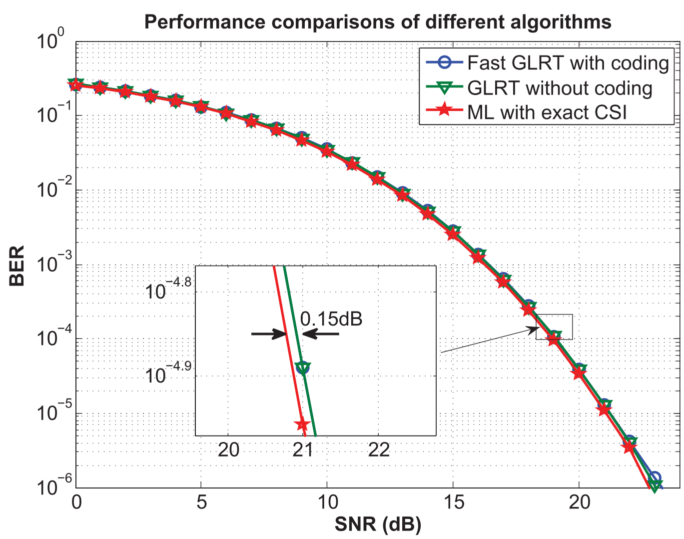
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

A Fast Blind Detection Algorithm for Outdoor Visible Light Communications

Volume 7, Number 6, December 2015

Yi-Jun Zhu, Member, IEEE
Zheng-Guo Sun
Jian-Kang Zhang, Senior Member, IEEE
Yan-Yu Zhang



DOI: 10.1109/JPHOT.2015.2495104

A Fast Blind Detection Algorithm for Outdoor Visible Light Communications

Yi-Jun Zhu,[1] ***Member, IEEE*, Zheng-Guo Sun,**[1]
Jian-Kang Zhang,[2] ***Senior Member, IEEE*, and Yan-Yu Zhang**[1]

[1]National Digital Switching System Engineering and Technological Research Center, Zhengzhou 450000, China
[2]Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON L8S 4K1, Canada

DOI: 10.1109/JPHOT.2015.2495104

Manuscript received September 2, 2015; revised October 21, 2015; accepted October 22, 2015. Date of publication October 27, 2015; date of current version November 6, 2015. This work was supported in part by the China National Science Foundation Council under Grant 61271253 and in part by the China National "863" Program under Grant 2013AA013603. The work of J. K. Zhang was supported in part by the Natural Sciences and Engineering Research Council of Canada. Corresponding author: Z.-G. Sun (e-mail: mailbox_of_sun@qq.com).

Abstract: In this paper, we consider an outdoor visible light communication system, in which on–off keying (OOK) modulation is utilized through an atmospheric turbulence-induced slow-fading channel. A new fast blind detection algorithm is proposed by following the generalized likelihood ratio test (GLRT) principle. In addition, a block coding scheme is presented to solve the unique identification issue and, thus, the error floor problem.

Index Terms: Visible light communication (VLC), blind channel estimation, log-normal fading channel, Rayleigh fading channel.

1. Introduction

Recently, as a new communication technology, visible light communication (VLC), has attracted tremendous attention [1]–[4], since it enables to provide broadband transmission with unlicensed spectrum and alleviate shortage of wireless spectrum resources [5]. It is no doubt that VLC is becoming an increasingly more attractive communication option in human life.

New generation of high-intensity light-emitting diodes (LEDs) which have permitted the replacement of incandescent-based lights, unfolds the potential of implementing a VLC system in an outdoor environment [6]. Traffic light signals and public illumination systems are two typical application examples, where VLC can show its advantages [7]. Compared with laser diode, LED has a large divergence angle, implying a lower requirement for acquisition pointing and tracking system. Therefore, outdoor VLC is more suitable for low-lost, low-rate, and short-to-medium distance applications [7], [8].

