Novel Soft-Feedback Equalisation Method for Multilevel Magnetic Recording

P. Shah*, M. Ahmed*, M. Ambroze†, C. Tjhai†, P. J. Davey*

*Centre for Research in Information Storage Technology, University of Plymouth, UK.
†Fixed and Mobile Communications Research, University of Plymouth, UK.
Email:{purav.shah,mahmed,m.ambroze,ctjhai,p.davey}@plymouth.ac.uk

Abstract— This paper investigates the use of multi-level modulation for magnetic recording using a novel Soft-Feedback Equalisation (SFE) approach. Different aspects of investigation are: 1) Multilevel Recording, 2) SFE and 3) Application of Turbo Codes. The SFE scheme is a model in which the partial response (PR) equaliser and Maximum A Posteriori (MAP) decoder are replaced by a linear filter with an iterative MAP decoder. Error correction codes (ECC) are applied to the multilevel recording system in order to achieve very low error-rates. Implementation of the SFE scheme for multi-level recording shows a reduction in complexity in comparison to various PRML schemes. The simulation results show a clear performance gain of multi-level-coded against binary-coded recording systems. At higher Signal-to-Noise Ratio (SNR), the coded multi-level SFE scheme overcomes the error floor effect produced in the coded multi-level PRML scheme, which is caused by minimum distance error events. Overall, this paper proposes the use of coded multilevel recording with SFE scheme at lower rates rather than coded binary recording at higher densities in order to achieve similar performance.

Keywords: Soft Feedback Equalisation, Multilevel, Magnetic Recording, Longitudinal Recording, PRML, MAP, Error Correction Codes, noise colouration.

I. INTRODUCTION

It has been shown that multilevel techniques operate closer to the channel capacity than binary for a bandwidth limited channel experiencing Additive White Gaussian Noise (AWGN) at increased Signal to Noise Ratio (SNR) [1]. Previous work [2] suggested that multi-level techniques, offered little, if any improvement of the magnetic recording capacity compared to the binary(two-level) system, and is eventually limited by amplitude irregularities in the magnetic channel.

Multilevel encoding of data gives its M set of symbols, a k-bit meaning, where $M = 2^k$. Since the magnetic recording system works at a higher SNR, we can take advantage of it and use multi-level encoding and ECC to achieve more bandwidth efficiency, i.e. more "information bits" can be stored in the transitions on the magnetic media. It is known that at higher code rates for AWGN channels, binary codes tend to deviate very quickly from their theoretical performance [1]. In order to achieve very low error-rates at a particular SNR, it is necessary to use state of the art error correction codes like Turbo Codes. SFE was introduced in [3], in which Turbo Equalisation was discussed with linear complexity.

SFE based multilevel recording is discussed which is based on decision feedback channel [4] principles and is in contrast to the popular PRML technique. It is not the same as Turbo Equalisation which was discussed at length in [5]. In this work, turbo codes are used as outer ECC codes and they are not in conjunction with the SFE process.

The design of the SFE block is independent of the number of levels used for recording and the overall process of SFE is non-linear. This paper examines the use of multilevel data in conjunction with powerful ECC, for PRML and SFE magnetic recording channels, to achieve increased channel capacity for a particular SNR in the operating region of the magnetic recording devices.

II. SYSTEM SIMULATION MODEL FOR SFE APPROACH OF MULTI-LEVEL RECORDING

Soft Feedback Equalisation is a technique which is based on filters with feedback algorithm for removing ISI from the magnetic recording readback channel data. In the PRML approach, the filter in the PR equaliser shortens the impulse response of the underlying channel. There is noise colouration and noise enhancement penalty in this process which changes as PW_{50} changes. This is because the dependence of noise colouration is non-linear [6]. The noise in magnetic recording channel is uncorrelated, and the equaliser modifies the correlation properties of the noise resulting in colouring of noise. The noise correlation affects the error rate of the PRML channel. In the proposed SFE scheme, a linear modified Lorentzian filter is used to estimate the amount of ISI introduced by the magnetic channel and the MAP decoder in the iterative loop tries to remove this estimated ISI. The overall decoding process is non-linear. This technique is in contrast with the PRML technique, since it does not use the introduced ISI, but instead it tries to remove the ISI using a feedback loop. As a result, there are no penalties of noise colouration or enhancement.

The feedback approach in the SFE system is an adaptive approach and thus the channel data remains in its original form without any alteration in the correlation properties of noise. The only problem is residual ISI obtained from linear super-positioning of certain error patterns. In this simulation model, ISI is treated as ISI noise $i(t)$.

