International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Performance Analysis of Coherent DP-16-QAM Optical Communication System

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ABSTRACT

In recent times, the telecom sector has been transformed by fibre optic connection. Even in the data networking sector, it has had a significant impact. With the advent of fiber-optic cable, data transmission over long distances and at higher data rates has been made possible, allowing for more efficient use of the transmission medium while also reducing the amount of loss experienced. DP 16-QAM is a digital coherent reception technology, gaining popularity on progress of Digital Signal Processing (DSP). Models of coherent DP-16 QAM with homodyne detection utilizing the OptiSystem software program are used to evaluate its performance in terms of BER values and constellation diagrams.The system is simulated for variable transmission distance, input power levels and data rates. The results are analyzed from constellation diagrams and BER performance analysis. After treating the output in the DSP unit, it was observed that increase in the data rate (bit rate) results in the increase in Bit Error Rate (BER). BER also increases with fiber optic length due to attenuation and non-linear distortions. Also, BER performance deteriorates due to substantial non-linear effects in the non-linear region, which leads to decrease in BER at the lower laser input power level and vice-versa

Keywords: Quadrature Amplitude Modulation (QAM), Digital Signal Processing (DSP), Dual Polarization, Homodyne system.

1.INTRODUCTION

The great sensitivity and selectivity of coherent optics are achieved by combining the received signal with a Local Oscillator (LO). As long as the LO light and the incoming signal have the same wavelength, phase, and polarization, they will produce a baseband signal that is considerably more prominent than the incoming signal, making it simple to detect. The coherent optical technology comes with the below advantages;

- Programmability
- High-gain soft-decision Forward Error Correction (FEC)
- Spectral shaping
- Strong mitigation to dispersion

It is possible to transfer additional data across a fibre optic cable using the Coherent Transmission method, which uses a combination of amplitude, phase, and polar modulation.

In fibre optics, often known as optical fibre, short bursts of light are used to transmit data down a thin, flexible tube. They work because the cladding of the fibre optic cables has a refractive index that is lower than the core's. As a result, all light travelling through the core is reflected back to the core/cladding border, resulting in complete internal reflection and encapsulating of the light. As a result of their superior capacity and transfer speeds, fibre optic connections have become more popular. Due of its increased bandwidth and quicker speeds, optical fibre can carry more data than conventional copper cable. Fiber optics are immune to electromagnetic interference since glass does not conduct electricity. As a result, signal losses are kept to a minimum.

Fiber optic cables must be turned into electrical signals in order to analyze the light and retrieve the data they carry. A photo-detector is the core of the receiver's technology. Using a photo-detector, the optical signal from the fibre optic connection may be translated to an electrical format and processed to retrieve the data then sent on to its intended destination.

DSP and homodyne detection were used in the OptiSystem simulation platform to implement DP-16-QAM [1]. An acceptable BER (i.e., one less than the FEC limit) was evaluated in this system's performance tests in low-turbulence circumstances for OSNR (Optical Signal to Noise Ratio). According to simulations, OSNR performance was not affected even in the face of harsh weather. Some of the system's advantages were its short, low cost, high capacity, and steady communication link in the context of rising environmental circumstances.

Fiber Bragg Gratings (FBG) [2] is one of the essential techniques that applied for limiting the dispersion. FBG was discussed by researchers which was a widely used component to compensate dispersion with linear chirp and Tanh apodization function, and additionally the authors embedded low pass Gaussian filter in the electrical part of the system to improve the Q-factor of the performance and eye diagram. The Q-factor of 30km length of the system with FBG was 20.2748, and by using FBG and Low Pass Gaussian Filter, the Q-factor managed to reach 26.9039, hence gave a better system performance. The system was analyzed with various fiber lengths and evaluated by using OptiSystem.

Chromatic and Polarization Mode Dispersions (PMD) are usually disruptive to optical communication systems running at high data rates and Dual Polarization (DP) [3]. Chromatic dispersion is frequently reduced by fixed filters. While adaptive filters such as channel equalizers often lower PMD owing to its stochastic character. In order to face the problem of creating next-generation optical networks, this paper recommended the usage of concurrent blind equalization designs with a butterfly structure.

