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Ber Performance Analysis of Various FSO Modulation Formats

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Abstract- The turbulence in an FSO link causes fluctuations in the intensity and the phase of the received signal. These fluctuations ultimately lead to the degradation in the link error probability and limit the system performance. This paper first focuses on survey of FSO system, modulation techniques used and environmental effects on link performance, while using different modulation techniques and turbulence models. In this paper, we investigate the bit error rate (BER) performance of various commonly used differentiated modulation formats in the FSO link - coherent subcarrier (SC-BPSK and PSK) and noncoherent (OOK, OOK-RZ, OOK-NRZ, and M-PPM) schemes in turbulent atmospheric environment. In our proposed design, BER performance of different modulation format has been evaluated on Free Space Optical Communication. We derive an analytical BER result of various signal in the distributed channel and carry out a comprehensive transmission performance comparison some of these modulation formats. We use both theoretical analysis and Matlab simulation to examine the BER performance. Here, the results have been mentioned for FSO system at different modulation format by taking values of the various parameters like: Data rate, Transmitter Wavelength, Aperture area, Transmitted power, Sigma.
Key words: Free Space Optics, Modulation Techniques, Attenuation Coefficiant, Noise Conditions, SNR, BER.

I. INTRODUCTION

Free space optical (FSO) communication has become a viable technology for a broadband wireless application which offers the potential of high bandwidth capacity over unlicensed optical wavelength.Within each of businesses, high speed fast Ethernet (100 Mbps) or even Gigabit Ethernet (1.0 Gbps) local area networks (LAN's) are common place. While these data networks meet the needs for local connectivity ithin a single floor or building, there is a rapidly increasing need for similar high data rate connection speeds between buildings either locally or nationwide. This demand for wide-area high bandwidth is fueled by increasing commercial use of the Internet, private Intranets, electronic commerce, data storage and backup, virtual private networks (VPNs), video conferencing, and voice over IP. We are seeing a growing demand for bandwidth in mobile communication, as the number of users is increasing significantly. The next-generation wireless communication systems therefore should be able to offer higher capacity to support various broadband wireless services such as the high-definition TV (HDTV 4–20 Mbps), computer network applications (up to 100 Mbps), mobile videophones, video conferencing, high-speed Internet access, and so on. In access networks, the technologies currently in use include the copper and coaxial cables, wireless Internet access, broadband radio frequency (RF)/microwave and optical fibre. These technologies, in particular copper/coaxial cables and RF based, have limitations such as a congested spectrum, a lower data rate, an expensive licensing, security issues and a high cost of installation and accessibility to all. Optical wireless communications (OWC) is an age-long technology that entails the transmission of information-laden optical radiation through the free space optics channel. The key to high bandwidth wide-area connectivity is to make use of the nationwide fiber optic backbone. Fiber run to every building would be the ideal solution to the last mile bottleneck from the standpoint of system availability. However, because of the high cost and the time to get right-ofway permits and to trench up the streets, fiber is not a very practical solution.

As for the fixed wireless access schemes, the options are as follows:

1. Worldwide interoperability for microwave access (WiMax), which is based on the IEEE 802 16d standard for fixed broadband wireless access with theoretical data rates up to 120 Mbps over a line-of-sight (LOS) link range of 50 km.
2. Broadband over power line (BPL) using the existing comprehensive wired network
3. Ultrawideband (UWB) technology, which bypasses the spectrum regulation, offers good propagation characteristics over a range less than a few tens of metresWith the introduction of microcells with reduced distances between transmitter and user, up to 1 km, higher data rates and mobile broadband services could be offered to a large number of end users. This will require the development of very high-capacity short-range links connecting the base station to the MSC, which in turn could be connected to the main trunk network via optical fibre cables.

Free Space Optical (FSO) networks, namely optical wireless networks,are wireless telecommunication systems that make use of freespace as a transmission medium to deliver optical data signals at highbit rates. FSO research started in the 1960s. The National Aeronauticsand Space Administration (NASA) Deep Space OpticalCommunications

Project "is to develop key technologies for theimplementation of a deep space optical transceiver and ground receiverthat will enable greater than 10X the data rate of a state-of-the-art deepspace RF system (Ka-band) for similar spacecraft mass and power."

The European Space Agency (ESA) started funding various FSOprojects since the summer of 1977, aiming to develop high-data-ratelaser links in space. Although optical wireless links provide high datarates, FSO communications have not prevailed so far in spite of a longinvestigative history.

