Novel Decoding of Run-Length Limited Codes for Visible Light Communication

He Wang and Sunghwan Kim

***Abstract*—**In this paper, we propose a new decoding algorithm based on maximum likelihood (ML) decoding of run-length limited (RLL) codes with on-off keying (OOK) modulation and Reed-Solomon (RS) codes in visible light communication (VLC) systems. Conventional RLL codes in VLC systems are used for 50% dimming and hard decision of RLL decoder is considered. However, in the receiver of our model, the RLL decoder based on ML decoding makes better estimation for channel decoder. Simulation results show that our proposed method get signal-to-noise ratio (SNR) gain in bit error rate (BER) compared with one of RLL hard decoding.

***Keywords*—**on-off keying (OOK), Reed-Solomon (RS) codes, run-length limited (RLL) codes, visible light communication (VLC).

I. Introduction

With the explosive demanding of bandwidth, the scarcity of spectrum leads visible light communication (VLC) to be attractive in people's view during recent years. VLC using visible light spectrum from 380 to 780 nm can provide both illumination lighting and communication functions together base on light emitting diodes (LEDs) technique. LEDs enhance energy efficiency under the fast nanosecond switching time. To invigorate the VLC industry, VLC standard is recently published by IEEE standard association [1]. In VLC standards, Reed-Solomon (RS) codes are also widely used as forward error correction (FEC) codes because of robust ability to correct burst errors [2]. Run-length limited (RLL) codes are also important since they guarantee the DC balance with equal 1s and 0s, such as Manchester, 4B6B and 8B10B codes in VLC standard. For the hardware constraint for practical usage, on-off keying (OOK) as a simple modulation is considered because of just sending binary data by on/off pulses in VLC [3].

Recent years, many researchers have been developing the efficient FEC for VLC [4]-[6]. A novel FEC coding scheme was proposed for VLC base on the Reed-Muller (RM) codes and OOK, and it provided more coding gain than VLC scheme with the conventional FEC codes [4]. A bent function is considered in VLC based on RM codes and an OOK modulation, which increases performance with accurate dimming target value [5]. Furthermore, RS codes with RLL codes and FSK modulation is proposed in [6], and it presented the spectral analysis of RLL codes. Even though these research [4]-[6] have been done, the bit error rate (BER) performance of RLL codes and RS codes in VLC is rarely considered. Therefore RLL codes which are used for guaranteeing DC balance and dimming 50% are considered, and BER performances are also shown.

In this paper, we propose an enhanced decoding based on maximum likelihood (ML) methods of RLL codes with OOK modulation and RS codes in VLC system. In our model, the receiver have a new architecture, RLL decoders make better outputs based on ML rule which takes advantage of soft value of VLC channel. Simulation results show that our proposed method get better BER performance compared with one of RLL hard decoding.

II. System Model

A. Proposed VLC system description

The block diagram of the proposed scheme is shown in Fig. 1. In Fig. 1 (a), the transmitter of the proposed system is shown, and each components of the transmitter are already defined in the VLC standard [1]. The 'message' in the transmitter denotes binary m-bit message corresponding to input of the VLC system. Then (n, k) RS codes over GF(2^l) in [2] are considered, where kl is equal to m. The output of RS encoder is nl-bit codeword. Next, in RLL encoder, RLL codes such as 4B6B codes or 8B10B codes [1] are inserted for balancing the total number of 0s and 1s in codeword to keep dimming 50%. Next, the LED emits OOK-modulated signal with the light signal $x(t)$, which has the average optical power expressed as

$$P_t = \frac{1}{T}\int_0^T x(t)\,dt \tag{1}$$

where T denotes light signal duration.

