International Journal of Engineering & Technology, 7 (3.8) (2018) 136-140

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

A Review On FSO By Using Different Modulation Techniques

Rajan Miglani[1], Sachal Charak[2], Sandeep Kumar Arora[3*], Mahedi Masud[4]

[1]*Lovely Professional University*
[2]*Lovely Professional University*
[3]*Lovely Professional University*
[4]*Taif University, Saudi Arabia*
**Corresponding author E-mail:sandeep.16930@lpu.co.in*

Abstract

Now a days as we are seeing that the free space optics is one of the emerging technology used for the replacement of the radio frequency wireless communication, due to their advantages over it like cost, speed, bandwidth, minimum error as well as efficient communication. The quality of services provided by the FSO is far better than the RF communication network. The free space optics is unlicensed band which make it less costly than the licensed band technology. As the atmospheric channel is used for transmission the effects of atmospheric condition effects the communication. In this paper we try to discuss all the modulation schemes which help to improve the performances of the optic system.

Keywords:*FSO;modulation;BER;OOK;PPM;PAM;PSK;OFDM;DPSK;QPSK;power efficiency; spectral efficiency*

1. Introduction

The rapidly increases in the wireless communication is one of the important change in the history of the communication technology. The first wireless technology take place is telegram which is invented in 1885. As the time move there is also the changes happened in the technology. Now that time is take place in which every user want the high speed network which cannot provided by the RF network so we have to see towards other technology and the optical fiber fulfill our demands. Recent year we are more focusing on the optical transmission [1]. The optical transmission in which we are transmitting the information wirelessly called as optical wireless communication or Free space optics (FSO). The FSO is the technology in which we transmitted the signal which is take places in the form of light through atmospheric channel. The light signal which is generated by the laser or LED is transmitted through the atmosphere and received by the PD (Photodiode) at receiver end. The FSO typically used the infrared spectrum for the transmission of the information signal. As the effects of the atmospheric conditions are less on IR wavelength but there are some ranges which experience distortion due to the molecules take places in the atmosphere[2]. The history of the free space optics is one of the ancient techniques which take in the eighth century. At that time the Roman and Greek solider use sunlight for the communication [3]. After that the fire, smoke, semaphore etc is used for point to point communication [4]. The photo phone is one of the first wireless phone which is invented but not commercially used in the market [5]. As the time changes the new advancement take place and the invention of laser and Light Emitting Diode (LED) take places which change the transmission of the optical wireless communication. Till date the filament lamps are used for the transmission of the information and the market of the FSO is also strict at one point. The inventions of the laser help to move forward in the direction of the FSO. The transmission should be in line of sight with the receiver section for the transmission of the voice signal, video etc in the optical wireless communication. The free spaces optics have many advantages over any conventional system like huge bandwidth which help us to transmit large number of data, narrow beam divergences which help us to transmit the signal to long distances with less misalignment. It also help to obtain high security as it is difficult to penetrate the narrow beam, the less power and mass requirement, easy to install, high speed, low cost as the cost of fiber and digging is removed so it is less costly than the convention technology.

The FSO is categories on the transmission bases like ultra shot range in which the communication is take places between the chips to chip or ultra shot range communication,[6] short range communication is define as the communication take place in wireless personal area network. This type of communication is take place in conference hall, in a room etc, medium range is a communication which take place in local area network. It is take place in society, in campus or in a corporate etc.[6] The range of this communication is up to kilometer, long range is a communication take place in wide area network. In this we have inter building connections, video surveillance network, back haul system etc. This is the network having range up to hundred kilometer and Ultra long range communication is take place between the inter satellite communication.[7] The range of this communication is very high. This type of communication is used for broadcasting, satellite to satellite communication etc. As we know that the atmosphere is used as the channel for this type of technology, so the atmospheric effect is the drawback of this technology, the one more drawback is the coverage area. The coverage area of the FSO is very less as the line of sight is the requirement for the free space optics.