Free-space laser communication network is very similar to fiber optic communication, except that instead of the light being contained within a glass fiber, the light is transmitted through the atmosphere. Since similar optical transmitters and detectors are used for free-space and fiber, similar bandwidth capabilities are achievable, Figure 1.

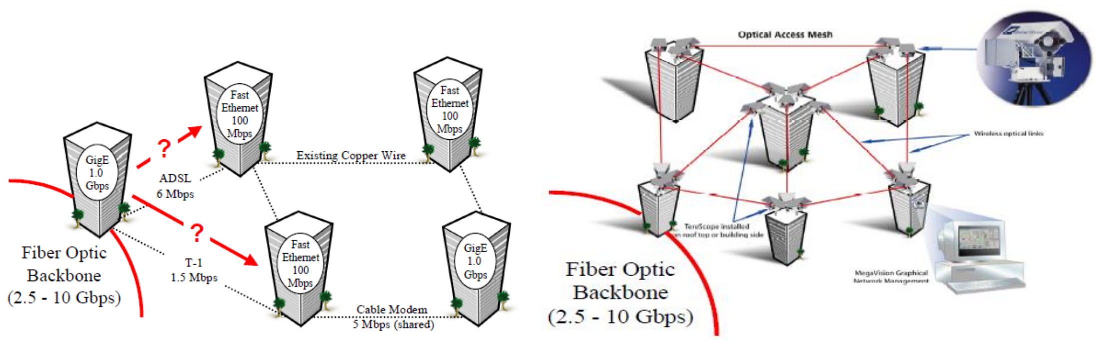


Figure 1 Standard solution and high-bandwidth cost-effective solution to the last mile problem is to use FSO

Before mentioning to the application areas we first list the advantagesof the technology as follows, Figure2.:

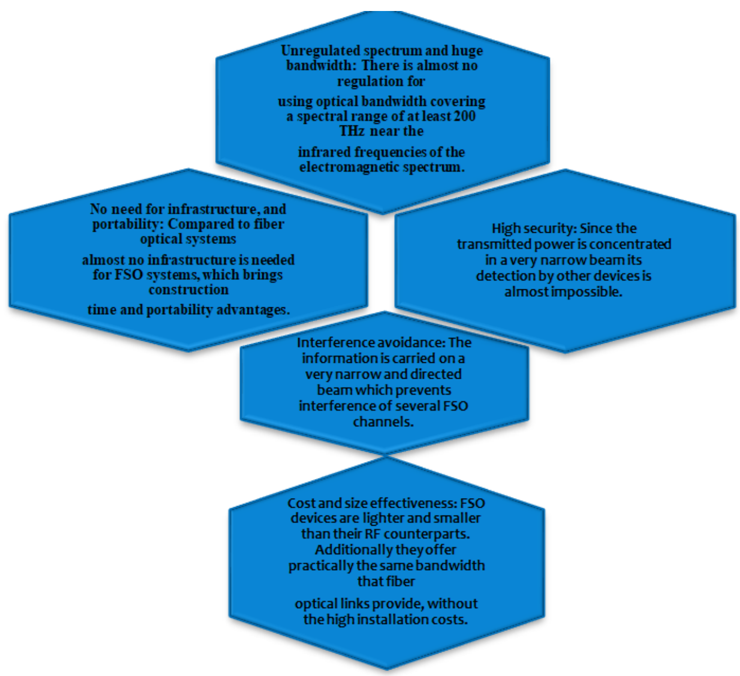


Figure 2 Advantages of the FSO technology

Classification of FSO networks: Due to their high potential for a broad spectrum of applications,FSO networks have been investigated and employed for networks thatspan a distance from a few meters to over thousands of kilometers. Asillustrated in Table 1, FSO networks can be roughly classified into threetypes:

Optical Wireless Satellite Networks (OWSNs),

OpticalWireless Terrestrial Networks (OWTNs), and

Optical WirelessHome Networks (OWHNs), according to the locations of opticaltransmitters and receivers and network range.

Table 1 Characteristics of Optical Wireless Satellite, Terrestrial and Home Networks.

