INTRODUCTION

Two-dimensional magnetic recording (TDMR) is a promising technology for boosting areal densities using sophisticated signal processing algorithms within a systems framework. The channel impairments comprise of 2D inter-symbol interference (ISI), 2D synchronization errors along with media and electronic noise sources, making it challenging for designing optimum algorithms and architectures for read/write channels.

2D ISI detection is known to be NP-hard. This poses us a need to develop efficient as well as optimal detection algorithms to handle other channel impairments along with the 2D-ISI.

Voronoi media model of TDMR:

- Magnetic grains are modeled as Voronoi cells. Each cell is a magnetization according to the location. Such grains contributes to a Gaussian random process.
- 2D ISI is created by the overlap of these Voronoi cells due to the cell boundaries.

2D GENERALIZED PARTIAL RESPONSE TARGET DESIGN

Signal received from the read channel is equalized using a linear equalizer to achieve a desired overall channel response called the partial response. The resultant signal is detected using a ML detector.

- GPR targets are widely used in conventional 1D magnetic recording
- Provides a trade-off between low-complexity linear equalizer and optimal ML detection

MMSE based design of PR target and equalizer:

\[ e_{\text{eq}} = f_{\text{eq}}(x) = x - f_{\text{eq}}(x) \]

\[ \text{MMSE} = E[(e_{\text{eq}} - f_{\text{eq}}(x))^2] = E[x^2] - 2E[f_{\text{eq}}(x)x] + E[f_{\text{eq}}(x)]^2 \]

Solution:

- \( f_{\text{eq}} = \frac{E[f_{\text{eq}}(x)x]}{E[x^2]} \)
- Monic constraint \( a_0 = 1 \)
- Unit energy \( a_0 = 1 \)

Separable PR targets:

\[ G_{\text{separable}} = [b_1 b_2 b_3 b_4] = \begin{bmatrix} b_1 & b_2 & b_3 & b_4 \end{bmatrix} \]

Aids in detection using row-column detectors.

- Iterative optimization of \( g_1 \) and \( g_2 \).

2D SOFT-OUTPUT VITERBI ALGORITHM

2D ISI Detection - Background:

- 2D ISI detection is NP-hard: ML detection is not practically feasible even for 64x64 pixel (512x512 sector).
- Trellis based algorithms: Use row-column detectors that exchange information in an iterative fashion.
- Graph based detector: Generalized belief propagation (GBP) algorithm uses message passing between regions instead of between nodes in a conventional BP algorithm.
- Performance of the 2D ISI detectors is not well understood.

2D Soft-output Viterbi Algorithm:

- Extend ideas of the 1D Viterbi algorithm.
- Make symbol decisions in raster scan order.
- Symbol decision is made by maximizing the likelihood probability of a local span (M) of the readback samples.

\[ P_r(x) = \max_m P(x|m) = \max_m \exp \left( \frac{1}{2} - \frac{1}{2} \sum g_j^T \cdot \sigma^{-1} \cdot g_j \right) \]

- ML Metric: \( g_j^T \cdot \sigma^{-1} \cdot g_j \)
- Bit decision is made by minimizing ML metric \( \delta_j = \arg \min \Gamma_j \)
- Soft-output is obtained by identifying nearest alternative path with wrong decision:

\[ LLL_j = \min_{a_1 \neq a_2} \Gamma_j \]

2D DATA-DEPENDENT NOISE PREDICTION

2D Burst Errors - Background:

- Thermal aspersities result in burst erasures on the medium.
- Challenge is to correct 2D burst erasures of any shape.

Idea: Use metrics from 2D-SOVA to identify defective region. The erasure is indicated in the soft-input in the form of the LDPC decoder.

2D BURST ERASURE CORRECTION

The readback signal strength is low in the defective region.

Following bit-patterns are seen at the output of detector in the defective regions:

\[ \begin{array}{c|c|c|c}
 0 & 1 & 0 & 1 \\
 0 & 1 & 1 & 0 \\
 \end{array} \]

Defect detection and burst erasure correction:

- Identify potentially defective regions using:
  - Threshold on readback signal
  - Identifying defective patter at the output of the detector
- Defective regions are marked with at least 3x3 bursts.
- Defective region is grown to include connected regions.
- The soft-information from the defective region is set 0 at the input of the LDPC decoder.

