Spatial Diversity and Multi Hop in FSO Communication Over Turbulence Channels

Mohamed Abaza¹, Raed Mesleh¹, Ali Mansour², and El-Hadi M. Aggoune¹

¹Sensor Networks and Cellular System (SNCS) Research Center, University of Tabuk, 71491 Tabuk, Saudi Arabia
²Lab STIC, ENSTA Bretagne, 2 Rue François Verny, 29806 Brest Cedex 9, France

mabaza.sncs@ut.edu.sa, rmesleh.sncs@ut.edu.sa, mansour@ieee.org, haggoune.sncsg@ut.edu.sa

Abstract

Free-space optical (FSO) communication systems have high data rate and perfect end-user communication solutions. On the other hand, FSO bit error rate (BER) performance degrades with the atmospheric turbulence and the weather attenuation. Spatial diversity and relay assisted techniques have been proposed in literature as a solution for these problems. However, authors concentrate on the comparison between either spatial diversity and single-input single-output (SISO) or relay assisted techniques and SISO. In this paper, comparisons between a multi hop decode and forward (DF) relay and a multiple-input single-output (MISO) system are driven under different turbulence and weather conditions. Our results show that multi hop DF relay outperforms MISO, with number of transmitters equal to the number of hops, using repetition codes for correlated case in the BER performance under different conditions.

Keywords: Free-space optical communications; atmospheric turbulence; spatial diversity; repetition Codes (RCs); decode and forward (DF) relay.

1- Introduction

Nowadays, free-space optical (FSO) communication systems have gained a lot of attention due to its high data rate and its advantage in end-user communication solution. FSO face a lot of challenges as atmospheric turbulence and weather attenuation effects. Atmospheric turbulence is the main reason of fading in FSO. Weather attenuation results from rain, snow, dust, fog or haze [1, 2]. Spatial diversity using intensity modulation with direct detection (IM/DD) as a cheap and simple technique is proposed [3–7] to mitigate the atmospheric turbulence.

In [8, 9], three methods are used based on orthogonal space time block codes (OSTBCs), repetition codes (RCs) and transmit laser selection (TLS). Simulation results show that RCs outperform OSTBCs [8], however lack of synchronization leads to make asynchronous OSTBCs better than RCs [10]. Also, the authors of [9] show that TLS perform better than RCs. However, TLS is more complex and it requires channel state information. RCs and OSTBCs in wireless optical communications using IM/DD is different than radio frequency (RF).

In fact, while RCs send the same information simultaneously from all transmitters. OSTBCs is quite different from standard OSTBCs by using IM/DD only positive signals can be transmitted so the negative part of signals is represented by its 1’s complement [8]. Relay assisted techniques can be a perfect tool in mitigation atmospheric turbulence as turbulence is directly proportional with distance. Using relay assisted, the distance will decrease so the turbulence effect will be also reduced.

Relay assisted techniques can be classified as amplify and forward (AF) (i.e., the signal and the noise are amplified at the relay) and decode and forward (DF) (i.e., the signal is regenerated at the relay so the noise is not amplified). DF system is more complex and suffers from delay time. Relay assisted techniques can be classified according to two types of connections: parallel (cooperative) or multi hop (serial). Parallel connection can be with or without direct link [11, 12].

To the best of our knowledge, only [13–16], discussed the comparison of BER performance on relay assisted diversity networks with spatial diversity in FSO communication systems. In [13], a parallel optical AF is employed where the received signal consists of two parts: one from the
direct path and the other from the relay. The authors of [13], considered log-normal channel and different weather attenuation.

Their results show that optical AF has better BER performance than 2 x 1 multiple-input single-output (MISO) using RCs especially when the source destination link is long or the attenuation factor is high. In [14], cooperative FSO communications with one relay DF and equal gain combining (EGC) at the receiver side using IM/DD is investigated. Rayleigh and log-normal channels are assumed. According to [14] the cooperative techniques outperform 2x1 MISO using RCs if the correlation between transmitters is considered.

