An Introduction to the HDD, modelling, detection and decoding for magnetic recording channels

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Outline

1. Overview of the Hard Disk Drive
   - Fundamental problem for magnetic recording
   - HDD current and future technologies
2. Magnetic Recording Media
3. Magnetic Recording Head
   - Writer
   - Reader
4. Servo
5. Magnetic Recording Channel (MRC)
   - The Encoder
   - Channel Model
   - The Equalizer
   - The iterative detector
   - The joint Viterbi detector/decoder
6. Future HDD Technologies

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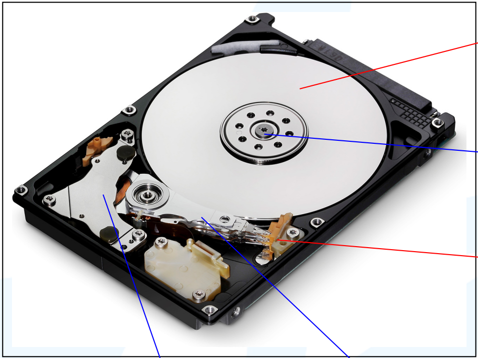
Overview of the Hard Disk Drive



Media: Magnetizable in one of 2 directions: stores binary data

Motor: Rotates at a stable speed with minimal run-out and spindle variation

Head: Converts electrical information into magnetic and back again

VCM (Voice Coil Motor): Actuator for positioning the head

Arm: Rigid mounting for the head

HDI: Head disk interface

Servo: Control scheme for positioning the head over a ~ 40 – 50nm track

Mechanics: Managing vibration, resonant freq, airflow, etc... for the servo

Coding and Signal Processing: Encoding the user data so that it can survive the passage through the channel and detecting/decoding the data on read-back. Our work also involves creating good models for the recording channel.

Fundamental problem for magnetic recording

Defining terms

Magnetic Anisotropy:

- Isotropic: The property of being independent of direction.
- Anisotropic: Not isotropic, dependent on the direction
- Magnetic anisotropy: A property of a magnetic moment or material that prefers to orient in a certain direction (the easy axis direction)
- Magnetic anisotropy field (symbol: H_k, units:kOe): A non-real magnetic field that can be imagined to be holding the moment in the easy-axis direction. The moment behaves as if such a field exists, though it does not.
- Magnetic crystalline anisotropy constant (symbol: K_u, units: J/m^3): The amount of energy needed to cause a volume of the magnetic material to flip

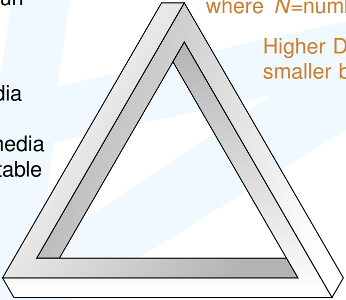
Magnetic anisotropy is the property that enables recording.

Fundamental problem for magnetic recording

The superparamagnetic limit and the media trilemma

3 different ways different ways (trade off) in which AD growth is halted:

1. Grains kept large→run out of SNR
2. Grains shrunk:
   - Big K_u → media unwriteable
   - Small K_u → media thermally unstable



Media SNR $\sim \log(N)$

where N=number of grains/bit

Higher Density → smaller bits
smaller bits → smaller grains

Thermal Stability: $\frac{K_u V}{k_B T} \geq 60$

Small grains become thermally unstable: Random variations due to temperature have non-zero probability to flip grains.

Writeability:

Write head field is limited. Media must have low enough K_u so that it can be magnetized by the writer.

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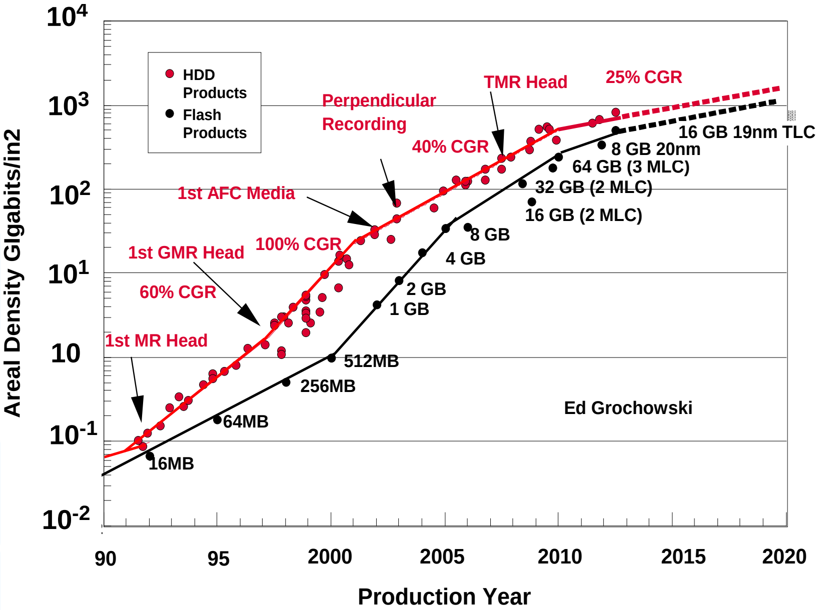
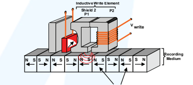
HDD Areal density trend



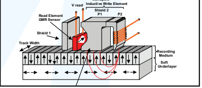
HDD current and future technologies

Previous Technology: Longitudinal Recording



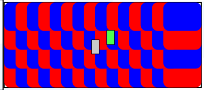
Longitudinal recording writes bits in the plane of the medium using fringe field from head.

Current Technology: Perpendicular Recording



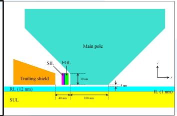
Perpendicular recording changed the orientation of the bits perpendicular to the medium and included an SUL. Medium now in the head gap.

Upcoming Technology: 2D/shingled magnetic recording



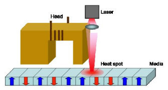
SMR/TDMR overlaps adjacent tracks into a 2D block of bits. 2D Processing also occurs using 2D equalization, detection and decoding techniques.

Future Technology: MAMR (μ-wave Assisted Magnetic Recording



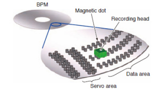
MAMR uses microwave frequencies to excite the grain magnetizations making them easier to switch. Enable switching smaller higher Ku grains.

Future Technology: HAMR (Heat Assisted Magnetic Recording



HAMR uses heat to thermally excite the grains and reduce Ku. This again enable smaller thermally stable grains to be used.

Future Technology: BPMR (Bit Patterned Media Recording



BPMR writes 1 channel bit per magnetic particle (island). These islands are engineered on a lattice that enables them to store data more reliably.

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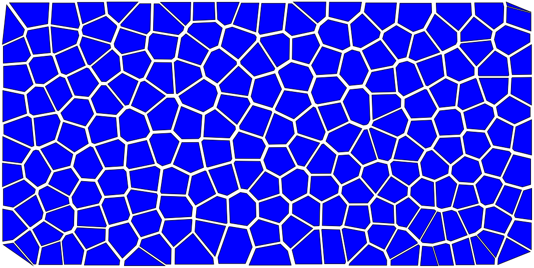
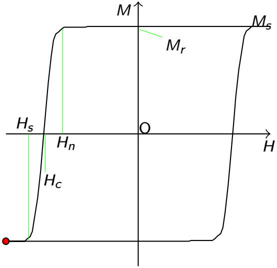
Magnetic Recording Media: Hysteresis loops

- Hysteresis loops plot
  - Applied field on the horizontal axis vs
  - Media magnetization on the vertical axis
- Field is applied perpendicular to the medium.
- Interesting hysteresis properties of the medium

H_n Nucleation field The field required to nucleate the switching
H_c Coercive field The field required to switch 50% of the media
H_s Saturation field field required to saturate the media
M_s Saturation magnetization All moments aligned maximally
M_r Remnant magnetization The remaining moment when the field is removed
S Squareness $S = H_n/H_s$





Magnetic Recording Media

Defining terms

Media Noise:

- Media noise is noise generated by the granular nature of the medium.
- Transitions written on the medium *must* follow the grain boundaries
  - Larger grains → more deviation in transition → more noise
  - Smaller grains → less deviation in transition → less noise
- Media noise manifests as transition jitter in the readback signal.
- Errors tend to be located around the transitions.

Media noise is the dominant noise source in magnetic recording channels.

Exchange coupling:

- Exchange coupling is a short-distance (nm-range) effect that exists between adjacent grains.
- Exchange coupled grains exert a magnetic force (field) on each other that tends to align the grains in the same direction.
- The stronger the exchange coupling, the more the grains will align.
- Exchange coupling causes grains to clump together into larger clusters.

We would like to have well isolated (exchange decoupled) grains.

