DOI: 10.3969/j. issn. 1673-5188. 2016. 02. 005
http://www.cnki.net/kcms/detail/34.1294.TN.20160329.1051.002.html, published online March 29, 2016

LDPC Decoding for Signal Dependent Visible Light Communication Channels

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Abstract

Avalanche photodiodes (APD) are widely employed in visible light communication (VLC) systems. The general signal dependent Gaussian channel is investigated. Experiment results reveal that symbols on different constellation points under official illuminance inevitably suffer from different levels of noise due to the multiplication process of APDs. In such a case, conventional log likely-hood ratio (LLR) calculation for signal independent channels may cause performance loss. The optimal LLR calculation for decoder is then derived because of the existence of non-ignorable APD shot noise. To find the decoding thresholds of the optimal and suboptimal detection schemes, the extrinsic information transfer (EXIT) chat is further analyzed. Finally a modified minimum sum algorithm is suggested with reduced complexity and acceptable performance loss. Numerical simulations show that, with a regular (3, 6) low-density parity check (LDPC) code of block length 20,000, 0.7 dB gain is achieved with our proposed scheme over the LDPC decoder designed for signal independent noise. It is also found that the coding performance is improved for a larger modulation depth.

Keywords

VLC; APD; shot noise; LDPC code

1 Introduction

Visible light communication (VLC) is an integrated dual-purpose technology to provide general lighting and high speed communications simultaneously [1]–[3]. Avalanche photodiode (APD), as one of photo detectors (PD), is widely employed in VLC due to its high sensitivity, high internal gain and wide bandwidth [4].

Different from the signal independent noise in radio frequency (RF) systems, noise in VLC systems is often signal dependent. Incident light induced PD shot noise is one of major noise sources in VLC, since a VLC system should provide ample illumination for general lighting. Moreover, the intensity of visible light is modulated by the information symbols in VLC. Therefore, symbols on distinct constellation points are contaminated by different noise levels, especially for transceivers adopting APD devices.

The impact of the shot noise on image processing has been well studied. Based on the inner correlative information of the sources, a locally adaptive DCT filtering method was proposed in [5]. The authors in [6] suggested to take the advantage of correlation of adjacent data. Arsenault et al. in [7] presented a square root method to transform the probability density function (PDF) of signal dependent Gaussian noise into that of approximately signal-independent Gaussian noise. The authors in [8] also tried maximum a-posterior estimation and maximum likelihood estimation to minimize the mean-square estimation error.

The existing works seldom considered the impact of shot noise on VLC systems. In [9], the author presented the capacity results of signal dependent Gaussian noise (SDGN) channels in higher and lower power regions, respectively. In our work, we consider an VLC transceiver encoded by an low-density parity check (LDPC) code [10] with on-off keying (OOK) modulation. A general SDGN channel model is established based on experimental results, which is different from the model proposed in [11], [12] for free space optical channel. We also discuss the optimal log likely-hood ratio (LLR) input for the belief propagation (BP) decoding algorithm in this paper. For the more practical minimum sum (MS) algorithm, we proposes an approximate LLR calculation to decrease the computational complexity and meanwhile increase the robustness. We also present the extrinsic information transfer (EXIT) chart decoding threshold analysis to assist the Monte Carlo simulation [13].

The remainder of this paper is organized as follows. In Section 2, a general SDGN channel model is investigated. Then

This work was supported by "973" project (No. 2013CB329204) and the National Natural Science Foundation of China (No. 61223001, No. 61461136003, and No. 61571118).

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we derive the optimal and approximated LLR for the BP and MS algorithms, respectively, in Section 3. The experimental and numerical simulation results are presented in Section 4 before the conclusions in Section 5.

2 System Model

Fig. 1 illustrates our experimental VLC transceiver. In this work, the information stream is first encoded by an LDPC code. The coded bits are then mapped to 2-PAM symbols with unit amplitude. Before the beam is amplified and superposed on proper offset, it is pre-equalized to mitigate the inter-symbol interference of LED chips [14]. Thus the optical signal x sent by LED can be written as

$$x=\beta(A_s s+I_s) \tag{1}$$

where A_s is the amplitude of symbol set by the power amplifier, I_b is the offset to turn on LED as well as to adjust the luminance, and β is the electro-optical coefficient. Accordingly, the modulation depth m is defined as $A_s/I_b \leqslant 1$.