	OWSNs	OWTNs	OWHNs - (IrDA)	OWHNs - (MSD, White LED)
Location	Orbit	High/open place	Indoor	Indoor
Link distance	~84,000 kilometers	~10 kilometers	~a few meters	~tens of meters
Channel	Vacuum channel	Air turbulent channel	Weak turbulent channel	Weak turbulent channel
RX/RX FOV	Very narrow	Narrow	30 degrees	Wide
Performance	Misalignment with	Atmospheric	Limited power for eye	Limited power for eye safety
Limiting factor	Long distance	turbulence	and LOS blockage safety	and multipath propagation
Hardware	Precise PAT	Turbulence-resistant	Lightweight, portable	Backbone between cells and
Requirement	technology (Ex. Automatic steerable gimbals/beam)	design (Ex. Spatial Diversity, RF/FSO, Hybrid architecture)	and inexpensive component	MSD–holographic optical diffuser
Misc	Long distance coverage and hard to maintain	Various impairment factor	Short-range point-to-point link	Exploiting reflections

II. ATMOSPHERIC EFFECTS AND PHOTODETECTOR DISTURBANCE

The transmission performance of a free-space optical (FSO) link could be severely degraded due to atmospheric turbulence, which causes the temporal and spatial fluctuation of light intensity. Both the space diversity reception technique and advanced modulation formats can successfully mitigate the transmission impairments of the atmospheric turbulence.Despite the major advantage of FSO, its widespread deployment is hindered by thecombined effects from numerous factors in which the greatest challenges are directlyattributable to the turbulence and fog, Figure 3. The atmospheric channel is unpredictable andvulnerable to different weather conditions, such as scattering and absorption, hence, therequirement for FSO links to offer link availability under such environments.Additionally, FSO networks may also experience from pointing errors.However, FSO links severely suffers from strong turbulence and is far away fromsatisfying the typical BER targets for FSO applications within the practical ranges ofSNR. In order to maximize the overall system throughput and link availability, the FSOcommunication terminals must dynamically react to the changes taking place within theatmospheric environment. Therefore, various techniques have been investigated andproposed to combat the deterioration of signal quality as a result of the atmosphericconditions and the link misalignment.

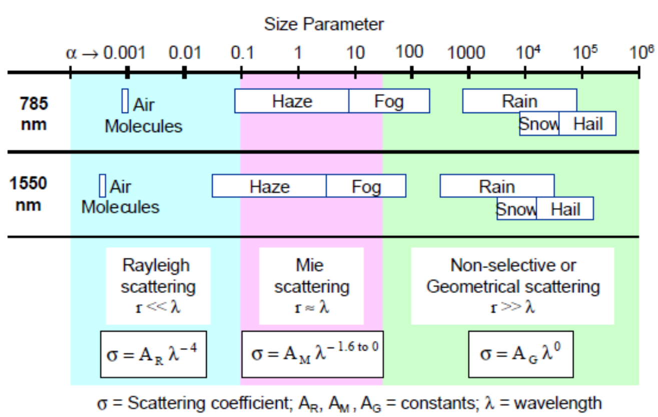


Figure 3 Size parameters of atmospheric scattering particles in Table 1 for laser wavelengths of 785 nm

and 1550 nm. Also plotted are the corresponding regions for Rayleigh, Mie, and non-selective or geometric scattering. For each type of scattering, the approximate relationship between the particle size and wavelength, and the wavelength power law of the attenuation coefficient is shown.

In most cases, Free-space optics (FSO) uses the atmosphere as the propagation medium. The latter is perturbed by different atmospheric phenomena (e.g., rain, fog, clouds, dust, smoke, smog, etc.) that can affect the transmission of a laser beam through the atmosphere. The most important challenges of the FSO communications, even in clear sky conditions, are: absorption, scattering, and scintillation. These impairments are wavelength dependent and cause - along the FSO links- optical signal losses, irradiance fluctuations, beam broadening, loss of spatial coherence of the optical wave.

In detail, absorption causes losses and occurs when a photon is absorbed by an atmospheric gaseous molecule that converts the photon into kinetic energy. Furthermore, the atmospheric absorption strongly depends on the wavelength Figure 4. In particular, the windows that present attenuation coefficient vs. wavelength, for which laser sources are available, are in the spectral range close to wavelengths of 785 nm, 830 nm, 1084 nm and 1550 nm.

