Optics Communications 388 (2017) 47–52

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Performance of an adaptive phase estimator for coherent free-space optical communications over Gamma-Gamma turbulence

Yiming Li, Chao Gao, Haodong Liang, Maoke Miao, Xiaofeng Li*

School of Astronautics and Aeronautics, University of Electronic Science and Technology of China, Chengdu 611731, China

ARTICLE INFO

Keywords:
Phase estimation
Coherent detection
Free-space optical communications
Turbulence

ABSTRACT

This paper investigates an adaptive phase estimator for coherent free-space optical (FSO) communication systems. Closed-form solutions for variance of phase errors are derived when the optical beam is subjected to Gamma-Gamma distributed turbulence. The adaptive phase estimator has improved upon the phase error performance in comparison to conventional phase estimators. We also demonstrate notable improvement in BER performance when applying our adaptive phase estimator to coherent FSO communication systems.

1. Introduction

Free-space optical (FSO)communication systems have recently received a great deal of attention in research and commerce. These systems can provide ultra-high data rates (at the order of multiple gigabits per second); are immune to electromagnetic interference; and have excellent security and large, unlicensed bandwidth [1]. Although direct-detection reception has been the dominant mode of detection in FSO systems due to its low realization complexity, recent advances in digital signal processing (DSP) have made coherent FSO systems more applicable. This has drawn considerable attention from both scholars and companies because of its excellent background noise rejection, enhanced transmit power efficiency, and improved frequency selectivity. However, coherent FSO systems suffer from phase noise and atmospheric turbulence.

The traditional method of compensating phase noise is to use a phase lock loop (PLL) that synchronizes the phase of a local oscillator (LO) with the transmitted signal (S). In particular, a decision-driven PLL scheme and balanced PLL scheme have been studied by Kazovsky respectively [2,3]. More recently, Niu has studied the error-rate performance degradation caused by phase compensation error in M-ary coherent FSO systems when applying PLL [4].

Moreover, advances in very-large-scale-integration (VLSI) technology have made it possible to convert the in-phase (I) and quadrature (Q) output of a coherent receiver to digital domain using high-speed analog-to-digital converters (ADCs) and applying DSP algorithms to demodulate signals. Given that phase noise can be estimated and compensated by DSP in a feedforward architecture, PLL is no longer necessary. Intensive research on phase estimation (PE) technology has been concentrated on fiber communication systems. A uniform filter that gives equal weighting to all estimated phases in the event of low phase noise was used in [5]; whereas, a one-shot estimator has been shown to be asymptotically optimal for high phase noise. Furthermore, a minimum mean square error (MMSE) algorithm has been used to achieve better performance in comparison with the two aforementioned algorithms [6]. Further details of the MMSE algorithm are outlined in [7].

In order to evaluate the performance of FSO systems, it is necessary to use an appropriate model to describe the fading characteristics induced by atmospheric turbulence. The lognormal distribution is often used to model weak turbulence conditions whereas the K-distribution is used to model strong turbulence. Gamma-Gamma distribution has also been proposed to describe scintillation over arbitrary turbulence conditions as a more general model. The properties of these models have been described by Andrews [8], while some recent advances have been discussed by Cui and Toselli [9,10]. Recently, the performance of coherent FSO systems has been analyzed based on the models listed above. For example, Kiasaleh introduced an analytical bit-error-rate (BER) expression for FSO communication links with differential phase-shift keying (DPSK) [11]. Multiple-input multiple-output (MIMO) systems have also been used to combat signal fading induced by atmospheric turbulence [12–15]. However, none of these studies have considered the performance degradation caused by phase noise.

