DC-free Multimode Code Design Using Novel Selection Criteria for Optical Recording Systems

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Abstract — *DC-free run-length limited codes have been the cornerstone of all three generations of optical recording, CD, DVD and BD. Research into very efficient coding methods is paramount for the upcoming fourth generation. Guided Scrambling (GS) is an efficient coding method that has been reported in the literature. Under GS rules, a user word is translated into a plurality of possible candidate words, and among the candidate words the encoder selects the codeword with the least low-frequency spectral content. In our paper, we will present results of our attempts to improve the performance of GS-based codes. We will present new selection criteria and evaluate their performance and complexity. Specifically, we will evaluate the new selection criteria to the 2/3(1,7) parity preserving code used in Blu-Ray Disc.*

Index Terms — Selection Criterion, GS, DC-free RLL code

I. INTRODUCTION

The design of codes for optical recording is essentially the design of the combined DC-free and runlength-limited (DCRLL) codes. An RLL constraint in optical recording plays a crucial role for the reduction of channel impairments and clock recovery. The DC-free property is for circumventing or reducing interaction between data written on disk and the servo systems that follow the track. In literatures [1][2], the design of DCRLL codes can be accomplished by several design techniques and has been mostly concentrated on byte-oriented DCRLL code with the small codeword length. The data recording industry has been moving towards detection scheme that can function well at high code rate such as 16/17, 24/25 and 32/33. For certain application, it is desirable that the code rate and codeword length of a modulation code for optical recording are even higher. However, unfortunately, the design of high-rate DCRLL code satisfying all of two constraints is far from obvious, and severely hampered by the large number of states of the finite-state machine (FSM) which models the channel constraints [3][4].

One possible solution for achieving high capacity adopts a weakly constrained code, instead of perfectly RLL constrained code, for designing recording code. Recently, multimode coding scheme is issued for next-generation optical recording [4][5]. The coding scheme is one of methods for constructing weakly constrained code with DC-free property. In multimode codes, each source word is translated into codewords of a selection set consisting of $L > 3$ codewords. The encoder evaluates the quality of each codeword in the selection set, and then transmits the codeword with the least DC-contribution. There are two key elements for multimode code design with DC-free property. One is a scrambler for translating source words into their corresponding selection sets, and the other is a good criterion for evaluating the quality of the candidate codewords. The spectral performance of the code greatly depends on both issues.

The best multimode coding scheme reported is guided scramble (GS) [6]. Originally, GS scheme is designed for fiber optic communication system required to DC-suppression, and its application is limited to the transmission system over fiber cables. In recent, its application is moving toward optical recording system requiring DC-free property. GS scheme exploits the linear shift feedback register as scrambler and augmenting step for generating the distinct candidate codewords. The DC-control of GS scheme can be achieved by developing selection criterion, which is one of the key elements of multimode code. The criteria developed can also be extended to any multimode coding scheme. Immink and Patrovics [4] assessed the spectral performance of the GS scheme under conventional criteria. With the same redundancy, the simulation results show that the performance of GS scheme with short codeword length is almost the same irrespective the selection criteria, while that with long codeword length is very sensitive to the selection criteria. This fact reveals that the selection criterion is indispensable for multimode code design with DC-free property and certain application.

The criteria reported for evaluating the quality of the candidate codewords are minimum running digital sum (MRDS), minimum squared weight (MSW) and minimum threshold overrun (MTO) [1][4][9]. The MRDS criterion that selects a codeword with minimum absolute RDS at the end of each codeword requires the simplest complexity, while its spectral performance is degraded as the length of codeword is increased. The MSW criterion that selects a codeword with the minimum variance of RDS among candidate codewords can achieve the best performance irrespective of the codeword length, while its complexity is large because it requires the squaring operation. The MTO criterion simply counts the number of times that the absolute value of RDS in the codeword is larger than the threshold predetermined by trial and error. Then, it selects the codeword with minimum overrun. The structure is simple compared to MSW, while it can select codeword with bad quality because it randomly chooses one if there are codewords with the same penalty. This paper suggests the minimum peak RDS (MPRDS) criterion that is simple to implement while its efficiency approaches that of the MSW criterion. The scheme does not require the exhaustive search of optimal threshold unlike MTO, and achieves the reasonable

