Error Rate Estimation in Perpendicular Recording using A Simple Systematic Model

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Outline

- BER Model overview
- BER Model details: Equalization and Geometric View of Error Probability
- BER Calculation Results and Discussions
  - General characteristics of signal and SNR
  - Effects of “a” Parameter on BER
  - Optimal PW_{50}/B
  - BER of an “ideal” system
Motivation and Goal

Define a simple channel model with:
- Input: basic physical parameters such as transition parameter, head geometry, etc.
- Output: system level parameters, **Bit error rate (BER)**, Byte error rate etc.

References:
Current Status:
What we already have

- Such model has been written for longitudinal recording.
- Noise inputs include DC, transition and Additive white Gaussian noise (AWGN) whose portions can be adjusted.
- Model has detailed structure as below, both parts are treated in simple ways:
Changes Made in Perpendicular Recording

- Change of Equalization Target:
  - Easiest way in the sense of longitudinal recording is use a differentiator (which is being tried and some data exists). Thus, in our model we will first try to use a perfect differentiator followed by a PR4 channel with 11 taps. Taps are optimized using adaptive equalization at each density.

- Change of Noise Auto-Correlation Matrix:
  - Second order noise auto-correlation matrix is different, due to the magnetization orientation or equivalently, the read head sensitivity function (field).
Overview of General Calculation Procedure

**Step I:** Obtain average magnetization, playback signal from isolated transition, etc.

**Step II:** Get optimized tap coefficients $w_n$ using a certain target.

**Step II:** Calculate replay noise autocorrelation matrices, both for stationary and non-stationary noise.

**Step IV:** Convolve with $w_n$ to obtain noise auto-correlation matrices after equalization $R_{eq}$.

**Step V:** Scan all N-bit sequence space to find worst error event. E.g. $N=8$ corresponds to a scan of 255x255 possible error events.
What can be done with the model

- Parametric study: e.g. density dependent, effect of transition parameter, cross track correlation length, geometrics.

- Try to get the measurement trend and other system level characteristics. Especially, investigate the main cause of catastrophic margin in the linear density limit (How much is from medium properties and head-media geometry)

- Other studies such as: thermal decay effect [3], off-track performance [4] (basically extends this model from 1-D to 2-D).

References:
[4] Hiroshi Ide, CMRR review meeting, 2000, UC San Diego
Details: Equalization and Geometric View of Error Probability

Equalization

Misequalization could be a problem @ high density due to limited number of taps

\[ V_{eq}(nB) = V(nB) \otimes w_n \]

* Credit goes to Peng Luo and Hiroshi Ide

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Equalization

Replay transition noise auto-correlation matrix before equalization:

\[ R_{\text{Transition}}(x_1, x_2) = \frac{\sqrt{< A >}}{W} \left(1 + \left(\frac{\sigma_A}{< A >}\right)^2\right)^{1/8} m_{\text{max}}^2 \]

\[ \int_{-\infty}^{\infty} h(x_1 + x', y)h(x_2 + x'', y)(1 + \frac{m(x^\leq)}{m_{\text{max}}})(1 - \frac{m(x^\geq)}{m_{\text{max}}})dx' dx'' \]

After equalization:

\[ R_{eq}(iB, jB) = \sum_{n,m} w_n w_m \left\{ R_{\text{transition}}((i + n)B, (j + m)B) \right. \left. + R_{\text{electronics}}((i + n)B, (j + m)B) + ... \right\} \]
Error Probability

\[ \{ a_i \} \xrightarrow{P} \{ Pa_i \} \quad \text{e.g.} \quad \{ 0 \ 0 \ 1 \ -1 \ 0 \ 0 \} \xrightarrow{P} \{ 0 \ 0 \ 1 \ 0 \ -1 \ 0 \} \]

Geometrically, error occurs if:

\[ \vec{u} \cdot \frac{\vec{v}}{\| \vec{v} \|} > \frac{\| \vec{v} \|}{2} \]
Error Probability Calculation (cont.)

