Improving Burst Error Tolerance of LDPC-Centric Coding Systems in Read Channel

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We report on the use of low-density parity check (LDPC)-centric error correction coding (ECC) for magnetic recording read channel in the presence of significant burst errors. Since an LDPC code by itself is severely vulnerable to burst errors due to its soft-decision probability-based decoding, we focus on LDPC-centric concatenated coding in which LDPC code is used as inner code. To improve the burst error tolerance, we propose a hybrid LDPC-centric concatenated coding strategy in which one inner LDPC codeword is replaced by another codeword with much stronger burst error correction capability. This special inner codeword reveals the burst error location information, which can be leveraged by the inner LDPC code decoding to largely improve the overall robustness to burst errors. Using a hybrid BCH-LDPC/RS concatenated coding system as a test vehicle, we demonstrate a significant performance advantage over its RS-only and LDPC-only counterparts in the presence of three different types of burst errors.

***Index Terms*—Burst error, LDPC.**

I. Introduction

WITH the continuous growth of hard disk drive areal density and rotational speed, burst defects are becoming an increasingly crucial issue (e.g., see [1]–[7]). Various burst defects may result in three different types of errors, including (i) write-in burst errors (i.e., a burst of bits are not genuinely recorded on the media), (ii) erasure burst errors (i.e., a burst of read-back signals suffer from significant signal magnitude attenuations), and (iii) excess saturation limit burst errors (i.e., a burst of read-back signals suffer from a significant DC voltage boost). Write-in and erasure burst errors are typically induced by media defects (MDs), track mis-registration, and head fly height fluctuation, while excess saturation limit burst errors are typically induced by thermal asperities (TA) and hence are also referred to as TA burst errors [3], [8], [9]. This paper concerns how to mitigate all these three types of burst errors from the read channel signal processing and coding perspective. In particular, motivated by recent great interest in using low-density parity-check (LDPC) [10]–[14] to improve read channel performance, this paper focuses on read channel with LDPC-centric coding systems. As we will show later, an LDPC-only coding system may not be able to sufficiently handle burst errors if such burst errors cannot be detected/located by preceding read channel signal processing. Although there exist read channel signal processing methods to detect these burst errors in current design practice, this work aims to deal with the problem largely from the coding perspective, which could complement with other methods and further improve the overall hard disk drive burst error tolerance.

To mitigate burst errors in hard disk drives, the essential challenge is how to most reliably and efficiently detect the occurrence and identify the location of bust errors. Given the location information of burst errors, read channel signal processing and coding systems can accordingly mitigate burst errors in relatively straightforward manners. The authors of [15] developed a method to detect the occurrence of burst errors, which nevertheless cannot locate them. The authors of [4] studied the mitigation of erasure and TA burst errors, where erasure burst errors are identified by analyzing the trellis signal detection output and the authors assumed that TA burst errors can be identified by tracking the read-back signal DC voltage in the front-end circuits. An enhanced erasure burst error detection method is developed in [5], which can more accurately capture erasure burst errors through more elegant analysis of precoders and trellis signal detection output. In summary, prior work mainly focused on mitigating read-back signal erasure burst errors under certain combinations of precoders and partial response (PR) targets, while leaving TA burst errors to read channel front-end circuits and completely ignoring write-in burst errors.

This paper aims to develop a method that can enable read channel employing LDPC codes universally mitigate all the three different types of burst errors without any constraint on the precoder. Because of the soft-decision probability-based nature of LDPC code decoding, LDPC-only coding solutions may not be able to achieve sufficient burst error tolerance, which will be demonstrated later. Hence, we only consider LDPC-centric concatenated coding systems in which LDPC code is used as an inner code. In particular, we focus on concatenated BCH-LDPC coding systems. As demonstrated in a recent study [16], concatenated BCH-LDPC coding tends to have three main advantages, including (1) it can be much easier to estimate the error correction performance down to very low sector error rate (SER) (e.g., 10^{-10} and below), (2) it can effectively leverage the bit error number oscillations in case of inner LDPC code decoding failures to improve the overall error correction performance, and (3) the silicon implementation cost can be reduced. However, as pointed out earlier, LDPC code decoding may suffer from significant performance degradation in the presence of long burst errors. As a result, LDPC-centric concatenated coding is also severely sensitive to long burst errors.

This paper presents a *hybrid concatenation* approach to improve the burst error tolerance of LDPC-centric concatenated coding systems. It is motivated by an obvious observation: if

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the location of burst errors is known, we can easily reduce the inner LDPC code decoding failure rates by erasing the burst errors (i.e., setting the magnitude of the corresponding soft input to LDPC code decoder to zero). The basic idea of this proposed hybrid concatenated coding is simple: In conventional concatenated coding, each outer codeword is partitioned into several equal-sized segments and all the segments are further encoded by the same inner LDPC code. In contrast, we propose to encode one segment using another inner code that has a much stronger burst error correction capability while still keeping all the other segments encoded by the same inner LDPC code. With a much better chance to survive significant burst errors, that particular segment can readily reveal the location of burst errors to the other LDPC-coded segments if we interleave all the inner codewords together. We should point out that this hybrid concatenation approach is similar to the "picket codes" for optical recording systems [17] in the sense that both use a stronger-than-others code to locate burst errors. While the "picket codes" are not concatenated codes and hence cannot directly employ LDPC codes, this work primarily focuses on LDPC-centric concatenated coding for hard disk drives.