Magnetic Recording Media: Issues

Desirable properties of magnetic recording media:

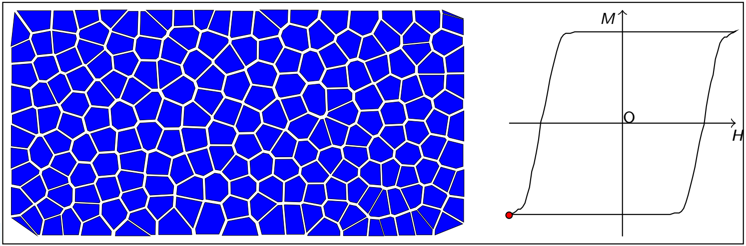
- Smaller grains → less media noise → higher densities
- Smaller grain-size variation
  - Variation in grain-size → more media noise
- Tighter magnetic property distributions
  - Tighter distributions in the magnetic properties → sharper transitions on the medium.
- Engineering multiple layered media
  - Exchange-coupled layers → more thermal stability while maintaining writeability.

μ-mag simulation hysteresis loops varying each of the parameters in this table are shown

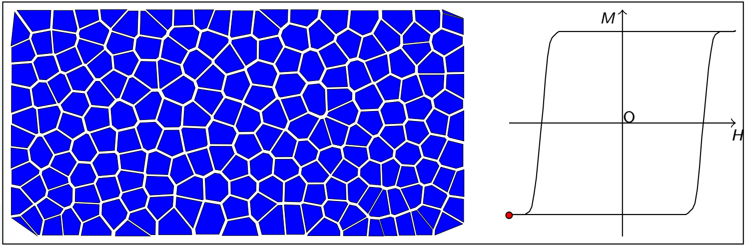
	nominal value		deviated value	
	μ	σ	μ	σ
K_u (J/m^3)	3.6e5	3%	3.6e5	13%
M_s (A/m)	4.8e5	3%	4.8e5	13%
A_x (J/m)	3e-12	3%	3e-11	3%
e_z	0°	1.7°	5°	1.7°

Varying σ_{Ku}

Deviated σ_{Ku} = 13%

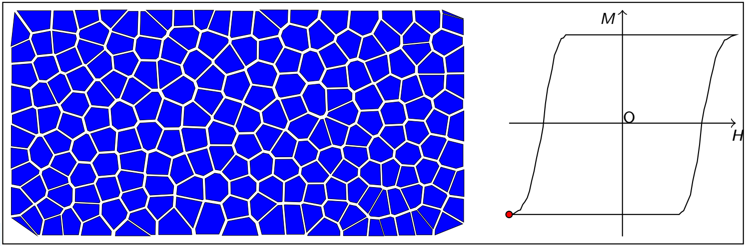


Nominal σ_{Ku} = 3%

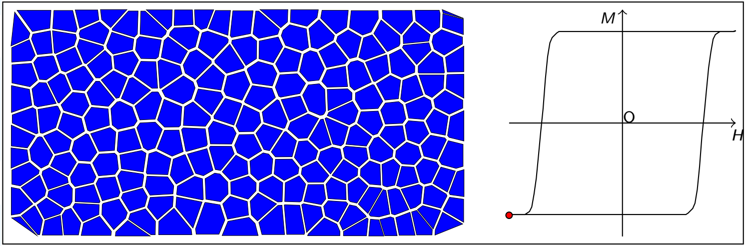


Varying σ_{Ms}

Deviated σ_{Ms} = 13%



Nominal σ_{Ms} = 3%



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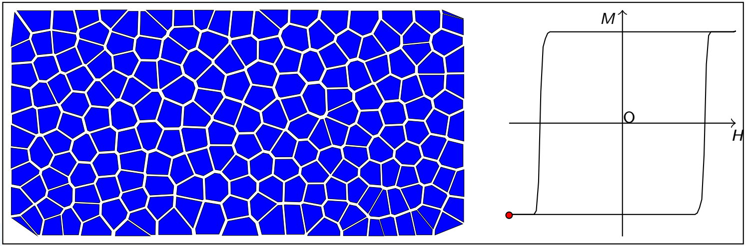
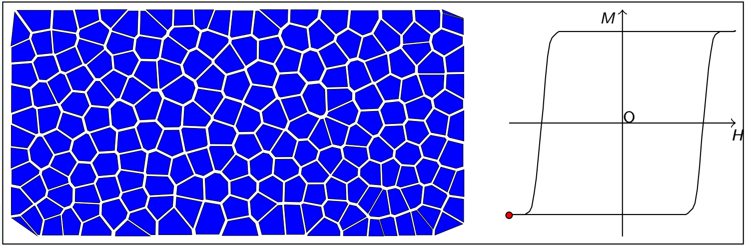
Varying A_x

Deviated A_x = 3e-11

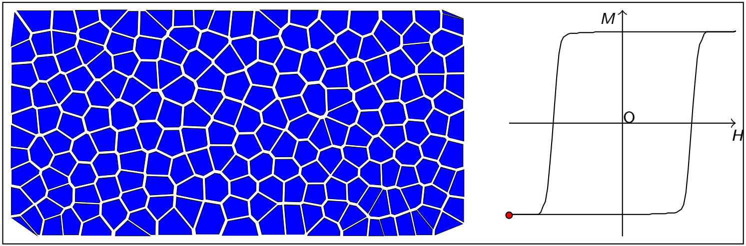


Nominal A_x = 3e-12

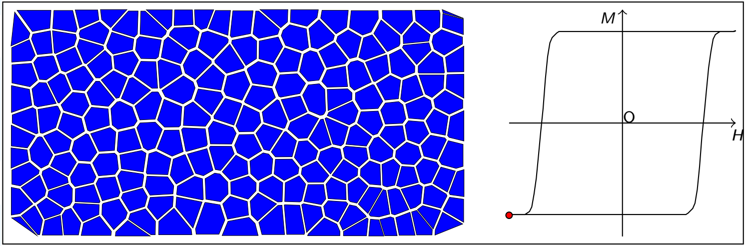


Varying e_z

Deviated e_z = 5°

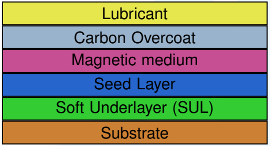


Nominal e_z = 0°



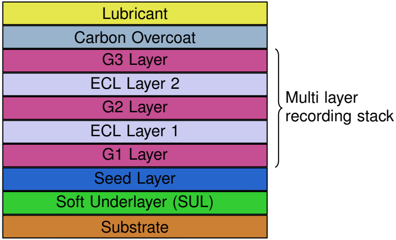
Multi-layer media

Layer thicknesses not to scale



Lubricant
Carbon Overcoat
Magnetic medium
Seed Layer
Soft Underlayer (SUL)
Substrate

Single Layer Media



Lubricant
Carbon Overcoat
G3 Layer
ECL Layer 2
G2 Layer
ECL Layer 1
G1 Layer
Seed Layer
Soft Underlayer (SUL)
Substrate

Multi layer recording stack

Multi Layer Media

- Multi-layer media (aka exchange coupled composite media, spring coupled media) provides more thermal stability for the same writeability.
- Each of the multiple layers have different K_u values and switch at different fields.
- The ECL layer controls the amount of coupling between layers:
- Soft layers help the harder layers to switch.
- Hard layers provide thermal stability to the soft layers.
- Commercial media today is multi-layered.

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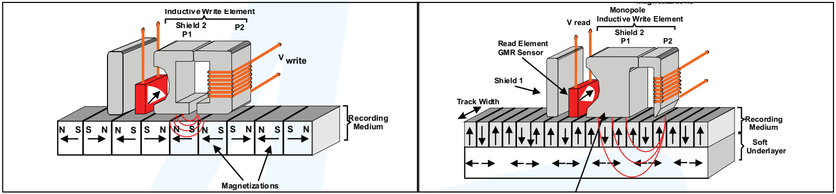
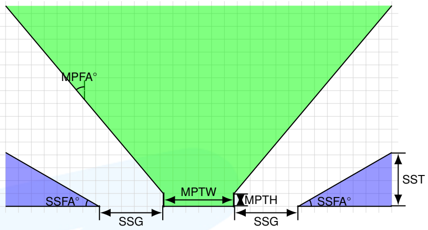
Magnetic Writer

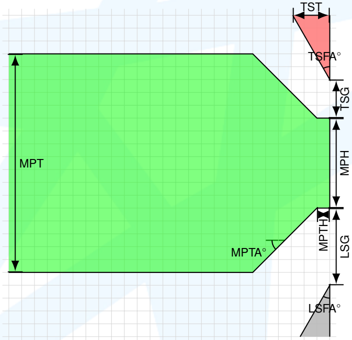


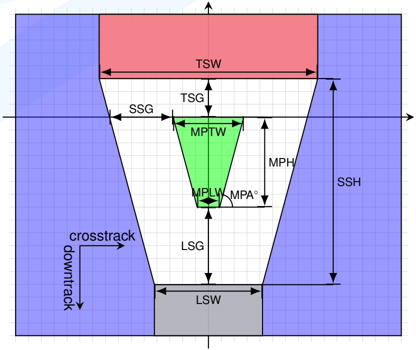
- Magnetic write head driven by the write current
  - Write current modulated by the channel bits
- Longitudinal recording (left)
  - Previous generation technology
  - Used the fringe field from the head gap to write.
- Perpendicular recording (right)
  - Perpendicular recording includes a soft underlayer (SUL)
  - Provides return path for the magnetic flux
  - Effectively putting the media in the write-gap
  - Doubles the amount of field that can be generated

