Transmission Proposal for 10GBASE-T

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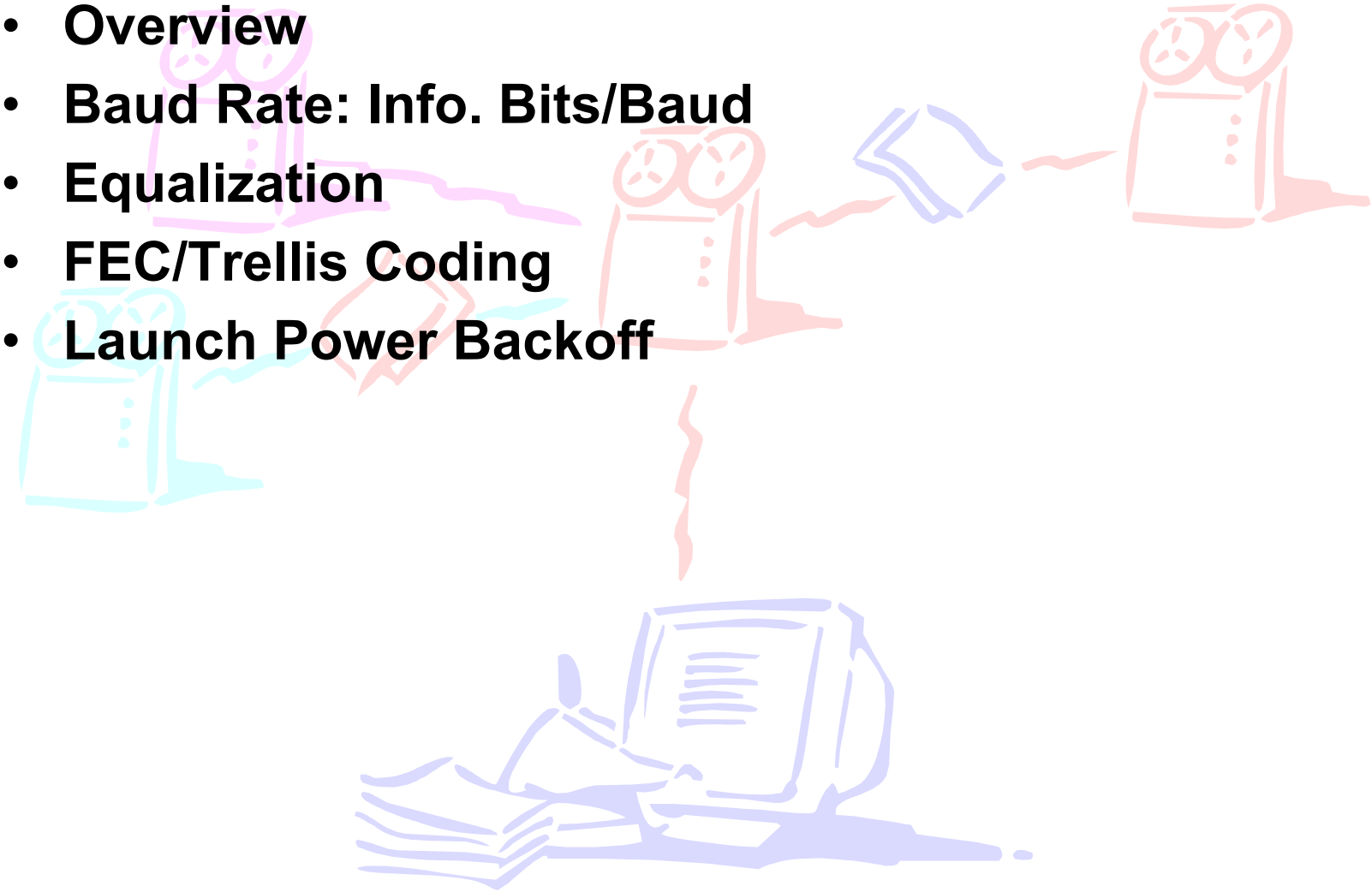
Outline

- Overview
- Baud Rate: Info. Bits/Baud
- Equalization
- FEC/Trellis Coding
- Launch Power Backoff



Overview: Key Choices to Make

- Line coding
  - Starts with baud rate (bandwidth)
  - Exact # levels of PAM tied to FEC choice
  - May requires overhead for MAC control symbols
    - Depends on coding
- FEC choice & partition
  - Includes both line coding & partition
- Launch voltage
  - Power consumption/Noise immunity tradeoff
  - EMI constraint
  - Power backoff for short lines