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performance irrespective of the number of candidate codewords like MSW, and only requires simple components (adder and comparator) while MSW requires squaring operator in addition to that of conventional criteria for implementation. For improving the performance of criteria, we also propose the sign change (SC) aided criteria. SC criterion is appended to the proposed and conventional criteria as sub-criterion, and then SC aided criteria reduce the probability selecting codewords with large DC-contribution among codewords with the same penalty. Thus, SC aided criteria can achieve better DC-suppression than those without SC. We also suggest the absolute RDS criterion (ABSRDS). This criterion is the simplified version of MSW because it uses absolute operation instead of the squaring operation of MSW for computing RDS variation. The scheme achieves the best performance among the proposed schemes. In addition, we introduce the complexity reduction (CR) versions of new and conventional criteria, which are CRMSW, CRABSRDS, CRMPRDS and CRMTO. CR criterion sparsely evaluates each codeword instead of checking at each bit of the codeword. The scheme requires definitely less complexity than the conventional schemes, and the performance loss is not noticeable in the range investigated. For displaying certain application of the proposed criteria, we apply the proposed criteria to 2/3(1, 7) parity preserving (PP) code [7], and GS scheme satisfying RLL constraints. For better DC-control of (1, 7) PP code, its encoding exploits look ahead (LA) algorithm that looks ahead some codewords. From the simulation results, we identify that the spectral performance of the proposed criteria outperforms that of conventional criteria.

This paper is organized as follows. We firstly start with some preliminaries in Section II. In Section III, we introduce the conventional and proposed criteria, and analyze their spectral performance. Section IV applies the proposed criteria to two DCRLL coding for optical recording systems. Finally, Section V remarks conclusion.

II. PRELIMINARIES

DC-free codes translate binary source sequences into binary channel sequences with spectral null at zero frequency. The amount of DC-content in channel sequences depends on the range of running digital sum (or digital sum value), in short RDS, of channel sequences. Let $x_i = \{\ldots, x_{-1}, x_0, \ldots, x_i, \ldots\}$, $x_i \in \{-1, 1\}$ be a binary sequence. The RDS z_i is defined as

$$z_i = \sum_{j=-\infty}^{i} x_j = z_{i-1} + x_i\,. \tag{2.1}$$

The literatures show that if z_i is bounded with small value, its power spectral density (PSD) vanishes at zero frequency [1][8]. Let the RDS z_i of sequences meet the condition $N_1 \le z_i \le N_2$ at any instant i, where N_1 and N_2 are two (finite) constants, $N_2 > N_1$. The digital sum variation (DSV, N) is defined as $N = N_2 - N_1 + 1$, and then sequences have DC-free property if N is sufficiently small.

The channel capacity $C(N)$ of maxentropic DC-free code can be easily computed if N is given [1], and is the important parameter for computing the efficiency of the implemented code. The other quantity is sum variance. Sum variance plays a significant role in the evaluation of the spectral property of the sequences. The reason is because the smaller the sum variance of sequences, the smaller its DC-content at low frequency.

Code efficiency [1] is given by

$$E = \frac{(1 - C(N))\sigma^2_{RDS}}{(1 - R)s^2} \tag{2.2}$$

where $1-C(N)$ and σ^2_{RDS} are the redundancy and sum variance of maxentropic DC-free sequences, respectively, and R is the code rate of the implemented code, and s^2 is variance of RDS values obtained at every bit position of sequences produced by implemented code. It means how redundancy-sum variance product of implemented code approaches to that of maxentropic sequence. Maxentropic DC-free sequences satisfy the following relationship between the sum variance and the redundancy [1]

$$0.2326 < (1-C(N))\,\sigma^2_{RDS} \le 0.25. \tag{2.3}$$

Since the codeword length that we are targeting is very long (greater than 50 bits), DSV is around 30. For large N, the redundancy-sum variance product of maxentropic sequences is approximately constant and equals 0.2326. Thus, E is given by

$$E \approx \frac{0.2326}{(1 - R)s^2}\,. \tag{2.4}$$

The efficiency in the equation (2.4) is used for discussing the performance of the proposed criteria.

