A Comparison of the Low-Frequency Properties of DC-free Codes Generated by Look-Ahead and Guided Scrambling Techniques

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Summary - *Suppression of the low-frequency (lf) components of the modulated data stream is a system requirement in optical recording which facilitates the usage of servo systems for reading the optical disc. Insufficient suppression of the lf components of the coded spectrum will lead to improper functioning of the servo systems, and/or acoustical noise generated by the servo systems, and/or additional power dissipation in the servo amplifiers.*

Low-frequency components are avoided in state of the art systems such as CD and DVD by using codes, called dc-free codes, *which suppress the energy in the lf range. Clearly, the more lf suppression, the more overhead in coding rate must be spent, and a sound trade-off has to be sought between proper lf suppression and coding efficiency. It has been found that lf suppression can also be improved by coding methods, which use a* look-ahead *(LA) algorithm that looks ahead p codewords, and evaluates, based on a suitable metric, the full search tree of 2^p possible choices of codewords in the tree.*

Recently, coding schemes, which use Guided Scrambling (GS) have been proposed for suppressing the lf content. It has been shown that GS schemes can achieve a lf suppression which is very close to the theoretical maximum. In this paper, we will report on a performance comparison of coding schemes based on Look-Ahead and Guided Scrambling techniques.

Keywords recording systems, dc-free codes, RLL, Guided Scrambling, Look-Ahead technique

1. Introduction

Coding techniques that produce a spectral null at zero frequency, have found widespread application in digital optical recording systems [1]. Suppression of the low-frequency components is a system requirement in optical recording which facilitates the usage of servo systems for reading the optical disc. EFM and EFMPlus, for example, which are employed in the CD and DVD, respectively, have been designed to sufficiently suppress the lf components in the encoded data stream.

There is a variety of methods for constructing dc-free codes. In essentially all methods, the encoder has the choice between codewords from a selection set of words that may represent a given source word in a given context. The encoder opts for transmitting the codeword (from the selection set) that minimizes a penalty function which is based on the RDS. Look-ahead coding schemes exploit the information of a number of future source words, and can trade long-term versus short-term profits in the evaluation of the penalty function. Immink and *et al.* have presented results of look-ahead schemes for EFM. [2].

A simple construction method [3], called *polarity switch*, is presented to exemplify the above. Under polarity switch rules, $(n-1)$ source symbols are supplemented by one symbol called the *polarity bit.* The encoder has the option to transmit the n-bit word without modification or to invert all n symbols. The rate of the code is $(n-1)/n$. The selection between the two alternative translations is made in such a way that the running digital sum after transmission of the new word is as close to zero as possible. The polarity bit is used at the decoder site to identify whether the transmitted codeword has been inverted or not. Spectral properties of the polarity bit code are described in [1, Chapter 10]. The polarity switch encoding method can be extended with a look-ahead (LA) algorithm which looks ahead p codewords, and evaluates, based on a suitable metric, the full search tree of 2^p possible choices of the polarity of each codeword in the tree. The tree is evaluated prior to the transmission of each new n-bit codeword. Look-ahead strategies can also be employed by dc-free runlength-limited (RLL) encoders, as was demonstrated by Immink *et al.* [2], who presented results for EFM.

Recently, a powerful method of suppressing the low-frequency content, called *Guided Scrambling* (GS) was presented in [4, 5]. Guided scrambling is a member of a larger class of coding schemes called *multi-mode* codes. In multi-mode codes, each source word may be represented by a member of a selection set consisting of $L = 2^p$ n-bit codewords, where p is the number of redundant bits in a codeword. The encoder selects and transmits that codeword having a minimum contribution to the low-frequency content according to a suitable metric. The code rate is $(n-p)/n$. Guided scrambling using efficient RLL encoders has been proposed in optical recording systems [6].

The principal aim of a coding technique is simple. It should achieve the deepest suppression of the power spectral density over the widest range of frequencies at the lowest price in terms of code redundancy and complexity. The range of frequencies with suppressed spectral content is usually called the *spectral notch width*. In the next section, we will present results of computer simulations conducted to compare the quality of spectral suppression, in terms of spectral notch width and spectral depth, of both the GS and LA coding method.