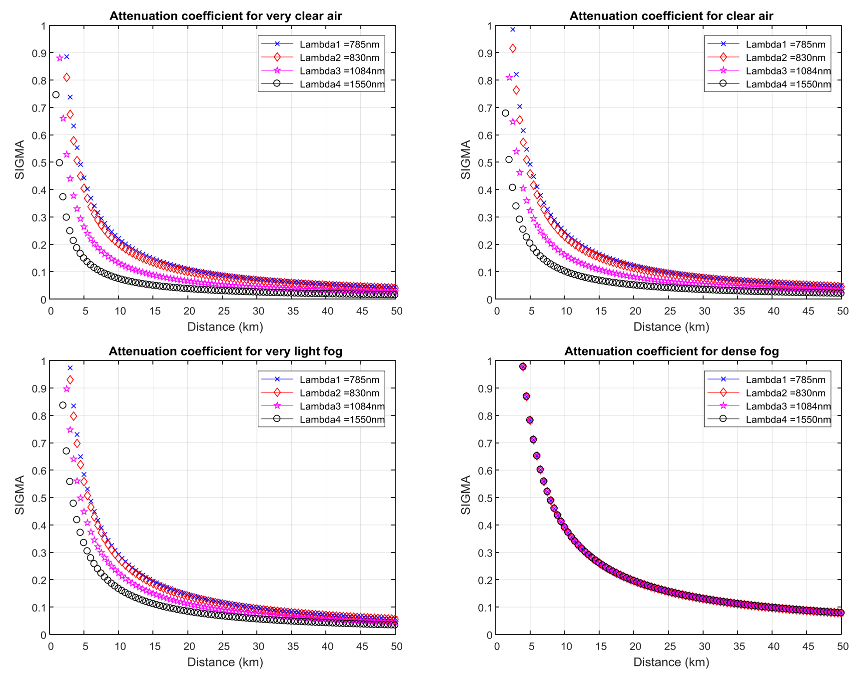


Figure 4 Attenuation coefficiant vs. distance under different weather conditions

For all therespective wavelengths, received signal quality is degraded rapidly, when link distance exceeds 4km at clear weather condition. Hence, at clear weather condition for all the respectivewavelengths, the maximum link distance should not exceed 4 km. Additionally, it is observedfrom Figure 4 that operating wavelength of 1550 nm showed better performance than other wavelengths.

A number of noise sources are associated with the optical communication systems, which include the thermal noise caused by thermal interaction between the free electrons and the vibrating ions in a conducting medium. Thermal noise obeys the Gaussian distribution with zero mean and unit variance and is regarded as a 'white' noise mainly because the power spectral density of this noise source is independent of frequency. While using a low resistance in the front end is capable of improving the frequency response, an excessive amount of thermal noise is generated by the pre-amplifier independent of the resultant photocurrent. The second type called the dark current shot noise which is arising from the transition of electrons from the valence to the conduction band. Furthermore, the appropriate channel model for FSO communication system using IM will depend on the background light. The background radiation, also called background noise or ambient noise, can degrade the performance of FSO links. It is due to the detection of photons generated by the environment (sun and sky). In general, the background radiation is greater than other noise processes so that it dominates the total shot noise, which is the summation of all type of noises. However, the unwanted background radiation is collected together with the desired signal at the receiver, which is statistically modelled as additive white Gaussian noise in time and space with zero mean and variance □2 = □0⁄2, where □0⁄2 is the two-sided PSD. The collected background noise is processed along with the desired signal and affects the overall system performance, Figure 5.