We investigate the effectiveness of this hybrid concatenated coding geared to the emerging 4K-byte sector format by considering all the three different types of burst errors, i.e., write-in burst errors, erasure burst errors, and TA burst errors. Moreover, we develop a signal redetection strategy that can further improve the tolerance to erasure burst errors. Under a representative perpendicular recording read channel, we carried out extensive simulations using hybrid concatenated BCH-LDPC/RS coding, in which one outer BCH codeword is partitioned into eight segments, one segment is encoded by an inner RS code and the other seven segments are encoded by an inner LDPC code. We considered two different overall code rates including 13/14 and 8/9. Moreover, for the purpose of comparison, we considered the LDPC-only and RS-only counterparts under different types of burst errors, and considered the use of the method presented in [5] for LDPC-only coding in the context of erasure burst errors. Simulation results demonstrated noticeable error correction performance advantages of such hybrid concatenated coding over all the other alternatives under both write-in and erasure burst errors. In the context of TA burst errors, LDPC-only option can outperform the proposed method if we assume all the TA burst errors can be *perfectly* captured by the front-end circuits when using the LDPC-only option. Because such an ideal assumption may not be valid in practice and the performance of LDPC-only coding is significantly worse than the proposed method under the other two types of burst errors, particularly write-in burst errors, it is reasonable to conclude that the proposed method, which can universally mitigate all the three different types of burst errors, is more preferable than the other coding alternatives in the presence of significant burst errors.

II. Proposed Hybrid Concatenated Coding

In conventional design practice of LDPC-centric concatenated coding, one sector of user data is first encoded by the outer code encoder, then each outer codeword is partitioned into v equal-length segments, and each segment is encoded by the inner LDPC code encoder. Let R_{LDPC} and R_{outer} denote the code rate of the inner LDPC code and outer code, respectively, the overall code rate $R_C = R_{\text{LDPC}} \cdot R_{\text{outer}}$. The authors of [16] demonstrate the potential of BCH-LDPC concatenation in magnetic recording read channel, however did not take into account of burst errors in the study. It is intuitive that, compared with RS codes that are being predominantly used in current practice, LDPC code may (much) more severely suffer from burst errors because of its soft-decision probability-based decoding. Hence, in the presence of significant burst errors, a straightforward LDPC-centric concatenation can become much less attractive for practical applications.

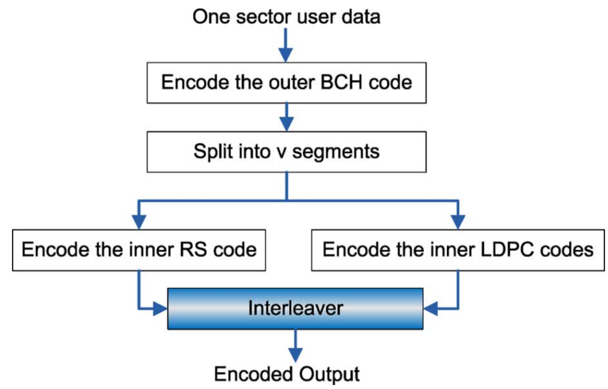

Fig. 1. Encoding data flow chart of the proposed hybrid concatenated coding.

In this work, we propose a *hybrid concatenation* approach to mitigate the impact of burst errors on LDPC-centric concatenated coding systems. The basic idea is to use an RS code instead of LDPC code to encode one segment, i.e., after we partition one outer codeword into v segments, $v-1$ segments are still encoded by the inner LDPC code as in conventional practice, while one segment is encoded by an RS code. By interleaving all the v inner codewords, we can take advantage of the strong burst error tolerance of RS codes to locate and erase burst errors in the other inner LDPC codewords, which can greatly reduce the impact of burst errors on the LDPC code decoding performance. Fig. 1 shows the encoding flow of this hybrid concatenation approach. To demonstrate the effectiveness of burst error erasure in LDPC code decoding, we carried out simulations on the decoding of a rate-8/9 512-byte LDPC code, assuming each sector suffers from 100-bit read-back signal erasure burst errors with a signal magnitude attenuation factor of 0.25. Fig. 2 shows the simulated SER performance in case that the burst errors are and are not erased. It clearly shows that the LDPC code decoding performance can be greatly improved if we are able to locate and erase the burst errors.

This naturally motivates us to study the potential of such a hybrid concatenated coding strategy. By simply using one inner RS code with strong burst error tolerance to locate the burst errors for the other inner LDPC codes, this design strategy can improve the overall robustness to burst errors while largely maintaining the advantage of using LDPC codes (e.g., support of iterative read channel detection and decoding, and superior correction performance for non-burst errors). As a result, the decoding data flow of the proposed hybrid concatenated coding is shown in Fig. 3. We always decode the inner RS code first, and if it is successfully decoded, we compare the input and output of the RS code decoder to identify all the possible burst errors. Due to the use of bit-by-bit interleaving among all the inner codewords,

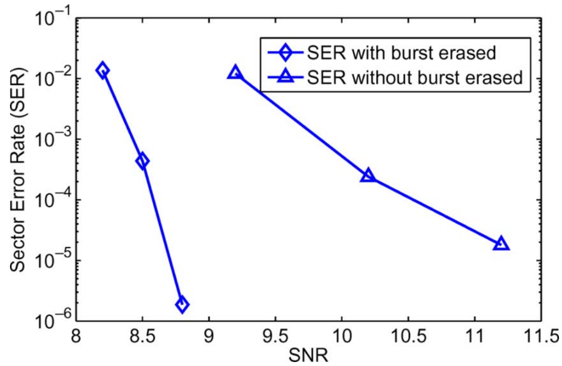

Fig. 2. Simulated SER performance of a rate-8/9 512-byte LDPC code in the presence of a 100-bit read-back signal erasure burst errors.

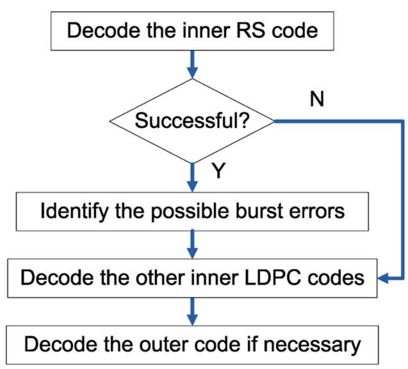

Fig. 3. Decoding data flow chart of the proposed hybrid concatenated coding.

we can erase the corresponding soft input in the decoding of all the other inner LDPC codes. Let R_{RS} denote the code rate of the inner RS code, and recall that each outer codeword is partitioned into v equal-sized segments, the overall code rate of the hybrid concatenated coding system can be calculated as

$$R_C = \left(\frac{1}{v} \cdot R_{\text{RS}} + \frac{v-1}{v} \cdot R_{\text{LDPC}}\right) \cdot R_{\text{outer}}. \quad (1)$$

Let $\mathcal{P}_A$ denote the probability that the RS code decoding fails, and $\mathcal{P}_B$ denote the probability that the hybrid concatenated code decoding fails even when all the burst errors in inner LDPC codewords have been erased. The code rates of all the component codes, i.e., outer code and inner LDPC and RS codes, should be appropriately determined so that $\mathcal{P}_A$ should be slightly less than $\mathcal{P}_B$ under target read channel condition, i.e., the RS code is sufficiently strong to ensure enough burst error tolerance without incurring too much code rate penalty.