At the receiver, following the APD optical-electro conversion, signals are enhanced by the trans-impedance amplifier (TIA) and the post amplifier. Then the symbol for detector can be expressed as

$$y=h\cdot x+n \tag{2}$$

where h represents the channel gain including the optical channel gain, the APD optical-electro coefficient and gain, etc.

In the perspective of noise source, noise n consists of thermal noise and incident light induced shot noise. Generally, dual-purpose illumination light and ambient light are two main sources of shot noise. Furthermore, since the incident visible light is broad-wavelength with ample lighting, the PDF of shot noise can approach Gaussian distribution [9], [15]. Accordingly, the variance of shot noise is proportional to the photocurrent I induced by incident light:

$$\sigma_s^2=\underbrace{2qBMF}_{\gamma}\cdot I \tag{3}$$

where q is the electron charge, B is the system bandwidth, F is the excess noise factor of APD, and M is the multiplicative ratio or gain of APD. Consequently, n can be formulated as

$$n=n_{sd}+\underbrace{\sqrt{\gamma I_a}\cdot n_a+\sigma_t\cdot n_t}_{n_{si}} \tag{4}$$

On the other hand, in the perspective of detection, the noise may be repartitioned as a signal dependent part $n_{sd}\sim N(0,\sigma_{sd})$ and a signal independent part $n_{si}\sim N(0,\sigma_{si})$. n_{si} comprises n_a and n_t, the independent Gaussian random variables for the ambient light (assumed isotropic) induced shot noise and thermal noise, respectively. The variances are the corresponding weighted factors in (4), where I_a is the photocurrent induced by ambient light and σ_t^2 is the variance of thermal noise.

Known from (3) and (2), the variance of signal dependent noise n_{sd} is proportional to transmit signal x:

$$\sigma_{sd}^2=\gamma\cdot\underbrace{h\cdot x}_{I_{sd}} \tag{5}$$

where $h\cdot x$ is actually the photocurrent I_{sd} induced by incident signal light x.

Applying (5) and (1), we obtain the averaged variance of signal dependent noise:

$$\bar{\sigma}_{sd}^2=\mathrm{E}_s\left(\sigma_{sd}^2\right)=h\gamma\beta I_b \tag{6}$$

Clearly, the averaged variance of signal dependent noise is irrelevant to instantaneous data signal value x.

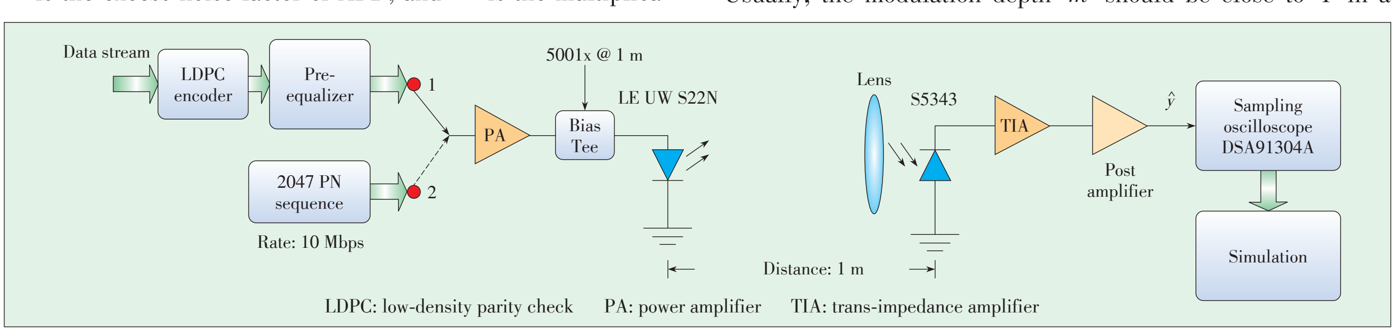
For convenience, we define a parameter f to indicate the ratio of the averaged variance of signal dependent noise to the variance of signal independent noise:

