Mitigation of Turbulence-Induced Scintillation Noise in Free-Space Optical Links Using Temporal-Domain Detection Techniques

Xiaoming Zhu, Joseph M. Kahn, *Fellow, IEEE*, and Jin Wang, *Student Member, IEEE*

***Abstract*—Atmospheric turbulence-induced intensity fluctuations can significantly impair the performance of free-space optical links. Temporal-domain detection techniques can be applied to mitigate these intensity fluctuations. If the receiver has knowledge of the joint temporal statistics of intensity fluctuations, maximum-likelihood sequence detection (MLSD) or pilot-symbol assisted detection (PSAD) can be employed. We experimentally demonstrate the effectiveness of these techniques in a 500-m terrestrial link using ON–OFF keying, where MLSD and PSAD yield signal-to-noise ratio gains of 2.4 and 1.9 dB, respectively.**

***Index Terms*—Optical communication, random media, signal detection.**

I. INTRODUCTION

FREE-SPACE optical transmission can provide high-speed links for a variety of applications. However, inhomogeneities in the temperature and pressure of the atmosphere lead to variations of the refractive index along the transmission path. This atmospheric turbulence can deteriorate the quality of the image formed at the receiver, and can cause fluctuations in both the intensity and the phase of the received signal [1]–[3]. These intensity fluctuations, often referred to as scintillation noise, can degrade the performance of links using intensity modulation with direct detection (IM/DD), particularly over ranges of several hundred meters or longer.

Two useful parameters describing turbulence-induced scintillation are d_0, the correlation length of intensity fluctuations and τ_0, the correlation time of intensity fluctuations. In typical terrestrial links with wind-driven turbulence, the correlation length d_0 is of the order of 1–10 cm, while the correlation time τ_0 is of the order of 1–10 ms or longer. When the receiver aperture D can be made much larger than the correlation length d_0, scintillation noise can be reduced by aperture averaging [3]. Likewise, when the receiver observation time τ_0 during each bit interval can be made larger than the correlation time τ_0, scintillation noise can be reduced via time averaging. However, it is not always possible to rely upon aperture averaging to reduce scintillation noise to an acceptable level because of receiver size constraints. Also at the bit rates of interest in most applications, $T_0 \ll \tau_0$ and time averaging is not a viable means to combat scintillation noise.

We have studied detection techniques [4]–[6] to mitigate scintillation noise in the regime when aperture averaging or time averaging cannot be relied upon to completely alleviate scintillation noise. These detection techniques are applicable to links employing ON–OFF keying (OOK) with DD. They are based on the statistical properties of turbulence-induced intensity fluctuations, as functions of both spatial and temporal coordinates. The techniques can be divided into two categories: spatial-domain and temporal-domain. In this letter, we briefly summarize three temporal-domain techniques: maximum-likelihood (ML) symbol-by-symbol detection, ML sequence detection (MLSD), and pilot-symbol assisted detection (PSAD). We present experimental results that demonstrate their effectiveness in mitigating scintillation noise.

II. SYSTEM MODEL

In this letter, we consider IM/DD links using OOK. Following the model described in [4], we assume that the receiver does not use an optical preamplifier, and that the dominant noise sources are ambient light shot noise and/or thermal noise. Hence, we model the noise as additive, white, Gaussian, and statistically independent of the received signal.

We denote the bit duration by T, and assume that the receiver integrates the received photocurrent for an interval $T_0 \leq T$ during each bit interval. We further assume that $T_0 \ll \tau_0$. Therefore, the light intensity can be viewed as constant during each integration interval. At the end of the integration interval, the resulting electrical signal can be expressed as

$$r_e = \eta(I_s + I_b) + n_w \tag{1}$$

where I_s is the received signal light intensity, I_b is the ambient light intensity, and η is the optical-to-electrical conversion efficiency. The additive white Gaussian noise n_w has zero mean and variance $N_0/2$. After subtraction of the ambient light level ηI_b, the electrical signal is $r = r_e - \eta I_b$.

