A Review on Performance Improvement and Power Optimization in Cooperative FSO Networks

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Abstract: *This paper reviews cooperative communication as a powerful solution for combating atmospheric turbulence induced fading. The various relaying techniques and cooperative strategies proposed in the recent times have been discussed, compared and analyzed in the context of performance improvement. The paper also discusses power optimization techniques as an efficient tool to maximize the overall capacity of the relay assisted networks. The paper provides the reader a wide range, informative view of the work done in the area of cooperative free space optical (FSO) networks.*

Keywords: *Free space optics, fading, cooperative system, atmospheric turbulence, power optimization.*

I. INTRODUCTION

Throughout the history of optical communication systems there have been some landmarks those have stood out during its evolution. Optical wireless communication (OWC) is the form of optical communication in which the signal is transmitted by using optical carriers such as visible, infrared (IR), and ultraviolet (UV) bands. Prior versions of OWC were smoke signals, fire beacons and semaphores [1]. Free Space Optics (FSO) is a type of OWC which operates in near IR band. OWC can be classified based on the below transmission ranges [2]-[6]:

1) Ultra-short range OWC, e.g., chip-to-chip communications in closely-packed multi-chip packages.
2) Short range OWC, e.g., under water communication, wireless body area network (WBAN).
3) Medium range OWC, e.g., indoor IR for wireless local area networks (WLANs).
4) Long range OWC, e.g., inter-building connections.
5) Ultra-long range OWC, e.g., deep space links.

FSO (Long Range OWC) is a line of sight (LOS) communication in which lasers and light emitting diodes (LED) are used as the transmitters. It has emerged as an alternative to Radio frequency communication (RF) for secured and reliable transmission of data, voice and video. It offers various advantages over existing RF communication such as license free spectrum, large bandwidth, high data rate, robustness to electromagnetic interference and high security [7]. FSO also provides a promising solution to the “Last Mile Access problem” by bridging the gap between the end user and fiber optic infrastructure already in place [8].

A. *Major Challenges in FSO*

- *Atmospheric loss*- It is the distortion caused by atmospheric channels which result in scattering, absorption and fluctuation of signals. With the presence of fog, smoke, gases and other suspended particles in the atmosphere, the optical signal gets attenuated [9], [10].
- *Scintillation*- It is caused by atmospheric temperature and pressure inhomogeneity under atmospheric turbulence. This further results in atmospheric turbulence induced signal fading [11].
- *Pointing losses (Misalignment losses)*- This loss occurs when the beam diverges from the propagating path through atmosphere [12].

Atmospheric turbulence induced fading (Scintillation) can be reduced by various techniques like Aperture averaging, Spatial diversity, Hybrid RF/ FSO link. There were certain limitations associated with each of these schemes due to which the alternate means of communication (Cooperative communication or Relay- assisted network) was required.

Table 1 shows the limitations of the mitigation techniques for scintillation.

Table 1: Limitations of Schemes Mitigating Scientillation

Mitigation Technique	Limitation
Aperture Averaging	Receiving aperture needs to be far greater than the spatial coherence distance in order to achieve several uncorrelated signals [8], [13].
Spatial Diversity (MIMO FSO)	1) Involves the usage of multiple transmit and receive apertures. 2) Performance of MIMO FSO degrades with channel correlation [14] - [17]. 3) Narrower sources should be placed for coupling more power from transmitter to receiver.
Hybrid System (RF/FSO)	Include loss of data during switch over from FSO to RF or vice versa and/or loss of real time operation due to temporary storage of data when switching [18].

Cooperative networks (or Relay assisted transmission) on the other hand have various positive factors encouraging its preference over Aperture averaging and Spatial diversity. Cooperative Diversity solution is always cost effective when compared to MIMO-FSO as it does not require adding more apertures to the receiver or transmitter. Cooperative diversity has emerged as a good practical alternative to MIMO-FSO systems considering the fact that MIMO-FSO could not deliver expected high performance gains [19]-[21]. As multiple relays under Cooperative diversity come into play, one of the critical issues to handle is the efficient management of power resources for increasing the transmission rate. Thus it is always desirable to have an optimal power allocation strategy to improve the order of diversity, reduce the error probability and maximize the capacity for individual base station. Power allocation under power and cost constraints is another challenging problem to consider. There has been some prior work focusing on optimal relay selection or relay placement in FSO considering optimal power allocation strategies [22].

