Fundamental of HDD Technology (8)

Outline

- Magnetic Recording Channel Model
- Write Process

Magnetic Recording Channel Model

Diagram of Data Storage Systems

[Diagram showing the process of data storage and retrieval, including encoder, decoder, modulator, and read channel with associated waveforms and codes.]
Basic Write/Read Process

Transition bits (NRZI format):
\{ 0 1 1 0 0 0 1 1 0 0 1 1 0 \}

Writing

\( g = \text{gap size} \)
\( d = \text{head-to-medium spacing} \)
\( v = \text{surface velocity} \)
\( \delta = \text{recording layer thickness} \)
Write Process

- ECC Encoder
- Modulation Encoder
- Precoder
- Nonlinear Transition Shift
- Write Precompensation

Error-Correction Code (ECC)

Notation:
ECC = Error-correction code
Write precomp = Write precompensation

Code rate \( R = \frac{k}{n} \leq 1 \)

- Improve error-rate performance
- Enhance reliability of the storage devices, thus increasing the recording densities.
- **Single bit error**
  - Occur due to a single short-duration noise event, which results in an extra pulse or a missing pulse

- **Bursts of errors**
  - Occur when a group of bits is detected erroneously
  - Due to defects of magnetic medium such as a scratch or a defective spot spanning over many bit periods

**Example – ECC**

- **Consider:**
  - A simple ECC capable of correcting a single error in a group of 16 bits, which requires the overhead of 8 bits for every 16-bit block.
  - An error will occur only if 2 or more bits out of 16 bits are in error.

- **If the probability of a single-bit error is** $p_0$, **then the probability of 2 bits being in error equals** $p_0^2$, **and we have a total of 120 possible 2-bit errors in a 16-bit sequence.**

- **Then, the probability of error using ECC is**
  \[
  P_b = \left(\frac{16}{2}\right) p_0^2 (1-p_0)^{14} = 120 p_0^2 (1-p_0)^{14}
  \]

  Let $P_b = 10^{-9} \Rightarrow p_0 = 3 \times 10^{-6}$

- **Typically, magnetic recording systems must provide a bit-error rate (BER) < 10^{-9}.**
- **The reliability of data recovery may be greatly boosted by using ECC’s.**
- **Once a certain number of errors are corrected by ECC, we can afford to increase the recording densities until reaching a required BER.**
- **Thus, the storage capacity with ECC trends to be larger than that without ECC.**

- **If the error rate is determined by random noise,**
  - Possible to calculate the signal-to-noise ratio (SNR), required to achieve a specific BER.

  - **Example:**
    - To achieve BER = $10^{-9}$ without ECC $\Rightarrow$ Require SNR = 22 dB
    - To achieve BER $\approx 3 \times 10^{-6}$ (with ECC) $\Rightarrow$ Require SNR = 19 dB
      - Yield a gain of 3 dB to spare
    - The reduction in the SNR required to achieve a specified error performance due to ECC is called the **coding gain.**
    - The coding gain in SNR allows increased recording densities.
For example, if the main source of noise is the medium noise,
- A reduction of track width by a factor of 2 ⇒ Lose SNR = 3 dB
  [S. X. Wang and A. M. Taratorin, 1999]
- Therefore, using ECC need 50% more disk space for extra bits, but the coding gain of 3 dB allows us to recording 100% more information by doubling track density.
- The net gain from ECC is 50% more storage capacity
- In general, using ECC will increase the storage capacity.