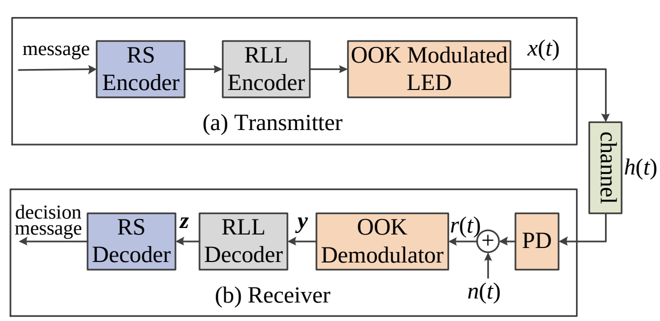

Fig. 1. Block diagram of the transmitter and the receiver of the proposed VLC system

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After passing through the VLC channel $h(t)$, the photodiode (PD) receives light in Fig. 1(b). Then, the received signal $r(t)$ is given as [7]

$$r(t) = R \cdot x(t) \otimes h(t) + n(t) \tag{2}$$

where " $\otimes$ " denotes convolution; R is the PD conversion efficiency (A/W); and $n(t)$ is additive white Gaussian noise (AWGN) which contains the shot and thermal noise. Since an OOK modulation is used for data transmission, according to [8] the received signal-to-noise ratio SNR (SNR_{rx}) is expressed as

$$\mathrm{SNR}_{\mathrm{rx}} = \frac{\left(R \cdot P_{rSignal}\right)^2}{\sigma_{shot}^2 + \sigma_{thermal}^2 + \left(R \cdot P_{rISI}\right)^2}, \tag{3}$$

where the desired signal power is

$$P_{rSignal} = \int_0^T x(t) \otimes h(t)\, dt \tag{4}$$

and the received power affected by inter-symbol interference is

$$P_{rISI} = \int_T^\infty x(t) \otimes h(t)\, dt. \tag{5}$$

A shot noise variance is expressed

$$\sigma_{shot}^2 = 2q\gamma\left(P_{rSignal} + P_{rISI}\right)B + 2qI_{bg}I_2B \tag{6}$$

where q is the electronic charge, B is equivalent noise bandwidth, and I_{bg} and I_2 are background current and the noise bandwidth factor, respectively [8]. In addition, the thermal noise variance is also expressed as

$$\sigma_{thermal}^2 = \frac{8\pi kT_k}{G}\eta AI_2B^2 + \frac{16\pi^2 kT_k\Gamma}{g_m}\eta^2A^2I_3B^3 \tag{7}$$

where the first two terms represent feedback-resistor noise and field-effect-transistor (FET) channel noise, respectively. K is Boltzmann's constant, T_k is absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of PD/unit area, Γ is the FET channel noise factor, g_m is the FET transconductance, and I_3 is the noise bandwidth factor [8].

In Fig. 1 (b), $r(t)$ is the input of OOK-demodulator, then OOK-demodulated signal $\boldsymbol{y}$ is the input of RLL decoder, our proposed method based on ML decoding is designed to make output $\boldsymbol{z}$ from the signal $\boldsymbol{y}$ and the decoding rules are explained in next subsection. Conventional Berlekamp-Massey (BM) decoding algorithm [2] is considered in the RS decoder in Fig. 1 (b) to decode $\boldsymbol{z}$. After decoding of RS codes, decision of message is done.

Our paper focuses on ML decoding of RLL codes, and a detailed description of our algorithm is then given as follow.

B. ML decoding of RLL codes

In the VLC standards [1], three RLL codes are considered, which are Manchester codes, 4B6B codes, and 8B10B codes. To explain the decoding of 4B6B codes and 8B10 codes, mapping relations between input and output of RLL codes need to be discussed. The mapping rules of 4B6B codes are listed in Table 1 [1]. The left column '4-bit' and the right column '6-bit' denote the 4-bit input and 6bit output of RLL encoder, respectively. The weight of 4B6B codeword is 3 and maximum run of 0s or 1s is 4. 8B10B codes are compose of 5B6B codes and 3B4B codes, where corresponding tables are Table II and Table III, respectively. 'RD' in Table II and Table III denotes running disparity. Since the number of 0's and the number of 1's in 5B6B codewords and 3B4B codewords are different, RD-codewords and RD+ codewords are used to keep number of 0s and 1s, equally to maintain DC balance.

TABLE I
MAPPING'S RELATION BETWEEN A 4-BIT SYMBOL AND A 6-BIT SYMBOL.

4-bit	6-bit
0000	001110
0001	001101
0010	010011
0011	010110
0100	010101
0101	100011
0110	100110
0111	100101
1000	011001
1001	011010
1010	011100
1011	110001
1100	110010
1101	101001
1110	101010
1111	101100

TABLE II
MAPPING'S RELATION BETWEEN A 5-BIT SYMBOL AND A 6-BIT SYMBOL.

