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The Role of Communications Signal Processing in Storage Systems

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Outline

- An Introduction to Storage Systems
 - Magnetic Tape
 - Magnetic Hard Disk Drives (HDDs)
 - Solid State Drives (SDDs)

- Signal Processing and Coding for Read Channels
 - Low-Density Parity-Check (LDPC) Decoders
 - Multi-Dimensional Equalizers and Detectors



Transmission vs. Storage

Digital Transmission Systems

- Transport data spatially
 - Communications channel

Digital Storage Systems

- Transport data temporally
 - Communications (read/write) channel

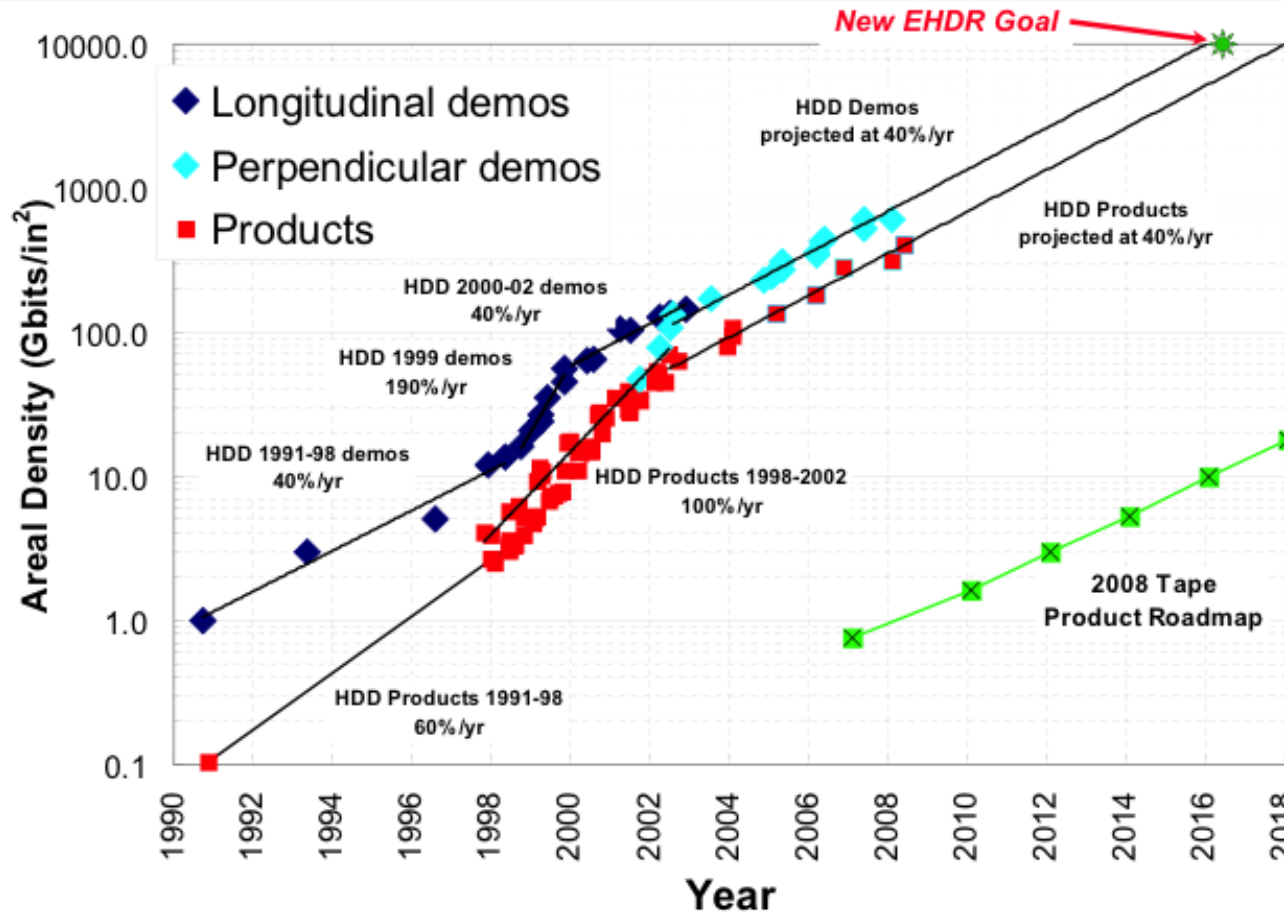
Historical Drivers

- Digital communications and coding \Rightarrow transmission
- Materials and devices \Rightarrow storage



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Storage Industry Trends



B. H. Schechtman, "The role of future magnetic tape technology for digital archive, preservation and sustainability," Digital Archive, Preservation and Sustainability Workshop, Baltimore, MD, 2008.



Magnetic Recording

- ❑ Magnetic Recording
 - Write process: magnetize the media → record user data
 - Read process: sense the magnetic flux change → recover user data
- ❑ Four Technology Generations
 - Longitudinal magnetic recording (LMR) – old
 - **Perpendicular magnetic recording (PMR)** – state-of-the-art
 - **Bit-patterned magnetic recording (BPMR)** – next generation
 - Heat-assisted magnetic recording (HAMR) – next generation
 - Two-dimensional magnetic recording (TDMR) – future generation



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LMR, PMR and BPMR

□ LMR

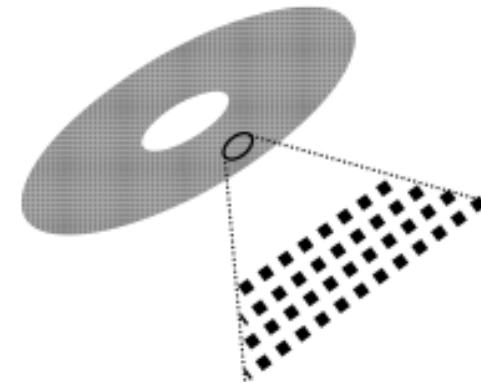
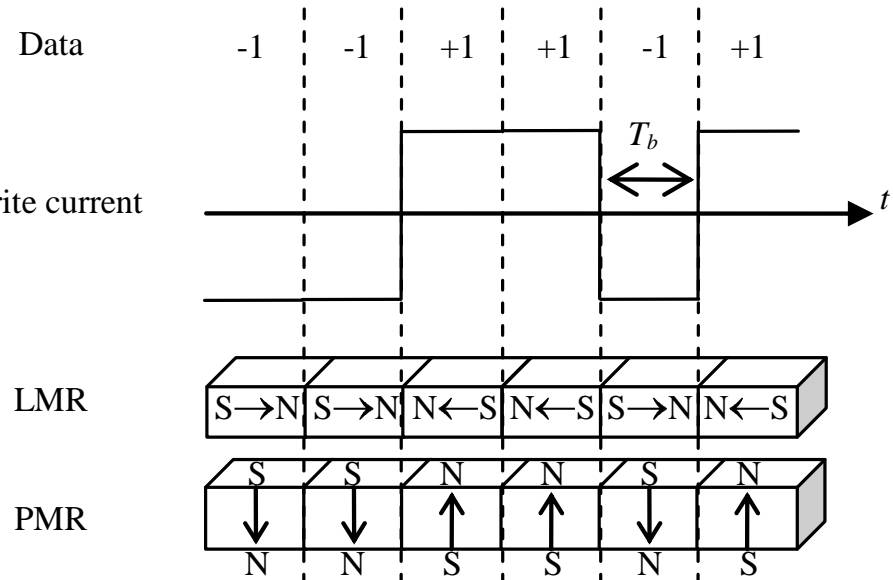
- Along the movement of the read head