$$f\triangleq\frac{\bar{\sigma}_{sd}^2}{\sigma_{si}^2} \tag{7}$$

In this way, given the averaged variance of received noise $\sigma_n^2=\bar{\sigma}_{sd}^2+\sigma_{si}^2$, we could easily evaluate the instantaneous noise variance $\sigma_r^2=\kappa_r\sigma_n^2, r=0,1$ at different constellation points:

$$\begin{cases}\kappa_0=1+\dfrac{fm}{1+f}, & s=+1\,;\\[2mm] \kappa_1=1-\dfrac{fm}{1+f}, & s=-1\,,\end{cases} \tag{8}$$

Usually, the modulation depth m should be close to 1 in a



▲**Figure 1. VLC system with OOK modulation. Switch to 1 for general transmission with LDPC channel coding; switch to 2 for SDGN VLC channel model verification.**

power efficient VLC system. When the channel is thermal noise dominated, e.g., $f \to 0$, $\kappa_0 \approx \kappa_1$, we define it as signal independent Gaussian noise (SIGN) channel. On the other hand, when shot noise is strong enough, e.g., $f \gg 0$, $\kappa_0 > \kappa_1$, we define it as signal dependent Gaussian noise (SDGN) channel. Our experiment shows that, in the absence of ambient light, at 500 lux luminance, $f \approx 2.7$; and at 1000 lux luminance, $f \approx 3$. These results indicate that, different from widely adopted SIGN channel model, the VLC channel is actually a SDGN channel. Therefore, the following signal detection and channel decoding algorithm should fully consider the impact of SDGN.

3 Analysis of Detection and Decoding

Optimal and sub-optimal detection strategies are used to calculate the LLR.

The optimal one takes the shot noise into account and is formulated as:

$$\Lambda_{opt} = \frac{1}{2}\log\frac{\kappa_1}{\kappa_0} + \frac{1}{2\sigma_n^2}\left[\frac{\left(y+h\beta A_s\right)^2}{\kappa_1} - \frac{\left(y-h\beta A_s\right)^2}{\kappa_0}\right] \quad (9)$$

where y is the alternating part of received signal $\hat{y}$.

The sub-optimal one is to ignore the shot noise and treat the SDGN channel as the conventional SIGN channel. The corresponding LLR is expressed as:

$$\Lambda_{sub} = \log\frac{\frac{1}{\sqrt{2\pi}\,\sigma_n}\exp\left(-\frac{\left(y-h\beta A_s\right)^2}{2\sigma_n^2}\right)}{\frac{1}{\sqrt{2\pi}\,\sigma_n}\exp\left(-\frac{\left(y+h\beta A_s\right)^2}{2\sigma_n^2}\right)} = \frac{2h\beta A_s y}{\sigma_n^2} \quad (10)$$

In conventional SIGN scenarios, the implementation of a LDPC decoder usually uses the MS algorithm, which only requires $\Lambda' = \Lambda \cdot \sigma^2 = 2y$ since onlythe compare procedure exists in the iterative decoding process.

Similarly, we wish to have an approximated expression Λ'_{opt} without the parameter of σ_n for the MS decoding:

$$\Lambda_{opt} \cdot 2\sigma_n^2 = \frac{1}{2}\log\frac{\kappa_1}{\kappa_0} \cdot 2\sigma_n^2 + \Lambda'_{opt} \quad (11)$$

The first term in (11), $\log\frac{\kappa_1}{\kappa_0} \cdot \sigma_n^2$, is actually ignored based on the following two factors. First, the absolute value of Λ'_{opt} is no less than 10 when the the signal to noise ratio (SNR), defined in (13), is greater than 0 dB. Second, in a reasonable range of f and m, $\log\frac{\kappa_1}{\kappa_0}$ is less than 10. Therefore, comparing to Λ'_{opt}, $\sigma_n^2 \log\frac{\kappa_1}{\kappa_0}$ is small enough to be ignored. The approximated detection is expressed as:

$$\Lambda'_{opt} = \frac{\left(y+h\beta A_s\right)^2}{\kappa_1} - \frac{\left(y-h\beta A_s\right)^2}{\kappa_0} \quad (12)$$

Besides, the correction factor α proposed in [16], [17] (usually set to 0.8 for code rate $R = 0.5$) should be considered for improving decoding performance.