5-bit	6-bit RD -	6-bit RD+	5-bit	6-bit RD -	6-bit RD +
00000	100111	011000	10000	011011	100100
00001	011101	100010	10001	100011	
00010	101101	010010	10010	010011	
00011	110001		10011	110010	
00100	110101	001010	10100	001011	
00101	101001		10101	101010	
00110	011001		10110	011010	
00111	111000	000111	10111	111010	000101
01000	111001	000110	11000	110011	001100
01001	100101		11001	100110	
01010	010101		11010	010110	
01011	110100		11011	110110	001001
01100	001101		11100	001110	
01101	101100		11101	101110	010001
01110	011100		11110	011110	100001
01111	010111	101000	11111	101011	010100

TABLE III
MAPPING'S RELATION BETWEEN A 3-BIT SYMBOL AND A 4-BIT SYMBOL.

3-bit	4-bit RD -	4-bit RD +	3-bit	4-bit RD -	4-bit RD +
000	1011	0100	100	1101	0010
001	1001		101	1010	
010	0101		110	0110	
011	1100	0011	111	1110	0001

To express 4B6B codes or 8B10B simultaneously, (c,o) is defined instead of (4,6) or (8,10). The input of OOK demodulator can be presented as vector $\boldsymbol{r}=(\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3,\ldots, \boldsymbol{r}_i,\ldots, \boldsymbol{r}_n)$, where $\boldsymbol{r}_i=(r_{i,1}, r_{i,2},\ldots, r_{i,o})$ is the i-th symbol and n is the code length of RS codes. Similarly, the input of RLL decoder is defined as $\boldsymbol{y}=(\boldsymbol{y}_1, \boldsymbol{y}_2, \boldsymbol{y}_3,\ldots, \boldsymbol{y}_i,\ldots, \boldsymbol{y}_n)$, where $\boldsymbol{y}_i=(y_{i,1}, y_{i,2},\ldots, y_{i,o})$. The output of RLL decoder is defined as $\boldsymbol{z}=(\boldsymbol{z}_1, \boldsymbol{z}_2, \boldsymbol{z}_3,\ldots, \boldsymbol{z}_i,\ldots, \boldsymbol{z}_n)$. The RLL decoder decodes $\boldsymbol{y}$ by processing (o-bit symbol) $\boldsymbol{y}_i$ and corresponding (c-bit symbol) $\boldsymbol{z}_i$ from i= 1 to n, separately. The block diagram about input and output of RLL decoder is shown in Fig. 2.

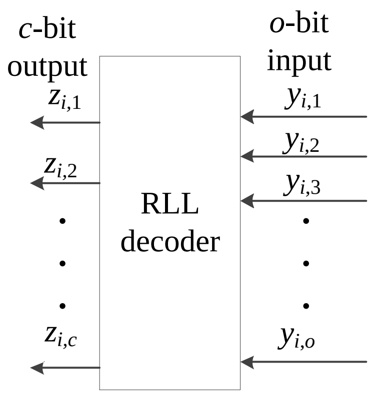

Fig. 2. RLL decoder process one symbol with o-bit input and c-bit output.

ML decoding rule of RLL codes is composed of 6 steps and is shown in Fig. 3. For n symbols, channel values are used for soft input in RLL decoder. The detail explanation about ML decoding step is described as follows.

Proposed decoding algorithm of RLL decoder:

Step1) Initialization: set i=1

Step2) Obtain every bit (of $\boldsymbol{y}_i$) probability which is defined as:

$$p\left(y_{i,j}=1\right)=\frac{1}{1+10^{LLR}} \tag{8}$$

where LLR (Log likelihood) with OOK demodulation is presented as

$$LLR=\log\frac{p\left(y_{i,j}=0\right)}{p\left(y_{i,j}=1\right)}=\frac{-2r_{i,j}+1}{2\sigma^2} \tag{9}$$

Step3) The symbol probability is defined as

$$p\left(\boldsymbol{y}_i\right)=\prod_{j=1}^{o}p\left(y_{i,j}\right) \tag{10}$$

we obtain 2^c probabilities corresponding to o-bit symbols.

Step4) Mapping: set $p(\boldsymbol{z}_i)= p(\boldsymbol{y}_i)$ according to Table I or Table II and Table III, corresponded c-bit symbols have same probabilities to o-bit symbols.