Magnetic Writer

- Magnetic writer when viewed from the ABS is trapezoidal in shape.
- Writer conducts the magnetic flux to the pole tip
- Trailing shield increases the trailing write-field gradient
  - Prevents overwriting of previously written bit
- Side shields increase the side write-field gradient
  - Prevents overwriting of adjacent tracks



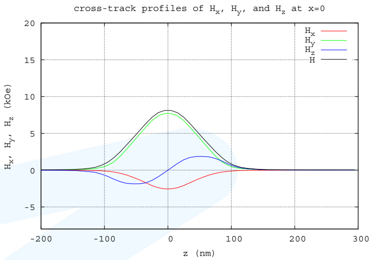


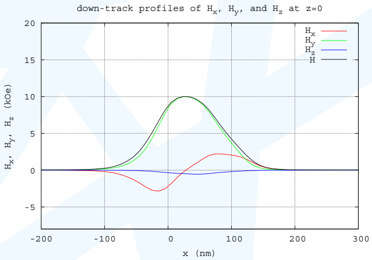


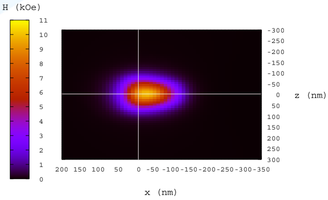
Magnetic Write fields

- Simulated magnetic fields generated by the writer are shown.
- 3 Components (Hx, Hy, Hz) for 1D slice of field in each direction
  - Cross-track Profile ⇒
  - 2D Profile ⇘
  - Down-track Profile ⇓
- In-plane components help in the switching.

Cross-track profile



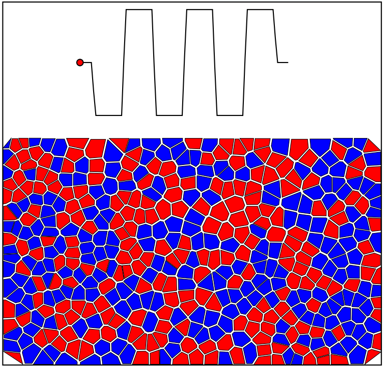




Down-track profile

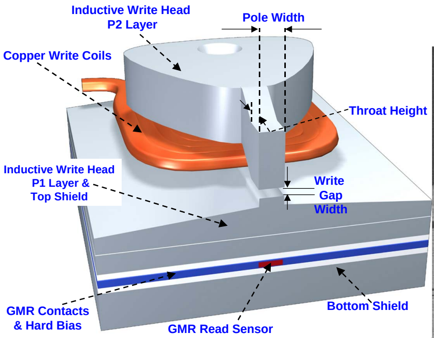
2D profile

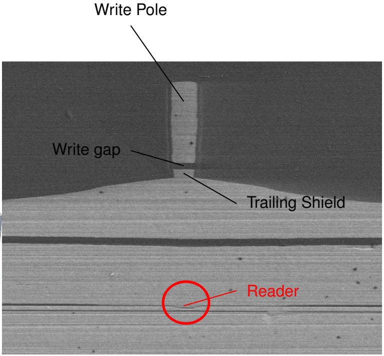
Magnetic writing simulation



Parameter		Value
Grain size	(nm)	9
σ_{gs}		16%
K_u	(J/m^3)	240e3
x σ_{Ku}		3%
M_s	(A/m)	480e3
σ_{Ms}		3%
H_k	(kOe)	10
σ_{Hk}		4.26%
e_z		0°
σ_{ez}		1.7°
velocity	(ms^{-1})	20
BL	(nm)	14

Magnetic Reader

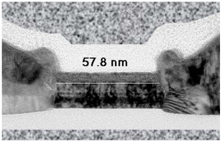


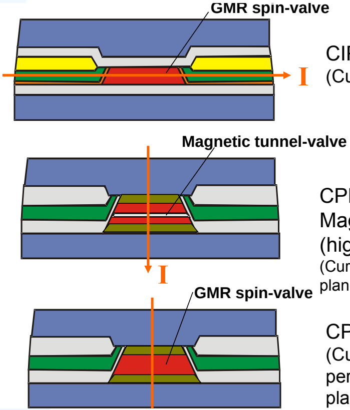


SEM x-section image

- Reader technology evolution:
  - ① AMR - Anisotropic magnetoresistive
  - ② GMR - Giant magnetoresistive
  - ③ TMR - Tunneling magnetoresistive ← current technology
- Magneto-resistive: The property of materials to change resistance in the presence of a magnetic field.

Magnetic Reader



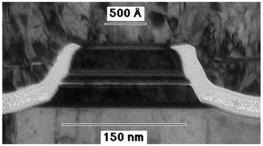


CIP-GMR
(Current-in-plane)

CPP-Tunnel Magnetoresistance (high R)
(Current-perpendicular-to-plane)

CPP-GMR (low R)
(Current-perpendicular-to-plane)

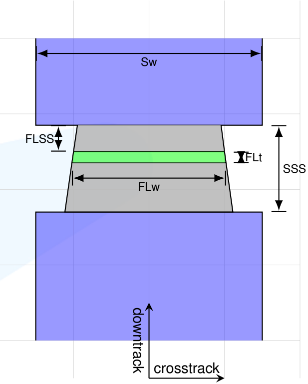
Tunnel-valve head

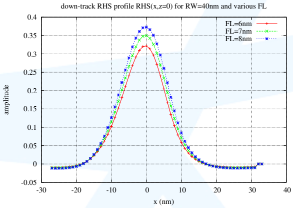


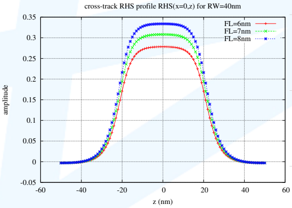
- Ambient magnetic field ⇒ free-layer to rotate
- → resistance change of the device.
- Pass current through to measure *R*
- Reader is sensitive to a region of the magnetic medium
- Characterized by read head sensitivity (RHS) function

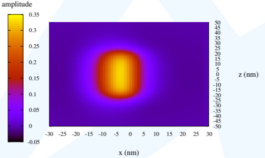
Model for the Read head sensitivity (RHS) function

Parameter	Symbol	Value
Free Layer thickness	FLt	6-8nm
Free Layer width	FLw	40nm
Free Layer to Shield Spacing	FLSS	3nm
Shield to Shield Spacing	SSS	25nm
Shield thickness	St	
Shield width	Sw	

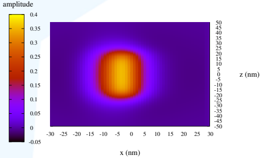



down-track RHS profile RHS(x,z=0) for RW=40nm and various FL

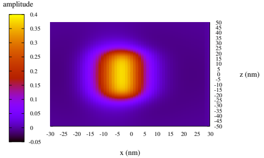

cross-track RHS profile RHS(x=0,z) for RW=40nm



FLt=6nm



FLt=7nm



FLt=8nm

$$\text{Readback} = \text{RHS} \otimes M_y$$

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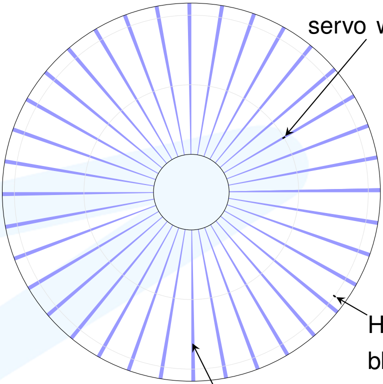
Servo

- The head needs to be positioned over and follow a ~ 40nm wide track
- Disturbance sources include:
  - Air-flow
  - The Motor
  - The VCM
  - External shock and vibe.
- Servo wedges run radially from ID to OD
- 200-300 servo wedges per revolution
- Head can deduce its position when reading a servo wedge
- Servo control algorithm puts the head “on track”
- Between wedges, flying “blind”

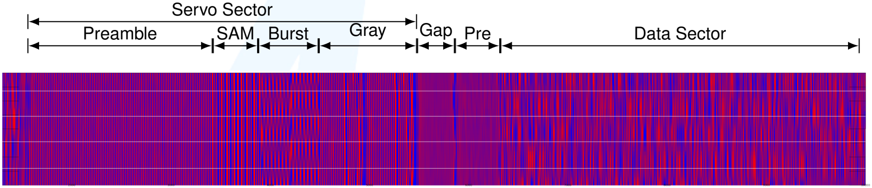


Head over servo wedge

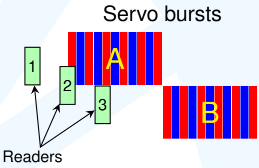
Head flying blind

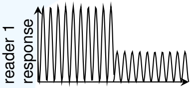
Servo wedges occupy from 3% to 5% of the total disk surface