The convergence criteria for the feedback loop is as follows: Initially the estimates of the noisy data are passed through a non-linear filter and error is calculated from the original readback data and the estimates. This error is then fed into a loop which uses an error minimising MAP algorithm in order
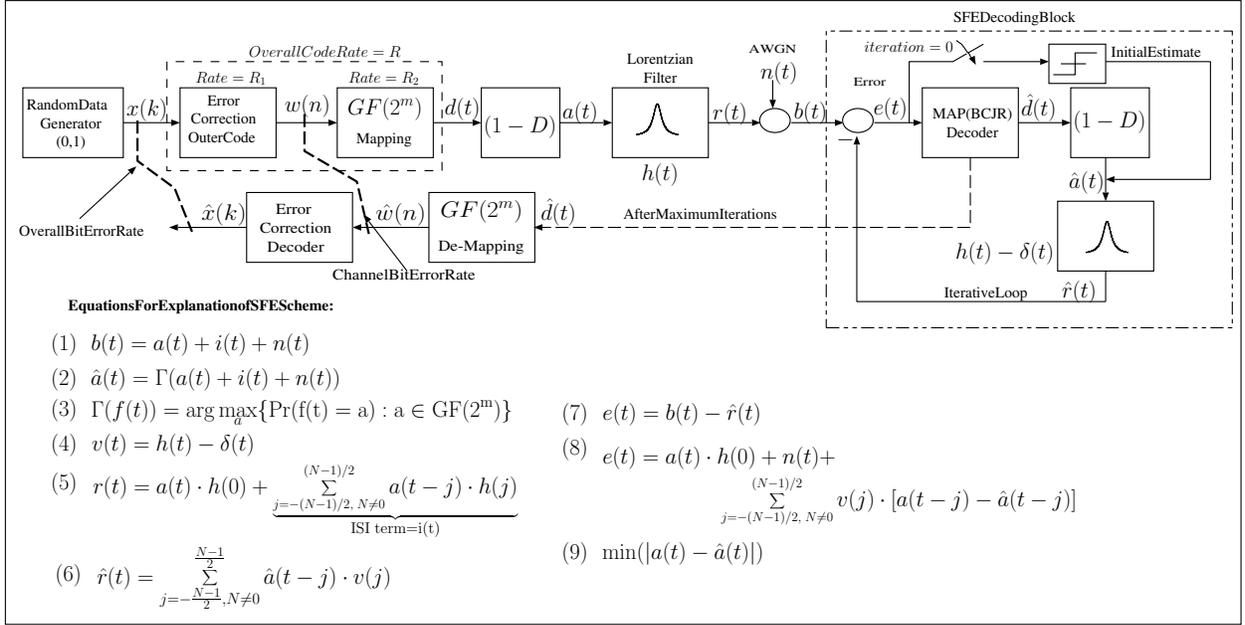
Fig. 1. Simulation Model of SFE Multilevel Magnetic Recording System

to locate the transitions. The error calculated tries to estimate and remove the ISI from the channel and as it goes through the iteration of the feedback loop. The convergence of the error depends upon the amount of ISI, the pattern of transitions and AWGN in the channel. Depending upon both the factors, the number of iterations required to achieve the performance of the system is set. The convergence equation is obtained by minimum mean squared error criterion [7].

Here, $\{x(k)\}$, where $x(k)\epsilon\{0, 1\}$ is the user data. The ECC encoder output is $\{w(n)\epsilon\{0, 1\}\}$ and the mapping output $d(t)$ depends upon the number of mapping levels used based on $GF(2^m)$. Here, m is the number of bits mapped together. The mapping for 4-levels is done by taking 2 bits at a time and mapping them as: 00 becomes 0, 01 becomes $1/3$, 10 becomes $2/3$, and 11 becomes 1. All the levels are equally spaced. For 4-levels, $d(t)\epsilon\{0, 0.33, 0.66, 1\}$ and for 2-levels, $d(t)\epsilon\{0, 1\}$.

The N coefficients of the Lorentzian Filter are $h(-\frac{N-1}{2}), \ldots, h(\frac{N-1}{2})$, where N is a positive odd integer. The value of the coefficients of the Lorentzian filter depends upon the value of PW_{50}. After passing $a(t)$ through the Lorentzian filter, the readback pulse $r(t)$ is obtained. The channel SNR definition in dB used for the system in the simulations is

$$SNR_{channel} = 10 \log_{10}\left(\frac{1}{2\sigma^2}\right) dB$$

where σ is the standard deviation of the Gaussian Noise distribution. The channel noise $n(t)$ is assumed to be AWGN whose variance, σ^2 is determined by the above SNR equation. This noise is then added to $r(t)$ giving $b(t)$.