\[
P(\xi > \frac{< Pe, Pe > - 2 < (P - P)a_i, Pe >}{2}) = 0.5 \text{erfc}(\frac{< Pe, Pe > - 2 < (P - P)a_i, Pe >}{2\sqrt{2 < Pe, R_{eq} Pe >}}) \\
\equiv Q(\frac{< Pe, Pe > - 2 < (P - P)a_i, Pe >}{2\sqrt{< Pe, R_{eq} Pe >}})
\]

-Generally, noise is non-Gaussian and highly directional, a further transformation is needed with the simple or more complicated decision boundary determination (investigation undergoing)
Results and Discussions:

- General characteristics of signal and SNR
- Effects of “a” Parameter on BER
- Optimal $PW_{50}/B$
- BER of an “ideal” system
Simplifications

- For this talk, only Transition noise is taken into account, electronics noise or more generally, stationary noise will be studied in the future.

- No NLTS, no percolation.

- On-track only
Replay Geometry of Keepered GMR Head

\[ \delta = 40 \text{nm} \]
\[ s = 8 \text{nm} \]
\[ d = 27.5 \text{nm} \]
\[ W = 383 \text{nm} \]
\[ t_{\text{free}} = 4 \text{nm} \]
\[ W_r = 166 \text{nm} \]

\[ \mu = \infty \]
\[ P = \infty \]
Nominal Parameters (cont.)

- Average grain diameter: \( <D> = 12 \text{ nm} \)
- Grain in-plane area relative distribution: 0.7
- Number of taps in equalizer: 11
- Track pitch: 457 nm (30 Gbits/in\(^2\) @ 500kfc)

Other Parameters (from Spinstand test):
- \( PW_{50} = 92.6 \text{ nm} \)
- \( SNR = 20.1 \text{ dB (rms/rms) @ log10(BER) = -6.35} \) (??)
Isolated Pulse ($a=8$ nm, tanh transition)

* Calculated PW50 about 20% smaller than experimental results for all “$a$”

![Normalized differentiated signal graph with PW$_{50} = 75.43$ nm]
Roll-Off Curve

\[ D_{50} = 458 \text{ kfi} = 54.6 \text{ nm}^{-1} \]

\[ \text{PW}_{50} \cdot D_{50} = 1.38 \]
SNR (assume $s_{cr} = <D>$)

- $a = 3$ nm
- $a = 8$ nm
- $a = 15$ nm

Peak-to-broad band SNR
Dependence of BER on “a”

* BER < $2 \times 10^{-16}$ (eps in Matlab) is forced to this value in this plot, just for easy visualization

** When density $< 200$ kfc, small interference occurs between bits and BER behaves like under a stationary noise

![Graph showing the dependence of BER on density for different values of “a”.](image)
Optimal $PW_{50}/B$ (Transition noise only)

(fix $a = 8$ nm, $B = 50$ nm and Track Pitch, Read width =166 nm and change $PW_{50}$ by changing gap length)
Effect of Different Parameters

<table>
<thead>
<tr>
<th></th>
<th>Current system</th>
<th>“Ideal” system</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>41</td>
<td>32</td>
</tr>
<tr>
<td>( d )</td>
<td>27.5</td>
<td>10</td>
</tr>
<tr>
<td>( \delta )</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>( a )</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>
Results

(change one parameter @ a time following the order in the previous table)
BER versus Density

for various “a”, fixed ideal geometry

$S_{cr} = 12 \text{ nm}$

$S_{cr} = 9 \text{ nm}$

Bit Error Rate (log10)

Density (kfc1)

-16  -14  -12  -10  -8  -6  -4  -2  0

0  200  400  600  800  1000  1200  1400

a=15  a=10  a=8  a=6  a=4.5  a=3

-2.4  -5.1  -7.7  -10.3
Conclusions and Future Work

- To achieve 1000kfcii “a” parameter must be reduced to about 3-4nm (with minimal exchange (s_{cr}=<D>)).

- Besides scaling geometry and keeping tight medium parameter distributions, reducing grain size is important (<D> of 7nm was suggested by Bertram and Williams to give low thermal decay). Further H_{k} should be increased.
Conclusions and Future Work (cont.)

- Apply to specific design of 200GBits/in² and beyond.

- Incorporate thermal and dynamic effects (e.g., from 3D micromagnetic simulations).

- Include specific edge track effects.

- Take measurements at CMRR.