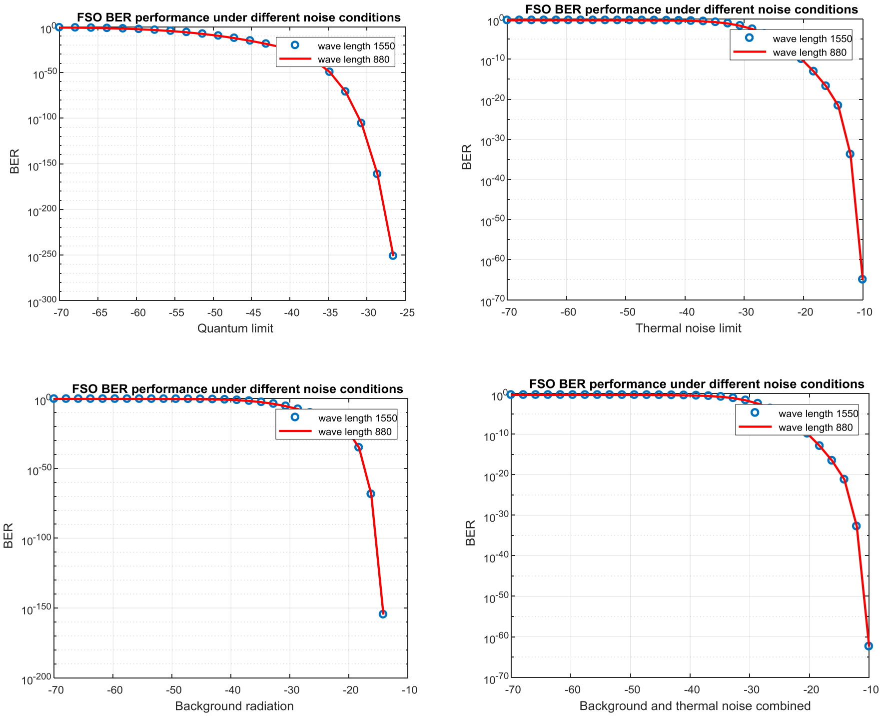


Figure 5FSO BER performance under different noise conditions

III. FSO MODULATION TECHNIQUES

BER plays a crucial role in an optical communication system. We present here simulation results to compare the performance of fog attenuation under different mathematical models. On the other hand, we consider different modulation format in the transmitter side because of its simplicity and resilience in the FSO communication system.

The stability and quantity of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat,the quality of the transmission is characteristics by the realized bit error rate. In this paper, we discuss the suitability of FSO models under these modulation formats and BER.

There are many different types of modulation schemes which are suitable for FSO communication systems, Figure 6, such as On-Off Keying (OOK), Pulse Position Modulation (L-PPM), Pulse Amplitude Modulation (M-PAM), Differential Phase Shift Keying (DPSK), Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK). Since the average emitted optical power is always limited, the performance of modulation techniques is often compared in terms of the average received optical power required to achieve a desired BER at a given data rate. It is very desirable for the modulation scheme to be power efficient, but this is however not the only deciding factor in the choice of a modulation technique.

Thetransmission of modulated light is greatly affected by theatmospheric parameters such as absorption, scattering, andnon-selective scattering. Absorption is caused due to gasespresent in the atmosphere, whereas scattering and nonselectivescattering is caused by big sized rain drops. Intemperature regions, fog and heavy snow are the primaryweather conditions that affect FSO link.

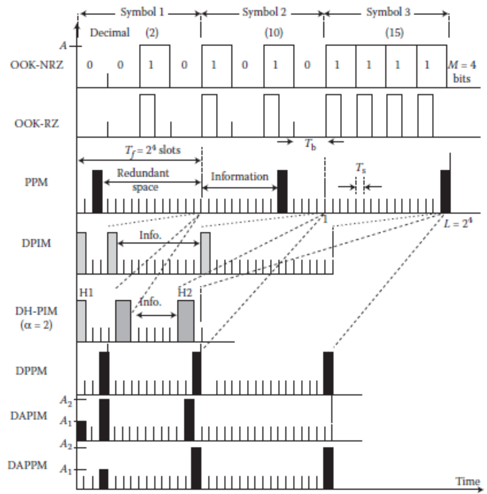


Figure 6 Time waveforms for OOK, PPM, DPI, DH-PIM, DPPM, DAPIM and DAPPM signals

Since the typical BER target is set as 10−9for most practical applications, this brings a large computational time for Monte-Carlo type simulation experiments. Therefore, development of analytical tools for BER performance are helpful in providing extensive comparative analysis among different FSO configurations, which will be the main focus of this paper. In this paper, we derive BER expressions for FSO links with and without channel state information (CSI) considering both spatially independent and correlated channels. The derived expressions quantify the effect of spatial diversity and spatial correlations in a log-normal channel.
The classical modulation technique used for FSO is OOK.This is primarily because of the simplicity of its design and implementation.It is not surprising therefore that the majority of the work reported in the literature is based on thissignallingtechnique.However,theperformanceofafixed threshold-level OOK in atmospheric turbulence is not optimal, as will be shown in the following section.In atmospheric turbulence, an optimal-performing OOK requires the thresholdleveltovaryinsympathywiththeprevailingirradiancefluctuationand noise, that is, to be adaptive.The PPM requires no adaptive threshold and is predominantlyusedfordeepspacefreespaceopticalcommunicationlinksbecause ofitsenhancedpowerefficiencycomparedtotheOOKsignaling.ThePPM modulation technique, however, requires a complex transceiver design due to tight synchronization requirements and a higher bandwidth than the OOK.

