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COMMUNICATION THEORY REVIEW PERSPECTIVE ON CHANNEL MODELING, MODULATION AND MITIGATION TECHNIQUES IN FREE SPACE OPTICAL COMMUNICATION

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Abstract: Free space optical communication (FSO) is wireless and fiber less based line of sight communication link. Various attributes like extremely high data rates, data security, cost efficiency, license free bands etc. have made FSO an attractive option in comparison to wired and RF communication links. Optically modulated data transverses through atmosphere before it is finally demodulated at the receiver. Here the medium itself is biggest challenge to overcome in pursuit to attain high degree of uptime efficiency of link. Meteorological effects like fog, smoke, winds etc may cause atmospheric induced fading leading to loss of information. In this paper, a thorough review of FSO channel modeling techniques has been carried out to understand the effect and impact of varying atmospheric turbulence conditions. These assessments are crucial from the point of view of link design, as effective channel modeling aids in minimizing the impact of atmospheric turbulence. Taking cue from its success in conventional RF systems, the spatial diversity techniques coupled with channel coding techniques have also been introduced in FSO to enhance the probability of detecting the signal through turbulent medium where regular singular links might fail to perform. Permutations of different diversity techniques along with effective channel coding and modulation techniques provide varying degree of immunity to FSO systems against fading effects have been discussed in paper.

Keywords: Free space optical (FSO) communication, channel modeling, modulation, spatial diversity, channel coding

1. INTRODUCTION

In present scenario, the migration from wired to wireless communication link has been an obvious trend seen in last couple of decades. Due to large scale deployment, the word *wireless* is often interpreted and even used as standard to describe radio frequency communication links. Directly or indirectly, the high tech wireless communication services, smart devices etc. have become an integral part of our daily life. The penetration of technology has lead to exponentional increase in demand for bandwidth and seamless communication.

However it must be kept in mind the RF spectrum is fundamentally a limited resource , moreover high licensing fees and limited data capacity pose a major demand supply hurdle in delivering high data services to end users [1]. Expecting this trend to continue and become even more severe in near future, there is an urgent need to shift towards higher sub bands of electromagnetic spectrum like visible and IR bands which can very well serve the purpose to serve data hungry services.

Optical wireless communication (OWC) or free space optical (FSO) communication links is a wireless communication links that use optically modulated data, transmitted though unguided medium like

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atmosphere. Using light as tool for communicate is not something new to mankind. Ancient Greeks and Chinese armies used sunlight and fire in battlefields alert and signal various tactics of warfare to their army posts located at far off and hostile areas [2]. However the earliest citation of light as information carrier relates to photo-phone experiment also known as world's first wireless telephone demonstrated by Alexander G. Bell [1].

Despite the fact that an optical wireless link was demonstrated as early in 19th century, the technology could never materialize in commercial and public domain. This was largely due to some inherit limitations associated with FSO like atmospheric turbulence, geometric losses, nascent stage of development of optical sources etc. However over the years, there has been massive up gradation in quality of light sources like LED's and lasers [3] which have made it possible to look towards optical wireless communication links as possible alternative to bandwidth starved RF regime.

In comparison to conventional RF based systems, FSO systems boast of certain unbeatable attributes like *(i)* FSO channels employ IR and visible part of electromagnetic spectrum which is does not require any license from government agencies *(ii)* FSO systems are plug and play devices which operate at physical layer and thus re-deployment is never a big issue *(iii)* FSO channels operate on frequencies of more than 3Thz, thus they can offer huge bandwidth and extremely high data rates to serve delay free internet services and transmission of ultra high quality videos and graphics. Experimental demonstrations recently have confirmed data rates as high as 160Gbps, *(iv)* Lastly, since FSO systems are line of sight based communication therefore the data security in FSO systems becomes inherited and unmatched. [4], [5], [6].