Accordingly, research on PE algorithms and coherent FSO systems have typically been conducted separately. However, traditional MMSE PE algorithms will yield a sub-optimal estimation and can cause notable performance degradation in coherent FSO systems because they are affected by atmospheric turbulence. To our knowledge, no theoretical analysis has been done to show the performance limit of PE algorithm when applied to FSO systems. Therefore, the objective of this paper is to investigate an adaptive phase estimator for coherent FSO receivers, which can achieve a better estimation and smaller performance penalties, in comparison to conventional phase estimators. In

* Corresponding author.
E-mail address: lxf3203433@uestc.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.optcom.2016.11.003
Received 13 September 2016; Received in revised form 1 November 2016; Accepted 2 November 2016
Available online 09 November 2016

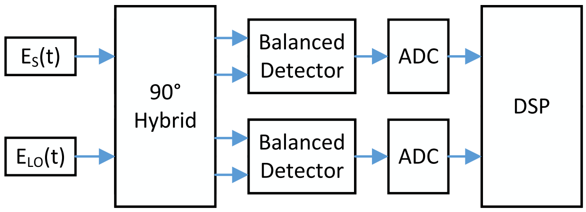

Fig. 1. Structure of optical coherent receiver.

Section 2, we describe the structure of our carrier phase estimator. In Section 3, we derive phase error variance formulas for this structure. Finally, simulation results are presented in Section 4.

2. Structure of carrier phase estimator

2.1. Signal and channel model

The structure of optical coherent receiver is shown in Fig. 1.

Here, the received signal, $E_R(t)$, is combined with a local oscillator (LO) laser using a 90° optical hybrid. Four tributaries following the 90° optical hybrid are detected by two pairs of balanced detectors, and the outputs of the balanced detectors correspond to I and Q signals. These signals are sampled by two high-speed analog-to-digital converters (ADCs) and processed by digital signal processor (DSP). The resulting complex signal has the form

$$r_k = s_k e^{j\theta_k} + n_k, \tag{1}$$

where s_k is a complex-valued symbol transmitted at the kth symbol period; n_k is the additive white Gaussian noise (AWGN); and θ_k is the carrier phase, which can be modeled as a Wiener process, as follows

$$\theta_k = \sum_{n=-\infty}^{k} \nu(n), \tag{2}$$

where $\nu(n)$ is independently identically distributed (i.i.d.) Gaussian random variables with zero mean and $\sigma_p^2 = 2\pi\Delta\nu T$. Additionally, $\Delta\nu$ signifies the linewidths of the signal and local laser, and T is the symbol period of the transmitted data.

2.2. MMSE phase estimator

When $SNR = E[|s_k|^2]/E[|n_k|^2]$ is fixed, which is a common sense in fiber communications, A Wiener filter can be applied to estimate the carrier phase of r_k in the sense of MMSE. The structure of this MMSE phase estimator is shown in Fig. 2. According to [6], we can write the output of the one-shot estimator as $\psi_k = \theta_k + n_{\prime k}$, where $n_{\prime k}$ is approximately i.i.d. Gaussian distributed with a zero mean and variance $\sigma_{n'}^2 = (2SNR)^{-1}$ when applying a decision directed (DD) phase estimator.

Moreover, a non-causal IIR Wiener filter has been shown to be the best Wiener phase estimator because it utilizes both the infinite past and infinite future of the sequence, ψ_k, to smooth the estimation [16]. This relationship can be written as

$$\hat{\theta}_k = \lim_{K\to\infty} \sum_{l=-K}^{K} \omega_l \psi_{k-l}. \tag{3}$$

Using conclusions in [16], the coefficients can be written as

$$\omega_l = \begin{cases} \frac{ar}{1-a^2}a^l, & l \ge 0 \\ \frac{ar}{1-a^2}a^{-l}, & l < 0 \end{cases}, \tag{4}$$

where $r = \sigma_p^2/\sigma_{n'}^2$ and $a = (1 + r/2) - \sqrt{(1 + r/2)^2 - 1}$.

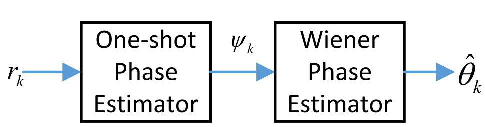

Fig. 2. Schematic of MMSE phase estimator.