Nonlinear distortion and optical signal-to-noise ratio (OSNR) estimations were proposed and demonstrated in [4]. When computing OSNR, training symbol link parameters and correlation procedures were taken into account. Two distinct nonlinear sensitivities in this computation resulted in these distortion estimates. For frame synchronization, the OSNR estimate approach relied on connection parameters, which had a low computing cost. Few complexity and no additional overhead were imposed by this nonlinear distortion estimation approach. The suggested OSNR estimate method worked well with a 200 Gbps 16 QAM DWDM system, which had errors of less than 1 dB

Because of the great sensitivity of coherent receivers, coherent optical fibre communications with data speeds of 100Gbit/s and beyond have lately been researched intensively [5]. Spectrally efficient modulation methods like M-ary Quadrature Amplitude Modulation (QAM) may be useful for coherent optical communications (M-QAM). Multi-level modulation formats were incorporated into coherent technologies and Wavelength-Division Multiplexed (WDM) systems to satisfy the total bandwidth need. Optical communication systems were examined to see whether they might be made more capable and extend their range by using coherent 16QAM schemes.

When it comes to high frequency modulation, 2bit/s or greater is considered the usual information ratio. There is a larger rate of information transfer in the M-ARY modulation than there is in M = 2 binary modulations in the same band. It is possible to increase the data rate-to-bandwidth ratio using M-ARY modulation at the expense of lower energy usage. The signal vector diagram shows that as M rises, the minimum range between signals points decreases.

The organization of the rest of the paper is as follows. Section II explains the technical significance. Section III discusses the implementation of the DP Transmitter & Receiver Section. Section IV presents simulations carried out for the proposed work. In Section V, the simulated results are discussed. Section VI gives the conclusions and future scope accomplished from the proposed work.

Technical Significance

Noise and interference may cause signals to be distorted, increasing the probability of receiving an inaccurate signal. Attracting the attention of the public was Amplitude Phase Shift Keying (APK). In comparison to ordinary M-ary modulation, the data rate-to-bandwidth ratio is improved with this modulation, as is the power consumption. For instance, the so-called "joint phase-amplitude modulation" happens when two separate base-band signals alter their amplitude and phase concurrently.

In order to modulate two orthogonal and identically frequency carrier signals, quadrature amplitude modulation (QAM) uses two mutually independent digital baseband signals. The modulated signals are accessible since they are orthogonal and share the same bandwidth. Digital signals may be sent in both phase and quadrature. Eq. (1) gives a generic expression for the QAM signal;

$$S_{MQAM}(t) = \sum_n A_n g(t - nT_s)\cos(\omega_c t + \theta_n) \qquad (1)$$

Baseband signal amplitude is represented by the sign An, the waveform is given by $g(t - nTs)$ and the signal width is given by Ts in the formula.

At the same time, Eq. (2), (3) & (4) may be used to convert the above expression to an orthogonal representation.

$$\sum A_n g(t - nT_s)\cos\theta_n]\cos\omega_c t - [\sum A_n g(t - nT_i)\sin\theta_n]\sin\omega_c t \qquad (2)$$

$$S_{MQAM}(t) = X(t)\cos\omega_c t - Y(t)\sin\omega_c t \qquad (3)$$

$$\begin{cases} X_n = c_n A \\ Y_n = d_n A \end{cases} \qquad (4)$$

Amplitude in QAM Yn can be expressed by Eq. (5);

$$\begin{cases} X_n = c_n A \\ Y_n = d_n A \end{cases} \qquad (5)$$

The criteria for mapping constellations are diverse, and the constellations have various distribution patterns. A star constellation and a square constellation may be found in the 16QAM constellation.

The use of APDs reduces part of the thermal noise, but it also increases the shot noise. Detection schemes that are just limited by shot-noise could be a viable option. Before it strikes the detector, coherent detection, a technique that uses a CW optical field to combine an incoming optical signal with a coherent signal, offers the response. In addition, because it translates phase fluctuations into amplitude variations, this approach may be used to encode phase modulation (FSK and PSK modulation formats).

A Local Oscillator (LO), a term taken from radio and microwave literature, is used to produce a coherent field at the receiver. Fiber interconnects and fiber optics are used to mix it with the incoming optical field. Eq. (6) and Eq. (7) show how the optical signal may be mixed to improve the receiver's performance;

$$E_S = A_S \exp\left[-i(\omega_0 t + \varphi_S)\right] \qquad (6)$$

$$E_{LO} = A_{LO} \exp\left[-i(\omega_{LO} t + \omega_{LO})\right] \qquad (7)$$

LO's amplitude, frequency, and phase are referred to as A_{LO}, ω_{LO}, and φ_{LO} respectively. After simply assuming that the two fields are similarly polarized, the scalar concept is applied to both Es and E_{LO}. $P = |Es + E_{LO}|2$ is the optical power incident on the photo-detector. Equation (Eq. 8) is derived from two equations above;

$$P(t) = P_S + P_{LO} + 2\sqrt{P_S P_{LO}}\,\cos(\omega_{IF} t + \varphi_S - \varphi_{LO}) \qquad (8)$$