Reed-Solomon (RS) codes are a common family of ECCs used in commercial hard disk drive because:
- Powerful in correcting burst errors
- Good at handling erasures ⇒ useful in the recording industry where channel imperfection due to scratches can be effectively modeled as erasures.
- A RS code is the most efficient code among the \((n, k)\) cyclic codes because it achieves the largest possible minimum distance:
\[
d_{\text{min}} = n - k + 1
\]

ECC Trend
- ECCs are basically independent of a bit detector.
- Trend:
  - Combine the ECC decoder and the bit detector.
  - Employ other ECCs that have large coding gains because they allow for higher recording densities.
    - Turbo codes
    - Low-density parity check (LDPC) codes
Example: Turbo Decoding

Modulation Code

- Normally, it is used to combat channel distortion and noise in transmission.
- In magnetic recording, it is used to eliminate or minimize the d.c. content in the read-back signal and to achieve spectrum shaping*.
- Specifically, it is designed to increase the distance between transitions in the recorded waveform, and thus reducing the intersymbol interference (ISI) effect.
- Run-length limited (RLL) codes are widely used for this purpose.

* Codes for spectrum shaping are used so that the spectrum of the transmitted signal matches the spectrum characteristics of the channel.

Run-Length Limited (RLL) Code

- It has a restriction on the number of consecutive 1’s and 0’s in a data sequence.
- It is determined by two parameters \((d, k)\), where
  - \(d\) denotes the minimum number of 0’s between two 1’s in a sequence.
  - \(k\) denotes the maximum number of 0’s between two 1’s in a sequence.
- Specifically, (when used with NRZI format)
  - \(d\) ⇒ Spread the transitions farther apart, thus reducing the ISI effect.
  - \(k\) ⇒ Ensure that the transitions occur frequently enough so that symbol timing information can be recovered from the signal.

Example: Rate-1/2 (1, 3) Miller Code

Coding rule:

<table>
<thead>
<tr>
<th>User bits</th>
<th>Coded bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X 0</td>
</tr>
<tr>
<td>1</td>
<td>0 1</td>
</tr>
</tbody>
</table>

\[ X = \begin{cases} 0 & \text{if the preceding symbol is 1} \\ 1 & \text{else} \end{cases} \]

User bits = \( \{ 1 \ 0 \ 1 \ 1 \ 1 \ 0 \ 0 \ 1 \} \)

RLL bits = \( \{ 01 \ 00 \ 01 \ 01 \ 00 \ 10 \ 01 \} \)

clearly, we have \(d = 1\) and \(k = 3\)
The price for RLL coding appears in a data rate change.
- # output bits > # input bits
- In other words, RLL coding introduces lots of redundant bits

From the previous example, we found that:
- Rate-1/2 (1, 3) RLL code \( \Rightarrow \) \( (d = 1, k = 3) \)
- 1 user bit is mapped into 2 coded bits \( \Rightarrow \) lose 50% of disk space

Example: 2/3 (1, 7) RLL Code

<table>
<thead>
<tr>
<th>User bits</th>
<th>Encoded bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>101</td>
</tr>
<tr>
<td>01</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>001</td>
</tr>
<tr>
<td>11</td>
<td>010</td>
</tr>
<tr>
<td>0000</td>
<td>101000</td>
</tr>
<tr>
<td>0001</td>
<td>100000</td>
</tr>
<tr>
<td>1000</td>
<td>001000</td>
</tr>
<tr>
<td>1001</td>
<td>010000</td>
</tr>
</tbody>
</table>

Example: 1/2 (1, 7) RLL Code

<table>
<thead>
<tr>
<th>User bits</th>
<th>Encoded bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0100</td>
</tr>
<tr>
<td>11</td>
<td>1000</td>
</tr>
<tr>
<td>00</td>
<td>000100</td>
</tr>
<tr>
<td>010</td>
<td>100100</td>
</tr>
<tr>
<td>011</td>
<td>001000</td>
</tr>
<tr>
<td>0010</td>
<td>00100100</td>
</tr>
<tr>
<td>011</td>
<td>00001000</td>
</tr>
</tbody>
</table>

Which RLL Code is Good?