Overview: Elements Considered

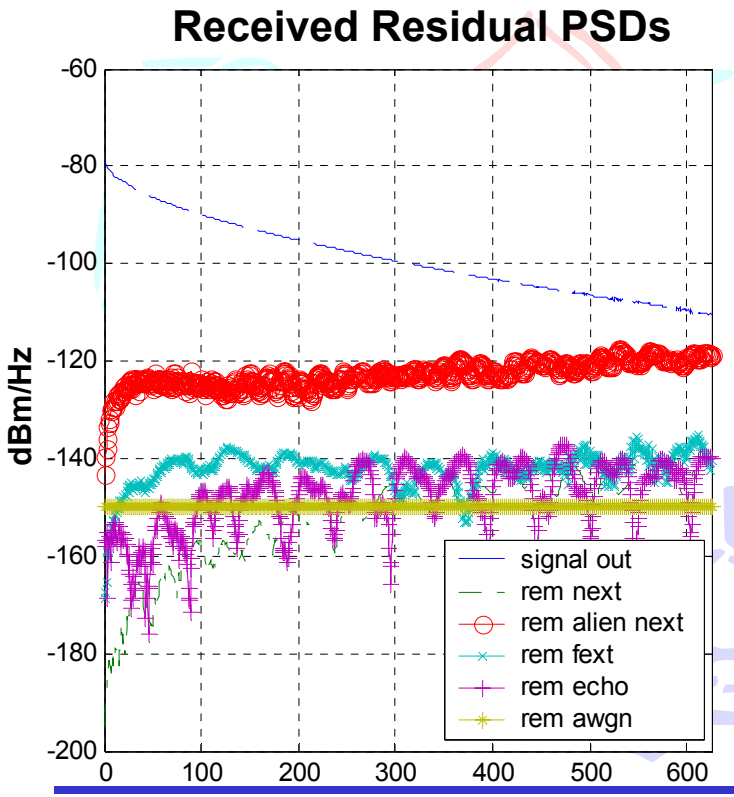
- Channel models
  - 55m Class E Objective:
    - Cabling ad hoc IL, NEXT, FEXT & RL models (http://www.ieee802.org/3/10GBT/public/material/10GBASE-T_Cat6_Model.zip)
    - Class E ad hoc ANEXT model, Class E ISO proposal (15 dB/decade)
  - 100m Class E+ Objective:
    - Class E ad hoc IL, NEXT, FEXT & RL models
    - Proposals from TR42, ISO, and 3rd parties
- EMI models
  - EMI radiative transfer function derived from measurements presented to IEEE 10GBASE-T Study Group
- Component effects
  - Magnetics bandwidths
  - Timing recovery effects
- Info bits/baud – determines baud rate
  - Based on Optimal DFE signal processing

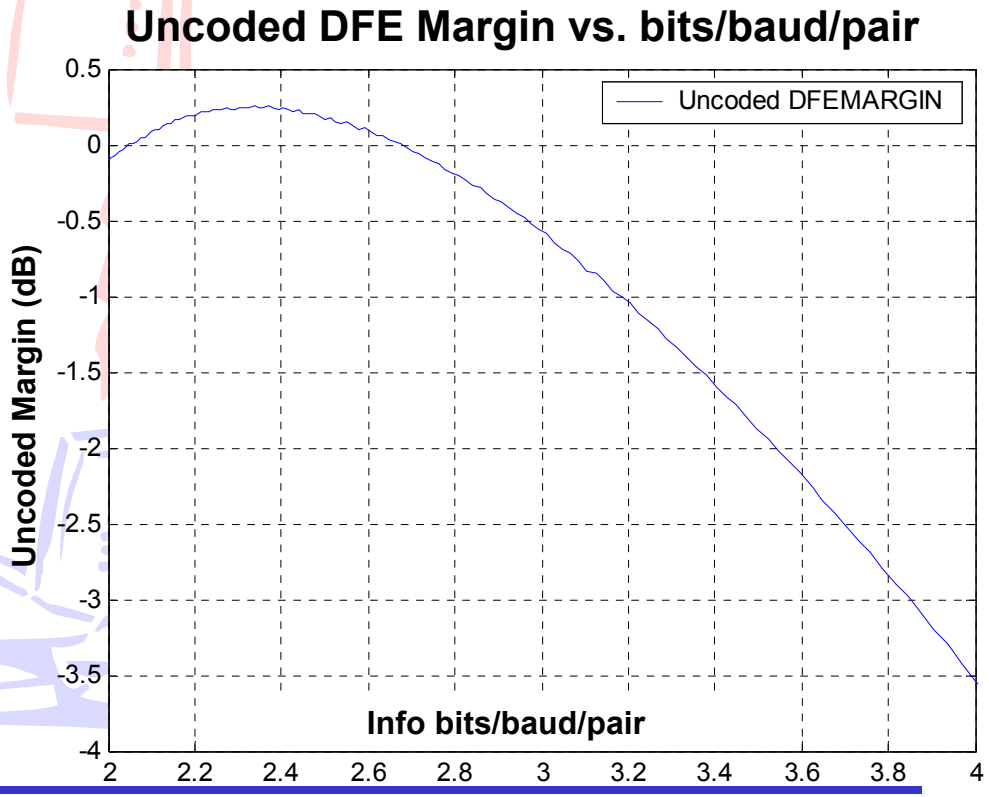
Baud Rate: Info bits/baud (/pair)