The intermediate frequency (IF) is defined as $vIF \equiv \omega IF/2\pi$. The optical signal is demodulated in two phases when $\omega 0 \neq \omega LO$ is present. A vIF intermediate frequency must be created first before the carrier frequency can be utilized (typically 0.1-5 GHz). The resultant radio-frequency signal is then processed electronically to retrieve the bit stream. The intermediate frequency isn't always essential. If ωIF is zero, there are two options for coherent detection: Homodyne and heterodyne detection techniques.

The local oscillator frequency ωLO is chosen to match the signal carrier frequency ω0 using this coherence detection technique. The photocurrent ($I = RdP$, where Rd is the detector's sensitivity) is given by Eq. (9), which can be found in the equation above;

$$I(t) = R_d(P_S + P_{LO}) + 2R_d\sqrt{P_S(t) P_{LO}}\,\cos(\varphi_S - \varphi_{LO}) \qquad (9)$$

$P_{LO} >> Ps$, and $Ps + P_{LO} \approx P_{LO}$ is a basic pattern in programming. The decision circuit uses the information in the final term of this equation to make a decision. It's assumed that the phase of the local oscillator (φLO) is in sync with the signal phase ($\varphi s = \varphi LO$) The homodyne signal may be found in Eq. (10).

$$I_p(t) = 2R_d\sqrt{P_s(t) P_{LO}} \qquad (10)$$

The $I(t)$ equation reveals another benefit of coherent detection. Since the final part of this equation specifically contains the signal's phase, data may be retrieved using the optical carrier's frequency or phase. Direct detection is unable to do this due to the loss of all signal phase information. Another lesson covers the various modulation schemes that need phase encoding.

Phase sensitivity is another disadvantage of homodyne detection. The phase of the local oscillator, φLO, is explicitly stated in the $I(t)$ equation above, therefore it is evident that φLO should be regulated. Except for the deliberate modulation of as, φs and φLO should remain constant. As time goes on, both φs and φLO change in a non-linear fashion. However, an optical phase-locked loop may maintain their differences $\varphi s - \varphi LO$ almost constant. The design of optical homodyne receivers is made more difficult by the implementation of such a loop. As a result, the two optical sources must satisfy severe requirements in terms of matching the transmitter and local oscillator frequencies.

Methodology

Fig. 1 and Fig. 2 illustrate the technique implemented in the paper. In-phase and quadrature (I/Q) 16-QAM modulators at the receiver utilize CW laser light as optical carriers for the X and Y polarizations at the transmitter. To create the DP-16-QAM signal, the X and Y modulated optical signals simultaneously using a polarization combiner. Each of the 16 QAM modulators is built from an M-ary pulse generator, a dual drive MZM, and a 90° phase shifter.