Ignoring intersymbol interference (ISI), the receiver detects signal light only when an ON-state bit is transmitted. The ith ON-state symbol intensity can be expressed as

$$I_i = I_0 \exp(2X_i - 2\chi) \tag{2}$$

where X_i is the log-amplitude of the optical signal, which can be modeled as a Gaussian random variable with a mean

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The authors are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720 USA (e-mail: wangjin@eecs.berkeley.edu).

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$\chi = E[X_i]$ and variance σ_X^2. The temporal joint probability distribution function (pdf) of log-amplitude sequence $\overrightarrow{x} = [X_{n_1} - \chi, X_{n_2} - \chi, \ldots, X_{n_m} - \chi]$ is assumed to be jointly Gaussian [4]

$$f_{\overrightarrow{x}}(\overrightarrow{x}) = \frac{1}{(2\pi)^{m/2}\sqrt{|C_X^{\mathrm{on}}|}} \exp\left[-\frac{1}{2}\overrightarrow{x} \cdot (C_X^{\mathrm{on}})^{-1} \cdot \overrightarrow{x}^T\right] \quad (3)$$

where C_X^{on} is the log-amplitude covariance matrix of the ON-state bit sequence, as defined in [5].

III. TEMPORAL-DOMAIN DETECTION TECHNIQUES

In this section, we briefly summarize the temporal-domain detection techniques described in [4]–[6]. We assume that the receiver does not have knowledge of the instantaneous state of intensity fluctuations. In ML symbol-by-symbol detection, only the marginal pdf of intensity fluctuations is known at the receiver, while in MLSD and PSAD, the joint temporal pdf is known.

A. ML Symbol-by-Symbol Detection

The ML symbol-by-symbol detector [4] chooses the symbol $\hat{s}$ using the rule

$$\hat{s} = \mathrm{argmax}_s p(r|s) \quad (4)$$

where $p(r|s)$ is the pdf of the signal r given $s \in \{\mathrm{off}, \mathrm{on}\}$. The rule (4) is implemented by comparing r to a fixed threshold that depends on χ, σ_X^2, and N_0.

B. MLSD

Given a reception $\overrightarrow{r} = [r_1, r_2, \ldots, r_n]$ in n consecutive bits, the MLSD [4] computes the likelihood ratio of each of the 2^n possible sequences $\overrightarrow{s} = [s_1, s_2, \ldots, s_n]$, where $s_i \in \{\mathrm{off}, \mathrm{on}\}$, and chooses

$$\begin{aligned}\overrightarrow{s} =& \mathrm{argmax}_{\overrightarrow{s}} p(\overrightarrow{r} \mid \overrightarrow{s})\\ =& \mathrm{argmax}_{\overrightarrow{s}} \int_{\overrightarrow{x}} f(\overrightarrow{x})\\ &\times \exp\left[-\sum_{i=1}^{n} \frac{\left(r_i - \eta s_i I_0 e^{2x_i}\right)^2}{N}\right] d\overrightarrow{x}. \end{aligned} \quad (5)$$

The MLSD exploits the temporal correlation of intensity fluctuations, and thus outperforms the symbol-by-symbol ML detector. Intuitively, the MLSD attempts to track the instantaneous state of the intensity fluctuations and adjust the threshold to the optimal value. A drawback of the MLSD is its high computational complexity, which is proportional to $n \cdot 2^n$.

Implementation of the MLSD is facilitated by using a single-step Markov chain (SMC) model for the temporal correlation of intensity fluctuations [5]. Defining $x_n = X_n - \chi$, and letting x_1^{n-1} denote $[x_1, \ldots, x_{n-1}]$, the SMC model assumes that

$$P\left(x_n|x_1^{n-1}\right) = P(x_n|x_{n-1}). \quad (6)$$

We have shown in [5] that the SMC model is an accurate approximation of the assumed higher-order joint statistics of intensity fluctuations. Using the SMC model, we can decouple each conditional probability $P(\overrightarrow{r} \mid \overrightarrow{s})$ in (5) into the product of a sequence of branch metric functions [5]. By using per-survivor processing (PSP) [7], we can significantly reduce the complexity of MLSD to the order of n^2. Two suboptimal, reduced-complexity MLSD schemes based on the SMC model and PSP are described in [5].