III. Performance Evaluation

This section presents computer simulations to demonstrate the effectiveness of the above hybrid concatenated coding strategy based upon the system architecture as shown in Fig. 4. The perpendicular recording channel is modeled as

$$z_k = \sum_m x_m h(kT - mT + \delta_m)$$

where

$$h(t) = erf\left(2t\sqrt{\ln 2}/(PW50)\right)$$

and the media jitter noise δ_m is modeled as a Gaussian variable $\mathcal{N}(0, \sigma_j^2)$. The parameter $PW50$ is defined as the pulse width of the derivative of $h(t)$ at half of its peak amplitude. As illustrated in Fig. 4, the perpendicular recording channel is also disturbed by a burst error generator that is able to model all the above three burst errors. The signal is further disturbed by additive white Gaussian noise (AWGN) $n_k \sim \mathcal{N}(0, \sigma_n^2)$. The random samples with the $\mathcal{N}(0, \sigma^2)$ distribution are scaled to generate the noises according to the following SNR definition [18]

$$\text{SNR} = \frac{\int_{-\infty}^{+\infty} (h(t) - h(t-T))^2 \, \text{d}t}{2\sigma_n^2 + 2\sigma_j^2 \int_{-\infty}^{+\infty} (h'(t))^2 \, \text{d}t}$$

where the signal energy is in the “dibit” response and the noise reflects the first-order jitter model. The channel output is followed by a 10-tap equalizer which equalizes the channel to a target of $1 + 0.75D$. A 3-tap noise predictor is used to whiten the colored noise, which is followed by an 8-state SOVA detector for soft-output signal detection. We fix the channel bit density, which is defined as the ratio PW50/T, as 2.3, and the total noise consists of 90% media jitter noise and 10% AWGN.

Targeting at 4K-byte user data per sector format, this study considered two different overall code rates including 13/14 and 8/9. In both cases, each outer BCH codeword is partitioned into 8 segments, and the specific system configurations are described as follows.

- *Overall code rate of 13/14*: The inner RS code is a rate-8/9 (511, 454, 27) RS code over $\text{GF}(2^9)$. The inner LDPC code is a rate-17/18 (3, 54)-regular quasi-cycle (QC) LDPC code, where the parity check matrix contains a 3×54 array of single-weight circulant matrices with size of 82 and all the circulant matrices are constructed randomly subject to the 4-cycle free constraint. Since the parity check matrix has two redundant rows, we denote this inner LDPC code as rate-17/18 (4428, 4184). Therefore, the codeword length of the BCH code is $7 \cdot 4184 + 4086 = 33374$ bits. Given the overall code rate of 13/14, we have that the information length is $\lfloor (7 \cdot 4428 + 4599) \cdot 13/14 \rfloor = 33052$ bits. Clearly, the outer BCH code should be constructed over $\text{GF}(2^{16})$, and its maximum correctable error number t is lower bounded by $\lfloor (33374 - 33052)/16 \rfloor = 20$. By setting $t = 20$ for the worst-case scenario, we have that the outer BCH code is a (33374, 33052, 20) binary BCH code. Moreover, for the purpose of comparison, we also considered both LDPC-only and RS-only coding systems. with the same code rate of 13/14. For LDPC-only coding system, we use a rate-13/14 (35616, 33072) QC-LDPC code with the parity check matrix column weight of 4. The code parity check matrix contains a 2×28 array of weight-two circulant matrices, where all the circulant matrices are constructed randomly subject to the 4-cycle free constraint. For RS-only coding system, we use a rate-13/14 (2967, 2755, 105) RS code over $\text{GF}(2^{12})$.
- *Overall code rate of 8/9*: The inner RS code is a rate-4/5 (511, 425, 42) RS code over $\text{GF}(2^9)$. The inner LDPC code is a rate-12/13 (3, 39)-regular quasi-cycle (QC) LDPC code, where the parity check matrix contains a 3×39 array

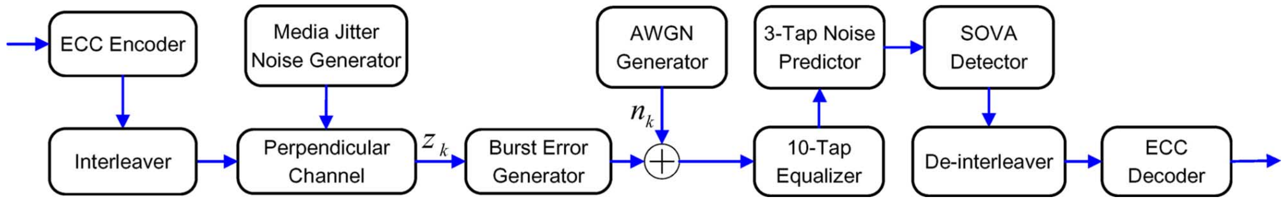

Fig. 4. Read channel system architecture assumed in this study.