□ PMR

- Vertical to the surface

□ BPMR

- One bit per island
- Perpendicularly magnetized





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PMR Channel Response

□ Isolated transition response $s(t)$

- Magnetic flux changes on transitions, $-1 \rightarrow 1$ or $1 \rightarrow -1$

- Dibit response $h(t) = s(t) - s(t - T_b)$

$$s(t) = V_p \tanh\left(\frac{\ln 3}{T_{50}} t\right)$$

$$r(t) = \sum_k a_k - a_{k-1} s(t - kT_b)$$

$$= \sum_k b_k s(t - kT_b)$$

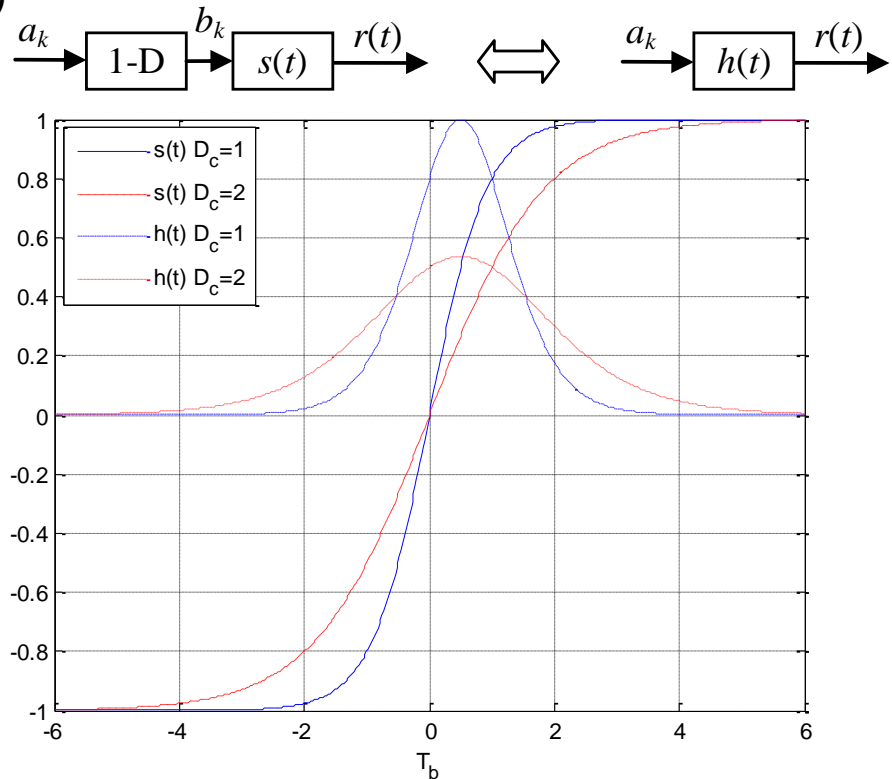
$$= \sum_k a_k h(t - kT_b)$$

□ Recording density

- $D_c = T_{50}/T_b$

□ User density

- $D_u = R^* D_c$

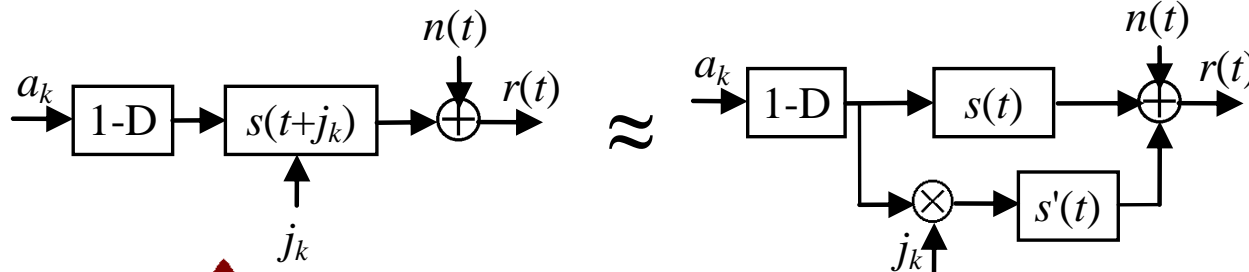
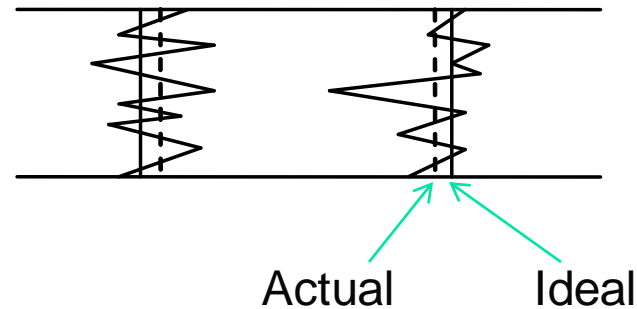




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PMR Channel Noise

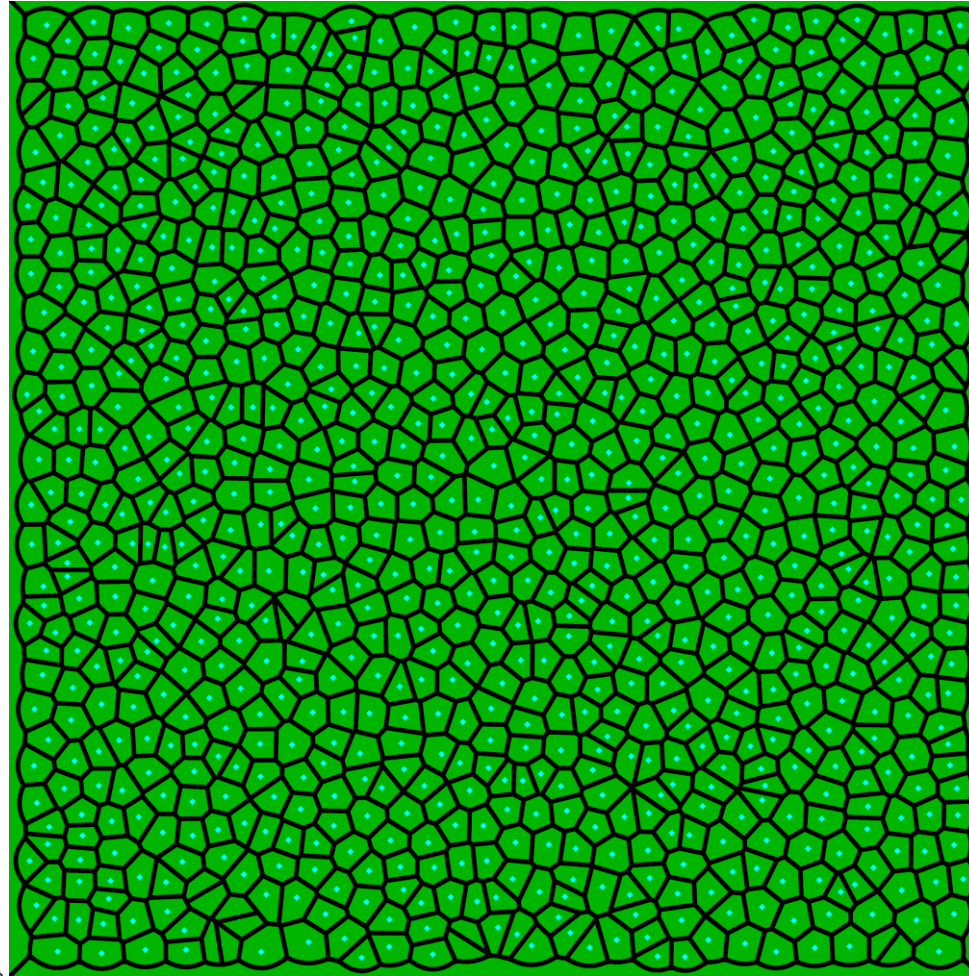
- ❑ Electronic noise (AWGN)
- ❑ Media noise (transition noise)
 - Pulse width jitter
 - Position jitter
- ❑ Position jitter
 - Time shift
 - 1st order approximation