The channel in the indoor VLC is static and stable [9]. However, the channel in the outdoor VLC is different and is attenuated by inhomogeneities in the temperature and pressure of the atmosphere, which leads to variations of the refractive index along the transmission path [10]–[12]. In this scenario, perfect channel information, in practice, is not easily obtainable and hence, blind detection was proposed in [13] and [14]. Unfortunately, its complexity and accuracy are not satisfactory. To improve error performance and reduce detection complexity, a simple transmission scheme is to send a training sequence [15]–[19]. However, it does not make full use of bandwidth and power.

Therefore, our target in this paper is first to develop a fast blind detection algorithm based on the generalized likelihood ratio test (GLRT) principle. Then, to eliminate the error floor issue, we consider a simple and spectrum-efficient block coding method. Finally, our proposed detection algorithm and transmission scheme will be tested by computer simulations for log-normal and Rayleigh fading optical channels with various sizes of transmission data blocks.

2. System Model

Let us consider an outdoor VLC system with a single LED at the transmitter linking a single photo-detector at the receiver through a flat fading channel. Hence, the resulting electrical signal model can be represented by

$$r = hs + n \tag{1}$$

where r denotes a received signal, s denotes a transmitted signal, which is randomly and equally-likely chosen from the OOK constellation, the received noise n is modelled as an additive white Gaussian with zero mean and variance $\sigma_n^2 = N_0/2$ [20], and h is the channel irradiance. Throughout this paper, we assume that random variable h is either log-normal or Rayleigh distributed. Log-normal fading usually arises in weak turbulence conditions. Its probability density function (pdf) is given by

$$f_H(h) = \frac{1}{2h\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln h)^2}{8\sigma^2}\right), h > 0. \tag{2}$$

Rayleigh fading emerges from a scattering model that is viewed as the composite field produced by a large number of non-dominating scatterers, each contributing random optical phase upon arrival at the detector [21]. Its pdf is

$$g_H(h) = \frac{e^{-h/2}}{2}. \tag{3}$$

In addition, we also assume that the channel h is a slow fading and that it is constant for the first L time slots, after which it changes to a new independent value that is fixed for next L time slots, and so on. At the receiver, all the L received signals can be collected in a compact vector form as

$$\mathbf{r} = h\mathbf{s} + \mathbf{n} \tag{4}$$

where $\mathbf{r} = [r_1, r_2, \ldots, r_L]^T$, $\mathbf{s} = [s_1, s_2, \ldots, s_L]^T$, and $\mathbf{n} = [n_1, n_2, \ldots, n_L]^T$. Our principal goal in this paper is to develop a fast blind decoding algorithm for efficiently and effectively estimating both h and $\mathbf{s}$ from the given received signal vector $\mathbf{r}$.

3. Fast Blind Detection Algorithm

For the channel model (4), we first notice that the pdf of the received signal $\mathbf{r}$ conditioned on $\mathbf{s}$ and h is given by

$$p(\mathbf{r}|\mathbf{s}, h) = \frac{1}{\left(\sqrt{2\pi\sigma_n^2}\right)^L} \exp\left(-\frac{\|\mathbf{r} - h\mathbf{s}\|^2}{2\sigma_n^2}\right). \tag{5}$$

Hence, the GLRT detector is to solve the following optimization problem:

$$\{\hat{h}, \hat{\mathbf{s}}\} = \operatorname{argmin}\|\mathbf{r} - h\mathbf{s}\|^2. \tag{6}$$

In order to efficiently solve this problem, we also note that the objective function in (6) can be represented by

$$\|\mathbf{r}-h\mathbf{s}\|^2=\sum_{i=1}^{L} r_i^2-2h\sum_{i=1}^{L} r_i s_i+h^2\sum_{i=1}^{L} s_i^2. \tag{7}$$