The remainder of the paper is organized as follows: Section II describes modulation and various channel modeling techniques used in FSO. Section III discusses about cooperative networks while Section IV presents optimal power allocation strategies in cooperative networks. Section V provides conclusion and the future aspects.

II. MODULATION AND CHANNEL MODELING

A. *Modulation*

Some of the most commonly used intensity modulation techniques in FSO are on-off keying (OOK), pulse position modulation (PPM), differential phase shift keying (DPSK) and differential quadrature phase shift keying (DQPSK). From the earlier work it is clear that OOK has high implementation simplicity but it suffers from the problem of dynamic thresholding whereas PPM has superior power efficiency as compared to OOK and does not require dynamic thresholding [23]. However its bandwidth efficiency is poor. DPSK which codes information on its phase can mitigate the effect of scintillation to some extent. DQPSK doubles the spectral efficiency by taking advantage of two signal quadratures of an optical carrier [24]. On the other hand subcarrier intensity modulation (SIM) provides high throughput and cost effective implementation, as compared with coherent modulation. In SIM the data is first modulated onto an RF signal, and then used to change the intensity of an optical source. The main limitation of SIM is its poor optical power efficiency [25].

B. *Channel Modeling*

Modeling random attenuation of the propagation channel requires channel state which arises due to three factors atmospheric turbulence, path loss and pointing errors.

1) *Modeling the Channel for Atmospheric turbulence:* Over the years many statistical models have been proposed for describing the atmospheric turbulence induced fading. Experimental data over different propagation paths have shown that the log-normal model is appropriate for weak turbulence regime [26]. Probability density function (PDF) of the received intensity *I* by this model is given by:

$$p(I) = \frac{1}{I\sqrt{2\pi\sigma_i^2}} \exp\left(- \frac{\left[\ln\left(\frac{1}{I_o}\right) + \frac{\sigma_1^2}{2}\right]^2}{2\sigma_i^2} \right)$$

where σ_i is the log intensity variance (Rytov variance), I stands for received irradiance intensity and I_0 stands for intensity in free space. Another doubly-stochastic scintillation model Gamma-Gamma has gained a wide acceptance in the current literature for moderate to strong turbulent regime [27]. In the Gamma-Gamma model, the PDF of received intensity I is given by-

$$p(I) = \frac{2\,(ab)^{(a+b)/2}}{\Gamma(a)\,\Gamma(b)}\, I^{\frac{(a+b)}{2}-1}\, K_{a-b}\left(2\sqrt{abI}\right),\ I > 0,$$

where the parameters a and b represent the effective numbers of large and small-scale turbulence cells, and $\Gamma(.)$ is the Gamma function. The K-distribution, originally proposed for the strong turbulence regime [28]. The PDF of the received intensity I by this model is given by:

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

where $Km(.)$ is the modified Bessel function of second kind and order m, and the parameter α determines the Scintillation index. In recent times several other models have also been used by the researchers to evaluate the performance of the system. The comparison of some mostly used models are listed in Table 2 [29], [30].

