An Efficient Decoding Strategy of 2D-ECC for Optical Recording Systems

Jun Lee and Kees A. Schouhamer Immink, *Fellow*, IEEE

Abstract — *Two-dimensional error correction codes (2D-ECCs) have been the cornerstone of all three generations of optical recording - CD, DVD and BD. Research into powerful error correction methods is paramount for the development of high-capacity optical recording systems. A Reed-Solomon product-code (RS-PC) for DVD systems performs error and erasure decoding by giving and taking erasure information between two ECCs. In this paper, we will present a new error correction method that performs erasure decoding using the only erasure information supplied from a modulation code decoder – more specifically, the EFMPlus code for DVD systems. We will evaluate the decoding efficiency of the new error correction method under a channel environment with various error types.*

Index Terms— Erasure decoding, RS-PC, EFMPlus code and DVD systems.

I. INTRODUCTION

Due to increasing demand for high-quality consumer products, optical storage systems such as DVD systems [1] and BD systems [2] have been developed to provide higher storage capacity by leading industrial consortia. One solution for achieving higher storage capacity is a powerful error correction technique. In order to correct the errors that may be included in the output stream of a modulation code [3] decoder, optical recording systems utilize 2-dimensional error correction codes (2D-ECCs).

The 2D-ECCs are composed of two ECCs and perform error and erasure decoding [4] by exchanging erasure information between two ECCs. The 2D-ECCs use a Reed-Solomon (RS) code [4] as an error correction code. The reason is to increase their error correction capability using erasure decoding of the RS code. When the erasure decoding is employed, an RS code with t error correction capability [4] is capable of correcting v errors and e erasures, where $2v+e \le 2t$. In other words, the number of maximum correctable errors by an RS code is t, while the number of maximum correctable erasures by RS code is $2t$. This implies that the performance of the 2D-ECCs depend on how efficient the used erasure decoding is.

The use of a modulation code in optical recording systems is essential for the reduction of inter-symbol interference, timing recovery and servo tracking. The decoder takes the output stream of a detector as its input. Under the decoding algorithm of the modulation code like the slide-block algorithm [3], the decoder decodes the output stream of a detector by searching a look-up table. If the input of the decoder does not exist in a look-up table, the decoder declares erasure to the corresponding output and then assigns a pre-defined value, which is one of the elements of a Galois field, to the erased position. The resulting output stream contains the errors and erasures. This erasure information can play a significant role in improving the error correction capability for RS decoders. However, under the conventional erasure-decoding rule of 2D-ECC, the 2D-ECC accomplishes the error and erasure decoding without using this erasure information stemming from the modulation code decoder. Also, it is possible that the 2D-ECC exchanges the incorrect erasure information with a high probability between two ECCs.

This paper proposes a new error correction method that performs error and erasure decoding using the only erasure information supplied from the modulation code decoder. The main goal of this paper is to increase error correction capability by improving the erasure decoding method of conventional 2D-ECC. This method requires no exchange of erasure information between two ECCs, and the erasure information only stems from the modulation code decoder. The erasure information may be more reliable than that of conventional 2D-ECC because the 2D-ECC is just designed to correct errors and erasures included in the output stream of the modulation code decoder. The performance of the proposed erasure decoding is evaluated under a DVD system. Thus, the modulation code is the EFMPlus code [5] and the 2D-ECC is a Reed-Solomon product-code (RS-PC) [6][7].

The paper is organized as follows. In Section 2, we overview the RS-PC for DVD system and introduce the problems inherent in its erasure decoding methods. In Section 3, we describe a new erasure decoding method. In Section 4, simulated results are shown. Finally, the conclusion is given in Section 5.

Jun Lee is with Digital Storage Research Laboratory, LG Electronics in Korea (e-mail: leejun28@lge.com).

Kees A. Schouhamer Immink is with Institute for Experimental Mathematics, Ellernstrasse 29-31, Essen, Germany (e-mail: immink@turing-machines.com).