Now, let $S=\sum_{i=1}^{L} s_i^2$ and rearrange the entries of $\mathbf{r}$ such that $r_{i1}\geq r_{i2}\geq\cdots\geq r_{iL}$, where the first index i is the original index of r_i in $\mathbf{r}$, and the second index $k=1,2,\ldots,L$ is the ordering number after arrangement. For example, if $\mathbf{r}=(r_1,r_2,r_3,r_4)^T=(1.1,1.3,0.2,0.3)^T$, then $r_{21}=1.3$, $r_{12}=1.1$, $r_{43}=0.3$, $r_{34}=0.2$ after arrangement. Since $s_i\in\{0,1\}$, we have $s_i^2=s_i$ and thus, $S=\sum_{i=1}^{L} s_i$. In fact, S denotes the number of $s_i=1$ for $i=1,2,\ldots,L$. Therefore, S is a nonnegative integer and $0\leq S\leq L$. Let s_{ik} be the corresponding symbol of r_{ik} for $k=1,\ldots,L$, and we let

$$R_S=\sum_{k=1}^{S} r_{ik}s_{ik}. \tag{8}$$

When $S>0$, since $s_{ik}=1$, $k=1,\ldots,S$, we attain $R_S=\sum_{k=1}^{S} r_{i_k}$, when $S=0$, we can have $\mathbf{s}=\mathbf{0}$ for the reason that all the entries of $\mathbf{s}$ is nonnegative and then, $\sum_{i=1}^{L} r_i s_i=0$. For the simplicity of presentation, when $S=0$, we make a convention that $R_S=0$ to indicate the fact that when $S=0$, the product sum $\sum_{i=1}^{L} r_i s_i$ is equal to zero. For any fixed S, from (7) we can obtain the equivalent form of the GLRT function as follows:

$$C(h,S)=\min_{\mathbf{s}}\|\mathbf{r}-h\mathbf{s}\|^2=\sum_{i=1}^{L} r_i^2-\mathbf{2}hR_S+h^2S. \tag{9}$$

When $S=0$, we have $R_S=0$, and thus, $C(h,S)=\sum_{i=1}^{L} r_i^2$ is a constant independent of h. When $S>0$, differentiating (9) with respect to h and letting the derivative be equal to zero yield

$$h=\frac{R_S}{S}. \tag{10}$$

Now, if we substitute (10) into (9), we get the following:

$$C(h,S)=\sum_{i=1}^{L} r_i^2-\frac{R_S^2}{S}. \tag{11}$$

Because the sum of r_i^2 is fixed, minimizing $C(h,S)$ over S is equal to

$$\max_{1\leq S\leq L}\frac{R_S^2}{S}. \tag{12}$$

After sorting, $R_S=r_{i1}+r_{i2}+\cdots+r_{iS}$. If we start with $S=1$, add r_{iS} to R_S and add one to S, then compute R_S^2/S for each increment in S. From $S=1$ to $S=L$, we can find the maximum value of R_S^2/S and let the corresponding value of S be $\hat{S}$. Then the number of 1's in the sequence $\mathbf{s}$ is given by $\hat{S}$ and the number of 0's is $L-\hat{S}$. Furthermore, we will observe that $s_{ik}=s_i$ for $i=1,2,\ldots,L$. Therefore, from $k=1$ to $k=\hat{S}$, we can make decision that the corresponding symbol of r_{ik} is decoded as $\hat{s}_i=1$, and from $k=\hat{S}+1$ to L, r_{ik} is decoded as $\hat{s}_i=0$, where $i=1,2,\ldots,L$ is the original index of r_i in $\mathbf{r}$.

In fact, in the high signal-to-noise ratio (SNR) region, R_S^2/S is increasing when $s_i=1$; when $s_i=0$, R_S^2/S would begin to decrease, as shown in Fig. 1, which vividly illustrates why R_S^2/S is chosen to estimate the number of 1's sent.