Table 2: Comparison of Fading Models

Turbulence induced fading model	**Turbulence Regime**	**Comments**
Log normal (LN)	Weak	Widely accepted for relatively short ranges in urban areas
Gamma-Gamma(G-G)	Moderate to strong	Lack of mathematical convenience as compared to LN
K distribution	Strong	Product of exponential and gamma distribution
I-K distribution	Moderate to strong	Less computational complexity than G-G model
Negative exponential	Negative exponential	Used where link length spans several kilometers
Double weibull	Moderate to strong	More accurate than G-G model
Log normal Rice	Moderate to strong	Log normally modulated exponential distribution
M-distribution	Moderate to strong	Includes K and G-G models
Double Generalized Gamma	Moderate to strong	More accurate than Double Weibull

2) *Modeling the Channel for Path Loss:* The path loss $h_l(z)$ of the laser power through a propagation path of length z is described by the exponential Beers-Lambert Law as-

$$h_l(z) = \frac{P(z)}{P(0)} = \exp(-\sigma z),$$

where $P(z)$ is the laser power at distance z, and σ is the attenuation coefficient. The path loss $hl(z)$ is considered as deterministic during a long period of time, and no randomness exists in its behavior.

3) *Modeling the Channel for Pointing Error:* When the Gaussian beam propagates in the turbulent atmosphere, pointing losses or misalignment losses occur due to the wind loads, thermal expansions and random building sways. The attenuation due to geometric spread with pointing error is denoted by $hp(r)$. When a pointing error of r is present, hp is a function of the radial displacement and angle. Due to the symmetry of the beam shape and the detector area, the resultant $hp(r)$ depends only on the radial distance r which is modeled by a Rayleigh distribution [31]. The probability distribution of hp can be expressed as-

$$f_{hp}(hp) = \frac{\gamma^2}{A_0 \gamma^2}\, h_p^{\gamma^2-1},\ 0 \le A_0$$

where $= \gamma = \omega_z / 2\sigma_s$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation at the receiver. where σ_s^2 is the jitter variance at the receiver and ω_z is the equivalent beam width.

III. COOPERATIVE NETWORKS IN FSO

In a wireless RF channel, cooperative diversity takes the advantage of broadcast nature of RF transmission where the signal that is transmitted by its source node is overheard by other nodes (relays). The source and its partner then jointly process and transmit this information further, thus creating a virtual antenna array though each of the node has only one antenna.

To the author's best knowledge Relay assisted cooperative network in FSO was first proposed in [32] where network capacity was investigated within mesh FSO from the system point of view. The relaying techniques have been used to compare the performance improvements against fading effects in wireless RF first and then in FSO transmissions.

A. Relaying Techniques

1) *Relaying through Multi-hop(Serial)transmission:* Multi-hop scheme when used in wireless RF channel though broadened the signal coverage but did not offer performance improvement against fading effects or diversity gain [33]. In case of FSO systems where signal fading is dependent on distance, multi-hop scheme takes the advantage of shorter hops and provides significant performance improvement. Tsiftsis has evaluated the outage probability for a multihop FSO system using Gamma-Gamma fading models without considering the path-loss [34].Though the usefulness of cooperative network as a method to broaden the coverage area was proved but did not reflect it as a fading mitigation tool. In [35], outage probability is calculated by considering both path-loss and fading effects.

In [36], the author has found that outage probability is minimized when the consecutive nodes are placed equidistant along the path from the source to the destination. Assuming an absorption loss of 0:43 dB/km with lognormal fading strength of $\sigma^2_x = 0{:}3$, distance between source and destination= 10 km, the performance gain of about 18 dB was found at the outage probability of 10^{-5} when two relays were used instead of one [37] (For evenly distributed relays).

2) *Relaying through Cooperative (parallel transmission) Diversity:* FSO is the line of sight transmission system so it cannot broadcast the signal unlike wireless RF transmitter. To take the advantage of broadcast nature of RF system, multiple apertures focused to relay nodes are deployed at the transmitter in parallel relaying technique.

Chadi had mentioned that cooperation through relay nodes is advantageous if the SNR is high, otherwise relays will forward too noisy signals resulting in performance degradation [38]. Fig. 1 depicts the combination of serial and parallel network established between the source and destination.