2.3. Structure of the adaptive phase estimator

In FSO communication, the SNR will be a random process induced by intensity scintillation. When applying the Gamma-Gamma distribution model [17], the intensity scintillation can be expressed as

$$f_{I_S}(I_S) = \frac{1}{\bar{I}_S}\cdot\frac{2}{\Gamma(\alpha)\Gamma(\beta)}(\alpha\beta)^{\frac{\alpha+\beta}{2}}\left(\frac{I_S}{\bar{I}_S}\right)^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\left(\frac{I_S}{\bar{I}_S}\right)}\right), \tag{5}$$

where $\bar{I}_S$ denotes the average irradiance of the channel; $K_\nu[\cdot]$ is the νth order modified Bessel function of the second kind; and α and β are the effective numbers of small-scale and large-scale eddies of the scattering environment, where the two scales are implemented mathematically by inserting heuristic spatial-frequency filters into weak-turbulence integrals for scintillation index.

This phenomenon will influence the instantaneous SNR of the system; thus, it will also influence the coefficients of the Wiener filter. Applying the average power of signal light to compute the coefficients of the Wiener filter yield inaccurate results when the instantaneous SNR is far from its average value. Doing so will lead to a suboptimal estimation of θ_k.

We have assumed that the channel characteristics vary sufficiently slowly to be measured, which is a common situation in FSO communication. Therefore, we propose a new structure to estimate θ_k, shown in Fig. 3. If the instantaneous SNR is properly measured, we can adaptively adjust the coefficients and generate an optimal estimation of θ_k. The performance limit of this new structure will be derived in Section 3.

3. Variance of phase error

3.1. Adaptive phase estimator

We have assumed that fading is sufficiently slow. Therefore, we can achieve ideal estimation of SNR, and can adaptively adjust the coefficients of our Wiener phase estimator according to this estimation. This situation is a stringent lower bound of our practical system. And the phase error satisfies

$$\sigma_\varepsilon^2 = \int_{-\infty}^{+\infty} (\hat{\theta} - \theta)^2 f(\hat{\theta} - \theta)\,\mathrm{d}(\hat{\theta} - \theta). \tag{6}$$

Applying total probability theorem, Eq. (6) can be rewritten as

$$\sigma_\varepsilon^2 = \int_{-\infty}^{+\infty} (\hat{\theta} - \theta)^2 \left[\int_0^{+\infty} f(\hat{\theta} - \theta|I_S) f(I_S)\,\mathrm{d}I_S\right] \mathrm{d}(\hat{\theta} - \theta), \tag{7}$$

or equivalently,

$$\sigma_\varepsilon^2 = \int_0^{+\infty} f(I_s)\cdot\sigma_\varepsilon^2\Big|_{SNR=SNR_0} \mathrm{d}I_s, \tag{8}$$

where $f(I_s)$ is Gamma-Gamma distributed obeying Eq. (5), and

$$\sigma_\varepsilon^2\Big|_{SNR=SNR_0} = \int_{-\infty}^{+\infty} (\hat{\theta} - \theta)^2 f(\hat{\theta} - \theta|SNR_0)\,\mathrm{d}(\hat{\theta} - \theta). \tag{9}$$

Eq. (9) is the general form of $\sigma_\varepsilon^2|_{SNR=SNR_0}$. In the case of MMSE estimation, based on Eq. (3), the variance of phase error takes the

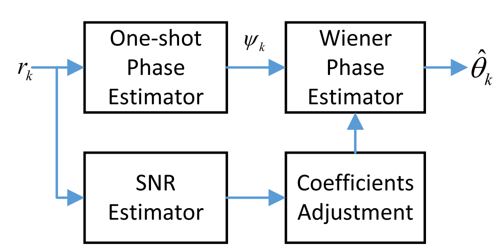

Fig. 3. Schematic of adaptive phase estimator for FSO communications.