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Soft-Input Soft-Output Run-Length Limited Decoding for Visible Light Communication

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ABSTRACT:- *In this letter, we propose a new algorithm based on a soft-input soft-output run-length limited (RLL) decoder in visible light communication (VLC) with on–off keying (OOK) modulation and Reed–Solomon (RS) codes. Conventional RLL codes are used for dimming adjustments in VLC; however, in our receiver model, the posterior probability matrix is produced by the new RLL decoder, and it can be matched as the input of the soft RS decoder to enhance the throughput in the VLC system. A significant advantage of our proposed method is that it leads to the enhancement of bit error rate (BER) and frame error rate (FER) performances without any change in the transmitter in VLC systems. The simulation results show that the majority of the BER and FER performances of our proposed method are better than those of hard-input hard-output RLL decoding and soft-input hard-output RLL decoding methods.*

Keywords*:- Soft-input soft-output (SISO), run-length limited (RLL) codes, visible light communication (VLC).*

I. INTRODUCTION

With widely used optical sources, such as light emitting diodes (LEDs) and laser diodes [1], visible light com-munication (VLC) techniques recently have garnered increas-ing attention. In VLC, modified lighting sources can be used to transmit information using LEDs. If we consider the hardware constraints for practical usage, on-off keying (OOK), the transmission of binary data by on/off pulses is widely adopted in VLC due to its simplicity [2]. Run-length limited (RLL) [3] codes take in random data symbols at the input and guarantee a DC balance with equal 1s and 0s at the output in order to allow every symbol to adjust dimming in VLC. Three RLL codes, Manchester, 4B6B, and 8B10B, are adopted in the VLC standard [4].

Since the emergence of VLC, a lot of work has been done to produce efficient transmission in VLC. In [5], a novel forward error correction (FEC) coding method based on modified Reed-Muller (RM) codes was proposed for pro-viding accurate dimming control in OOK-modulated VLC. Moreover, a modified RM coding scheme made from the bent function for dimmable VLC was proposed in [6], suggesting a new method to simultaneously contain minimal compensation symbols in supporting multiple dimming target values and to improve coding gain. In power line communication with frequency shift keying, the efficient combination of RLL sequences and Reed-Solomon (RS) codes was proposed [7]. Recently, a novel soft-input hard-output RLL decoder was pro-posed, and it showed enhancement of the bit error rate (BER) performance in VLC [8]. However, the drawbacks of the RLL decoder [8] was that the decoder was designed to produce a hard-decision output for the RS decoder based on the Berlekamp-Massey (BM) algorithm, which sacrificed some more valuable soft information; and complexity improved much more with the number of candidates increased since more RS decoders were needed. Therefore, research relating to soft-output RLL decoder to enhance the VLC performance is needed.

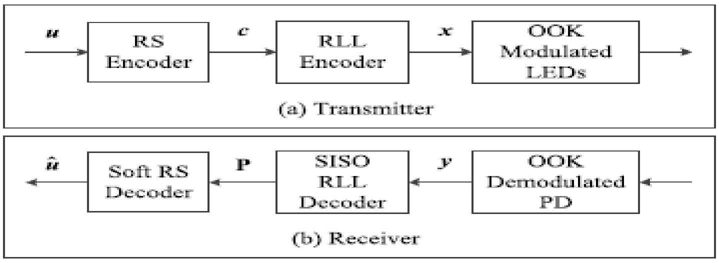

Fig. 1. Block diagrams of the transmitter and receiver in the proposed VLC system.

In this letter, we propose a new decoding algorithm based on the soft-input soft-output (SISO) RLL decoder in VLC with an OOK modulation and RS codes. The proposed SISO RLL decoder produces reliable soft output, which can be used as a soft input of the RS decoder to enhance the throughput in the VLC system. Simulation results show that our proposed algorithm obtains better BER and frame error rate (FER) performances than those of conventional RLL decoding and referred RLL decoding [8].

II. SYSTEM MODEL

2.1 Proposed VLC Systems

A block diagram of the proposed system is shown in Fig. 1. The transmitter in Fig. 1 (a) is composed of an RS encoder, an RLL encoder, and OOK-modulated LEDs; it is similar to the transmitter in the VLC standard [4].