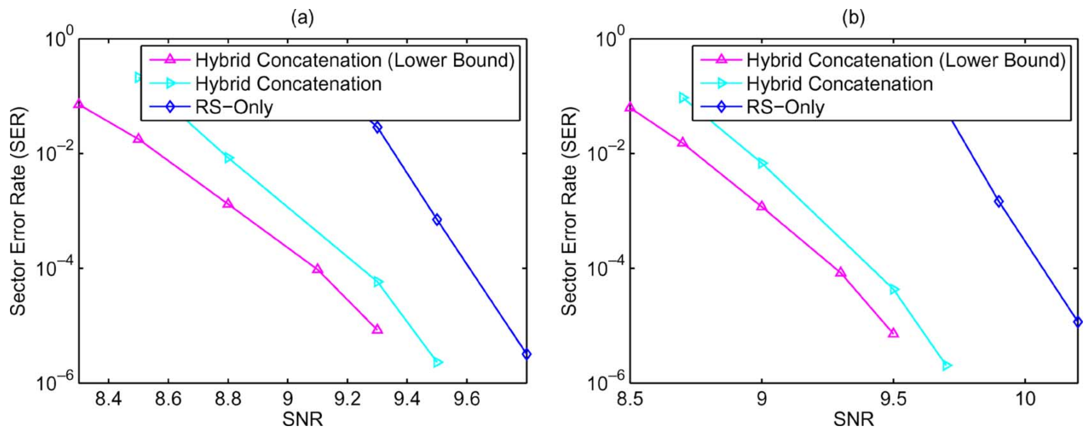

Fig. 5. Simulated SER performance of the rate-13/14 hybrid concatenated coding and RS-only coding in the presence of one segment of (a) 600-bit and (b) 800-bit write-in burst errors.

of single-weight circulant matrices with size of 118 and all the circulant matrices are constructed randomly subject to the 4-cycle free constraint. Since the parity check matrix has two redundant rows, we denote this inner LDPC code as rate-12/13 (4602, 4250). With the similar calculation above, we have that the outer BCH code is a (33575, 32722, 53) binary BCH code. We also consider a rate-8/9 (36864, 32770) QC-LDPC code with the parity check matrix column weight of 4 and a rate-8/9 (3072, 2731, 169) RS code over $\mathrm{GF}(2^{12})$.

In all the simulations, LDPC decoding carries out 32 internal iterations and there is no global iteration between signal detector and LDPC decoder in order to reduce simulation computational complexity. Based upon the above read channel architecture, we studied the performance of hybrid concatenated coding in the presence of write-in burst errors, read-back signal erasure burst errors, and TA burst errors, as elaborated in the remainder of this section.

A. Write-In Burst Errors

Write-in burst errors refer to the failure of genuinely recording the data on the target track. If the write head is off track during the write operation, it can fail to write the target track and even accidentally overwrite the data stored on an adjacent track. Write-in burst errors may also occur if the write head flies too high during the write operation. In case of write-in burst errors, the read head may read back the previously recorded data or the data intended to be recorded on an adjacent track. Therefore, we model write-in burst errors by replacing a consecutive segment of data within one sector with another random data sequence.

Fig. 5 shows the simulated SER results when every sector contains one segment of 600-bit and 800-bit write-in burst errors, respectively, when the overall code rate is 13/14. Firstly, we note that, because the LDPC-only coding system completely fails to work in the presence of write-in burst errors according to our simulations, Fig. 5 does not include the SER performance curve for the LDPC-only coding system. For the SER performance of the proposed hybrid concatenated coding, Fig. 5 shows two curves: one curve corresponds to the SER lower bound assuming the burst errors are perfectly located, and another curve shows the SER performance when we use the RS code to estimate the location of the burst errors with inevitable estimation inaccuracy. The simulated results clearly show that the hybrid concatenated coding can achieve good coding gain over its RS-only counterpart. The results also show that the coding gain over RS-only approach tends to increase as we increase the burst error length. Finally, we note that, for the hybrid concatenated coding, the dB gap between the lower bound and the realistic SER curve tends to reduce as we increase the SNR. This is because, under higher SNR, we can estimate the position of the burst errors more accurately and hence the curve tends to be closer to the lower bound.

Fig. 6 shows the simulated SER results with the overall code rate of 8/9. As the code rate reduces from 13/14 to 8/9, the LDPC-only coding scheme becomes much more robust to write-in burst errors and hence achieve comparable performance with the RS-only coding scheme, as shown in Fig. 6. Meanwhile, we note that the hybrid concatenated coding has even greater performance gain over the RS-only coding system, compared with the rate-13/14 case. Therefore, the results suggest that, as we reduce the overall code rate, the hybrid concatenated coding has a higher gain over its RS-only counterpart but less gain over its LDPC-only counterpart.

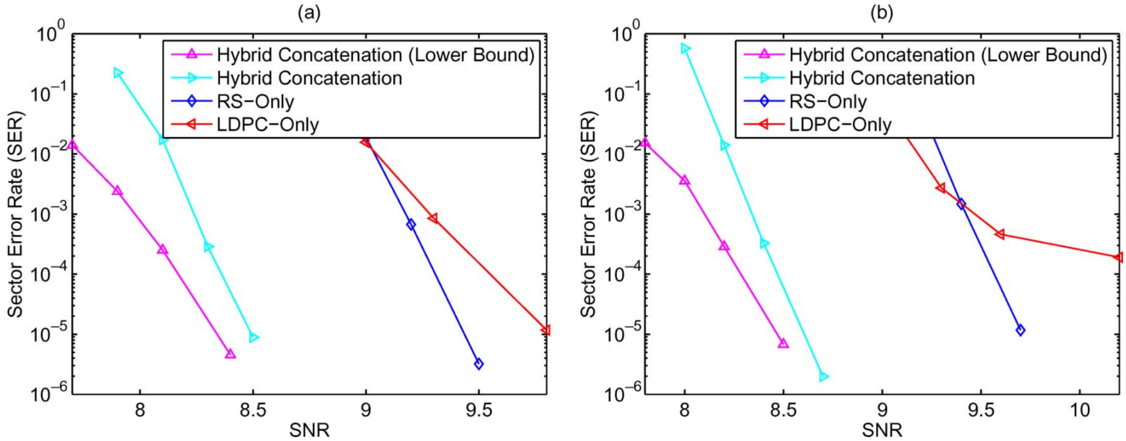

Fig. 6. Simulated SER performance of the rate-8/9 hybrid concatenated coding and RS-only coding in the presence of one segment of (a) 600-bit and (b) 800-bit write-in burst errors.