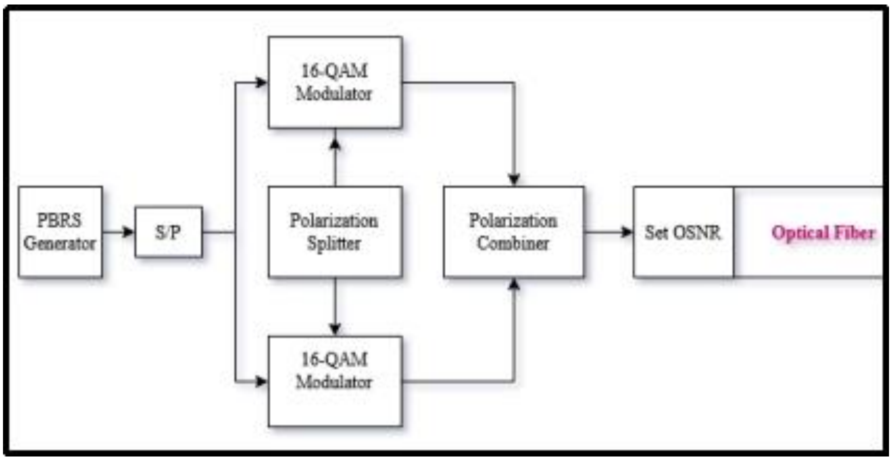

Fig. 1: Basic Block diagram of methodology used: Transmitter

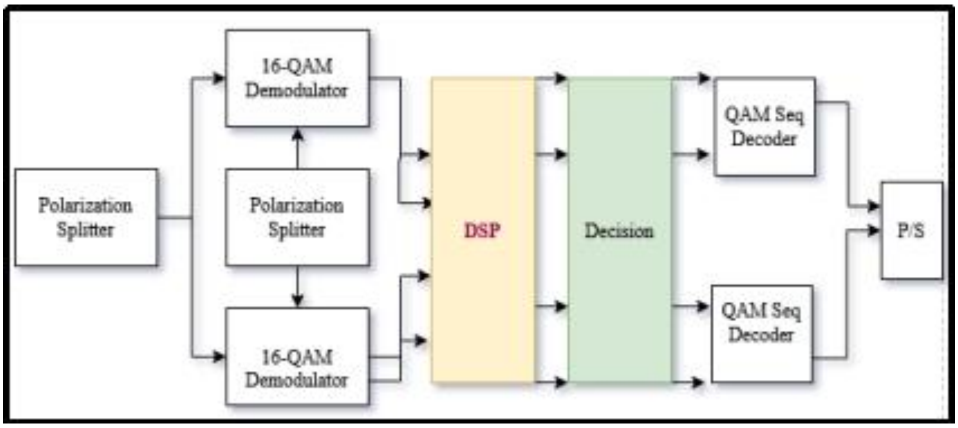

Fig .2: Basic Block diagram of methodology used: Receiver

There is a 90° phase shift in the lower optical signal. As a result, the optical signal from the cross coupler is 16-QAM modulated. Bias inputs of 2 V and -2 V are required for each modulator to operate at its null point of operation. In the QAM sequence generator, 16-QAM symbols of four bits each are generated from the incoming data stream. The receiver's decision unit is then followed by balanced photodetectors, EAs, and electronic amplifiers.

There are a variety of advanced algorithms in the advanced digital signal processing unit to correct for different signal defects. BPS is a method for minimizing phase misalignment between transmitters and receivers by repeatedly doing tests until the optimal phase is determined. The balanced photodetectors reduce the system's intensity noise. After removing the photocurrents, intensity changes in both branches are precisely correlated and cancel each other out.

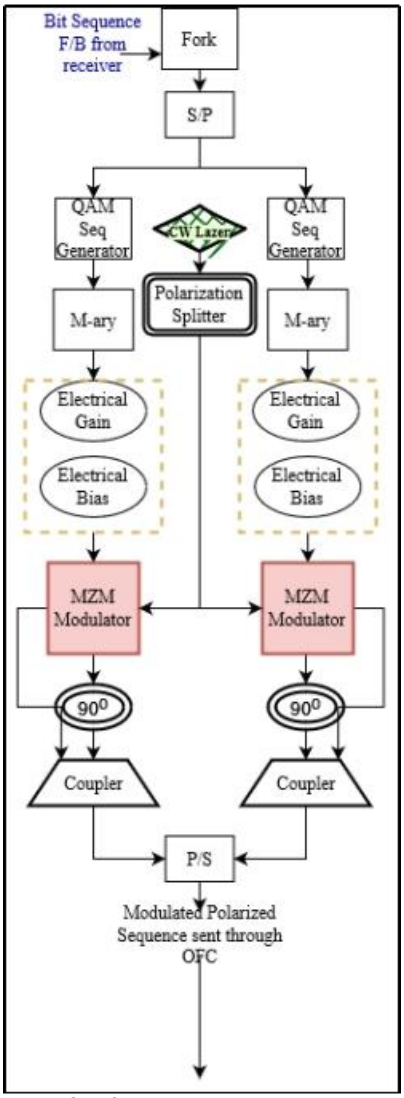

Fig. 3. Flowchart: Transmitter Section

The transmitter is divided into two sections having an upper path and a lower path as shown in Fig. 3. A QAM Sequence generator takes the bit sequence output from the serial to parallel converter as input. A constellation diagram is generated using the output of a QAM Sequence generator by an M-ary pulse generator. A M-ary pulse generator uses the QAM Sequence generator's output to help generate a constellation diagram. The signal from the M-ary pulse generator is forked using a 1x2 fork component. Using electrical gain and bias, this may be further adjusted. The MZM Modulator accepts the signal once it has been changed. The second input to the MZM Modulator is the CW laser's dual polarization signal. The signal from the laser source is polarized using a polarization splitter. The polarization considered is 0 and 90º. The output of the splitter is then passed to a 2x2 coupler. The signal behaves as the second input to the MZM Modulator. The same design principle is followed for the lower path of the transmitter section. The signal is modulated by the MZM Modulator. One of the outputs of the MZM Modulator is connected to a 2x2 coupler, which introduces a 90-degree phase shift. The polarization combiner fuses the output of the coupler. This modulated signal from both the upper and lower paths of the transmitter section will be passed through an optical fiber to the receiver section of the circuit.