When we talk about the atmospheric effects three hurdles come across us are scattering, absorption and turbulence. When we talk about the atmospheric absorption the different types of molecules present in the atmosphere help to produces this effect.[8] As we

Copyright © 2018 Authors. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

know that the water is easily absorbed the light, which means the water vapors take places in the atmosphere help in the cause of the atmospheric absorption. Scattering is the effect which is also take places in the guided optical communication. The scattering is the effect in which the light travelling in the medium is scattered by the particles which take place in the atmosphere. What amount of the scattering take place is dependent on the radius of the particle through which the scattering takes place. The deflection in the angle of the light take places which causes the scattering. When the radius of the particle is less than the wavelength the types of scattering take place is called as the Rayleigh scattering and when it is almost same is called as the Mie scattering. Till now we are talk about the gases or the solid particles take places in the atmosphere causes the effect. Now we talk about the atmosphere weather conditions like rain, fog, snow etc which also make our communication system performances poor.[1] From all these weather condition the effect of the Fog is more as compare to the all other effects because the wavelength we used for the communication is almost same at which the effect of fog take places. It can change the characteristics of the optical signal or can completely hinder the passage of light because of absorption, scattering, and reflection. The effect of the snow is depend on the size of the snow there are some cases where the size of snow particles is very large which completely block the light which have to transmit. Till here we are considering the losses which are caused by hazel atmosphere but there is some other effect take places in the clear atmosphere called as the turbulences. It is the effect which caused by the temperature, solar wind and atmospheric pressure which help in changing the reflective index of the light.[9] These type of effect produces the fading or sparking in the signal due to which we have to face the loss of information. The fluctuation in the signal causes the change in the amplitude and the phase of the signal, so at the receiver end the proper information or signal is not received which reduces the performances of the network. The different types of theory are introduced to reduce the effect of the turbulences. Beam steering is defined as the dimensions of the swirl are larger than the transmitter beam dimensions, it will deflect the beam as a whole in random manner from its original path. The effect of the beam wandering is commonly take places in the long range communication like satellite communication. If the eddy dimension is of the order of beam dimension, then the swirl will act like lens that will focus and de-focus the incoming beam leading to irradiance fluctuations at the receiver and the process is called scintillation. There are different types of model take places which is used to reduces the effect of the scintillation. These models are named as log normal, K distribution, I-k distribution which is used commonly at the low level of turbulences. As the level of turbulences increased we have to shifted towards new models named as Gamma-Gamma(GG) model, Double Weibull distribution model, Double Gamma - Gamma model(DGG), quasi-static model etc. when the dimension of the distortion is less than the beam dimension is called as the beam Spreading. The effect of the beam spreading is take places at the receiver section at which the power of the signal at the receiver end is reduced as well as the receiver aperture angle is also effected[10]. The one more effect which causes the deduction in the signal quality is called as background effect. This effect is take places when due to the reflection, sunlight scattering or when we convert the optical signal into the electrical signal. This effect is commonly take place as a background radiation. When the level of background noise is increases it effect the receiver sensitivity. The passion model is used to reduce the effect of the background noise.

To overcome these all above drawbacks we use the different types of modulation schemes at the transmitter end. This modulation schemes help us to modulate the intensity of the transmitted signal which carry the information. The different types of modulation take places in the optical wireless communication are Amplitude modulation, phase modulation, frequency modulation and polarization modulation. These different types of modulation is used as per the requirement of the scenario which is disguised by the energy efficiency, power requirement, spectral efficiency etc[11]. In this paper we present the review of the FSO communication by primary focusing towards the modulation schemes used to improve the performances of the link.

2. Modulation Techniques Used in FSO

There are many modulation techniques used in the FSO. The most commonly used modulation technique called as OOK (On Off Keying). Due to its simplicity and BW (Bandwidth) efficiency made the technique common. The OOK is the modulation technique which is based on the binary number in which the meaning of 'on' is 1 or true and the meaning of 'off' is 0 or false. The 1 and o is used to represent the presence of the light in which the 1 represent the presence of light and the 0 represent the absence of the light.[ct]. The on off keying modulation technique required adaptive threshold for the better results as compare to the IM/DD modulation technique[12].The OOK modulation technique is combined with the line coding technique to improve the results. As we can study from that the OOK NRZ have moderate signal to noise ratio (SNR), low cost where as the RZ is highly sensitive.[11]. The OOK is commonly suffering from the poor spectral and energy efficiency. The amplitude distortion is also the drawback of this type of modulation technique. The power and the energy are very important parameter whenever we choose the modulation technique for the FSO system. The energy efficiency is the parameter which is related with the data rate and the spectral efficiency is the parameter which is related with the information rate.