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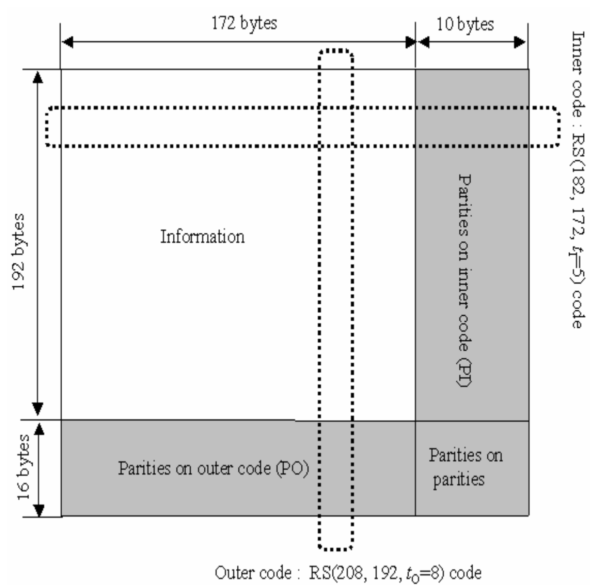

Fig. 1. RS-PC structure for DVD systems

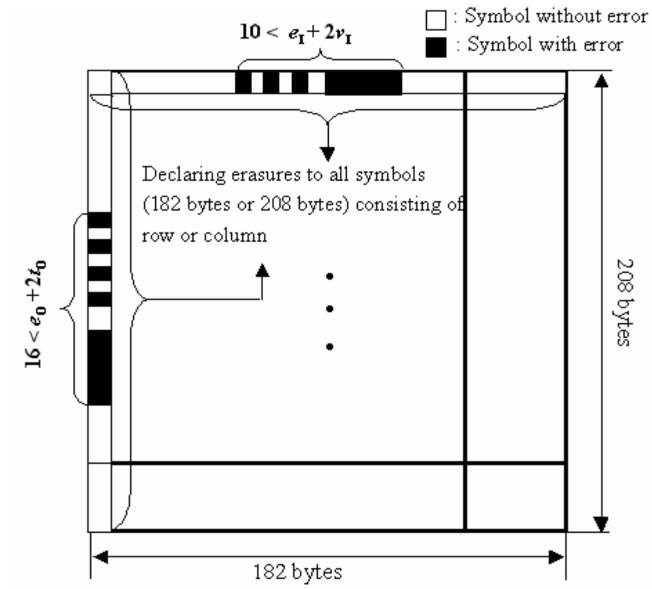

Fig. 2. The incorrect erasure declaration under the conventional decoding rule of RS-PC.

II. RS-PC FOR DVD SYSTEMS

Erasure decoding technique plays a significant role in error correction systems because it can correct twice as many erasures as it can errors ($e + 2v \leq 2t$). For erasure decoding, optical recording systems adopt a 2-dimensional structure with two ECCs. Each of the two ECCs provides erasure information to the other. Based on that erasure information, ECCs can perform erasure decoding in addition to error-only decoding. Thus, the accuracy of the erasure information supplied is a key factor in deciding the performance of the 2D-ECCs. This Section simply introduces the conventional error and erasure decoding method of the RS-PC, and describes its drawbacks.

The RS-PC is illustrated in Figure 1. Each row of information is encoded by RS (n=182, k=172, t_I=5) code (namely, inner code) over GF (2^8), where n and k are the length of the codeword and information respectively. All columns are encoded by RS (208, 192, t_O=8) code (namely, outer code).

Error and erasure decoding consists of two steps. First, RS-PC decodes each row (column) by inner code (outer code) and then, if the number of error bytes is over 5 (8), such rows (columns) result either in a mis-correction or in a decoding failure. If it is a decoding failure, the RS-PC declares erasures to the codeword (182 bytes or 208 bytes) in that row (column). Second, after mapping the erasure information to error-position over outer code (inner code), outer code (inner code) performs the error and erasure decoding about all columns (rows).