The modulated signal from the transmitter is passed through the optical fiber to the receiver section. The length of the optical fiber is varied from 10 to 100 kms to check the reliability or the maximum range for seamless transmission.

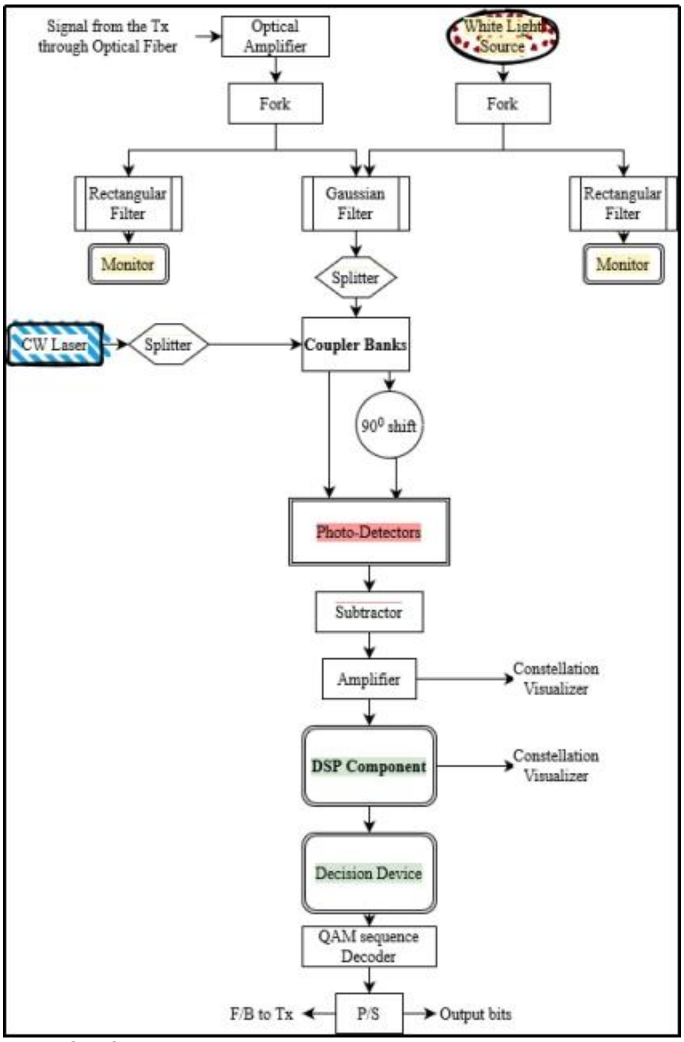

Fig. 4. Flowchart: Receiver

The white-light source is given as input to the 1x2 fork component. The output of the fork from one branch is then given to rectangular filter whose output is estimated through an optical analyzer. The output from the fiber is 1st amplified using an optical amplifier to improve signal quality, then is given as input fork 1x2. The output of the fork from one branch is given to an optical rectangular filter and analyzed. The other output from both the forks are combined using a power combiner

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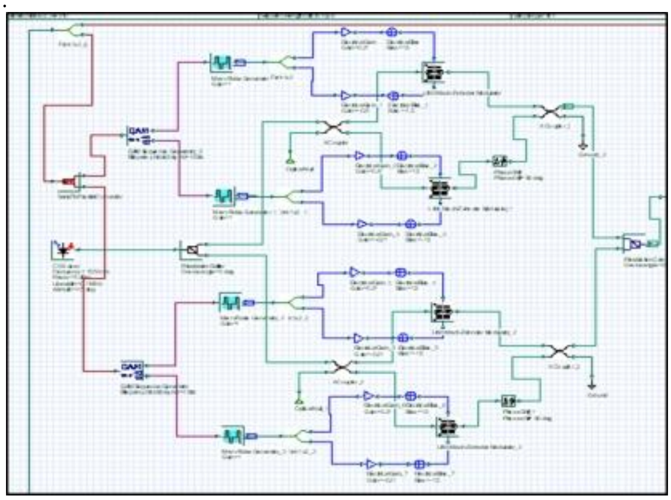

