Optik xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Performance analysis of multihop heterodyne free-space optical communication over general Malaga turbulence channels with pointing error

Wael G. Alheadary*, Ki-Hong Park, Mohamad-Slim Alouini

King Abdullah University of Sciences and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 11 August 2017
Accepted 14 August 2017

Keywords:
Free-space optical (FSO)
Multihop relaying
Atmospheric turbulence
CSI-assisted relaying
Malaga channel
Bit error rate (BER)
Adaptive transmission
Achievable spectral efficiency (SE)

ABSTRACT

This work investigates the end-to-end performance of a free space optical amplify-and-forward (AF) channel-state-information (CSI)-assisted relaying system using heterodyne detection over Malaga turbulence channels at the presence of pointing error employing rectangular quadrature amplitude modulation (R-QAM). More specifically, we present exact closed-form expressions for average bit-error rate for adaptive/non-adaptive modulation, achievable spectral efficiency, and ergodic capacity by utilizing generalized power series of Meijer's G-function. Moreover, asymptotic closed form expressions are provided to validate our work at high power regime. In addition, all the presented analytical results are illustrated using a selected set of numerical results. Moreover, we applied the bisection method to find the optimum beam width for the proposed FSO system.

1. Introduction

Recently, free-space optical (FSO) communication systems have attracted attention thanks to their high capacity and low cost over unlicensed optical spectrum compared to radio frequency (RF) and fiber optic communication [1]. Specifically, traditional RF spectrum band has been scarce and it requires high cost to reserve a licensed spectrum band. Moreover, it is not cost-and time-effective to deploy fiber optic technology due to the difficulty of wiring fiber optic cables especially in rugged environments. These features of FSO communication systems potentially enable solving the issues that the radio frequency (RF) communication systems face due to the expensive and scarce spectrum [1]. However, atmospheric turbulence and pointing errors may lead to a significant degradation in the performance of the FSO communication systems. Specifically, atmospheric turbulence is highly variable and unpredictable due to weather effect [2]. Furthermore, pointing error is usually caused by thermal expansion, dynamic wind loads, weak earthquakes and misalignment. These factors impose exaggerated fading and power loss on FSO links [3,4].

The degradation effects of atmospheric turbulence and pointing errors on the design and performance of FSO links have been investigated theoretically. For instance, Sandalidis et al. [5] investigated an FSO link over K distributed turbulence fading channels subjected to pointing error. Additionally, Zhu and Kahn [6] analyzed the performance of FSO links over lognormal distribution. Actually, most of the contributions were restricted to specific turbulence models such as Lognormal

---

* Corresponding author.
E-mail address: wael.headary@kaust.edu.sa (W.G. Alheadary).

http://dx.doi.org/10.1016/j.ijleo.2017.08.087
0030-4026/

Please cite this article in press as: W.G. Alheadary, et al., Performance analysis of multihop heterodyne free-space optical communication over general Malaga turbulence channels with pointing error, Optik - Int. J. Light Electron Opt. (2017), http://dx.doi.org/10.1016/j.ijleo.2017.08.087

distribution for weak turbulence and Gamma–Gamma distribution for weak-to-strong turbulence [7]. As a generalization, Malaga turbulence model has been developed as a unified distribution where most of the fading models are considered as special cases such as K-distribution, HK-distribution and Rice–Nagakami distribution, and characterizes a wide range of (weak to strong) turbulence conditions [8]. Performance analysis of optical wireless communications with pointing errors over Malaga fading model was presented in [9,10]. Ansari et al. [11] investigated the performance of FSO systems utilizing intensity modulation and direct detection (IM/DD) and heterodyne detection over Malaga channels with pointing error model. They proposed closed-form of bit error rate (BER), ergodic capacity, achievable spectral efficiency (SE), and outage probability (OP) using Meijer's G-function. However, the utilization of Meijer's G-function in the closed form expression does not give an explicit insights on the dependence of performance metric on the channel parameters.