2D JOINT TIMING RECOVERY AND SIGNAL DETECTION

Sampling locations with 2D timing errors:

- Ideal location
- Frequency offsets
- Phase offsets
- Litter offsets

2D Random Walk Model:

- Timing estimates are discretized to multiples of \( 6_\text{B} \) and \( 6_\text{P} \).
- The 2D joint timing recovery and signal detector uses 2D random walk model to estimate the timing error.

Joint 2D Interpolative Timing Recovery and Signal Detection

- Extends 2D SOVA to include timing information in the definition of the detector’s state.
- Operates in the raster-scan order.
- Timing errors and bit-values are estimated by ML criterion for a local span of samples.
- Samples at estimated ideal locations are recovered using optimal interpolation filters.
- Optimal interpolation filters are designed for every possible discrete time-offset using MMSE criterion.

2D ITERATIVE TIMING RECOVERY SCHEME

Raster scan order:

- Timing estimates of future bits are not available to estimate timing error for the current position.
- Only forward noise prediction can be done using the past estimates.

Iterative timing recovery scheme:

- Two instances of the joint timing-detection algorithm operating in different directions.
- The two detectors exchange extrinsic LLRs and timing estimates.
Signal Processing for Two-Dimensional Magnetic Recording Channels

Chaitanya Kumar Matcha and Shayan Garani Srinivasa

Department of Electronic Systems Engineering, Indian Institute of Science, Bengaluru, 560012, India.

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## Outline

1. **TDMR Introduction**
   - Two-Dimensional Magnetic Recording

2. **Low Complexity 2D ISI Detection**
   - 2D Partial Response Target Design
   - 2D SOVA - Locally Optimal Detection

3. **2D SOVA with Timing Error Detection**
   - 2D SOVA State with Timing Information
   - Forward Prediction of Correlated Noise and Timing Errors
   - Iterative 2D SOVA-TED

4. **2D Defect Detection and Burst Erasure Correction**
   - Use Statistics from Readback Signal and 2D SOVA to Identify Erasures

5. **Conclusion**
**Goal:** Increase Areal Densities beyond 1 Tb/in$^2$

**Idea:** Instead of writing in circular tracks that are far apart, pack the tracks closer allowing for 2D-ISI and use sophisticated signal processing algorithms.

(a) Grains are magnetized according to the bit-values.

(b) Readback-signal is the sum of contributions from all grains.

(c) Non-ideal sampling with frequency offsets.

**Figure:** Voronoi-based granular media model.
TDMR Challenges

**2D inter-symbol interference (2D ISI):**
- 2D ISI detection in NP-hard.
- 2D coding techniques are generally 'difficult'.

**Media Noise:**
- Irregularities in sizes/positions of grains become prominent with decrease in bit-size.

**2D Burst Erasures**
- Traditional 1D ECCs are not suitable.

**2D Timing and Synchronization Issues:**
- Accurate timing is important with the reduction in bit-sizes.
- Frequency offsets in down-track direction due to timing errors in cross-track direction and vice-versa.

**Others**
- Read/write head design, suitable materials for the recording medium, etc.
Partial response (PR) equalization: Combined advantage of
- Low-complexity equalization.
- Performance of the ML detector.

\[
\sum \text{PR equalizer ML Detector } h(i, j) f(i, j) \]
\[
\text{Partial response target } = g(i, j) \]
\[
y(i, j) a(i, j) \hat{a}(i, j) \]
\[
n(i, j) z(i, j) \text{Channel response} + + \]

**Figure**: Combined response of the channel and the PR equalizer is approximated as PR target.

**Our contributions:**
- Extending 1D techniques to design 2D PR targets
  - unit energy and monic constraints.
- Design of separable and non-separable 2D PR targets to aid 2D ISI detection.
Locally optimal surface based detector.

Operates in raster scan order.

2D Soft-output Viterbi algorithm:

- Maximizes likelihood probability of a local span \((M)\) of \(y_{i,j}\):
  \[
  \hat{x}_{i,j} = \arg\max_x p\left(y_{i,j}^{(M)} \mid a\right)
  \]

- Equivalently, minimizes the ML metric given by:
  \[
  \Gamma_{i,j}(x) = \| y_{i,j}^{(M)} - \hat{y}_{i,j}^{(M)} \|^2,
  \]
  where \(\hat{y}_{i,j} = g^T a^{(i,j)}_G\) are the ideal-samples.