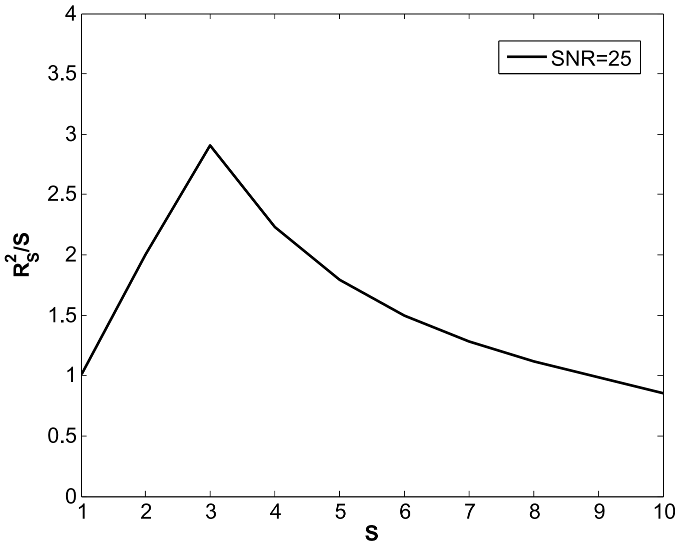


Fig. 1. Value of R_S^2/S changes with S.

All the above discussions can be summarized as the following algorithm:

Algorithm 1 (Fast GLRT Decoding Algorithm)

The optimal estimates of the channel h and signal $\mathbf{s}$ are determined as follows:

1. Estimate the number of 1's sent:

$$\hat{S} = \text{argmax}_{1 \leq S \leq L} \frac{R_S^2}{S} \tag{13}$$

2. Estimate the channel:

$$\hat{h} = \frac{R_{\hat{S}}}{\hat{S}} \tag{14}$$

3. Decode symbols: For $k = 1, 2, \ldots, \hat{S}$, $\hat{s}_i = \hat{s}_{ik} = 1$, and for $k = \hat{S} + 1, \ldots, L$, $\hat{s}_i = \hat{s}_{ik} = 0$, where $i = 1, 2, \ldots, L$ is the original index of r_i in $\mathbf{r}$, k is the ordering number of r_{ik} after arrangement.

It can be observed that the main complexity of Algorithm 1 comes from sorting the received signal, whose complexity is $O(L\log L)$. Hence, the overall complexity of Algorithm 1 is $O(L\log L)$.

4. Computer Simulations

In this section, we carry out computer simulation to illustrate the error performance of our fast GLRT algorithm presented in Section 3.

The simulation results for the log-normal fading channel are first shown in Fig. 2, where the blue line designates the bit error rate performance of the GLRT algorithm and the black line shows the bit error rate performance of the mean value algorithm reported in [22]. In addition, we also plot the curve, denoted by the red line, for the bit error rate performance when the channel is exactly known at the receiver. From Fig. 2, we can see both the red curve and the blue curve are very close when SNR is smaller than 17 dB. However, when SNR is larger than 17 dB, the gap between them increases and an error floor appears.

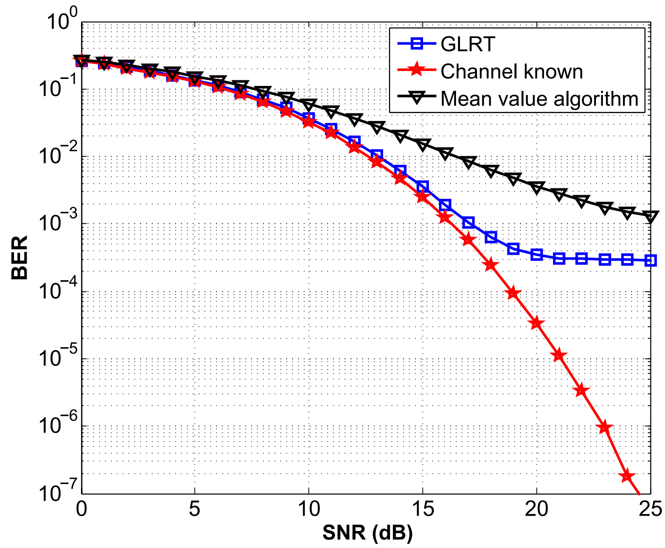


Fig. 2. Comparisons with GLRT, channel known, and mean value algorithm with one LED in log-normal channel of $\sigma = 0.3$. The block length is 10.