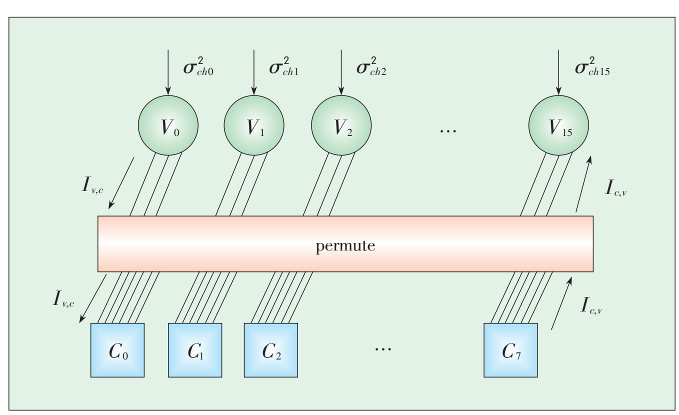
Protograph Extrinsic Information Transfer Chart (PEXIT) is a tool commonly used to evaluate the performance of a coding system. Here, PEXIT analysis [18] is used to investigate the impacts of shot noise on the performance of LDPC coded VLC systems. This method is utilized for accurate performance analysis in various scenarios such as fading channels [19] and half-duplex relay channels [20]. The calculation procedure in **Fig. 2** is similar to that in [18], except the initialization step. In this way, the convergence behavior of the LDPC decoding with different detection schemes can be evaluated by the fast numerical computation without extensive BER simulations. A lower threshold indicates that a better decoding performance can be achieved. Obviously, the gap between the decoding thresholds η_{opt} and η_{sub} varies depending on the parameters of SDGN channel.

4 Experimental and Numerical Results

In this section, we experimentally verify our proposed VLC SDGN channel model. Then, the BER performance of the SDGN channel is compared with that designed for the SIGN channel. The SDGN channel parameters, the modulation depth m and the power ratio f, are investigated from the perspective of decoding threshold with EXIT charts. The performance of the proposed modified MS algorithm is also evaluated.

4.1 The Experiment

To simulate the illuminance in the office, we adjust the bias current to keep the luminance at the receiver around 500 lux. Then a pilot sequence with length of 2047 at 10 Mbps symbol rate, which is much less than the channel bandwidth, is sent to estimate the shot noise variances at different OOK constella-



▲Figure 2. PEXIT calculation procedure.

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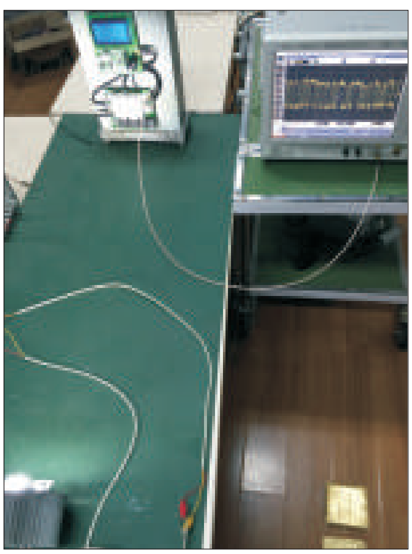
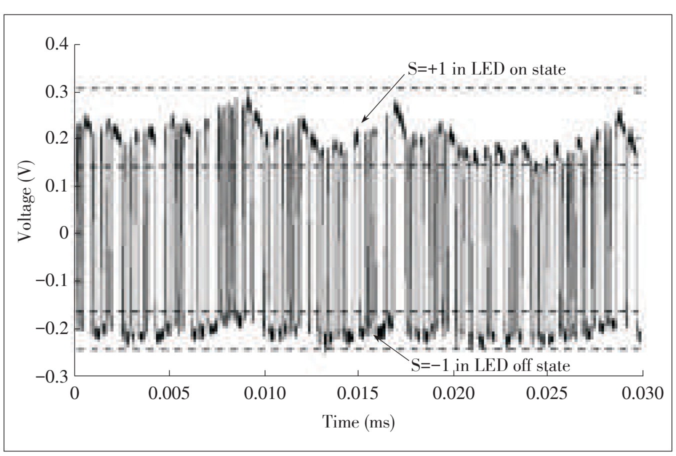
tions. After a proper amplification, the received signals are sampled at the rate of 200 Mbps with Agilent T&M DSA91304A. The detailed verification setup is shown in Fig. 1 and the physical platform is in **Fig. 3**.