3) *Inter-relay Cooperation:* A new dimension of cooperative diversity is inter-relay cooperation. In case of parallel relaying, a signal is first transmitted

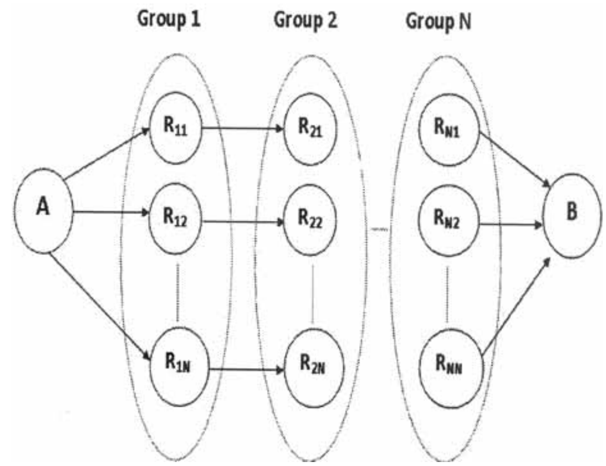

Fig. 1: Multi-hop parallel network

from source A to relays, however as a concept of inter-relaying signal is not directly forwarded to destination B. Instead the relays R_1 and R_2 (as shown in Fig. 2) first cooperate with each other to improve the fidelity of reconstructed signals before sending it to destination B [39].

Scenario 1- The number of links between source A to destination B in the absence of inter relay communication (IRC) are 5 (A-R_1 R_1 - B, A - R_2, R_2- B and A-B).

Scenario 2 (One way IRC) - It is between either R_1 - R_2 or R_2 - R_1 the maximum number of links getting generated are 6 (A - R_1, R_1 - B, A- R_2, R_1 - R_2, R_2 - B and A - B).

Scenario 3 (Two way IRC)- In case of two way interrelay communication, the maximum number of links getting generated are 7 (A - R_1, R_1 - B, A - R_2, R_1 - R_2, R_2 - R_1, R_2 - B and A - B).

It has been demonstrated in [38] that in the absence of channel state information (CSI) one-way IRC is most appropriate when R_1 is near to A and R_2 is near to B.

Also all active parallel relaying is most appropriate if both relays R_1 and R_2 are near to either source A or destination B.

B. Cooperative Strategies

Various cooperative strategies have been proposed for relay assisted FSO. Most commonly used strategies include Amplify & Forward (AF) [40], [41] and Decode & Forward (DF) [42], [43] protocols.

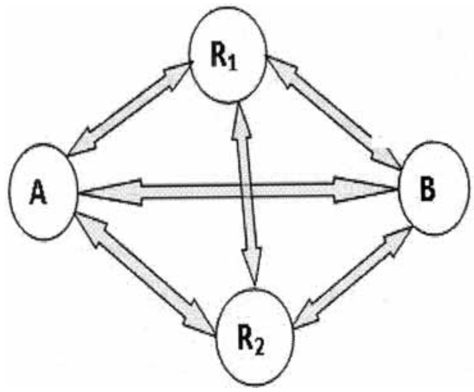

Fig. 2: Inter-relay cooperation

In AF relaying, the received signal is first amplified at each relay node before it is re-transmitted to the following relay node. In DF, the received signal is first detected and demodulated in order to recover the original data and then regenerated for relaying to the following node.

Adaptive bit detect and forward (ABDF) and adaptive decode and forward (ADF) have also been proposed in [44], where the relay transmits data only if it can receive error free frames of data from the source or when the SNR at the relay is large enough, respectively. When channel state information (CSI) is available at the relays and the source, it is proposed to select the best relay among multiple parallel relays [45],[46].

In [35], the author has shown the usefulness of relay assisted FSO using both types of cooperation strategies considering the log-normal channel model, an atmospheric attenuation of 0.43 dB/km, refractive index structure parameter $C_n^2 = 10^{-14}\ m^{-2/3}$, a total link span (between source and destination) of 5 km, and a target outage probability of 10^{-6}. The performance improvement results are listed in Table 3.

IV. POWER OPTIMIZATION

Efficient power optimization techniques are required in cooperative communication for transmission rate maximization, transmit power minimization and outage probability reduction [47]-[51]. Power allocation strategies depend on whether the CSI is available at transmitter or not.