3.1 On-Off Keying (OOK)

This type of modulations is the dominant modulation scheme employed in commercial terrestrial FSO communication systems. This is primarily due to its simplicity and resilience to the innate nonlinearities of the laser and the external modulator. OOK modulation can use either NRZ or RZ pulse formats. In NRZ-OOK, an optical pulse of peak power “αe PT” represents a digital symbol “0” while the transmission of an optical pulse of peak power “PT “ represents a digital symbol “1 ”.The probability of error for NRZ-OOK-coded optical data, detected with a photodiode, can be expressed as a function of the Signal-to-Noise Ratio (SNR) as :

$$BER_{NRZ-OOK} = \frac{1}{2}\, erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right)$$

In RZ-OOK, the required SNR is equal to half “-3dB ” of the required SNR of the regular NRZ-OOK to achieve the same BER performance, with the expense of doubling the bandwidth [1], and the BER for RZ-OOK can be expressed as a function of SNR as follows:
For Gaussian noise, the BER for L-PPM scheme can be expressed as:

$$BER_{NRZ-OOK} = \frac{1}{2}\, erfc\left(\frac{1}{\sqrt{2}}\sqrt{SNR}\right)$$

3.2 Pulse Position Modulation (PPM)

In this modulation scheme, each pulse of a laser can be used to represent one or more bits of information by its position in time relative to the start of a symbol whose duration is identical to that of information bits it contains. And the great advantage of PPM scheme is the elimination of decision threshold dependence on the input power [7]. Bits in block encoding are transmitted in blocks instead of one at a time. Optical block encoding is achieved by converting each word of "K1 " bits into one of "L=2K1 " optical fields for transmission.

For Gaussian noise, the BER for L-PPM scheme can be expressed as:

$$BER_{PPM} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR\frac{L}{2}\log_2 L}\right)$$

Substituting "L=2K1" in (6), one can derive another form for the BER for L-PPM scheme as a function of the number of bits as follows:

$$BER_{PPM} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{K_1 2^{K_1-1} SNR}\right)$$

Pulse position modulation (PPM) scheme is an orthogonal modulation technique. PPM requires both slot and symbol synchronization. Pulse position modulation (PPM), where information is encoded into the position of the optical pulse rather than amplitude, offers higher resilience to turbulence due to the availability of soft demodulation algorithms. The technique can improve on the power efficiency of OOK, but at the expense of an increased bandwidth requirement and greater complexity.

3.3 Pulse Amplitude Modulation (PAM)

It is a form of signal modulation where the message information is encoded in the amplitude of a series of signal pulses; and the BER for M-PAM scheme can be expressed as follows:

$$BER_{PAM} = \frac{1}{2} erfc\,\frac{\left(\sqrt{SNR\log_2 M}\right)}{2\sqrt{2}(M-1)}$$

Substituting "M=2K2 ", one can derive another form for the BER for M-PAM as a function of the number of bits as follows:

$$BER_{PAM} = \frac{1}{2} erfc\left(\frac{\sqrt{SNR\,K_2}}{2\sqrt{2}\left((2^{K_2}-1)\right)}\right)$$

In the presence of scintillation, the unconditional BER Pe = E[Pec] is derived using the Gauss-Hermite quadrature integration as:

$$P_e = \int_0^\infty \frac{1}{2} exp\left(-\frac{1}{2}SNR_e\right) p_i(I)\,dI = \frac{1}{2\sqrt{\pi}}\sum_{i=1}^{n} w_i\, exp\left(-K^2 exp\left(x_i 2\sqrt{2}\sigma_i - \sigma_i^2\right)\right)$$

3.4 RZ-OOK and NRZ-OOK

It is a form of modulation schemes are widely used in commercial FSO communication systems because of their ease of implementation, bandwidth efficiency and cost effectiveness. Simplest form of FSO links are on-off keying (OOK) modulated links which involve presence and absence of optical pulse for binary '1' and binary '0' respectively. Besides ease of modulation and development, following features have made unbeatable option in comparison to conventional RF systems. The relation BER and SNR for NRZ-OOK modulated signal is as follow:

$$BER_{NRZ-OOK} = \frac{1}{2} erfc\left(\frac{\left(\sqrt{SNR}\right)}{2\sqrt{2}}\right)$$

While BER for RZ-OOK modulated signal is given by:

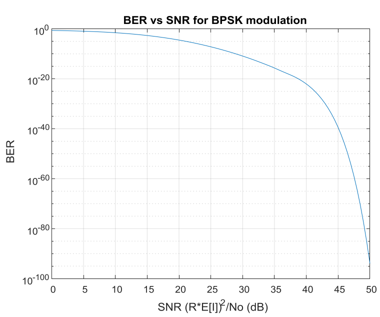
$$BER_{RZ-OOK} = \frac{1}{2} erfc\left(\frac{(\sqrt{SNR})}{2}\right)$$