- Determines necessary & used bandwidth
  - Performance, Power & EMI Constrained
- DFE systems generally have a unique optimum
- Performance vs. baud rate on DFE channels is not identical to AWGN channels
  - Rate loss is channel dependent
    - (Rate loss in DFEs under "pinch off" conditions: ref. T1E1.4/97-241)
- Optimal DFE Margin (Salz) normalized to bits/baud:
  - Uncoded Margin = -10*log10(Salz_MSE)-Capacity_SNR+12.27dB
  - Capacity SNR = 10*log10(2^(2*bits/baud/pair) – 1) dB

Baud Rate: 55m Class E Ad Hoc Model

- Very shallow optimum
- ANEXT Model exhibits <10dB/decade ANEXT slope

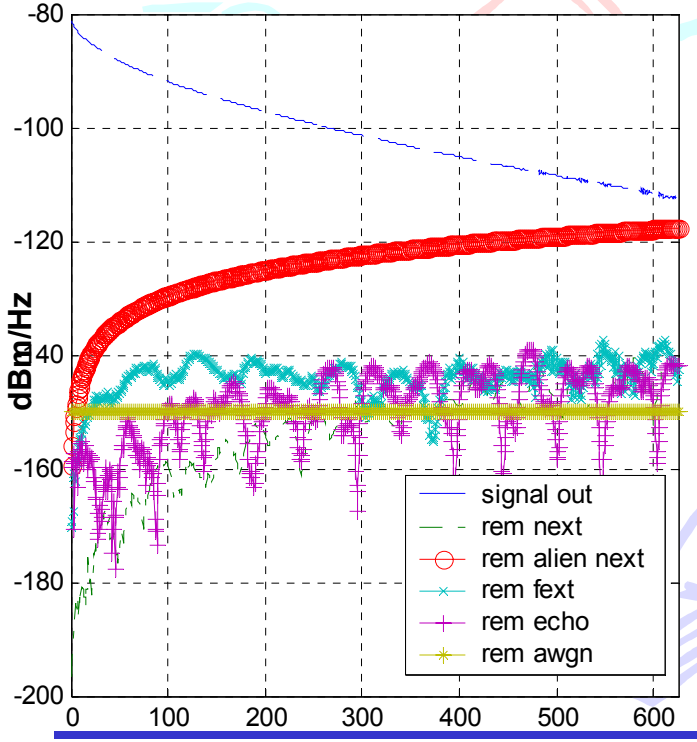




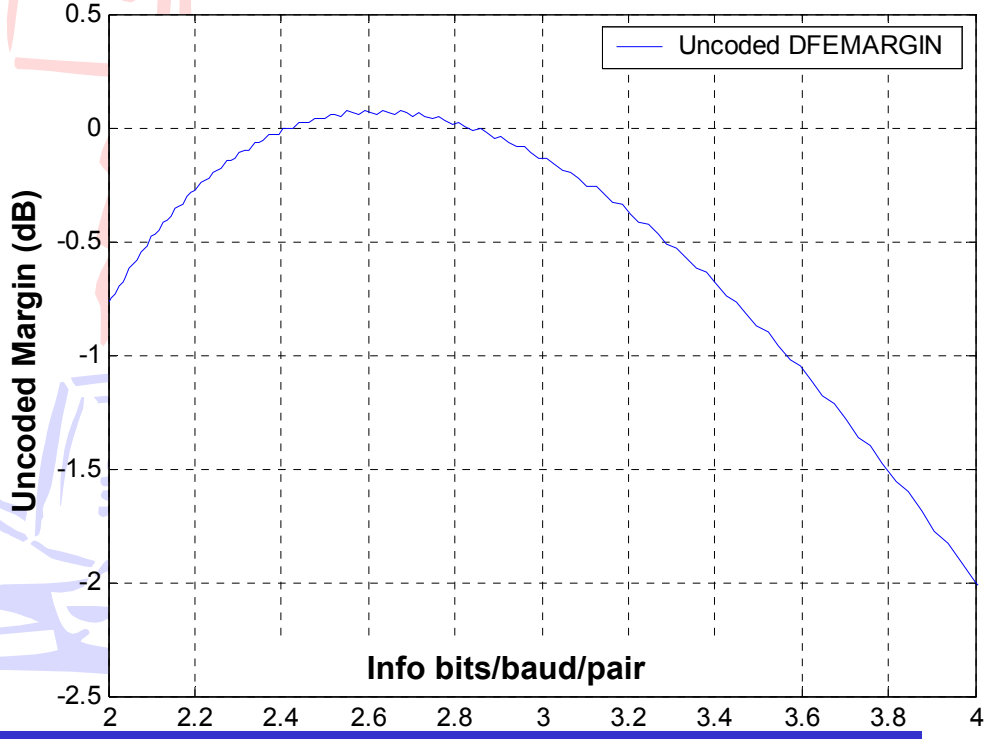
Baud Rate: 55m Class E with 15dB / decade ANEXT model

- Optimum shifts towards 3 bits/baud & steepens
- ANEXT Model based on presentations
  - Conforms with data(hayes_1_0303.pdf, abughalazeh_1_0903.pdf)
  - ANEXT Loss = 47-15log10(f/100) + 2.5 dB (limit line adj)

