A long-haul 100 Gbps hybrid PDM/CO-OFDM hybrid FSO transmission system:Impact of climate conditions and atmospheric turbulence

PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electronics and Communication Engineering with specialization in Specilisation in Communication Systems by the A P J Abdul Kalam Kerala Technological University

by

AKSHAYA S R

TKM20ECCS02

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

TKM COLLEGE OF ENGINEERING

KOLLAM 691 005

2022

A long-haul 100 Gbps hybrid PDM/CO-OFDM hybrid FSO transmission system:Impact of climate conditions and atmospheric turbulence

PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electronics and Communication Engineering with specialization in Specilization in Communication Systems Engineering by the A P J Abdul Kalam Technological University

by

AKSHAYA S R

(TKM20ECCS02)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

TKM COLLEGE OF ENGINEERING

KOLLAM 691 005

2022

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

TKM COLLEGE OF ENGINEERING

KOLLAM 691 005

CERTIFICATE

Certified that this thesis titled **"A long-haul 100 Gbps hybrid PDM/CO-OFDM hybrid FSO transmission system:Impact of climate conditions and atmospheric turbulence"** is a bonafide record of the work done by **AKSHAYA S R** (Reg. No. TKM20ECCS02) under my supervision, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electronics and Communication Engineering with specialization in Communication Systems by the A P J Abdul Kalam Technological University.

Guide
Prof.AMINA N
Assistant Professor
Dept. of ECE, TKMCE

Coordinator
Dr.NISHANTH.N
Associate Professor
Dept. of ECE, TKMCE

HoD
Prof.ABID HUSSAIN
Head, Dept. of ECE
Dept. of ECE
TKMCE

Acknowledgement

I own my heartfelt gratitude to GOD ALMIGHTY for all the blessings showered on me during the course of this project. I express my wholehearted thanks to the management of the college, TKMCE, for providing me an opportunity to do studies in this esteemed institution. I would like to express deepest appreciation towards Dr. T.A. Shahul Hameed, Principal for providing the facilities for my studies and constant encouragement in all achievements. I sincerely thank Prof. Abid Hussain M, Head of the Department for providing necessary information regarding the project and also his support in completing it. I also thank my coordinator,Dr.Nishanth N, Associate Professor in Electronics and Communication Engineering Department who gave expert supervision, encouragement and constructive criticism.I am indebted to my guide Prof. Amina N , Assistant Professor in Electronics and Communication Engineering Department who gave valuable suggestion, new ideas and also guidance in preparing this project. At last I must express our sincere heartfelt gratitude to all the staff members of Electronics and Communication Engineering Department who helped me directly or indirectly during this course of work.

AKSHAYA S R

TKM20ECCS02

ABSTRACT

Free space optics system(FSO) is significantly degraded by attenuation under different climatic conditions. An FSO transmission system with high-speed transmission capability is proposed by hybridization of PDM with CO-OFDM .The m-ary modulation scheme like 4-QAM analysis were obtaining. The impact of different climatic condition on system performance is investigated. Though simulations briefly explains the 100Gbps 4-QAM information transmission at 0.5km.The proposed system reduces channel fading,improves information rate,maximum transmission distance. This work is considered as future FSO system in adverse climatic conditions.

Contents

List of Figures

Chapter 1

INTRODUCTION

The FSO system is transmitting signals by arranging the free optical carriers in line-of-sight (LOS) set up between the communicating buildings or depots.The technology behind FSO hooked many research teams to analyse the advantages. The main advantage towards the FSO is listed as the secure data transmission,high speed transmission through the communication link, easy implementation and installation.FSO is license free and also the Last-mile access etc.Because of these merits it can be employed for high bandwidth application area in the signal transmission. In FSO, the data is carried by an optical signal which propagates to the free space affected by the adverse external climatic condition and in account that the optical signal degrades due to scattering and power absorption .So in FSO the quality of the received signal definitely degrades. Irregular atmospheric motion is one more case that degrades the FSO take on which influence differences in intensity and also the phase of laser beam at the receiver. Now a days through the study the researchers put forward and examined distinct topics about the optics, modulation schemes,diversity,RF signals in FSO, OFDM techniques, and also the channel coding to avoid the main problem caused by the atmospheric irregularities in FSO.

The OFDM is defined as a digital multi-carrier modulation term uses to maintain high data rate applications, high-performance in local area networks, wireless and also the multimedia communication. The polarization division multiplexing (PDM) were the different high speed information streams are transmitted by maintaining on the orthogonal polarized beams of laser source.

A hybrid PDM-CO-OFDM based Hybrid FSO transmission system is designed and examined the performance under the received power in effect of climate conditions.

Chapter 2

LITERATURE REVIEW

Development of a novel hybrid PDM/OFDM technique for FSO system and its performance analysis . [1]

A new system design for FSO communication is gave here by hybridizing PDM and OFDM. This system is performed under examined hybridized PDM, OFDM and analysis was performed under different climatic conditions.The proposed system gives an advanced performance capacity and spectral efficiency.The capacity, spectral efficiency and performance of PDM based FSO is disgraced due to the presence of of Fog. The presence of FOG leads to low visibility, less availability of FSO.This system is designed on hybridizing PDM/OFDM.

Long Reach High Capacity Hybrid MDM-OFDM-FSO Transmission Link Under the Effect of Atmospheric Turbulence. [2]

The system is designed,evaluated and analyzed using the coherent detection implemented to OFDM FSO link. The FSO link is subjected to analyze under the effect in atmospheric conditions.The 4- level QAM OFDM data signals were modulated using MDM. The independent signals were carriying 20Gb/s data.Observing on OFDM-SDM-FSO system in case of geometric losses and unfavorable climatic conditions.From the analysis and investigation concludes that the system performance degrades due to the increase of beam divergence angle.

Performance Analysis of MIMO CO-OFDM FSO System under Joint Effect Channel. [3]

The system comprises MIMO CO-OFDM in free space optical system. For the signal detection the system depoying Diversity combining,maximum ratio combin-

ing(MRC) and equal gain combining(EGC)schemes. The OFDM based FSO system analysis shown for distinct climatic condition at its maximum range. The sensitivity of receiver and reliability against channel fading is investigated and improved.These performance were evaluated by including coherent detection to OFDM.

PolSK and ASK Modulation Techniques Based BER Analysis of WDM-FSO System for Under Turbulence Conditions.[4]

Here high capacity FSO system is designed accordingly by using 4-channel WDM architecture employing PolSK.The system is subjected to analysis on BER for different climatic conditions. The given System react to the cross-channel effects as reduced value.The phase related variations of transmitting signal are also verified and analysed.

BER analysis of SS-WDM based FSO system for Vellore weather conditions. [5]

Here the proposed system model is deployed in vellore campus and analysed the results.The performance of the system get evaluated and considered the system as a cost effective one. The depoyment of 6.24 Gbps spectrum slicing WDM-based FSO system is used for varying climatic condition in states.The features of communication of data in the rate of 1.5GB/s provided with a bandwidth of 1550nm is examined.In the system the main disadvantage focus out by depoying in the campus was due to the wind,height of the building,atmospheric variations and refractive index the system gets degraded.

10 Gigabit/s OFDM based FSO communication system using M-QAM modulation with enhanced detection. [6] Here the system design proposed as the communication through FSO using MQAM. System is OFDM based communication with 10 Gigabit/s. The system subjected to examine on different climatic conditions Using an OFDM system. Using the OFDM system find out the maximum value of reach to weather conditions. Main demerit of these systems were in the system beam divergence,receiver aperture,transmitter power,weather conditions in FSO.

Performance of 120 Gbps Single Channel Coherent DP-16-QAM in Terrestrial FSO Link under Different Weather Conditions. [7]

In the proposed system a single carrier system is evaluated at 120Gbps.The system is a coherent transceiver one. It is observed under terrestrial Free Space Optical Link. The FSOL is examined in basis of various climatic seems like haze,rain,fog etc.. From

the results the system shows good signal to noise ratio for hard weather conditions. The main advantage to the system is good SNR,low cost,high capacity,short reach and strong communication link in weak environments.Main challenge to last mile communication. The proposed system was simulated according to the transmission range of 120Gbps.

Chapter 3

SYSTEM DESIGN

The proposed FSO system schematic which is designed and simulated using Optisystem version 14 software. In the given system,the PDM communication technique grows the capacity and efficiency of the system and the CO-OFDM is applied to produce strength against fading effects. Two individualistic high-speed data streams are noticed using a different Psuedorandom Bit Sequence(PRBS)unit.Each independent data is directed to a M-ary QAM generator block which encodes the data stream in two quardrature phase.The PDM/CO-OFDM technique used to realize the 4QAM at 100Gbps transmission rate.This data stream is modulated with 512 sub carriers over 1024 IFFT points using an OFDM modulator block. In the work, a continous wave laser is used to produce optical carrier beam.A polarization beam splitter seperate the optical laser beam to produce orthogonally polarized signals. An optical modulator modulates each information over different SOP beam as shown in figure 3.1.This signals are then combined by PBC and then given to the free space channel.