2. Evaluation of the spectral performance

In order to assess the quality of the low-frequency suppression, various suitable yardsticks have been proposed and evaluated [1, Chapter 10]. A first yardstick measures the power spectral density (PSD) at a very low frequency, say, at $10^{-4} f_c$, where f_c denotes the channel bit frequency. The second yardstick is the variance of the running digital sum, in short, *sum variance*. It has been found [7] that the sum variance of an encoded dc-free sequence is inversely proportional to the width of the spectral notch.

We have written a computer program to simulate the performance of the encoder. The spectral performance of any method depends heavily on the metric used for selecting a codeword. For both encoding schemes we used the sum variance of the new codeword (and the future words in LA) as a metric for the selection of a codeword. We have conducted many simulations of which we will present a few typical results. For all simulation results presented, the redundancy of both, LA and GS, coding techniques is fixed at 1%.

Figure 1 shows the measured power spectral density $H(f_c)$ at a very low frequency, namely $f_c = 10^{-4}$, as a function of p. We observe that for $p > 2$ both methods achieve approximately the same amount of suppression at the very low-frequency end. The application of the second yardstick, sum variance, leads to a different result.

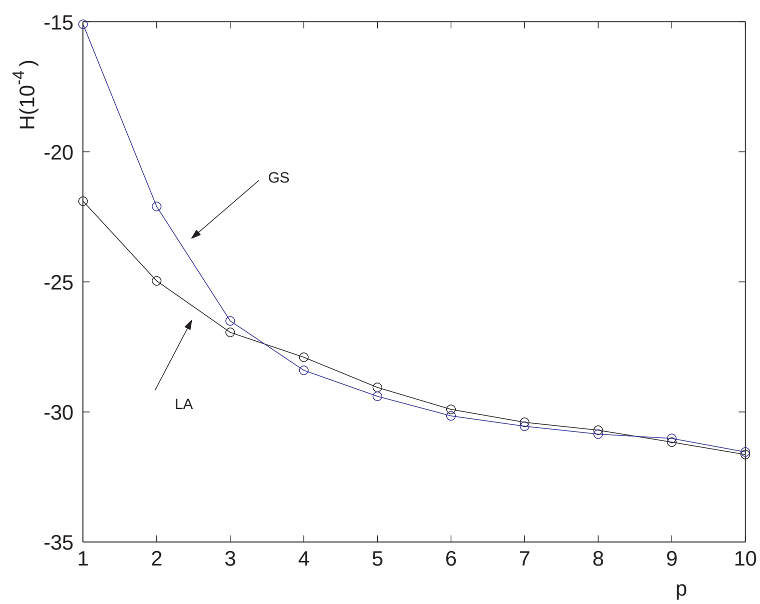

Figure 1: Spectral density measured at $f_c = 10^{-4}$ of sequences encoded by the guided scrambling (GS) method and the look-ahead (LA) polarity switch method as a function of p. The code redundancy is fixed at 1%. The LA method uses a search tree of 2^p branches, while the GS method has a selection set of 2^p codewords.

Figure 2 shows the sum variance of the encoded sequence as a function of p. We observe that the sum variance of sequences encoded by the GS method is significantly smaller than the one obtained by the look-ahead method. Justesen's relationship predicts that the spectral notch made by the Guided Scrambling is much smaller than the one made by the Look-Ahead method.

Figure 3 shows, for $p = 8$, the power spectral density (PSD) as a function of the (channel) bit frequency. We may readily observe the difference in performance of both schemes. In the typical instance shown, the spectral notch of the sequences encoded by the GS method is about 50% wider than the one produced by the LA method. As a result, the spectral densities at $f_c < 10^{-4}$ are about the same, but at frequencies near $f_c \approx 210^{-3}$ we notice that GS performs some 5 dB better than LA. We conclude that, indeed, LA yields improved suppression at the very low-frequency range, but at mid frequencies, $f_c \approx 10^{-3}$, it fails to do so. Given the severe sensitivity of the radial and focus servo systems [8] in optical recording systems, specifically in the range near $f_c \approx 10^{-3}$, we may seriously doubt, given the outcomes of the presented computer simulations, the usefulness in recording practice of look-ahead techniques for suppressing the low-frequency content.

