Enhancing the decoding performance of optical wireless communication systems using receiver-side predistortion

Qi Wang,[1] **Zhaocheng Wang,**[1] **Sheng Chen,**[2,3] **and Lajos Hanzo**[2,*]

[1] *Tsinghua National Laboratory for Information Science and Technology (TNList), Department of Electronic Engineering, Tsinghua University, Beijing 100084, China*
[2] *Electronics and Computer Science, University of Southampton, Southampton SO17 1BJ, UK*
[3] *King Abdulaziz University, Jeddah 21589, Saudi Arabia*

[*] *lh@ecs.soton.ac.uk*

Abstract: White light emitting diodes (LEDs) have been widely utilized for illumination owing to their desired properties of inherent bright output, high efficiency, low power consumption and long life-time. They are also increasingly applied in optical wireless communications for realizing high data rate transmission. This paper presents an improved scheme relying on the insertion of a simple predistortion module before the decoder at the receiver of optical wireless communication systems that use white LEDs. The proposed predistortion scheme exploits the inherent nature of mixing the three unequal optical-power primary colours in generating white light to enhance the system's performance. Specifically, we design this predistortion module by minimizing the upper bound of the error probability in conjunction with a soft-decision decoder. Our simulation results demonstrate that the detection performance is considerably improved with the aid of the proposed predistortion module.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications; (040.0040) Detectors.

References and links

1. IEEE Std. 802.15.7-2011, Part 15.7: Short-Range Wireless Optical Communication Using Visible Light (2011).
2. R. Wang, J. Y. Duan, A. C. Shi, Y. J. Wang, and Y. L. Liu, "Indoor optical wireless communication system utilizing white LED lights," in *APCC* (2009), pp. 617–621.
3. D. W. K. Wong and G. Chen, "Optical design and multipath analysis for broadband optical wireless in an aircraft passenger cabin application," IEEE Trans. Veh. Technol. **57**(6), 3598–3606 (2008).
4. M. D. Higgins, R. J. Green, and M. S. Leeson, "Optical wireless for intravehicle communications: a channel viability analysis," IEEE Trans. Veh. Technol. **61**(1), 123–129 (2012).
5. A. M. 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 J. **4**(5), 1465–1473 (2012).
6. G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 Gbit/s visible optical wireless transmission based on RGB LED," Opt. Express **20**(26), B501–B506 (2012).
7. F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, and K. Huang, "3.22-Gb/s WDM visible light communication of a single RGB LED employing carrier-less amplitude and phase modulation," in *OFC/NFOEC* (2013), OTh1G.4.
8. N. Fujimoto and H. Mochizuki, "477 Mbit/s visible light transmission based on OOK-NRZ modulation using a single commercially available visible LED and a practical LED driver with a pre-emphasis circuit," in *OFC/NFOEC* (2013), JTh2A.73.

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

9. Y. Tanaka, T. Komine, S. Haruyama, and M. Nakagawa, “Indoor visible light data transmission system utilizing white LED lights,” IEICE Trans. Commun. **E86-B**(8), 2440–2454 (2003).
10. J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. (McGraw-Hill, 2008).
11. J. M. Kahn and J. R. Barry, “Wireless infrared communications,” Proc. IEEE **85**(2), 265–298 (1997).
12. X. Zhu and J. M. Kahn, “Free-space optical communication through atmospheric turbulence channels,” IEEE Trans. Commun. **50**(8), 1293–1300 (2002).
13. A. J. Viterbi, “Convolutional codes and their performance in communication systems,” IEEE Trans. Commun. Technol. **19**(5), 751–772 (1971).
14. T. Komine, J. H. Lee, S. Haruyama, and M. Nakagawa, “Adaptive equalization system for visible light wireless communication utilizing multiple white LED lighting equipment,” IEEE Trans. Wireless Commun. **8**(6), 2892–2900 (2009).
15. D. J. C. MacKay, “Good error-correcting codes based on very sparse matrices,” IEEE Trans. Inf. Theory **45**(2), 399–431 (1999).
16. L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, “Optimal decoding of linear codes for minimizing symbol error rate,” IEEE Trans. Inf. Theory **20**(2), 284–287(1974).
17. IEEE Std. 802.11-2012, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications (2012).
18. 3GPP2 C.S0002-F v1.0, Physical Layer Standard for cdma2000 Spread Spectrum Systems (2012).