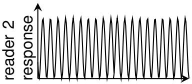
Reverse Engineering the Servo Wedge

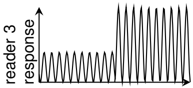


Preamble	Preamble is used to synchronize/initialize loops
SAM	Sector address mark is an index identifying the current sector
Burst	This gives the information of the cross-track position
Gray	A gray-code that is probably used as a track-index
Gap	A gap between the servo sector and data sector
Pre	Some known pre-data
Data	The encoded data written onto the medium







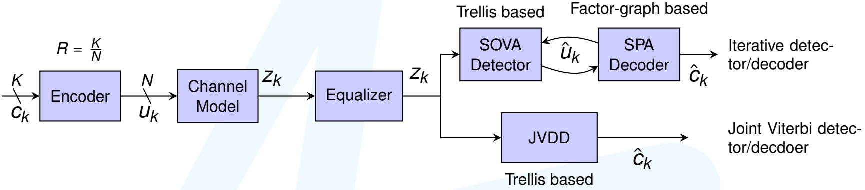


$$PES = \frac{A - B}{A + B}$$

Outline

1. Overview of the Hard Disk Drive
   - Fundamental problem for magnetic recording
   - HDD current and future technologies
2. Magnetic Recording Media
3. Magnetic Recording Head
   - Writer
   - Reader
4. Servo
5. Magnetic Recording Channel (MRC)
   - The Encoder
   - Channel Model
   - The Equalizer
   - The iterative detector
   - The joint Viterbi detector/decoder
6. Future HDD Technologies

Magnetic Recording Channel (MRC)

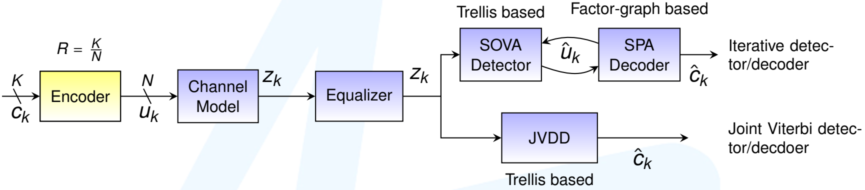


- The magnetic recording channel (MRC) has many similarities to the communications channel:
  - The comms channel transports data from here to there
  - The MRC transports data from now to later
  - Both distort the signal and introduce noise

- Main distortions on the MRC
  - Intersymbol interference (ISI)
  - Media noise
  - Non-linear transition shifts

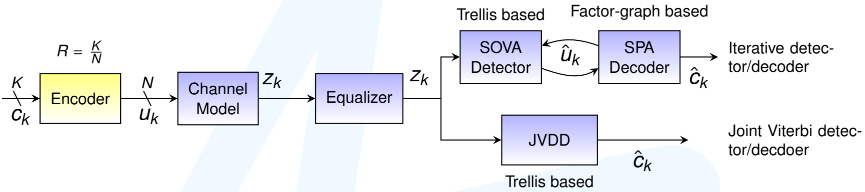
- Current MRC use LDPC codes and pattern dependent noise predictive detection

The Encoder

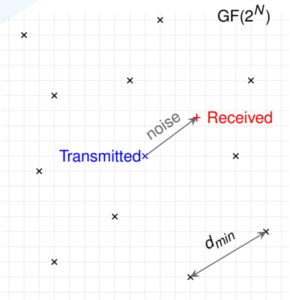


- LDPC Block Codes are used in the MRC.
  - Block codes have a generator matrix **G**.
  - And parity check matrix **H**.
- **G** is $K \times N$. Generates the codeword during encoding
  - **c**= **u** $\times$ **G**. **c** is $1 \times N$ codeword, **u** is $1 \times K$ userword.
  - Systematic codes effectively $M = N - K$ parity bits to the user word
- **H** is $M \times N$. Checks whether a bit sequence is a legal codeword.
  - LDPC codes have **H** matrices with a low proportion of 1's.
  - MRC's use quasi-cyclic codes ⇒ reduce memory requirement

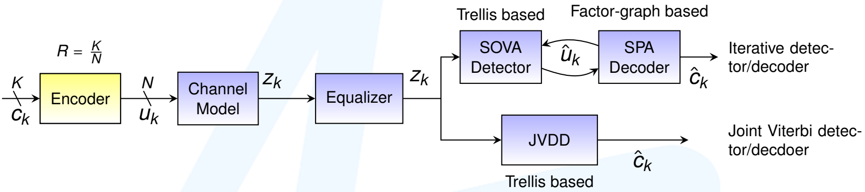
The Encoder



- The code breaks up GF(2^N) into 2 spaces:
  1. The space of legal codewords
     - $\mathbf{c} = \mathbf{u}\mathbf{G}$ and $\mathbf{c}\mathbf{H}^T = \mathbf{0}$.
  2. The space of non-codewords
     - $\mathbf{c}\mathbf{H}^T \neq \mathbf{0}$.
- d_{min}: minimum distance btw codewords
- Desirable qualities for the code:
  - Large d_{min}
  - No short cycles (large girth)
  - Longer CWL ⇒ ↑ performance
  - Low/no error floor



The Encoder



Trellis based

Factor-graph based

$R = \frac{K}{N}$

K

c_k

Encoder

N

u_k

Channel Model

z_k

Equalizer

z_k

SOVA Detector

$\hat{u}_k$

SPA Decoder

$\hat{c}_k$

Iterative detector/decoder

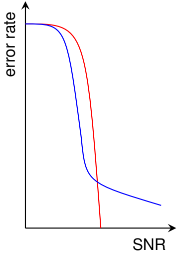
JVDD

$\hat{c}_k$

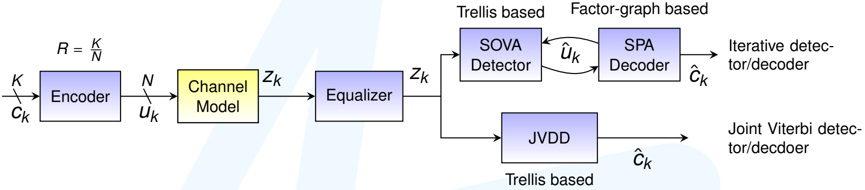
Trellis based

Joint Viterbi detector/decdoer

- Error floors are the bugbear of the coding designers
- Error floors can manifest from different sources
- Error floor of interest here: from the code
    - Subject of significant research effort
    - Caused by trapping sets in the code FG
- MRC need to deliver error rates of 10^{-14}
    - Difficult to check for error-floors
- HDD industry switching from 512byte→4096byte.
    - Longer CWL ⇒ better performance.



The Channel Model



$R = \frac{K}{N}$

K c_k → Encoder → N u_k → Channel Model → z_k → Equalizer → z_k

Trellis based: SOVA Detector ⇄ $\hat{u}_k$ ⇄ SPA Decoder: Factor-graph based → $\hat{c}_k$ Iterative detector/decoder

JVDD (Trellis based) → $\hat{c}_k$ Joint Viterbi detector/decdoer

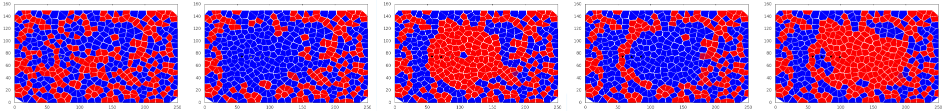
- To realistically reproduce waveforms for channel simulations
- Simple model:
  - Additive white Gaussian noise (AWGN) Model
  - Everybody’s first time model
- Intermediate model
  - Jitter channel model
  - Captures more realistically the media noise characteristic
  - Divorced from the physics of recording
- Comprehensive MRC Model
  - μ-mag simulation and GFP model.