In [15], with the same cooperative scheme of [14] gamma-gamma model and misalignment channel are considered. They achieve a BER performance better than two transmitter following TLS under certain relay location. In [16], the authors introduce three modified types of parallel DF: bit detect and forward (BDF), adaptive bit detect and forward (ABDF) and adaptive decode and forward (ADF). To evaluate the performance of the three proposed models the authors assume that the link quality between source and destination similar to the link quality among cooperative paths.

This assumption means that BDF and ABDF have no considerable gains over direct link at moderate signal to noise ratios (SNRs), but ADF approximately has the same performance as that of the case of two transmitters. In this paper, we consider a multi hop DF relays with equal hop length for IM/DD FSO systems in log-normal channel taken into consideration different weather attenuation effects. This multi hop model is compared with IM/DD MISO using RCs with and without the correlation effects among the transmitters.

Our results show that the proposed multi hop model outperforms the correlated MISO system for different turbulence and weather attenuation losses especially when the link attenuation is high.

2 - System Description

a. Single-Input Single-Output (SISO)

Figure 1 illustrates the SISO scheme connection. On-off keying (OOK) signals are transmitted through laser over a log-normal channel which suffers from path loss due to weather effects and an additive white Gaussian noise (AWGN), $n(t)$, result from background noise limited receiver [8].

where $x(t)$ is the transmitted information bits, $L$ is the propagation distance, $r(t)$ is the received signal and $\hat{x}(t)$ is the estimated received bits.

![Fig. 1: SISO scheme.](image-url)
b. MISO Using RCs

Figure 2 illustrates the MISO scheme connection using RCs. OOK signals are transmitted simultaneously through $N_t$ lasers over a correlated log-normal channel which suffers from path loss due to weather effects and an AWGN. At the receiver the photodetector combines the multiple signals with the same weight as the received irradiance are real and positive [8]. Correlation effect, $\rho$, is a function of the separation distance $d$ among transmitters, Please note that for fair comparison the total power must be divided among the transmitters.

![Fig. 2: MISO scheme using RCs.](image)

$$x(t) \xrightarrow{\text{OOK Modulator}} \quad d \quad \xrightarrow{\text{Tx}_1} \quad \xrightarrow{\text{Rx}} \quad x(t)$$

$$\text{OOK de-Modulator}$$

$$n(t)$$

$$r(t)$$

$c$. Multi Hop DF Relay

The multi hop DF relay scheme connection is illustrated in Fig. 3. This scheme transmits information in $N_h$ hops. Each hop is considered as a SISO link with equal and short distance. Where every relay receives the signal, regenerates it (no accumulative AWGN) and send it again either to the next relay or to the final destination. Because the link will be shorter both turbulence effect and weather attenuation effect will be decreased.

![Fig. 3: Multi hop DF relay scheme.](image)

$$x(t) \xrightarrow{\text{OOK Modulator}} \quad \xrightarrow{\text{DF Relay}} \quad \xrightarrow{\text{Rx}} \quad x(t)$$

$$\text{OOK de-Modulator}$$

$$n(t)$$

$$r(t)$$

3 - Numerical Results and Discussions

According to [17], the target BER for FSO is $10^{-9}$, wavelength $\lambda = 1550$ nm, $L = 1200$ m, $C_{n^2} = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ and $\alpha = 20 \text{ dB/km}$ for light fog attenuation in the morning, $C_{n^2} = 5 \times 10^{-14} \text{ m}^{-2/3}$ and $\alpha = 0.43 \text{ dB/km}$ for clear weather condition on strong sunlight condition, $\rho = \{0, 0.3\}$ and hops lengths are equal.
In Fig. 4, the direct link distance is about 1200 m and the relay is fixed in the middle distance. Light fog is considered with low turbulence as fog does not happen in strong sunshine. Exact and approximated BER for multi hop techniques have perfect match. Our simulations show that DF dual hop relay required less SNR at the target BER than dual transmitters using RCs with $\rho = 0.3$ and SISO by 22.7 dB and 26.5 dB, respectively.