Original RS (n, k) codes [9] over GF(2q) are considered where n ≤ 2q and GF(2q) is {β1, β2, . . . , β2q }. The K-Symbol message u = (u1, u2, u3……. uk), where ui is in GF(2q), can be mapped to a corresponding polynomial u(x) = u1 + u2 x + · · · + uk x k.The codeword of the RS encoder, , c = (c1, c2, . . . , cn), is defined as ci = u(αi) for i = 1, 2,..., n, n, where α1, α2,...,αn, are n distinct elements in GF(2q). A frame in this letter is considered as a codeword in the physical layer. To represent one q-bit vector, t = (t1,t2,...,tq), from a Galois field element for RLL encoding, the transfer function V is considered to be V (α) = t. Since the transfer function is a bijection, if α = β for α and β in GF(2q), then V (α) = V(β). Therefore, any element β in GF(2q) can be mapped to one of 2q distinct binary vectors t. Next, in an RLL encoder, the q-bit vector V(ci) corresponding to the symbol ci is encoded to an s-bit RLL codeword xi = (xi,1, xi,2,..., xi,s) according to the mapping rule E [1] as E(V (ci)) = xi for i = 1, 2,..., n. Then, the concatenated output of RLL codes x = (x1, x2,..., xn) is OOK-modulated and emitted to the channel.

The receiver in Fig. 1 (b) is composed of an OOK demodulated photodiode (PD), an SISO RLL decoder, and a soft RS decoder. The received OOK-demodulated signal, y (= x + n), is the input of the RLL decoder, where n is additive white Gaussian noise (AWGN) with variance σ2 [5], [6]. The RS decoder based on the Koetter-Vardy (KV) algorithm [10], which is an extension of the Guru Swami-Sudan (GS) algorithm [11], is considered for soft decoding. Our letter focuses on SISO RLL decoding combined with soft RS decoding.

2.2. *Soft-Input Soft-Output RLL Decoder*

Since 4B6B and 8B10B RLL codes in the VLC standards [1] are provided for combination with RS codes, they are considered in this letter. Here (q,s) represent (4, 6) or (8, 10). The (q,s) RLL codes have an one-to-one mapping rule E between q-bit vectors and s-bit codewords, and the average weight of each s-bit codeword is s/2 in order to maintain a DC balance.

The input of the RLL decoder is defined as y = (y1, y2,..., yn), where yi = (yi,1, yi,2,..., yi,s) for i = 1, 2,..., n. The RLL decoder decodes y by processing (s-bit codeword) yi and outputs a reliable matrix, which can be used in soft RS decoding [10]. The reliable defined as

$$\mathbf{P} = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{2^q,1} & p_{2^q,2} & \cdots & p_{2^q,n} \end{bmatrix}$$

where pz,i is the posterior probability that the transmitted symbol ci is βz for z = 1, 2,..., 2q when the yi is received. It is assumed that, if the transmitted variable ci is uniformly distributed with equal probability, then pz,i can be calculated using Bayes' theorem,

$$p_{z,i} = p\left(c_i = \beta_z \,|\, \mathbf{y}_i\right) = \frac{p\left(\mathbf{y}_i \,|\, c_i = \beta_z\right) p\left(c_i = \beta_z\right)}{p\left(\mathbf{y}_i\right)}.$$

Therefore, $p_{z,i}$ = Δp(yi|ci = βz), where is a constant valuesince p(ci = βz) is $1/2^q$.

The proposed decoding rule of RLL codes is composed of five steps. The received signal y = (y1, y2,..., yn) is used for soft input in the RLL decoder, the i-th column of matrix P is produced for i = 1, 2,..., n. A detailed explanation about SISO RLL decoding steps is provided below.

Step 1: Initialization $i = 1$.
Step 2: The *s*-bit codeword probability is defined as

$$p\left(y_i|x_i\right) = \prod_{j=1}^{s} p\left(y_{i,j}|x_{i,j}\right),$$

$$\text{where} \quad p\left(y_{i,j}|x_{i,j} = \theta\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\left(y_{i,j}-\theta\right)^2}{2\sigma^2}},$$
for $\theta = 0, 1$.

Step 3: According to the mapping rule [1] that $E(V(c_i)) = \mathbf{x}_i$, the corresponding *q*-bit vectors have the same probabilities with *s*-bit codewords, then

$$p(V(c_i) = V(\beta_z)) = p(x_i).$$

Step 4: Calculate the *i* –th column in the reliable matrix:

$$\begin{aligned} p_{z,i} &= \Delta p\left(y_i\,|c_i = \beta_z\right) = \Delta p\left(y_i\,|V\left(c_i\right) = V\left(\beta_z\right)\right) \\ &= \Delta p\left(y_i|x_i\right), \end{aligned}$$

where $V(\beta_z)$, $z = 1, 2, \ldots, 2_q$ correspond to all indicated vectors from elements of GF(2_q).
Step 5: Calculate all the probabilities of the *i* -th column from $i = 1$ to n, if $i < n$, $i \leftarrow i + 1$ and go to **Step 2**, else stop.