- Factors needed to be considered when choosing RLL codes:
  - Parameters: \( d \) and \( k \)
  - Code rate, \( R \)
  - Capacity, \( C \)
  - Code efficiency, \( \eta \)
  - Density ratio, \( DR \)
- In practice, we need to compromise all factors to best suit for a given system.
- Some RLL codes:
  - Rate 1/2 – (2, 7) code
  - Rate 4/5 – (0, 2) code \( \Rightarrow \) Group-Coded Recording (GCR) code
  - Rate 8/9 – (0, 3) code
**A (0, G/I) RLL Code**

- Widely used in PRML systems
- No constraint on transition separation, i.e., two transitions may be written without additional zeros between them (i.e., \( d = 0 \))
- The notation \((G/I)\) appears because of the specific realization of PRML channel when a stream of user bits is split into odd and even bits.
  - \( G \) = maximum # of 0’s between 1’s in odd data sequence
  - \( I \) = maximum # of 0’s between 1’s in even data sequence

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**Summary: RLL Codes**

- Error propagation might occur when decoding RLL codes.
- Recently, a \((0, G/I)\) sequence is employed in the PRML system.
  - Example:
    - Rate 8/9 - \((0, 4/4)\) code
    - Rate 16/17 - \((0, 6/6)\) code
- High rate RLL codes are desirable in order to reduce redundancy.

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**Write Process**

- Data bits are converted into a rectangular current waveform by the modulator.
  - This write current is applied to the write head to produce the magnetic write field in the medium near the head gap.
  - By switching the direction of the write current, magnetization transitions can be written in the medium.

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**Commercial digital recording systems normally employ binary saturation recording** (i.e., only two data levels).

- If more than two data levels were recorded:
  - **Nonlinearity** would cause a major problem
  - Signal-to-disturbance ratios would diminish considerably
**Comparison of Recording Modes**

**Longitudinal Recording**
- As Bit Length $\rightarrow$ O, $H_d \rightarrow 4 \pi M_s$
- Demag field $H_d$ resists bit length reduction
- Medium: In-plane anisotropy
  - Low $M_s$
  - High $H_C$
  - Thin $\delta_L$

**Perpendicular Recording**
- As Bit Length $\rightarrow$ O, $H_d \rightarrow 0$
- Demag field $H_d$ diminishes with bit length reduction
- Medium: Perpendicular anisotropy
  - High $M_s$
  - High $H_C$
  - Thick $\delta_P$

**Single Pole Type head**

- **Current longitudinal writer (Ring-type head)**
- Writer design
  - "Single pole tip"
- **New perpendicular writer (Single-Pole type head)**

- Perpendicular recording needs writer that can supply the field that perpendicular to media plane
- Longitudinal writer can supply field with longitudinal component more than perpendicular component $\Rightarrow$ Not effective for perpendicular recording
- Single pole tip writer is design specifically to produce very high perpendicular field component approximately 3-4 times more field strength than longitudinal writer.

**Media Soft Underlayer**

- **Soft Underlayer**
- Adding soft magnetic underlayer is like adding a virtual "mirror"
  - A perfect mirror image can improve field strength from writer by 200%
  - Enable media to has higher switching field
- Media grain volume also effectively increases by 200%
- Higher robustness against data loss
Magnetizations and Fields

- **Longitudinal**
- **Perpendicular**

Writing & Reading of LMR vs. PMR

- **LMR**
  - Longitudinal recording
  - Writing
  - Reading and Signal

- **PMR**
  - Perpendicular recording

**In LMR read-back**:
- Peak signal at transitions
- But Zero signal between transition

**In PMR read-back**:
- Zero signal at transitions
- But Non-Zero between transition

Data Format

- Two data formats for generating the write current waveform:
  - Non-return-to-zero-interleaved (NRZI): “1” ⇒ transition
    “0” ⇒ no transition
  - Non-return-to-zero (NRZ): The amplitude level of the waveform directly reflects the given binary bit.

<table>
<thead>
<tr>
<th>Channel bits</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NRZI</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

NRZI & NRZ Relationship

**Precoder**: \( P(D) = \frac{1}{1 \oplus D} \)

\( \oplus \) = a modulo-2 addition

- \( 0 \oplus 0 = 0 \)
- \( 1 \oplus 1 = 0 \)
- \( 1 \oplus 0 = 1 \)
- \( 0 \oplus 1 = 1 \)

**Example**:

<table>
<thead>
<tr>
<th>NRZI:</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ:</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Summary: NRZI & NRZ

- In the NRZ scheme:
  - "1" means one direction of medium magnetization,
  - "0" means opposite direction of medium magnetization.