A. Power Allocation in Absence of CSI

When the CSI is not available, the power must be equally distributed among all the possible $2N$ +1 links

Table 3: Performance Analysis in Cooperative Networks

Relaying Technique	Cooperative Strategy	No. of relays	Improvement in power margin (dB)
Multihop transmission (with equidistant relays)	DF	1	18.5
	DF	2	25.4
	AF	1	12.2
	AF	2	17.7
Cooperative diversity	DF	2	20.3
	DF	3	20.7
	AF	2	18.1
	AF	3	20.2

(A - B, A - R_1, A - R_2, ...A R_N and R_1 - B, R_2 - B, ...R_N - B) and the high performance gains can be obtained with relatively small energies.

$$P_0 = P_{1-1} = ...P_{1-N} = P_{2-1} = ... P_{2-N} \frac{1}{(2N + 1)},$$

where N is the number of relays in the transmission path from A to B. $P0$ is the fraction of the total power that is dedicated to the direct link A - B,P_{1-N}, P_{2-N} is the fractions of the total power dedicated to links A-R_N - B, respectively. In order to ensure the same transmission level as in non-cooperative systems, the following equality must be satisfied

$$P_0 + \sum_{n=1}^{N} [P1 - n + P2 - n] = 1$$

B. Power Allocation in Presence of CSI

When the CSI is available, the power allocated to each link can be optimized in order to minimize the conditional error probability(CEP). In [31], author has proposed the power allocation strategy that is based on minimizing the upper bound on the CEP. The minimization problem is solved by the method of Lagrange multipliers with the solution satisfying the Karush-kuhm-Tucker (KKT) conditions in order to ensure non-negative powers.

The reason for considering the upper bound rather than the exact expression of CEP is that minimizing the CEP is difficult and does not produce the simple close form solutions and the other reason is that the highest performance gains of the diversity techniques are obtained in the high SNR region and in this particular regime the upper bound becomes very close to the expression of CEP.

In [22], it is proven that in the presence of CSI highest performance gain can be obtained when the entire power is transmitted along the strongest link instead of dividing the total power among all links available in the transmission path.

Table 4 gives the details of the collated data for the optimal power allocation with one and two relays helping the source variable. The channel coefficients are modeled as zero mean, complex Gaussian random variables with variances 2 σ^2_r, $\sigma^2_{r,d}$ and P_i is the i^{th} relay node power. From the Table 4, it is clear that equal power allocation is not optimal. As the relays get closer to the source, the equal power allocation scheme tends to be optimal. If the relays are close to the destination, the optimal power allocation can result in a significant performance improvement. It has been further studied in [52] that if peak and/or average power constraint exists in the system then power optimization among few best paths will provide optimal solution. Peak power constraint is related to the maximum intensity that can damage the human eye while the average power constraint per transmission is imposed on some battery operated devices to provide certain transmission data rate over a particular time period. Power allocation strategies in non orthogonal (multicast) AF cooperative network under sum power constraint are found in [44].

Table 4: Optimal Power Allocation for One or Two Relays ($\sigma^2_{s,d}$ =1)

RELAY CLOSE TO SOURCE				
No. of Relays	$\sigma^2_{s,r}$	$\sigma^2_{r,d}$	P_0/P	P_1/P
One Relay	10	1	0.5393	0.4607
Two Relays	10	1	0.3830	= P2/P = 0.3085
RELAY CLOSE TO DESTINATION				
No. of Relays	$\sigma^2_{s,r}$	$\sigma^2_{r,d}$	P_0/P	P_1/P
One Relay	1	10	0.8333	.1667
Two Relays	1	10	0.7500	= P2/ P = 0.1250

V. CONCLUSION

The aim of this paper is to present the impact of relay assisted transmission techniques and different cooperative strategies on the performance of FSO systems against fading effects. In this paper authors have provided an overview of contribution and limitation of different transmissions techniques and their comparison in terms of improving the performance of FSO systems. The authors have also discussed about the efficient power optimization techniques in relay assisted FSO and the concept of power allocation strategies depending upon CSI.