The drawbacks of RS-PS are given as follows. In the first decoding process, the inner code (outer code) can just perform error-only decoding. In addition, if the number of error bytes in each row (column) exceeds 5 (8), inner code (outer code) declares the erasure to the codeword (182 bytes or 208 bytes) in such row (column). Note that the symbols included in the erased row (column) may or may not be in error. In this case, it is possible that the inner code(outer code) supplies the incorrect erasure information to the outer code (inner code) and then outer code (inner code) unreliably performs the error and erasure decoding. Outer code also can supply inaccurate erasure information to inner code in the same manner. If the symbol error rate after detection is high, phenomena like the above will more frequency happen and the decoding efficiency of the RS-PC will decrease. In the RS-PC, the approach of iterative error correction between inner code and outer code is possible. However, under conventional erasure decoding methods for RS-PC, the approach does not induce the improvement of performance. Figure 2 shows incorrect erasure declarations under the conventional error correction of RS-PC. In Figure 2, v_I and v_O are the number of error bytes included in the shown row and column respectively, and e_I and e_O are the number of erasures declared in the shown row and column respectively. In Figure 2, inner code and outer code declare erasure to the shown row and column if $2v_I + e_I > 10$ ($=2t_I$) and $2v_O + e_O > 16(=2t_O)$, respectively. For better decoding efficiency of error correction systems, the research of a technique for supplying more accurate erasure information is essential.

III. A NEW ERROR CORRCTION TECHNIQUE

The output stream of the modulation code decoder may contain the errors and erasures, referred to as *a priori* information. This output stream is rearranged for the decoding-unit for 2D-ECC, and then it is fed to the 2D-ECC. The RS-PC treats the *a priori* information as error and performs error and erasure decoding based on the erasure information generated by two ECCs in the error correction process. This *a priori* information may be more accurate than that of the RS-PC because the RS-PC is just

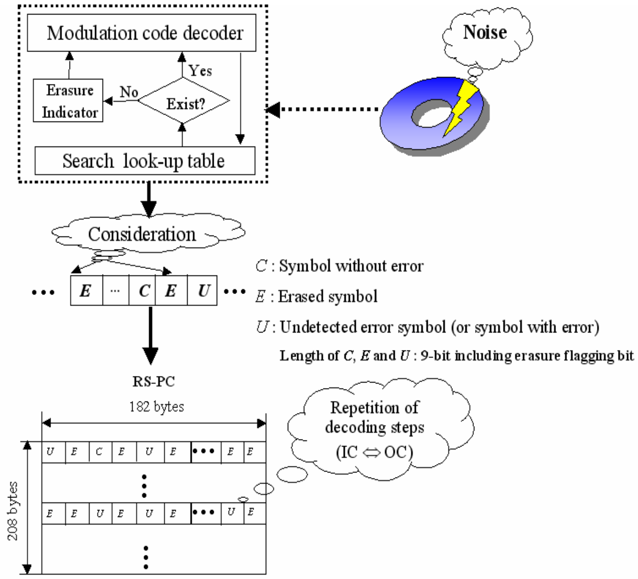

Fig. 3. A new error and erasure correction strategy for RS-PC

designed to control the errors and erasures contained in the output stream of the modulation code decoder. Thus, for erasure decoding, the consideration of this *a priori* information can be expected to improve the decoding efficiency of RS-PC. This method performs the erasure decoding using the only *a priori* information without exchanging the erasure information between two ECCs.