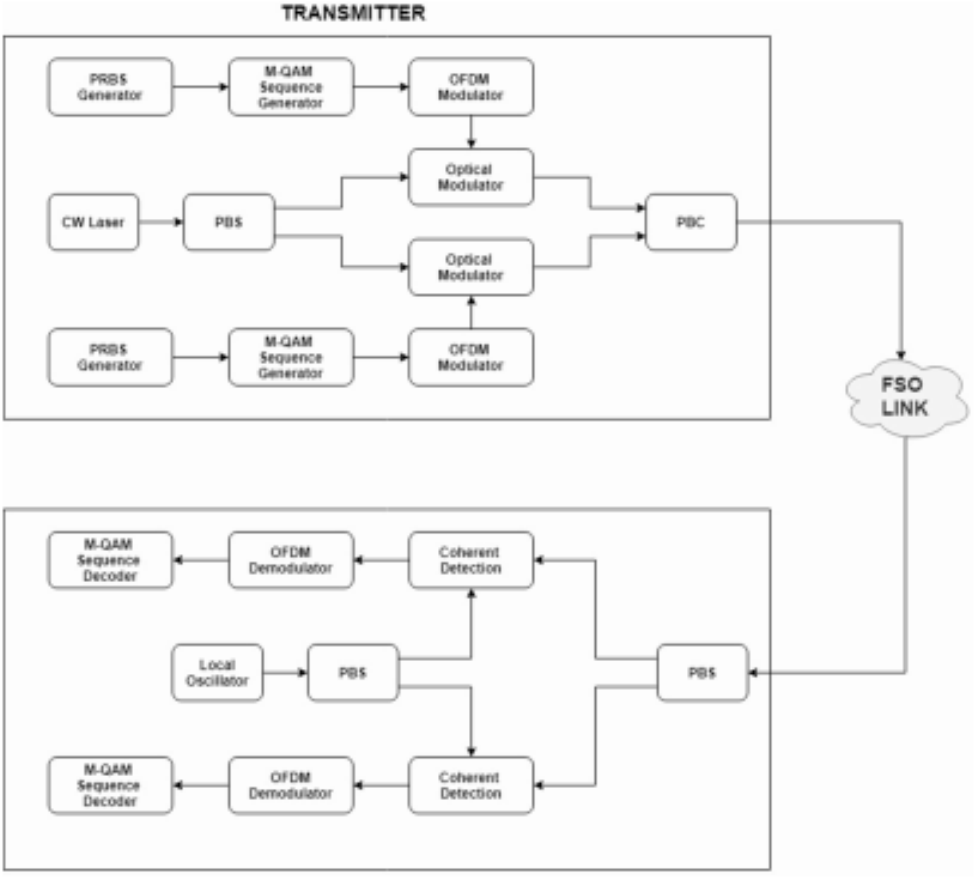

Figure 3.1: Schematic of the proposed FSO

The basic principle of OFDM is the IFFT demand the simultaneous communication of parallel data streams over each to each orthogonal sub-carriers with overlay frequency bands.The main advantage of OFDM application is High-spectral efficiency ,large capacity,low-cost performance and reliability against multipath fading,ISI,and frequency selective fading.The input binary information streams at the transmitter is converted to parallel information streams are unite using an M-ary quadrature amplitude modulator.The signal is aimed to an IFFT block,a guard interval is comprise to avoid ISI and overlapping of sub-carriers in order to continue orthogonality.Time domain signal is transformed to a serial data by the addition of cyclic prefix.

Digital signal is transfigure to an analog signal.The data transmission is over a wireless channel.In the receiver part,the cyclic prefix from the received signal is first gets eliminated and eventually a serial to parallel conversion and FFT algorithum. An M-ary demodulator resulted by a parallel to serial converter is used here to recover the transmitted signal is shown in figure 3.2. The atmospheric values are formed to

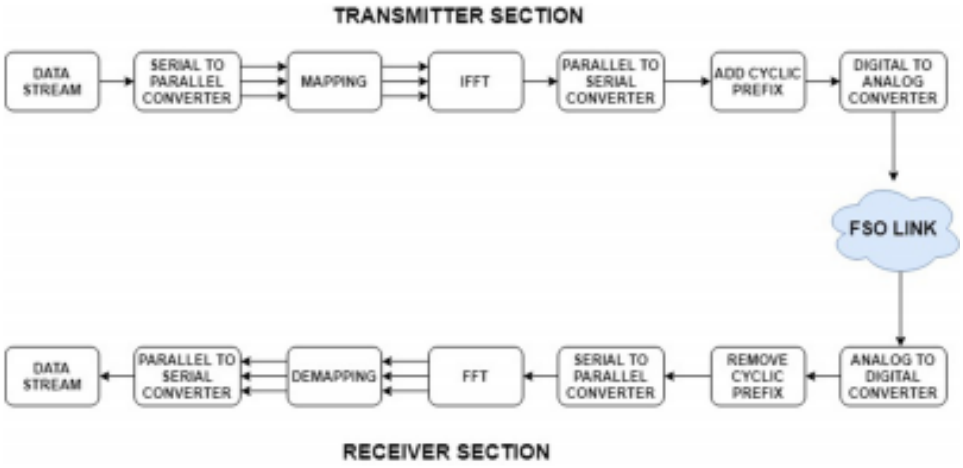

Figure 3.2: Diagram of OFDM system

the software using the parameters and certain attenuation for conditions of climate shown in figure 3.3.

Operating frequency	193.1 THz
Laser linewidth	0.1 MHz
Transmission power	15 dBm
Diameter of transmitter antenna	5 cm
Diameter of receiver antenna	20 cm
Receiver Losses	1 dB
Angle of divergence	2 mrad
Dark current	10 nA
PIN photodiode responsivity	1 A/W
Thermal noise power density	10^{-22} W/Hz
Ratio of ionization of PIN photodiode	0.9

Climate type	Specific attenuation (dB/km)
Clear	0.14
Low haze	2
Mild haze	4
Heavy haze	10
Light rain	6.27
Medium rain	9.64
Heavy rain	19.28
Light fog	34
Moderate fog	85
Dense fog	340

Figure 3.3: parameters and attenuation

Chapter 4

SOFTWARE

OptiSystem 14.0 software is used for the simulation of outcomes. Optisystem software is creative,quickly emerging, strong representation tool that provide users to design,check,and simulate to a certain extend all type of optical stream in the transmission of wide spectrum of optical networks.It provides transmission of optical communication system sketch and arrangement from basic level to system level.The results were visually included and also the analysis and structure. Optisystem provide users to stimulate the streams in both frequency and time domain: Optical networks frame composed of OTDM,SONET/SDH rings. Single -mode transmission and multi-mode transmission. Free space optics(FSO), Radio over fiber, OFDM, Amplifiers, and Lasers mainly EDFA,SOA,Raman,Hybrid ,fiber lasers. Optical signal processing,Electrical signal processing and Digital signal processing. Sub system design ,direct detection,coherent detection at transmitter and receiver stream. Modulation schemes like RZ,NRZ,CSRZ, DB,DPSK, QPSK,QAM-16,QAM-64. The Eye diagram, Q-factor,BER analysis, signal power,optical signal to noise ratio ,the constellation plots,polarization states analysis as system performance. The Optisystem Library of components comprise thousands of components that allow to go in for parameters and constants that is been measured from real systems.Users can include new components as subsystems , user explained libraries also. The users can use MATLAB,SPICE like tools for the simulation of results.

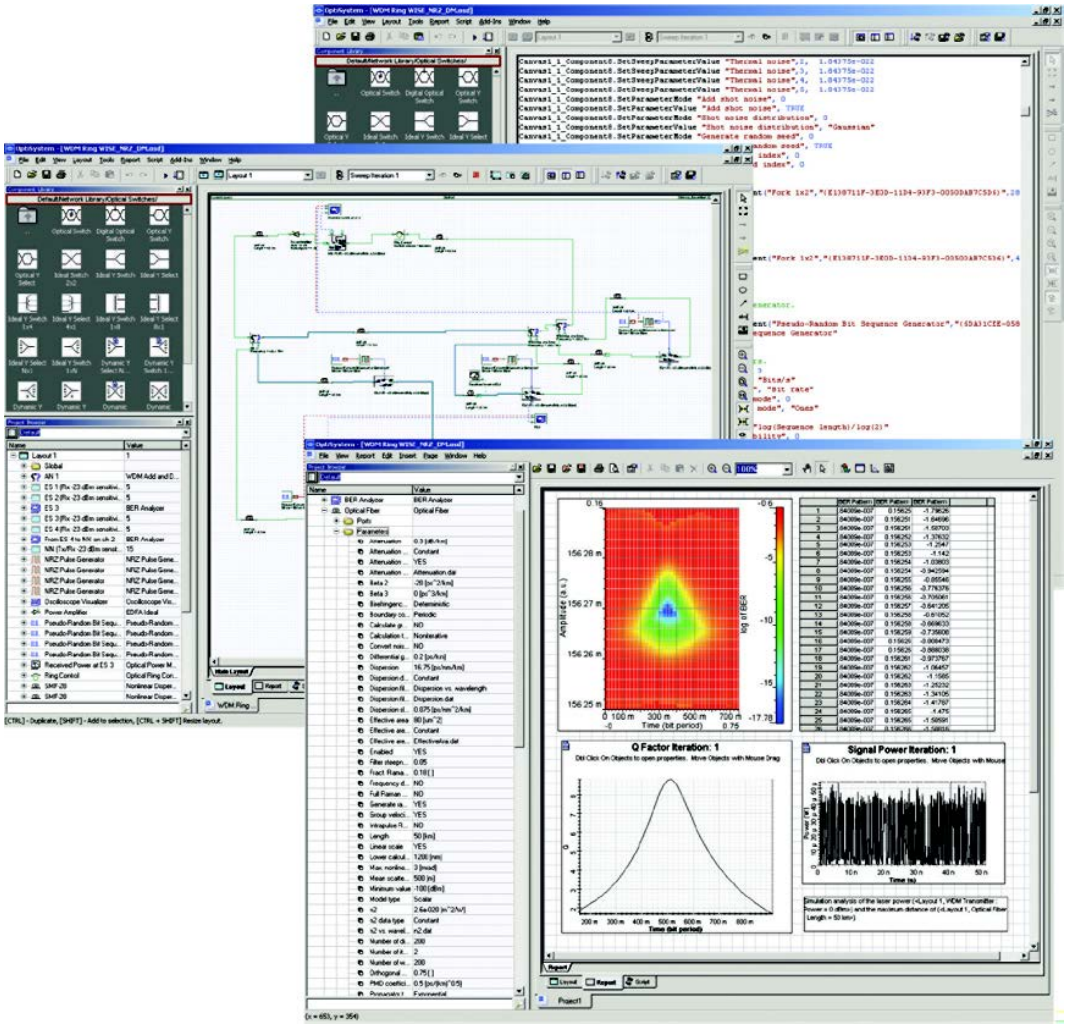

Figure 4.1: Schematic of software

Optisystem shows diverse signal template for optical and electrical signals in the library. By numerical analysis method the system performance like BER, Q-factor were calculated in optisystem. The imagining tools frame the optical Spectrum, eye diagrams,polarization state,constellation plot.

