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Unequal error control scheme for dimmable visible light communication systems

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ABSTRACT

Visible light communication (VLC), which has the advantages of a very large bandwidth, high security, and freedom from license-related restrictions and electromagnetic-interference, has attracted much interest. Because a VLC system simultaneously performs illumination and communication functions, dimming control, efficiency, and reliable transmission are significant and challenging issues of such systems. In this paper, we propose a novel unequal error control (UEC) scheme in which expanding window fountain (EWF) codes in an on–off keying (OOK)-based VLC system are used to support different dimming target values. To evaluate the performance of the scheme for various dimming target values, we apply it to H.264 scalable video coding bitstreams in a VLC system. The results of the simulations that are performed using additive white Gaussian noises (AWGNs) with different signal-to-noise ratios (SNRs) are used to compare the performance of the proposed scheme for various dimming target values. It is found that the proposed UEC scheme enables earlier base layer recovery compared to the use of the equal error control (EEC) scheme for different dimming target values and therefore afford robust transmission for scalable video multicast over optical wireless channels. This is because of the unequal error protection (UEP) and unequal recovery time (URT) of the EWF code in the proposed scheme.

1. Introduction

With the explosive growth of wireless communications and multimedia applications in recent years, radio resources are becoming increasingly scarce. This has paved the way for the emergence of and high interest in visible light communication (VLC), which utilizes white light-emitting diodes (LEDs), as a promising green-IT technology for both illumination and communication [1–6]. VLC has many advantages, which include very large bandwidth, high security, and freedom from license-related restrictions and electromagnetic-interference [7]. Furthermore, the use of LEDs as a transmitter in a VLC system facilitates multimedia multicast and broadcast applications.

Because a VLC system simultaneously performs illumination and communication functions, i.e., the LED is not only used as an illumination device, but also as a communication device, dimming control, efficiency, and reliable transmission are significant and challenging issues in such systems. Usually, dimming, which is used to produce variable brightness of the light, is achieved in a VLC system by on–off keying (OOK) modulation. Several other simple pulse modulation methods have also been proposed, such as pulse width modulation (PWM), variable pulse position modulation (VPPM), and multiple pulse position modulation (MPPM). To improve the success probability of data transmission and eliminate costly requirements for re-transmission, forward error correction (FEC) schemes are usually used to protect against channel errors. However, when using FEC codes for reliable communication in a VLC system, the equal probability of 1's and 0's within a data packet is usually not guaranteed, and this results in bias and variation of the lighting brightness. To address this issue, the concept of compensation symbols (CSs), which involves the insertion of dummy symbols simply to satisfy the dimming requirement within a data packet, has been introduced [2].

In recent years, error correcting coding schemes with dimming support by using CSs to achieve target dimming levels and enhance the communication performance of VLC systems have been intensively studied [8–11]. In [8], an FEC coding method based on a modified Reed–Muller (RM) code for accurate dimming control in VLC systems is proposed. An RM code-based FEC coding method that enables accurate dimming control in OOK-based VLC systems is also proposed in [9]. Furthermore, in [10] the authors introduce an adaptive FEC scheme that utilizes low-density parity-check (LDPC) codes for efficient

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dimming to achieve target brightness levels in dimmable VLC systems. Owing to the advantages of fountain codes [12] in terms of complexity, performance, and flexibility, they have been exploited as feasible FEC solutions. Moreover, because fountain codes can adapt to any erasure channel with unknown or varying characteristics, they are especially suitable for packet-level coding. In [11], the authors propose an error control scheme that uses fountain codes in dimmable VLC systems, and demonstrate the superiority of the codes to modified RM codes in terms of the actual overhead and code rate. The error control scheme proposed in [11] provides equal error control (EEC) to every symbol within a data packet. However, in many practical applications, e.g., image and video systems, some information are more important and require better protection, thus necessitating unequal error protection (UEP) among the transmission data. In other words, such applications require error correcting codes with unequal error protection (UEP) and unequal recovery time (URT) capabilities. To the best of our knowledge, the use of an unequal error control (UEC) scheme in dimmable VLC systems is yet to be investigated.

In this paper, we propose a novel UEC scheme that utilizes expanding window fountain (EWF) codes [13] for different dimming target values in OOK-based VLC systems. To evaluate the performance of different dimming target values, we apply the proposed UEC scheme to H.264 scalable video coding (SVC) bitstreams in a VLC system. The main contributions of this paper include the following:

(1) A novel UEC scheme with dimming support is proposed for dimmable VLC systems. Because scrambling and dimming compensation are utilized, different dimming target values can be achieved using the least amount of compensation symbols (see Appendix A).
(2) We present the derivation of the relationships among the actual overhead at the transmitter, the dimming target value, and the actual reception overhead at the receiver for the same transmission duration that produces a dimming target value of 12.5 % when using EWF coding with overhead ε.
(3) We demonstrate the application of the proposed UEC scheme to H.264 SVC bitstreams in a VLC system and evaluate the performance of the dimmable VLC system for different dimming target values.
(4) Due to the ratelessness of EWF codes, the proposed dimmable VLC system with a UEC scheme affords robust transmission for scalable video multicast over optical wireless channels.