The authors have gathered the data by referring to various available literatures on relaying techniques in order to showcase the improvement in FSO using cooperative networks. In the near future the complexity of FSO system will continue to increase. Further improvements in transmission rate maximization and outage probability reduction are required to prove cooperative communication as a powerful solution for combating atmospheric turbulence induced fading.

REFERENCES

[1] D. Killinger, “Free space optics for laser communication through the air,” *Optics* & *Photonics News*, vol. 13, pp. 36-42, Oct. 2002.

[2] M. R. Feldman, S. C. Esener, C. C. Guest, and S. H. Lee, “Comparison between electrical and optical interconnect based on power and speed consideration,” *Applied. Optics*, vol. 27, no. 9, pp. 1742-1751, Sept. 1998.

[3] F. Hanson and S. Radic, “High bandwidth underwater optical communication,” *Applied Optics*, vol. 47, no. 2, pp. 277-283, Jan. 2008.

[4] H. Elgala, R. Mesleh, and H. Haas, “Indoor optical wireless communication:Potential and state-of-the-art,” *IEEE Communications Magazine*, vol. 49, no. 9, pp. 56-62, Sept. 2011.

[5] V. W. S. Chan, “Optical satellite networks,” *IEEE/OSA Journal of Lightwave Technology*, vol. 21, no. 11, pp. 2811-2827, Nov. 2003.

[6] X. Zhu and J. Kahn, “Free-space optical communication through atmosphericturbulence channels,” *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1293-1300, Aug. 2002.

[7] D. Kedar and S. Arnon, “Urban optical wireless communication networks: the main challenges and possible solutions,” *IEEE Commun. Mag.*, vol. 42, no. 5, pp. s2-s7, May. 2004

[8] V. W. S. Chan, “Free-space optical communications,” *IEEE/OSA Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4750-4762, Dec.2006.

[9] C. C. Davis, I. I. Smolyaninov, and S. D. Milner, “Flexible optical wireless links and networks,” *IEEE Communications Magazine*, vol. 41, pp. 51-57, March. 2003.

[10] D. C. O’Brien, S. Quasem, S. Zikic, and G. E. Faulkner, “Multipleinput multiple output systems for optical wireless: challenges and possibilities,” *Proceedings of SPIE, Free-Space Laser Communications VI*, vol. 6304, Aug. 2006, San Diego, CA.

[11] L. C. Andrews, R. L. Phillips, C. Y. Hopen, and M. A. Al-Habash,“Theory of optical scintillation, ”*Journal of Optical Society of America (JOSA) A*, vol. 16, no. 6, pp. 1417-1429, June. 1999.

[12] L. C. Andrews and R. L. Phillips, *Laser beam propagation through random media*, SPIE Press, 2nd edition, 2005.

[13] G. Proakis and M. Salehi, *Digital communications*, McGraw-Hill, 5th edition, New York, 2008.

[14] W. O. Popoola, “Subcarrier intensity modulated free-space optical communication system,” *Ph.D. dissertation, School Comput., Eng. Inf. Sci.,Univ. Northumbria*, Newcastle upon Tyn, U.K., Sep., 2009.

[15] S. G. Wilson, M. Brandt-Pearce, Q. Cao, and J. H. Leveque, “Freespace optical MIMO transmission with *Q*-ary PPM,” *IEEE Transactions on Communications*, vol. 53, no. 8, pp. 1402-1412, Aug. 2005.

[16] S. M. Navidpour, M. Uysal, and M. Kavehrad, “BER performance of free-space optical transmission with spatial diversity,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2813-2819, Aug. 2007

[17] M. K. Simon and M.S. Alouini, *Digital communication over fading channels*, John Wiley & Sons, 2nd edition, New York, 2005.

[18] H. Tapse and D. K. Borah, “Hybrid optical=RF channels: characterization and performance study using low density parity check codes,”*IEEE Transactions on Communications*, vol. 57, no. 11, pp. 3288-3297,Nov. 2009.

