BER Performance of M-ary PPM Free-Space Optical Communications with Channel Fading

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***Abstract*—In this paper, we have shown the advantage of using 4-ary pulse position modulation (PPM) using intensity modulation with direct detection (IM/DD) as a power efficient system over coherent differential phase shift keying (DPSK) as a bandwidth efficient system in free space optical (FSO) weak turbulence channel (log-normal channel) and strong turbulence channel (negative-exponential channel). The comparison is done using avalanche photodetector (APD) and PIN receivers. A correct expression is derived for DPSK in negative-exponential channel using APD. The performance of 4-ary PPM is enhanced using high order 256-PPM modulation and forward error correction (FEC). We employed standard Reed-Solomon RS (255,239) and RS (255,223). This work was further extended by exploiting concatenated Reed-Solomon codes, RS (255,239) as an outer code and RS (255,223) as an inner code for higher efficiency.**

Keywords—Free space optical (FSO), M-ary pulse position modulation (M-ary PPM), differential phase shift keying (DPSK), concatenated Reed-Solomon (CRS) codes, atmospheric turbulence channel, PIN photodiode, avalanche photodiode (APD).

I. INTRODUCTION

Free space optical (FSO) systems have several advantages over radio-frequency (RF) technology such as significantly large bandwidth, license-free and high interference immunity. FSO systems are also less vulnerable to snow and rain. It has attracted considerable attention for a variety of applications like last mile connectivity, optical-fiber backup and enterprise connectivity. On the other hand, the performance of FSO link is highly affected by fog and atmospheric turbulence. Atmospheric turbulence causes random fluctuations at the received signal intensity, i.e., channel fading, which leads to an increase in the bit error rate (BER) of the optical link [1, 2].

Current FSO communication systems employ intensity modulation with direct detection (IM/DD) and use light emitting diodes (LEDs) or laser diodes (LDs) as transmitters and PIN photodiodes or avalanche photodetectors (APDs) as receivers. These devices modulate and detect only the intensity of the carrier not its phase. Furthermore, biological safety reasons constrain the average radiated optical power, thereby constraining the average signal amplitude. The most reported modulation technique used for FSO is the on-off keying (OOK) which offers bandwidth efficiency but lacks power efficiency. Pulse position modulation (PPM) achieves high power efficiency and improves the system performance at the expense of reduced bandwidth efficiency compared with other modulation schemes. The optimal PPM order is high, since a higher order modulation creates the higher peak power needed to overcome the weak average power. To mitigate this problem, M-ary PPM was suggested as a suitable modulation scheme for FSO systems [3]. The infrared data association (IrDA) specification for the 4 Mbps short distance wireless infrared links specifies a 4-PPM modulation scheme [4].

Differential phase shift keying (DPSK) is bandwidth efficient when coherent systems are employed in the sense that its performance is higher than IM/DD systems against thermal noise. It also supports higher spectral efficiency. On the other hand, a coherent optical receiver is much more complex than a simple direct detection receiver [5, 6]. Reed-Solomon (RS) codes are a class of block codes that operate on symbols rather than bits. Hence, RS codes can correct both random bit errors and burst symbol errors. Moreover, their hard decoding algorithm can be easily implemented even at a high operation speed. International Telecommunication Union-Telecommunication (ITU-T) adopted forward error correction (FEC) scheme based on RS (255,239) codes for 10 Gbps practical optical fiber transmission systems [7]. The concatenated code was proposed as a practical method to construct longer codeword length and better error-correction performance. It is a special method that a long code can consist of some short codes. Concatenated Reed-Solomon codes are used to improve the bust error correction capability of RS codes [8, 9].

For a high bit rate optical communications, APD is frequently the photodetector of choice due to its internal gain, which provides better sensitivity than PIN photodiode. On the opposite side, APD has many drawbacks as the high cost, the complex circuit, the temperature sensitivity and the need of high voltage power. This makes PIN more reliable than APD especially in low rates. Improvements in materials and development of advanced device structures will set the stage for future systems that will take the benefit of APDs and avoid the drawbacks [10, 11].

In recent papers, binary PPM without coding in log-normal and negative-exponential channels is obtained using APD and PIN [12]. RS-coded M-ary PPM in log-normal channel is obtained in [7, 13]. Unlike the previous references, another approach was proposed in [3, 14] where RS-coded M-ary PPM in log-normal and negative-exponential channels are obtained using APD.

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DPSK has been evaluated in a log-normal channel assuming a shot-noise-limited system [15]. M-ary PPM is compared with DPSK assuming a shot-noise-limited system in a log-normal channel [16].