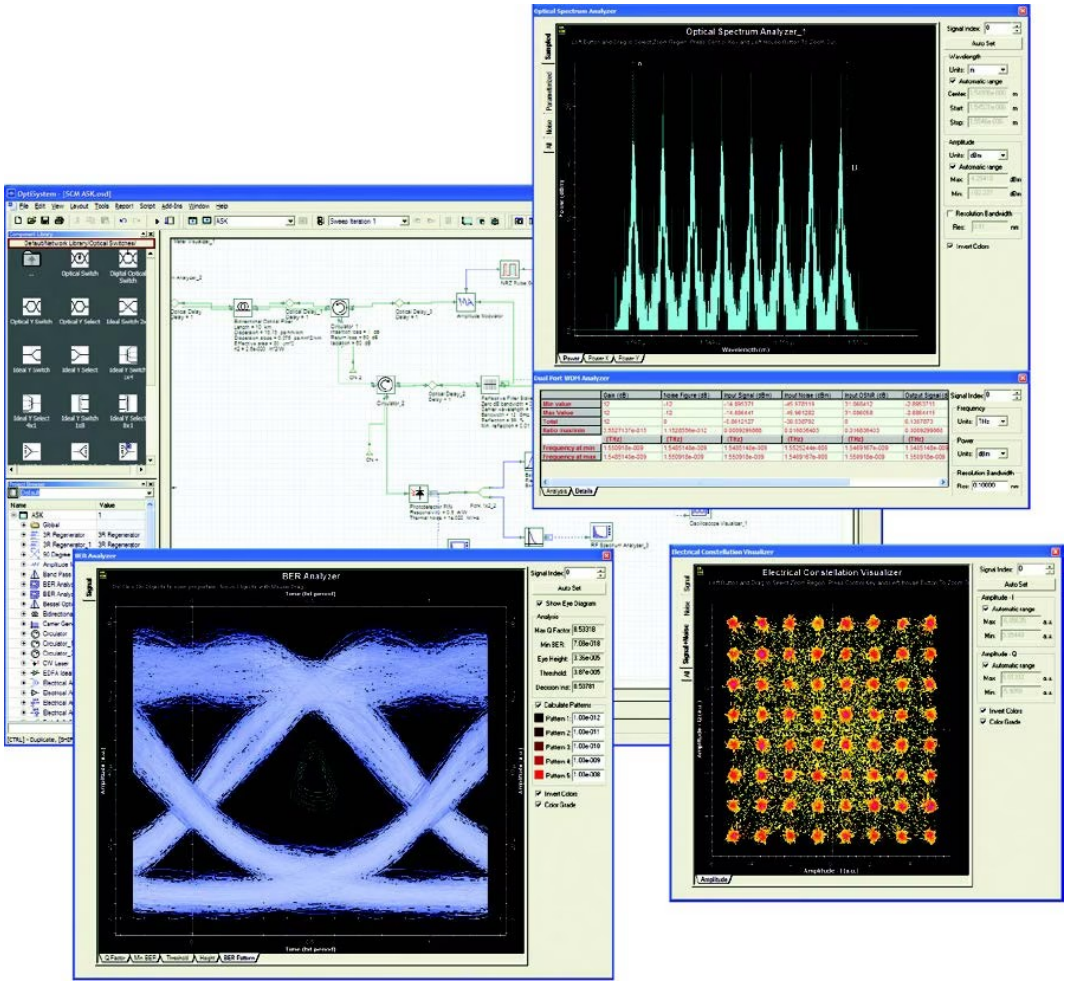

Figure 4.2: Schematic of BER, OSA, Constellation Diagram

The optisystem's Transmitter library includes a broad choice of optical bases. The electrical pulse generators, optical modulators ,Fabry perot,VSCEL also the optical signal pulse generators were in the library. The transmitter library includes electrical modulators like QAM,PAM,OFDM and multi-mode signal generators. Receivers library consist of all the model for optical communication. It is mainly focused on the design of receiver sub-systems. The Components in receivers library hold on the Clock/data recovery,3R named as regenerators, photodetectors,Demodulators, Decoders and Digital signal processing sets for single and dual polarization coherent systems.

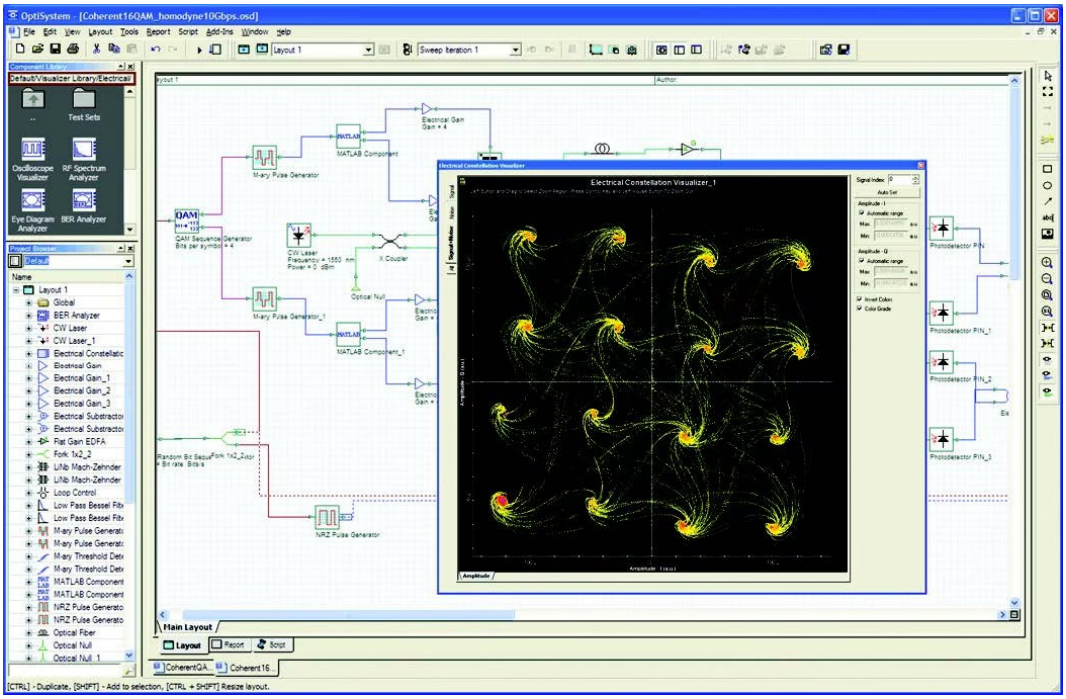

Figure 4.3: Schematic of Component Library

Optical fiber schemes were used to build the single mode and multi mode signal transmission. It contain dispersion,PMD,and linear,non-linear defects.

Chapter 5

SIMULATION AND RESULTS

The figure 5.1 shows the simulation of the system design in optisystem software. The system is designed for 500 m FSO channel range at 0.14 attenuation here it as

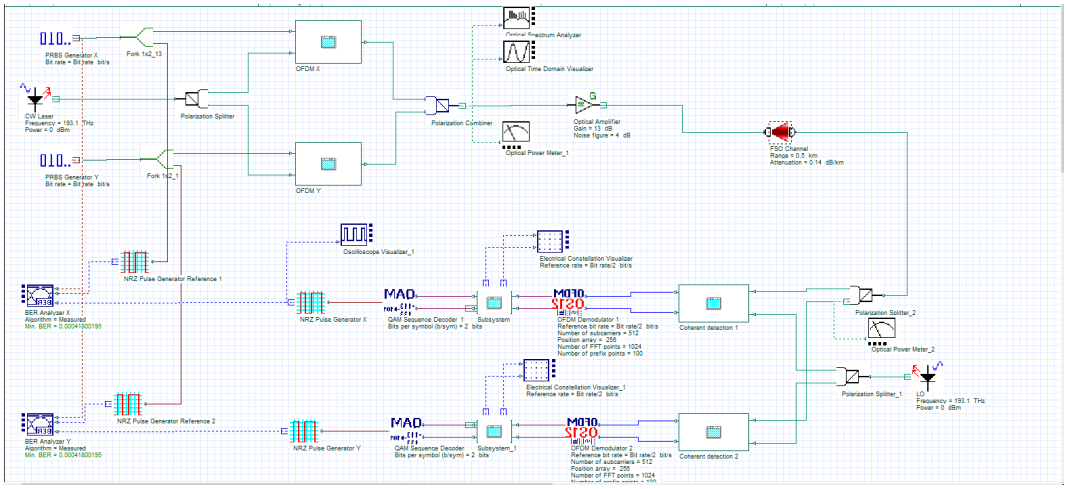

Figure 5.1: Simulation of system

clear condition. Numerically a 100 Gbps single channel FSO system including hybrid PDM/CO-OFDM 4 QAM transmission of data stream with a range in 0.5km is designed and investigated here. The figures 5.2, 5.3, 5.4 shows the optical spectrum of transmitted signal ,received power and Constellation plot respectively.The transmitted signal power is -12.87dBm.In a wireless channel considering the case of power in dBm studies explaining that the received power from -30dBM to -80dBm is as excellent and good ones and the power to -100dBm to -110dBm etc.. were poor ones.