Filtering of $a(t)$ with the first Lorentzian filter introduces ISI in the channel. This is the point where the ISI noise $i(t)$

comes into account. Thus, the noisy channel output has two additional components: ISI noise $i(t)$ and AWGN $n(t)$, where $i(t)$ is a function of $a(t)$.

The noisy channel output $b(t)$ is then thresholded, using a threshold device and the output of the threshold device is used as an initial estimate of the dicode output given as $\hat{a}(t)$. This thresholding process is controlled by an open switch which closes only during the $0th$ iteration. Thus, it is only used in the beginning of the feedback process. The thresholding is performed depending upon the number of levels used. The thresholded data $\hat{a}(n)$ consists of $n(t)$ and $i(t)$. Thus,

$$\hat{a}(t) = \Gamma(a(t) + i(t) + n(t)), \qquad (1)$$

where

$$\Gamma(f(t)) = \arg \max_a\{\Pr(f(t) = a) : a \in GF(2^m)\}$$

and $\Pr(f(t) = a)$ is the a-priori probability of $f(t)$ being a, which can be simply obtained from the probability density function of a Gaussian distributed random variable [7]. Once the estimates are achieved, the estimates go through another lorentzian function filter, where the middle lorentzian sample, i.e. the peak value is set to 0. It is set to 0 in order to estimate the ISI introduced by the first lorentzian filter. This modified Lorentzian function is denoted as

$$v(t) = h(t) - \delta(t), \qquad (2)$$

where $\delta(t)$ is a unit amplitude impulse at $t = 0$ and zero elsewhere. The N tap coefficients of the second filter are $v(-\frac{N-1}{2}), \ldots, v(\frac{N-1}{2})$ with $v(0) = 0$, where N is a positive odd integer. The output from the second filter $\hat{r}(t)$ is cancelled from the output $b(t)$, resulting in error output $e(t)$. This error sequence is passed through the MAP detector and passed through $(1 - D)$ and the estimates are updated as $\hat{a}(t)$.

As the MAP output $\hat{d}(t)$ enters into the convergence loop, it tries to minimise the effect of ISI completely since it is dependent upon the error $e(t)$. After the convergence has reached, which is after 5 iterations, Bit Error Rate (BER) and Frame Error Rate (FER) are calculated at the points shown in the block diagram.

When ECC is introduced in the system, the input to the SFE channel is given from the ECC encoder output $w(n)$. After convergence has been reached, the output of the MAP decoder $\hat{d}(t)$ is given to the ECC decoder. The points of overall BER and FER calculation with ECC are also shown in the block diagram. The equations explaining the above process are as shown in figure(1).

III. ECC SPECIFICATIONS

The outer ECC code used for the simulation is a $1/3$ rate turbo code. The design of turbo codes is achieved using tail-biting recursive systematic convolutional codes with feed-forward polynomial $F_f = [37]_8$ and feed-back polynomial $F_b = [23]_8$ for an overall rate $1/3$ turbo code. The turbo decoder is iterative parallel concatenated MAP decoder with extrinsic information exchange [8]. The interleaver used is an $S - random$ interleaver [9]. The block length is set to 500 information bits and the maximum number of iterations is set to 50. At least 100 error blocks were collected for each BER point.

Denoting the code rate of the error correcting code as R_1 and the code-rate for the 4-level system as $R_2 = 2$, the overall code rate of the 4-level system is

$$R = R_1 \times R_2 = 2R_1$$

IV. RESULTS AND DISCUSSIONS

The simulation parameters for the different coded and uncoded schemes are as below:

- Binary PR-MAP: PW_{50}=2.4, GPR=[1,−0.5,−0.5], ECC used is rate $1/3$ Turbo Code as specified in the ECC specifications.
- 4-Level PR-MAP: PW_{50}=1.2, GPR=[1,−0.8,−0.2], ECC used is rate $1/3$ Turbo Code as specified in the ECC specifications.
- 4-Level SFE-MAP: PW_{50}=1.2, maximum number of iterations in feedback loop is set to 5, ECC used is rate $1/3$ Turbo Code as specified in the ECC specifications.
- Uncoded 4-Level PR-MAP: PW_{50}=1.2, GPR=[1,−0.8,−0.2]