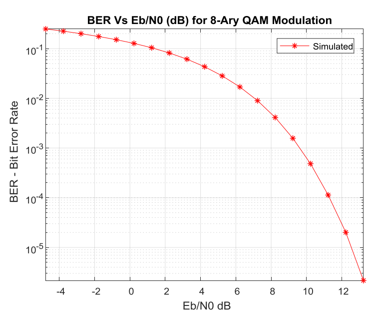
The BER characteristics of the NRZ and RZ-OOK modulation formats under different fog models are studied. The results show that the wavelength 1550nm has a greater advantages than the other wavelength, therefore, a 1550nm is a more suitable wavelength compared with 850nm for FSO under fog effect. Furthermore, the performance of RZ-OOK is better than the NRZ-OOK, the Kruse model is more sensitive for fog attenuation compared with the other models.

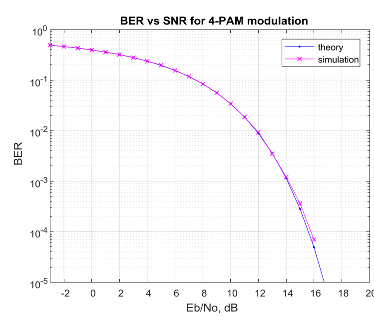
Among the various modulation schemes, OOK isvery simple in implementation and bandwidthefficient. This modulation scheme requires adaptivethreshold in turbulent atmospheric conditions forbest results. Using this scheme, the light sourceis turned on to transmit a logic “one” and turned offto transmit logic “zero”. It is also known as nonreturnto zero (NRZ) modulation. Besides NRZ,return to zero (RZ) coding can also be used in whichthe logic “one” returns to zero in the middle of thesample. RZ shows higher sensitivity than NRZ.OOK is affected by amplitude distortion i.e. fadingand propagation of signal through different roots.These issues are least effective when sky is clear.Apart from the above mentioned schemes, coherentmodulation schemes such as binary phase shiftkeying (BPSK) and differential phase shift keying(DPSK) can also be used. Under all theturbulence conditions, the BER performance ofsubcarrier BPSK is always better than that ofOOK.The coherent receivers are one to two timesmore sensitive than OOK systems but instead of thatthe complexity of coherent system is also more.OOK are more robust than coherent systems. As aresult, OOK systems have been preferred for opticallinks inside the atmosphere.

IV. ANALYSIS

There are many different types of modulation schemes which are suitable for FSO communication systems such as On-Off Keying (OOK), Pulse Position Modulation (L-PPM), Pulse Amplitude Modulation (M-PAM), Differential Phase Shift Keying (DPSK), Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK). Since the average emitted optical power is always limited, the performance of modulation techniques is often compared in terms of the average received optical power required to achieve a desired BER at a given data rate. It is very desirable for the modulation scheme to be power efficient, but this is however not the only deciding factor in the choice of a modulation technique.We will analyze the bit error performance - BER for FSO communication systems using PSK, BPSK, M-QAM, M-PAM, M-PPM, OOK, OOK-RZ, OOK-NRZ modulation schemes through AWGN noise and fading (Rayleigh and Rice) channels. The implementation of BPSK modulation techniques sets the main criterion for comparing the variation of BERs with respect to different Eb/No signal noise ratios. AWGN channel performance is the best among all channels because they have the lowest BER in BPSK modulation schemes, and the amount of noise that occurs in the BER channel is much smaller than the fading channel. The performance of Rayleigh's fading channel is the worst of all, because the BER of this channel is highly influenced by noise under the BPSK modulation scheme. Rice fading chanel is the best, Figure 7.