1. Introduction

White light emitting diodes (LEDs) have emerged as a promising technology to replace incandescent or fluorescent lights for illumination owing to their inherent benefits of bright output, high efficiency, high tolerance to humidity, low power consumption, and long life-time. LEDs are also increasingly applied to indoor and intra-vehicle optical wireless communications due to their attractive features of fast switching, low cost, and broad bandwidth [1–4]. The visible light emitted by LEDs can be modulated and encoded to carry a high-rate data while the main role of illumination remains unaltered, because the blinking rate of modulated light waves is far beyond the fusion frequency of the human eye. The optical pulses transmitted by the LED lights can be detected by photodiodes (PDs) or avalanche photodiodes (APDs). Gigabit wireless transmissions have been achieved by using white LED lights [5–7].

Generally, white LEDs are classified into two types, namely, single-chip LEDs and RGB-type LEDs. Single-chip LEDs use a single blue LED that excites yellow phosphor to create white light emission. A 477 Mbps system was implemented using single-chip white LEDs and on-off-keying (OOK) modulation [8], while the transmission rate can be increased to 1 Gbps by rate-adaptive discrete multi-tone (DMT) modulation [5]. However, the slow response of the phosphor in the single-chip LEDs limits the modulation bandwidth, whereas the power efficiency is reduced when combined with a blue filter in order to reject the phosphorescent components. By contrast, RGB-type LEDs combine the lights from the LEDs of three primary colours, which are red, green and blue, and these three LEDs emit their corresponding coloured lights simultaneously. RGB-type LEDs are more desirable than single-chip LEDs for the sake of enhancing the transmission rate, since their three wavelengths can be used to carry multiple data streams independently, thus offering a wavelength division multiplexing (WDM) capability. Recently, a 3.4 Gbps transmission rate has been achieved using RGB-type white LEDs and DMT modulation [6].

White light may be synthesised as a combination of three primary colours with unequal optical powers. Intriguingly, the human eye exhibits wavelength selectivity [9] and for the sake of illumination comfort, the white light emitted by RGB-type white LEDs should be closely matched to the light emitted by fluorescent bulbs, which is the mixture of the three primary colours each having an inherently different emitted optical power. At the receiver, the conversion efficiency between the optical and electronic signals is also different for each primary colour. Therefore, the signal power received from each optical to electronic (O/E) converter corresponding to each primary colour is different. Consequently, the achievable system performance is limited by the weakest received signal. Moreover, since convolutional codes, Reed-Solomon codes, turbo codes or low density parity check (LDPC) codes are widely adopted in practice as the forward error correction (FEC) mechanism [10] to improve the system's performance. However, having different reliabilities for the three received signals will degrade the performance of soft-decision decoder, which will be dominated by the least reliable component.

In this contribution, a novel scheme is proposed for improving the performance of the soft-decision decoder by introducing a simple predistortion module before the decoder, which significantly enhances the achievable performance of the optical wireless communication system utilizing white LEDs. The basic idea of the proposed predistortion module is that a more reliable received signal should contribute more to both the branch- and path-metric calculation in the soft-decision decoding process, while a less reliable received signal should have a de-weighted contribution in the soft-decision decoding process. More specifically, the proposed predistortion module applies different weights to the received signals corresponding to the three primary colours, where the specific weighting factors are designed for minimizing the union upper bound of the error probability for the soft-decision decoder. Our simulation results confirm that this predistortion scheme significantly improves the achievable decoding performance.

The remainder of this paper is organized as follows. In Section 2, the optical wireless communication system utilizing white LEDs is presented, while in Section 3, the proposed predistortion module is described and its performance is analyzed theoretically. In Section 4, the performance of the systems with and without the proposed predistortion module are compared via simulations, and our conclusions are drawn in Section 5.

2. System model

A typical optical wireless communication system using RGB-type white LEDs is shown in Fig. 1, apart from the proposed predistortion block. At the transmitter, the information bits are encoded by the channel encoder. The coded bits are then serial to parallel (S/P) converted into three streams and each bit-stream is sent to the chip of a primary colour LED for modulation. Due to the complexity associated with phase or frequency modulation, current optical wireless communication systems typically use intensity modulation with direct detection (IM/DD), such as OOK, pulse-position modulation (PPM) and subcarrier modulation [11]. Since OOK modulation is the most widely used scheme owing to its simplicity, we consider the OOK modulation scheme in this paper. The modulated optical signals of the three primary colour LEDs are mixed using the specific optical power mixing ratio to produce white light, which is emitted into the