Too overcome the drawbacks of the OOK modulation techniques we use other modulation techniques like PPM (Pulse Position modulation), MPPM (Multi Pulse or Multicarrier PPM). The single pulse PPM is helping us to obtain the transmission which is energy efficient [14] whereas the spectral efficiency is not improved as per the requirement. To improve the spectral efficiency of the system we need to multiply pulse PPM. It helps us to maximize the energy efficiency as well as the spectral efficiency by using the M number of laser source with N number of receiver. The PPM is a modulation technique which eliminates the requirement of the dynamic threshold which is the prime parameter of the OOK [15]. In [16] we obtain high spectral and energy efficiency when the laser source is the half of the time slots used in the network. As the PPM is the energy efficient we can use it where the high amount of energy is required like deep sea or space communication. The MPPM modulation helps us to improve the peak to average power ratio (PAPR)[17]. When we use the MPPM modulation the performance of the peak power is better than PPM while the average power have the better performances at PPM modulation than the MPPM [19]. The drawback of this modulation technique is the switching speed. As we are working in optical to electrical network the requirement of the switching speed is high because the bandwidth provided by the optical is very large than the electrical. When we try to improve the switching speed parallel the cost is also increased. The one more drawback of this modulation technique is at the receiver end where it is difficult to demodulate the modulated signal because of using binary convolution codes. To overcome this disadvantage we use the decoding method called as SISO (Soft Input and Soft Output)[20].by using the additional module we increases the complexity of the network. The version of PPM is the differential pulse position modulation technique (DPPM). In this modulation the transmission of the data stream is take place, in which every pulse is follow by the empty slot which helps us to improve the bandwidth efficiency of the system [21].

Now we move to other modulation techniques used in the FSO named as PWM (Pulse width modulation) and DPIM(digital pulse interval modulation). The PWM have higher average width as compare to the PPM for the same bit rate which help to reduces the inter symbol interferences(ISI) but when we talk about the power efficiency the PPM is much better than the PWM[22]. The

PPM and the PWM are come under the synchronous modulation technique where as the DPIM is the asynchronous modulation technique. When we used the PPM and PWM we have to take care about the synchronization between the modulator and demodulator but the requirement of the synchronization is not take places in the DPIM. In the digital pulse interval modulation the transmission of the information is represented by the empty slots which take places in the data stream [11]. The spectral efficiency of the DPIM is very much larger than the PPM and PWM due to the reason that it does not have the fix length of data stream. In this the completion of the symbol period is not required [23]. The problem in the DPIM is at receiver end. At the receiver end when the data stream is received in which the empty slots that does not contain any information decoded as information slots which causes the error at the receiver end. Pulse is followed by the empty slot which helps us to improve the bandwidth efficiency of the system.

The one simplest modulation technique which not uses the adaptive threshold called as subcarriers intensity modulation (SIM). In the SIM the information is first modulated by using RF signal and then converted into the optical to modulate the intensity of the light [24]. When we compare the SIM with OOK we can see that the throughput of the SIM is much better than the OOK. The fluctuation in the phase is less in the SIM as compare to the on off keying modulation where as when we talk about the power efficiency the OOK is much better than the SIM but the SIM provide us the high amount of capacity [25]. The OFDM (orthogonal frequency division multiplexing) one of the important multiplexing technique which provided us the resistance against the inter symbol interferences (ISI). In OFDM the multiplexing of the two subcarriers take place which is orthogonal to each other. At one time slot the one subcarrier at the 90 and the other subcarrier at 0 so the chance of ISI is reduced very much. As the OFDM is very emerging technology used in the wireless communication which provided us very good result, so the researcher try to use it in the optical wireless communication as the demand of the users increased day by day. To use the OFDM in the optical communication is one of the great challenges as the merging of these both techniques is very difficult. Both of these techniques come from different domain as the OFDM in come under RF communication and the FSO is come under the optical wireless communication so one uses the electrical signal and other use the light signal for data transmission. As both have different constraint that is OFDM is bipolar where as the optical is unipolar. In OFDM we used coherent reception where as the FSO used direct reception [26]. The optical orthogonal frequency division multiplexing (OOFDM) provided us the advantage of long distance data transmission as compare to the other modulation schemes but we have to make a tradeoff between the distance and the power loss. The capacity of the system which uses the OOFDM is also improved at minimum cost [28]. The below is the table I in which we provided the calculation formulas of the BER for different types of modulation schemes.