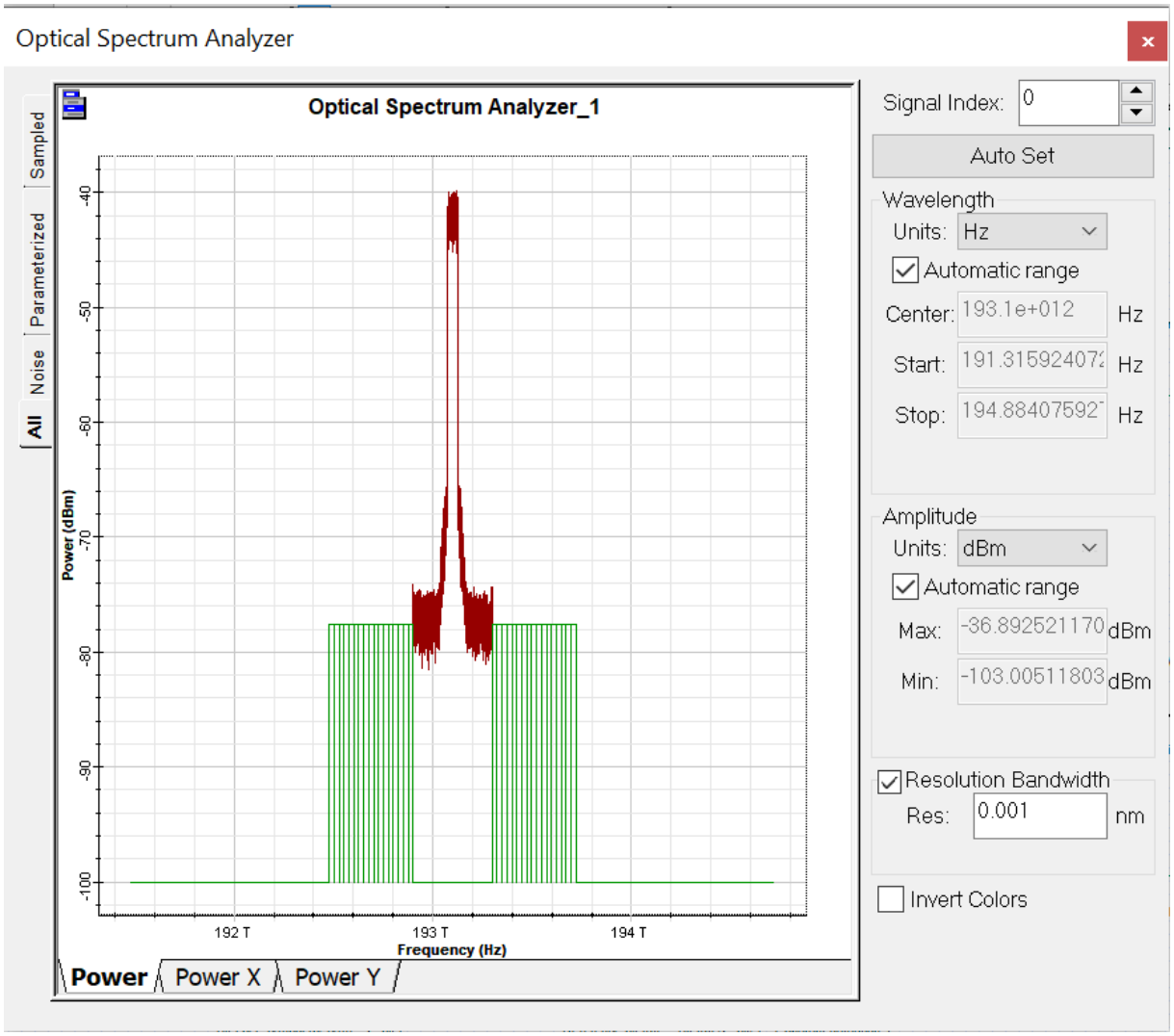

Figure 5.2: Received Optical Spectrum

The highest optical power observed is -14.33.dBm for 4-QAM at clear condition.

Figure 5.3: Received Optical Power

The minimum OSNR condition and highest range is attained by the 4 QAM signal.The rising figure of bits transmitted per symbol lowers the length between near by constellation symbols which diminishes the effectivness of the demodulator to correctly regain the data stream. The simulations of normal FSO consist of received spectrum,constellation plot, received power. All the modification given to the system were observed with these results respectively. In literature survey distinct methods were depoyed with CO-OFDM FSO transmission system using MQAM,Spectrum slicing WDM so on.The systems show high spectral effeciency ,high sensitivity,as well as good Q-factor.The system were mainly degrades due to the climatic variations.

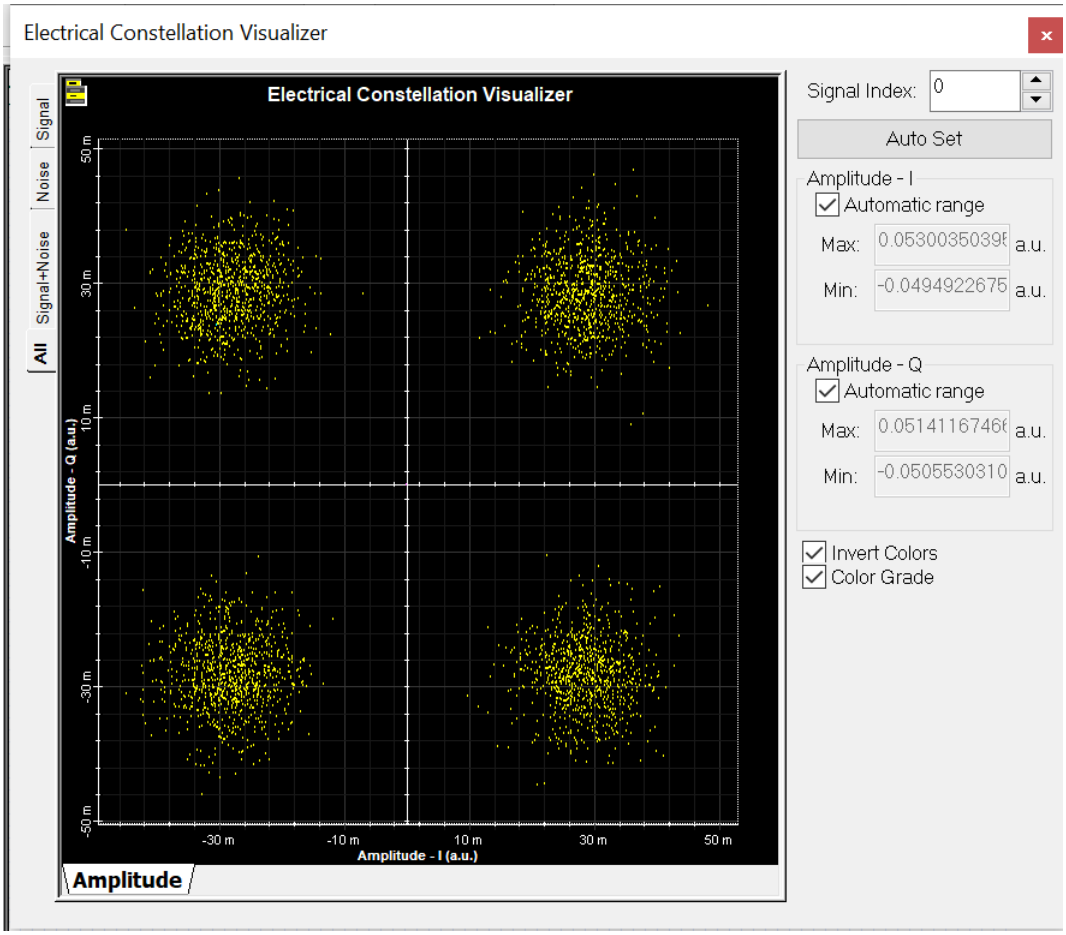

Figure 5.4: Constellation Plot of FSO transmission in 4QAM.

The constellation plot explains the digital signal in signal space. In the x-yplane the signal is represented with respect to amplitude and phase.If noise is more in the signal,in constellation diagram the plot is spreaded.

From analysis of literature surveys the suggested PDM/CO-OFDM based system is well defined for 4-QAM modulation.This is the idea behind the simulation of 4-QAM including PDM/CO-OFDM. Figure 3.3 shows the specific attenuation range for climatic conditions.

The system is evaluated under clear condition(0.14dB/km),Low haze(2dB/km) and Mild haze(4dB/km) conditions and stimulated the constellation plot,received power,received optical spectrum accordingly.The received spectrum of PDM/CO-OFDM system evaluated under 4dB/km shows 3dB bandwith in the range 0.05THz.For 500m FSO transmission in Mild haze,the received power obtained is -16.27dBm. The Q-factor is 34.5302 and BER is 0.000418 in the system. While comparing to the non coherent detection of OFDM the system shows less spectral efficiency. In all the observed condition the transmitted power is same and also the FSO range as 500m. The received power under attenuation 2 dB/km observed as -18.279 dBm.