Fig. 4 shows the sampled alternating current (AC) waveform of received pilot sequences. According to the previous OOK mapping rules, symbol 0 is mapped to constellation $s = +1$, representing LED on state, and symbol 1 is mapped to constellation $s = -1$, representing LED off state. Known from (8), the induced shot noise for symbol 0 is larger than symbol 1. It is obvious that the amplitude fluctuations at $s=+1$ are much larger than those at $s=-1$, which is consistent with the SDGN channel model.

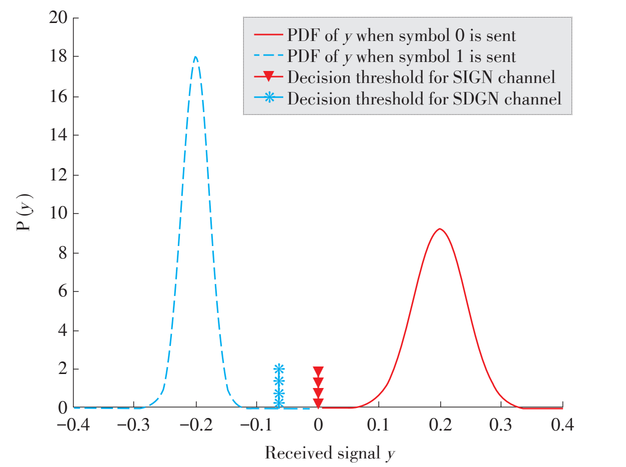
In **Fig. 5**, the corresponding conditional PDF of symbol 0 and symbol 1 are plotted, respectively. We also give the corresponding hard decision thresholds for the SIGN channel and SDGN channel. The well-known hard decision threshold for SIGN channel is 0. While the expression of hard decision threshold for SDGN channel is generally complicated, which depends on lots of parameters and can be evaluated with the MAP rule [21] if all the parameters have been known at the receiver.



◀Figure 3. Platform for SDGN VLC channel model verification.



▲Figure 4. AC part of amplified received signals.



PDF: probability density function
SDGN: signal dependent Gaussian noise
SIGN: signal independent Gaussian noise

▲Figure 5. The corresponding conditional PDF of symbol 0 and symbol 1 over the SDGN channel.

Based on our evaluation, the power ratio $f \approx 1.4$ in our experimental system is under 500 lux luminance in presence of ambient lights, smaller than that in absence of ambient lights. These results will be applied in our next numerical decoding simulation for performance evaluations.

4.2 LDPC Decoding Performance Evaluations

Before starting our simulation, we would like to define SNR as:

$$\frac{E_b}{N_0} = \frac{(\mu_0 + I_b)^2 + (\mu_1 + I_b)^2}{2R(\sigma_0^2 + \sigma_1^2)}, \tag{13}$$

where R is the LDPC code rate. This definition can be applied to both SDGN and SIGN channels. A regular (3, 6) LDPC code of block length 20 k is used in the decoding simulation. The maximum number of iterations for both the BP and MS algorithms is set to 100.