- Soft-outputs: Using alternate ML metric corresponding to the wrong decision.
  \[
  LLR_{i,j} = \min_{a, a_{i,j} = -1} \Gamma_{i,j}(x) - \min_{a, a_{i,j} = 1} \Gamma_{i,j}(a).
  \]
**Idea:** Include timing information in the definition of ML metric.

- The ideal sampling locations are approximated by discretizing the timing locations.
  - Using a finer grid with discrete offsets $\delta \bar{B}_x$ and $\delta \bar{B}_y$.
  - $\delta \bar{B}_x$ and $\delta \bar{B}_y$ are factors of non-ideal sampling intervals $\bar{B}_x$ and $\bar{B}_y$.
- Oversample the signal and interpolate to the estimated ideal sampling locations.
  - Optimal interpolation filters are designed using MMSE criterion.
ML Metric with Data-Dependent Noise Prediction

- Media noise is prominent in TDMR
  - Arises from the irregular bit-boundaries $\Rightarrow$ correlated and pattern dependent.
- Correlated media noise has to be whitened for computing ML metric.
- Effect of media noise can be reduced by noise prediction using neighborhood noise samples.
- The updated ML metric with DDNP is given by
  \[
  \Gamma_{i,j} \left( \hat{a} \left( P^{(i,j)} \right), a_{i,j}, a \left( S^{(i,j)} \right), \delta_T (i,j) \right) 
  = \left\| \left( \hat{e}_M - \mu_M(k) \right) W(k) - \left( \hat{e}_N - \mu_N(k) \right) P(k) \right\|^2 ,
  \]
  where
  - $\hat{e}_{i,j} = \tilde{y}_{i,j} - g^T a_G^{(i,j)}$ are noise samples, $W(k)$ and $P(k)$ are noise-whitening and prediction filters.
Iterative 2D Timing Recovery Algorithm

Figure: Two instances of 2D SOVA-TED operating in a turbo loop. The two instances exchange timing and bit-decision information with each other.

Idea: Use two instances of joint 2D timing recovery and signal detection algorithm in a turbo loop

1. Iteratively improve the timing estimates and bit-decisions.
2. Backward noise-prediction can be done using noise samples from previous iteration.

Figure: $7 \times 7$ noise prediction region $N$. Backward noise prediction can be done using noise estimates from previous iteration in a closed-loop configuration.
Simulation Results

(a) CONFIG1: Raw-BER vs SNR in a closed-loop configuration.

(b) CONFIG2: Raw-BER vs SNR in a closed-loop configuration.

- > 1.2 dB SNR gain using turbo-loop over open-loop configuration.
- Separable frequency offsets give better performance.
- Corresponds to 10% gain in areal density.
2D Defect Detection and Burst Erasure Correction

**Figure**: Defect detector indicates the estimated erasure locations to the LDPC decoder.

**Figure**: Defect detection algorithm: a) Potentially defective region is obtained using signal thresholding and defective patterns; b) Defective regions of at least $3 \times 3$ burst sizes are identified; c) Defective region is grown to include the potentially defective neighbors.

- Defective location is estimated using
  - Threshold on the signal level.
  - Defective patterns at the output of 2D SOVA.
- Belief propagation (BP) algorithm can correct erasures if the erasure locations are indicated.
- 2D SOVA and LDPC decoder operate in turbo loop to achieve further gains.
Defect Detector - Simulation Results

(a) Efficiency of the defect detector.

(b) BER performance of the burst erasure correction algorithm with 38x38 bursts.

- >90% efficiency of the defect detection algorithm as designed.
- Burst erasure correction with proposed algorithm
  - is within 0.5 dB of the performance of ideal defect detector for deep defects.
  - outperforms the ideal defect detector by 0.9 dB for shallow defects.
Summary:

- We have proposed a low complexity 2D signal detection algorithm:
  - 2D Separable and non-separable PR target design techniques.
  - 2D SOVA with data dependent noise prediction.
  - 1 patent filed on adaptive PR target design.
- We have proposed a joint iterative 2D timing recovery and signal detection algorithm.
  - Iterative scheme to enable backward and forward noise prediction.
- We have proposed a method for 2D defect detection and burst erasure correction.

In progress:

- Closing on the exact analysis of 1D sequential detection algorithms.
- Analysis of 2D detection and timing recovery algorithms is in progress.


Thank you!