Received Residual PSDs

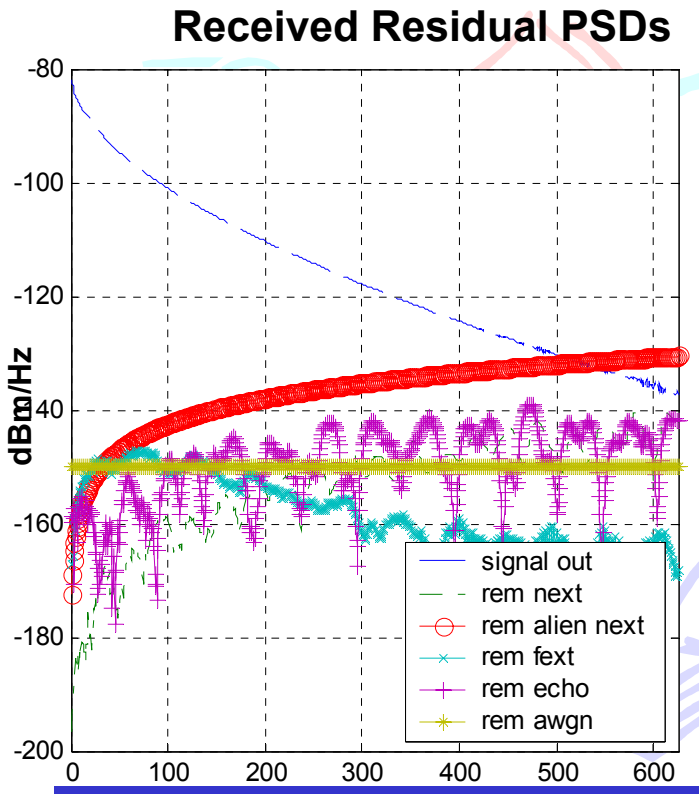


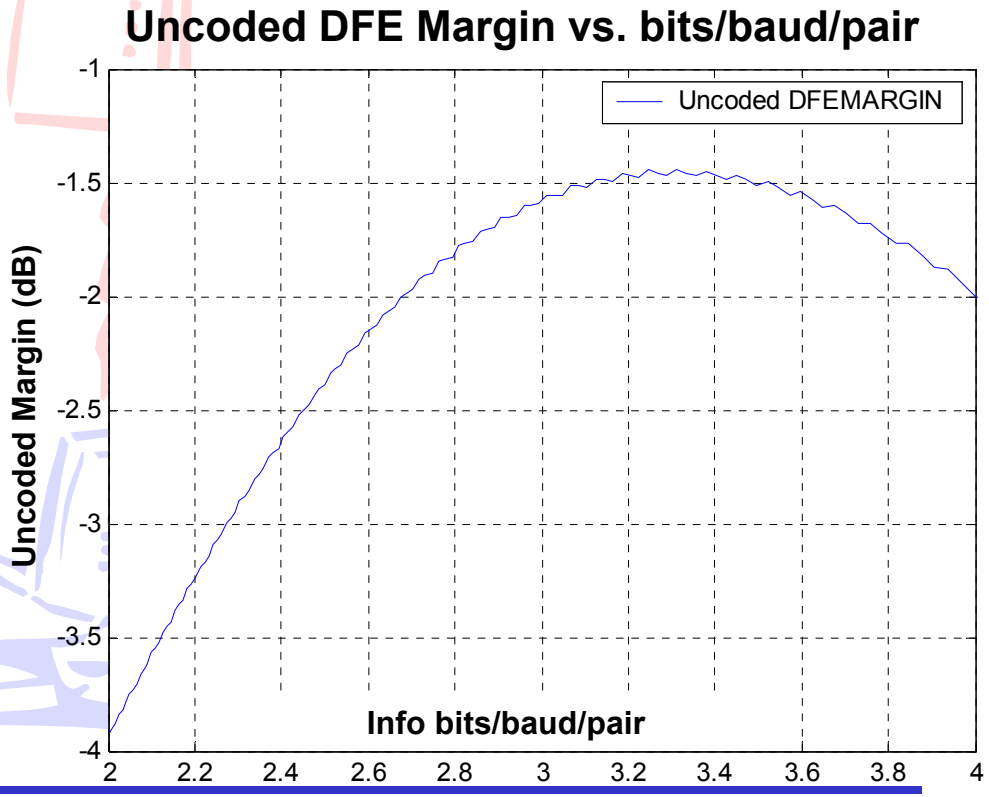
Uncoded DFE Margin vs. bits/baud/pair



Baud Rate: 100m Class E+ Example