Fig. 6 shows the BER results of BP decoding using different detection schemes. The parameters m and f for SDGN channel are set to be 1 and 1.4 according to the previous measurements. The simulation results indicate that the iterative decoding with optimal detection for the SDGN channel achieves the best performance. The gain results from two factors. First, due to the shot noise, half of symbols are contaminated by noises with larger power, and the remaining symbols are with lower noise power. With the iterative channel decoding, these symbols help eliminate the errors by symbols with higher noise power. Second, the optimal detection scheme obtains the accurate LLR for the SDGN channel. Therefore, the shot noise component should be properly considered on the SDGN VLC chan-

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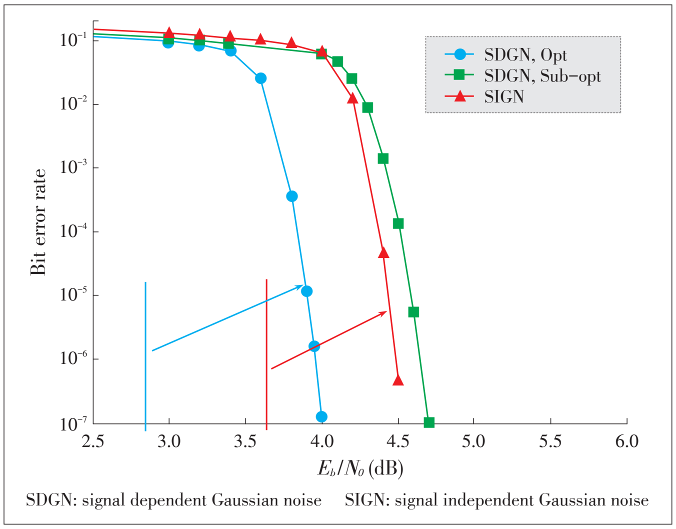
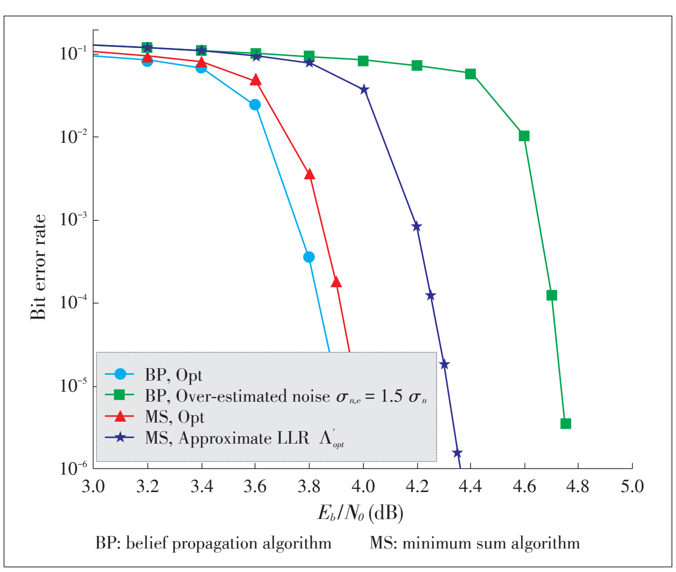


▲Figure 6. Simulation results with SDGN channel and SIGN channel, where *m* = 1; *f* = 1:4.

nel.

The two vertical lines in Fig. 6 represent the numerical decoding thresholds with optimal and sub-optimal detection schemes on the SDGN channel, respectively. As mentioned before, the PEXIT chart is used to evaluate the performance alongside the decoding simulation. Clearly, the BER performances are quite consistent with the corresponding thresholds, indicating that the numerical thresholds calculated by PEXIT charts can reliably predict the decoding performance with different detection schemes.