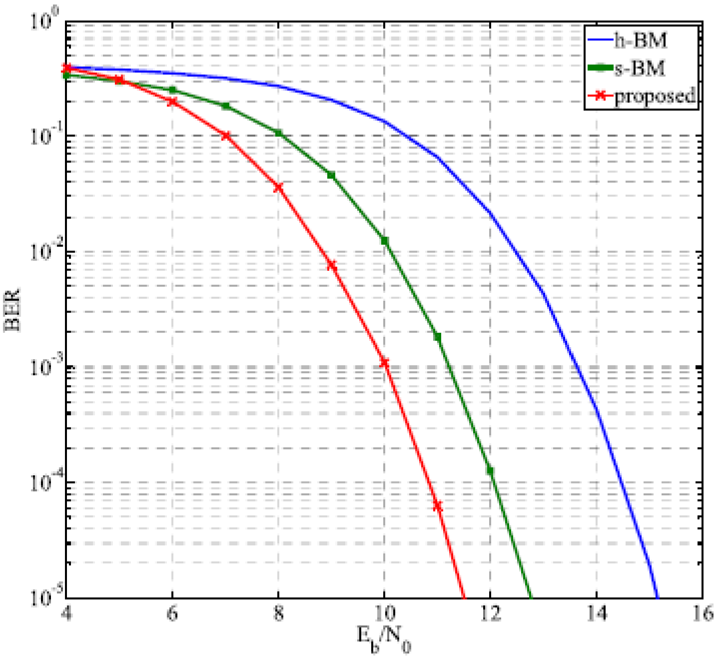

Fig. 2. BER performances of 4B6B RLL codes with RS (15, 3) codes.

III. SIMULATION RESULTS

The performances of the proposed RLL decoding based on soft RS decoding are compared with those of hard-input RLL decoding with BM and soft-input RLL decoding with BM [8] which corresponding to ‘proposed’, ‘h-BM’, and ‘s-BM’, respectively (in from Fig. 2 to Fig. 9). In these figures, E_b/N_0 is used for the signal-to-noise ratio (SNR), where E_b is the bit energy, and N_0 is the noise energy. The same SNR is also explained in [5], [6], and [8]. To demonstrate performance gain, the required SNRs of the proposed scheme and the referenced scheme for target performance are listed in Table I and Table II. The dB gain in these tables is the difference between the required SNR of the 'referenced' scheme and the 'proposed' scheme, and the percent gain is defined as

$$\frac{\text{required SNR of 'referenced' one}}{\text{required SNR of 'proposed' one}} \times 100(\%).$$

The 'Gain_A' and 'Gain_B' in Table I and Table II are the gains when 'h-BM' and 's-BM' are used as the 'referenced' scheme, respectively.

The BER results of 4B6B RLL codes are shown in Fig. 2, Fig. 3, Fig. 4, and Fig. 5, and the required SNRs and gains at BER=10^{-5} are listed in Table I.

TABLE I

THE REQUIRED SNR AND GAIN AT BER=10^{-5}

BER		proposed	s-BM [8]	h-BM	Gain_A		Gain_B	
RLL	RS				dB	%	dB	%
4B6B	(15, 3)	11.51	12.77	15.16	1.26	110.9	3.65	131.7
	(15, 7)	9.81	10.28	12.77	0.47	104.7	2.96	130.1
	(15, 11)	10.11	9.97	12.61	-0.14	98.6	2.50	124.7
8B10B	(64, 32)	10.33	10.69	11.12	0.36	103.4	0.79	107.6

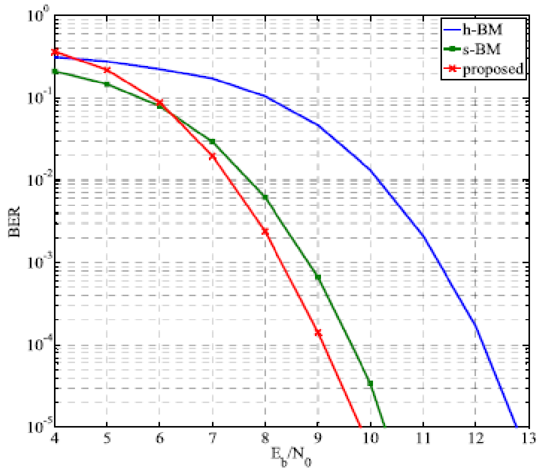

Fig. 3. BER performances of 4B6B RLL codes with RS (15, 7) codes.