Under current DVD systems, this *a priori* information cannot be utilized as error-position information for RS-PC erasure decoding. The reason is because the pre-defined value used for representing *a priori* information is one of the elements over $GF(2^8)$ consisting of a codeword of error correction code. The erasure decoding of the RS-PC using the only *a priori* information can be realized by the following method. The realization is possible by appending erasure–indication bits to the output symbol of a modulation code decoder. Thus, the EFMPlus code decoder outputs 9 bits, which include both the erasure-indication bit (1 bit) and its output symbol (8 bits), instead of just the 8 bits. If the erasure indication bit among the 9 bits is set to 1, it means that the symbol at that position is erased. A pre-defined value for expressing the *a priori* information is no longer one of elements over $GF(2^8)$ and thus it is distinguished from elements consisting of the RS codeword. For error correction, the RS-PC searches for this pre-defined value in its decoding unit and then maps it to the error position. Sequentially, RS-PC can perform erasure decoding based on the only error position. Based on this error position, repeatable error corrections between inner code and outer code are possible and this approach induces an incredible performance gain compared to the same approach of RS-PC under conventional erasure-decoding rules. Figure 3 shows the proposed erasure decoding procedure. In Figure 3, the modulation code is the EFMPlus code and its decoder outputs 8 bits after taking 16 bits as its input. Under the given decoding rule, the decoder decodes the output stream by searching a look-up table. If the input of the decoder does not exist in the look-up table, the decoder outputs 9 bits of a pre-defined value. The corresponding output is referred to as the erased symbol, or E. In case the input of the decoder is in error but it exists in the look-up table, the decoder outputs 9 bits in which the erasure indication bit is set to 0. The corresponding output is referred to as an undetected error symbol, or U. The output stream of the decoder contains the erased symbol E, the symbol with an error U and the symbol without error, or C. This output stream is rearranged to 208 by 192 bytes and is input into the RS-PC. Finally, RS-PC accomplishes the erasure decoding based on the only erased symbol without exchanging erasure information between the two ECCs, and this decoding is repeatedly performed between inner code and outer code.

IV. SIMULATION RESULTS

In simulation, the decoding block for RS-PC is referred to as a frame, and the number of total frames (T) used is 200. The number of total error bytes added to the input of the modulation code decoder is SER × the frame size (208 by 192 bytes), where SER (%) stands for Symbol Error Rate. The types of errors tested are random errors (R, %), short burst (S%), and long burst errors (L, %). In simulation, the length of R is 1 byte, the length of S is between 5 and 40 bytes and the length of L is between 40 and 182 bytes. In the channel model of this work, the ratio of E to U depends on the types of errors tested and their distribution. All simulation figures show the ratio of E to U and a Lena Image reflecting the given error-types and their distribution at specific SERs. In the figures, the X-axis means $-10\log_{10}$ (SER) and the Y-axis means the uncorrected symbol error rate. Figures 4 and 5 represent the performance of RS-PC under (R =100%) and (R =33%, S =33% and L =34%), respectively. From simulation results, we can identify that RS-PC using the proposed erasure decoding (in short, I (Improved) RSPC) outperforms conventional RS-PC irrespective of error types and their distributions. Simulation results reveal that the proposed erasure decoding method clearly overcomes the drawback of conventional erasure decoding methods, while conventional RS-PC performs erasure decoding by exchanging incorrect erasure information with a high probability between inner code and outer code. In the approach of repeatable error correction between two ECCs, the RS-PC using the proposed erasure decoding method achieves incredible performance gains as the number of iterations increases, while conventional RS-PC does not. This fact implies that two RS-PC ECCs do not generate precise erasure information under conventional erasure decoding even if they employ repeatable error correction.

Under the more various channel environments, we also tested a new erasure decoding method and the results have