Till now in this paper we only focus on the binary modulation techniques. Now the time comes we have to focus on the multi level modulation techniques which used in the FSO to improve the capacity of the system. The M –ary ASK have the capability to provided us the less sensitivity against the distortion as compare to the OOK modulation [30]. The different types of multi level modulation help us to obtain the higher level of spectral efficiency which we cannot obtain by using the binary types of modulation schemes.[29]. The multi level modulation techniques are receiver sensitive. As the dispersion parameters effect star increasing in the FSO link the sensitivity provided by the modulation start decreasing. The first multi level modulation technique we are going to study is Pulse Amplitude Modulation (PAM). The PAM is a modulation technique in which the amplitude of the pulse is used for the modulation of the signal. It is analog modulation technique which is also used with light devices to improve the energy efficiency of the devices. The LED is one of the examples of this which use the PAM for controlling purpose. The PAM is the BW efficient scheme as compare to other modulation schemes like PPM,OOK etc. the complexity provided by the PAM is at higher side. In [31] see that increase in the number of bits for a particular value of the signal to noise ratio there is change in the BER towards the negative side when we are using the LPPM where as when we are using the MPPM when the number of bits increases for the particular SNR the enlargement show in the BER performances. There is the declined in the average power of the LPPM with increases in the no. of bits of the signal where as the is balloon in the bandwidth of the signal but when we talk about the M-PAM there is totally vice a versa situation take places with increases in the bits help us to improve the average power of the signal but the decline shows in the BW of the signal[31]. So as per our requirements we use these techniques. As per real scenario we analyze that the requirement of the power is more or bandwidth. If the power efficiency requirement is more we use the LPPM and when the demand of the bandwidth increased we use the M-PAM in the FSO system. Quadrature Amplitude Modulation (QAM) is the modulation technique in which we use the two carrier signal which is modulated by the amplitude modulation. When we talk about the wireless communication we use the QAM with PAM called as Q-PAM. The Q PAM is a modulation technique which helps us to improve the intensity of the light which is generated by the laser. The improved intensity means more carriers to modulate so the power and spectral efficiency rise. The variable emission is required to grab the advantages of the Q-PAM modulation technique. The variable emission is provided by the variable lasers and the cost of the laser is too much which means that this technique is costly which the drawback of it is.

Now let talk about the modulation schemes which use their phases for the modulation of the signal. In these categories the first modulation scheme come under our mind is Binary Phase shifting Keying modulation (BPSK). The PSK is the digital modulation scheme in which we use the phase of the signal for modulation. In this change in the phase take place with respect to the reference signal. The BPSK is a binary PSK in which we work with two phase that are 0^o and 180^o. There we have only to phases which we use for modulation of the signal that is the reason we called it as binary PSK. The BPSK is commonly used in the wireless devices like Bluetooth, Radio frequency identification where the range of the source and the destination is less. From [15] we can see that the demand of power used by the BPSK is very less as compare to the QPSK (Quadrature Phase Shift Keying). The QPSK is modulation technique in which we have four phases around that the modulation takes place. The QPSK use two bits at a time which increases the capacity of the network. For particular value of the signal to noise ratio is less for the BPSK as compare to the QPSK to obtain the BER. As we discuss above that we can modulate two bit at a time by using the QPSK, so the bandwidth efficiency provided by the QPSK is much more than the PSK. For modulating two bits the requirement of the power is also high so at the criteria of the power efficiency the QPSK fails when we compare it with the BPSK. When we are move ahead in the phase modulation we come across at a modulation technique called as DPSK (Differential Phase Shifting Key).

DPSK is a modulation technique in which we change the phase of the signal without considering the reference signal. DPSK is used to overcome the drawback of the QPSK and PSK. The different types of modulation effects which effects the signal reduces when we use the signal which is modulated by the DPSK[32] the performance of the differential encoding QPSK(DQPSK) is almost same with as compare with the DPSK. The data rate provided by the DQPSK is twice higher than DPSK as the two bits are transmitted at the same time. The DQPSK have more spectral efficiency as compare with the DPSK but when we talk about the power the DPSK is better. The carrier less amplitude and phase modulation (CAP) is a modulating technique which is almost same like the QAM but the only difference is in the phase of the signal. The

QAM modulated two carrier signal where as the CAP combine them and filter it. When we use this modulation scheme in the FSO we find that the energy efficiency of the signal improved when we compare it with PAM. The cost of using CAP is less than the PAM. The all above discussion we have in which we try to touch all the modulation schemes used in the FSO. The above is the Table II in which we try to summarize all the above discussion. The table shows us the different types of qualities take places in the different modulation schemes.