Micromagnetic (μ-mag) simulations

- μ-mag simulations involve solving the Landau-Liftshitz Gilbert (LLG) equations numerically
- LLG: $$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \mathbf{H}_{tot} - \alpha \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{tot}) \qquad (1)$$
  - $\mathbf{M}$ is the magnetization vector
  - $\mathbf{H}_{tot}$ is the total field experienced by $\mathbf{M}$.
  - α is a phenomenological damping parameter that helps to match the model to experimental results
- The LLG describes the behavior of a magnetic particle $\mathbf{M}$ in the presence of a magnetic field $\mathbf{H}_{tot}$.
- In μ-mag simulations $\mathbf{H}_{tot}$ is the sum of:
  - $\mathbf{H}_k$: The anisotropy field
  - $\mathbf{H}_m$: The magnetization from the surrounding grains
  - $\mathbf{H}_e$: The external field from the head
  - $\mathbf{H}_x$: The exchange field from exchange coupled grains (nearest neighbors)
- Solving (1) numerically predicts the magnetization behavior

The Grain-flipping probability (GFP) Model

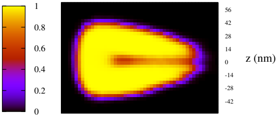
- μ-mag simulations produce grain magnetizations that we can sample at the end of each bit:



After bit 0 After bit 1 After bit 2 After bit 3 After bit 4

- The GFP model keeps count of:
  - The grains in the region that *could* flip (denominator array)
    - Grains magnetized opposite to the applied field can flip
  - The grains in the region that *do* flip (numerator array)
- As a function of:
  - ① The grain's x-position
  - ② The grain's y-position
  - ③ The grain's anisotropy field H_k
  - ④ The surrounding bit pattern

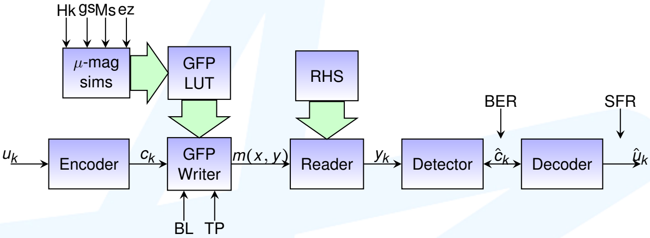
Yellow: prob=1
Black: prob=0



- $$\frac{\text{numerator array}}{\text{denominator array}} = \text{probability array of grains flipping}$$

The Grain-flipping probability (GFP) Model

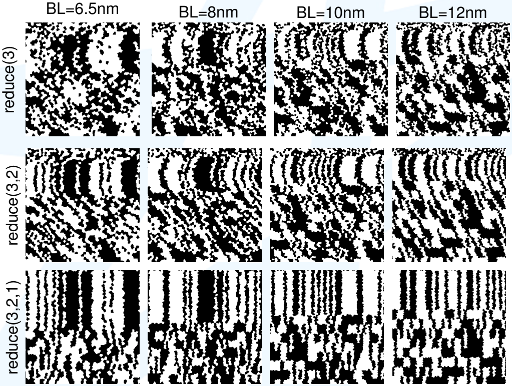
- GFP model ties channel simulations to physics of recording

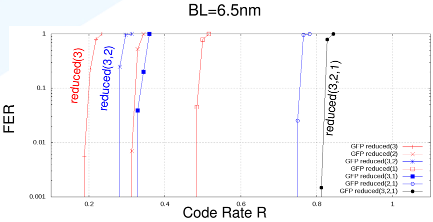


- GFP channel model flips grain using a RNG
  - Reproduces the μ-mag output orders of magnitude faster
  - Generates waveforms fast enough for channel simulation.
- Convolve the output with the RHS, slice → readback
- SNR, BER, SFR (sector failure rate) can be estimated
  - Varying media parameters (K_u, M_s)
  - Varying head parameters (write head field, RHS)
  - Varying writing parameters (eg: TP, BL)

GFP - Model order reduction (MOR)

- Numerator and denominator are multi-dimensional arrays.
- Arrays can be summed over one of their dimensions
    - Reduces the array dimensionality
    - Increases samples per bin → reduces noise
    - Takes out effect of the removed variable

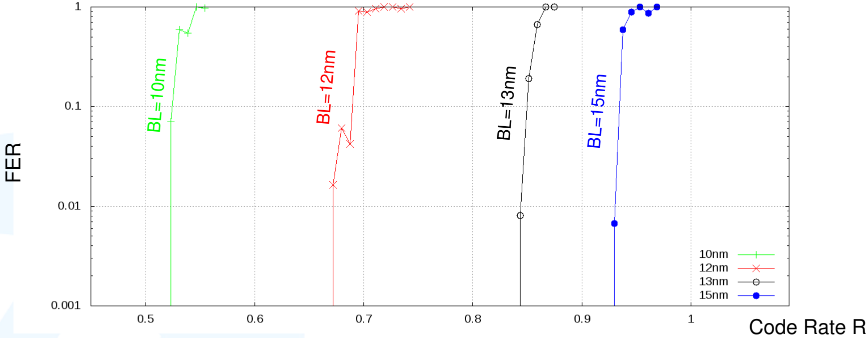




Elidrissi et. al “Modeling of Two-Dimensional Magnetic Recording and a Comparison of Data Detection Schemes”, *IEEE Trans. Magn.*, pp 3685 - 3690, Vol 47, No. 10, Oct 2011

GFP - Density estimation

- GFP channel simulations were run with state-of-the-art HDD parameters (for 2011)
- CBL of 10nm, 12nm, 13nm and 15nm are used here

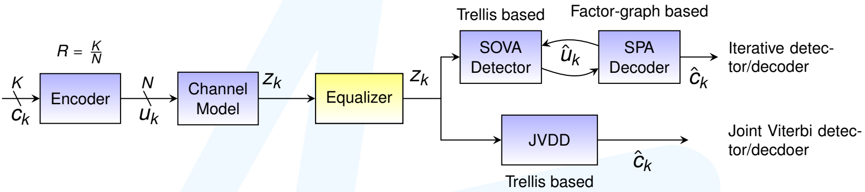


Parameter	Value
grain size	7.5nm
Bit Aspect Ratio (BAR)	6
CWL	4096

BL	CAD	R	UAD
10nm	1075Gbpsi	0.51	548 Gbpsi
12nm	747Gbpsi	0.66	492 Gbpsi
13nm	636Gbpsi	0.83	528 Gbpsi
15nm	478Gbpsi	0.92	440 Gbpsi

Elidrissi et. al “Modeling of Two-Dimensional Magnetic Recording and a Comparison of Data Detection Schemes”, *IEEE Trans. Magn.*, pp 3685 - 3690, Vol 47, No. 10, Oct 2011

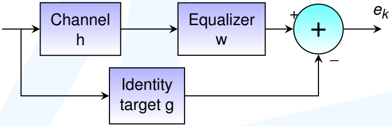
The Equalizer



- The equalizer shapes the channel response into something more suitable for the detector
- Unshaped channel response is typically fairly long.
- → Excessive states in the ensuing trellis-based detector.
- We design the equalizer such that the combined channel is of some known, more manageable shape.
- Types of equalization:
    - Full response equalization
    - Partial response equalization
    - Generalized partial response (GPR)

Equalizer: Full response equalizer

- Full response equalizer attempts to completely invert the channel response:



Channel h

Equalizer w

\+

−

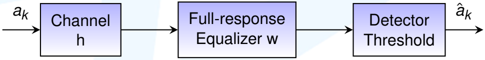
e_k

Identity target g

Equalizer designed to minimize the power of e_k: $E[e_k^2]$

This is the MMSE criterion

- If the equalizer is properly designed, detection of the input bits becomes easy: just threshold.



a_k

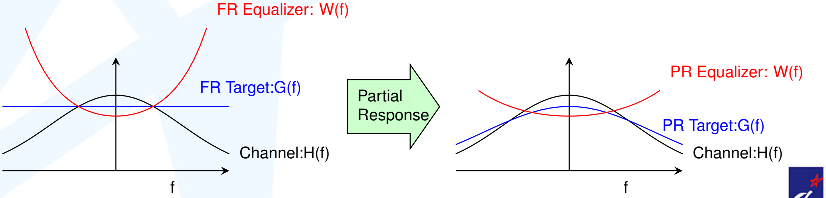
Channel h

Full-response Equalizer w

Detector Threshold

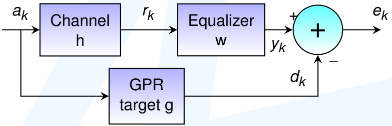
$\hat{a}_k$

- Problem with full response equalizer: Noise enhancement



Generalized/Partial Response Equalizer Design

- Partial Response Equalizer Design: solve w given g and h.
- Generalized partial response (GPR): solve w and g given h.



Equalizer designed to minimize the power of e_k: $E[e_k^2]$

This is the MMSE criterion

$$y_k = \mathbf{w}^T \mathbf{r}_k,\ \text{where } \mathbf{w} = [w_0 w_1 \dots w_{N_w-1}]^T \text{ and } \mathbf{r}_k = [r_k r_{k-1} \dots r_{k-N_w+1}]^T$$
$$d_k = \mathbf{g}^T \mathbf{a}_k,\ \text{where } \mathbf{g} = [g_0 g_1 \dots g_{N_g-1}]^T \text{ and } \mathbf{a}_k = [a_k a_{k-1} \dots a_{k-N_g+1}]^T$$
$$\mathrm{E}[e_k^2] = \mathrm{E}[d_k^2 - 2d_k y_k + y_k^2] = \mathbf{g}^T\mathbf{A}\mathbf{g} - 2\mathbf{g}^T\mathbf{P}\mathbf{w} + \mathbf{w}^T\mathbf{R}\mathbf{w}$$

$$\text{where } \mathbf{A} = \mathrm{E}\begin{bmatrix} a_k a_k & a_k a_{k-1} & \cdots & a_k a_{k-N_g+1} \\ a_{k-1} a_k & a_{k-1} a_{k-1} & \cdots & a_{k-1} a_{k-N_g+1} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k-N_g+1} a_k & a_{k-N_g+1} a_{k-1} & \cdots & a_{k-N_g+1} a_{k-N_g+1} \end{bmatrix} \Rightarrow N_g \times N_g$$

$$\mathbf{P} = \mathrm{E}\begin{bmatrix} a_k r_k & a_k r_{k-1} & \cdots & a_k r_{k-N_w+1} \\ a_{k-1} r_k & a_{k-1} r_{k-1} & \cdots & a_{k-1} r_{k-N_w+1} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k-N_g+1} r_k & a_{k-N_g+1} r_{k-1} & \cdots & a_{k-N_g+1} r_{k-N_w+1} \end{bmatrix} \Rightarrow N_g \times N_w$$

$$\mathbf{R} = \mathrm{E}\begin{bmatrix} r_k r_k & r_k r_{k-1} & \cdots & r_k r_{k-N_w+1} \\ r_{k-1} r_k & r_{k-1} r_{k-1} & \cdots & r_{k-1} r_{k-N_w+1} \\ \vdots & \vdots & \ddots & \vdots \\ r_{k-N_w+1} r_k & r_{k-N_w+1} r_{k-1} & \cdots & r_{k-N_w+1} r_{k-N_w+1} \end{bmatrix} \Rightarrow N_w \times N_w$$