The paper applies the proposed criteria to GS scheme, which is a multimode coding scheme, for examining their performance. Figure 1 represents the operation procedure of GS algorithm. In Figure 1, symbols T and $\oplus$ denote the shift register and modulo-2 addition, respectively. The operation process of GS algorithm is executed as follows. In the first step, the source word $X = \{x_1,\ldots,x_m\}$, $x_i \in \{0, 1\}$and $i = 1,\ldots,m$, is preceded by all the possible binary sequences of length $(r-1)$ to generate the $L' = 2^{r-1}$ vectors of $\mathbf{B}=\{\boldsymbol{b}_1,\ldots,\boldsymbol{b}_{L'}\}$, $\boldsymbol{b}_j = \{b_1,\ldots,b_n\}$ and $j = 1,\ldots,L'$. In the second step, each vector of length $n=m+r-1$ consisting of $\mathbf{B}$ is provided to linear shift feedback register. Then, set $\mathbf{B'} = \{b'_1,\ldots,b'_{L'}\}$ is produced, In the third step, the vectors in $\mathbf{B'}$ are preceded by both a one and a zero, and are shuffled by the scrambler with polynomial $x+1$ again. Then, selection set $\mathbf{C} = \{\mathbf{c}_1,\ldots,\mathbf{c}_L\}$, $L=2^r$, is produced. Each vector of $\mathbf{C}$ is composed by modulo-2 addition values between the current input and previous output of scrambler. This step embodies the polarity bit principle. In the fourth step, the given criterion selects and transmits codeword ($\mathbf{c}_{best}$) with the least DC-contribution out of candidate codewords. At receiver end, the codeword is firstly descrambled by using $x+1$ polynomial, and then after removing the first bit, it is descrambled. The original source word X is eventually reconstructed by removing r-1 bits.

III. SELECTION CRITERIA

There are two key components for multimode code design with DC-free property. The first one is the scrambler for converting source words into their corresponding selection sets, and the second one is the selection criterion, or metric, for evaluating the quality of the candidate codewords. The DC-control of multimode code can be achieved by developing a better criterion. This section offers an overview of the conventional criteria, it introduces new criteria, and evaluates their performance.

A. Conventional Criteria

MRDS: MRDS is often called word-end RDS (WRDS). MRDS is criterion that selects a codeword with minimum absolute RDS at the end of each codeword. The scheme computes the absolute RDS values of candidate codewords and selects one with the minimum absolute RDS if there is no other codeword with the same minimum absolute RDS. Otherwise, it randomly selects one. The scheme requires the simplest complexity, while its spectral performance is degraded as the length of codeword is increased.

MSW: MSW is criterion that selects a codeword with minimum squared weight. The squared weight (w_{sq}) is defined as the expectation of the squared RDS values at each bit position of the codeword. The smaller w_{sq}, the smaller its DC-content at low frequency. MSW criterion can achieve the optimal performance irrespective of the codeword length, while its complexity is large because it requires the squaring operation.

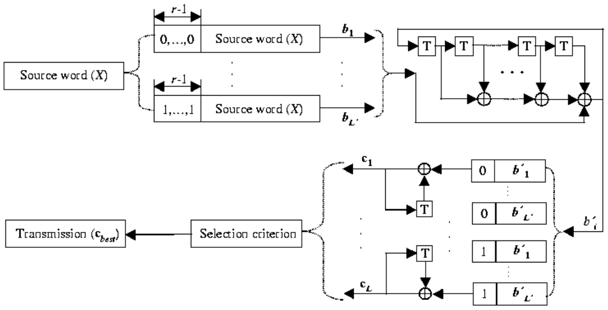


Fig. 1. The operation procedure of GS algorithm.