However notwithstanding the above highlighted features, FSO links at times may be partially or fully crippled due to atmospheric adversities like water droplets, moisture, smoke, dust, gasses etc. The information carrying photons may get attenuated to variable degrees, depending upon the concentration of these particles. The prime cause of this attenuation is scattering and absorption of the optical field leading to loss of information. Since the unguided medium in OWC links i.e. atmosphere is highly unpredictable and may consist of range of particles of different physical dimensions in addition to atmospheric turbulences which may lead to varying amount of distortion and attenuation. Over the last decade, experiments have been conducted to find out ways to limit, if not completely eradicate, the effects of atmospheric turbulence on FSO links. Slew of these measures include efficient light sources, use of higher order and noise immune digital modulation techniques and introduction of spatial diversity to improve detection of signals.

The survey paper has been divided into four sections. Section II focuses on study of effective channel modeling to ascertain the impact of atmospheric effects on link degradation while mitigating techniques like channel coding and spatial diversity techniques to limit the effect of link degradations have been compiled in section III. Section IV contains current and future trends associated with making FSO links commercially feasible and deployable.

2. FSO LINK CHANNEL MODELING

In wireless communication to transmit the signal from transmitter to receiver a medium is required that is known as channel. The signal when travel from channel gets affected by various losses.

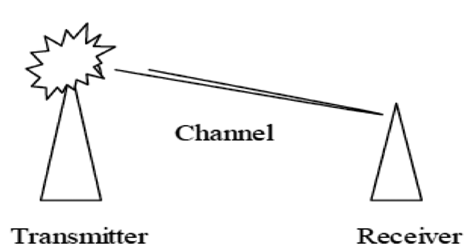

Figure 1: Symbolic schematic for FSO link

For these channels many models have been proposed and experimentally verified that describe the extent of channel losses. There are various losses which affects the performance of FSO. These losses are named as misalignment losses, atmospheric losses, atmospheric turbulence induced fading and background noise. In misalignment loss the causes are beam wander and building sway. In beam wander the beam deviates from its real path due to deflection in optical beam [7] and building sway originates from earthquakes, wind loads and vibrations. In atmospheric loss the causes are rain, pollution, fog, snow etc. Because of water particles absorption occurs which leads to scattering in which incident light changes its path [8].These atmospheric losses has negligible affects in clear atmosphere but there is another effect known as fading caused by variations in temperature results in atmospheric turbulence. This atmospheric turbulence leads to the fluctuations in phase and amplitude of a signal which results channel fading [7]. Some parameters are characterized the atmospheric turbulence: the inner scale of turbulence is l_0 and outer scale is L_0 and index of refraction $C^2_{n.}$ Kolmogorov theory explains these parameters in detail [9].The atmospheric turbulence strength is varies from weak to strong fading in FSO. To describe the quantity of turbulence, the scintillation index (SI) is used which is denoted by eq.1

$$\sigma^2_I = E\{I^2\}/E\{I\}^2 - 1 \tag{1}$$

Where *I* is intensity of optical wave and *E{.}* defines the expected value of *I*. In this paper we have defined various channel models for the distribution of turbulence. Some basic channel models are Lognormal, Negative–exponential, K-distribution and Gamma-Gamma model. [10] Proposed that for long propagation paths the lognormal model is appropriate only for weak turbulence condition. The negative exponential is used for very strong turbulence condition [11] while the K distribution [12] was proposed for strong turbulence and the probability density function (pdf) of intensity is given in eq.2

$$p(I) = \frac{2}{\Gamma(\alpha)}(\alpha I)^{\alpha-1/2} K_{\alpha\text{-}1}\left(2\sqrt{\alpha I}\right), \quad I>0, \alpha>0, \tag{2}$$

Where $K_m(.)$ is Bessel function of order m,α used for calculation of scintillation index as:$\sigma^2_I = 1+2/\alpha$. These all above models can be used for weak or for strong turbulence. Few other models have been proposed based on doubly stochastic theory in which both small and large turbulence eddies affect the light beam. The I-K distribution [13] is obtained based on this theory but it does not correlate with experimental data. So another model based on doubly stochastic theory has been proposed which is widely known as Gamma-Gamma model [11]. In this intensity I is product of two random variables. These random variables(X and Y) represent small and large scale turbulence .The probability density function (pdf) of I for this model is given in eq.3

$$p(I) = \frac{2(\alpha,\beta)\dfrac{(\alpha+\beta)}{2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha\text{-}1}\left(2\sqrt{\alpha\beta I}\right), \; I>0 \tag{3}$$

The $\Gamma(.)$ is gamma function and α and β are number of small and large scale turbulence eddies. The scintillation index(SI) of this model is:$\sigma^2_I = (1/\alpha)+(1/\beta)+(1/\alpha\beta)$. After this some other models has been proposed based on doubly stochastic theory like double weibull distribution[14] which is more accurate than the Gamma-Gamma model for weak to strong turbulence.