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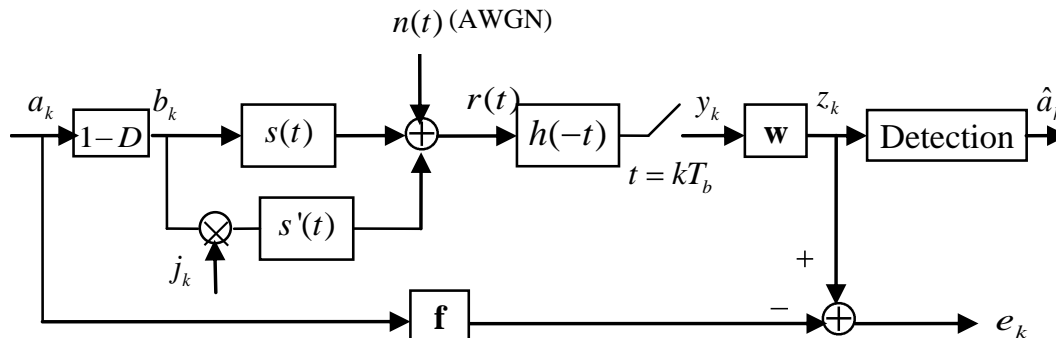
Magnetic Media





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Equalized PMR Channels



- ❑ Matched filter $h(-t)$, with $h(t) = s(t) - s(t - T_b)$
- ❑ Generalized PR targets: design the equalizer \mathbf{w} and the optimized targets \mathbf{f} , by minimizing $E e_k^2$.

$$\text{SNR} = \frac{V_p^2}{N_0 + M_0}$$

Jitter noise
power
percentage

$$\alpha\% = \frac{M_0}{M_0 + N_0} \times 100\%$$

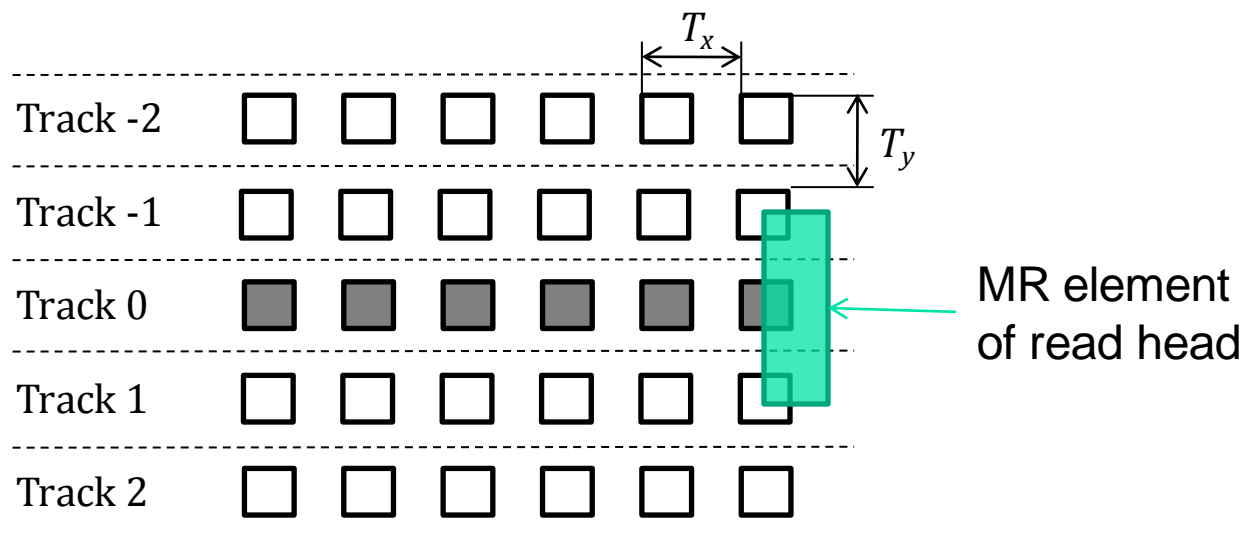
N_0 : the height of single-sided power spectral density of $n(t)$

M_0 : the average transition noise **energy** associated with an isolated transition



Bit-Patterned Media

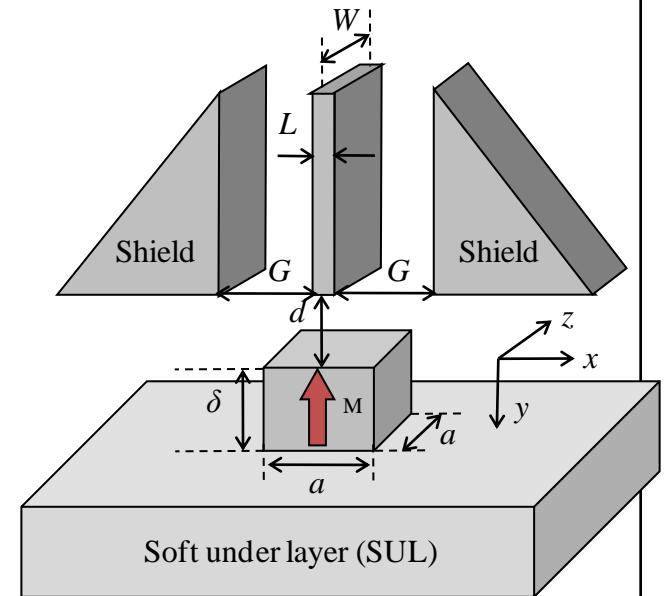
- Extremely high areal density
 - Small bit period \rightarrow strong ISI
 - Small track pitch \rightarrow strong ITI
 - 2D response of isolated island is needed





Bit-Patterned Recording

- 2D response of island
 - Shielded MR or GMR head is assumed
 - Approximate $\psi_s(x, z)$ the magnetic potential on ABS
 - Zero potential on shields
 - Full potential on MR element
 - Predict $\psi(x, y, z)$, the potential under the head
 - $\psi(x, 0, z) = \psi_s(x, z)$
 - The readback voltage (by 3D reciprocity formula)



$$V(x, z) = C \int_{-\infty}^{\infty} dx' \int_d^{d+\delta} dy' \int_{-\infty}^{\infty} dz' \left[\frac{\partial \psi(x', y', z')}{\partial y'} \right] M_y(x' - x, y', z' - z)$$