[19] N. D. Chatzidiamantis, M. Uysal, T. A. Tsiftsis and G. K. Karagiannidis,“Iterative near maximum-likelihood sequence detection for MIMO optical wireless systems,” *IEEE/OSA Journal of Lightwave Technology*, vol. 28, no. 7, pp. 1064-1070, Apr. 2010.

[20] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and M. Uysal,“Optical wireless links with spatial diversity over strong atmospheric turbulence channels,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 2, pp. 951-957, Feb. 2009.

[21] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, “An overview of MIMO communications: a key to gigabit wireless,” *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198-218, Feb. 2004.

[22] C. Abou-Rjeily and S. Haddad, “Cooperative FSO systems: Performance analysis and optimal power allocation,” *J. Lightw. Technol.*, vol. 29, no. 7, pp. 1058-1065, Apr. 2011.

[23] Z. Ghassemlooy and W. O. Popoola, *Mobile and Wireless Communications Network Layer and Circuit Level Design*, chapter Terrestrial Free-Space Optical Communications, pp. 355-392, InTech, Jan. 2010.

[24] Y. Han and G. Li, “Theoretical sensitivity of direct-detection multilevel modulation formats for high spectral efficiency optical communications,” *IEEE Journal on Selected Topics on Quantum Electronics*, vol.12, no. 4, pp. 571-580, July. 2006.

[25] W. O. Popoola, “Subcarrier intensity modulated free-space optical communication system,” *Ph.D. dissertation*, School Comput., Eng. Inf. Sci.,Univ. Northumbria, Newcastle upon Tyn, U.K., Sep., 2009.

[26] J. H. Churnside and R. G. Frehlich, “Experimental evaluation of lognormally modulated Rician and I-K models of optical scintillation in the atmosphere,” *Journal of Optical Society of America (JOSA) A*, vol.6, no. 11, pp. 1760-1766, Nov. 1989.

[27] F. E. Goodwin, “A review of operational laser communication systems,” *Proceedings of the IEEE*, vol. 58, no. 10, pp. 1746-1752, Oct. 1970.

[28] E. Jakeman and P. Pusey, “Significance of K distributions in scattering experiments, ”*Physical Review Letters*, vol. 40, pp. 546-550, Feb. 1978.

[29] N. D. Chatzidiamantis, H. G. Sandalidis, G. K. Karagiannidis, S. A. Kotsopoulos, and M. Matthaiou, “New results on turbulence modeling for free-space optical systems,” *IEEE International Conference on Telecommunications (ICT)*, pp. 487-492, Apr. 2010, Doha, Qatar.

[30] A. Jurado-Navas, J. M. Garrido-Balsells, J. F. Paris, and A. Puerta-Notario, “General analytical expressions for the bit error rate of atmospheric optical communication systems,” *Optics Letters*, vol. 36, no. 20, pp. 4095-4097, Oct. 2011.

[31] A. Farid, S. Hranilovic, “Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors,” *J. Lightw. Technol.*, vol. 25, no. 7, pp.1702-1710, July. 2007.

[32] A. Acampora and S. Krishnamurthy, “A broadband wireless access network based on mesh-connected free-space optical links,” *IEEE Personal Communications*, vol. 6, no. 10, pp. 62-65, Oct. 1999.

[33] E. Bayaki, R. Schober, and R. Mallik, "Performance analysis of MIMO free-space optical systems in Gamma-Gamma fading,"*IEEE Transactions on Communications*, vol. 57, no. 11, pp. 3415-3424, Nov. 2009.

[34] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and N.C. Sagias, "Multihop free-space optical communications over strong turbulence channels," *International Conference on Communications (ICC)*, vol. 6, pp. 2755-2759, June. 2006, Istanbul, Turkey.

[35] M. Safari and M. Uysal, "Relay-assisted free-space optical communication," *IEEE Transactions on Wireless Communications*, vol. 7, no.12, pp. 5441-5449, Dec. 2008.