MTO: MTO criterion utilizes the parameter, RDS threshold, denoted by $T > 0$, predetermined by trial and error. MTO criterion counts the number of times that the absolute value of the RDS is larger than T. Here, the counted value is termed as the penalty of the codeword. Then, it selects the codeword with minimum overrun. If two or more codewords have the same penalty, one of them is randomly chosen and transmitted. The scheme is simple compared to MSW, while it can select codeword with bad quality because it randomly chooses one if there are codewords with the same penalty. Besides, the scheme also needs the exhaustive search for a good optimal threshold.

B. Proposed Criteria

B.1. Two Main Criteria and One Sub-Criterion

MPRDS: In optical recording system, the width of the spectral notch region from the zero frequency must be as large as possible for servo signal, and the DSV value is inversely proportioned to the notch width [1]. Thus, for minimizing the DSV, MPRDS criterion selects the codeword having minimum peak RDS. The peak RDS is the maximum absolute RDS value in a codeword. This scheme achieves good performance irrespective of the length of candidate codewords like MSW and requires simple operation (compare and update MPRDS value) for implementation unlike MSW (square RDS value at each bit position and calculate average).

ABSRDS: This criterion is the simplified version of MSW. It exploits the absolute operation instead of the squaring operation of MSW. Firstly, this criterion calculates the integral of absolute RDS of bipolar recording sequence up to a given position. As a result, the codeword with minimum absolute RDS variation is selected. The scheme achieves better performance that is close to that of MSW than MPRDS, and its complexity is definitely simple compared to MSW.

SC: The (conventional and proposed) main criteria randomly select and transmit one codeword if there are two or more codewords satisfying the given criterion. The random selection has the possibility that the codeword with larger DC-content out of codewords with the same penalty is chosen. If a criterion reducing this possibility is collaborated with the main criteria, the performance improvement of conventional criteria is obvious.

Frequent sign change of RDS in a codeword means that the RDS values are near from the zero, in other words, the DSV is small with high probability compared to the case of less sign change. Thus, if the SC criterion is applied to main criteria for investigating the quality of candidate codewords, the criteria with SC can control DC content better than those without SC. Figure 2 shows the operation procedure of MPRDS/SC as an example. This criterion can be performed by two steps. Firstly, the scheme computes the PRDS and counts the number of SC of candidate codewords. Secondly, the criterion selects one with large SC if there are codewords with the same MPRDS, otherwise, it selects codeword with MPRDS. The reason that SC is selected as a sub-criterion is because it cannot guarantee that the DSV value is small without the main criteria. The reasonable thought is supported by simulation results.

B.2. Complexity Reduction Method

We introduce the complexity reduction (CR) versions of the proposed and conventional criteria, which are CRMSW, CRABSRDS, CRMPRDS and CRMTO. The CR criterion evaluates the selection metric at regular intervals instead of each bit position in the candidate codewords. If the interval is equal to one, then it is just the criterion without CR. Thus, we can save the computation time for selecting codeword using the CR. The performance loss is not noticeable at the surveyed intervals. The CR criterion is developed for reducing the complexity of main criteria, and can be also applied to others with SC. Let us simply overview CRMTO/SC explaining the concept of CR. The scheme observes MTO penalty at regular intervals, while it counts the number of SC at every bit position. Then, it selects the codeword with minimum penalty. If the penalty of two or more codewords is equal, one with the largest SC is selected and transmitted.

C. Simulation Results

This section evaluates the performance of the proposed criteria. Figure 3 shows the efficiency comparison among the proposed and conventional criteria as the number of redundancy bits changes.

In Figure 3, the connected points have the same redundancy (1-*R*), codeword length $r/(1-R)$, and selection set of size 2^r. From Figure 3, we can notice the following.

1. The MRDS/SC criterion is not efficient for long-term low frequency minimization like MRDS even if it outperforms MRDS irrespective of the number of redundancy bits. The MTO/SC criterion is efficient for long-term low frequency suppression, and its efficiency outperforms the MTO criterion. In addition, the efficiency difference between MTO and MPRDS is clearly noticeable, but the efficiency of MTO/SC really approaches to that of MPRDS/SC. The results imply that MTO can select a lot of codewords with large DC-contribution if we do not add SC criterion, and SC definitely prohibits the random selection among codewords with the same penalty.