The rest of this paper is organized as follows. In Section 2, we present the proposed VLC system model in which EWF codes are embedded using a UEC scheme. The detailed encoding and decoding procedure of the proposed scheme are also described. In addition, we derive the relationships among the actual overhead at the transmitter, the dimming target value, and the actual reception overhead at the receiver for the same transmission duration that produces a dimming target value of 12.5 % when using EWF coding with overhead ε. In Section 3, we present the results of the performed simulations. We finally conclude the paper in Section 4.

2. System model

2.1. Proposed VLC system model

The block diagram of the proposed VLC system is shown in Fig. 1. The input of the EWF encoder is assumed to be a K source information symbol set $I = \{I_1, I_2, \ldots, I_K\}$, where each symbol I_i consists of N bits. The procedure of the EWF encoding is presented in the next subsection. The EWF encoder generates a potentially limitless number of encoded symbols that can be represented by an output set $C = \{C_1, C_2, \ldots\}$, where each encoded symbol C_i consists of N bits. Cyclic redundancy check (CRC) bits are added to each encoded symbol to detect transmission errors. By using efficient scrambling, on the one hand, a dimming value of 50 % can be obtained on the transmitter side without any additive compensation bits. On the other hand, the binary encoded symbols can be randomized to significantly simplify bit synchronization on the receiver side. To achieve target dimming values other than 50 %, a dimming compensator can be used to control the total number of 1's and 0's using compensation symbols based on the particular target dimming value. The output symbols of the dimming compensator are all modulated by an OOK modulator to generate the modulated signal $s(t)$. The modulated signal is then transmitted by the LED. The electrical signal $s(t)$ is converted into the corresponding optical signal $x(t)$ in the LED, the average optical power P_t of which is given by $P_t = \frac{1}{T}\int_0^T x(t)dt$ [8,11], where T is the light signal duration.

After passing through the optical wireless channel $h(t)$, once the delayed optical signal is received, it is converted into an electrical signal by a photodiode (PD). In a VLC system that uses intensity modulation and direct detection (IM/DD), the received signal $r(t)$ is given by [4,8,9,11]

$$r(t) = R\cdot\int_{-\infty}^{+\infty} x(\tau)h(t-\tau)d\tau + n(t) \tag{1}$$

where R is the PD conversion efficiency, $n(t)$ is the additive white Gaussian noise (AWGN) which contains the shot and thermal noise.

As shown in Fig. 1, $r(t)$ is the input signal of the OOK demodulator. After OOK demodulation, each output symbol is passed through the dimming eliminator to remove the compensation symbols. The symbols that will be passed through the descrambler are then obtained. After descrambling, the CRC detector is used to determine whether each symbol has been received correctly. It should be noted that only the correctly received symbols are used for the EWF decoding, as will be described later in this paper.

2.2. Proposed unequal error control scheme

Fountain codes such as Luby-Transform (LT) codes [14] and Raptor codes [15] have been proposed for flexible and efficient FEC solutions for information transmission. However, such codes are equal error protection (EEP) codes. There has been the recent development of fountain codes designed with UEP, expanding window fountain (EWF) codes being an example. EWF codes, which afford novel methods for achieving UEP and URT, can be used to protect source information bits based on their level of importance.

2.2.1. Encoder

In the illustration in Fig. 1, a K source information symbol set $I = \{I_1, I_2, \ldots, I_K\}$ is the input of the EWF encoder, where each symbol I_i consists of N bits. The encoding procedure of the EWF code is as follows.

(1) *Division*. The K source information symbols are divided into r importance classes $s_1, s_2, \ldots, s_r$ as shown in Fig. 2. The classes contain $\alpha_1 K, \alpha_2 K, \ldots, \alpha_r K$ symbols, respectively, where $\sum_{i=1}^{r}\alpha_i = 1$. The importance of the classes decreases with increasing class index, i.e., the i-th class is more important than the j-th class for $i < j$. The division into importance classes can be compactly described by the generating polynomial $\Pi(x) = \sum_{i=1}^{r}\Pi_i x^i$, where $\Pi_i = \alpha_i$ [13].

(2) *Windowing*. Based on the above division, the r expanding windows can be defined for the K source information symbols, with each window contained in the next window. It should be noted that the i-th window consists of the first $k_i = \sum_{j=1}^{i}\alpha_i K$ input symbols. Consequently, $k_1 < k_2 < \cdots < k_r = K$. Clearly, the most important symbol class s_1 is contained in all the windows, and the r-th window contains all the K symbols.

(3) *Encoding*. Each EWF encoded symbol is generated by performing standard LT encoding on only the input symbols uniformly chosen at random from the selected window, which can also be randomly chosen with respect to the window selection probability. Moreover, the