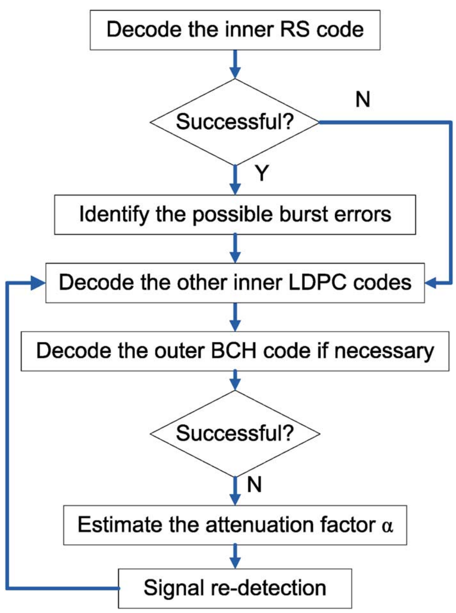

Fig. 7. Enhanced decoding flow chart of the revised concatenated LDPC and BCH coding system with redetection.

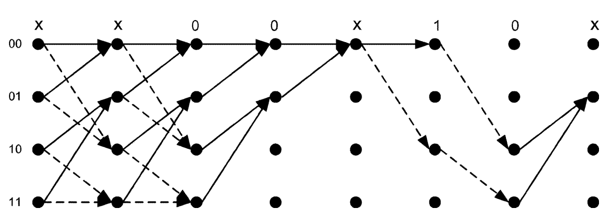

Fig. 8. Illustration of trellis branch pruning to reduce signal redetection computational complexity.

B. Erasure Burst Errors

Erasure burst errors refer to magnitude attenuation of read-back signals during read operations. If the read head is off track during the read operation, it will read back a weak signal from the target track or even the data from adjacent tracks. Normally, because of guard band between adjacent tracks, off-track read heads more likely read back attenuated signal from the target track. Erasure burst errors also occur when read head flying height is so high that a sequence of read signals suffer from significant magnitude attenuation. Besides, the MD also has the similar erasure effect on the read-back signal. In this work, we model erasure burst errors as a segment of read-back signals attenuated by a constant factor α. Hence, the input to the signal detector in the presence of erasure burst errors will change from $(\sum_i a_i x(n-i) + n_k)$ to $(\alpha \sum_i a_i x(n-i) + n_k)$, where $x(n)$ is the interleaved bit stream, a_i is the coefficient of the ideal equivalent channel, and n_k represents additive white noise. Clearly, without the knowledge of attenuation factor α, the calculated branch metrics may significantly differ from ideal ones, which may largely degrade the performance of the signal detector and hence the succeeding ECC decoding. Intuitively, if we can somehow estimate the value of the attenuation factor α, we may be able to reduce the signal detection performance degradation. Accordingly, we enhance the data flow of this hybrid concatenated coding system as shown in Fig. 7, where we need to address two issues, i.e., how to estimate the attenuation factor and how to realize the signal redetection.

To estimate the attenuation factor α, we can apply statistical estimation based on the principle of minimum mean square error (MMSE). Define ideal channel output $X(n) = \sum_i a_i x(n-i)$ and let $Y(n)$ represent the actual input to the signal detector, i.e., $Y(n) = (\alpha \sum_i a_i x(n-i) + n_k)$. Hence, we have a linear system $Y = \alpha \cdot X + n$ where n is additive white noise. According to the orthogonal principle, we can estimate α using $E(Y \cdot X)/E(X^2)$ with MMSE. Although $Y(n)$ is readily available, we have to first estimate the ideal channel output $X(n)$. In this regard, we propose to simply treat the inner LDPC code decoding hard decision output as original channel input $x(n)$, based on which we can directly calculate $X(n) = \sum_i a_i x(n-i)$.

Once we obtain the estimated attenuation factor α, we can repeat the signal detection for the data sequence corrupted by the burst errors, where we simply take into account of the signal amplitude attenuation in the branch metric computation. Since signal redetection occurs after we have carried out inner LDPC code decoding for the first time, we may leverage those successfully decoded inner LDPC codewords to reduce the computational complexity and improve the reliability of the redetection soft output. Recall that each outer BCH codeword is parti-