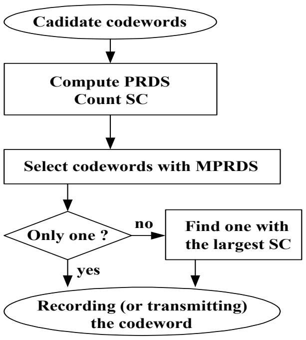
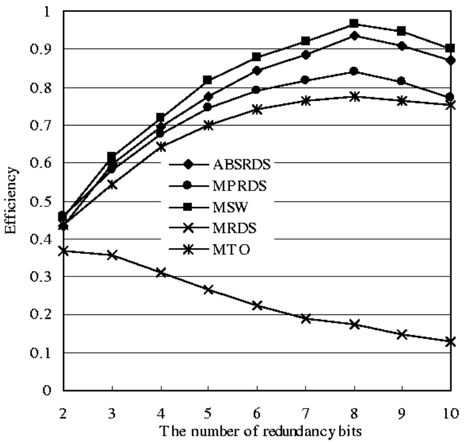
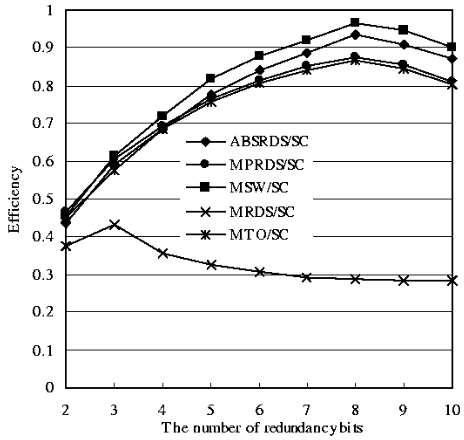


Fig. 2. Codeword selection procedure for MPRDS/SC criterion.



(a) Criteria without SC



(b) Criteria with SC

Fig. 3. The efficiency of the proposed criteria at (1-*R*)=1/56.

2. The efficiency of MPRDS/SC outperforms that of conventional criteria except for MSW, and the efficiency difference between MPRDS and MPRDS/SC is small. Thus, the difference of spectral performance between them is not distinguished. The fact can be identified through the power spectral density of Figure 4. It infers that MPRDS itself can achieve better DC-control unlike MTO criterion.

3. The ABSRDS criterion almost perfectly uses the chance provided by broader selection sets. Thus, its efficiency approaches to that of MSW. The fact implies that ABSRDS well confine the upper bound of absolute RDS like MSW. The efficiency difference between ABSRDS (or MSW) and ABSRDS/SC (or MSW/SC) is much smaller than that between MPRDS and MPRDS/SC. Thus, the difference of spectral performance between them is not noticeable. Here, we note that criteria with SC clearly have the spectral gain even if its difference is small.

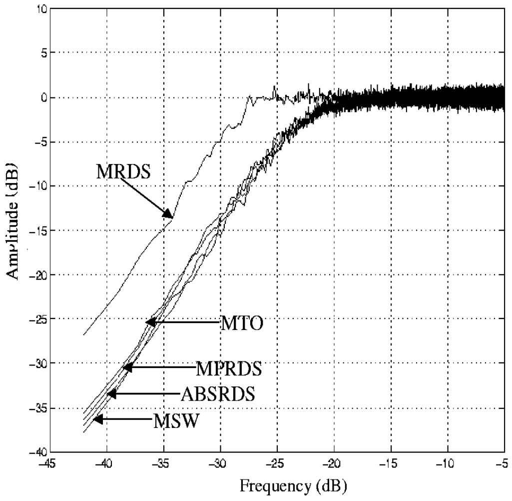
Figure 4 illustrates the power spectral density (PSD) of codewords generated by each criterion when the number of redundancy bits is 6. Figure 4 has a horizontal axis f_c (dB) and a vertical axis $H(f_c)$ (dB), where dB is defined by $10\log f_c$ and $10\log H(f_c)$, respectively, and f_c is channel sequence frequency. Here, the channel sequence denotes the sequence encoded by GS algorithm. The results in Figure 4 show that the proposed main criteria can independently control DC-content in sequences, but the conventional main criteria except for MSW need the support of SC. The suggested main criteria clearly reduce the possibility that two or more codewords in a selection set have the same penalty value. As a result the performance of the proposed main criteria is not deteriorated compared to that of the proposed main criteria with SC.