Results shown in figure(2) show the variation of bit error rate on SNR for different configurations of the multi-level recording system. For an uncoded 4-level PR-MAP system, the desired BER of 10^{-5} is achieved at 25 dB SNR. To achieve the same BER, the PR-MAP system with ECC requires almost 10 dB less channel SNR compared to the uncoded system. In comparison, the coded binary system needs 6 dB less SNR than the coded 4-level system. The coded 4-level SFE-MAP system has similar performance as the coded 4-level PR-MAP system. As seen from the figure(2), the coded SFE-MAP
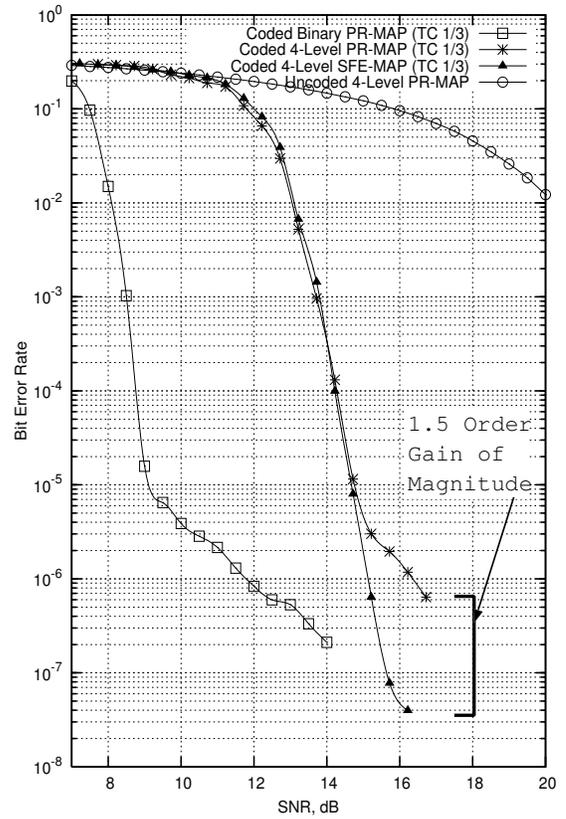
Fig. 2. Performance Comparison of Different Multilevel Recording Channels

scheme performs better than PR-MAP scheme in the operating region(19-22 dB) with rate $1/3$ turbo code. The difference in performance is about 1.5 orders of magnitude in the error floor region. Also from figure(2), the error floor of binary coded system is same as the error floor of 4-level coded systems.

In terms of complexity, the SFE-MAP has less complexity than PR-MAP. This is because of the removal of the PR-Equaliser. The trellis structure for the PR-MAP multi-level system is based on the number of levels used and also on the length of the GPR targets. As in the case of SFE-MAP multi-level system, it is only based on the number of levels used. For a 4-level PR-MAP system with GPR target length of 3, each segment of the trellis has 64 paths and the maximum number of states is 16, while for a 4-level SFE-MAP system, each segment of the trellis has only 16 paths and maximum number of states is 4.

At lower density, the colouration of AWGN introduced by the PR equaliser would be less. The loss in terms of SNR dB calculated for a 4-level PRML system is about 0.5 dB at PW_{50} = 1.2 for the 4-level GPR target. Similarly at $PW_{50} = 2.4$, the calculated loss is about 2.10 dB for the binary GPR target. The use of multi-level signalling enables the use of lower rate error correction codes with larger minimum distances. In the normal operating region (19-22dB channel SNR) of the magnetic recording systems , it is seen from figure(2) that if both the binary and 4-level system performance curves

are extended for a higher SNR, the error floor merges. It is observed that this error floor merge is caused by the ECC properties and not by the modulation technique used. The SFE scheme performs better for the multi-level recording system with ECC than PR-MAP.

The use of rate $1/3$ turbo code show that lower rate codes with better ECC properties used with multilevel signalling and lower recording densities can have equivalent performance compared to binary coded systems with high recording densities.

V. CONCLUSION

The proposed new SFE scheme performed better than PRML scheme in magnetic recording. Simulation results were presented for the comparison of both the schemes. This paper gives an insight into a new type of magnetic recording which is better in terms of complexity, performance and implementation. Equations were presented to clearly explain the convergence criterion of the SFE scheme. Application of multi-level signalling in magnetic recording has been shown to be beneficial, when the operating region of magnetic devices and low error rates were discussed. The SFE scheme performed better than PR-MAP scheme when ECC was implemented because the noise colouration effect was reduced which was caused by the PR-equaliser in the PR-MAP scheme. The error floor region which is the operating region of magnetic recording devices was shown and it was presented that the binary coded system had similar error floor to that of 4-level coded system.

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