Step5) Maximum likelihood (ML): output $\boldsymbol{z}_i$= argmax $p(\boldsymbol{z}_i)$.

Step6) If $i<n$, set $i\leftarrow i+1$, then go to step for another symbol. Else ($i=n$), stop.

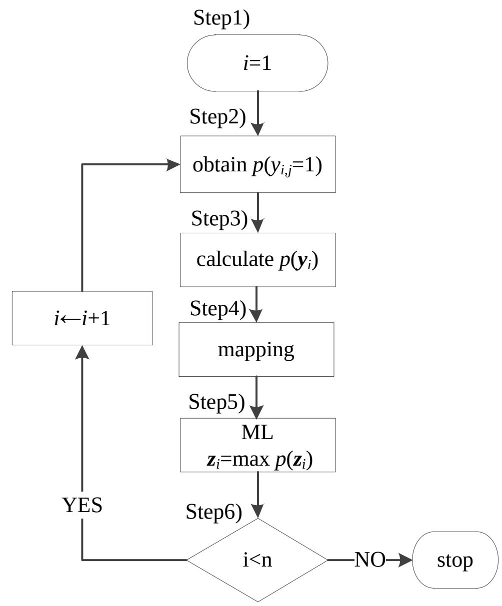

Fig. 3. ML decoding process of RLL codes.

III. Simulation Results

Two cases are considered, which are 4B6B RLL codes with RS (15,3) and RS (15,11) codes, and 8B10B RLL codes with RS (64,32) codes, since the RS codes with the lowest rate and the highest rate over GF(2^4) in VLC standard [1] are RS (15,3) and RS (15,11) codes, respectively, and RS (64,32) codes are defined over GF(2^8) in VLC standard [1].

Performance of the proposed ML decoding of RLL decoder is also compared with one of the referred RLL decoder with hard decoding. E_b/N_0 is used for SNR, where E_b is bit energy and N_0 is noise energy. This SNR is same with one in [4] and [5]. The simulation resultes are shown in Fig. 4, Fig. 5, Fig. 6, and Table IV.

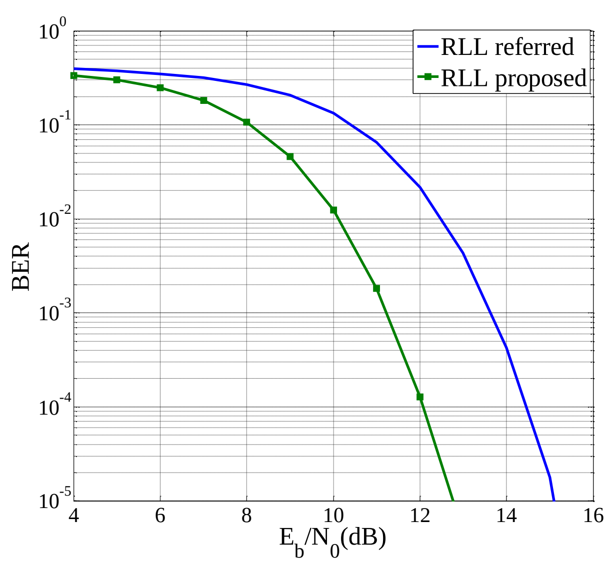

Fig. 4. BER performances of the RS (15,3) codes over GF(2^4) with 4B6B RLL codes and OOK modulation

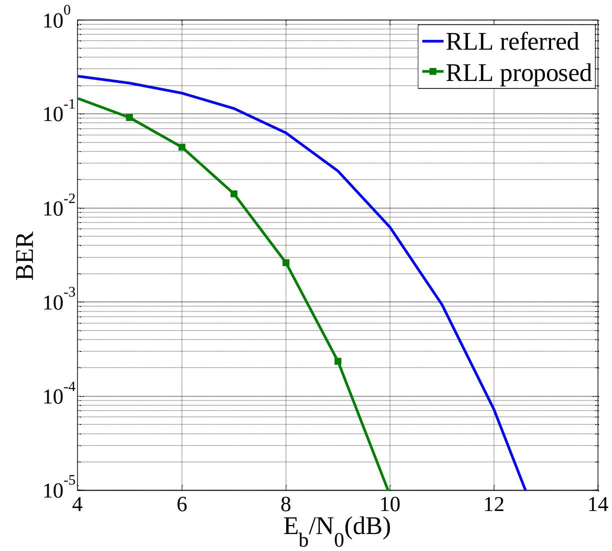

Fig. 5. BER performances of the RS (15,11) codes over GF(2^4) with 4B6B RLL codes and OOK modulation