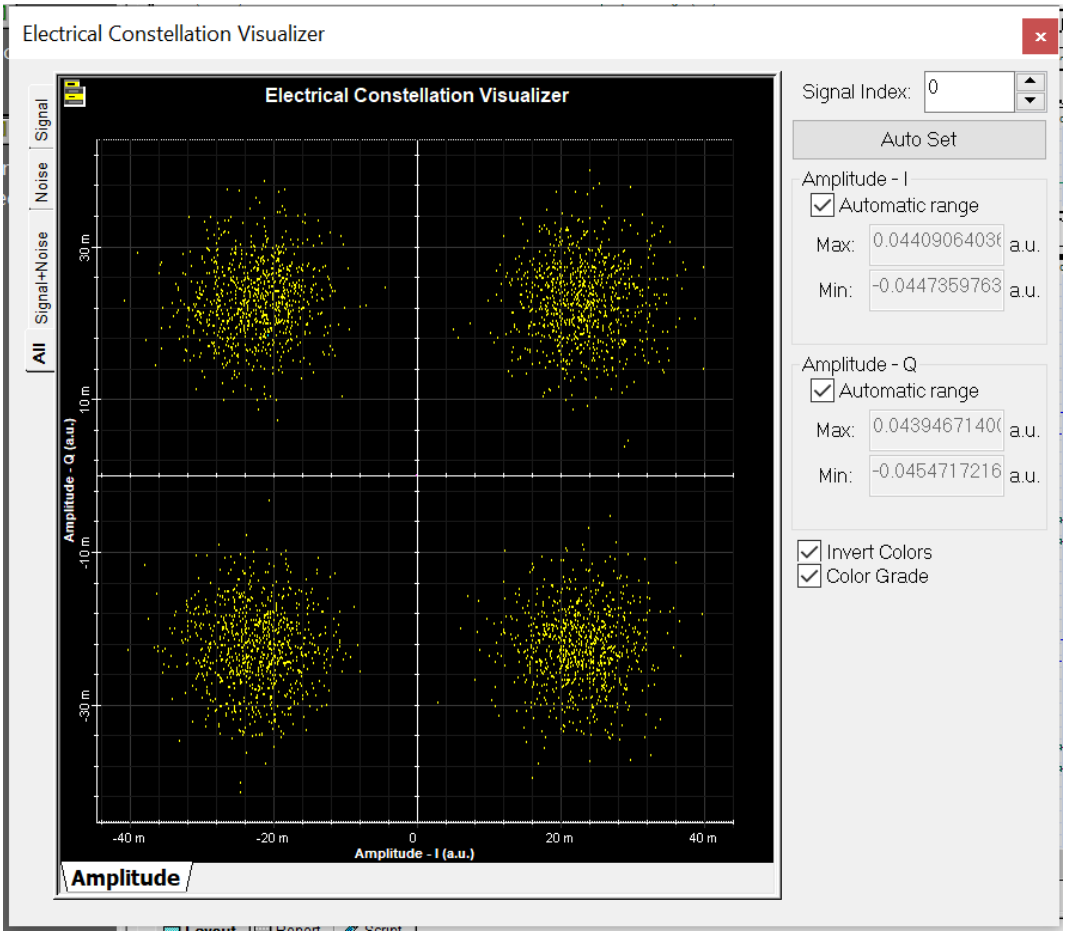

Figure 5.5: Constellation plot of Mild haze

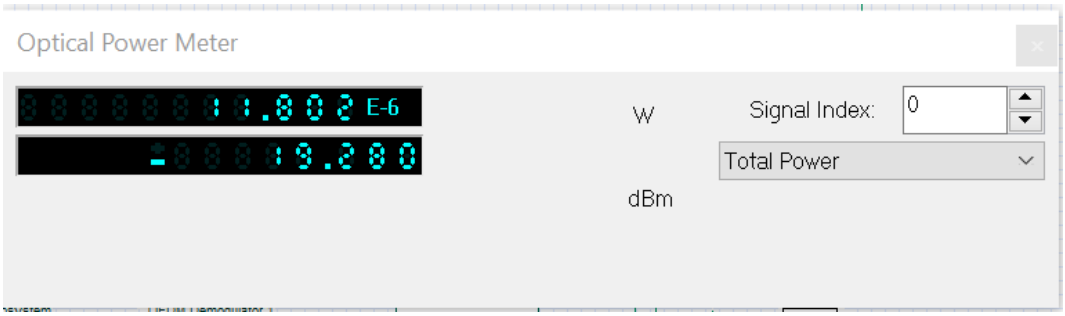

Figure 5.6: Received power of attenuation 4 dB/km

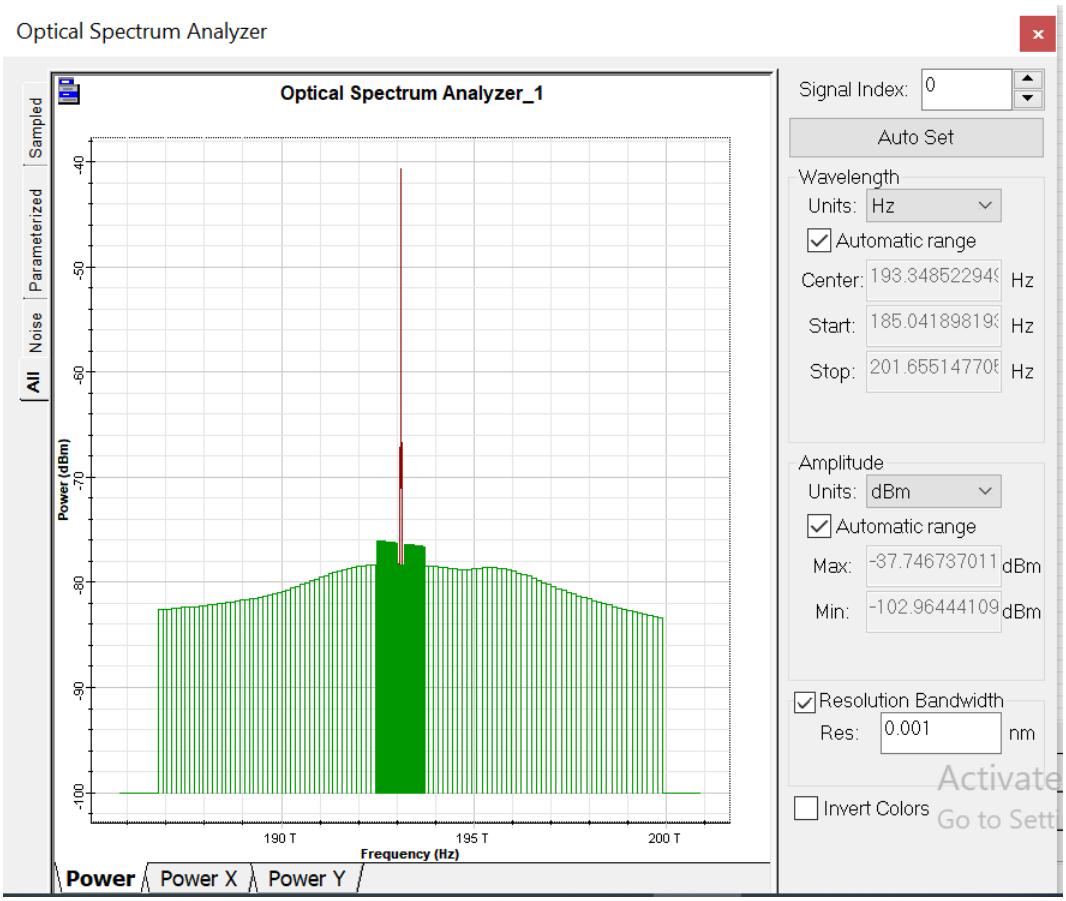

Figure 5.7: Received spectrum at attenuation 4dB/km

The system is subjected to some modifications. At first it is a single channel FSO including hybrid PDM/CO-OFDM transmission system. System is modified as Two channel FSO system mainly aim on the enhancement of FSO communication links under Complex enviornment. The single channel FSO under attenuation 4dB/km is simulated and results obtained. The result of a single channel hybrid FSO system is simulated first. It is observed that the received spectrum contains spectral efficiency and the power is observed as -18.89dBm. The 3dB bandwidth obtained from the

received spectrum were 0.027THz.