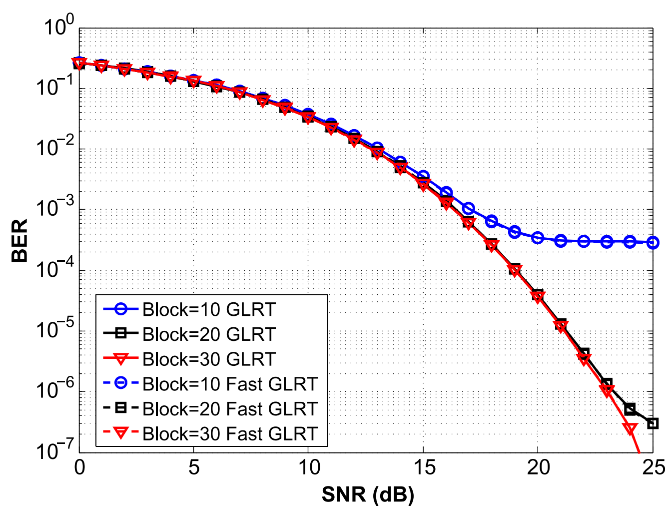


Fig. 3. GLRT and Fast GLRT with one LED in log-normal channel of $\sigma = 0.3$. The block length is 10, 20, and 30.

To examine how the length of the block affects the error performance of our algorithm for the log-normal channel, we also carry out computer simulations for various sizes of blocks, as shown in Fig. 3. We can observe from Fig. 3 that when the block length becomes longer, the performance becomes better, and the error floor comes later, since we have more received signals to estimate the channel more accurately. However, the error floor cannot disappear, since when the symbols in a block are all zeros, there is no channel information in the corresponding received signals.

This error floor issue was also observed in [13]. In practice, a simple method to solve this issue is the one bit training scheme, i.e., to insert one bit 1 at the head of each transmission block. In this paper, we consider another simple and more spectrum-efficient block coding scheme to eliminate the error floor. It is noticed that the essential reason of the error floor for the OOK modulation is that there is one transmission data block whose entries are all zeros.

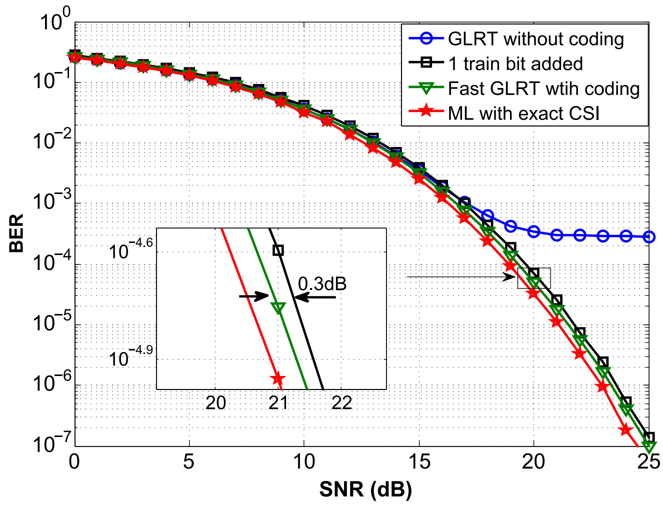


Fig. 4. Performance comparisons with different algorithms in log-normal channel of $\sigma = 0.3$ with effective 10 information bits in one block.

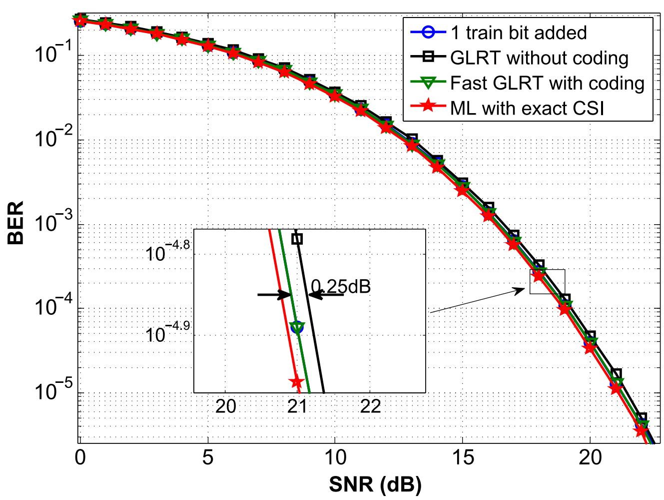


Fig. 5. Performance comparisons with different algorithms in log-normal channel of $\sigma = 0.3$ with effective 20 information bits in one block.