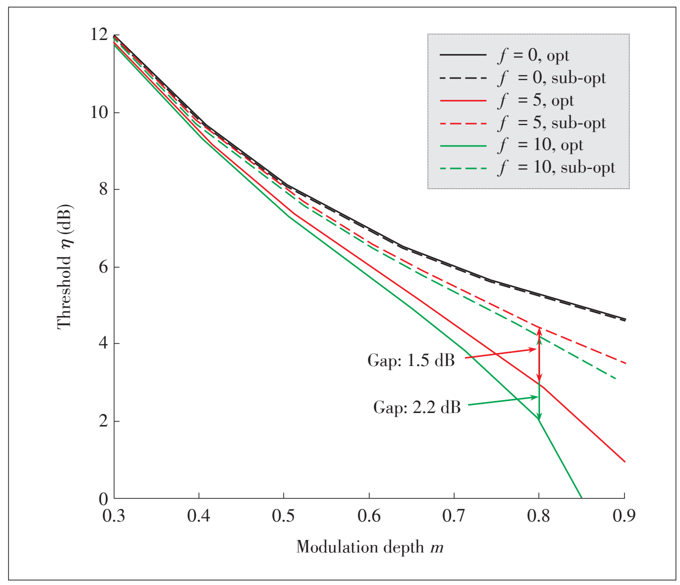
The MS algorithm has a little poorer performance than the BP algorithm (**Fig. 7**). Decoding with the approximated LLR from (12), the gap will be widen to about 0.4 dB. However, decoding performance with optimal detection is sensitive to the



▲Figure 7. BP and MS decoding simulation results with SDGN channel, where *m* = 1; *f* = 1:4.

error of σ_n. The performance of the BP algorithm with an over-estimated $\sigma_{n,e} = 1.5\sigma_n$ is obviously worse than the MS algorithm using approximation LLR without the need of estimating σ_n. It is worthwhile to reduce the detection and decoding complexity and increase the robustness by sacrificing some performance.

Fig. 8 shows the effects of changing the noise power ratio f and the modulation depth m from the perspective of decoding thresholds. The decoding threshold decreases when the



▲Figure 8. The decoding threshold of optimal and sub-optimal detection on the SDGN channel, where different channel parameters are specified.

channel parameter m or f increases. The difference between the thresholds is small at rather low modulation depth since the amplitudes of bit 0 and bit 1 tend to be equal when m goes to zero. In a specific VLC system, the modulation depth m is usually predetermined and fixed, in which case a large noise power ratio f contributes to better performance for the optimal detection scheme. This means higher performance gain can be achieved by the optimized detection scheme with lower thermal and background noise level at the APD receiver.

5 Conclusions

In this paper, we investigate the shot noise of VLC systems employing APD. A general signal dependent Gaussian noise channel is discussed. We present the accurate and approximated LLR evaluation on the SDGN channel for the decoding of LDPC code, respectively. The numerical results demonstrate that our proposed scheme achieves better performance than traditional schemes designed for the SIGN channel. 0.7 dB gain is achieved at the BER of 10^{-6} when the modulation depth equals 1 and the noise power ratio equals 1.4. The proposed system performance could be further improved by increasing

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the modulation depth of power amplifier circuit and decreasing the thermal noise in the TIA circuit.

References

[1] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 Gbit/s visible optical wireless transmission based on RGB LED," *Optics Express*, vol. 20, no. 26, pp. B501–B506, 2012. doi: 10.1364/OE.20.00B501.

[2] A. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, "1-Gb/s transmission over a phosphorescent white LED by using rate-Adaptive discrete multitone modulation," *IEEE Photonics Journal*, vol. 4, no. 5, pp. 1465–1473, 2012. doi: 10.1109/JPHOT.2012.2210397.

[3] J. Vǔcić, C. Kottke, S. Nerreter, K.-D. Langer, and J. W. Walewski, "513 Mbit/s visible light communications link based on DMT-modulation of a white LED," *Journal of Lightwave Technology*, vol. 28, no. 24, pp. 3512–3518, 2010. doi: 10.1109/JLT.2010.2089602.

[4] S. Morris and H. S. Shin, "Optimal communication," *Journal of the European Economic Association*, vol. 5, no. 2-3, pp. 594-602, 2007. doi: 10.1162/jeea.2007.5.2-3.594.

[5] R. öktem, K. Egiazarian, V. V. Lukin, N. N. Ponomarenko, and O. V. Tsymbal, "Locally adaptive DCT filtering for signal-dependent noise removal," *EURASIP Journal on Advances in Signal Processing*, vol. 2007, no. 1, p. 042472, 2007. doi: 10.1155/2007/42472.