Generalized Partial Response Equalizer Design

- Use Lagrange multipliers to perform constrained minimization
  - Force $g_0 = 1 \Rightarrow [100\ldots0]\mathbf{g} = \mathbf{i}^T\mathbf{g} = 1$
  - To avoid the trivial solution **g=w=0**
- The method of Lagrange multipliers defines a cost function J
  - Things we want to minimize plus the Lagrange multiplier λ
  - Differentiate J wrt to the minimization variables and λ
  - Solve the ensuing equations

Cost function: $J = \mathbf{g}^T\mathbf{A}\mathbf{g} - 2\mathbf{g}^T\mathbf{P}\mathbf{w} + \mathbf{w}^T\mathbf{R}\mathbf{w} - 2\lambda(\mathbf{i}^T\mathbf{g} - 1)$

$$\nabla_g J = 2\mathbf{A}\mathbf{g} - 2\mathbf{P}\mathbf{w} - 2\lambda\mathbf{i} = \mathbf{0} \qquad (1)$$

$$\nabla_w J = -2\mathbf{P}^T\mathbf{g} + 2\mathbf{R}\mathbf{w} = \mathbf{0} \qquad (2)$$

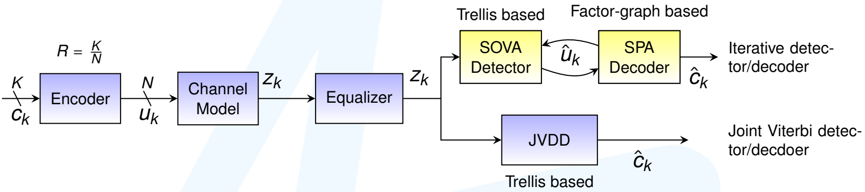
$$\nabla_\lambda J = \mathbf{i}^T\mathbf{g} - 1 = 0 \qquad (3)$$

$$(2)\Rightarrow \mathbf{w} = \mathbf{R}^{-1}\mathbf{P}^T\mathbf{g}$$

$$(1)\Rightarrow 2\mathbf{A}\mathbf{g} - 2\mathbf{P}\mathbf{R}^{-1}\mathbf{P}^T\mathbf{g} - 2\lambda\mathbf{i} = 0 \Rightarrow \mathbf{g} = \lambda\left(\mathbf{A} - \mathbf{P}\mathbf{R}^{-1}\mathbf{P}^T\right)^{-1}\mathbf{i}$$

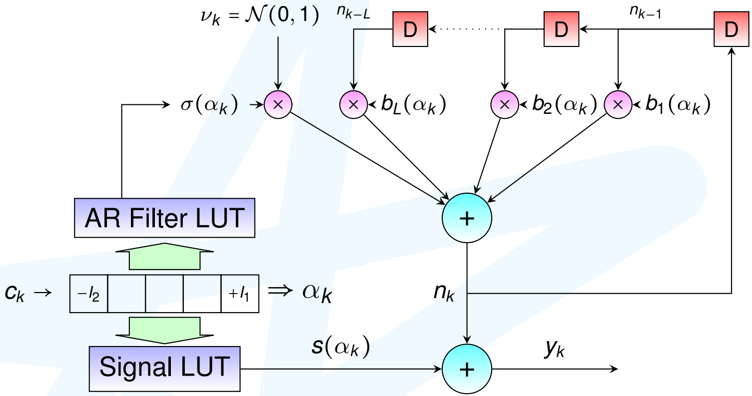
$$(3)\Rightarrow \lambda\mathbf{i}^T\left(\mathbf{A} - \mathbf{P}\mathbf{R}^{-1}\mathbf{P}^T\right)^{-1}\mathbf{i} = 1 \Rightarrow \lambda = \frac{1}{\mathbf{i}^T\left(\mathbf{A} - \mathbf{P}\mathbf{R}^{-1}\mathbf{P}^T\right)^{-1}\mathbf{i}}$$

The iterative detector



- After equalization to known target, iterative detector returns detected/decoded bits
- The iterative detector consists of:
  - Data-dependent noise-predictive (DDNP) detector
    - The noise from the equalized channel is coloured and data-dependent
    - White-noise Viterbi Algorithm is suboptimal
    - DDNP Viterbi Algorithm performs better.
    - Optimal if the noise is as expected by the model (AR)
  - LDPC decoder
    - The sum-product algorithm (SPA)
    - Operating on a factor graph (FG)

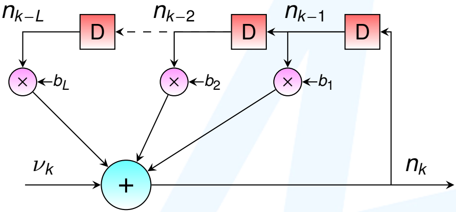
DDNP Model



“A Signal Dependent Auto-regressive Channel Model”, A. Kavcic, A. Patapoutian, *IEEE Trans. Magn. Sept 1999*

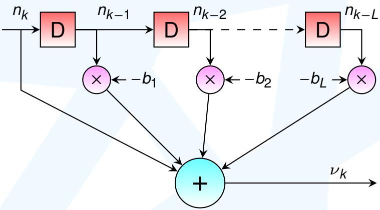
- The noise in the model is auto-regressive (AR) of order L
  - The AR coefficients are data-dependent
  - The noise coloration is data-dependent
- The signal component comes from a look-up table
  - Signal vector α_k defined by range $l_1 \rightarrow l_2$

DDNP Noise prediction



- Noise coloring filter
- Auto-regressive
- White noise input
- Colored noise output

$$n_k = \sum_{l=1}^{L} b_l n_{k-l} + \nu_k$$

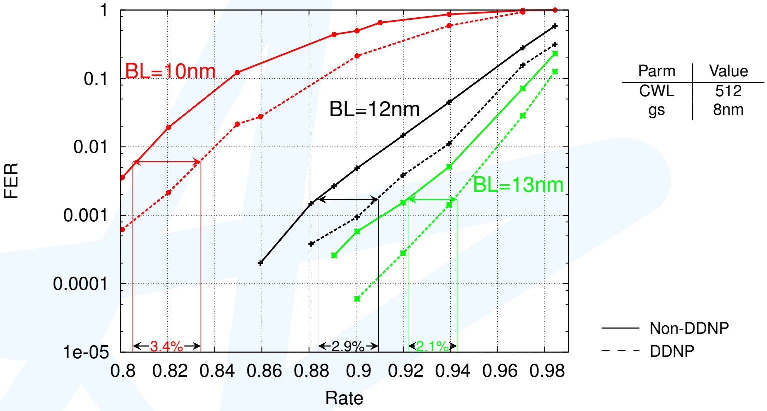


- Noise whitening filter
- Moving average
- Inverse of noise coloring filter

$$\nu_k = n_k + \sum_{l=1}^{L} -b_l n_{k-l}$$

- Whitened noise ν_k less power than colored noise n_k
- DDNP detector uses ν_k to compute metrics in the trellis.