In this paper, we have shown that 4-PPM (using IM/DD) is more efficient than DPSK (using coherent modulation and demodulation) in both log-normal and negative-exponential channels using two different receivers PIN and APD. The improvement of the system due to increasing the modulation level and using FEC was shown by using standard RS (255,239) and we use also used lower rate RS (255,223) which increases the system performance over the standard one. For higher coding gain, concatenated codes are used. In particular, concatenated RS (255,239) is used as an outer code and RS (255,223) is used as an inner code with interleaver between them, which gives high improvement compared to the standard RS (255,239).

The results of the uncoded FSO system are compared with 4-PPM. The binary PPM is excluded as it has the same bandwidth efficiency as 4-PPM, while requiring about 3 dB more optical power for the same BER [17].

The remainder of the paper is organized as follows. The models of FSO channels are presented in Sec. 2. Our system is extended in Sec. 3 by applying FEC. Based on the described model, a numerical analysis of the system is carried out in Sec. 4. This is followed by the main conclusion in Sec. 5.

II. FREE-SPACE OPTICAL MODELS

A. Log-Normal Channel

The log-normal channel is classified as weak turbulence, which is characterized by a scintillation index less than 0.75. In general, the scintillation index is a complicated function of the beam parameters, propagation distance, heights of the transmitter and the receiver, and the fluctuations in the index of refraction. In fact, the main source of scintillation is due to fluctuations (due to temperature variations) in the index of refraction, which is commonly known as optical turbulence. The log-normal model is also valid for propagation distances less than 100 m in [18].

The bit error rate (BER) of M-ary PPM in a log-normal channel using APD is given by [19]

$$P_b^M \le \frac{M}{2\sqrt{\pi}} \sum_{i=-N, i\neq 0}^{N} w_i Q\left(\sqrt{\frac{e^{2(\sqrt{2}\sigma_k x_i + m_k)}}{F e^{\sqrt{2}\sigma_k x_i + m_k} + K_n}}\right) \quad (1)$$

where M is the modulation level, w_i and x_i are the weight factors and the zeros of the Hermite polynomial which are well tabulated in [20]. K_n and F will be defined in Eqs. (4) and (5), respectively.

The following equations from (2) to (9) illustrate the log-normal model proposed in [18, 21, and 22]

The scintillation index (σ^2_{SI}) as a function of the variance of the log-normal channel (σ^2_k)

$$\sigma_{SI}^2 = e^{\sigma_k^2} - 1 \quad (2)$$

The average photons per slot ($E\{K_s\}$) is a function of the mean (m_k) and the variance of the log-normal channel and has the form

$$E\{K_s\} = e^{\left(\frac{\sigma_k^2}{2} + m_k\right)} \quad (3)$$

The total noise photons per slot, K_n, which results from background noise and thermal noise, is

$$K_n = \frac{2\sigma_n^2}{(E\{g\}q)^2} + 2FK_b \quad (4)$$

where K_b is the average background noise photons per slot, $E\{g\}$is the average gain of the APD and q is the electron charge.

The noise factor, F, of the APD is defined by

$$F \approx 2 + \varsigma E\{g\} \quad (5)$$

where ς is the ionization factor.

The variance, σ^2_n, of the thermal noise in one slot is defined by

$$\sigma_n^2 = \left(\frac{2KTT_{slot}}{R_L}\right) \quad (6)$$

where T is the effective absolute temperature of the receiver, K is Boltzmann constant, R_L is the APD load resistance and T_{slot} is the PPM slot duration which is related to the data rate, R_b, by

$$T_{slot} = \frac{\log_2(M)}{MR_b} \quad (7)$$

The BER of DPSK in a log-normal channel using APD is given by

$$P_b \le \frac{1}{2\sqrt{\pi}} \sum_{i=-N, i\neq 0}^{N} w_i \exp\left(-\frac{e^{2(\sqrt{2}\sigma_k x_i + m_k)}}{F e^{\sqrt{2}\sigma_k x_i + m_k} + K_n}\right) \quad (8)$$

The variance, σ^2_n, of the thermal noise in a DPSK bit is defined by

$$\sigma_n^2 = \left(\frac{2KTT_b}{R_L}\right) \quad (9)$$

where T_b is the DPSK bit duration. Equations (3) and (4) apply for DPSK but with definition average photons per bit (PPB) instead of average photons per slot.