[6] K. Hirakawa and T. W. Parks, "Image denoising for signal-dependent noise," in *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing*, Philadelphia, USA, 2005, pp. 29–32. doi: 10.1109/ICASSP.2005.1415333.

[7] H. Arsenault, C. Gendron, and M. Denis, "Transformation of film-grain noise into signal-independent additive Gaussian noise," *Journal of the Optical Society of America*, vol. 71, no. 1, pp. 91–94, 1981. doi:10.1364/JOSA.71.000091.

[8] G. K. Froehlich, J. F. Walkup, and R. B. Asher, "Optimal estimation in signal-dependent noise," *Journal of the Optical Society of America*, vol. 68, no. 12, pp. 1665–1672, 1978. doi:10.1364/JOSA.68.001665.

[9] S. M. Moser, "Capacity results of an optical intensity channel with input-dependent Gaussian noise," *IEEE Transactions on Information Theory*, vol. 58, no. 1, pp. 207–223, 2012. doi:10.1109/TIT.2011.2169541.

[10] T. J. Richardson and R. L. Urbanke, "The capacity of low-density parity-check codes under message-passing decoding," *IEEE Transactions on Information Theory*, vol. 47, no. 2, pp. 599–618, 2001. doi:10.1109/18.910577.

[11] M. N. Khan and W. G. Cowley, "Signal dependent Gaussian noise model for FSO communications," in *Proc. IEEE AusCTW.*, Melbourne, Australia, 2011, pp. 142–147. doi:10.1109/AUSCTW.2011.5728752.

[12] M. N. Khan, "Importance of noise models in FSO communications," *EURASIP Journal on Wireless Communications and Networking*, vol. 2014, no. 1, pp. 1–10, 2014. doi:10.1186/1687-1499-2014-102.

[13] S. ten Brink, G. Kramer, and A. Ashikhmin, "Design of low-density parity-check codes for modulation and detection," *IEEE Transactions on Communications*, vol. 52, no. 4, pp. 670–678, 2004. doi:10.1109/TCOMM.2004.826370.

[14] L. Zeng, D. O'Brien, H. Le-Minh, K. Lee, D. Jung, and Y. Oh, "Improvement of date rate by using equalization in an indoor visible light communication system," in *Proc. IEEE ICCSC*, Shanghai, China, May 2008, pp. 678-682. doi: 10.1109/ICCSC.2008.149.

[15] J. Kahn and J. Barry, "Wireless infrared communications," *Proc. IEEE*, vol. 85, no. 2, pp. 265–298, 1997. doi:10.1007/978-1-4615-2700-8.

[16] J. Chen and M. Fossorier, "Near optimum universal belief propagation based decoding of low-density parity check codes," *IEEE Transactions on Communications*, vol. 50, no. 3, pp. 406–414, 2002. doi:10.1109/26.990903.

[17] J. Heo and K. Chugg, "Optimization of scaling soft information in iterative decoding via density evolution methods," *IEEE Transactions on Communications*, vol. 53, no. 6, pp. 957–961, 2005. doi:10.1109/TCOMM.2005.849782.

[18] G. Liva and M. Chiani, "Protograph LDPC codes design based on exit analysis," in *Proc. IEEE GLOBECOM.*, Washington, USA, 2007, pp. 3250-3254. doi:10.1109/GLOCOM.2007.616.

[19] T. V. Nguyen, A. Nosratinia, and D. Divsalar, "Threshold of protograph-based LDPC coded BICM for rayleigh fading," in *Proc. IEEE GLOBECOM.*, Houston, USA, 2011, pp. 1–5. doi:10.1109/GLOCOM.2011.6133952.

[20] T. V. Nguyen, A. Nosratinia, and D. Divsalar, "Bilayer protograph codes for half-duplex relay channels," *IEEE Transactions on Wireless Communications* , vol. 12, no. 5, pp. 1969–1977, 2013. doi:10.1109/TWC.2013.040413.111745.

[21] H. L. Van Trees, *Detection, estimation, and modulation theory*. Hoboken, USA: John Wiley & Sons, 2004. doi:10.1002/0471221082.

Manuscript received: 2015-11-17

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