Figure 5 presents the sum variance of codewords selected by GS scheme with the efficiency corresponding to each point of Figure 3. The results indirectly supports why the proposed criteria achieve larger efficiency, and MTO/SC obtains the efficiency better than MTO, and the efficiency difference between MTO/SC and MPRDS/SC is not noticeable.

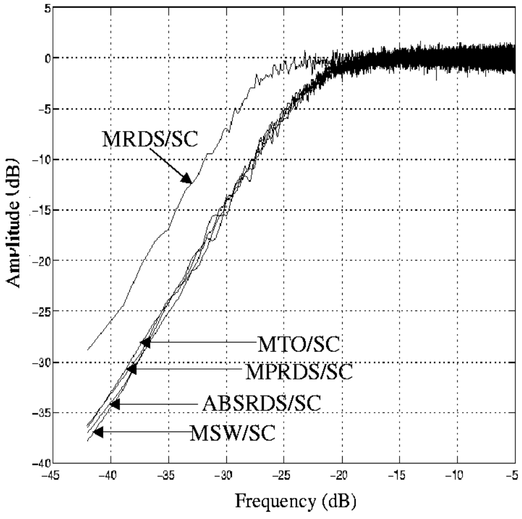
Table 1 shows the spectral performance of CR criteria at regular intervals I = 5, 10, 15 and 20. From Table 1 and Figure 4, we can identify that CR criteria have the performance loss at critical frequency ($H(10^{-4})$) compared to criteria without CR, but the loss is not noticeable. As a result, the CR criteria achieve the reliable DC-suppression at critical frequency for optical recording system. The fact infers the possibility that GS scheme with CR criteria can be applied to optical recording system with less complexity.

TABLE 1
The spectral performance of CR criteria at r=6 and H (10^{-4})

I	CRMSW	CRABSRDS	CRMPRDS/SC	CRMTO/SC
5	-33.42dB	-34.17dB	-33.53dB	-33.45dB
10	-32.82dB	-34.08dB	-33.48dB	-32.82dB
15	-32.75dB	-33.99dB	-32.62dB	-32.75dB
20	-32.48dB	-33.60dB	-32.55dB	-32.48dB

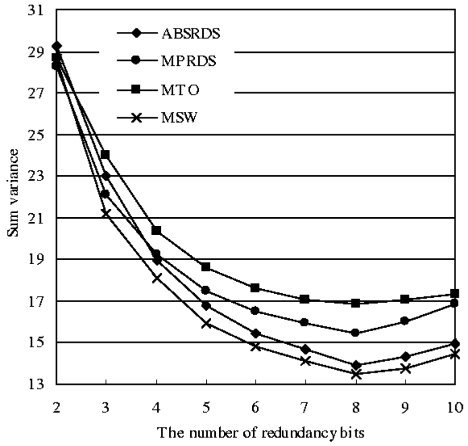


(a) Criteria without SC

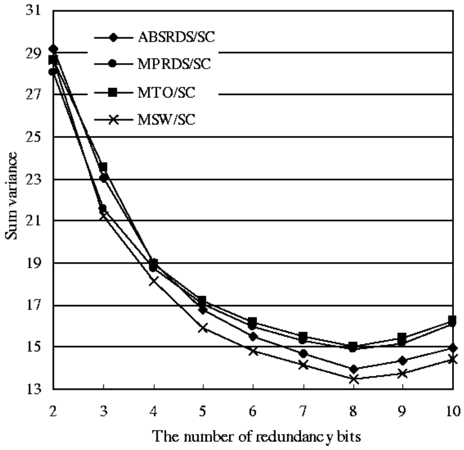


(b) Criteria with SC

Fig. 4. The spectral performance of the proposed criteria when r=6.