Hence, the error floor can be eliminated by getting rid of such block. For the block length L, there are totally 2^L transmitted data blocks. Therefore, there are in total $2^L - 1$ data blocks left after such elimination, and the resulting transmission bit rate is

$$R_b = \frac{2^L - 1}{2^L}.$$

Here, it can be seen clearly that as L goes to infinity, R_b tends to 1 bit per channel use. Figs. 4 and 5 show the error performance comparison between this block coding scheme, denoted by the green line, and the one bit training scheme, denoted by the black line, for the log-normal fading channel, where the blue curve is also plotted to show the error performance of our Algorithm 1 with no coding.

It can be observed that the gap between the green line and the black line is about 0.30 dB in Fig. 4 and 0.25 dB in Fig. 5. In addition, we also observe that the error performance of our blind

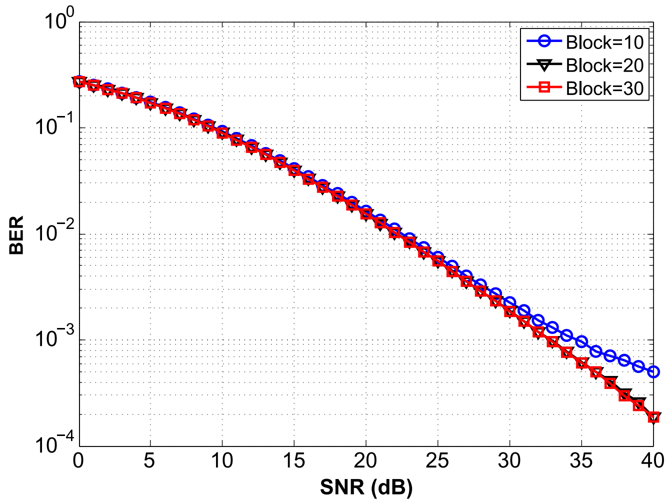


Fig. 6. Fast blind algorithm performance with one LED in the Rayleigh channel and the block length is 10.

algorithm with coding is very close to that of a theoretical optimal receiver with exact channel state information (CSI), and the gap is about 0.40 dB when $L = 10$ and 0.15 dB when $L = 20$, respectively. Similarly, the simulation result for the Rayleigh channel is also shown in Fig. 6.

5. Conclusion

In this paper, we have developed a fast GLRT detection algorithm for an optical communication system, in which OOK modulation is used through an atmospheric turbulence-induced slow fading channel. With this decoding algorithm, a simple and spectrum-efficient block coding scheme has been presented to solve the error floor problem. Its error performance and comparison with one-bit training scheme have been examined by comprehensive computer simulations for the log-normal and Rayleigh fading channels with various sizes of transmitted data blocks.

Acknowledgment

The authors wish to thank the anonymous reviewers for their valuable suggestions.