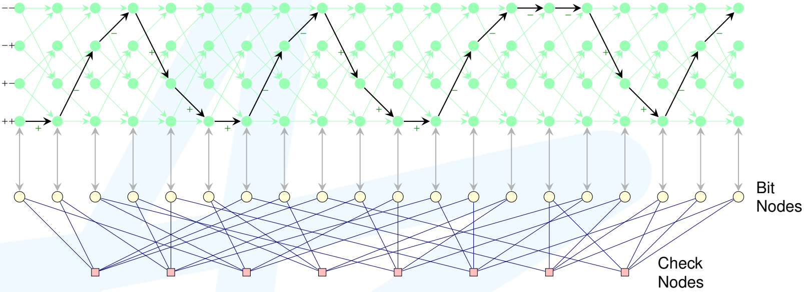
DDNP performance comparison via GFP model



Parm	Value
CWL	512
gs	8nm

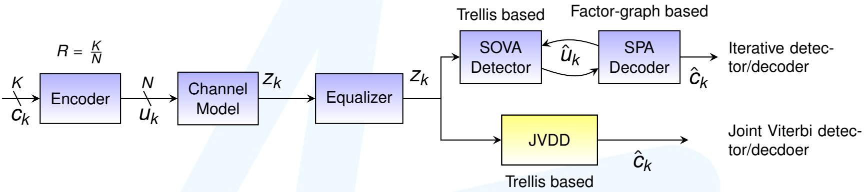
- Results over the GFP channel model at various bit lengths
- Using iterative detector, with and without DDNP.
- DDNP always performs better than non-DDNP
- Shorter BL → more media noise → more gain for DDNP

Iterative detector



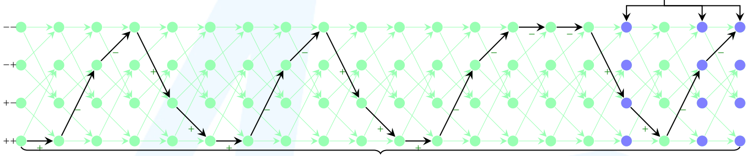
- Detector algorithm (DDNP-SOVA) operates on the trellis
  - Returns channel probabilities, passes the decoder.
- Decoder algorithm (SPA) operates on the factor graph
  - Iterates a number of times between bit and check nodes
  - Returns a-priori probabilities to the detector
- Global iterations from detector trellis to decoder FG.
- Sometimes an interleaver sits between the two.

The joint Viterbi detector/decoder



- State of the art: Iterative detector
  - SOVA detector knows about the channel
  - SPA decoder knows about the code
  - Exchange information between them iteratively.
- JVDD: proposed competitor to the iterative detector
  - Knows about both the channel and the code
  - Performs both detection and decoding *jointly* on a trellis
  - Based on the Viterbi algorithm
  - Conditionally optimal over AWGN/ISI channel
    - Optimum with sufficient computing resources
  - Main challenge:
    - Managing the complexity/performance trade-off

JVDD Algorithm



parity check nodes

metric thresholding

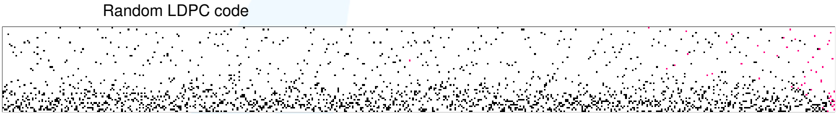
① Metric thresholding

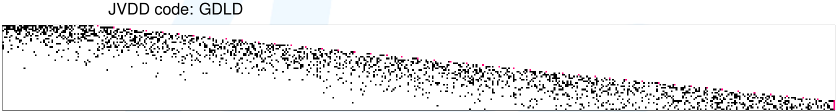
- Metrics computed for survivors (same as Viterbi)
- Discard survivors where $\mathit{metric} > \mathit{minMetric} + \texttt{threshold}$
- Viterbi algorithm: equivalent to `threshold`=0
- Implication: No. survivors grows as JVDD progresses

② Parity checks

- Discard survivors that fail parity check
- Only retain survivors where: $\hat{\mathbf{c}}\mathbf{H}^T = \mathbf{0}$
- **H** is $M \times N$ parity check matrix with
  - M rows: each row is a parity check
  - N cols: each col corresponds to a channel bit
- Check occurs on last “1” of any row in the **H** matrix
- Parity checking curbs no. survivors

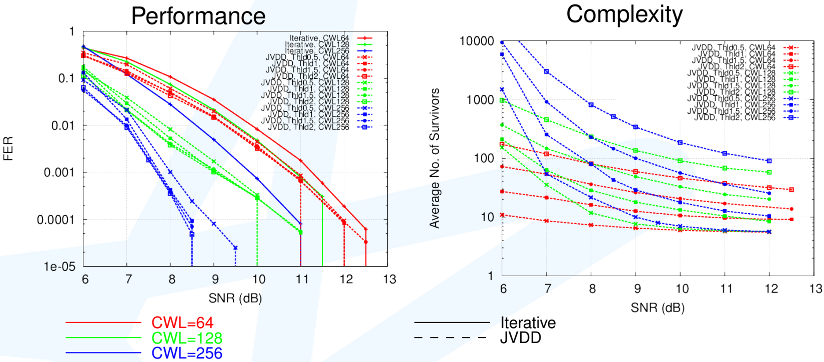
JVDD Codes





- Two **H** matrices shown with Black pixels = 1, white pixels = 0
  - Top figure shows a (512,52) random code.
  - Bottom figure shows a (512,52) JVDD code.
- Last “1” in each row of both matrices marked by red pixel.
  - Random LDPC code has last “1” in each row clumped towards end of matrix
  - JVDD code has last “1” in each row more uniformly distributed through the matrix
- Parity checking in JVDD can occur throughout trellis when using JVDD codes

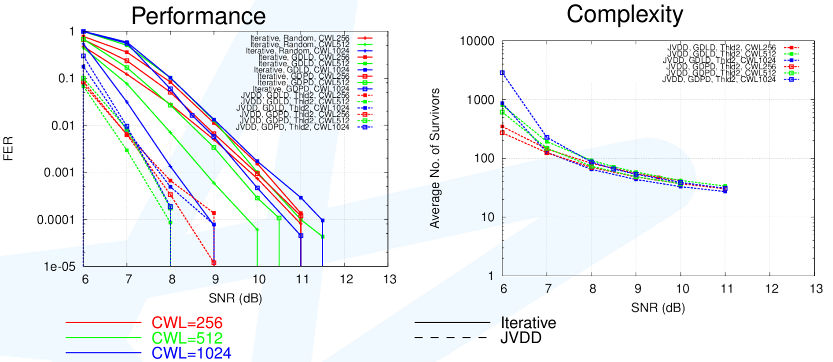
JVDD over AWGN/ISI Channel: short CWL



- Performance plots for the JVDD vs iterative detector
- Complexity plots (in avg no of surv) for the JVDD.

- Both iterative detector and JVDD using random codes
- JVDD greatly outperforming iterative detector at short CWL
  - By more than 2dB.

JVDD over AWGN/ISI Channel: inter CWL



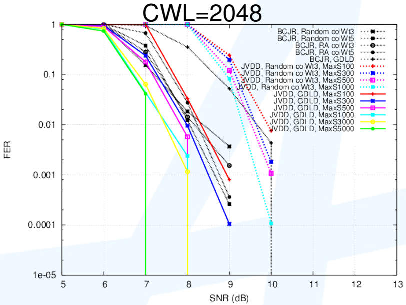
Performance

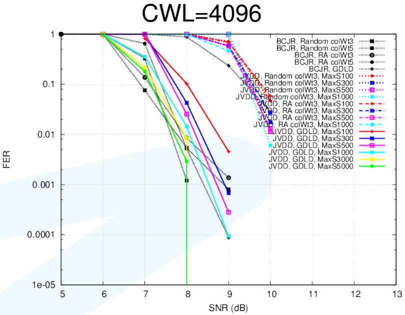
Complexity

- Iterative detector using both random codes and JVDD codes
- JVDD using only JVDD codes.

- Iterative doing better with random than JVDD codes.
- But even with random codes, JVDD outperforms it with JVDD codes.

JVDD over AWGN/ISI Channel: long CWL





iterative in black
JVDD Colored
\- - - - - JVDD with random codes

- JVDD codes can't handle⇒ introduce `maxNoSurv` parameter.
  - Limit maximum number of surv in trellis
- JVDD codes outperform random codes (for JVDD algo) even with `maxNoSurv` parameter.
- Iterative performance begins to surpass JVDD at long CWL

JVDD over a magnetic recording channel

Constant Media Parameters

MWW (nm)	91	M_s	480 emu/cc
Background	AC	σ_{Ms}	3%
N_{track}	4	K_u	3.6e6 erg/cc
N_{bit}	1024	σ_{Ku}	3%
Bit length (nm)	15	A_x	3e-7 erg/cm
Grain-size (nm)	6	σ_{Ax}	3%
Grain pitch (nm)	7	easy axis	0°
Grain size σ	20%	easy axis σ	1.7°
Reader width RW (nm)	30		

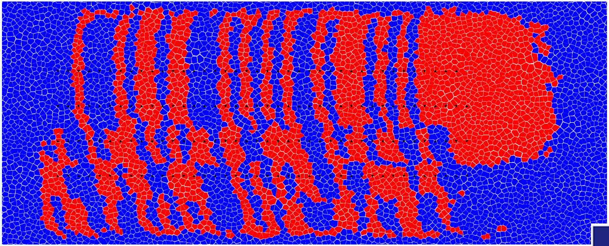
Variable Media Parameters

Track pitch TP (nm)	30	34	42	50
Reader pitch RP(nm)	10 48	26 50	34	42
Reader offset RO (nm)	-4	-2	-0	
Equalizer type	1D	SMR	TDMR	
Reader Configuration	single	triple		