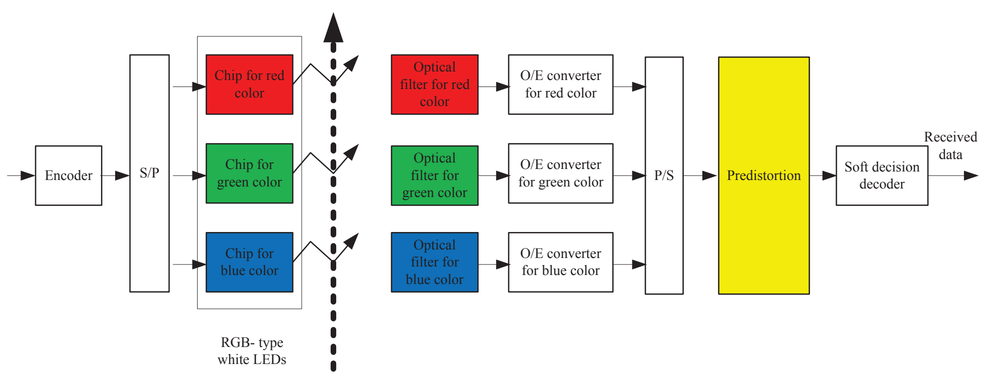

Fig. 1. Optical wireless communication system using RGB-type white LEDs with the proposed predistortion module inserted before the decoder at receiver.

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

air. At the receiver, the optical filters tuned for the three primary colours attenuate the ambient light and separate the three primary colour signals. The optical signals are then converted to their electronic counterparts by the O/E converters. The three received electronic signals are then parallel to serial (P/S) converted into the single signal stream which is used as the input to the soft-decision decoder.

Table 1. Combination of three primary colours and the corresponding optical power mixing ratio $M_r : M_g : M_b$ for emitting white light [9].

Type	Red	Green	Blue
1. Wavelength (nm)	600	555	480
Mixture ratio	1	0.89	2.51
2. Wavelength (nm)	610	555	475
Mixture ratio	1	1.43	2.29
3. Wavelength (nm)	610	555	450
Mixture ratio	1	2.62	1.96
4. Wavelength (nm)	610	565	450
Mixture ratio	1	11.17	7.19

Efficient illumination is always treated as the first priority for white LEDs. Therefore, when using white LEDs for optical wireless data transmission, it is important to ensure that the white light is produced by using the appropriate optical power mixing ratio of the three primary colours. Let us denote the optical powers emitted from the red, green and blue LEDs by M_r, M_g and M_b, respectively. In [9] four combinations of the optical power mixing ratio $M_r : M_g : M_b$ were defined for the sake of emitting the white light. The corresponding wavelengths and the weighting factors of the three primary colours are listed in Table 1. Clearly, the three primary colours must have unequal optical emitted powers for producing white light. According to [12], the O/E conversion efficiency η is calculated as

$$\eta = \gamma \frac{e\lambda}{hc}, \tag{1}$$

where γ is the quantum efficiency of the photo detector, e is the electron charge, λ is the signal wavelength, h is Plank's constant, and c is the speed of light. For different colours, both the wavelengths and the quantum efficiencies of the photo detector are different. Therefore, the conversion efficiencies between the optical and electronic signals are also different for the three primary colours, which are defined as η_r, η_g and η_b for the red, green and blue colours, respectively. The amplitude of the electronic signal at the receiver is proportional to the intensity of the received light. If we denote the electronic energies received per symbol from the red, green and blue LEDs as E_r, E_g and E_b, respectively, it becomes clear that we have

$$\sqrt{E_r} : \sqrt{E_g} : \sqrt{E_b} = M_r\eta_r : M_g\eta_g : M_b\eta_b. \tag{2}$$

Since the energies of the electronic signals received from different LEDs are not equal, the reliability of the signal received from each O/E converter corresponding to each primary colour is also different, and this is known to impose a performance degradation on the soft-decision decoder at the receiver.

3. Proposed predistortion module

Our proposed predistortion module is inserted before the decoder, as shown in Fig. 1, in order to "predistort" the received signal before it is passed to the soft-decision decoder. Let us denote the electronic signal received from the P/S converter as $r(t)$, which is formed by the serially concatenated signals gleaned from the red, green and blue colour O/E converters. The different weighting factors of the predistortion block for the red, green and blue signals are denoted as F_r, F_g and F_b, respectively. The output signal $r'(t)$ of the predistortion block is then given by

$$r'(t) = \begin{cases} r(t)\cdot F_r, & r(t) \in \text{red light;} \\ r(t)\cdot F_g, & r(t) \in \text{green light;} \\ r(t)\cdot F_b, & r(t) \in \text{blue light.} \end{cases} \tag{3}$$

The basic objective of predistortion is to assign a more reliable signal a higher weight and a less reliable signal a lower weight, in order to assist the decoding process. However, the weighting factors of the predistortion block must be carefully selected to optimize the achievable system performance.