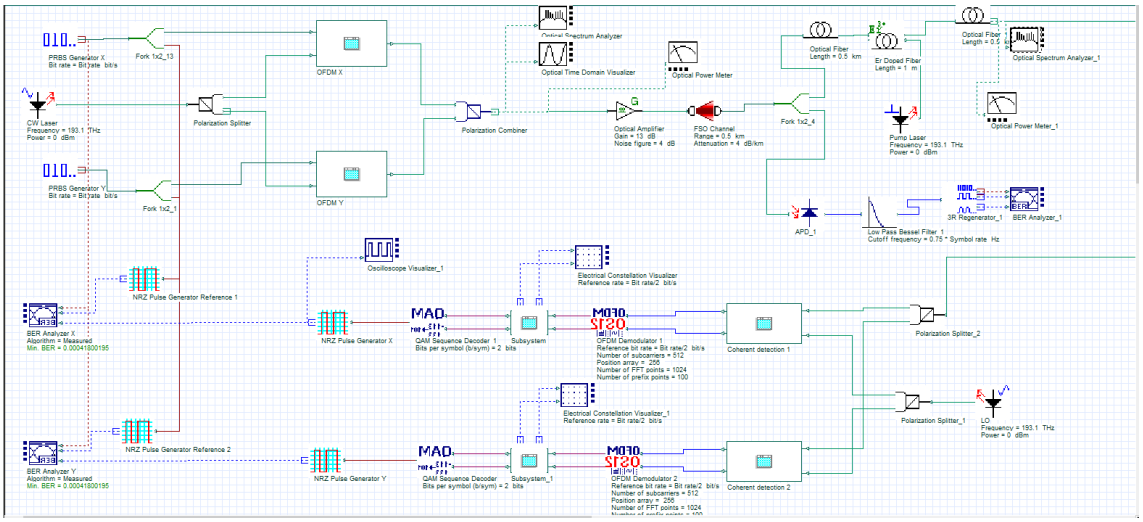

Figure 5.8: Single channel Hybrid FSO

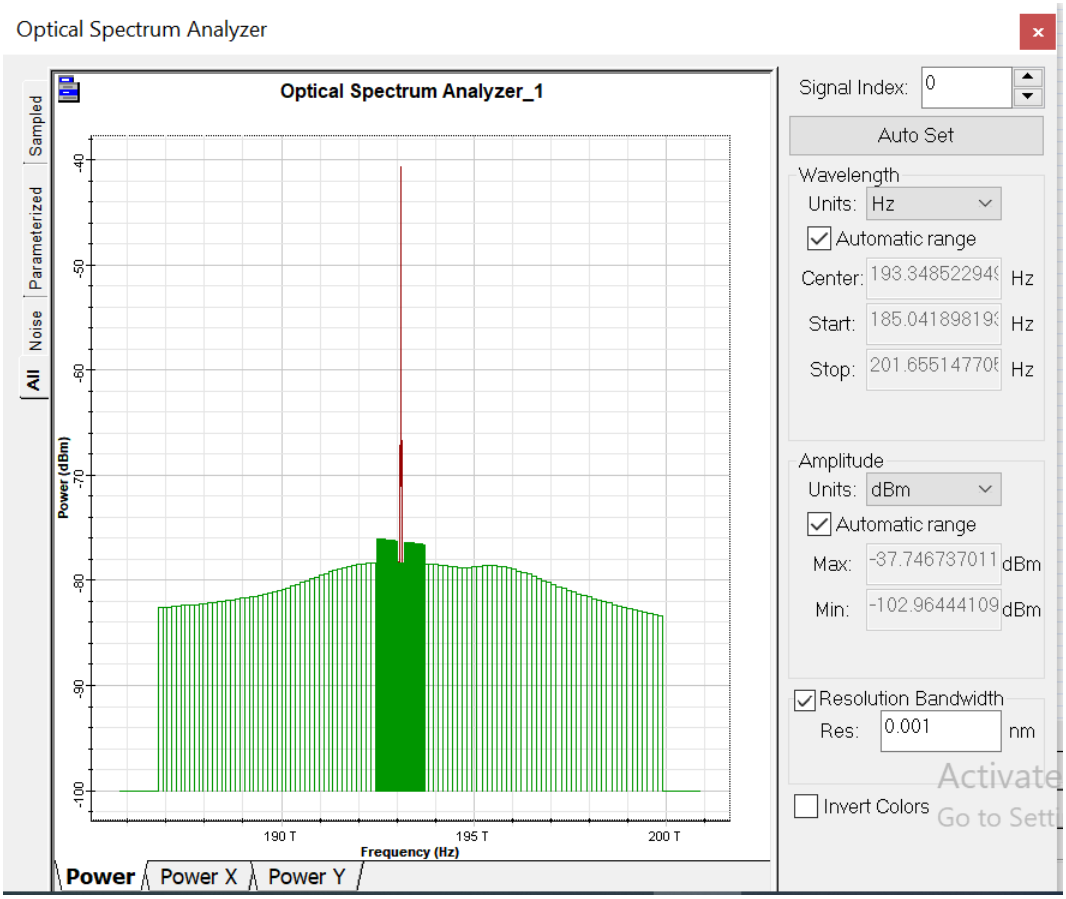

Figure 5.9: Received Spectrum of Hybrid FSO

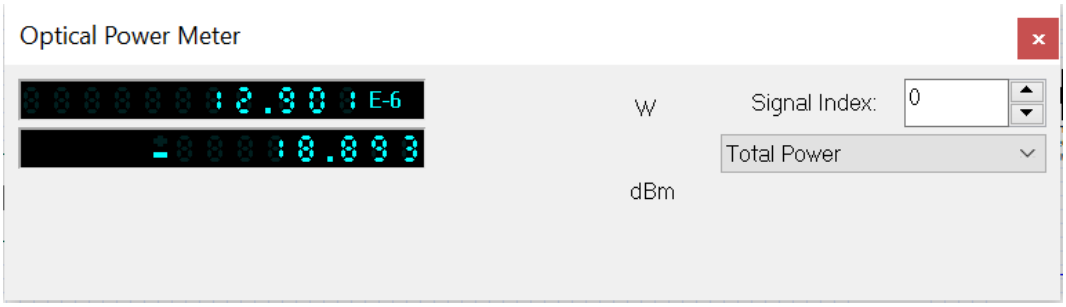

Figure 5.10: Received Power of Hybrid FSO

The system is evaluated to increase the transmission range incorporating optical fibers and analyzed the received power of the same transmission system.This is the idea of 100 Gbps hybrid PDM/CO-OFDM hybrid FSO transmission system. The term hybrid FSO here initiated in the system using optical fibers.The main advantage to incorporating this hybrid FSO to the system is the increment of the transmission distance in an acheivable range with an expected received power.

The two channel system was modified as two channel hybrid PDM hybrid FSO system. The system is analysed and simulated.The range of two channel FSO communication system were set to 500m,with an attenuation 4dB/km.The system gets analysed using both APD and PIN photodiodes.Using APD by replacing PIN photodiodes the variation is in the constellation diagram. A better constellation diagram is observed than PIN photodiode in the system. A comparision is done using the single channel Hybrid FSO to the Dual channel hybrid FSO. In normal single channel hybrid FSO with an attenuation 4dB/km and range upto 500m ,there noticed -18.89 dBm received power.The received optical spectrum was observed. The bandwidth in 3dB is observed here as 0.027dBm. Spectral efficiency is observed.In the previous system the bandwidth in 3dB is observed as 0.05THz. In dual channel hybrid FSO system the transmission distance of FSO set to 500m and attenuation 4db/km respectively.This is same for all the condition taken here. From the analysis of Dual channel hybrid FSO the spectral efficiency is spotted as in same 3dB,but the received optical power is observed as -17.395dBm.

