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FSO channel estimation for OOK modulation with APD receiver over atmospheric turbulence and pointing errors

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ABSTRACT

In the free-space optical (FSO) links, atmospheric turbulence and pointing errors lead to scintillation in the received signal. Due to its ease of implementation, intensity modulation with direct detection (IM/DD) based on ON–OFF-keying (OOK) is a popular signaling scheme in these systems. For long-haul FSO links, avalanche photo diodes (APDs) are commonly used, which provide an internal gain in photo-detection, allowing larger transmission ranges, as compared with PIN photo-detector (PD) counterparts. Since optimal OOK detection at the receiver requires the knowledge of the instantaneous channel fading coefficient, channel estimation is an important task that can considerably impact the link performance. In this paper, we investigate the channel estimation issue when using an APD at the receiver. Here, optimal signal detection is quite more delicate than in the case of using a PIN PD. In fact, given that APD-based receivers are usually shot-noise limited, the receiver noise will have a different distribution depending on whether the transmitted bit is '0' or '1', and moreover, its statistics are further affected by the scintillation. To deal with this, we first consider minimum mean-square-error (MMSE), maximum *a posteriori* probability (MAP) and maximum likelihood (ML) channel estimation over an observation window encompassing several consecutive received OOK symbols. Due to the high computational complexity of these methods, in a second step, we propose an ML channel estimator based on the expectation–maximization (EM) algorithm which has a low implementation complexity, making it suitable for high data-rate FSO communications. Numerical results show that for a sufficiently large observation window, by using the proposed EM channel estimator, we can achieve bit error rate performance very close to that with perfect channel state information. We also derive the Cramer–Rao lower bound (CRLB) of MSE of estimation errors and show that for a large enough observation window, this CRLB can be adequately tight.

1. Introduction

1.1. Background

Under clear sky conditions, the reliability and performance of free space optical (FSO) links can be severely affected by atmospheric conditions and pointing errors [1]. Due to the inherent complexity of phase modulation and the related high implementation complexity, most current commercial FSO systems use intensity modulation with direct detection (IM/DD) based on ON–OFF keying (OOK) [2]. This way, at the receiver, the optical signal is converted to an electrical one by a photo-detector (PD). While PIN PDs are typically suitable for ranges up to several hundred meters, for long-haul links, avalanche PDs (APDs) are the preferred solution, despite their higher cost [3]. Thanks to their high internal gain, they can provide improved signal-to-noise ratio (SNR) capability, as compared with PIN-based receivers. In such receivers, shot noise is mostly dominant [3], whose distribution can be well approximated by a Gaussian [4]. The mean and the variance of this random process will depend on the received signal intensity, thus on the transmitted symbol (i.e., whether the transmitted bit is '0' or '1') as well as on the actual channel fading coefficient. Note that for OOK demodulation, the receiver requires the knowledge of the channel state information (CSI) to adjust the detection threshold [5,6]. Since the channel fading affects both the received signal intensity and the receiver noise parameters, the CSI should be estimated of enough accuracy. It is worth mentioning that the coherence time of FSO channels is usually very large (typically on the order of *ms*), and hence, the channel fading

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coefficient remains constant over a large number of consecutive bits for typical transmission rates of FSO communications [1].

1.2. Related works

Channel estimation has been extensively investigated in the context of radio-frequency (RF) networks (see [7], and the references therein). However, due to the particularities of OOK modulation and APD-based receivers, such channel estimation techniques and results are not directly applicable to FSO systems. So, it is important to develop appropriate channel identification solutions and decision metrics for optimal signal detection. A number of previous works have studied this issue. In [8,9], the authors investigated channel estimation over atmospheric turbulence for the case of pulse position modulation (PPM). Note that PPM has a lower bandwidth efficiency compared to OOK [1]. In [10,11] for an FSO system using OOK modulation, the channel is estimated using some pilot symbols. Also, in [12], the estimated channel was exploited to adjust the detection threshold at the receiver. However, it is well known that the insertion of pilot bits inside each data frame, incurs a signaling overhead, i.e., a loss in the effective data throughput. Obviously, it is highly preferable to avoid using a pilot overhead while ensuring the good receiver performance, i.e., accurate data detection.