Table 1
Models with turbulence condition

Model	*Turbulence condition*
Lognormal[4]	Weak(intractable)
Negative exponential[5]	Very strong(tractable)
K-distribution[6]	Strong(tractable)
Gamma-gamma[5]	Weak to strong(tractable)

3.. MITIGATING TECHNIQUES IN FSO

The FSO link performance degrades due to various effects like rain, snow, fog and fading. In order to reduce these effects various techniques are used. The channel coding, modulation, spatial diversity are some mitigating techniques. In this paper we review the combined effect of these techniques.

(a) **Channel Coding and Modulation:** The channel coding is mitigating technique which is basically used in weak turbulence conditions in which several codes are used. The convolution codes, Reed Solomon codes, Turbo codes, Low density parity check codes (LDPC) are some basic coding techniques which are further used with modulation schemes. In order to transmit the signal over long distance we have to change the characteristics of carrier signal or to superimpose the message signal on carrier signal. The most common used technique for modulation is on-off keying (OOK). It is a binary modulation technique which directly use (on) for presence and (off) for absence of light pulse in modulated data. OOK requires dynamic thresholding and it has poor energy and spectral efficiency [18],[19],[20]. So to overcome the problems related to energy efficiency PPM (pulse-position modulation) is a powerful solution [15], [16].

Table 2
Modulation schemes in FSO

Modulation	*Comments*
OOK[18],[19],[22]	Simple but requires dynamic thresholding at receiver.
PPM[20],[19]	High energy efficiency.
MPPM[17],[19],[20]	Has more bandwidth efficiency than PPM.
PWM[21]	Good spectral efficiency, provide immunity against inter-symbol interference (ISI).
DPIM[23],[24]	More bandwidth efficiency than PPM and PWM.

The MPPM (multi-pulse PPM) have higher spectral and bandwidth efficiency in comparison to PPM [16], [17] but it increases demodulation complexity [18].

Coding and modulation combinations: As in [25], [26] the convolution codes are defined with modulation techniques. [27]The use of Low density parity check (LDPC) with MIMO has been proposed

.In which it has been shown that to obtain the channel capacity two coding techniques with MIMO are proposed the first is Repition MIMO scheme and second is space-time (ST) coding based MIMO. After this the LDPC codes with modulation techniques further proposed. In [28] the use of LDPC codes with OFDM modulation is further proposed and it has been shown that the use of OFDM modulation with LDPC outperforms the LDPC coded OOK modulation in terms of coding gain and spectral efficiency. For the coded FSO systems, error performance bounds were further derived and the uncorrelated channels are considered with requirement of interleavers [29]. In recent studies it has been shown that exploiting the channel reciprocity in FSO eliminates the need of interleavers [30].By the channel reciprocity, the channel state information (CSI) can be estimated at transmitter and this is further used in selecting the best encoder decoder pair [31].Several works were proposed based on finite size interleavers. The LDPC coding with interleaving proposed. The combined use of three coding techniques in which use of interleaved turbo codes, concatenated reed Solomon and convolution codes are proposed[17].The convolution codes are best for any kind of turbulence condition.

Rate less coding is classic example of flexible coding which allows change of coding rate based on channel condition without use of interleavers [60]. In[32] the convolution codes with PPM modulation was proposed and a comparative evaluation have been given in presence of background noise for Poisson and APD(avalanche photo diode) case as shown in table 3.Various other works related to error correction using non binary coding have been proposed. But with high complexity in decoding computation and it becomes severe in high rate FSO. The reed Solomon (RS) coding with PPM was proposed and it has been shown that RS codes are low complexity solution for this modulation [33]. The PPM modulation is widely used modulation technique because it has higher power efficiency [20],[19].

Table 3
Modulation with coding techniques.