B. Negative-Exponential Channel

The negative-exponential channel is classified as strong turbulence, which is characterized by a scintillation index equal one. The negative-exponential model is valid for propagation distances more than 100 m or several kilometers in [18, 23].

The BER of M-ary PPM in the negative-exponential channel using APD, P_b^M is given by [18]

$$P_b^M \le \frac{M}{2} \sum_{i=-N, i\neq 0}^{N} w_i |x_i| Q\left(\frac{E\{K_s\} x_i^2}{\sqrt{F E\{K_s\} x_i^2 + K_n}} \right) \quad (10)$$

The BER of DPSK in the negative-exponential channel using APD, P_b is derived in [22]

$$P_b \le \sum_{i=-N, i\neq 0}^{N} w_i |x_i| \exp\left(-\frac{E\{K_s\}^2 x_i^4}{E\{K_s\} x_i^2 + K_n} \right) \quad (11)$$

Applying the same procedure of derivation of log-normal channel in [22] to negative-exponential channel, we found a typo in (11); it must be corrected in the form

$$P_b \le \frac{1}{2} \sum_{i=-N, i\neq 0}^{N} w_i |x_i| \exp\left(-\frac{E\{K_s\}^2 x_i^4}{F E\{K_s\} x_i^2 + K_n} \right) \quad (12)$$

To get the BER expression for both M-ary PPM and DPSK for PIN photodector, both noise factor (F) and gain (E{g}) must be set to unity [9].

III. FORWARD ERROR CORRECTION

In case of coding, R_b in (7) must be multiplied by (n/k), where n is the codeword length and k is the message length.

The symbol error rate (P_{symbol}) can be calculated from bit error rate (P_b^M) as [23]

$$P_{symbol} = P_b^M \left(\frac{2(M-1)}{M} \right) \quad (13)$$

When an RS symbol bits is equal to m M-ary symbols bits, this will given by [24]

$$P_q = 1 - (1 - P_{symbol})^m \quad (14)$$

where m is the number of repetition of M-ary bits. In our case, similar to the RS code, the employed 256-PPM has eight bits per symbol. Hence, m will be unity.

The probability of the uncorrectable symbol error (P_{ues}) due to RS codes can be given by the formula [25]

$$P_{ues} \le \frac{1}{n} \sum_{i=t+1}^{n} i \binom{n}{k} P_q^i (1 - P_q)^{n-i} \quad (15)$$

where t =((n-k)/2) is the symbol error correcting capability.

In case of concatenating codes, equation (15) must employ to the inner decoder. In this case, the matching between the RS symbols will allow to apply directly (16) for the outer decoder under the assumption that the interleaver is ideal.

$$P_{outer} \le \frac{1}{n} \sum_{i=t+1}^{n} i \binom{n}{k} P_{ues}^i (1 - P_{ues})^{n-i} \quad (16)$$

The BER for inner and outer decoders are given by [26]

$$P_{b,inner} = P_{ues} \left(\frac{n+1}{2n} \right), P_{b,outer} = P_{outer} \left(\frac{n+1}{2n} \right) \quad (17)$$

IV. NUMERICAL RESULTS AND DISCUSSIONS

Based on the described model, the average number PPB, which is equal to ($E\{K_s\}/\log_2 M$) in M-ary PPM and $E\{K_s\}$ for DPSK, is evaluated at BER 10^{-9} in Figs. 1-3. This BER is considered as a practical performance target for the FSO link [27].

In these figures, the value of scintillation index (σ^2_{SI}) is taken 0.1 for weak turbulence and it is unity for strong turbulence. The values of other parameters are taken as: bit rate = 2.4 Gbps, background noise = 20 photons per bit, R_L = 50 Ω, N = 5, ς = 0.028, T = 300°K, and E{g} = 150.

Since most laser systems operate under a fixed power level constraint, $E\{K_s\}$ and K_b in case of coding must multiply by the factor of the coding rate (k/n) for fair comparison with the uncoded system. This is because, for a fixed power, the energy must be scaled as a result of coding [28].