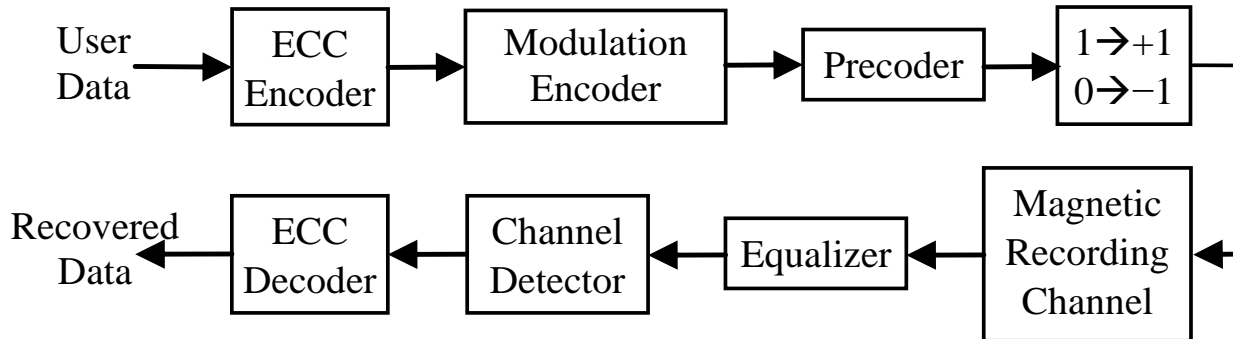


Channel Impairments

- Electronic noise**
- ISI & ITI**
- Island location jitter
- Island shape and size fluctuation
- Written-in errors



Coded Read Channel

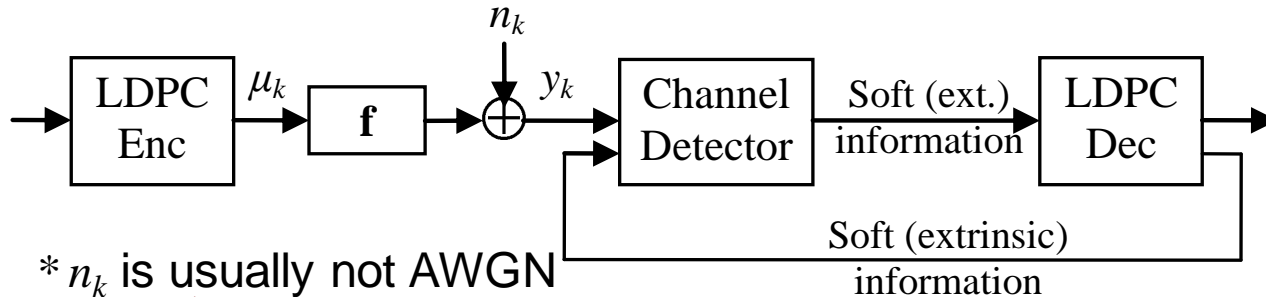


ECC: low-density parity-check (LDPC) code

Without modulation code

Equalized channel with PR target \mathbf{f}

Equivalent channel: LDPC coded PR channel



* n_k is usually not AWGN



Belief Propagation

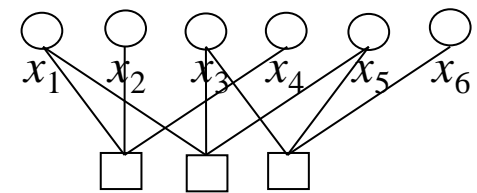
□ \mathbf{x} is a codeword iff $\mathbf{H}\mathbf{x}=\mathbf{0}$

□ Parity-check matrix \mathbf{H}

■ Factor graph

■ $x_j \rightarrow$ columns, $c_i \rightarrow$ rows

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}$$



$c_1 \quad c_2 \quad c_3$

□ Belief-propagation (BP)

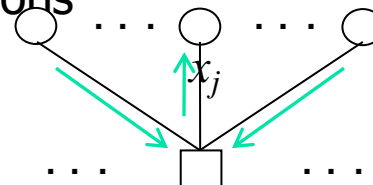
■ Channel messages as local evidence

■ Initialize the belief on variable nodes x_j 's by local evidence

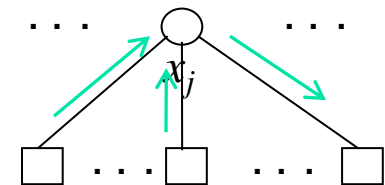
■ Row step (checks-to-variables)

■ Column step (variables-to-checks)

■ Repeat the row and column steps till: find a valid codeword or reach the maximum number of iterations



checks-to-variables



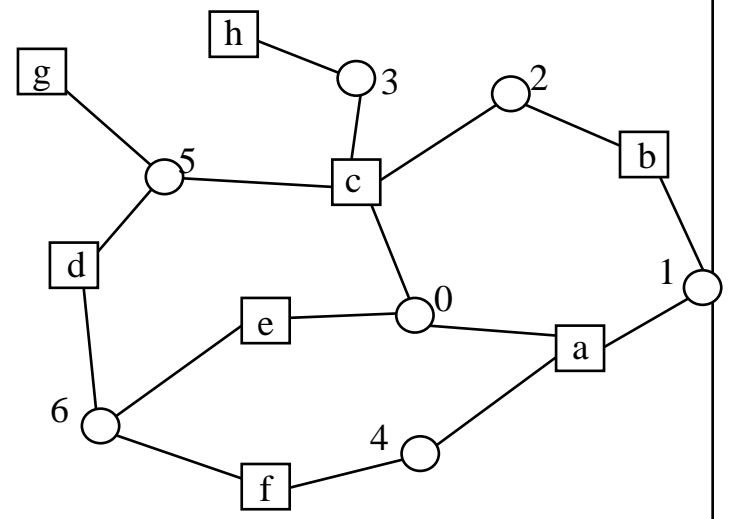
variables-to-checks

c_i



Sub-Optimal BP Decoding

- ❑ Optimal BP decoding
 - Tree-like graph (cycle-free)
 - **Independent local evidence**
- ❑ Cycles make BP sub-optimal after a few iterations
 - Depends on the girth (the length of the shortest cycles)
- ❑ Issue on PR channels
 - Correlated channel messages
 - BP decoding is sub-optimal from the very first iteration



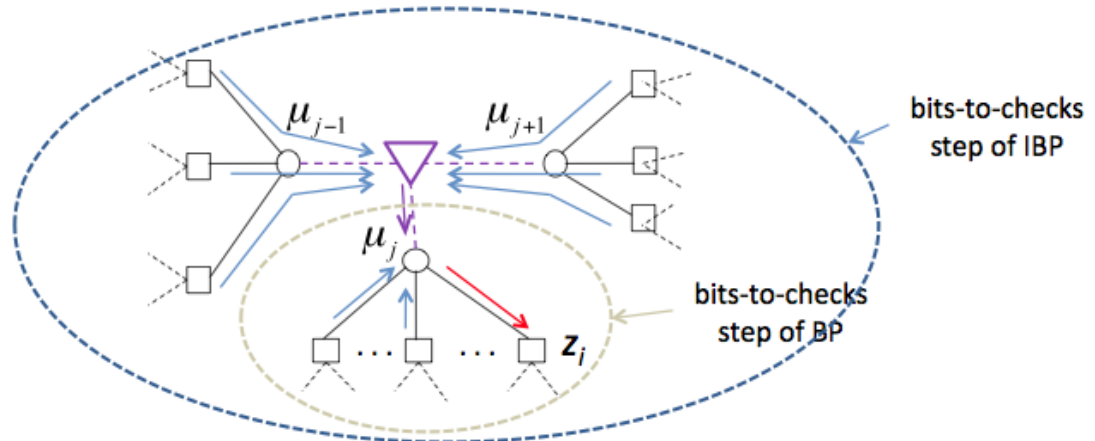


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Improved BP Decoder

□ Key points of the improved BP (IBP)