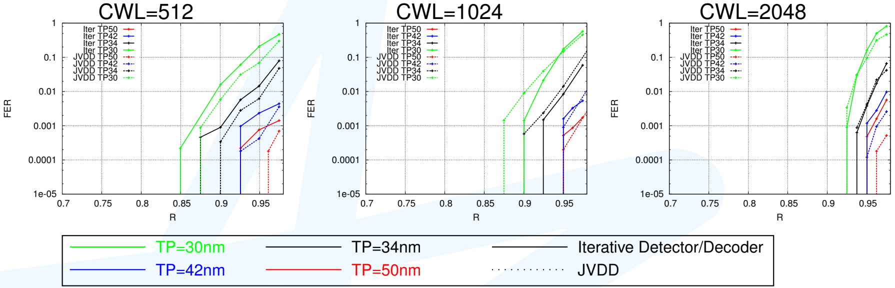
Detector/Decoder Parameters

JVDD	threshold	2	Iterative	LDPC iterations	150
	maxSurv	10000, 30000		global iterations	6
	code	GDLD		code	random LDPC
	CWL	512,1024,2048		CWL	512,1024,2048

Sample μ-mag simulation output:
DC-erase, TP=50
4 tracks x 40bits



JVDD over a magnetic recording channel



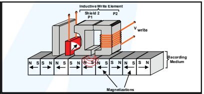
- JVDD generally outperforming iterative detector
- Improvement gap decreasing with increasing CWL
- But benefits at increasing CWL include:
  - Waterfall curves become more steep
  - Code rate increases
- Reducing TP ⇒ more noise from track-edge ⇒ more errors ⇒ lower code rates needed to correct them.

Outline

1. Overview of the Hard Disk Drive
    - Fundamental problem for magnetic recording
    - HDD current and future technologies
2. Magnetic Recording Media
3. Magnetic Recording Head
    - Writer
    - Reader
4. Servo
5. Magnetic Recording Channel (MRC)
    - The Encoder
    - Channel Model
    - The Equalizer
    - The iterative detector
    - The joint Viterbi detector/decoder
6. Future HDD Technologies

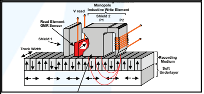
Future HDD Technologies

Previous Technology: Longitudinal Recording



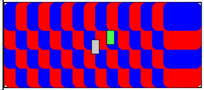
Longitudinal recording writes bits in the plane of the medium using fringe field from head.

Current Technology: Perpendicular Recording



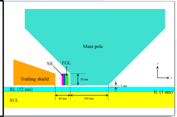
Perpendicular recording changed the orientation of the bits perpendicular to the medium and included an SUL. Medium now in the head gap.

Upcoming Technology: 2D/shingled magnetic recording



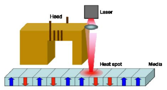
SMR/TDMR overlaps adjacent tracks into a 2D block of bits. 2D Processing also occurs using 2D equalization, detection and decoding techniques.

Future Technology: MAMR (μ-wave Assisted Magnetic Recording)



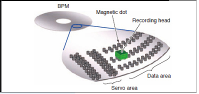
MAMR uses microwave frequencies to excite the grain magnetizations making them easier to switch. Enable switching smaller higher Ku grains.

Future Technology: HAMR (Heat Assisted Magnetic Recording



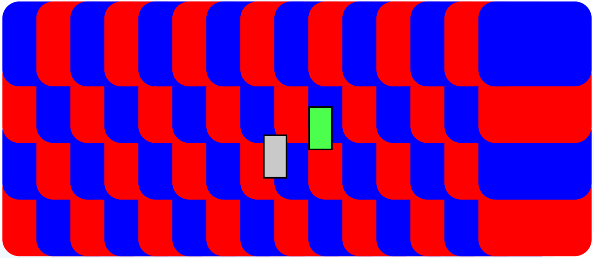
HAMR uses heat to thermally excite the grains and reduce Ku. This again enable smaller thermally stable grains to be used.

Future Technology: BPMR (Bit Patterned Media Recording



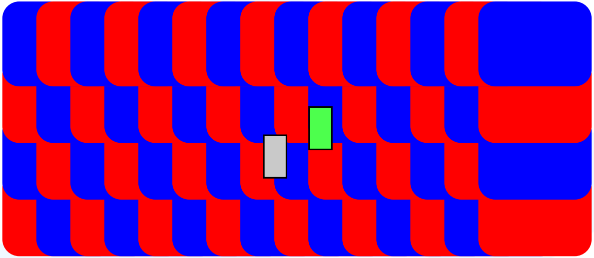
BPMR writes 1 channel bit per magnetic particle (island). These islands are engineered on a lattice that enables them to store data more reliably.

SMR/TDMR



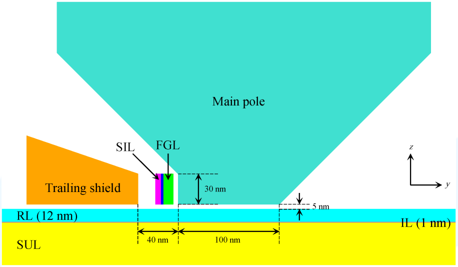
- SMR: Shingled Magnetic Recording
  - Enables writing of narrower tracks with wider writers
    - Writers designed for tight gradients on trailing edge, and one side
  - Information written in blocks rather than tracks
  - SMR considered an intermediate technology to carry the industry over until MAMR/HAMR/BPMR mature
  - Is currently being implemented in product today.

SMR/TDMR



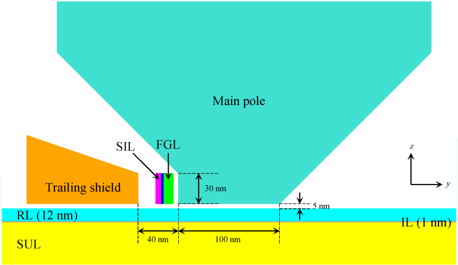
- TDMR: Two-dimensional Magnetic Recording
  - Enables reading of narrower tracks with wider readers
    - Wider readers⇒ ITI (intertrack interference)
    - TDMR mitigates ITI by using 2D detectors
  - Requires multiple readback to be processed at a go
    - Involves putting multiple reader elements on the head
    - Involves changing 1D channel ⇒ 2D channel
  - 2D channel
    - Greater computational complexity
    - Best TDMR scheme still being investigated

Energy assisted Magnetic Recording: MAMR



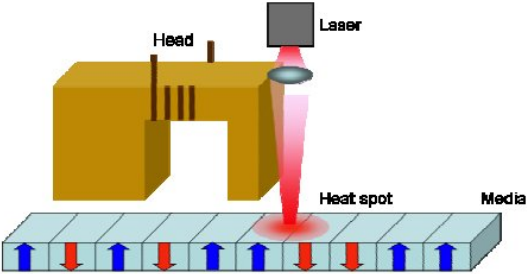
- Energy assisted magnetic recording helps to overcome the superparamagnetic limit
- Use small grains with higher $K_u \Rightarrow$ difficult to write
- Inject energy (heat or microwaves) during writing.
  - Energy helps the switching process
  - Effectively brings down K_u during writing
- Limiting factor:
  - How well the energy can reduce K_u
  - The combined gradient of the magnetic + energy assist

Energy assisted Magnetic Recording: MAMR



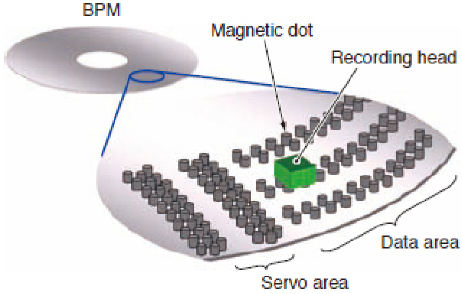
- The energy source in MAMR is microwaves
  - Grains have a natural tendency to precess
  - When excited near resonant frequency ⇒ become unstable
  - Application of a magnetic field completes the switch
- Microwave field applied via spin torque oscillator (STO)
  - STO oscillates when driven with a current
- Challenges:
  - Generating a stable μ-wave assisting field
  - Design/placement of the STO.

Energy assisted Magnetic Recording : HAMR



- Energy source in HAMR is heat from a laser.
  - Grains lose their magnetism when hot ($T > T_c$, $T_c \gtrsim$ 600K)
  - Cooling grains align with external field.
- Challenges
  - Generting a small thermal spot (The NFT)
  - Light delivery to the NFT
  - Creating very small high K_u grains
  - Overcoat and lubricants that work at high temp

BPMR



- BPMR aligns the “grains” on the medium in a regular lattice.
- Ordered rather than random grains. SNR $\nsim$ log(N).
- Store each bit on 1-2 islands (7-12 grains for granular media)
- Challenges
  - Creation of regular arrays of nanoparticles for the media
    - Electron lithography
  - Cheaply manufacturing BPMR disks
- Synchronizing the write field to the islands

Thank you