Modulation-Coding	*Comments*
PPM-Convolution codes[32]	Better performance than RS coding if in decoding Tanmetrics used and worse performance than RS coding if δ-max demodulation used.
PPM,PSK-Turbo Codes	Turbo coded PSK perform better in terms of BER
OFDM-LDPC codes[28]	Outperform LDPC coded OOK in terms of spectral efficiency and coding gain.

(b) Spatial diversity: The diversity can be achieved by using multiple beams at transmitter (MISO), multiple apertures at receiver side (SIMO) or using both multiple beams and multiple apertures (MIMO). It is a effective solution in order to mitigate the fading in FSO. For diversity schemes the number of transmitting beams represented by M and number of apertures represented by N.

SISO-This is the general model in which only single input and single output is there.

Figure 2: SISO Link Schematic

Diversity at Transmitter-The multiple beams used at transmitter(MISO) to realize transmit diversity as in figure 3.The repetition coding(RC) signaling scheme is used for these systems in which same signal can be send over multiple beams.

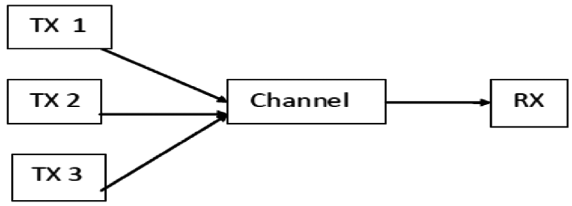

Figure 3: MISO diversity (3x1)

Diversity at receiver-The multiple apertures used at receiver side (SIMO) to realize receive diversity in Figure 4.Several number of apertures with smaller size at the receiver can be used instead of using a single large aperture in order to reduce fading efficiently.

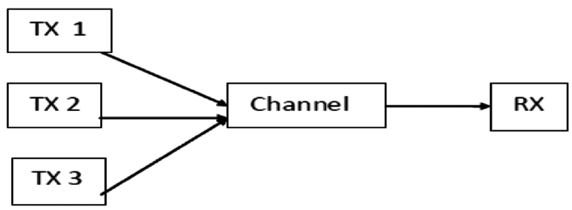

Figure 4: SIMO diversity (1x3)

MIMO-The multiple beams and multiple apertures are used in MIMO in figure 5.It is very popular technique. Mostly MIMO systems are used RC at transmitter in order to give efficient results for fading.

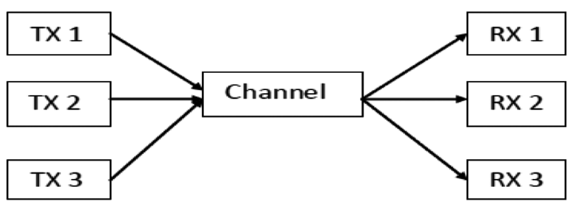

Figure 5: MIMO diversity (3x3).

(c) Fading correlation: For underlying sub channels the diversity techniques are efficient for uncorrelated case. The uncorrelated means the fading of each sub channel is independent from other sub channels .But if we have a case of correlated fading the performance of these diversity techniques is impaired by correlation. In Figure 6 shows the sub channels (c1, c2, c3 and c4) for (2x2) MIMO system.