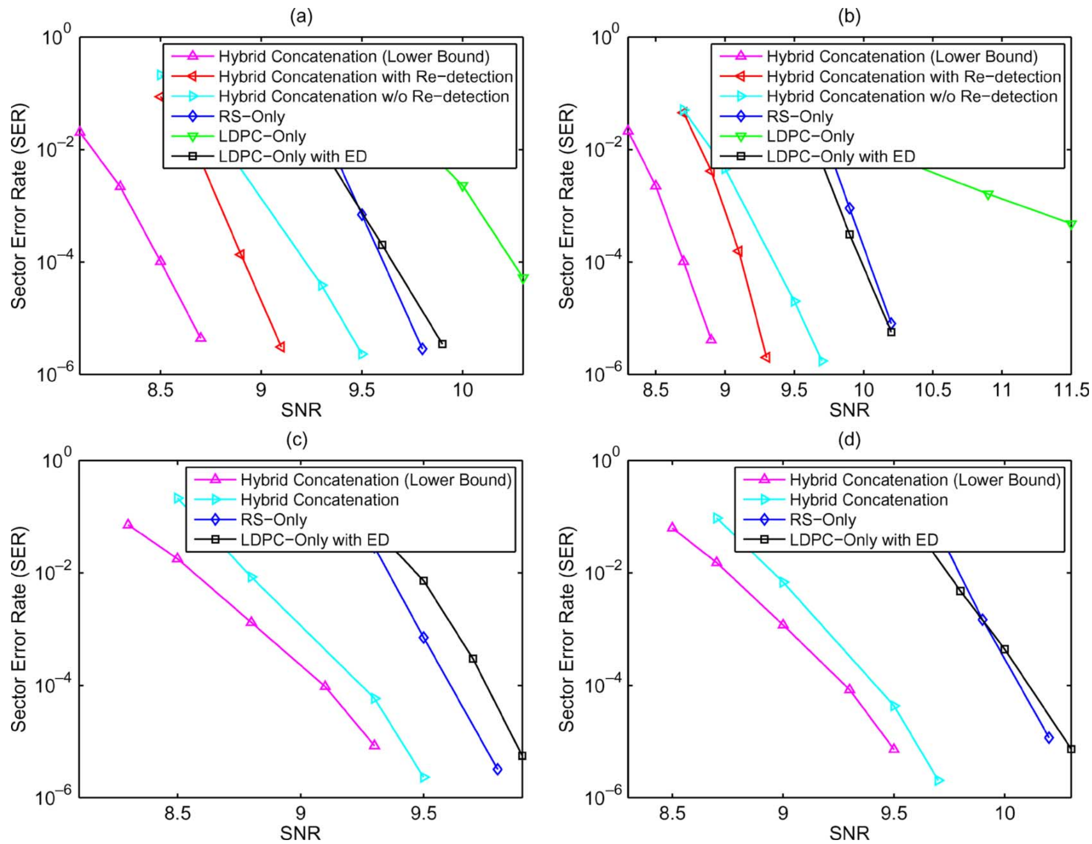

Fig. 9. Simulated SER performance of the rate-13/14 hybrid concatenated coding, RS-only coding, and LDPC-only coding in the presence of one segment of erasure burst errors with (a) 600-bit length, $\alpha = 0.25$, (b) 800-bit length, $\alpha = 0.25$, (c) 600-bit length, $\alpha = 0$, (d) 800-bit length, $\alpha = 0$.

tioned into v segments. Suppose k segments out of v segments have been successfully decoded before we invoke signal redetection, there are at least k bits for every v bits are known. Leveraging these known bits, we can accordingly prune certain trellis branches as illustrated in Fig. 8, which shows a four-state trellis with eight-bit input bits stream "xx00x11x", where "x" denotes unknown bits to be detected. With less number of branches, the computational complexity can be accordingly reduced. Moreover, in terms of branch metric calculation, we can also feed the soft output of LDPC code decoding as *a priori* information to enhance the signal detection performance.

For the purpose of comparison, we also carry out the simulation where LDPC-Only coding is used and erasure burst errors are detected using the erasure detection (ED) method developed in [5]. All the parameters and configurations are set exactly same as those in [5]. Accordingly, Fig. 9 shows the simulation results of the three different coding systems in the presence of erasure burst errors. The attenuation factor $\alpha = 0.25$ and $\alpha = 0$ correspond to partial and full erasure, respectively. We also consider two different burst error lengths for each attenuation factor α. Similarly, in all cases, we show the ideal lower bound of SER for the hybrid concatenated coding assuming we have a perfect knowledge of burst error location and attenuation factor α. Moreover, we also show the SER performance of the hybrid concatenated coding when signal redetection is enabled and disabled (note that, when signal redetection is disabled, we simply erase the soft input to LDPC code decoders at the identified burst error locations).

In case of partial erasure (i.e., $\alpha = 0.25$), simulation results as shown in Fig. 9(a) and (b) demonstrate about 1.1 dB and 1.3 dB gain over RS-only coding when the burst length is 600 and 800, respectively. It outperforms the LDPC-only coding assisted with ED by around 1.2 dB and 1.3 dB when the burst length is 600 and 800, respectively. The LDPC-only coding system has the worst performance and even fails to work when the burst length reaches 800, which further demonstrates the significant vulnerability of LDPC codes themselves to burst errors. We note that, as we increase the read channel SNR, the gap between hybrid concatenated coding with and without signal redetection tends to increase. This is because, at lower SNR the inner LDPC code decoding hard decision output contains more bit errors, which will directly degrade the accuracy of estimated α and hence make the signal redetection less effective. A higher SNR will lead to reduced bit errors in inner LDPC code decoding hard decision output, which will make the estimated α more accurate and hence make the signal redetection more effective.

In case of full erasure (i.e., $\alpha = 0$), signal redetection will not produce any performance gain and LDPC-only coding completely fails to work, hence Fig. 9(c) and (d) do not show the the corresponding simulation curves. The results show about 0.5 dB and 0.7 dB gain over RS-only coding when the burst length is 600 and 800, respectively. Compared with the LDPC-only coding system assisted with ED, the proposed hybrid concatenated coding achieves 0.6 dB and 0.8 dB gain when the burst length is 600 and 800, respectively. Clearly, the above simulation results show that the proposed hybrid concatenated coding