![Fig. 4: BER of FSO in log-normal fading channel and light fog ($C_n^2 = 1.7 \times 10^{-14} \text{ m}^{-2/3}; \alpha = 20 \text{ dB/km}$). Distance between source and destination = 1200 m and distance between hops is 600 m.](image)

In Fig. 5, the similar parameter set of Fig. 4 is employed but in clear weather condition. The superior advantages of multi hop scheme are reduced as it only results from mitigation of turbulence. We observe that DF dual hop relay required less SNR at the target BER than dual transmitters using RCs with $\rho = 0.3$, dual transmitters using RCs with $\rho = 0$ and SISO by 4.5 dB, 0.75 dB and 11.3 dB, respectively. Multi hop scheme has worsen BER performance in low SNR than SISO and correlated MISO.

![Fig. 5: BER of FSO in log-normal fading channel and light fog ($C_n^2 = 5 \times 10^{-14} \text{ m}^{-2/3}; \alpha = 0.43 \text{ dB/km}$). Distance between source and destination = 1200 m and distance between hops is 600 m.](image)

In Fig. 6, the direct link distance is 1200 m and two relays are fixed in the middle distance. Light fog is considered with low turbulence. In this case, we noticed that DF triple hop relay required less SNR at the target BER than triple transmitters using RCs with $\rho = 0.3$ and SISO by 28.3 dB and 33.9 dB, respectively. This means that triple hop outperforms dual hop by 7 dB. On the other hand, increasing the number of transmitter to three will enhance the performance only by 1.4 dB. The gap of spatial diversity does not mitigate weather attenuation effects.

![Fig. 6: BER of FSO in log-normal fading channel and light fog ($C_n^2 = 1.7 \times 10^{-14} \text{ m}^{-2/3}; \alpha = 20 \text{ dB/km}$). Distance between source and destination = 1200 m and distance between hops is 600 m.](image)
In Fig. 7, similar conditions to Fig. 6 are employed but in clear weather condition. Results show that DF triple hop relay required less SNR at the target BER than triple transmitters using RCs with $\rho = 0.3$ and SISO by 2.4 dB and 13 dB, respectively. It is worth noticing that triple transmitters using RCs with $\rho = 0$ outperforms DF with triple hops by 1.6 dB however, uncorrelated case cannot exist in real applications due to limited space for transmitter units. We should add that multi hop scheme has low BER performance in low and medium SNR under clear weather condition.

Finally, comparing dual hop DF with correlated $3 \times 1$ MISO shows that multi hop scheme has better performance for both clear and light fog attenuations by 0.3 dB and 21.2 dB, respectively.

4-Conclusions

In this manuscript, multi hop DF relay and MISO system are investigated under different turbulence and weather conditions. Our results show that multi hop DF is more reliable than MISO using repetition codes under correlation effect at BER = $10^{-9}$. Different atmospheric challenges are simulated with the same link power for the sake of this comparison.

Acknowledgment

The authors gratefully acknowledge the support for this work from SNCS Research Center at University of Tabuk under the grant from the Ministry of Higher Education in Saudi Arabia.
References


Mohamed Abaza (S09) received both the B.Sc. and the M.Sc. degrees in Electronics and Communications Engineering from the Arab Academy for Science, Technology and Maritime Transport (AASTMT) (Cairo-Egypt) in 2009 and 2012, respectively, From 2009 to 2012, he was a teaching assistant in AASTMT. Since December 2012 he has been a Ph.D. candidate at the "Universite de Bretagne Occidentale" - UBO (Brest, France). He is also an associate researcher in Sensor Networks and Cellular Networks Research Center (Tabuk, Kingdom of Saudi Arabia). He is an author of a book, 3 international journals and 2 international conferences. He is serving as a reviewer for many IEEE conferences. His current research interests include multiple-input multiple-output techniques and optical wireless communications.