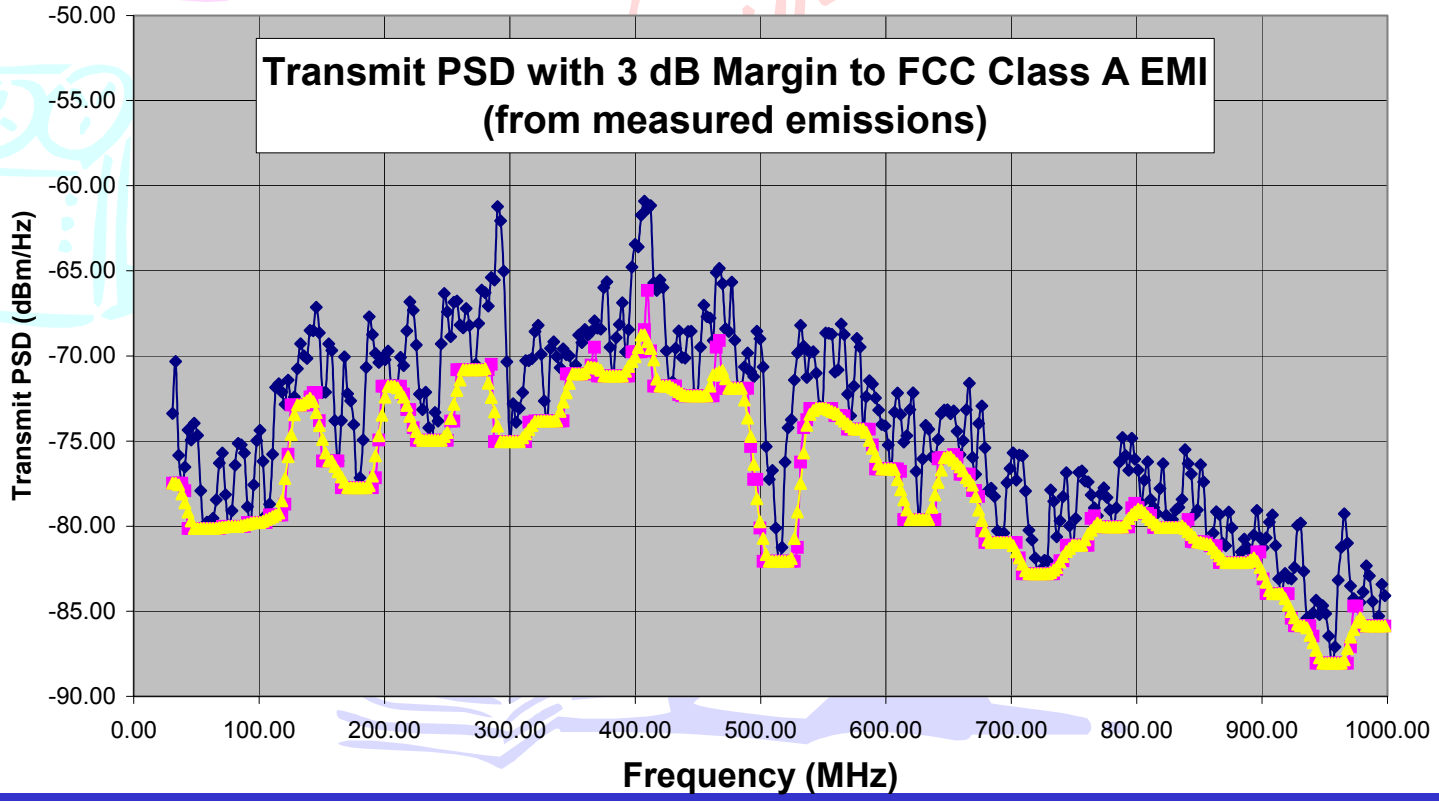
- **DFE Margin vs. info bits/baud strongly favors lower baud rates**
  - **ANEXT Loss = 60-15*log10(f/100) + 2.5dB (limit line adj.)**