Recently, multihop relaying has gained an increasing attention due to its efficient technique to expand the coverage of wireless networks with low power requirements while offering high data-rate at the end-to-end communication [12]. Moreover, multihop relaying has been proposed to reduce the turbulence fading and increase the reliability of the FSO channel. In Tsiftsis et al. [12], the OP of a multihop relaying FSO system with amplify-and-forward (AF) or decode-and-forward (DF) relays over Gamma–Gamma turbulence is discussed. In addition, Datsikas et al. [13] investigated the performance of end-to-end multihop FSO system using variable and fixed-gain relays over strong turbulence fading channels. More recently, pointing error was introduced to analyze the multihop FSO systems with heterodyne detection over Gamma–Gamma fading [14].

Furthermore, to enhance the spectral efficiency, adaptive modulation is considered as a promising solution. It varies modulation orders according to the channel condition in turbulent fading channels. For each instantaneous fading state, this technique enables to reach the maximum achievable data rate under the predefined channel quality requirement. Such system provides higher spectral efficiency than non-adaptive modulation scheme while maintaining fixed allowable transmit power and target BER requirement. In [15], the performance behaviour of subcarrier intensity modulation (SIM) systems over the Gamma–Gamma turbulence channels has been emphasized. They derived closed-form solutions of non-adaptive and adaptive modulation employing M-ary phase shift keying (M-PSK) and rectangular quadrature amplitude modulation (R-QAM), but they focused only on strong turbulence. In [16], we generalized the performance analysis of adaptive SIM systems over general Malaga channel without pointing error.

In this paper, we analyze multihop FSO relaying with heterodyne detection over Malaga atmospheric turbulence channel with pointing error. Here we summarize the contribution of paper:

- We first derive the multihop probability density function (PDF) of AF channel-state information (CSI)-assisted multihop relaying system using heterodyne detection over Malaga turbulence channels with pointing error. Unlike [14,17], the generalized power series of Meijer's G-function are employed to present the performance metrics in closed form. Therefore, the mathematical expressions of PDF, cumulative density function (CDF) and moment generating function (MGF) are tractable to be applied to calculate the performance metrics.
- We derive BER performance employing R-QAM of multihop relaying based on non-adaptive and adaptive modulation. Moreover, we obtained the closed form results of SE, OP and ergodic capacity.
- Moreover, asymptotic results at high signal-to-noise ratio (SNR) can be easily deductible from the closed form results.
- The closed form expressions and their asymptotic results will be validated with numerical results.
- Numerical optimization using bisection method has been proposed to find out the optimum beam width of end-to-end multihop FSO system to minimize the BER performance.

The rest of this paper is structured as follows: Section 2 describes the system and channel models. Section 3 investigates and validates the BER performance of non-adaptive and adaptive systems utilizing R-QAM. Section 4 derive the ergodic capacity results. Optimum beam width of the proposed system of N-hop relays has been obtained in Section 5. Numerical results and discussions are presented in Section 6. Finally, Section 7 concludes the presented work.

2. System and channel models

2.1. System model

In this work, we present an FSO system using coherent modulation with heterodyne detections. In this system model, the transmitter converts modulated electric signal into optical intensity signal. Then, the modulated beam will be sent over the atmospheric turbulence channel with pointing error. As the channel coherence time is on the order of msec and the data rate is assumed to be on the order of Gbps, we can therefore assume in our analysis a slow fading channel model [18]. At the receiver, the received optical signal is mixed with a local oscillator (LO). Then, it converted into an electrical signal using photodetector and demodulated to recover the transmitted data as shown in Fig. 1, which is elaborated in [19]. For heterodyne detection [20], the instantaneous electrical SNR is computed as

$$\gamma = \frac{\eta_e h}{N_0}, \tag{1}$$

Please cite this article in press as: W.G. Alheadary, et al., Performance analysis of multihop heterodyne free-space optical communication over general Malaga turbulence channels with pointing error, Optik - Int. J. Light Electron Opt. (2017), http://dx.doi.org/10.1016/j.ijleo.2017.08.087