Raed Mesleh (S00-M08-SM13) holds a Ph.D. in Electrical Engineering from Jacobs University in Bremen, Germany and several years of post-doctoral wireless communication and optical wireless communication research experience in Germany. In October 2010, he joined University of Tabuk in Saudi Arabia where he is now an assistant professor and the director of research excellence unit. His main research interests are in spatial modulation, MIMO cooperative wireless communication techniques and optical wireless communication. Dr. Mesleh publications received more than 1113 citations since 2008. He has published more than 50 publications in top-tier journals and conferences, and holds 7 granted patents. He also serves as on the TPC for academic conferences and is a regular reviewer for most of IEEE/OSA Communication Societies journals and IEEE/OSA Photonics Societies journals.
Ali MANSOUR received his M.S degree in the electronic electric engineering on Sept. 1992 from the Lebanese University, his M.Sc. and Ph.D. degrees in Signal, Image and Speech Processing from the "Institut National Polytechnique de Grenoble - INPG (Grenoble, France) on July 1993 and Jan. 1997, resp., and his HDR degree (Habilitation a Diriger des Recherches. In the French system, this is the highest of the higher degrees) on Nov. 2006 from the Universite de Bretagne Occidentale -UBO (Brest, France). His research interests are in the areas of blind separation of sources, high-order statistics, signal processing, passive acoustics, cognitive radio, robotics and telecommunication.

From Jan. to July 1997, he held a POST-DOC position at Laboratoire de Traitement d'Images et Reconnaissance de Forme (INPG Grenoble, France). From Aug. 1997 to Sept. 2001, he was a RESEARCH SCIENTIST at the Bio-Mimetic Control Research Center (BMRC) at the Institut of Physical and Chemical Research (RIKEN), Nagoya, Japan. From Oct. 2001 to Jan. 2008, he was holding a TEACHER-RESEARCHER position at the Ecole Nationale Superieure des Ingenieurs des Etudes et Techniques d'Armement (ENSIETA), Brest, France. From Feb. 2008 to Aug. 2010, he was a SENIOR-LECTURER at the Department of Electrical and Computer Engineering at Curtin University of Technology (ECE-Curtin Uni.), Perth, Australia. During Jan. 2009, he held an INVITED PROFESSOR position at the Universite du Littoral Cote d'Opale, Calais, France. From Sept 2010 till June 2012, he was a PROFESSOR at University of Tabuk, Tabuk, KSA. He also served as the ELECTRICAL DEPARTMENT HEAD at the University of Tabuk. Since Sept 2012, he has been a PROFESSOR at Ecole Nationale Superieure de Techniques Avancees Bretagne (ENSTA Bretagne), Brest, France. He is the author and the co-author of three books. He is the first author of several papers published in international journals, such as IEEE Trans. on Signal Processing, Signal Processing, IEEE Trans. on Wireless Communication, IEEE Trans. On Antennas & Propagation, IEEE Signal Processing Letters, NeuroComputing, EURASIP Journal on Advances in Signal Processing, IEICE and Artificial Life, Robotics, etc. He is also the first author of many papers published in the proceedings of various international conferences.

Finally, Dr. Mansour was elected to the grade of IEEE Senior Member in February 2006. He has been chair, co-chair and a scientific committee member as well as a member of Technical Program Committees (TPC) in many international conferences. He is an active reviewer for a variety of international journals in different engineering fields. He was a Lead Guest Editor at "EURASIP Journal on Advances in Signal Processing - Special Issue on Signal Processing Methods for Diversity and Its Applications".

el-Hadi M. Aggoune received his MS and Ph.D. Degrees in Electrical Engineering from the University of Washington (UW), Seattle, USA. He is a Professional Engineer registered in the State of Washington, and Senior Member of the Institute of the IEEE. He has taught graduate and undergraduate courses in Electrical Engineering at a number of universities in the US and abroad. He served at many academic ranks including Endowed Chair Professor and Vice President and Provost. He was the winner of the Boeing Supplier Excellence Award. He was also the winner of the IEEE Professor of the Year Award, UW Branch. He is listed as Inventor in a major patent assigned to the Boeing Company. His research work is referred to in many patents including patents assigned to ABB, Switzerland and EPRI, USA. Currently he is a Professor and Director of the Sensor Networks and Cellular Systems (SNCS) Research Center, University of Tabuk, Tabuk, Saudi Arabia. He authored many papers in IEEE and other journals and conferences. His research interests include modeling and simulation of large scale networks, sensor networks, scientific visualization, and control and energy systems.