[36] M. A. Kashani, M. Safari, and M. Uysal, "Optimal relay placement and diversity analysis of relay-assisted free-space optical communication systems," *IEEE/OSA Journal of Optical communications and Networking*, vol. 5, no. 1, pp. 37-47, Jan. 2013.

[37] C. K. Datsikas, K. P. Peppas, N. C. Sagias, and G. S. Tombras, "Serial free-space optical relaying communications over Gamma-Gamma atmospheric turbulence channels," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 2, no. 8, pp. 576-586, Aug. 2010.

[38] C. Abou-Rjeily , "All-Active and Selective FSO Relaying: Do We Need Inter-Relay cooperation? ," *Journal of lightwave technology*, vol. 32, no. 10, pp.1899-1906, May. 2014 .

[39] C. Abou-Rjeily and S. Haddad, "Inter-Relay Cooperation: A New Paradigm for Enhanced Relay-Assisted FSO Communications," *IEEE Trans. Commun.*, vol. 62, no. 6, pp. 1970-1982, June. 2014.

[40] G. Karagiannidis, T. Tsiftsis, and H. Sandalidis, "Outage probability of relayed free space optical communication systems," *Electronics Letters*, vol. 42, no. 17, pp. 994-996, Aug. 2006.

[41] K. P. Peppas, A. N. Stassinakis, H. E. Nistazakis, and G. S. Tombras,"Capacity analysis of dual amplify-and-forward relayed freespace optical communication systems over turbulence channels with pointing errors," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 9, pp. 1032-1042, Sept. 2013.

[42] M. R. Bhatnagar, "Average BER analysis of differential modulation in DF cooperative communication system over gamma-gamma fading FSO links," *IEEE Commun. Lett.*, vol. 16, no. 8, pp. 1228-1231, Aug. 2012.

[43] S. Aghajanzadeh and M. Uysal, "Outage performance and DMT analysis of DF parallel relaying in FSO IM/DD communications," *in Proc. IEEE Veh. Technol. Conf.*, 2012, pp. 1-5.

[44] M. Karimi and N. Nasiri-Kenari, "BER analysis of cooperative systems in free-space optical networks," *IEEE=OSA Journal of Lightwave Technology*, vol. 27, no. 12, pp. 5639-5647, Dec. 2009.

[45] M. Bhatnagar, "Performance analysis of decode-and-forward relaying in gamma-gamma fading channels," *IEEE Photonics Technology Letters*, vol. 24, no. 7, pp. 545 -547, Apr. 2012.

[46] N. D. Chatzidiamantis, D. S. Michalopoulos, E. E. Kriezis, G. K.Karagiannidis, and R. Schober, "Relay selection protocols for relayassisted free-space optical systems," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 1, pp. 92-103, Jan. 2013.

[47] G. Caire, G. Taricco, and E. Biglieri, "Optimum power control over fading channels," *IEEE Trans. Inf. Theory*, vol. 45, pp. 1468-1489, July. 1999.

[48] A. Mercado and B. Azimi-Sadjadi, "Power efficient link for multihop wireless network," *in Proc.* 41*st Allerton Conf. Commun., Control, Comput.*, Monticello, *IL*, Oct. 1-3, 2003, pp. 1837-1847.

[49] M. O. Hasna and M. Alouini, "Optimum power allocation for relayed transmissions over Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1999-2004, Nov. 2004.

[50] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplify-and-forward relay network: Optimum power allocation versus selection, "*IEEE Trans. WirelessCommun.*, vol. 6, no. 8, pp. 3114-3123, Aug. 2007.

[51] K. T. Phan, T. Le-Ngoc, S. A. Vorobyov, and C. Tellambura, "Power allocation in wireless multi-user relay network," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2535-2545, May. 2009.

[52] P. Gong, P. Xue, D. Park and D. K. Kim, "Optimum power allocation in a nonorthogonal amplify-and-forward relay- assisted network," *IEEE Trans. on Vehicular Technology* ,vol.60, pp. 890-900, March. 2011.

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