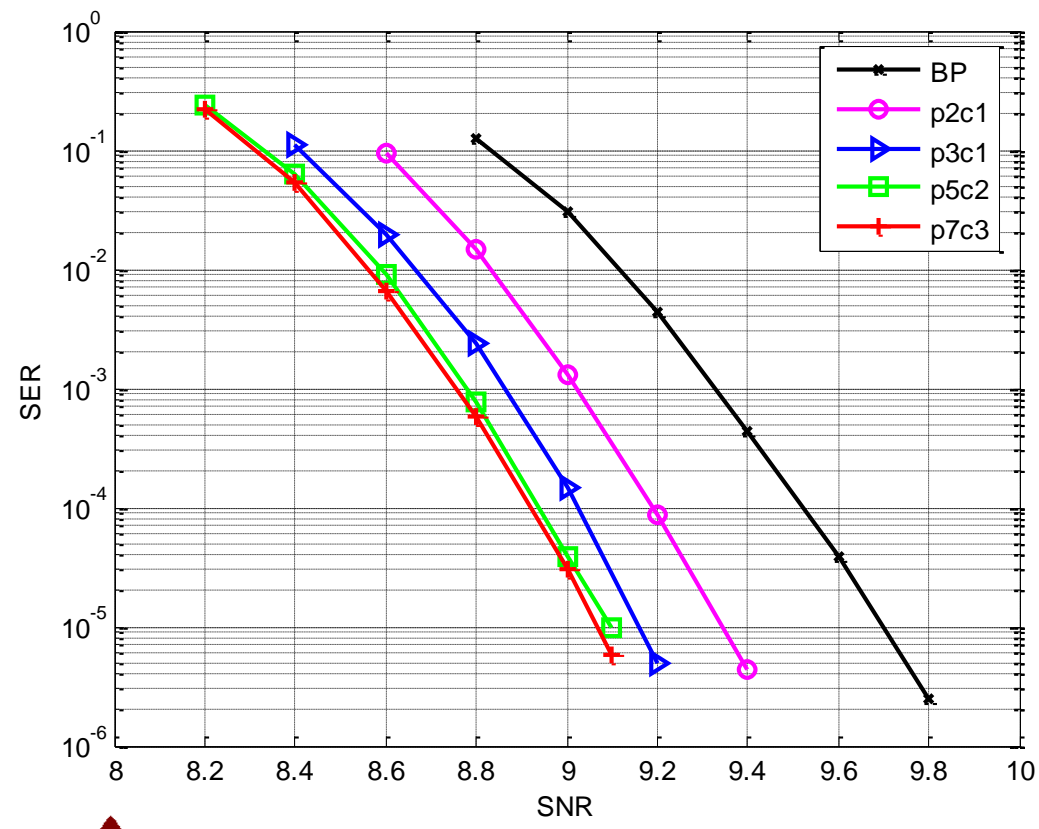
- Channel messages $L(.)$ for bits are also needed in the initial run
- Same row step (checks-to-bits) as standard BP
- A correction term is applied in the column step (bits-to-checks)
 - Taking into account the correlations between channel messages
 - Need checks-to-bits information on bits $\underline{\mu}^{(c+1)}$



W. Chang and J. R. Cruz, "An improved belief-propagation decoder for LDPC-coded partial-response channels," *IEEE Trans. Magn.*, to appear, 2010.

Performance Results

- Up to 0.6-dB gain

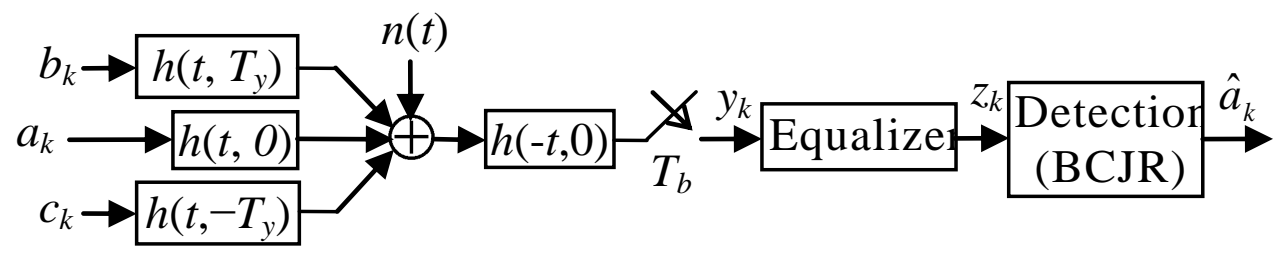




BPMR Channel Model

□ Simple channel model

- Carefully choose T_y so that ITI is mostly caused by the two nearest side tracks.
- a_k, b_k and c_k are $\{-1, +1\}$
- Matched filter $h(-t, 0) = h(t, 0)$, where $h(t, 0) = h_x(t)$
- No media noise (Island location jitter, shape & size fluctuation)
- $SNR = 1/\sigma^2$; $\sigma^2 = N_0/2$ of $n(t)$

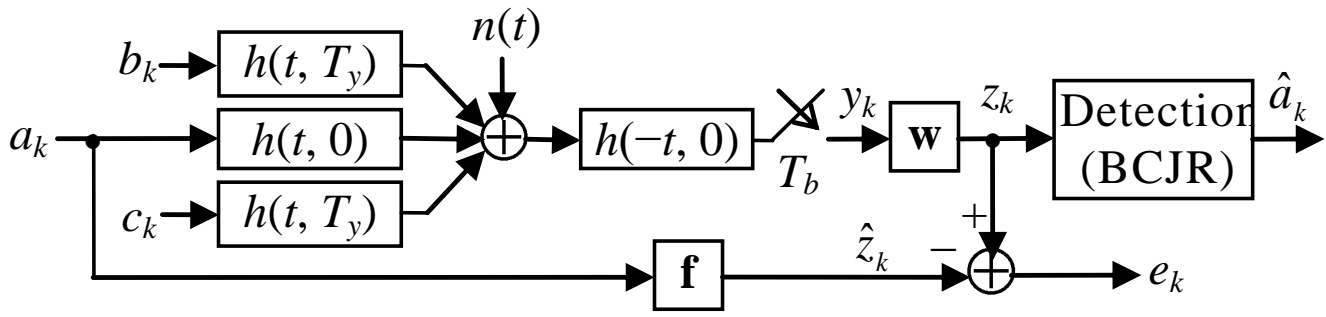


T_x (bit period), T_y (track pitch).