Table 2: Survey of different modulation schemes.

Modulation schemes	References	Qualities in FSO
OOK	11,12	Adaptive threshold, low power efficiency, low cost, ease to implement, binary technique, moderate SNR, highly sensitive.
PPM	14,15,11	Synchronous, energy efficient, average power is more than MPPM, dynamic threshold not required.
MPPM	17,11	Improved PAPR, high spectral efficiency, low peak power.
DPPM	21,11	Higher spectral efficiency compare to the MPPM, improved power efficiency than PPM
PWM	22	High average width and spectral efficiency as compare to PPM, better response towards ISI, low power efficiency than PPM, synchronous.
DPIM	11,22,23	No requirement of synchronization, large bandwidth as compare to PPM and PWM, difficult to demodulate.
SIM	24,11,25	Adaptive threshold, high throughput than OOK, less phase fluctuation, more capacity, low power efficiency, less costly.
OOFDM	26	Highly resist toward ISI, long range, difficult to combine.
M-ASK	30	Less sensitive compare to OOK.
PAM	29	Higher spectral efficiency, more complex to implement, moderate power efficiency.
MPAM	31	Higher spectral efficiency compare to PAM, required dynamic threshold at destination.
QAM	23,29	Higher intensity, more power and spectral efficiency as compare to PAM.
BPSK	11,14	Power efficient as compare to QPSK
QPSK	32,11	High capacity, low power efficiency, high spectral efficiency.
DPSK	32,31	More capacity, less data rate as compare to the DQPSK, less spectral efficiency.
DQPSK	32	Higher data rate, high bandwidth efficiency, low power efficiency.
CAP	33	More energy efficient as compare to the PAM, less costly, simple implementation.

3. Conclusion

In this paper we survey on the different modulation techniques which we are using in the free space optical communication to improve the performance level of the system. From here we conclude that all the modulation techniques have there on perspective of advantages and disadvantages. Some techniques are good in energy efficiency and some are good in power efficiency. It is dependent on the situation which modulation technique is required by user.

References

[1] Khalighi MA & Uysal M (2014), Survey on Free Space Optical Communication: A Communication Theory Perspective, *IEEE Communications Surveys and Tutorials*, pp.2231-2258.

[2] Bloom S, Korevaar E, Schuster J, & Willebrand H (2003), Understanding the performance of free-space optics, *Journal of Optical Networks*, Vol. 2, no. 6,pp. 178–200, Jun. 2003.

[3] Holzmann GJ & Pehrson B, *The Early History of Data Networks (Perspectives)*. Hoboken, NJ, USA: Wiley, (1994).

[4] Huurdeman AA, *The Worldwide History of Telecommunications*, Hoboken, NJ, USA: Wiley-Interscience, (2003).

[6] Lee S, Kwon JK, Jung SY, & Kwon YH (2012), Evaluation of visible Light communication channel delay profiles for automotive applications, *Eurasip Journal Wireless Communication Network*, Vol.12, no. 1, pp. 370-378.

[7] Chan VWS (2003), Optical satellite networks, *Journal of Light and. Technololgy*, Vol. 21, no. 11, pp. 2811–2827.

[8] Kaushal H et al.(2017), Free Space Optical Communication, *Optical Networks, Springer*.

[9] Andrews LC, Phillips RL, Hopen CY, & Al-Habash MA (1999), Theory of optical scintillation,*Journal of Optical Society*, Vol. 16, no. 6, pp. 1417–1429.

[10] Wayne DT (2010), The PDF of irradiance for a free space optics communication Channel: *A physics based model at the University of Central Florida.*

[11] Kaur G, Singh H, Sappal AS (2017), Free Space Optical Using Different Modulation Techniques:A Review, *International Journal of Engineering Trends and Technology* , Vol. 43, no.2 , pp.412-410.