References

[1] D. O. A. M. Street, P. N. Stavrinou, and D. Edwards, "Indoor optical wireless systems—A review," *Opt. Quant. Electron.*, vol. 29, no. 3, pp. 349–378, Mar. 1997.
[2] A. Acampora, "Last mile by laser," *Sci. Amer.*, vol. 287, no. 1, pp. 48–53, Jul. 2002.
[3] J. Grubor, S. Randel, K.-D. Langer, and J. W. Walewski, "Broadband information broadcasting using LED-based interior lighting," *J. Lightw. Technol.*, vol. 26, no. 24, pp. 3883–3892, Dec. 2008.
[4] H. Sugiyama, S. Haruyama, and M. Nakagawa, "Brightness control methods for illumination and visible-light communication systems," in *Proc. IEEE 3rd ICWMC*, 2007, p. 78.
[5] S. C. J. L. S Randel, F. Breyer, and J. W. Walewski, "Advanced modulation schemes for short-range optical communications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 16, no. 5, pp. 1280–1289, Sep./Oct. 2010.
[6] I. Lee, M. Sim, and F. Kung, "Performance enhancement of outdoor visible-light communication system using selective combining receiver," *IET Optoelectron.*, vol. 3, no. 1, pp. 30–39, Feb. 2009.
[7] N. Lourenço, D. Terra, N. Kumar, L. N. Alves, and R. L. Aguiar, "Visible light communication system for outdoor applications," in *Proc. 8th Int. Symp. CSNDSP*, 2012, pp. 1–6.
[8] M. L. Zhang, P. Zhao, and Y. J. Jia, "A 5.7 Km visible light communications experiment demonstration," in *Proc. IEEE 7th ICUFN*, 2015, pp. 1–3.
[9] K. Lee, H. Park, and J. R. Barry, "Indoor channel characteristics for visible light communications," *IEEE Commun. Lett.*, vol. 15, no. 2, pp. 217–219, Feb. 2011.
[10] R. M. Gagliardi and S. Karp, *Optical Communications*, vol. 1. New York, NY, USA: Wiley-Interscience, 1976.
[11] A. Zilberman, N. S. Kopeika, and Y. Sorani, "Laser beam widening as a function of elevation in the atmosphere for horizontal propagation," in *Proc. Aerosp./Def. Sens., Simul., Controls*, 2001, pp. 177–188.

[12] T. J. Schulz, "Optimal beams for propagation through random media," *Opt. Lett.*, vol. 30, no. 10, pp. 1093–1095, May 2005.
[13] M. Riediger, R. Schober, and L. Lampe, "Blind detection of on–off keying for free-space optical communications," in *Proc. IEEE CCECE*, 2008, pp. 001361–001364.
[14] N. D. Chatzidiamantis, G. K. Karagiannidis, and M. Uysal, "Generalized maximum-likelihood sequence detection for photon-counting free space optical systems," *IEEE Trans. Commun.*, vol. 58, no. 12, pp. 3381–3385, Dec. 2010.
[15] O. Rousseaux, G. Leus, and P. Stoica, "Generalized training based channel identification," in *Proc. IEEE GLOBE-COM*, 2003, pp. 2432–2436.
[16] C. Tellambura, M. G. Parker, Y. J. Guo, S. J. Shepherd, and S. K. Barton, "Optimal sequences for channel estimation using discrete Fourier transform techniques," *IEEE Trans. Commun.*, vol. 47, no. 2, pp. 230–238, Feb. 1999.
[17] X. Zhu, J. M. Kahn, and J. Wang, "Mitigation of turbulence-induced scintillation noise in free-space optical links using temporal-domain detection techniques," *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 623–625, Apr. 2003.
[18] X. Zhu and J. M. Kahn, "Pilot-symbol assisted modulation for correlated turbulent free-space optical channels," in *Proc. IEEE Int. Symp. Opt. Sci. Technol.*, 2002, pp. 138–145.
[19] H. Moradi, H. H. Refai, and P. G. LoPresti, "Thresholding-based optimal detection of wireless optical signals," *J. Opt. Commun. Netw.*, vol. 2, no. 9, pp. 689–700, Sep. 2010.
[20] M. K. Simon and V. Vilnrotter, "Alamouti-type space–time coding for free-space optical communication with direct detection," *IEEE Trans. Wireless Commun.*, vol. 4, no. 1, pp. 35–39, Jan. 2005.
[21] Q. C. S. G. Wilson, M. Brandt-Pearce, and I. J. H. Leveque, "Free-space optical MIMO transmission with Q-ary PPM," *IEEE Trans. Commun.*, vol. 53, no. 8, pp. 1402–1412, Aug. 2005.
[22] L. Liu, "Rate-adaptive techniques for free-space optical channels," Ph.D. dissertation, Dept. Elect. Comput. Eng., McMaster Univ., Hamilton, ON, Canada, 2013.