We consider a classic convolutional code as an example. When the soft-decision Viterbi decoder [13] is used, a common technique of estimating the attainable performance of the decoder is to use the union upper bound of the first event error probability, which is given by [10]

$$P_e \leq \sum_{d=d_{free}}^{\infty} n_d P_d, \tag{4}$$

where d_{free} is the free distance of the convolutional code, n_d denotes the number of trellis-paths having a distance d from the all-zero path that merge with the all-zero path for the first time and P_d represents the pairwise error probability. Furthermore, n_d is the coefficient of the polynomial $T(B,D)|_{B=1}$ derived from the transfer function $T(B,D)$ [13]. The optical wireless channel may be modelled by an additive white Gaussian noise (AWGN) channel due to the line of sight user scenario of high-rate optical wireless communication systems using white LEDs [14]. For the AWGN channel having the noise power spectral density $N_0/2$, the pairwise error probability P_d for OOK modulation can be expressed as

$$P_d = Q\left(\sqrt{\frac{d\,E_s}{N_0}}\right), \tag{5}$$

where E_s denotes the energy per symbol and $Q(x)$ represents the standard tail probability of the Gaussian distribution with zero-mean and unit variance, which is given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt. \tag{6}$$

Since the energy received from each O/E converter corresponding to each primary colour is different, the overall energy of each path is also different. Thus, the union upper bound of the first event error probability in the absence of the predistortion block can be rewritten as

$$P_e \leq \sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(r_{d,k}\sqrt{E_r} + g_{d,k}\sqrt{E_g} + b_{d,k}\sqrt{E_b}\right)^2}{d\,N_0}}\right), \tag{7}$$

where k represents the kth path at a distance of d from the all-zero path that merges with the all-zero path for the first time, while the numbers of '1s' transmitted from the red, green and blue LEDs in the kth path is defined as $r_{d,k}$, $g_{d,k}$ and $b_{d,k}$, respectively. Apparently, we have $r_{d,k} + g_{d,k} + b_{d,k} = d$, and the upper bound in Eq. (7) is larger than that given in Eq. (4).

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

In order to improve the performance of the soft-decision Viterbi decoder, the predistortion block allows the more reliable signals to contribute more to both the branch- and path-metric calculation, while reducing the contribution of the less reliable signals, by weighting the three signals gleaned from the three O/E converters corresponding to the primary colours of red, green and blue with the weighting factors of F_r, F_g and F_b. The weighting changes both the desired signal energy and the noise power gleaned from each O/E converter simultaneously and proportionally to the squared value of the weight applied, and therefore the union upper bound of the first event error probability can be expressed as

$$P_e \leq \sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(r_{d,k}F_r\sqrt{E_r}+g_{d,k}F_g\sqrt{E_g}+b_{d,k}F_b\sqrt{E_b}\right)^2}{\left(r_{d,k}F_r^2+g_{d,k}F_g^2+b_{d,k}F_b^2\right)N_0}}\right). \tag{8}$$

Based on Cauchy-Schwarz inequality, the union upper bound in Eq. (8) is minimized as follows

$$\begin{aligned}
&\sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(r_{d,k}F_r\sqrt{E_r}+g_{d,k}F_g\sqrt{E_g}+b_{d,k}F_b\sqrt{E_b}\right)^2}{\left(r_{d,k}F_r^2+g_{d,k}F_g^2+b_{d,k}F_b^2\right)N_0}}\right)\\
&=\sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(\sqrt{r_{d,k}}F_r\cdot\sqrt{r_{d,k}E_r}+\sqrt{g_{d,k}}F_g\cdot\sqrt{g_{d,k}E_g}+\sqrt{b_{d,k}}F_b\cdot\sqrt{b_{d,k}E_b}\right)^2}{\left(r_{d,k}F_r^2+g_{d,k}F_g^2+b_{d,k}F_b^2\right)N_0}}\right)\\
&\geq\sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(r_{d,k}F_r^2+g_{d,k}F_g^2+b_{d,k}F_b^2\right)\cdot\left(r_{d,k}E_r+g_{d,k}E_r+b_{d,k}E_r\right)}{\left(r_{d,k}F_r^2+g_{d,k}F_g^2+b_{d,k}F_b^2\right)N_0}}\right)\\
&=\sum_{d=d_{free}}^{\infty} \sum_{k=1}^{n_d} Q\left(\sqrt{\frac{\left(r_{d,k}E_r+g_{d,k}E_r+b_{d,k}E_r\right)}{N_0}}\right),
\end{aligned} \tag{9}$$