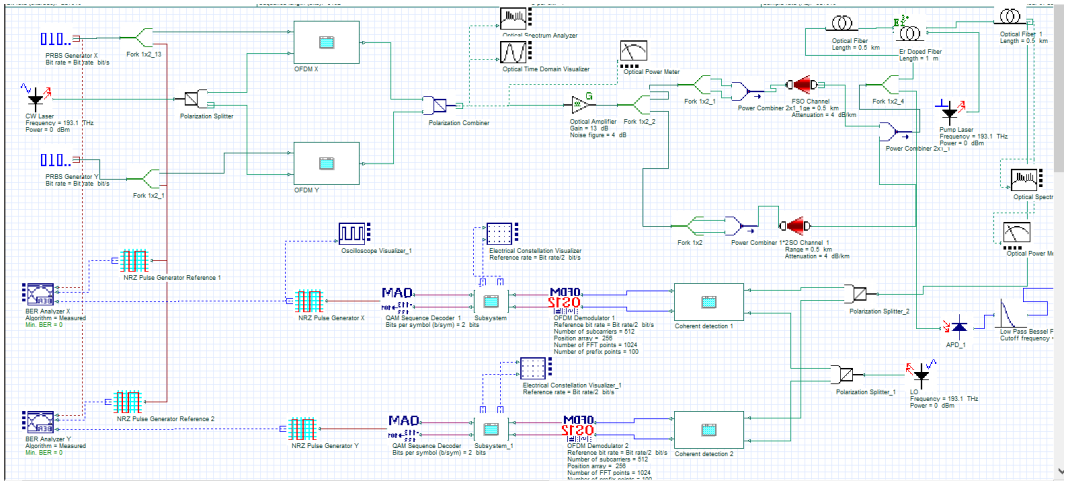

Figure 5.11: Hybrid PDM/CO-OFDM hybrid FSO with Dual channel

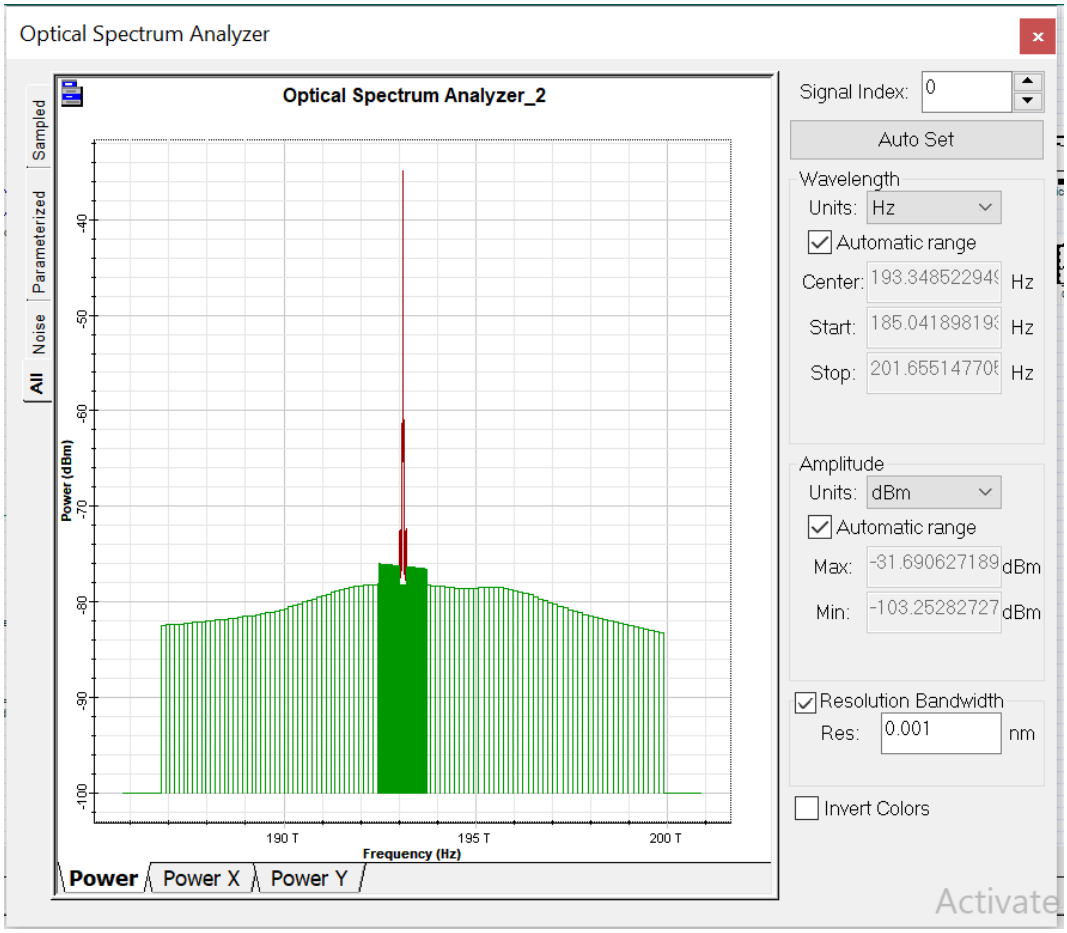

Figure 5.12: Hybrid FSO received Spectrum

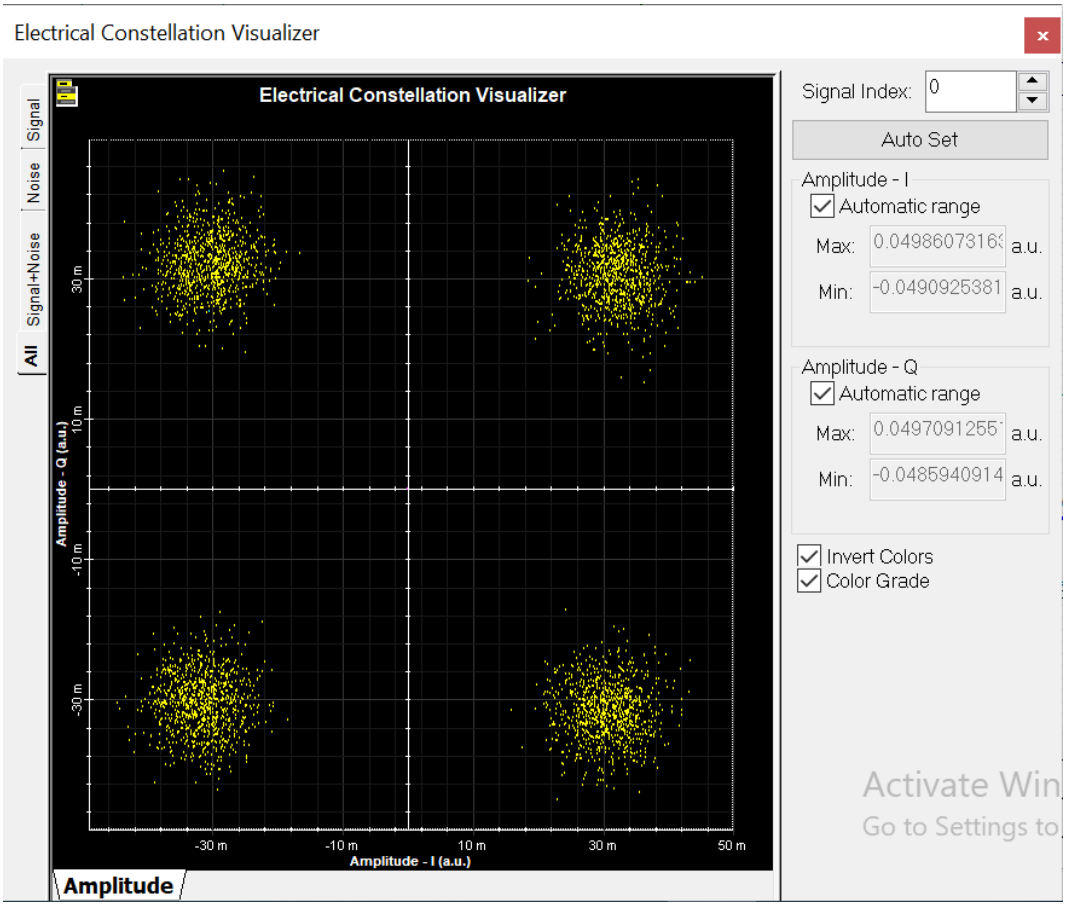

Figure 5.13: Constellation Diagram of dual channel

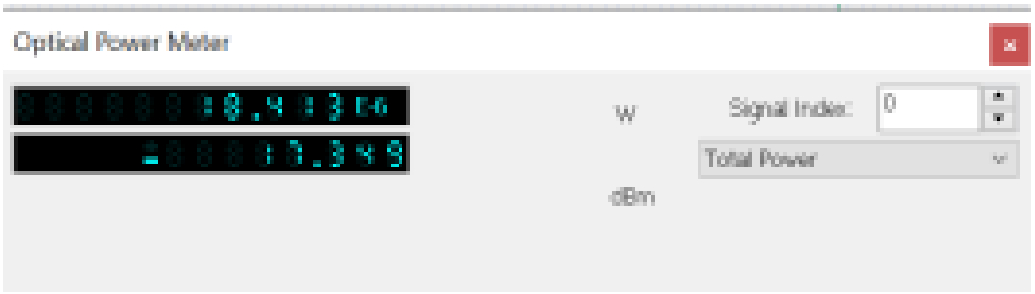

Figure 5.14: Received power of hybrid FSO with Dual channel

The system is evaluated at different range of transmission through the optical fibers. Here the two channel FSO at a range of 0.5km is directed to the two optical fibers .Erbium doped fiber in between the optical fibers.The maximum range of optical fibers are up to 1.5km in the system and erbium doped fiber maximum range up to 3m .The transmission distance of optical fibers evaluated with a range varying from 0.5km to 1.5km. The received power and constellation plots were observed with in these range . As the system explained in figure 5.1,in the hybrid FSO also

the attenuation evaluated under the range of 0.14dB/km,4dB/km respectively. The figures 5.11,5.12,5.13,5.14 expalins the simulation results of hybrid FSO using PIN photodiodes. Next the Dual channel FSO system is observed under by replacing PIN diodes as APD.