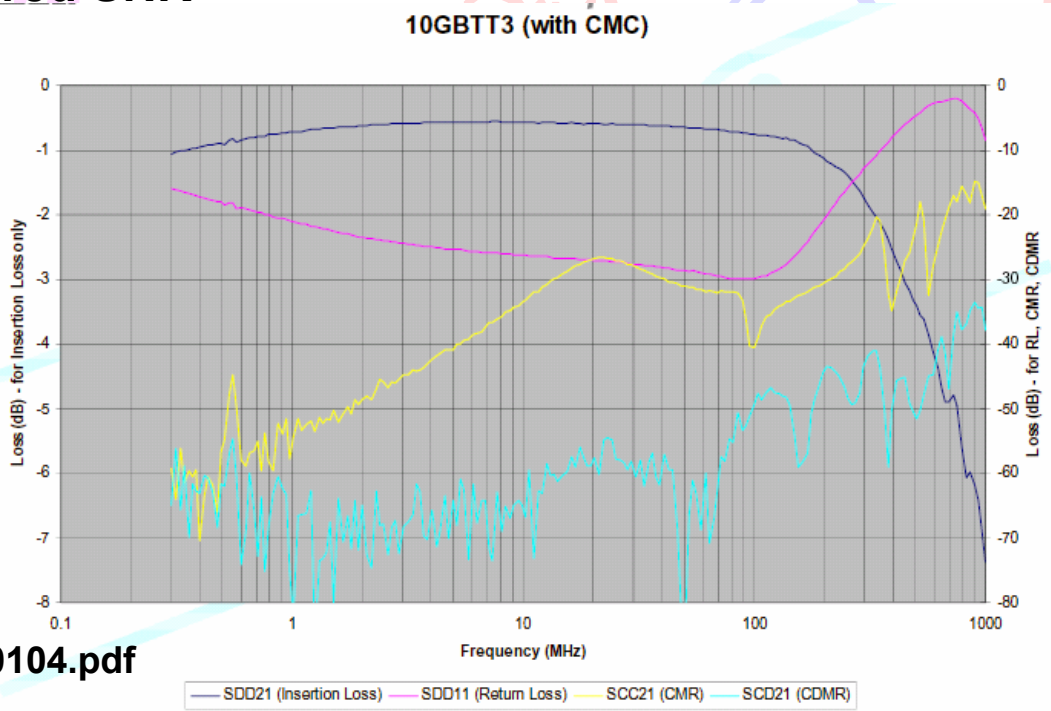
Baud Rate: EMI

- **Used Field Radiated EMI measurements to estimate transmit PSD within FCC Class A**
  - **Issues emerge above 500 MHz**