(a) Criteria without SC



(b) Criteria with SC

Fig. 5. The sum variance of the proposed criteria at (1-R)=1/56.

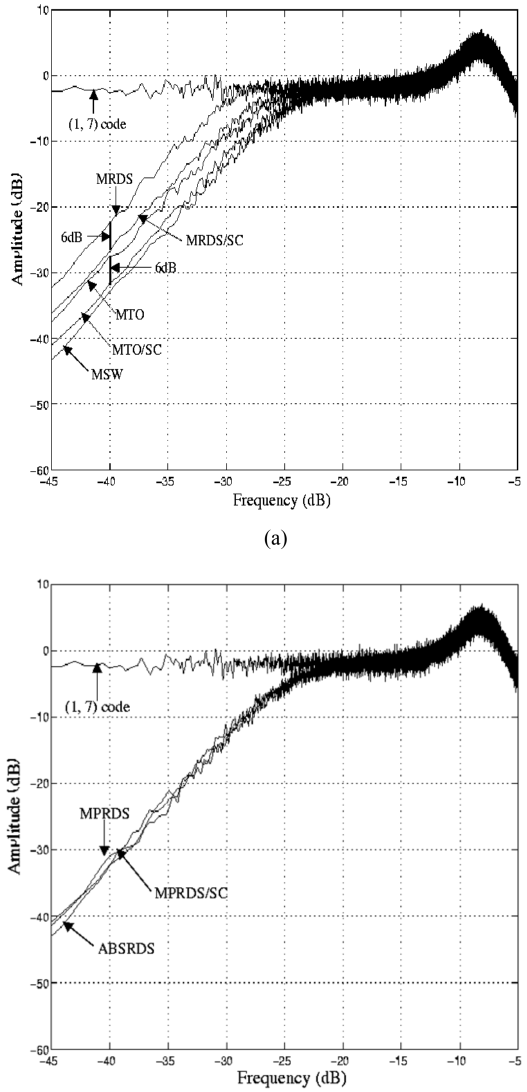
IV. APPLICATIONS

This section introduces two applications exploiting the proposed criteria applying to GS scheme with RLL constraints and the 2/3 (1, 7) PP code.

A. GS scheme with Runlength-Limited (RLL) Code

The scheme can be implemented by inserting RLL code encoder between the second scrambler and selection criterion in Figure 1. As a result, the whole transmitted sequence satisfies RLL constraints. In the scheme, the RLL code is the fixed-length code because GS scheme accomplishes the block based encoding and decoding. The RLL code used in this work is the 2/3 (1,7) code, and its DC-content is large.

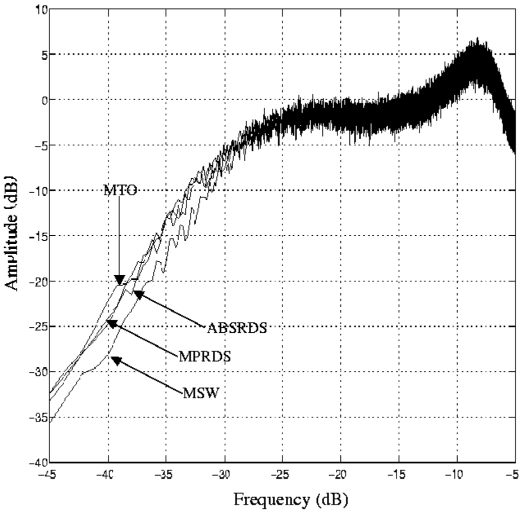
Figure 6 presents the spectral performance of GS scheme using conventional and proposed criteria. The code rate of GS scheme is 330/504 (r=6), and the redundancy is 1/56. Here, the code rate (R) of the scheme is given by $R=(m\times r)/((m+1)\times r\times 3/2)$. From simulation