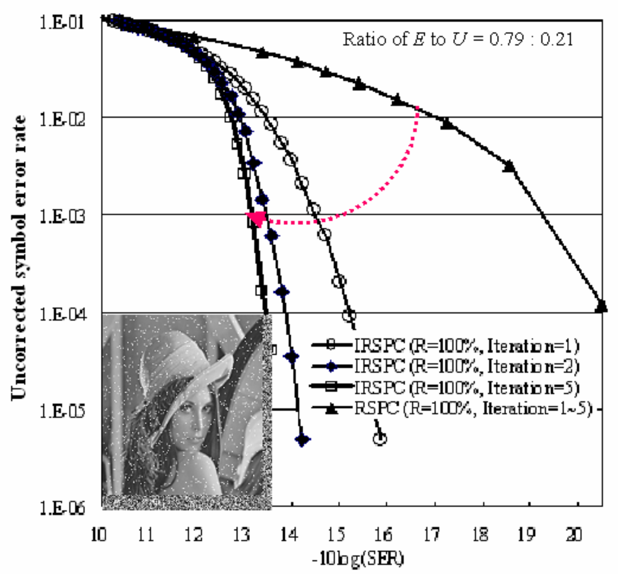

Fig. 4. Performance comparison at *R*=100%

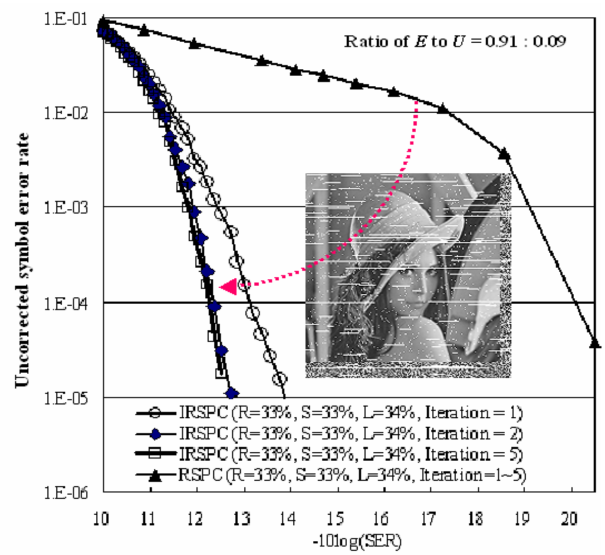

Fig. 5. Performance comparison at *R*=33%, *S*=33% and *L*=34%

shown that the new method outperforms the conventional method no matter the channel environment. This section introduces two applications exploiting the proposed criteria applying to GS scheme with RLL constraints and the 2/3 (1, 7) PP code.

V. CONCLUSION

We have proposed an efficient erasure decoding method using the only erasure information provided from the modulation code decoder. This new method definitely overcomes the drawbacks of conventional erasure decoding methods for DVD systems. The improvement of performance is induced by independent erasure decoding of two ECCs. The new method achieves high performance gains irrespective of error types and their distribution, and can easily be applied to optical recording systems such as BD systems with minor modifications. Thus, we conclude that the proposed method can be a candidate for next-generation storage systems requiring more reliable error control systems.

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BIOGRAPHY

Jun Lee received his B.S. and M.S. degree from Dongguk University, Seoul, Korea in 1998 and 2000, respectively. Since March 2000, he has been a Ph.D. student in Dept. of Electronic Engineering at Dongguk University. In 2003, he received Ph. D. degree and he joined the faculty of Samsung Advanced Institute of Technology (SAIT), Suwon, Korea, and he is currently working with LG Electronics. His research interests are signal processing and coding for storage systems and communication theory.

Kees Schouhamer Immink received his PhD degree from the Eindhoven University of Technology. He was with Philips Research Labs in Eindhoven from 1968 till 1998. He founded and became president of Turing Machines Inc. in 1998. He is, since 1994, an adjunct professor at the Institute for Experimental Mathematics, Essen University, Germany. Immink designed coding techniques of virtually all consumer-type digital audio and video recording products, such as Compact Disc, CD-ROM, CD-Video, Digital Audio Tape recorder, Digital Compact Cassette system, DCC, Digital Versatile Disc, DVD, Video Disc Recorder, and Blu-ray Disc. He received widespread recognition for his many contributions to the technologies of video, audio, and data recording. He received a Knighthood in 2000, a personal 'Emmy' award in 2004, the 1996 IEEE Masaru Ibuka Consumer Electronics Award, the 1998 IEEE Edison Medal, 1999 AES Gold Medal, and the 2004 SMPTE Progress Medal. He was named a fellow of the IEEE, AES, and SMPTE, and was inducted into the Consumer Electronics Hall of Fame, and elected into the Royal Netherlands Academy of Sciences and the US National Academy of Engineering. He served the profession as President of the Audio Engineering Society inc., New York, in 2003.