where the last equality holds only when we have

$$F_r : F_g : F_b = \sqrt{E_r} : \sqrt{E_g} : \sqrt{E_b}. \tag{10}$$

Furthermore, the average energy per symbol after the predistortion block should remain unchanged, and this requires that

$$F_r^2 + F_g^2 + F_b^2 = 3. \tag{11}$$

Therefore, the optimal weighting parameters for the predistortion block are given by

$$F_r = \frac{\sqrt{3}M_r\eta_r}{\sqrt{M_r^2\eta_r^2+M_g^2\eta_g^2+M_b^2\eta_b^2}}, \tag{12}$$

$$F_g = \frac{\sqrt{3}M_g\eta_g}{\sqrt{M_r^2\eta_r^2+M_g^2\eta_g^2+M_b^2\eta_b^2}}, \tag{13}$$

$$F_b = \frac{\sqrt{3}M_b\eta_b}{\sqrt{M_r^2\eta_r^2+M_g^2\eta_g^2+M_b^2\eta_b^2}}. \tag{14}$$

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

Interestingly, the weighting factors given in Eq. (12) to Eq. (14) depend only on the emitted optical powers and on the conversion efficiencies of the O/E converters, but they are unrelated to the structure of the convolutional code. Therefore, they are optimal for any convolutional code.

The computational complexity of the proposed predistortion module Eq. (3) is extremely low, requiring only a single accumulation and a multiplication operation. The optimal predistortion module is implemented by using the weightings F_r, F_g and F_b given in Eq. (12) to Eq. (14). Given this optimal predistortion block, the union upper bound of the first event error probability is minimized and, therefore, the performance of the soft-decision decoder is significantly enhanced. This will be demonstrated by the bit error ratio (BER) simulation results presented in Section 4.

For other soft-decision decoders, such as the belief propagation (BP) decoder of LDPC codes [15] and the BCJR decoder of turbo codes [16], the error performance bounds are less straightforward to obtain, since their code structures are complex and the decoding algorithms are iterative. Therefore, finding the optimal weighting parameters of the predistortion module for these other soft-decision decoders is challenging. Fortunately, the optimal weighting parameters of the predistortion block derived for the soft-decision Viterbi decoder may nonetheless be beneficial for employment in soft-decision aided LDPC and turbo decoders, as we will demonstrate in Section 4.

4. Simulation results

The BER performance of the proposed predistortion block was evaluated by simulation. Two cases of different mixture ratios of the optical powers emitted from the red, green and blue LEDs were considered in order to create white light. For Case 1, the mixing ratio of the optical emitted powers was $M_r : M_g : M_b = 1 : 2.62 : 1.96$ and the corresponding wavelengths of the red, green and blue colours were 610 nm, 555 nm and 450 nm, respectively. By contrast, for Case 2, the mixing ratio was $M_r : M_g : M_b = 1 : 11.17 : 7.19$ and the corresponding wavelengths of the red, green and blue colours were 610 nm, 565 nm and 450 nm, respectively. For both cases white light was emitted and the main role of lighting was not perturbed by optical wireless communication. These two cases of white LEDs corresponded to the Types 3 and 4 of white LEDs defined in [9] (see Table 1). Again, OOK modulation was adopted. For simplicity, the O/E conversion efficiencies for the three primary colours, namely η_r, η_g and η_b, were assumed to be equal. Naturally, this did not alter the fundamental nature of the unequal powers of the three received electronic signals corresponding to the red, green and blue LEDs. Case 2 represented a much more uneven optical power mixture of the three primary colours for emitting white light.

A convolutional code, a LDPC code and a turbo code were used in our simulation study. The convolutional code employed had a code rate of 1/2, while its constraint length was 7 and the generator polynomials were $[171, 133]_8$. The decoder adopted for this convolutional code was the soft-decision Viterbi decoder with the trace back length of five times of the constraint length. The LDPC code used in the simulations was that of the IEEE 802.11 standard with a codeword-length of 1944 bits and a code rate of 1/2 [17]. The BP decoder was employed for this LDPC code and the maximum number of iterations was set to 30. Finally, the turbo code used in the simulations was specified by the 3GPP2 recommendation, which had a code rate of 1/3 and an interleaver length of 1440 bits [18]. The BCJR decoder was used for this turbo code and the number of iterations was set to 6. The bandwidth of each primary color signal was assumed to be 100 MHz, yielding the overall transmission rates of 150 Mbps and 100 Mbps for the rate 1/2 and 1/3 codes, respectively.