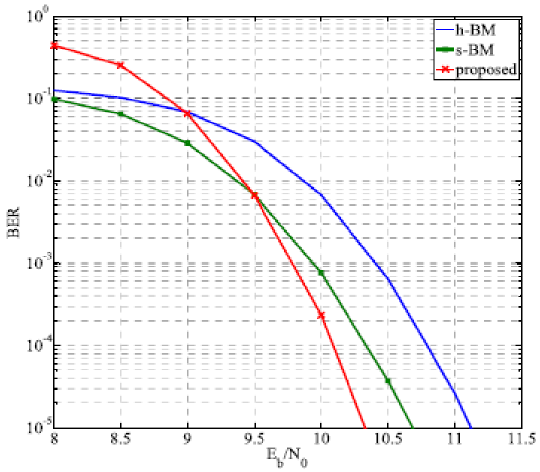

Fig. 5. BER performances of 8B10B RLL codes with RS (64, 32) codes.

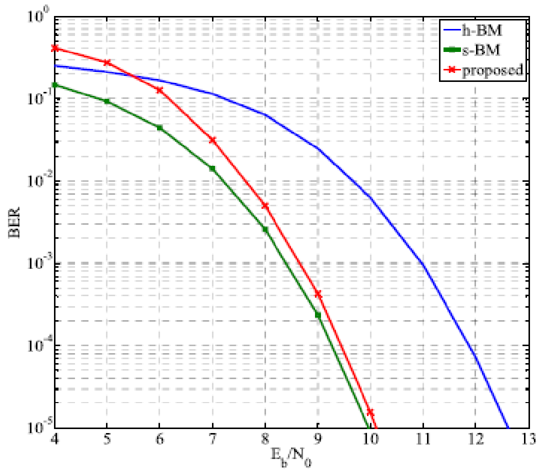

Fig. 4. BER performances of 4B6B RLL codes with RS (15, 11) codes.

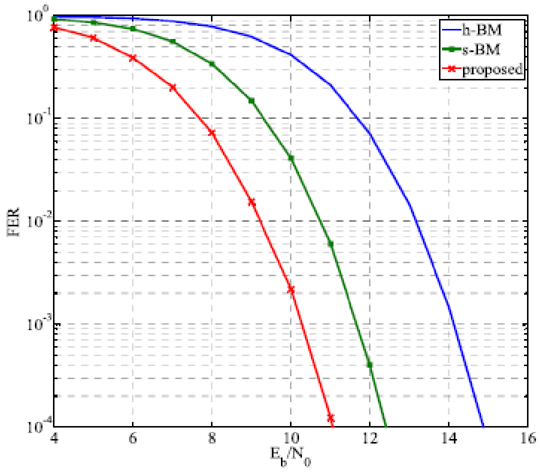

Fig. 6. FER performances of 4B6B RLL codes with RS (15, 3) codes.

As shown, the BER performances of the proposed scheme are better than those of conventional RLL decoding ('h-BM') and those of 's-BM' [8] except in Fig. 4. In Fig. 2, Fig. 3, and Fig. 4, the performance gain of 4B6B RLL codes is larger when low-rate RS codes are used since the symbol probabilities updated from the proposed scheme are more effective for RS codes with a larger minimum distance [11]. In Fig. 3 and Fig. 5, the rates of RS codes are nearly the same, but the performance gain for 4B6B is better than that of 8B10B since the code rate of the 4B6B codes is lower than that of 8B10B code.

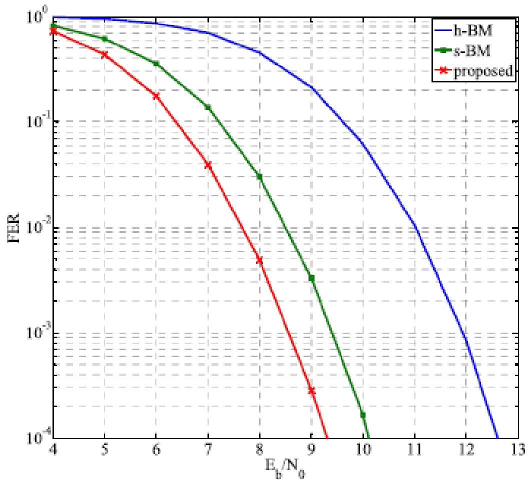

Fig. 7. FER performances of 4B6B RLL codes with RS (15, 7) codes.

