Efficient transmission based on RGB LED lamp for indoor visible light communication

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We investigate the multilevel modulation for red-green-blue light emitting diode (RGB LED). A simple approach for extracting soft values from the modulation is proposed. The mapping way from bits to the modulated symbols for the multilevel modulation is also investigated. The modified modulation is obtained through the brute force. Based on the Monte Carlo simulations, the proposed approach and modified modulation are confirmed and better bit error rate (BER) performances are obtained.

OCIS codes: 060.4510, 040.5160, 230.3670.

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Light emitting diode (LED), a new generation of solid-state light source, has been intensively studied in various fields of applications, such as lighting, automobiles, transportation, and communication[1−4]. Given the advantage of fast response in switching on and off, return-to-zero (RZ) on-off-keying (OOK) modulation can be easily introduced into the LED-based visible light communication (VLC)[5]. O'Brien *et al.* have shown that the typical lighting levels provide a communications channel with a signal-to-noise ratio (SNR) in excess of 40 dB for indoor visible light communication[6]. The SNR fluctuation was reduced to 0.9 dB by the specific LED lamp arrangement, as reported in Ref. [7]. Komiyama *et al.* have studied the visible light communication system using red-green-blue (RGB) LED lights, using convolutional codes as the error-correcting code[8].

In state of the art, low density parity check (LDPC) code was almost the best error control coding, which was originally invented by Gallager[9]. The LDPC code has been widely used in binary phase shift keying (BPSK) modulation: it requires a soft value for decoding at the receiver[10].

In this letter, the multilevel modulation for RGB LED is investigated using the LDPC code as the error-correcting code. A simple approach for extracting soft values from the RGB based three-bit multilevel modulation is proposed to obtain the bit error rate (BER) curves of the transmission system using the Monte Carlo simulations. For the LDPC decoding algorithm, we illustrate the bit-flipping (BF) decoding algorithm[9] and the standard belief propagation (BP) algorithm[11], which depends on hard decision and soft value, respectively. Considering that the modulation in Table 1 as the natural approach, we modify the mapping system from bits to modulated symbols and obtained a better performance of the transmission system.

The LDPC matrices H (504, 252, 0.5) were created according to Mackay's construction rule 1A[10]. A 252 × 504 matrix (252 rows, 504 columns) was randomly created with a weight per column of three, weight per row as uniform as possible, and an overlapping between any two columns not greater than one. The simplified block scheme of the proposed system is depicted in Fig. 1. We took 252 bits of data as a block. After encoding using the LDPC code, we obtained the block with 504 bits of data. The data were then sequentially divided into three groups and modulated in the RZ-OOK modulation for the R, G, and B units of the RGB LED lamp. The line-of-sight (LOS) was used as the optical channel and the additive white Gaussian noise (AWGN) was used as the channel noise in the transmission system[12]. At the receiving end, the signal was expressed as $y_i = Hx_i + n_i$, where y_i is the received signal, H is the channel gain, x_i is the transmitted signal from the LED lamp, and n_i is the AWGN with zero mean. The optical receiver converts the optical signal to an electrical signal.

Considering the linear response of the optical receiver, such as PDA36A (THORLABS), the responses were about 0.4, 0.3, and 0.2 A/W for the wavelength in the region of R, G, and B, respectively. The electrical signals were 2, 1.5, and 1, in proportion with the same optical power of R, G, and B units of the RGB LED lamp, respectively. Table 1 lists the RZ-OOK modulation with the RGB LED. The last column is the respective response of the receiver. PDA10A was used instead of the PDA36A. The response of the PDA10A has a wavelength of about 0.4, 0.25, and 0.17 A/W in the R, G, and B region, respectively. In this situation, it is difficult to distinguish whether the received signal comes from the red light or the light mixed with green and blue. The expected result was obtained by adjusting the drive current of the three units of the lamp, as illustrated in Fig. 2. The first three pulses are the responses of the R, G, and B units, respectively. The pulse width was expanded to compensate for the loss of drive current to ensure the color mixing and obtain white light illumination in the RZ-OOK modulation.

For the proposed modulation, the hard decision is the same as the ordinary multilevel amplitude modulation. We introduced the approach for extracting the soft values from the RGB-based three-bit multilevel modulation. An example of the detailed illustration was also provided for clarity. We assumed that the three bits of '1 0 0' need to be sent. According to the modulation rule, we may expect the response of the receiver to be '2', as illustrated in Table 2. A response with '2.3422' from the

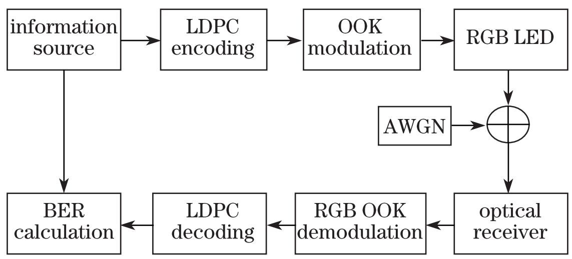

Fig. 1. Simplified block scheme of transmission based on RGB LED.