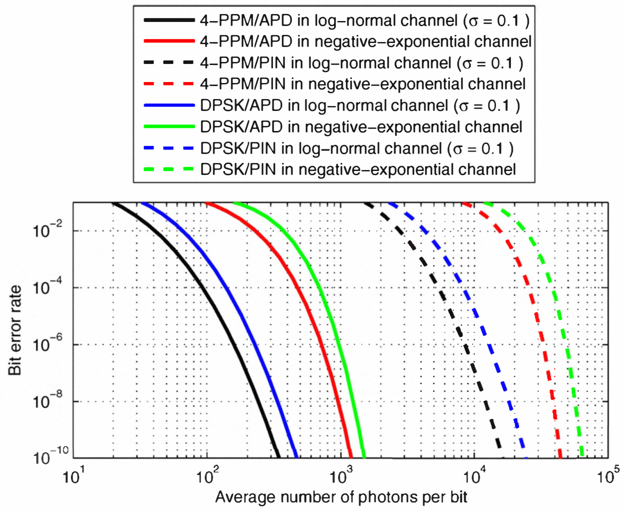

Figure 1. BER for both 4-PPM and DPSK using PIN/APD receivers for different fading channels.

In Fig. 1, we compare between DPSK as a bandwidth efficient system and 4-PPM as a power efficient system in fading channels. We found that, at a negative-exponential channel, the average PPB is 40000 photons for 4-PPM and 60000 for DPSK in PIN to achieve a BER of 10^{-9}. To save power, we use APD which decreases this requirement to 1081 and 1376, respectively. This significant improvement is due to the high internal gain of the APD. While in a log-normal channel (weak turbulence), we found the average PPB to be 14500, 20620 using PIN receiver and 280, 400 using APD for log-normal and negative-exponential channels, respectively.

To further improve the power efficiency, we use higher order modulation (256-PPM). The corresponding gain appears in Fig. 2. Given the log-normal channel using PIN receiver, the average PPB is decreased to 1126 photons which is better than DPSK by 12.63 dB and than 4-PPM by 11.01 dB. While, using APD receiver, the average PPB is decreased to 82 photons which is better than DPSK by 6.88 dB and than 4-PPM by 5.33 dB, respectively.

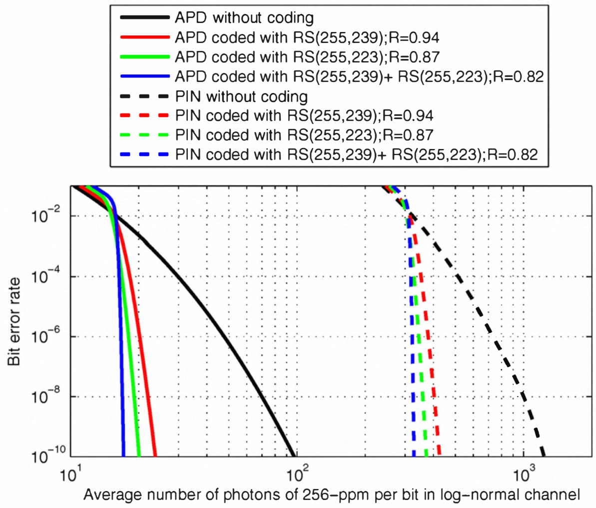

Figure 2. BER for 256-PPM using PIN/APD receivers in log-normal channel with scintillation index 0.1.

Alternatively, the power consumed can be decreased by exploiting FEC with the same target (BER = 10^{-9}). With the FEC employed, we compare several codes, the standard RS (255,239) of ITU-T G.975, RS (255,223) and two concatenated codes RS (255,223) as an inner code and RS (255,239) as an outer code. We found that, they achieve coding gain 4.31, 4.89 and 5.37 dB in PIN receiver and 5.52, 6.13 and 6.83 dB in APD, respectively.

The negative-exponential channel is investigated in Fig. 3. Using M-ary PPM with PIN receiver the average PPB is decreased to 2895 photons which is better than DPSK by 13.17 dB and than 4-PPM by 11.4 dB. While, using APD receiver, the average PPB is decreased to 291 photons which is better than DPSK by 6.75 dB and than 4-PPM by 5.7 dB. Using FEC, we achieved a coding gain of 2.28, 2.83 and 3.36 dB with the PIN receiver and 4.23, 5 and 5.77 dB with the APD, respectively.

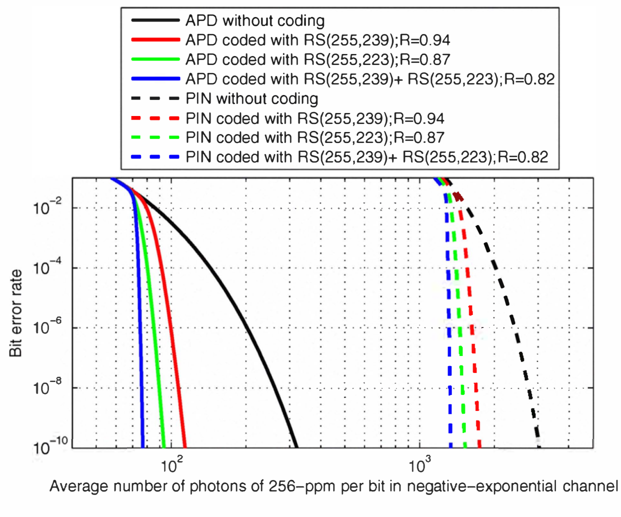

Figure 3. BER for 256-PPM using PIN/APD receivers in negative-exponential channel.