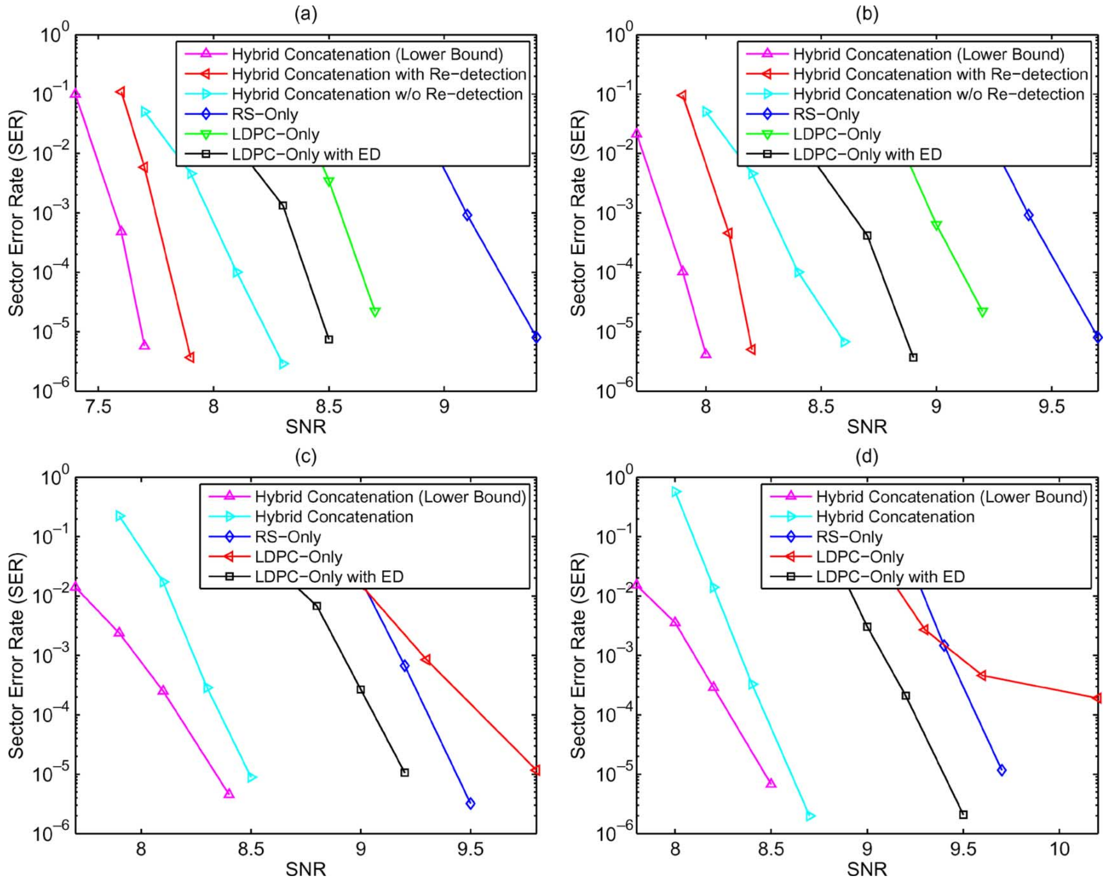

Fig. 10. Simulated SER performance of the rate-8/9 hybrid concatenated coding, RS-only coding, and LDPC-only coding in the presence of one segment of erasure burst errors with (a) 600-bit length, $\alpha = 0.25$, (b) 800-bit length, $\alpha = 0.25$, (c) 600-bit length, $\alpha = 0$, (d) 800-bit length, $\alpha = 0$.

strategy can achieve very good gain in the presence of read-back signal erasure burst errors.

We repeated the same simulations for the case of overall code rate of 8/9. Fig. 10 shows the simulation results, from which similar conclusions can be drawn with respect to the comparison among different coding schemes and the advantages of the proposed hybrid concatenated coding scheme. Moreover, by comparing Fig. 9 and Fig. 10, we can observe how overall code rates may impact the effectiveness of different coding schemes. From Fig. 9(a), (b) and Fig. 10(a), (b) in case $\alpha = 0.25$, we can see that, as the overall code rate reduces, the hybrid concatenated coding scheme tends to realize a higher gain over its RS-only counterpart. Meanwhile, compared with the other two schemes, the LDPC-only coding scheme tends to benefit most as we reduce the overall code rate. Similar conclusion can be derived from Fig. 9(c), (d) and Fig. 10(c), (d) in case $\alpha = 0$.

C. TA Burst Errors

As elaborated in [4], TA burst errors are modeled by overwriting the equalized signal with the peak amplitude of the isolated pulse. In this work, we assume that the location of TA burst errors changes randomly sector by sector. Fig. 11 shows the simulated SER results when every sector contains one segment of 600-bit and 800-bit TA burst errors, respectively. For overall code rate of 13/14, Fig. 11 shows both the SER lower bound assuming the burst errors are perfectly located and the SER performance when we use the RS code to estimate the location of the burst errors with inevitable estimation inaccuracy. In case of LDPC-only coding, we assume that the TA burst errors can be perfectly identified using read channel front-end circuits, and are subsequently erased. Under such an ideal but apparently unfeasible assumption, LDPC-coding can achieve the best performance as shown in Fig. 11. Fig. 12 shows the results of rate-8/9 case, which again shows that LDPC-only coding scheme tends to benefit most from overall code rate reduction.

Based upon the above performance evaluation and comparison under write-in, erasure, and TA burst errors, we may conclude that the proposed hybrid concatenated coding strategy appears to be the most preferable option that can very well accommodate all these three types of burst errors. Moreover, this proposed design strategy does not demand any assistance from front-end circuits, certain types of precoder and analysis of trellis signal detection output, which can largely simplify the overall read channel design.

D. Performance Comparison in the Absence of Burst Errors

In this section, we study the performance of various coding options when burst errors are not considered. With the exactly same configurations as above, we carry out simulations for LDPC-only, RS-only and the proposed hybrid concatenated coding system without considering any burst errors. Moreover,

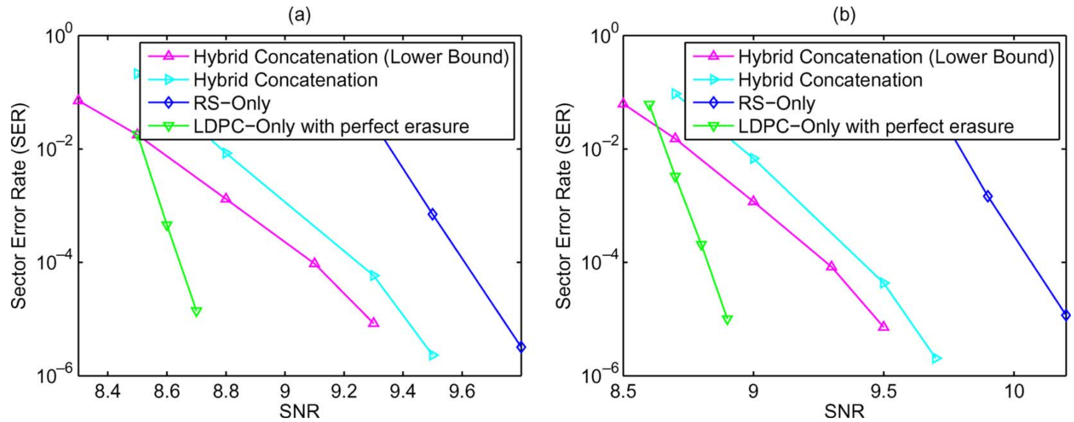

Fig. 11. Simulated SER performance of the rate-13/14 hybrid concatenated coding, RS-only coding and LDPC-only coding with perfect erasure in the presence of one segment of (a) 600-bit and (b) 800-bit TA burst errors.