The BER performance obtained both with and without the predistortion block are illustrated in Figs. 2–4 for the convolutional code, LDPC code and turbo code, respectively. The BER

#199501 - $15.00 USD   Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

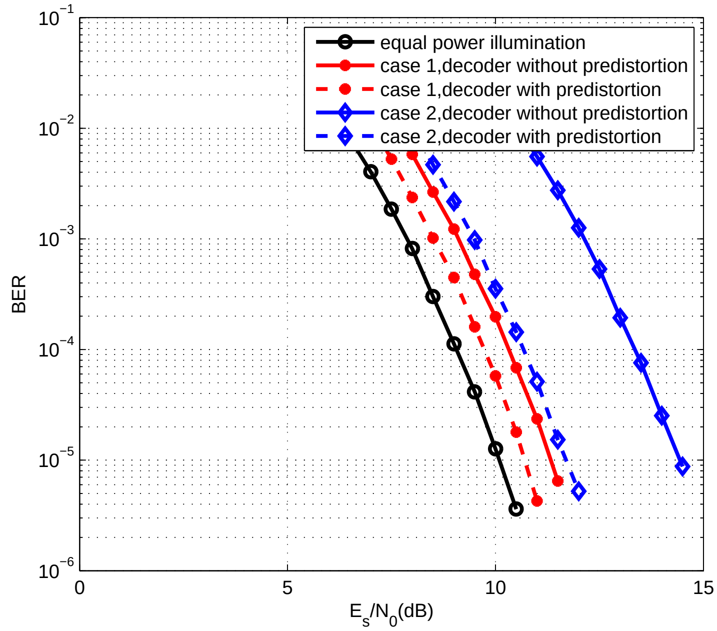

Fig. 2. BER performance comparison of the RGB-type LED based optical wireless systems with and without the predistortion module. The convolutional code with the soft-decision Viterbi decoder is employed.

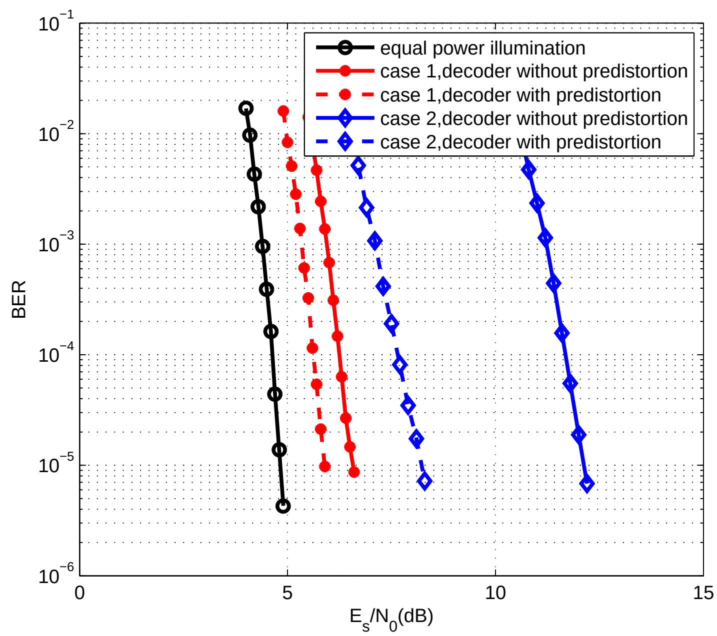

Fig. 3. BER performance comparison of the RGB-type LED based optical wireless systems with and without the predistortion module. The LDPC code with the BP decoder is employed.

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

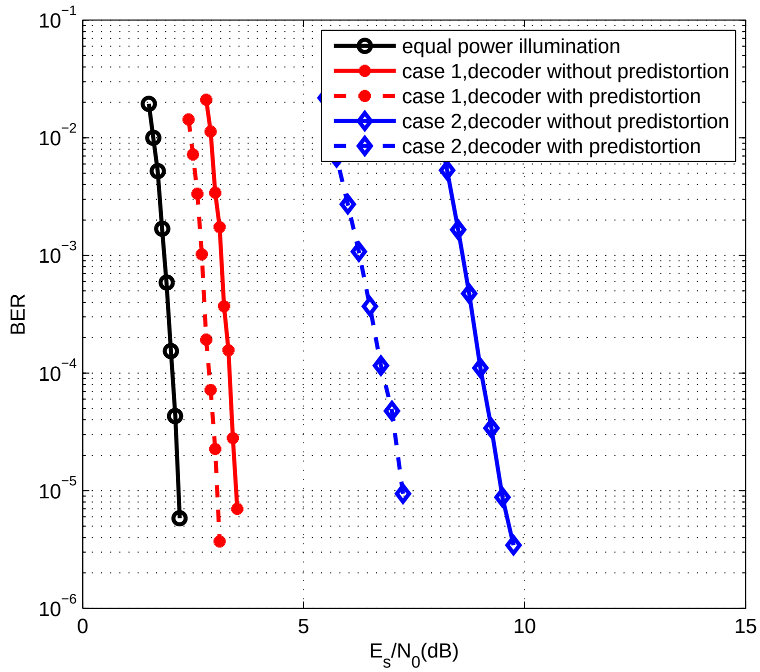

Fig. 4. BER performance comparison of the RGB-type LED based optical wireless systems with and without the predistortion module. The turbo code with the BCJR decoder is employed.