The average PPB to achieve a BER of 10^{-9} for an FSO communication system in log-normal and negative-exponential channels using FEC and two different receivers (PIN and APD) is summarized in Table I.

TABLE I AVERAGE NUMBER OF PPB REQUIRED TO ACHIEVE BER 10^{-9} USING FEC.

Receiver/ Channel	256-PPM using RS(255,239) (ITU-T G.975)	256-PPM using RS(255,223)	256-PPM using RS(255,239) + RS(255,223)
PIN/negative-exponential channel ($\sigma^2_{SI=1}$)	1712	1510	1335
APD/ negative-exponential channel ($\sigma^2_{SI=1}$)	110	92	77
PIN/log-normal channel ($\sigma^2_{SI=0.1}$)	417	365	327
APD/log-normal channel ($\sigma^2_{SI=0.1}$)	23	20	17

V. CONCLUSION

In this paper, the obtained results proved the power efficiency advantage of 4-PPM over DPSK in log-normal and negative-exponential channels using two different receivers; PIN and APD. The use of M-ary PPM improves the performance of the FSO system tolerance for the intensity fluctuations induced by atmospheric turbulence.

In addition, results showed that APD outperform PIN receiver in saving power. It is found that, using 256-PPM with APD receiver with the proposed concatenated code in negative-exponential channel requires 77 PPB to achieve a BER of 10^{-9}. While using the same system without coding in log-normal channel requires 82 PPB. This means that, FEC helps to upgrade the existing uncoded FSO system to work on several kilometers rather than being limited to 100 m.

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REFERENCES

[1] Yi Xiang, Liu. Zengji, Yue Peng, and Shang Tao, "BER performance analysis for M-ary PPM over gamma-gamma atmospheric turbulence channels," Proceeding of the 6th International Conference on Networking and Mobile Computing (WiCom), Chengdu, China, pp. 1-4, Sep. 2010.

[2] Bobby Barua, "Comparison the performance of free-space optical communication with OOK and BPSK modulation under atmospheric turbulence," International Journal of Engineering Science and Technology (IJEST), vol. 3, no. 5, pp. 4391–4399, May 2011.

[3] S. Sheikh Muhammad, Tomaz Javornik, Igor Jelovcan, Zabih Ghassemlooy, and Erich Leitgeb, "Comparison of hard-decision and soft-decision channel coded M-ary PPM performance over free space optical links," European Transactions on Telecommunications, vol. 20, no. 8, pp. 746–757, Dec. 2009.

[4] S. Hranilovic, *Wireless Optical Communication Systems*, Springer Science + Business Media, Boston, USA, 2005.

[5] V. K. Prabhu and J. Salz, "On the performance of phase-shift-keying systems," Bell System Technical Journal, vol. 60, no. 10, pp. 2307-2343, Dec. 1981.

[6] T. Pfau, S. Hoffmann, O. Adamczyk, R. Peveling, V. Herath, M. Porrmann, and R. Noé, "Coherent optical communication: towards realtime systems at 40 Gbit/s and beyond," Optics Express, vol. 16, no. 2, pp. 866-872, Jan. 2008.

[7] Juanjuan Yan, Zheng Zheng, Weiwei Hu, and Anshi Xu, “Improved performance of M-ary PPM free-space optical communication systems in atmospheric turbulence due to forward error correction,” Proceeding of the 10th International Conference on Commununication Technology (ICCT), Guilin, China, pp.1- 4, Nov. 2006.

[8] Jianguo Yuan, Ze Jiang, Youju Mao, and Wenwei Ye “Forward error correction concatenated code in DWDM Systems,” Frontiers of Optoelectrons in China, vol. 1, no. 1, pp. 20-24, Sep. 2008.

[9] Ivan Djordjevic, William Ryan, and Bane Vasic, *Coding for Optical Channels*, Springer, New York, 2010.

[10] Joe C. Campbell, “Recent advances in telecommunications avalanche photodiodes,” Journal of Lightwave Technology, vol. 25, no. 1, pp. 109-121, Jan. 2007.