C. PSAD

In many high-bit-rate free-space links, the bit interval is much shorter than the intensity correlation time, i.e., $T \ll \tau_0$. Hence, the instantaneous state of the intensity fluctuations does not change much for many consecutive bit intervals. In PSAD [6], we periodically insert an ON-state pilot symbol prior to a block of $M-1$ information bits to form an M-bit block. The receiver then uses the received intensity of the pilot symbols preceding and following each block to aid in detection of the $M-1$ information bits.

We let r_i denote the received signal in the ith information bit in the frame, where $1 \leq i \leq M-1$, and let r_0 and r_M denote the received signals in the PS of the current frame and the next frame. The pilot-symbol assisted ML (PSA-ML) [6] decision rule maximizes the joint conditional probability of $\overrightarrow{r} = [r_0, r_i, r_M]$ conditioned on the ith information bit s_i

$$\Lambda(\overrightarrow{r}) = \frac{p(\overrightarrow{r}\,|s_i = 1)}{p(\overrightarrow{r}\,|s_i = 0)} \underset{\mathrm{off}}{\overset{\mathrm{on}}{\gtrless}} 1. \quad (7)$$

Under the pilot-symbol assisted variable threshold (PSA-VT) decision rule [6], we further simplify (7) by assuming that the received PS signals are noise-free, and use a time-varying decision τ_i threshold following:

$$\tau_i = \frac{(r_0)^{a_i^0}(r_M)^{a_i^M}}{2} \quad (8)$$

where

$$\begin{bmatrix} a_i^0 \\ a_i^M \end{bmatrix} = \begin{bmatrix} 1 & b_X\left(\frac{MT}{\tau_0}d_0\right) \\ b_X\left(\frac{MT}{\tau_0}d_0\right) & 1 \end{bmatrix}^{-1} \begin{bmatrix} b_X\left(\frac{iT}{\tau_0}d_0\right) \\ b_X\left[\frac{(m-i)T}{\tau_0}d_0\right] \end{bmatrix}$$

and $b_X(\cdot)$ is the normalized covariance function of intensity fluctuations, which characterizes their temporal correlation [4].

IV. EXPERIMENTS

We have performed transmission experiments to demonstrate the effectiveness of the MLSD and PSAD techniques in mitigating scintillation noise. Because our proof-of-concept system employs a personal computer (PC) for data acquisition and decoding, the bit rate is limited to 3 kb/s. Using appropriate special-purpose hardware, these detection techniques can be implemented at the bit rates of interest in most applications (megabits per second to gigabits per second).

Our experimental system is shown in Fig. 1. At the transmitter, we employ a 675-nm 0.95-mW (Class II) laser diode module with an output beam divergence of 0.35 mrad. We

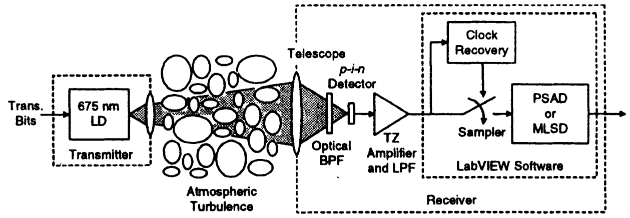

Fig. 1. Experimental 3-kb/s free-space optical link using PSAD or MLSD to mitigate turbulence-induced scintillation noise.

modulate the injection current to achieve OOK with nonreturn-to-zero pulses. The receiver uses a telescope with an entrance aperture diameter of $D = 8$ cm. An optical bandpass filter with 10-nm bandwidth $(-3$ dB$)$ is used to minimize ambient light noise. A 1.1-mm^2 p-i-n photodiode is coupled to a transimpedance preamplifier and a second-order Bessel lowpass filter having a 2-kHz bandwidth $(-3$ dB$)$. The back-to-back receiver sensitivity is -69 dBm at a bit-error probability of 10^{-4}. Received electrical signals are sampled using a PC-interfaced data acquisition card, and the MLSD or PSAD algorithms are implemented in LabVIEW software.