curve obtained from the case of the equal optical power radiations from the red, green and blue LEDs is also included as the benchmark, which represents the lower bound BER obtained with the aid of an equal optical power mixture of $M_r : M_g : M_b = 1 : 1 : 1$. This idealised BER performance however is unattainable in practice owing to the requirement of the unequal optical power radiations of the three primary colours in order to emit white light.

It can be clearly seen from the results shown in Figs. 2–4 that a significant performance gain can be attained using the proposed predistortion block. Specifically, at the BER level of 10^{-5} and for the unequal optical power mixture of the three primary colours of Case 1, we achieved the performance gains of 0.6 dB, 0.7 dB and 0.5 dB, respectively, for the convolutional code, LDPC code and turbo code over the corresponding systems operating without predistortion. As expected, the attainable BER performance of Case 2 is considerably poorer than that of Case 1, because in Case 2 the optical power distribution of the red, green and blue LEDs is much more uneven. The performance gain attained by the proposed predistortion block however is significantly higher in Case 2. Quantitatively, at the BER level of 10^{-5}, the predistortion scheme attained SNR gains of 2.8 dB, 3.9 dB and 2.2 dB, respectively, for the convolutional code, LDPC code and turbo code. The results of Figs. 2–4 also confirm that the best BER performance is obtained with the equal optical illumination powers of the red, green and blue LEDs. However, the equal optical power mixture of the three primary colours cannot produce white light and, therefore, it cannot carry out the primary lighting function.

Iterative detections aided codes, such as turbo and LDPC codes outperform convolutional codes at the same code rate. This can be observed by comparing the BER performance of the LDPC and convolutional codes in Figs. 2 and 3, where the both codes have the same 1/2 code rate. The BER performance of a turbo code having a code rate of 1/3 is shown in Fig. 4 to be

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013

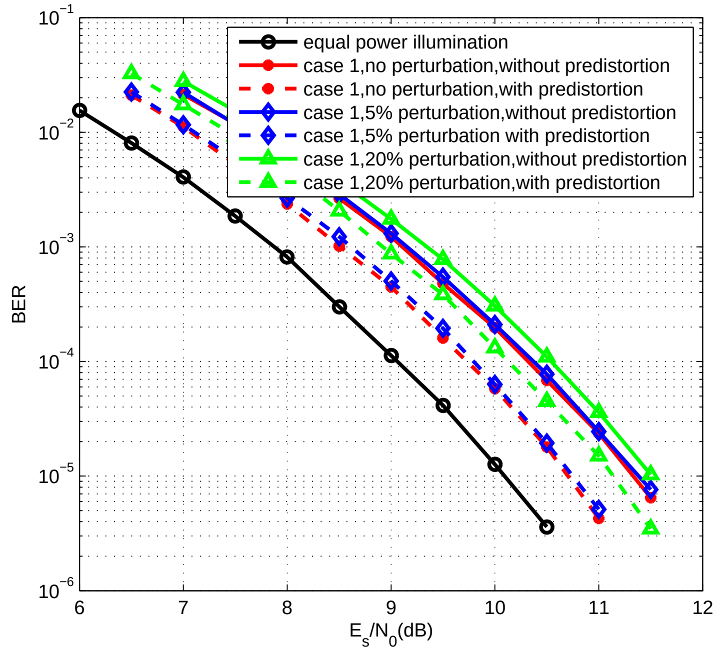

Fig. 5. BER performance comparison of the case-1 RGB-type LED based optical wireless systems with and without the predistortion module under the blue LED illumination perturbation. The convolutional code with the soft-decision Viterbi decoder is employed.