[11] David R. Goff, *Fiber Optic Reference Guide: A Practical Guide to Communications Technology*, Focal Press, Burlington, 2002.

[12] Neda Cvijetic, Stephen G. Wilson, and Maite Brandt-Pearce, “Performance bounds for free-space optical MIMO systems with APD receivers in atmospheric turbulence,” IEEE Journal on Selected Areas in Communications, vol. 26, no. 3, pp. 3-12, Apr. 2008.

[13] S. Sheikh Muhammad, T. Javornik, I. Jelovcan, E. Leitgeb, and O. Koudelka, “Reed Solomon coded PPM for terristal FSO links,” Proceeding of the 7th International Conference on Electrical Engineering (ICEE), Lahore, Pakistan, pp.1- 5, Apr. 2007.

[14] Nazmi A. Mohammed, Mohammed R. Abaza, and Moustafa H. Aly, “Improved performance of M-ary PPM in different free-space optical channels due to Reed Solomon code Using APD,” International Journal of Scientific & Engineering Research, vol. 2, no. 4, pp. 1-4, Apr. 2011.

[15] Song Gao, Anhong Dang, and Hong Guo, “Performance of wireless optical communication systems using DPSK modulation,” Proceeding of the 11th International Conference on Advanced Communication Technology (ICACT), Phoenix Park, Korea, pp. 1793-1796, Feb. 2009.

[16] Nestor D. Chatzidiamantis, Harilos G. Sandalidis , George K. Karagiannidis, and Michail Matthaiou, “A simple statistical model for turbulence-induced fading in free-space optical Systems,” IEEE International Conference on Communications (ICC), Cape Town, South Africa, pp. 1-5, May 2010.

[17] K. Akhavan, M. Kavehrad, and S. Jivkova, “High-speed power-efficient indoor wireless infrared communication using code combining - part I,” IEEE Transactions on Communications, vol. 50, no. 7, pp. 1098–1109, Jul. 2002.

[18] Kamran Kiasaleh, “Performance of APD-based, PPM free-space optical communication systems in atmospheric turbulence,” IEEE Transactions on Communications, vol. 53, no. 9, pp. 1455-1461, Sep. 2005.

[19] Mohammed R. Abaza and Kamran Kiasaleh, Erratum to “Performance of APD-based, PPM free-space optical communication systems in atmospheric turbulence,” IEEE Transactions on Communications, in press.

[20] Milton Abramowitz and Irene A. Stegun, *Handbook of Mathematical Functions with. Formulas, Graphs, and Mathematical Tables*, Washington, D.C., U.S. Government Printing Office, 1972.

[21] Wasiu Oyewole Popoola, "Subcarrier intensity modulated free-space optical communication systems," Doctoral Dissertation, School of Computing, Engineering and Information Sciences, Northumbria University, Newcastle, UK, Sep. 2009.

[22] Wansu Lim, Tae-Sik Cho, Changho Yun, and Kiseon Kim, “BER performance of coherent DPSK free-space optical systems with APD over turbulence channels,” Proceeding of the 14th OptoElectronics and Communications Conference (OECC), Hong Kong, China, pp. 1-2, Aug. 2009.

[23] Jagtar Singh and V.KJain, “Performance analysis of BPPM and M-ary PPM optical communication system in atmospheric turbulence,” IETE Technical Review, vol. 25, no. 4, pp. 145-152, July-Aug. 2008.

[24] T. Aaron Gulliver, “Matched Q-ary Reed-Solomon codes with M-ary modulation,” IEEE Transactions on Communications, vol. 45, no. 11, pp. 1349-1353, Nov. 1997.

[25] J. G. Proakis, *Digital Communications*, McGraw-Hill, New York, 1983.

[26] Konstantinos Spyridis and Clark Robertson, “Performance simulation and analysis of M-ary frequency-shift keying with Reed Solomon encoding, coherent demodulation, and hybrid soft decision-hard decision decoding,” Proceeding of the Military Communications Conference (MILCOM 2010), San Jose, USA, pp. 694-699, Nov. 2010.

[27] Murat Uysal and Jing Li, “BER performance of coded free-space optical links over strong turbulence channels,” Proceeding of the 59th Vehicular Technology Conference (VTC), Milan, Italy, pp. 352-356, May 2004.

[28] Kamran Kiasaleh, “Turbo-coded optical PPM communication systems,” Journal of Lightwave Technol., vol. 16, no. 1, pp. 18–26, Jan. 1998.