Other Components

- **Magnetics performance falls off beyond 500 MHz**
  - **Adversely effects noise susceptibility & EMI in addition to received SNR**



ref: dihn_1_0104.pdf

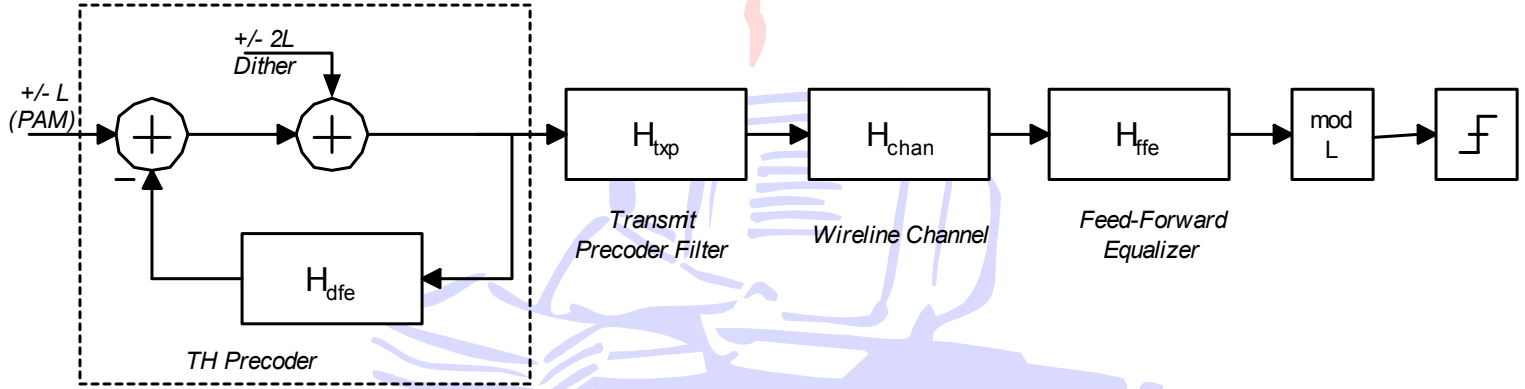
- **Timing jitter degrades SNR as baud rate increases (10*log10(fb1/fb2) relative loss in ADC quant noise PSD)**

Baud Rate: Conclusions

- Choice of info bits/baud (baud rate) is a function of tradeoffs in:
  - Long-line Performance
  - ANEXT Robustness
  - Meeting EMI
  - Other component effects (e.g., Magnetics, timing)
- 3 bits/baud/pair is within 1 dB of optimum point for DFE SNR for all cases, and closer on hard cases
- 3 bits/baud/pair allows transmit PSD to roll off before 500 MHz
  - Meets EMI, aligns with magnetics rolloff

Equalization: Tomlinson-Harashima

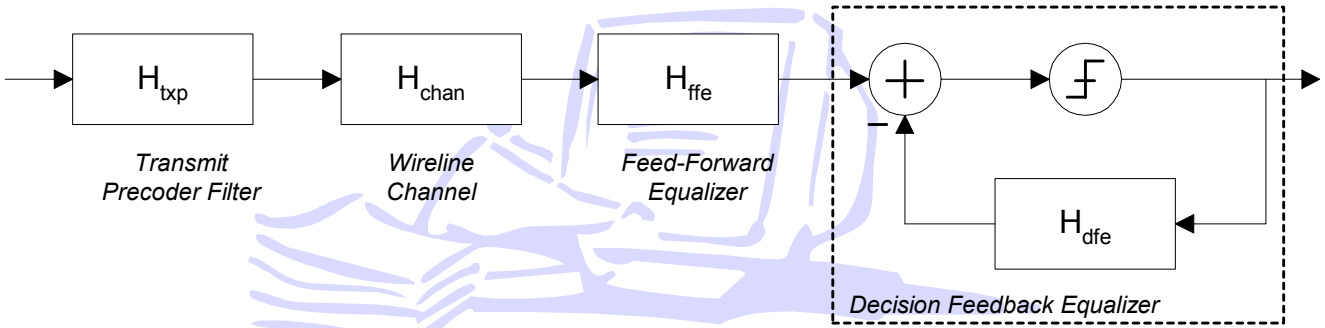
- **Alleviates DFE error propagation in coded systems**
  - **Cost is large amplitude "dither" element added to signal**
    - **Transmit power penalty is small for large # PAM levels**
  - **Problems:**
    - **Dither couples through NEXT, FEXT & Echo paths**
    - **High PAR & extra dynamic range increases complexity**
    - **Incompatible with shaping gain**
    - **Requires tight circuit timing loop for feedback filter**