[12] Ghassemlooy Z, Popoola W, & Rajbhandari S (2013), Optical Wireless Communications: System and Channel Modelling With MATLAB, *New York: CRC Press*.

[13] Henniger H and Wilfert O, An Introduction to Free Space Optical Communications, *Radio Engineering*, Vol.19, no. 2. pp.10-18.

[14] Lesh J (1982), Capacity limit of the noiseless, energy efficient optical PPM Channel, *IEEE Transaction of Communication*, Vol. 31, no. 4, pp. 546–548.

[15] Elganimi TY (2013), Studying the BER Performance, Power and Bandwidth Efficiency for FSO Communication Systems under Various Modulation Schemes , *Proceedings of IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies*.

[16] Wilson SG, Cao Q, Baedke M (2005), Optical Repetition MIMO Transmission with multipulse PPM, *IEEE Journal on selected areas in communications*, Vol. 23, no. 9, pp.23-30.

[17] Moision B and Hamkins J (2005), Multipulse PPM on discrete memorylessChannels, *Jet Propulsion Lab*., Pasadena, CA, USA,pp.42–160.

[18] Sugiyama H and Nosu K (1989), MPPM: A method for improving the band utilization efficiency in optical PPM," *Journal of Light wave Technology*, Vol. 7, no. 3,pp. 465–471.

[19] Simon MK & Vilnrotter VA (2004), Performance analysis and tradeoffs for dual-pulse PPM on optical communication channels with direct detection, *IEEE Transaction of Communication* , Vol. 52, no. 11, pp. 1969–1979.

[20] Xu F, Khalighi MA & Bourennane S (2009), Coded PPM and multipulse PPM and iterative detection for free-space optical links, Journal of *Optical Communication Network*, Vol. 1, no. 5, pp. 404–415.

[21] Shiu D & Kahn JM (1999), Shaping and non equiprobable signaling for Intensity-modulated signals, *IEEE Transaction of Information Theory*, Vol. 45, no. 11, pp. 2661–2668.

[22] Fan Y & Green RJ (2007), Comparison of pulse position modulation and pulse width modulation for application in optical communications, *Optical Engineering*, Vol. 46, no. 6, pp.65-72.

[23] Ghassemlooy Z, Hayes AR, Seed NL & Kaluarachchi ED (1998), Digital pulse interval modulation for optical communications, *IEEE Communication Magazine*, Vol. 36, no. 12, pp. 95–99.

[24] Kahn JM & Barry JR (1997), Wireless infrared communications, *Proceedings of IEEE*, Vol. 85, no. 2, pp. 265–298.

[25] Ali MAA (2016), Performance Analysis of WDM-FSO Link under Turbulence Channel, *Journal of World Scientific News*, pp.160-173.

[26] Armstrong J (2009), OFDM for optical communications, *Journal of Lightwave Technology*, Vol. 27, no. 3, pp. 189–204.

[27] Shieh W and Djordjevic I (2009), OFDM for Optical Communications, *New York, NY, USA*.

[28] Wei JL, Ingham JD, Cunningham DG , Penty RV & White IH, Performance and power dissipation comparisons between 28 Gb/s

NRZ, PAM, CAP and optical OFDM systems for data communication applications, *Journal of Lightwave Technolgy*, Vol. 30, no. 20, pp. 3273–3280.

[29] Hranilovic S, *Wireless Optical Communication Systems* (2005). New York,NY, USA: Springer-Verlag.

[30] Avlonitis N, Yeatman EM, Jones M & Hadjifotiou A (2006), Multilevel amplitude shift keying in dispersion uncompensated optical systems , *Proceedings of IEEE Optoelectronics*, Vol. 153, no. 3, pp. 101–108.

[31] Elganimi TY (2013),Performance Comparison between OOK, PPM and PAM Modulation Schemes for Free Space Optical (FSO) Communication Systems: Analytical Study, *International Journal of Computer Applications* , Vol. 79, no.11, pp.11-20.

[32] Wang Z , Zhong WD, Performance Comparison of Different Modulation Formats Over Free-Space Optical (FSO) Turbulence Links With Space Diversity Reception Technique, *IEEE Photonic Journal*, Vol.1, no.6, pp.32-40.

[33] Han Y and Li G (2006), Theoretical sensitivity of direct-detection multilevel modulation formats for high spectral efficiency optical communications, *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 12, no. 4, pp. 571–580.