- In the NRZI scheme:
  - "1" means transition
  - "0" means no transition

Advantage:
- With knowledge of the channel characteristics, the precoder can be chosen to partly
  - Undo the channel distortion
  - Reducing the equalization burden at the receiver
- Precoder help prevent catastrophic error propagation.
- A widely used precoder in commercial HDD is

\[ P(D) = \frac{1}{1 + D^2} \]
Example

Transfer function of a precoder

\[ P(D) = \frac{1}{1 + D^2} \]

Block diagram

\[ D \quad D \]

Output equation

\[ b_k = a_k \oplus b_{k-2} \]

Nonlinearity in Write Process

- Refer to a phenomenon that causes linear superposition to be invalid.
  - The readback signal can be represented by the linear combination of the transition pulses according to the pulse amplitude modulation (PAM) technique.

- Included:
  - Partial erasure
  - Hard transition shift
  - Overwrite
  - Nonlinear transition shift

Nonlinearity – Partial Erasure

- Also known as nonlinear amplitude loss
- Percolation occurs at high densities
  - Regions across the track become partially erased and the amplitude loss results from an effective trackwidth narrowing.

Nonlinearity – Hard Transition Shift

- In magnetic recording, the erasure of old information is accomplished by directly writing new data pattern over old data pattern.
  - An easy transition is written if the head field is in the direction of the incoming magnetization
  - A hard transition when the head field is opposing the incoming magnetization
  - More difficult to write because it requires more head field to saturate the magnetization under the head gap
  - A hard transition always gets shifted later than desired in the absence of other nonlinear effects
Nonlinearity – Overwrite

- The erasure of old information is accomplished by directly writing new data pattern over old data pattern.
- The write field must be sufficient to reduce any residual original information to levels low enough not to cause errors while reading the new data.

How to compute an overwrite ratio:

- First, write a square-wave pattern at frequency $f_1$.
- Then, overwrite with a square-wave pattern at frequency $f_2$ (mostly often $f_2 = 2f_1$).
- The overwrite ratio $(f_2/f_1)$ is the level of the residual $f_1$ signal $V_{r2}(f_1)$ divided by the original $f_1$ signal level $V_{r1}(f_1)$.
- Define
  \[
  OW = 20 \log \left( \frac{V_{r2}}{V_{r1}} \right) \text{ in dB}
  \]
- For typical magnetic recording system, $OW < -30$ dB

Nonlinearity – Nonlinear Transition Shift (NLTS)

- Occur due to the demagnetizing field from previous written transitions.
- Since opposite charges attract each other, the two magnetic transitions (dibit) must be shifted closer.
- NLTS always causes the transition to be written earlier than desired.

  - Data dependent
  - Degrade the SNR of the channel
  - Serious problem at high recording densities

Since the incoming magnetization direction is unknown during the write process, hard transition shift cannot be removed by write precompensation.
Use write precompensation to combat with NLTS

- Intentionally delay switching the write current so that the resulting transition center is in the desired location.

- PRML detection is capable of handling large amounts of linear ISI, but it is based on the assumption that the recording channel is linear.

- Even moderate amounts of NLTS can cause high error rates in PRML systems.

- NLTS cannot be eliminated but can be reduced to achieve better linearity of the recording channel by using write precompensation.

### NLTS in Longitudinal Recording

**transition bits**
0 1 0 1 0 1 1 0 0

**write current**

**medium magnetization**

- disk motion
- shifted transition
- original transition

**Write Precompensation**

- Used to combat with NLTS.

- Adjust the transition delay of the write current by taking into account of neighboring write bits.

- Techniques to determine amount of precompensation and bit patterns:
  - Extracted pulse shape
  - Frequency-domain technique

- High recording densities require a high-order write precompensation because the impact of older transitions becomes significant.