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Single-Track Equalization



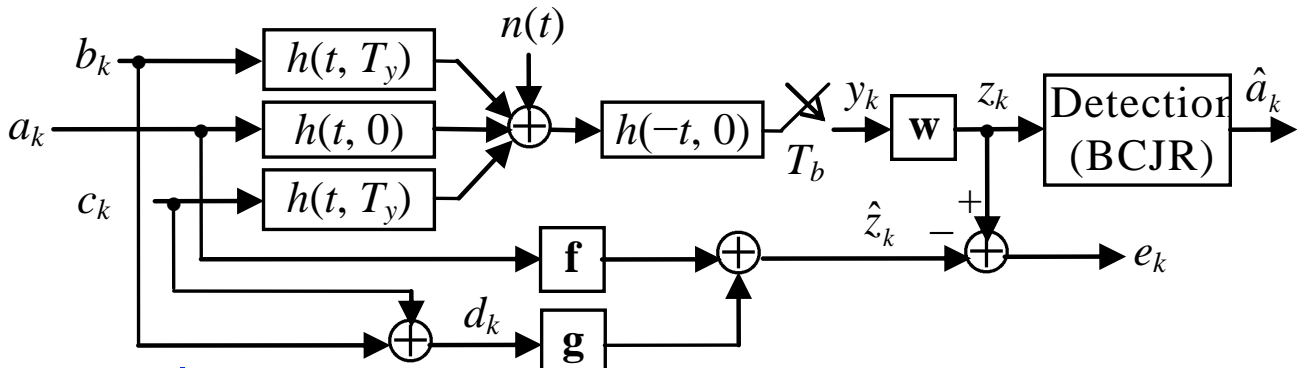
- 1D equalizer: $\mathbf{w} = [w_{-N}, \dots, w_0, \dots, w_N]^T$
- 1D GPR target: $\mathbf{f} = [f_0, \dots, f_{L-1}]^T$
- Mean-squared error:
- Read back single track
- Sense three tracks
- 1D detector

$$\text{MSE}_{\text{SE}} = E e_k^2 = \mathbf{f}^T \mathbf{R}_a \mathbf{f} + \mathbf{w}^T \mathbf{R}_y \mathbf{w} - 2\mathbf{w}^T \mathbf{R}_{y,a} \mathbf{f}$$

- ITI is treated as additive noise



Joint-Track Equalization



- ❑ Still 1D equalizer: $\mathbf{w} = [w_{-N}, \dots, w_0, \dots, w_N]^T$
- ❑ 2D GPR target: $\mathbf{f} = [f_0, \dots, f_{L_1-1}]^T, \mathbf{g} = [g_0, \dots, g_{L_2-1}]^T$
- ❑ b_k and c_k have equivalent contribution, so use $d_k = b_k + c_k$.
- ❑ Mean-squared error
- ❑ Read back single track
- ❑ Still sense three tracks
- ❑ 2D detector
- ❑ Recover data on center track only

$$\text{MSE}_{\text{JE}} = E e_k^2 = \mathbf{f}^T \mathbf{R}_a \mathbf{f} + \mathbf{g}^T \mathbf{R}_d \mathbf{g} + 2\mathbf{f}^T \mathbf{R}_{a,d} \mathbf{g} + \mathbf{w}^T \mathbf{R}_y \mathbf{w} - 2\mathbf{w}^T (\mathbf{R}_{y,a} \mathbf{f} + \mathbf{R}_{y,d} \mathbf{g}).$$

W. Tan and J. R. Cruz, "Signal processing for perpendicular recording channels with intertrack interference," *IEEE Trans. Magn.*, vol. 41, no. 2, pp. 730-735, Feb. 2005.



2D Detection

- ❑ Named “joint-track detection” *
- ❑ The trellis has multiple inputs: $\{a_k, b_k, c_k\}$ or $\{a_k, d_k\}$
- ❑ The detection of a_k on either trellis are equivalent
- ❑ Trellis complexity
 - $\{a_k, b_k, c_k\}$ trellis: $2^{(L_1-1)} \times 4^{(L_2-1)}$ states; 8 branches from each state
 - $\{a_k, d_k\}$ trellis: $2^{(L_1-1)} \times 3^{(L_2-1)}$ states; 6 branches from each state
- ❑ Detection on the $\{a_k, d_k\}$ trellis
 - The BCJR algorithm is used to compute the APPs $P(a_k, d_k | \mathbf{z})$, by treating $\{a_k, d_k\}$ as one symbol
 - Get the APP of a_k by marginalization

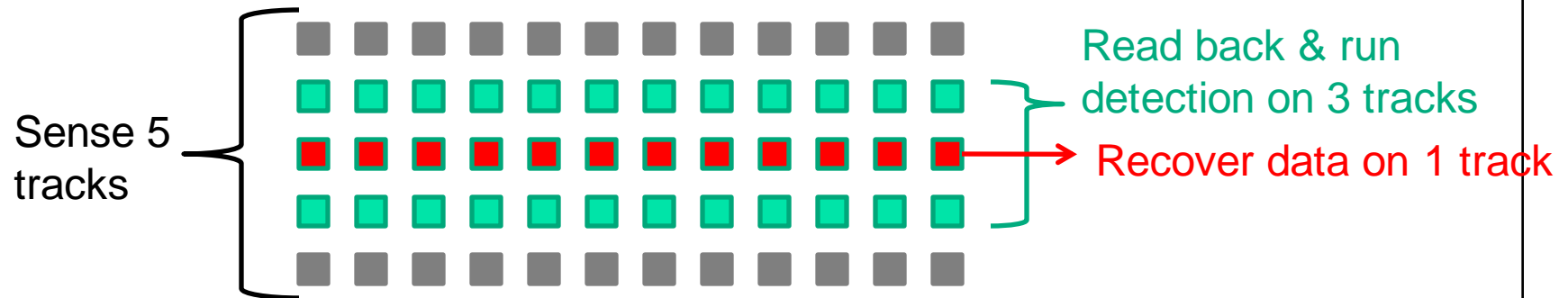
$$P(a_k | \mathbf{z}) = \sum_{d_k} P(a_k, d_k | \mathbf{z}).$$

*W. Tan and J. R. Cruz, “Evaluation of detection algorithms for perpendicular recording channels with intertrack interference,” *J. Mag. Magnetic Materials*, vol. 287, pp. 397-404, 2005.