3. Conclusions

We have assessed two algorithms for suppressing the low-frequency content of sequences generated by dc-free codes. The two methods are Look-Ahead (LA) and Guided Scrambling (GS). We have found that, for a given fixed encoding complexity, the spectral density at the very low-frequency range $< f_c = 10^{-4}$ is about the same for the two methods. However, the width of the spectral notch of sequences generated by the Guided Scrambling method is significantly, about 50%, larger than that of sequences generated by the Look-Ahead method. At frequencies near $f_c \approx 10^{-3}$ we notice that GS performs some 5 dB better than LA. Given the observed insufficient suppression of the mid frequencies, look-ahead schemes will find limited practical usefulness in optical recording systems.

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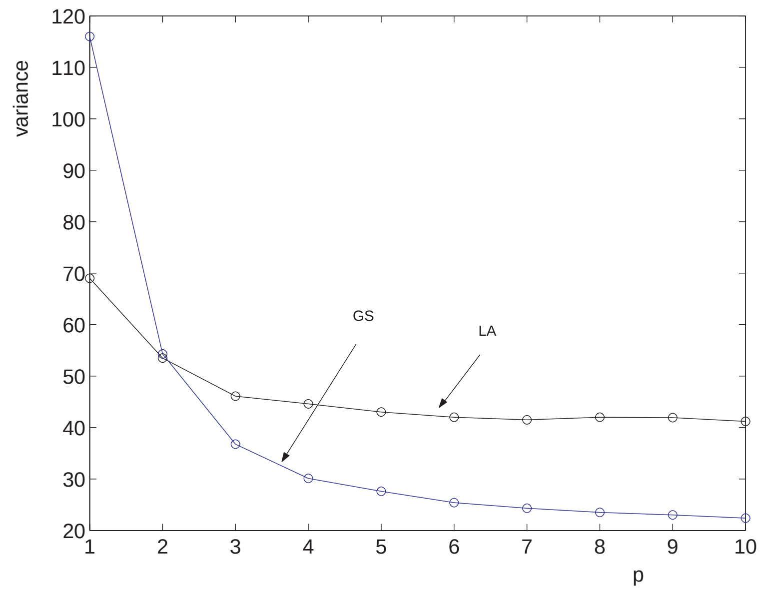

Figure 2: Sum variance of sequences encoded by the guided scrambling (GS) method and the look-ahead (LA) polarity switch method as a function of p. The code redundancy is fixed at 1%. The LA method uses a search tree of 2^p branches, while the GS method has a selection set of 2^p codewords.

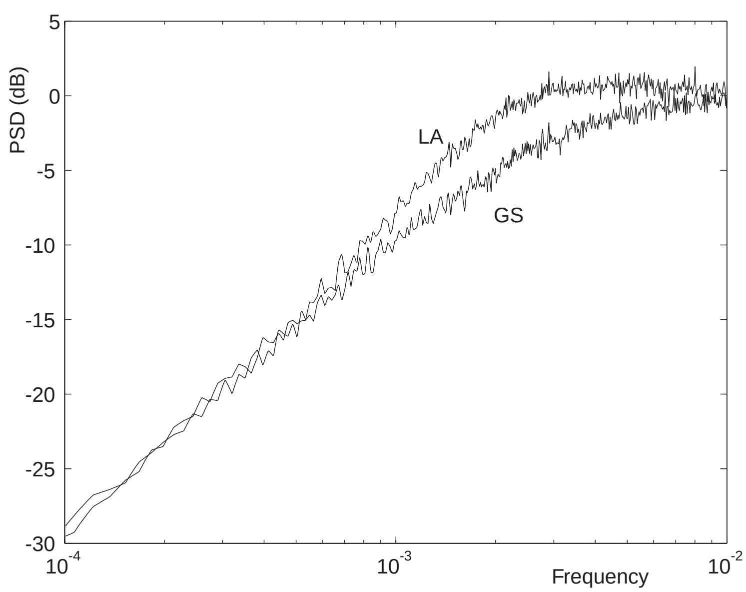

Figure 3: Spectra of sequences encoded by the guided scrambling (GS) method and the look-ahead (LA) polarity switch method. The LA method uses a search tree of 2^8 branches, while the GS method has a selection set of 2^8 codewords.