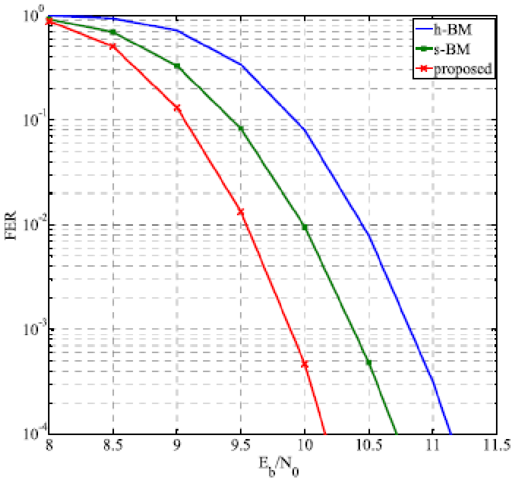

Fig. 9. FER performances of 8B10B RLL codes with RS (64, 32) codes.

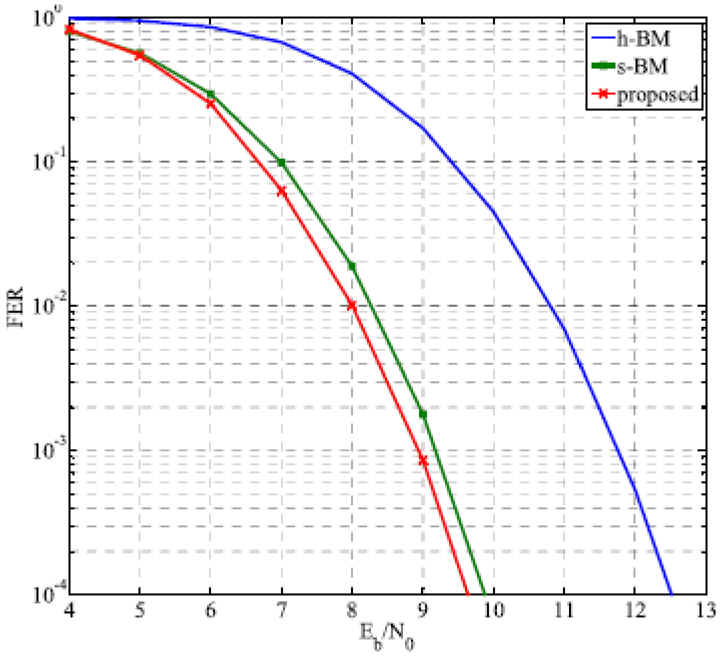

Fig. 8. FER performances of 4B6B RLL codes with RS (15, 11) codes.

Under the same conditions, FER results are shown in Fig. 6, Fig. 7, Fig. 8, and Fig. 9, and the required SNRs and gains at FER=10^{-4} are listed in Table II.

TABLE II

THE REQUIRED SNR AND GAIN AT FER=10^{-4}

FER		proposed	s-BM [8]	h-BM	Gain_A		Gain_B	
RLL	RS				dB	%	dB	%
4B6B	(15, 3)	11.05	12.42	14.90	1.37	112.3	3.85	134.8
	(15, 7)	9.31	10.12	12.61	0.81	108.7	3.30	135.4
	(15, 11)	9.64	9.89	12.52	0.25	102.5	2.88	129.8
8B10B	(64, 32)	10.16	10.72	11.14	0.56	105.5	0.98	109.6

IV. CONCLUSION

A new soft-input soft-output RLL decoding in VLC has been proposed in this letter. We modified receiver part in VLC, as the new receiver architecture, the soft information from channel is decoded into a reliable matrix by the proposed RLL decoder, then the reliable matrix can be used for the conjugated soft RS decoder to enhance the throughput in the VLC system. The proposed scheme shows better BER and FER performances than those of the referenced schemes (‘h-BM’ and ‘s-BM’). Our proposed schemes can especially increase throughput of a VLC scheme with ARQ. An acknowledgement section may be presented after the conclusion, if desired.

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