Fig. 5. Transmitter Simulation

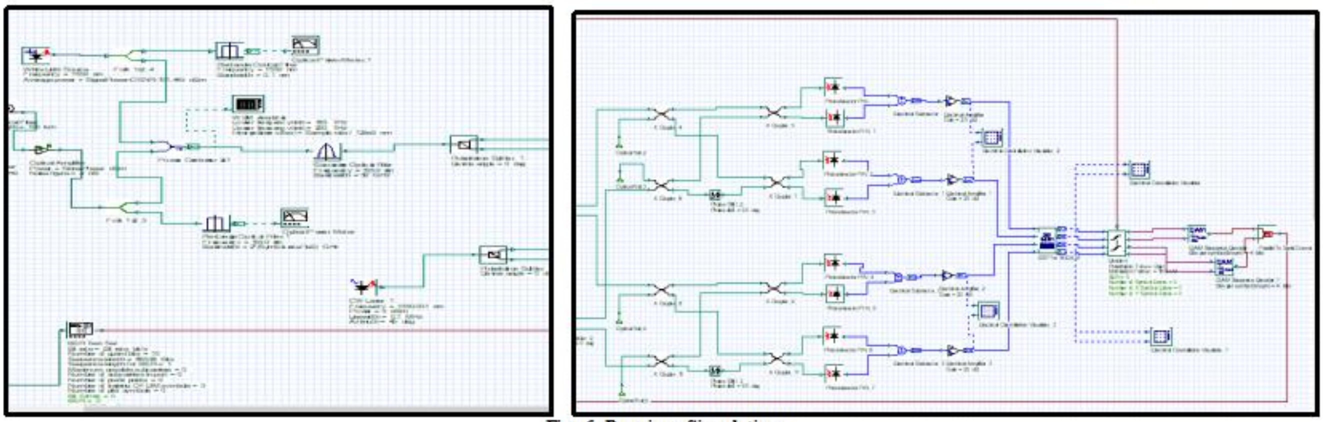

Fig. 6. Receiver Simulation

The optical Gaussian filter receives the combined output from the combiner. A polarization splitter receives the filter's output. There are 2 outputs from the splitter. Input from the CW Laser is given to another polarization splitter which gives 2 outputs. Each output of the polarization splitter is then given to a cross coupler. This implementation is represented in Fig. 4. One of the output of the cross coupler is given a phase shift and given as input to another set of cross couplers. This gives 8 outputs in total which is distributed as a set of 4. Each set of output is given to a PIN Photodetector. The output of the detector is then given to a subtractor which gives the difference between the presented input. Finally, a constellation visualizer is used to observe the increased signal. In each set, the DSP component receives four inputs from the output. After coherent detection, a DSP for 16-QAM component is used to execute a digital domain impairment compensation to aid recover the transmitted signal. In coherent systems, this should be used with 16-QAM modulation and single- or dual-polarization multiplexing (X and Y channels).

Back propagation (BP) is used to compensate for nonlinearity. An optical communications system that is coherent uses a linear map of the received photo-currents, which allows digital processors to access both amplitude and phase of the optical field.CD and fibre nonlinearity may be accounted for digitally by using an inverse fibre model.

Error power between an equalization output and a constant is reduced by using the CMA algorithm. To correct the phase discrepancy between the local oscillator and the input signal, the BPS method is applied. The output of the DSP component is then given to the Decision making device. This bit sequence is then fed to QAM decoder to give the final set of decoded bits. A parallel to serial converter combines the bit sequence to a single stream which is given as feedback to the transmitter section to minimize error. This will enable the system to have control over the SNR and BER.

Simulation

This section gives simulation circuit using the design parameters described in the previous chapter, as seen in Fig. 5 and Fig.6. The circuit is evaluated based on the experimental simulations made on it in terms of data rate, fibre length, and input power. The design parameters are given in Table. I

TABLE. I. DESIGN PARAMETERS

Parameters	Values
Bit Rate	112 Gbps
Samples per Bit	4
Sequence Length	65536
Laser Centre Frequency	193.1 THz
Laser Line Width	0.1MHz
Attenuation	0.2 dB/km
Electrical Amplifier Gain	20 dB
Photo Detector Responsivity	1 A/W
Photo Detector Dark Current	10 nA

Results & Discussion

A. *Performance analysis for varied data-rate*

The data-rate is varied from 15Gpbs to 40Gbps. Fig. 7(a) represents constellation of the output of the Receiver before the Digital Signal Processing (DSP) unit for 20Gbps. The constellation is distorted as can be seen in the graphic because to noise, amplitude, and phase problems.