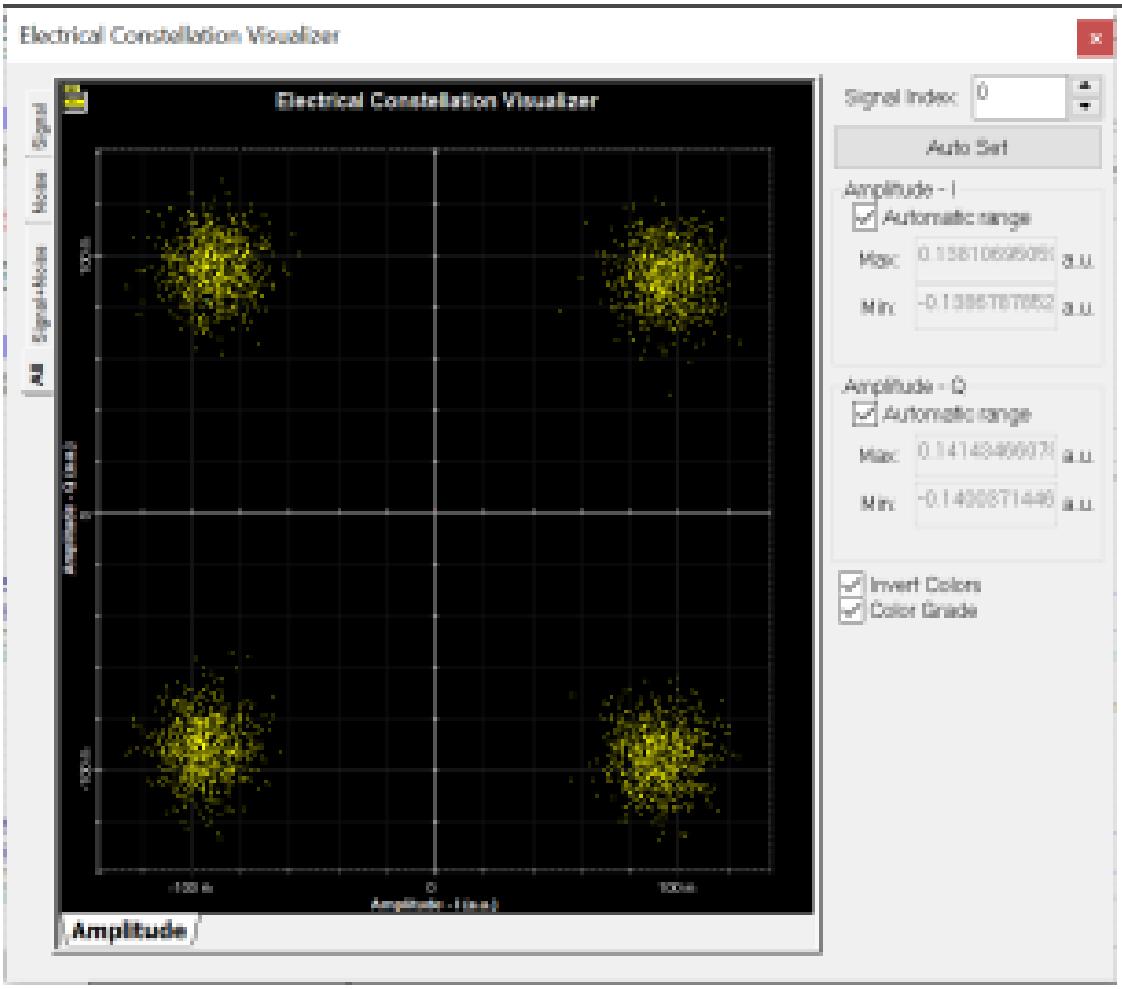

Figure 5.15: Hybrid FSO with APD-Constellation plot

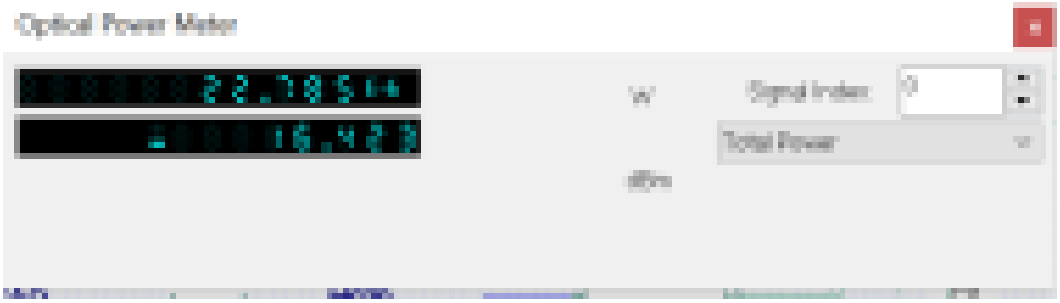

Figure 5.16: Hybrid FSO- Received power with APD

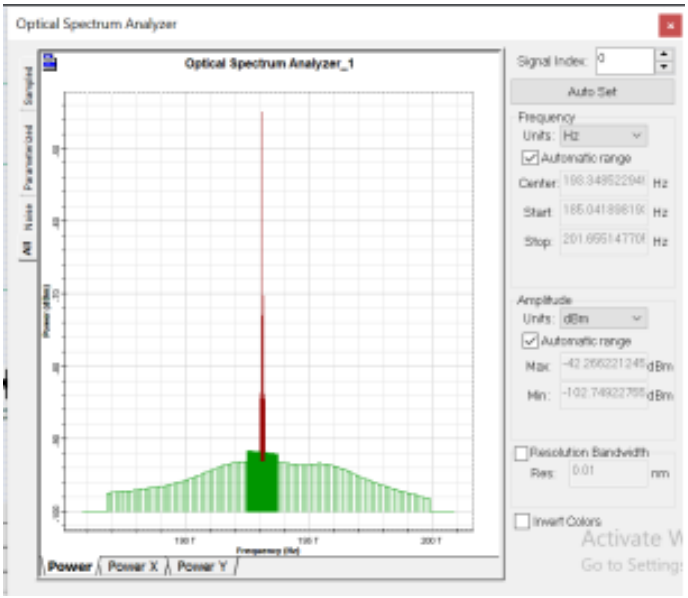

Figure 5.17: Hybrid FSO- Received spectrum

The highest received power obtained here as -16.423dBm.Narrow spectrum is obtained than using PIN photodiodes. Also the constellation plots are better.Using the hybrid fiber FSO the system can transmit the information range in 100-Gbps 500m FSO range with a highest received power.Successfully demostrated a Hybrid FSO in the range of 0.5 km.The hybrid FSO PDM/CO-OFDM with APD shows good spectral efficency,received optical power and better constellation plots. The further works were considered in future to increase the transmission distance of FSO.

Chapter 6

CONCLUSION

This work reports a Two channel FSO system with Hybrid PDM/CO-OFDM Hybrid FSO technique to increase the transmission range of information capacity.The system propose the reliability in fading at complex environments.The proposed Hybrid FSO system performance in means of received power is investigated for 4-QAM modulation scheme. The observed data indicate that using Hybrid FSO,implementing to the normal Hybrid PDM/CO-OFDM FSO system which gains highest received power.The transmission distance improved as 1000m than the previous system.The impact of climate condition upto 4dB/km is investigated and observed. Better constellation plots and result showing transmission of 100 Gbps 4-QAM data with in the range upto 1000m incorporating hybrid FSO with highest received power.

REFERENCES

[1] **D. Nguyen, J. Bohata, M. Komanec, S. Zvanovec, B. Ortega, Z. Ghassemlooy**, "Seamless 25 GHz transmission of LTE 4/16/64- QAM signals over hybrid SMF/FSO and wireless link", *J. Lightwave Technol. 37 (24) (2019) 6040–6047.*

[2] **D. Kakati, S.C. Arya,**" Performance of 120 Gbps single channel coherent DP-16-QAM in terrestrial FSO link under different weather conditions", *Optik 178 (2019) 1230–1239.*

[3] **A. Amphawan, S. Chaudhary, V. Chan**, "Optical millimeter wave mode division multiplexing of LG and HG modes for OFDM Ro-FSO system", *Opt. Commun. 431 (2019) 245–254.*

[4] **D. Kakati, S.C. Arya**, "Performance of grey-coded IQM-based optical modulation formats on high-speed long-haul optical communication link", *IET Commun. 13 (18) (2019) 2904–2912.*

[5] **G. Kaur, D. Srivastava, P. Singh, Y. Parasher**," Development of a novel hybrid PDM/OFDM technique for FSO system and its performance analysis", *Opt. Laser Technol. 109 (2019) 256–262.*

[6] **M. Singh, J. Malhotra,**" Performance comparison of high-speed long-reach mode division multiplexing-based radio over free space optics transmission system using different modulation formats under the effect of atmospheric turbulence", *Opt. Eng. 58 (4) (2019), 046112-1-9.*

J. Jeyaseelan, S. Kumar, B. Caroline," Performance analysis of free space optical communication system employinh WDMPOLSK under turbulent weather conditions", *J. Optoelectron. Adv. Mater. 20 (9) (2018) 506–514.*

[8] **J. Jeyaseelan, S. Kumar, B. Caroline,**" PolSK and ASK modulation techniques based BER analysis of WDM-FSO system for under turbulence conditions", *Wireless Pers. Commun. 103 (4) (2018) 3221–3237.*

[9] **J. Li, Z. Bai, Y. Yang, K. Pang, S. Sun, T. Han, K. Kwak**, "Performance analysis of MIMO CO-OFDM FSO system under joint effect channel", *in: 18th International Symposium on Communications and Information Technologies (ISCIT), 2018, pp. 26–31.*

[10] **N. Badar, R. Jha, I. Towfeeq**, "Performance analysis of 80 (810) Gbps RZ-DPSK based WDM-FSO system under combined effects of various weather conditions and atmospheric turbulence induced fading employing gamma-gamma fading model", *Opt. Quant. Electron. 50 (2018) 1–11.*

[11] **S. Chaudhary, X. Tang, X. Wei**," Comparison of LaguerreGaussian and donut modes for MDM-WDM in OFDM-RoFSO transmission system", *AEU Int. J. Electron. Commun. 93 (2018) 208–214.*

[12] **K. Prabu, S. Charanya, Mehul Jain, D. Guha,**" BER analysis of SS-WDM based FSO system for Vellore weather conditions", *Opt. Commun. 403 (2017) 73–80.*

[13] **H. Kaushal, G. Kaddoum**, "Optical communication in space: challenges and mitigation techniques", *IEEE Commun. Surv. Tutorial 19 (1) (2017) 57–96.*

[14] **H. Sarangal, A. Singh, J. Malhotra, S. Chaudhary**," A cost effective 100 Gbps hybrid MDM–OCDMA–FSO transmission system under atmospheric turbulences", *Opt. Quant. Electron. 49 (2017). Article ID-184.*

[15] **N. Kumar, A. Teixeira,** "10 Gbit/S OFDM based FSO communication system using M-QAM modulation with enhanced detection", *Opt. Quant. Electron. 48 (2016) 1–7.*

[16] **A. Malik and P. Singh,** "Free space optics: current applications and future challenges," International Journal of Optics, vol. 2015, Article ID 945483, 2015.", *Opt. Quant. Electron. 48 (2016) 1–7.*

[17] **X. Fang, A. Khalighi, C. Patrice, and B. Salah,** "Channel coding and time-diversity for optical wireless links," Optics Express, vol. 17, no. 2, pp. 872–887, 2009.

[18]**I. B. Djordjevic, B. Vasic, and M. A. Neifeld,** "LDPC coded OFDM over the atmospheric turbulence channel," Optics Express, vol. 15, no. 10, pp. 6336–6350, 2007.

[19]**J. S. Nandaniya, N. B. Kalani, and G. R. Kulkarni,** "Comparative analysis of different channel coding techniques," *International Journal of Computer Networks*

Communications, vol. 4, no. 2, pp. 84–89, 2014.

[20]**D. Shah, B. Nayak, and D. Jethawani,** "Study of different atmospheric channel models," *International Journal of Electronics and Communication Engineering Technology, vol. 5, no. 1, pp. 105–112, 2014.*

[21]**M. Grover, P. Singh, P. Kaur, and C. Madhu,** "Multibeam WDM-FSO system: an optimum solution for clear and hazy weather conditions," *Wireless Personal Communications, vol. 97, no. 4, pp. 5783–5795, 2017.*

[22]**S. Dimitrov,** "Analysis of OFDM-based intensity modulation techniques for optical wireless communications," University of Edinburgh, 2013.

[22]**Al-Gailani, S. A., Mohammad, A. B., Shaddad, R. Q.** (2012). "Evaluation of a 1 Gb/s free space optic system in typical Malaysian weather." *In 2012 IEEE 3rd international conference on photonics* (pp. 121–124).

[23]**Dhasarathan, V., Singh, M., Malhotra, J.** " Development of high-speed FSO transmission link for the implementation of 5G and Internet of Things". *Wireless Networks, 26, 2403–2412.*

[24]**Kumar, N., Rana, A. K.**. Impact of various parameters on the performance of free space optics communication system. Optik, 124, 5774–5776.

[25]**Ciaramella, E., Arimoto, Y., Contestabile, G., Presi, M., D'Errico, A., Guarino, V., et al.** (2009). 1.28 terabit/s (32x40 Gbit/s) WDM transmission system for free space optical communications. *IEEE Journal on Selected Areas in Communications, 27(9), 1639–1645*