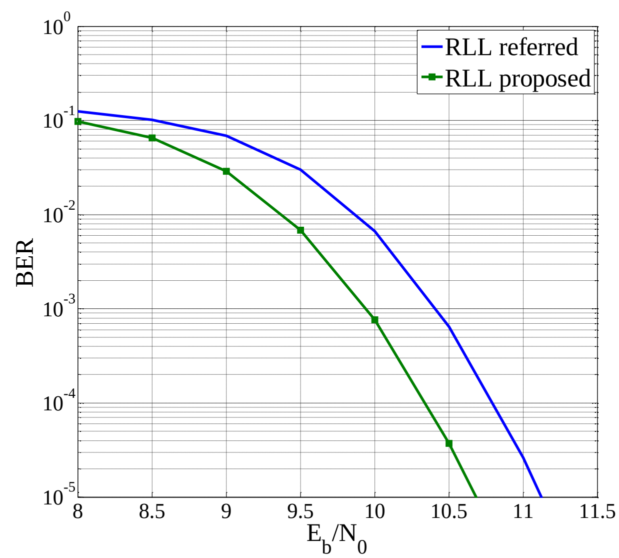

Fig. 6. BER performances of the RS (64,32) codes over GF(2^8) with 8B10B RLL codes and OOK modulation.

TABLE IV

THE E_b/N_0 (dB) OF PROPOSED RLL CODES AND REFERRED RLL CODES AT BER=10^{-5}

	RLL referred	RLL proposed	gap
RS (15,3)	15.10	12.77	2.33
RS (15,11)	12.61	9.97	2.64
RS (64,32)	11.12	10.68	0.44

From Fig. 4, Fig. 5, and Fig. 6, the BER performances of the proposed scheme are better than ones of the RLL with hard decoding. For 4B6B RLL codes, the BER performances of high-rate RS codes are better than one with low-rate RS codes. To investigate the performance enhancement at BER=10^{-5}, the required SNR and performance gain are shown in Table IV.

IV. Conclusion

ML decoding of RLL codes with an OOK modulation and RS codes in VLC has been proposed in this paper. As the new receiver architecture, the proposed RLL decoder makes better output based on ML rule which making use of soft value from a VLC channel. From simulation results, the proposed ML decoding of RLL codes shows better performance than conventional RLL codes. This decoder can be applied to VLC systems which required more reliable transmission without changes of VLC transmitter.

References

[1] IEEE Std 802.15.7, "IEEE standard for local and metropolitan area networks-part 15.7: Short-range wireless optical communication using visible light, " *IEEE Computer Society*, pp.248:271, 2011.

[2] J.G. Proakis and M. Salehi, "Digital Comunications" *McGraw-Hil*, pp.471-475,2008.

[3] K. Lee and H. Park, "Modulations for visible light communications with dimming control," *IEEE Photonics Technology Letters*, vol. 23, no. 16, pp. 1136-1138, Oct. 2010.

[4] S. Kim and S.-Y. jung,"Novel FEC coding scheme for dimmable visible light communication based on the modified Reed-Muller codes", *IEEE Photonics Technology Letters*, vol.23, no.20, pp.1514-1516, Oct.15, 2011.

[5] S. Kim and S.-Y. jung,"Modified Reed-Muller coding Scheme Made from the Bent Function for Dimmable Visible Light Communication", *IEEE Photonics Technology Letters*, vol.25, no.1, pp.11-13, Jan.1, 2013.

[6] A. Mengi. and A.J.H. Vinck,"Code Frequency Modulation with RLL Sequences for CENELEC Band Applications," *IEEE International Symposium on Power Line Commun. and Its Applications* (*ISPLC*), pp.133-137, Mar. 2007.

[7] 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 Comm.*, vol. 8, no. 6, June 2009.

[8] T. Komine, M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Trans. On Consumer Electron.*, vol. 50, no. 1, pp. 100-107, Feb. 2004.

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