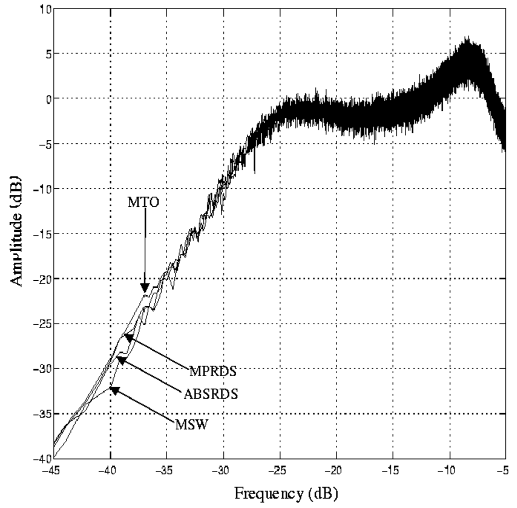
(a)

(b)

Fig. 6. Spectral performance of the GS scheme with RLL constraints and *R*=330/504 using various criteria.



(a) *n* =0



(b) *n*=3

Fig. 7. Spectral performance of (1,7) PP code using *n* LA algorithm.

results, we can identify that the proposed criteria can conduct better DC-control compared to conventional criteria even if GS scheme satisfies given RLL constraints. However, compared to GS scheme without RLL code, it shows the performance loss even if it has the acceptable performance at critical frequency for optical recording. We can conclude that GS scheme satisfying RLL constraints can clearly construct the DC-free code with small rate loss even if it uses RLL code with large DC-content, and thus it is a promising candidate for optical recording.

B. 2/3 (1, 7) PP Code Using Look-Ahead Algorithm

Parity preserving (PP) means that the modulo-2 addition of a source word (the "parity") is always equal to that of the corresponding channel word. The mapping rule of 2/3 (1, 7) PP code used in this paper is based on the second Table of [7]. This paper uses look ahead (LA) algorithm for better DC-control of (1, 7) PP code.

Encoding step of (1, 7) PP code using n LA algorithm is processed as follows. The scheme primarily inserts n+1 DC-control bits in the bitstream of the n+1 source words at regular interval. Then, it generates the two tree structure consisting of 2^n possible candidate codewords. Finally, the 2^{n+1} possible codewords is evaluated by selection criterion, and the root codeword of the tree with the least DC-contribution is transmitted. Here, the encoding method with $n = 0$ is the normal encoding method of (1, 7) PP code.

Figure 7 represents the spectral performance of (1,7) PP code using new and conventional criteria when $n = 0$ and $n = 3$, respectively. Here, the redundancy is 1/56. From results, we can identify that the spectral performance of (1, 7) PP code using LA algorithm is more reliable, and the proposed criteria contribute to the phenomenon.

V. CONCLUSION

This paper has proposed two new criteria for evaluating candidate codewords for the multimode coding scheme. Two main criteria are MPRDS and ABSRDS. The MPRDS criterion is very efficient for minimizing long-term low frequency content, and it has a very simple complexity, while the performance of ABSRDS is less than that of MSW, ABSRDS requires less complexity than MSW. The SC criterion complements the random selection among codewords with the same penalty. Thus, the criterion contributes to their efficiency improvement by supporting the main criteria. CR criteria can be realized by computing penalty at regular intervals instead of every bit position. Certainly, CR criteria reduce the computation time for investigating the quality of codewords, and the performance difference between CR criteria and criteria without CR is not noticeable.

We have discussed the performance of the proposed criteria in terms of efficiency, sum variance and spectral performance. From our simulation results, we have identified that the proposed criteria achieve a higher efficiency than the conventional criteria, leading to a smaller sum variance and improved spectral performance. In two applications, DC-control using the proposed criteria is compatible with MSW even if they have much less complexity. Thus, we conclude that the proposed criteria are promising candidates for the reliable DC suppression method of multimode codes in the next generation of optical recording.

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BIOGRAPHY

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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.