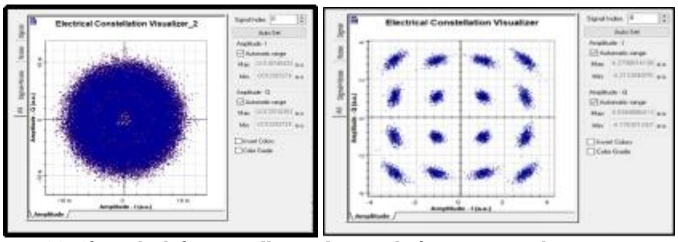

Fig 7(a). (*from the left*) Constellation diagram before DSP: 20Gbps
7(b). Constellation diagram after DSP: 20Gbps

Fig. 7(b). represents the constellation at the output at the DSP unit of the receiver section for 20 Gbps data-rate input and it is evident that the noise, amplitude and phase distortions and impairments are treated in the DSP unit which has improved the clarity in the constellation.

B. Performance analysis for varied optical fibre length

Optical fibre length is varied from 10kms to 100kms. Fig. 8(a) shows the output constellation at the receiver before the DSP unit for a fibre with a length of 10 km. Due to noise, amplitude distortions, and phase distortions, the constellation is warped. Optical fibre reveal the (nonlinear) sources of signal distortions and data loss.

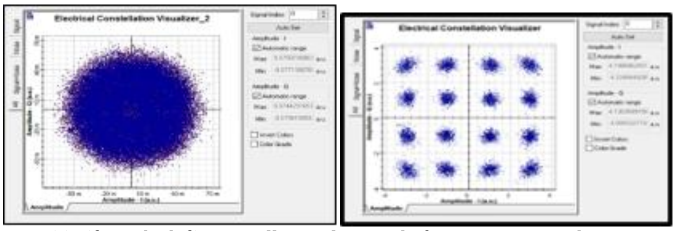

Fig. 8(a). (*from the left*) Constellation diagram before DSP w.r.t: 10kms
8(b). Constellation diagram after DSP: 10 Kms

Fig. 8(b) represents the constellation at the output at DSP of the receiver section for the 10 Kms length of optical fiber. It is seen that the noise, amplitude and phase distortions, along with the (nonlinear) sources of distortions & loss of information is treated by the DSP unit which has improved the clarity in the constellation.

Fig. 9(a) and 9(b) illustrate constellation diagram for length 100kms. It is observed from the diagram, the increase in optical fiber length, increases the listed distortions. As per our experimental results, we achieve optimum BER when optical fiber length = 50kms for a DP signal.

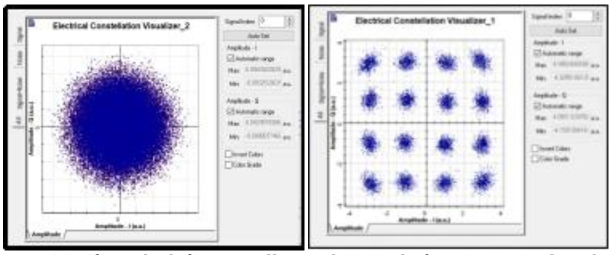

Fig. 9(a). (*from the left*) Constellation diagram before DSP w.r.t length: 100 Kms. 9(b). Constellation diagram after DSP: 100 Kms

C. Performance analysis for varied input laser power

Limitations arise from the amplified spontaneous emission noise that is virtually independent of the signal input power when the input power is 0 dBm. Figure 10(a) shows how the OSNR will deteriorate as a result of increased spontaneous emission noise.

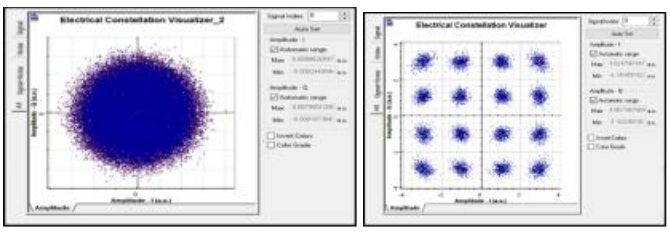

Fig. 10(a). (*from the left*) Constellation diagram before DSP :0 dBm
10(b). Constellation diagram after DSP: 0

Fig. 10(b) represents the constellation at the output of DSP unit at the receiver section for the 0 dBm input power level. The noise and impairments are treated by the DSP unit which has improved the clarity in the constellation.