Optical signals are transmitted over a 500-m outdoor path between Cory Hall and Doe Library on the University of California, Berkeley Campus. Because of the relatively large photodiode size, turbulence-induced image degradation has negligible impact over the transmission range employed. The intensity correlation length can be estimated as $d_0 \approx \sqrt{\lambda L}$, where λ is the transmission wavelength and L is the transmission range [3], yielding $d_0 \approx 1.8$ cm. Although the receiver aperture $D = 8$ cm is somewhat larger than this estimate of d_0, aperture averaging does not completely eliminate scintillation noise, and the observed standard deviation of the log-amplitude is $\sigma_X = 1.6$. Based on experimental measurements, we estimate the intensity correlation time to be $\tau_0 \approx 35$ ms, which is much longer than the receiver observation interval $\tau_0 \approx 0.01$ ms. Hence, both MLSD and PSAD are expected to be effective in mitigating scintillation noise. We have implemented MLSD using the SMC model and the Method 2 described in [5], and have implemented PSAD using PSA-VT with a frame size of $M = 12$ bits.

Our experimental results are shown in Fig. 2, which shows the bit-error probability for ON-state bits versus the average received electrical signal-to-noise ratio (SNR) for various detection techniques. The measured results for ML symbol-by-symbol detection, PSAD, and MLSD are indicated by squares, triangles, and circles, respectively. Using measured values of σ_x and τ_0, we have used the theories described in [4]–[6] to compute the dashed, dotted-dashed, and solid lines, respectively. We obtain excellent agreement between experimental and theoretical results with no adjustable parameters. As compared to symbol-by-symbol detection, we observe experimentally that PSAD gives an SNR gain of about 1.9 dB, while MLSD yields an SNR gain of about 2.4 dB (both at 10^{-3} error probability). Even larger gains are expected for longer propagation paths with larger values of the log-amplitude standard deviation σ_X.

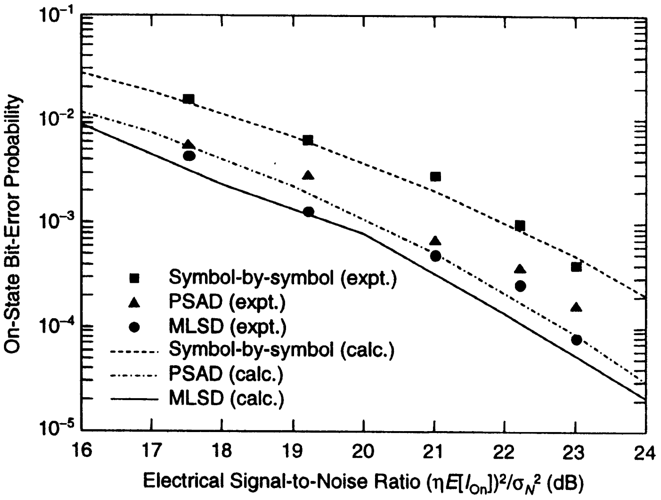

Fig. 2. Bit-error probability for ON-state bits versus average received electrical SNR in a 500-m outdoor transmission experiment.

REFERENCES

[1] J. W. Goodman, *Statistical Optics*. New York: Wiley, 1985.

[2] S. Karp, R. Gagliardi, S. E. Moran, and L. B. Stotts, *Optical Channels*. New York: Plenum, 1988.

[3] L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media*. Bellingham, WA: SPIE, 1998.

[4] X. Zhu and J. M. Khan, "Free-space optical communication through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 50, pp. 1293–1300, Aug. 2002.

[5] ——, "Markov chain model in MLSD for free-space optical communication through atmospheric turbulence channels," *IEEE Trans. Commun.*, to be published.

[6] ——, "Pilot-symbol assisted modulation for correlated turbulent free-space optical channels," presented at the SPIE 46th Annu. Meeting, San Diego, CA, July 29–Aug. 3, 2001.

[7] R. Raheli, A. Polydoros, and C.-K. Tzou, "Per-survivor processing: A general approach to mlse in uncertain environments," *IEEE Trans. Commun.*, vol. 43, pp. 354–364, Feb. 1995.