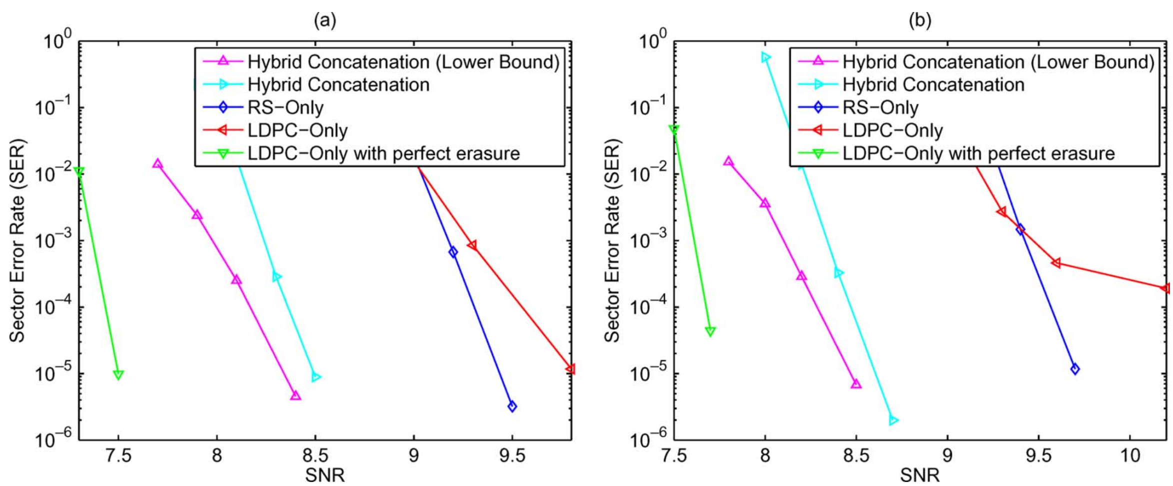

Fig. 12. Simulated SER performance of the rate-8/9 hybrid concatenated coding, RS-only coding and LDPC-only coding with perfect erasure in the presence of one segment of (a) 600-bit and (b) 800-bit TA burst errors.

we further run simulation for regular BCH-LDPC concatenated coding, i.e., each outer BCH codeword is partitioned into 8 segments all of which are encoded by the same rate-17/18 inner LDPC code. Hence, in the context of BCH-LDPC concatenation, the outer BCH code is able to correct up to 36 bit errors. We note that, except RS-only coding, we carried out up to 4 detection/decoding iterations for the other three coding options. Fig. 13 shows the simulation results. As we could expect, the LDPC-only coding can achieve the best performance as well as the sharpest waterfall when burst errors are not considered. Meanwhile, because of the big code rate loss due the use of RS inner code for burst error detection, the hybrid concatenated coding can only achieve a performance similar to RS-only coding.

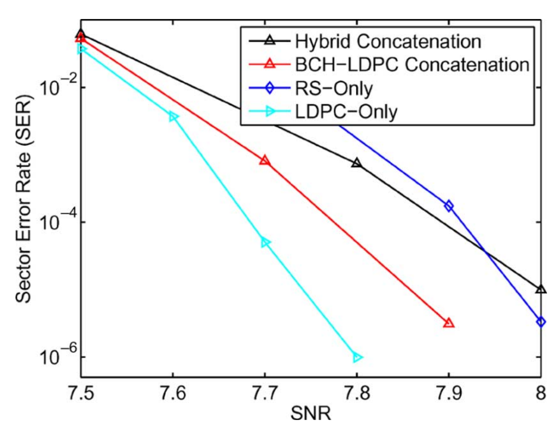

Fig. 13. Comparison of different coding systems without burst errors.

Finally, we note that, although this work did not quantitatively investigate and evaluate the silicon implementation of the proposed hybrid concatenated coding scheme and the comparison with other competing coding schemes, it is worthy to qualitatively discuss the hardware implementation issue. First of all, it should be pointed out that, compared with its RS-only or LDPC-only counterparts, although the hybrid concatenated coding scheme demands the silicon implementation of three different types of decoders, each decoder can be much less resource demanding. It is well known that the computational complexity of RS and BCH decoding is quadratically proportional to t. Since the RS and BCH codes used in this hybrid concatenated coding scheme do not have a big value of t, particularly compared with the RS-only coding scheme, their decoder implementation complexities can be relatively very small. The silicon complexity of LDPC decoders is proportional to the code length.

As a result, the silicon overhead of the inner LDPC code decoder in the hybrid concatenated coding can be much less than that of a 4KB LDPC code decoder in LDPC-only scheme. Therefore, although this proposed hybrid concatenated coding scheme demands three different decoders, its overall silicon implementation complexity is not necessarily higher than other competing solutions. Meanwhile, it should be pointed out that, from the system design and verification point view, the proposed hybrid concatenated coding scheme is certainly more demanding than the other single-code schemes.

IV. CONCLUSION

This paper proposes a hybrid LDPC-centric concatenated coding design strategy that can achieve strong robustness to various burst errors in magnetic recording read channel. The key idea is to replace one inner LDPC code with another inner code such as RS code with much better burst error correction capability. This particular inner code can reveal the burst error location information to the other inner LDPC codewords, which enables the use of soft input erasure to largely improve inner LDPC code decoding performance in the presence of significant burst errors. A signal redetection approach is developed to further improve the hybrid LDPC-centric concatenated coding performance in the presence of erasure burst errors. Using a hybrid concatenated BCH-LDPC/RS coding design as an example, we carried out simulations under three different types of burst errors, including write-in, erasure and TA burst errors. Results demonstrate the advantages of this proposed design solution over both RS-only and LDPC-only solutions. We believe such hybrid LDPC-centric coding provides an attractive option to readily leverage the appealing advantages of LDPC code and meanwhile well mitigate its burst error vulnerability in practical magnetic recording applications.

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