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Multi-Track Detection



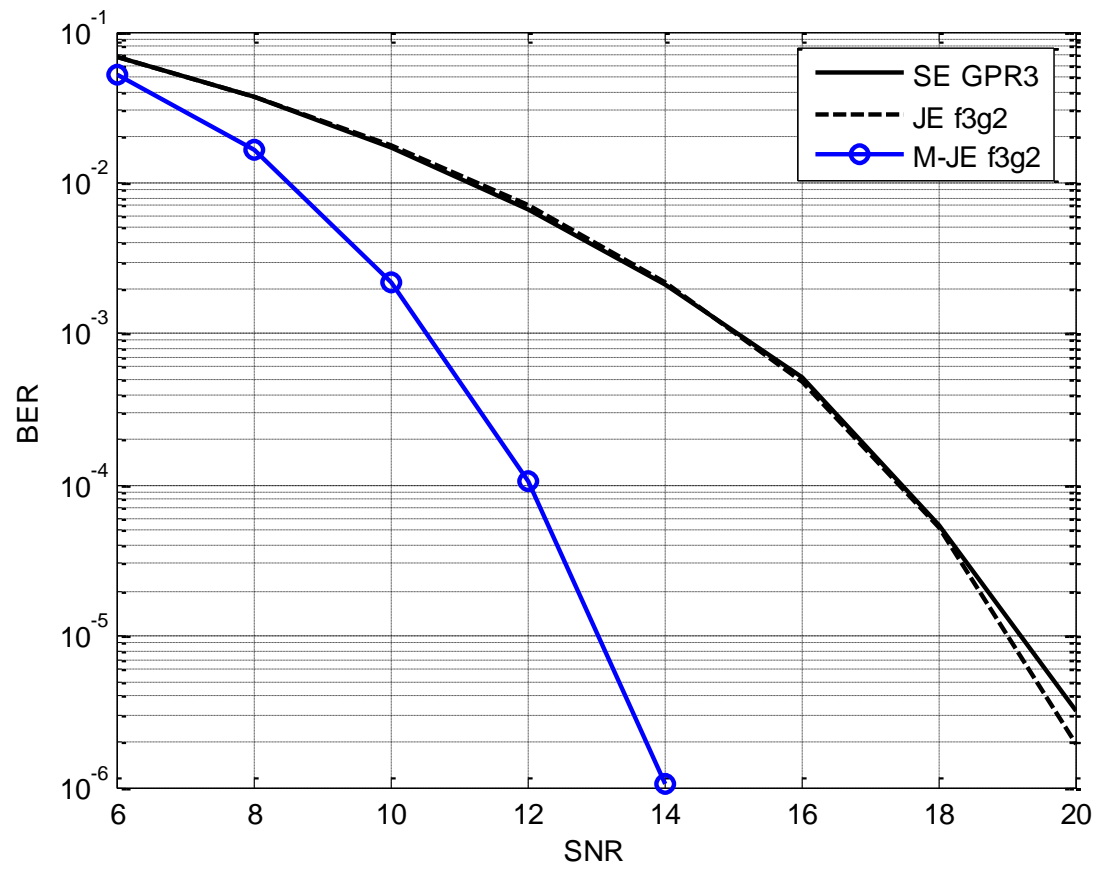
□ Basic idea

- Read back equalized signal from all three tracks
- Perform detection on the two side tracks
- The center track detection is aided by the APP information from the side tracks
- Multiple- or single-read head



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Simulations Results

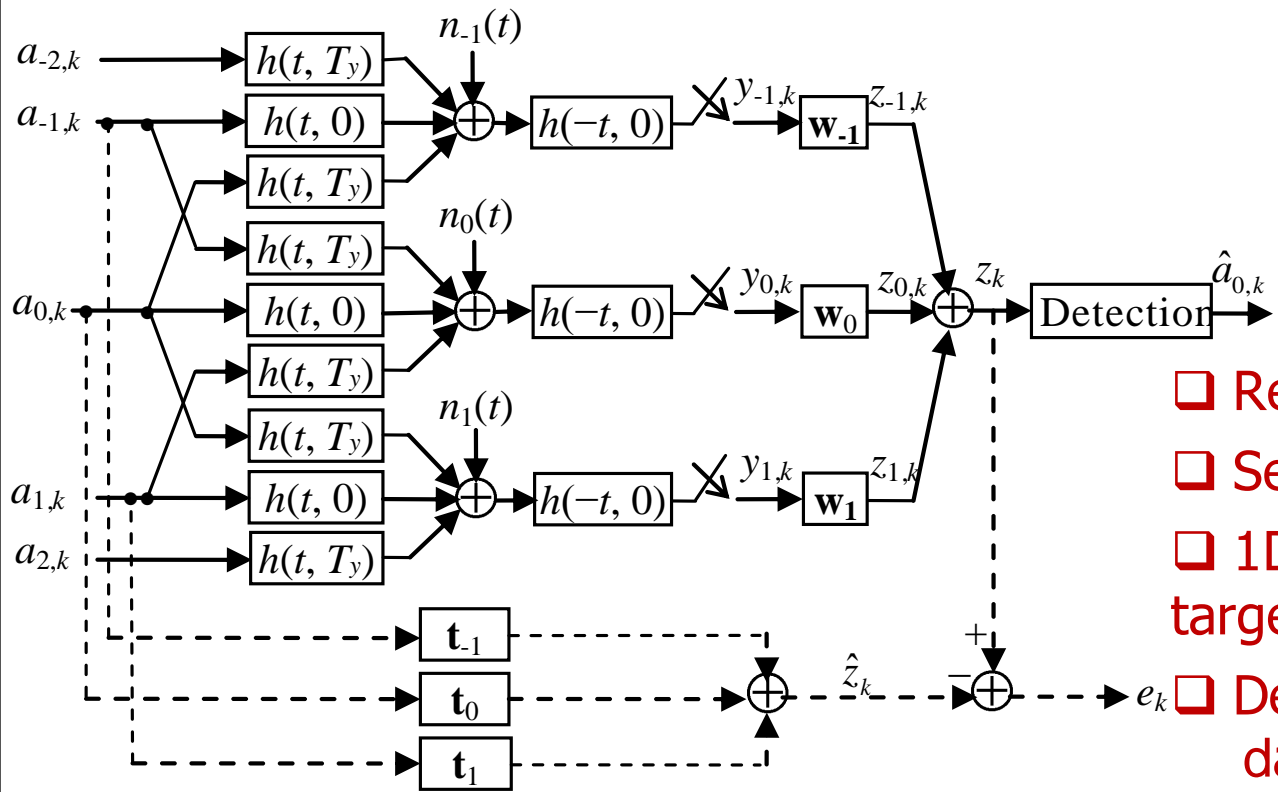


- M-JE f3g2: MTD with JE on all three tracks
- 6-dB gain



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2D Equalization



- Read back 3 tracks
- Sense 5 tracks
- 1D or 2D GPR target
- Detect & recover data $a_{0,k}$ on center track only

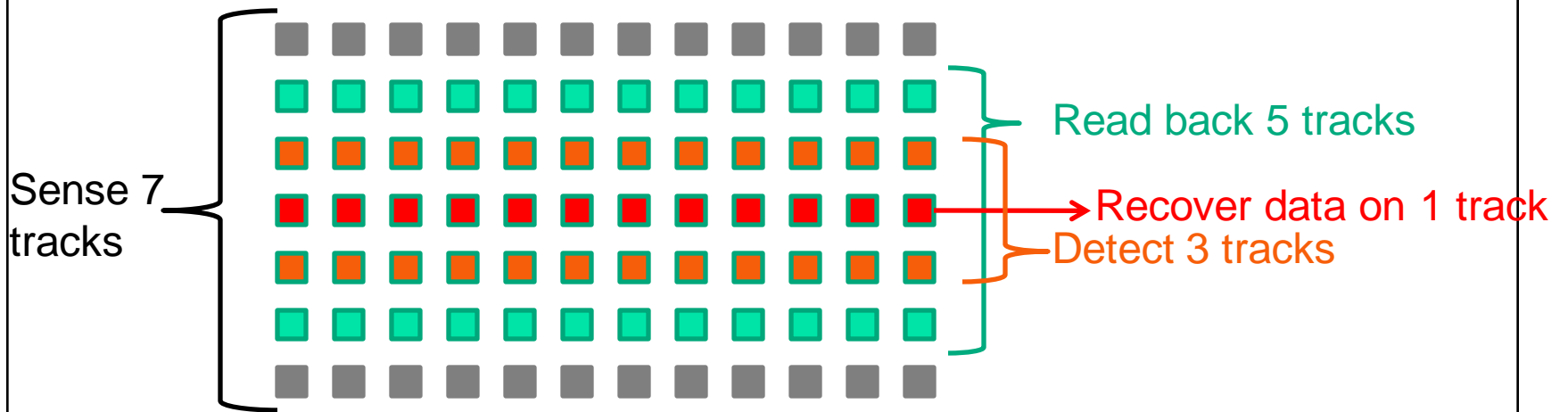
$n_{-1}(t)$, $n_0(t)$ and $n_1(t)$ are assumed to be independent of each other and have the same double sided power density height of σ^2 .

S. Nabavi and B. V. K. Vijaya Kumar, "Two-dimensional generalized partial response equalizer for bit-patterned media," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2007, pp. 6249–6254.



