CO-OFDM 20 km optical link (a) Spectrum of the input signal (b) Constellation at the output of coherent optical Receiver (c) Constellation before channel estimation (d) Constellation after channel estimation (e) Constellation after carrier phase estimation (f) EVM

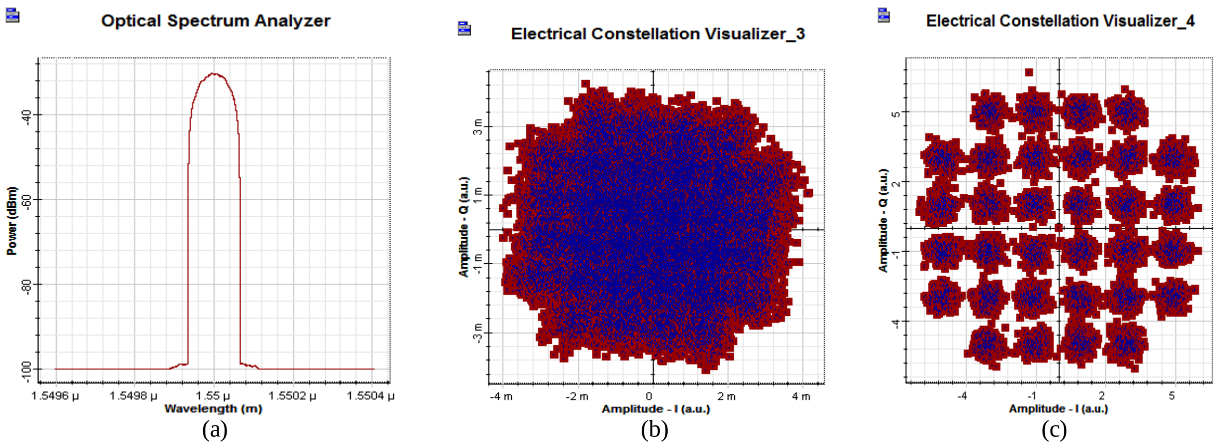


Fig. 10. QAM-32 coherent 20 km optical link (no OFDM) (a) Spectrum of input signal (b) Constellation after channel estimation (c) Constellation after carrier phase estimation

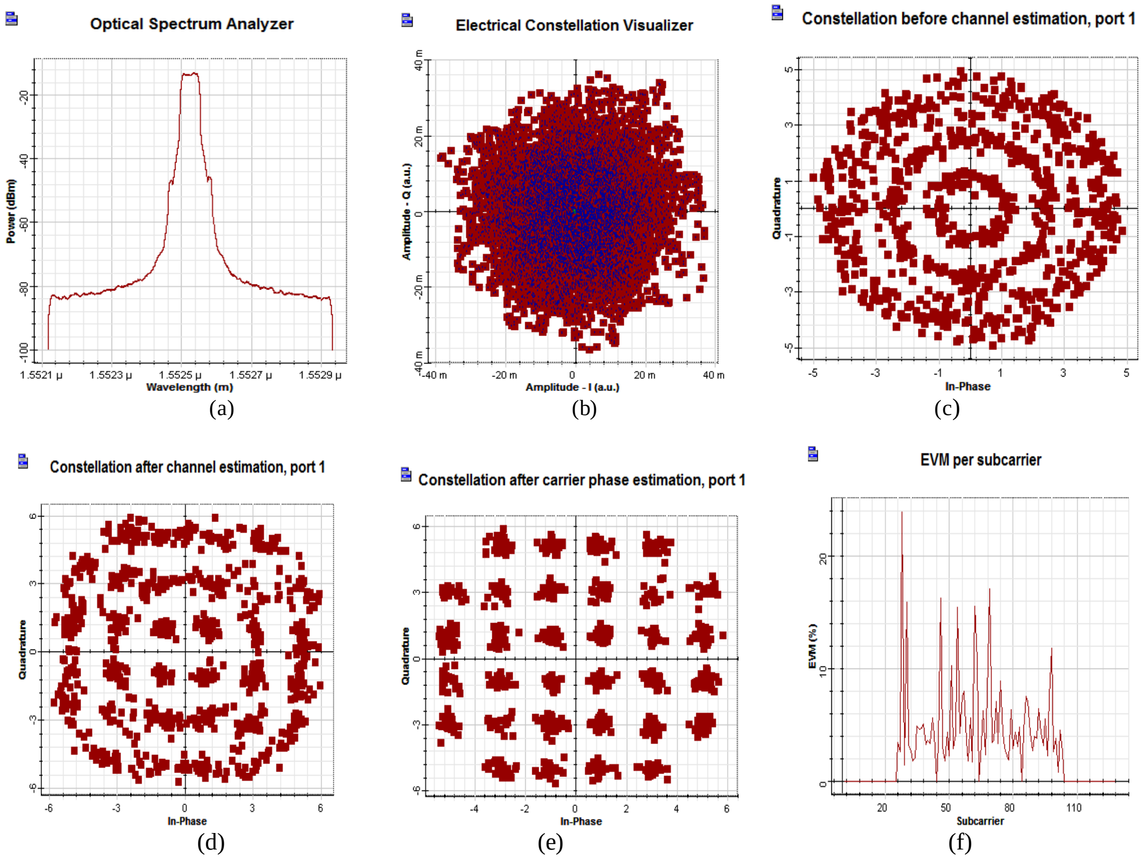


Fig. 11. QAM-32 CO-OFDM 20 km optical link (a) Input spectrum (b) Constellation at coherent receiver (c) Constellation before channel estimation (d) Constellation after channel estimation (e) Constellation after phase estimation (f) EVM

7. Conclusions

CO-OFDM is inherently spectrally efficient technique as it has overlapped subcarriers. It has been found that OFDM when used along with the higher order modulation format QAM has effectively compensated CD and polarization mode dispersion in single mode fiber. Combining CO-OFDM QAM with dual polarization further pushes the Spectral efficiency but at the cost of increased receiver complexity.

In this work, M-ary QAM OFDM system was considered and its maximum reach length was analyzed for M= 16, 32, 64. It was found that for a QAM-16 link, using direct detection the reach length obtained was only

20km but with coherent detection it was increased to 150 km. It was verified that for a QAM-16 OFDM link, by employing dual polarization the system capacity is increased but at the cost of reduced reach length. As we move to higher order modulation namely QAM-32 based OFDM, dual polarization outperforms single polarization. Similar results were obtained for QAM-64 based OFDM link.

In future this work can be further extended to study the compensation of non linear effects present in fiber. Also the effect of increasing the laser power on the system performance can be analysed. Another aspect that can be considered is that what type of changes need to be incoprporated in DSP component so that a particular BER and EVM is maintained as we move from QAM-16 to QAM-32 technique.

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