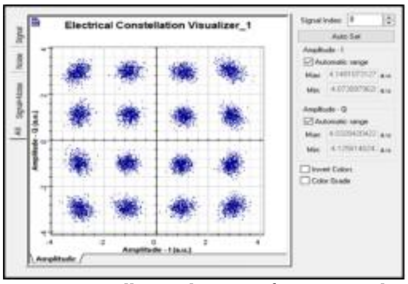

Fig. 11 Constellation diagram after DSP: 20dBm

Fig. 11 represents the 20 dBm input power level. The amplified spontaneous emission noise decreases with the increase in input power level, which in turn increases the OSNR. This is evident from the improved clarity in the constellation diagram.

Performance evaluation: BER vs Optical Fiber Length

It is evident from Fig. 12 that BER increases with increase in Fiber optic length. This is due to dispersion, attenuation, noise and non-linear sources of distortions. The simulated circuit provides optimum performance up to 50kms Optical fiber length. The experimental results are tabulated in Table II.

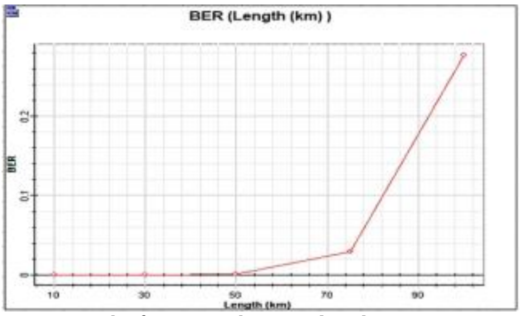

Fig. 12. Graph of BER vs Fiber optic length

TABLE II. VARIED FIBER OPTIC LENGTH W.R.T TO BER VALUES

LENGTH (KMS)	BER
10	0
20	0
50	0.000732645
75	0.0294127
100	0.276757

D. Performance Evaluation: BER vs Input Power Level

From Fig. 13, Non-linearity occurs at higher input powers while linearity occurs at lower input powers in the fibre channel. It is observed from the graph that when the input power is less than 12 dBm (<12dBm), BER performance improves with the increase in laser power.

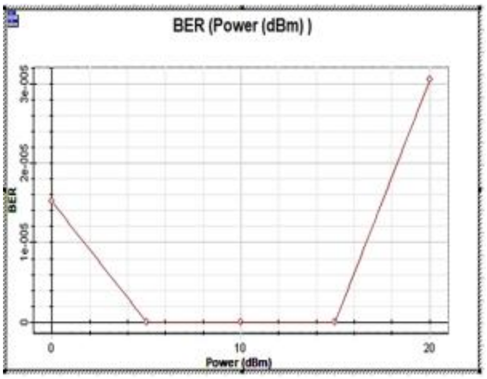

Fig. 13. Graph of BER vs Input Power Level

Also, the system's performance degrades substantially with increased laser power in the non-linear area, due to significant non-linear effects. The results are tabulated in Table III.

TABLE III. VARIED INPUT POWER LEVEL W.R.T TO BER VALUES

POWER LEVEL(DBM)	BER
0	0.52634×10^{-5}
5	0
10	0
15	0
20	0.05269×10^{-5}

Conclusion & Future Scope

Performance study of coherent DP-16 QAM under optical fibre communication system was shown. It was possible to correct for signal distortions such as Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), and Constant Modulus Algorithm (CMA) using BPS and CMA. For varying optical fibre length, input power levels in decibels, and data rates, the transceiver system provides up to 112 Gbps of data transfer at an acceptable overall system noise ratio (OSNR) For the simulated circuit, the maximum transmission distances range from 10 kilometers to 100 kilometers, with best results at 50 kms.

Proposed solutions to large capacity last-mile issues are offered. It will support and provide greater data rates at a lower cost and more communication capabilities for future generations of high-speed broadband connections. Coherent receivers have enabled extensive DSP for digital demodulation and equalization in fiber-optic networks. Wireline and wireless network also employ extensive transmit DSP for pulse shaping and pre-equalization to continue optimizing channel capacity use. These techniques have not yet been introduced into fiber networks largely due to the lack of high precision D/A converters that can operate at the > 30 GS/s needed.

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