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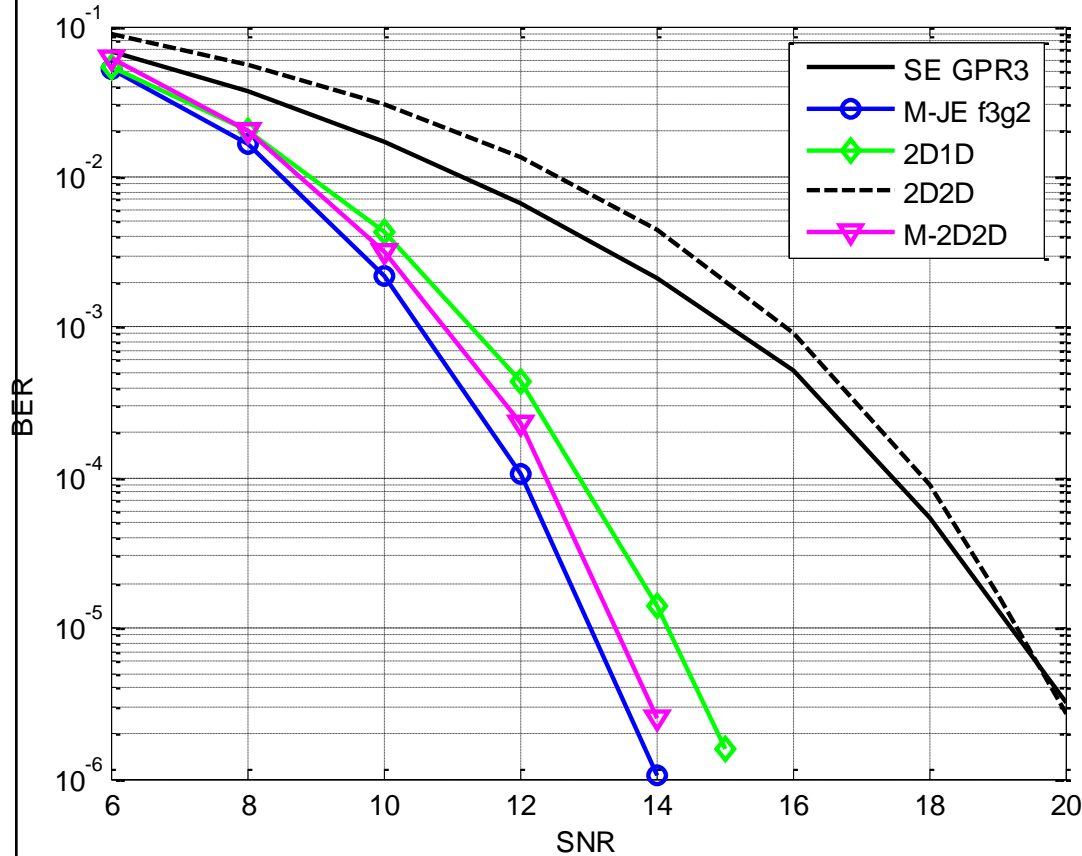
MTD with 2D Equalization





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Simulation Results



- ❑ M-2D2D: 2D2D on all 3 tracks detected
- ❑ 2D2D has poor performance, which can be explained by its EMSE
- ❑ M-2D2D performs worse than M-JE, due to the poor performance of 2D2D



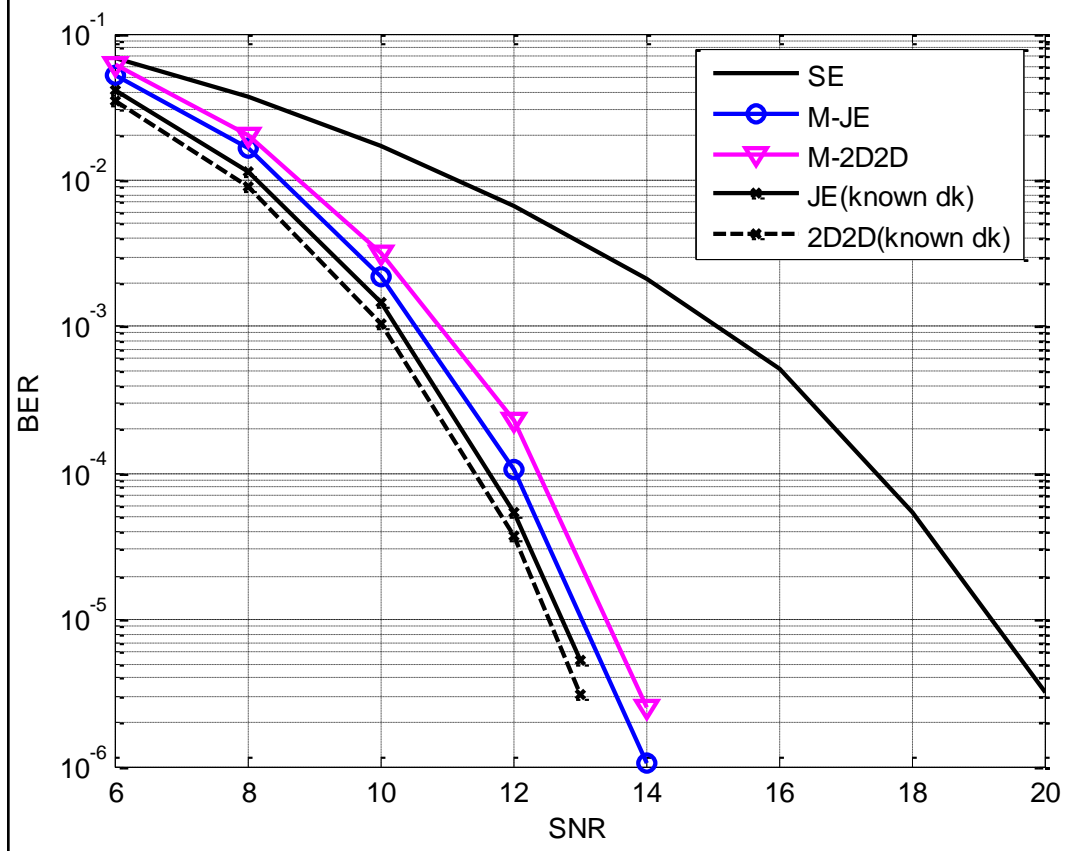
Performance Bounds

- ❑ MTD uses the APPs of the side tracks to help the data recovery on the center track.
- ❑ The best performance of MTD is achieved if the data on side tracks are detected without error
- ❑ We simulated the JE and 2D2D channels with known data on the side tracks to get the performance limit of MTD
 - $\text{MSE} = \text{var}\{e'_k\}$
 - When d_k is known, the joint trellis defaults to a simple trellis which only has memory for a_k . The contribution of d_k only affects the branch values



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Performance Results



- The performance limits of JE and 2D equalization with MTD are close
 - $MSE_{2D2D} < MSE_{JE}$, but similar
- M-JE recovers most of the gain but is simpler than M-2D2D
- To achieve the performance limits better estimation on the side tracks is needed



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Summary

Equalization method	Sense tracks	Readback tracks	Equalizer	Target	Detect tracks (APPs)	Recover tracks
SE	3	1	1D	1D	1	1
JE	3	1	1D	2D	1	1
2D1D	5	3	2D	1D	1	1
2D2D	5	3	2D	2D	1	1
MTD-JE	5	3	1D	2D	3	1
MTD-2D	7	5	2D	2D	3	1



Conclusion

- Communications Signal Processing
 - Enabling technology for extremely high density storage
 - 10 Tb/in² magnetic recording
 - Bit-patterned media
 - Heat-assisted recording
 - Two-dimensional recording



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Acknowledgement

I wish to acknowledge the invaluable contributions of my former student Dr. Wu Chang to the research reported in this presentation.