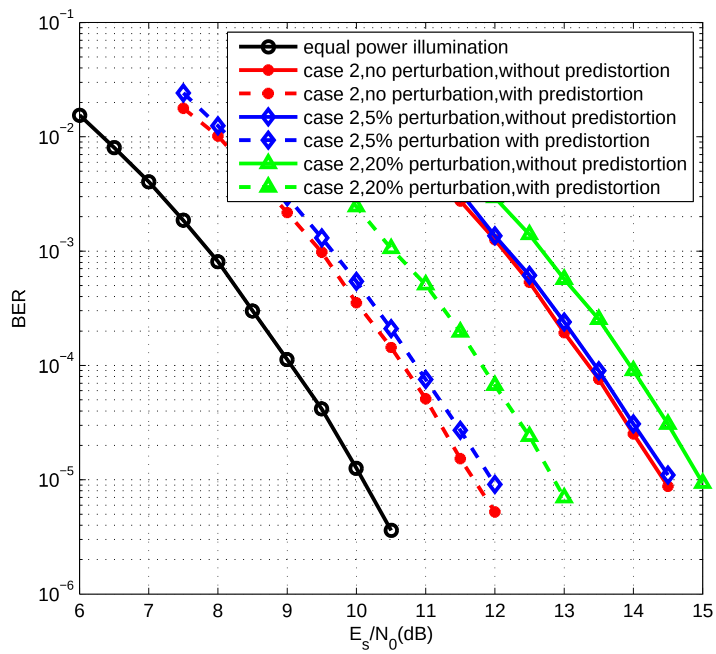

Fig. 6. BER performance comparison of the case-2 RGB-type LED based optical wireless systems with and without the predistortion module under the blue LED illumination perturbation. The convolutional code with the soft-decision Viterbi decoder is employed.

#199501 - $15.00 USD Received 14 Oct 2013; revised 21 Nov 2013; accepted 22 Nov 2013; published 3 Dec 2013
(C) 2013 OSA 16 December 2013 | Vol. 21, No. 25 | DOI:10.1364/OE.21.030295 | OPTICS EXPRESS 30304

better than that of the half-rate LDPC code characterized in Fig. 3, which is not unexpected owing to the turbo code's lower rate.

The illumination perturbation is dominated by the LED drivers and it is usually very small. To investigate the robustness of the proposed predistortion scheme to illumination perturbation, we used the system employing a convolutional code relying on the soft-decision Viterbi decoder to design the following experiment. We imposed 5% and 20% perturbations on the blue LED, but the predistortion module still utilized the weight factors designed for no illumination perturbation. The remaining simulation parameters were kept the same. The BER performance attained both with and without the predistortion block is illustrated in Figs. 5 and 6 for the case-1 and case-2 RGB-type LED based optical wireless systems, respectively. When imposing a 5% perturbation in the blue LED, in case-1 the performance degradation remained negligible, as seen from Fig. 5. By contrast, the predistortion assisted system suffers from a modest performance loss of about 0.44 dB when the perturbation is increased to 20%. Nonetheless, the system still outperforms the scenario operating without the predistortion module by about 0.36 dB.

Similarly, when considering case-2, we observe from Fig. 6 that the predistortion assisted system suffers from a small performance loss of about 0.26 dB under the 5% illumination perturbation imposed on the blue LED. When the perturbation is increased to 20%, the degradation of the predistortion assisted case-2 increases to about 0.89 dB, but it still offers a performance gain of about 2.12 dB over the system operating without predistortion. The results shown in Figs. 5 and 6 confirm that the proposed predistortion scheme is robust to illumination perturbation.

5. Conclusions

For high rate optical wireless communication systems utilizing RGB-type white LEDs, the emitted optical powers of the three primary colours are inherently unequal, when carrying out the primary function of producing white light for illumination. Using unequal optical power mixing ratios of the red, green and blue LEDs however results in different reliabilities of the received signals related to the three primary colours, which degrades the attainable decoding performance at the receiver. In this contribution, we have proposed a simple yet effective predistortion scheme for enhancing the decoding performance of the soft-decision decoder. The proposed predistortion module applies different weights to the received signals corresponding to the three primary colours, so that a more reliable signal contributes more to the soft-decision decoding process while a less reliable signal makes a lower contribution. Although the optimal predistortion weights are derived by minimizing the upper bound of error probability for the system employing classic convolutional codes relying on a classic soft-decision Viterbi decoder, they are also applicable to LDPC codes using the BP decoder as well as to turbo codes employing the BCJR decoder. Our simulation results have demonstrated that significant decoding performance enhancements can be achieved with the aid of the proposed predistortion module for all the these three soft-decision decoders. The results obtained also indicate that the performance of the proposed predistortion module is robust to illumination perturbation.

Acknowledgments

This work was supported by National Nature Science Foundation of China (Grant No. 61271266), National Key Basic Research Program of China (Grant No. 2013CB329203), and National High Technology Research and Development Program of China (Grant No. 2012AA011704).