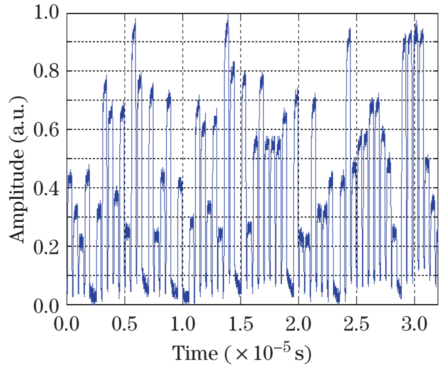

Fig. 2. Received waveform of the RGB-based multilevel modulation.

optical receiver was obtained because of the interference with the noise as the AWGN. The bits of '0 1 1' may be demodulated by the hard decision, thus bit errors may occur. For the proposed algorithm, we calculated the distance between the received response and the eight different kinds of expected response and obtained the value of '2.3422, 1.3422, 0.8422, 0.1578, 0.3422, 0.6578, 1.1578, and 2.1578'. The reciprocal of these values were taken, and then normalized by adding them. The results obtained were '0.0295, 0.0515, 0.0821, 0.4380, 0.2020, 0.1051, 0.0597, and 0.0320'. These values may be considered as the probability of the received signal. Similar to Ref. [13], we obtained the soft values of the three bits as '0.6011, 0.3881, and 0.3733' for bit '1' and as '0.3989, 0.6119, and 0.6267' for bit '0'. Therefore, we may obtain the correct bits of '1 0 0' from the soft value alone.

Taking the system model as illustrated in Fig. 1, we obtained the numerical results using the Monte Carlo simulations with the LDPC decoder to the maximum of 30 iterations for both BF and BP algorithms, as shown in Fig. 3. When the BER is approximately at a 10^{-5} level, the LDPC coded system with the BF decoding algorithm may save more than 3 dB of energy power. Based on the proposed soft value extracting method, the BP decoding algorithm can maintain the BER value under 10^{-6} when the value is 10^{-2} with the uncoded transmission.

In the three-bit multilevel modulation, eight different symbols for the RGB LED lamp exists, which has the R, G, and B units for switching on and off. Using a simple calculation, we may obtain 40 320 mapping systems from bits to modulated symbols. Considering that the previous modulation as the natural approach, we used a computer by brute force to find the best mapping system. The bits arrangement was fixed, as shown in the first column of Table 1. The expected response, which corresponds to the 'on' or 'off' state for the R, G, and B units of the LED, were arranged in random permutation. Under the 50 000 numerical calculations with the SNR value of 13 dB, we obtained the best approach of modulation, as illustrated in Table 2.

The BER curves were obtained using a similar numerical method before, as shown in Fig. 4. We obtained a better BER performance in all the ranges of the SNR values for both uncoded and coded transmissions. For the BF decoding algorithm, the modified modulation may gain a coding of more than 1 dB versus the natural way when the value of BER is 10^{-6}. Based on the proposed soft value extracting method, the BP decoding algorithm may save nearly 2 dB of energy power in the same circumstances. Compared with the uncoded transmission, the BP algorithm with the modified modulation may obtain more than 10 dB of coding gain when the value of BER is about 10^{-6}.

In conclusion, we investigate the multilevel modulation for the RGB LED and propose a simple approach for extracting the soft values from a specific

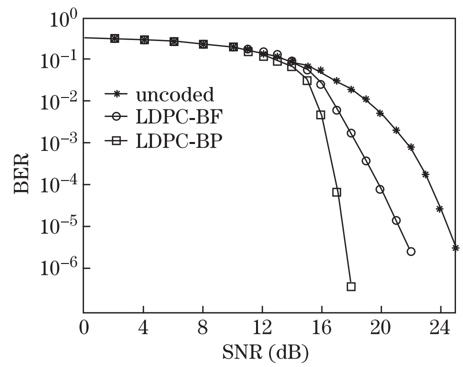

Fig. 3. BER versus SNR values with the three-bit RGB-based multilevel modulation.

Table 1. Three-bit Multilevel Modulation

Bits	R	G	B	Response
0 0 0	off	off	off	0
0 0 1	off	off	on	1
0 1 0	off	on	off	1.5
0 1 1	off	on	on	2.5
1 0 0	on	off	off	2
1 0 1	on	off	on	3
1 1 0	on	on	off	3.5
1 1 1	on	on	on	4.5

Table 2. Modified Modulation

Bits	R	G	B	Response
0 0 0	off	on	off	1.5
0 0 1	on	off	off	2
0 1 0	off	off	on	1
0 1 1	off	on	on	2.5
1 0 0	on	on	on	4.5
1 0 1	on	on	off	3.5
1 1 0	off	off	off	0
1 1 1	on	off	on	3

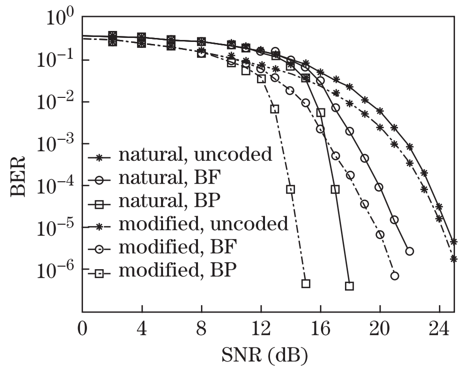

Fig. 4. BER versus SNR values with two different mapping ways.

modulation. Using numerical analysis with simplified LDPC coded transmission, the effectivity of the soft value is verified. The mapping system from the bits to the modulated symbols for the multilevel modulation is also studied. The modified modulation is designed through brute force. The numerical results show that the modified modulation provides better performances. More than 10-dB coding gain is achieved when the BP decoding algorithm adopted with the modified modulation.

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