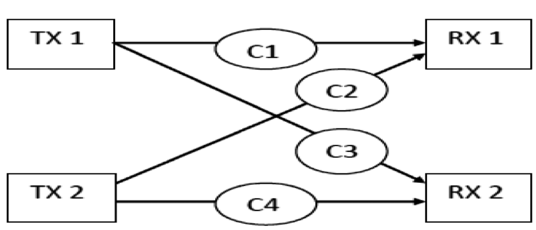

Figure 6: MIMO (2x2) - sub-channel representation

(d) **Effect of fading correlation on space diversity:** For FSO system with space diversity the evaluation of fading correlation made via wave-optics simulation. The experimental works for fading correlation in MISO and SIMO are presented in [34].The performance of MISO and SIMO via wave-optics simulation presented in [35] and it is observed that the fading correlation increases with the link distance and with the increased receiver aperture. Further works are presented in order to compare the performance of uncorrelated fading case (ideal) with fading correlated case. The effect of fading correlation on BER in SIMO diversity with log-normal model given in[35],[36] shown in table 4.For the case of K-distributed fading and multivariate Gamma-gamma fading the exponential correlation model was proposed[37],[38] and it has been shown that this model is not applicable for most FSO systems. By considering the case of four transmitter beams and single aperture in Gamma-Gamma model was studied where the correlation in fading channels modeled by using Gaussian approximation [39].For SIMO system(1x2) the α-μ distribution is considered which approximates the sum of two correlated Gamma-gamma random variables for evaluate the BER of the receiver and shown that the proposed work loses its accuracy for increased diversity order[40].The Padè approximation is also used for sum of correlated Gamma-gamma random variables in order to obtain the PDF from their moment generating function(MGF)[41].It should be noted that by using doubly stochastic theory the small scale fading assume as uncorrelated and correlation assign to large scale fading[42]. Table 4. Effect of fading correlation in different diversity schemes

Channel	*Diversity*	*Distribution*	*Comments*
Log-normal[35][36]	SIMO	Joint distribution of received signals	In comparison with independent channel correlation, the correlated fading degrades the performance of diversity.
Gamma-gamma channel[39]	MISO	Gaussian approximation	Reduces the power requirement for operation at low BER. Cost effective solution.
Gamma-gamma channel[40]	SIMO	α- μ distribution	Loses accuracy for increased diversity order.
Gamma-gamma [41].	SIMO	Padè approximation	Poor method for very low BER(<10-8)

4. CURRENT WORK AND FUTURE OF FSO

As in RF wireless communication the co-operative diversity is an alternative way for realizing the spatial diversity advantages [43],[44].The co-operative diversity is based on that idea of RF wireless communication in which a source node transmits the data to other nodes which can be defined as relays.Multi-hop transmission is a similar technique to relay-assisted transmission [45]. These types of schemes are used to enlarge the coverage of signal but they do not provide performance improvement in wireless communication systems against fading effects. In [46] the Relay-assisted FSO system was proposed and the mesh FSO network was considered for network capacity. The K and Gamma-gamma model was proposed with multi-hop FSO system to evaluate the outage probability[47].After these parallel relaying systems were proposed [48],[49].

The other technique was proposed to increase the reliability of FSO links and that is Hybrid RF/FSO system in which RF and FSO link used in parallel to each other. The RF link provides the backup in case the FSO system becomes inoperative and the RF link is also less affected by turbulence conditions and pointing errors [50].The Coherent FSO systems in which the optical carrier amplitude and optical carrier phase is considered in encoding the information. The coherent detection in FSO considered for increasing the receiver sensitivity [51], [52].In [53] it is explained that the background noise rejected by coherent detection. The system spectral efficiency increased by sending the information on amplitude and phase of the optical system [54].From IM/DD schemes the whole trend has shifted towards coherent detection. The performance of coherent detection in turbulence condition was proposed and after this it has been shown that coherent systems have improved performance as compared to IM/DD [53].It was shown that the previous result is true only when the thermal noise affects the non-coherent receivers [55]. By considering the K-distribution and binary modulation schemes the performance of coherent system was proposed [56].The receive diversity with coherent FSO systems also proposed in [57] and it has been shown that as compared to non-coherent systems the fading and background noise more reduced by diversity schemes. After this there are several works done on MIMO coherent systems. The MIMO coherent system with ST coding proposed in [58].A special technique proposed in which the phase noise estimation and wavelength diversity used by MIMO coherent system [59].

5. CONCLUSION

The FSO systems because of its large bandwidth can be used in various applications and provides more reliable transmission as compared to RF systems. For FSO systems the 10Gbps transmission rate is already there and there is research going on for high transmission rates than 10Gbps. There is lot of work going on Physical (PHY) layer design in FSO systems to overcome the various link loses. The various methods and techniques used for physical layer design like modulation techniques, channel coding, spatial diversity. The most commonly used channel model is Gamma-Gamma model because of its capability to work in weak to strong turbulence regime. We conclude that the higher modulation techniques have higher energy efficiency as compared to OOK which is simple to implement but has poor spectral and energy efficiency. Various space diversity methods can also be used as mitigation techniques to improve bit error rate performances of FSO links. We hope this review will provide valuable resources to understanding the researches in current FSO communication.

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