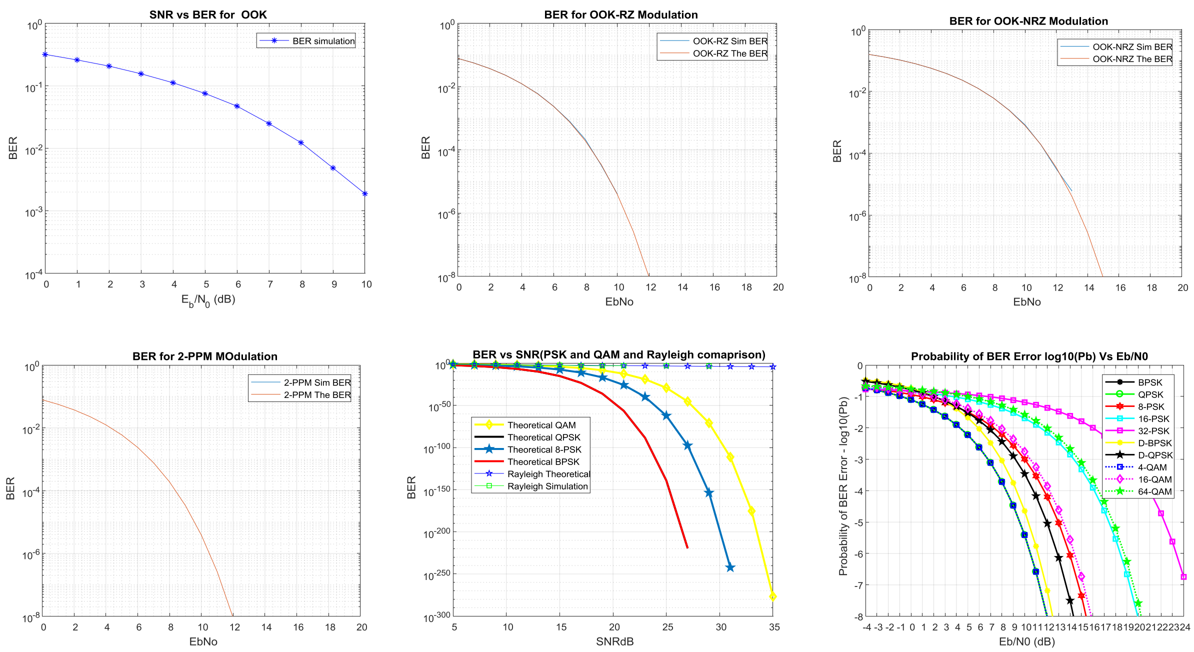


Figure 7BER waveforms for BPSK, M-QAM, M-PPM, OOK, OOK-RZ, OOK-NRZ, M-PPM, PSK and all together

V. CONCLUSIONS

From the BER performance of BPSK, DPSK and M-QAMmodulation techniques for a turbulent FSO link, we found that for higher order M-QAM, the BER performance ofM-QAM degrades. 16-QAM gives better BER performance than64-QAM.DPSK and 8-QAM behave more or less the similar but for higher values of M (16-QAM and 64-QAM) the performance of DPSK is far better.For lower values of SNR up to 15dB, the performance of all the modulation techniques is more or less the similar but for higher SNR values. BPSK modulation technique deliversbetter BER performance than the other discussed techniques.Moreover, the BER performance also gets degraded as the link range is increased.Apart from the above mentioned schemes, coherent modulation schemes such as binary phase shift keying (BPSK) and differential phase shift keying (DPSK) can also be used. Under all the turbulence conditions, the BER performance of subcarrier BPSK is always better than that of OOK.The coherent receivers are one to two times more sensitive than OOK systems but instead of that the complexity of coherent system is also more.Besides NRZ, return to zero (RZ) coding can also be used in which the logic “one” returns to zero in the middle of the sample. RZ shows higher sensitivity than NRZ. OOK is affected by amplitude distortion i.e. fading and propagation of signal through different roots. These issues are least effective when sky is clear. OOK are more robust than coherent systems. As a result, OOK systems have been preferred for optical links inside the atmosphere. The technique can improve on the power efficiency of OOK, but at the expense of an increased bandwidth requirement and greater complexity. Furthermore, theperformance of RZ-OOK is better than the NRZ-OOK, theKruse model is more sensitive for fog attenuationcompared with the other models.Pulse position modulation (PPM) scheme is an orthogonal modulation technique. PPM requires both slot and symbol synchronization. Pulse position modulation (PPM), where information is encoded into the position of the optical pulse rather than amplitude, offers higher resilience to turbulence due to the availability of soft demodulation algorithms. The PPM modulation technique improves on the power efficiency of OOK but at the expense of an increased bandwidth requirement and greater complexity. Both quadrature amplitude modulation (QAM) and multilevel pulse amplitude modulation (PAM) are spectrally efficient modulation schemes suitable for LED-based communications, but are less power efficient, PAM pulse amplitude modulation is used to improve the data throughput, bandwidth capacity and peak-to-average power ratio. In PAM, the symbol length and pulse amplitude are modulated according to the input data bit stream.While the normalized average power requirement for M-PAMschemeincreases with the increase of the number of bits can be sent, and the normalized bandwidth requirement decreases with the increase of the number of bits can be sent.On the other hand,L-PPMschemeis the power efficient modulation scheme can be used in FSO communication systems, but whenthebandwidth efficiency is taken into consideration, M-PAMschemeis a prime candidateto use in FSO communication systems.

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