1.3. Contributions

In this paper, to increase the bandwidth efficiency of FSO links and to avoid any pilot overhead at the transmitter, we propose efficient data-aided channel estimation methods. We firstly consider the minimum mean-square-error (MMSE), the maximum *a posteriori* probability (MAP) and the maximum likelihood (ML) criteria to develop channel estimators. We show that the MMSE estimator requires evaluating complex integrals whereas the MAP and ML estimators need complex numerical computations to find the instantaneous channel attenuation coefficient. Hence, from a practical (real-time) implementation point of view, the computational complexity of these estimators may not be suitable for an FSO system working at very high data-rates. To reduce the complexity of the channel estimator, in a second step, we propose an iterative ML estimator based on the expectation–maximization (EM) algorithm. Nevertheless, as known from the general convergence property of the EM algorithm, there is no guarantee that the iterative steps of EM converge to the global maximum unless an accurate initial estimate is provided [13]. In practice, several initial estimates are used to initialize the EM algorithm in order to guarantee its convergence toward a global maximum. However, obtaining these initial estimates requires sending several training sequences which leads to a loss of the bandwidth efficiency. To solve this problem, we use a blind averaging scheme to calculate the initial channel estimate, without requiring any training symbol. The important point is that the proposed EM-based channel estimator incurs a negligible increase in the receiver's computational complexity and processing delay since it requires only one iteration to converge, making it particularly suitable for practical implementations. We will show that the proposed estimator can achieve performance very close to the perfect CSI case, provided that the observation window is sufficiently large. We also derive the Cramer–Rao lower bound (CRLB) that we use as a benchmark and show that for a large enough observation window, the CRLB becomes a quite tight bound for the mean-square-error (MSE) of the proposed channel estimator.

1.4. Paper structure

In Section 2, we describe our system model along with our main assumptions. In Section 3, we present the different proposed channel estimators for the FSO receiver and derive the expression of the CRLB. Next, in Section 4, we present our numerical results to study the performance of the proposed method, and lastly in Section 5, we draw our conclusions.

2. System model

We assume an IM/DD FSO link with non-return-to-zero (NRZ) OOK modulation over an atmospheric turbulence channel in the presence of pointing errors. In the sequel, we first introduce the received signal model and data detection under consideration and then, summarize the channel model that we consider in this study.

2.1. Signal model and data detection

As mentioned previously, we consider the use of an APD at the receiver. The exact distribution of APD output electrons in response to the mean of absorbed photons is rather complex [4], but it can accurately be approximated by a Gaussian, provided that the mean of absorbed photons is sufficiently large, what is usually the case in practice [3]. This simplifies the derivation of closed form analytical expressions for evaluating the system performance. This way, the mean and the variance of this Gaussian distribution will be mG and mG^2F, respectively, where m denotes the average number of the absorbed photons, G is the average APD gain and F is its excess noise factor [4]. The APD output photocurrent corresponding to the kth symbol interval, i.e., $[(k-1)T_b, kT_b)$ with T_b being the symbol duration, can be written as [14]:

$$r_k = \mu h s_k + n_k, \tag{1}$$

where h denotes the channel attenuation coefficient, incorporating the channel loss and the effects of atmospheric turbulence and pointing errors, assumed to be constant over a large number of transmitted bits. Also, s_k denotes the transmitted symbol with transmitted optical power P_t, which takes the values of P_1 or P_0 for the cases of the transmission of a bit '1' or '0', respectively, for the considered NRZ OOK signaling scheme. In the sequel, without loss of generality, we assume that $P_0 = \alpha_e P_1$ where α_e is the optical source extinction ratio and has the range $0 \le \alpha_e < 1$. Furthermore in (1), the parameter μ equals $\frac{eG\eta}{\tilde{h}_p \nu}$, where e denotes the electron charge, η is the APD quantum efficiency, ν is the optical frequency and $\tilde{h}_p$ stands for the Planck constant. Also, n_k is the photo-current noise, including thermal noise, dark current, as well as the shot noise arising from the received signal and the background radiations. While dark current noise can practically be neglected, a Gaussian distribution can accurately model the sum of other noise sources with the variance given as follows

$$\sigma_{tot}^2 = \sigma_{s,i}^2 h + \sigma_0^2; \quad \text{for } i \in \{0,1\}, \tag{2}$$

where $\sigma_{s,1}^2 = 2eGF\mu BP_1$ and $\sigma_{s,0}^2 = \alpha_e \sigma_{s,1}^2$ are the variances of the shot noise for the cases of the transmission of a bit '1' and a bit '0'. Also, B is the bandwidth of the receiver low-pass filter, which is placed at the transimpedance amplifier (TIA) output, and is set approximately to $1/T_b$ [3]. Also, $\sigma_0^2 = \sigma_b^2 + \sigma_{th}^2$ where $\sigma_b^2 = 2eGF\mu BP_b$ is the variance of shot noise due to background power P_b and $\sigma_{th}^2 = \frac{4K_bT_rB}{R_l}$ is the variance of thermal noise with K_b being the Boltzmann constant, T_r the receiver's equivalent temperature, and R_l the resistance of the TIA. Note that the presented formulation can be simplified to the case of PIN PD by setting $F = 1$ and $G = 1$. According to (2), the variance of the signal-induced shot noise depends on the transmit optical power (here, P_0 or P_1) and also on the channel coefficient h. Then, for optimal signal detection (i.e., OOK demodulation) the received signal r_k should be compared with a threshold γ_{th}.

The average link bit error rate (BER) is given by

$$P(e) = \int_0^\infty P(e|h) f_h(h) dh, \tag{3}$$