TH Precoded Channel Equalizer Block Diagram

Equalization: Precoded DFE

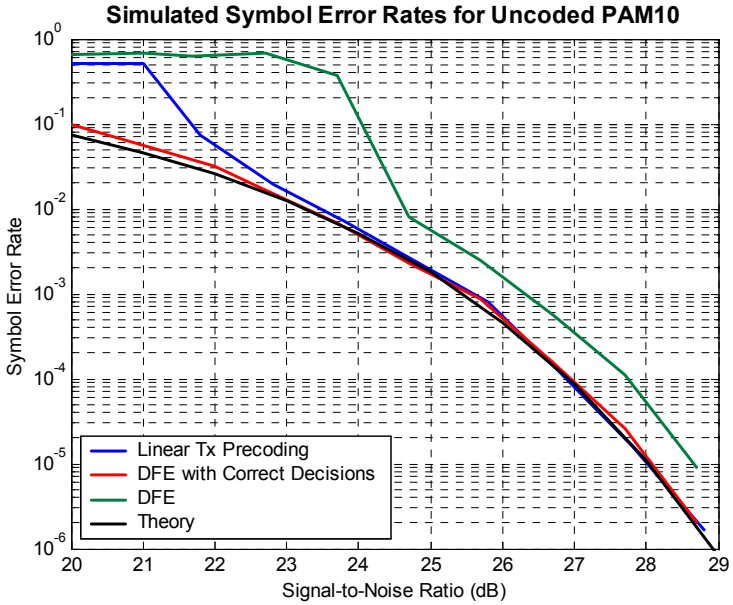
- **Adaptive Linear precoding can shape DFE response to minimize error propagation**
  - **Small transmit power penalty for preemphasis**
    - **10GBASE-T not generally transmit power limited**
  - **Can be combined with other transmit filtering**
  - **Can be combined with constellation shaping gain**
  - **Feedforward structures minimize circuit timing issues**

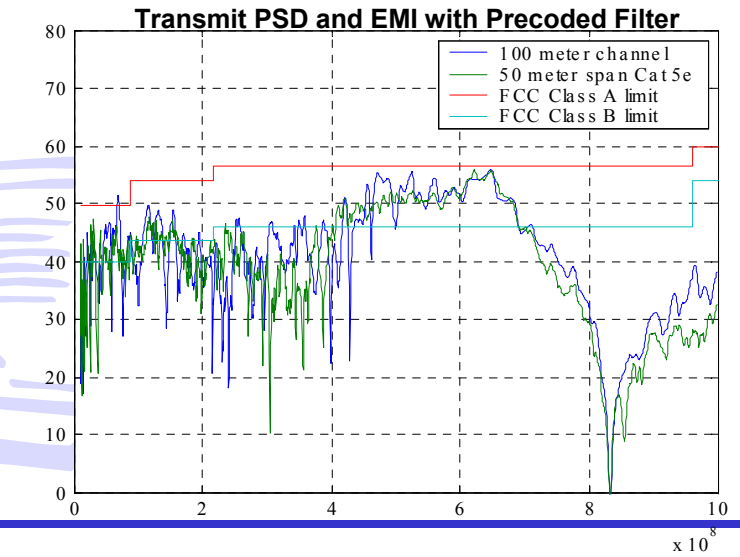


DFE-based Channel Equalizer Block Diagram

Equalization: Precoded DFE

- Precoder coefficients trained at startup to adapt to varying line lengths
- Max DFE feedback coefficient can be constrained < .25
- DFE can be shaped to avoid catastrophic error propagation





FEC/Trellis coding: Latency

- Applications show need for lower latency codes
  - Distributed computing, clustering require capability for low latency operation
    - Includes propagation, code and signal processing latency
    - Long lines mask PHY latency (propagation delay)
- Generic Ethernet places no hard requirement on 10GBT
  - Legacy of the fact that 802.3ae was engineered for multi-km links (light time > 5 usec)
- Previous Ethernet has not stated latency as a requirement
- High latency codes PERMANENTLY bar technical innovation from achieving low latency operation
- Additional coding gain can be achieved by layering an outer code, if necessary, on long lines without impairing minimum PHY latency on shorter lines

Code Proposal: 4D-4W-Trellis Code

- 4D (across pairs) PAM-10 with 4-way time-interleave and constellation shaping
- Advantages
  - Meets 3 bits/baud information rate
    - Encodes control symbols into modulation, avoiding rate loss
  - Provides for minimal latency operation (<< .25usec)
  - Provides for constellation shaping gain (0.64 dB)
  - 4-way interleave allows lower-rate decoder clocking
  - Interleave mitigates noise correlation effects
  - Interleave mitigates error propagation effects
  - Low complexity hardware encoding & decoding
  - Allows concatenation for layering block FEC if desired for improved impulsive noise or long line performance

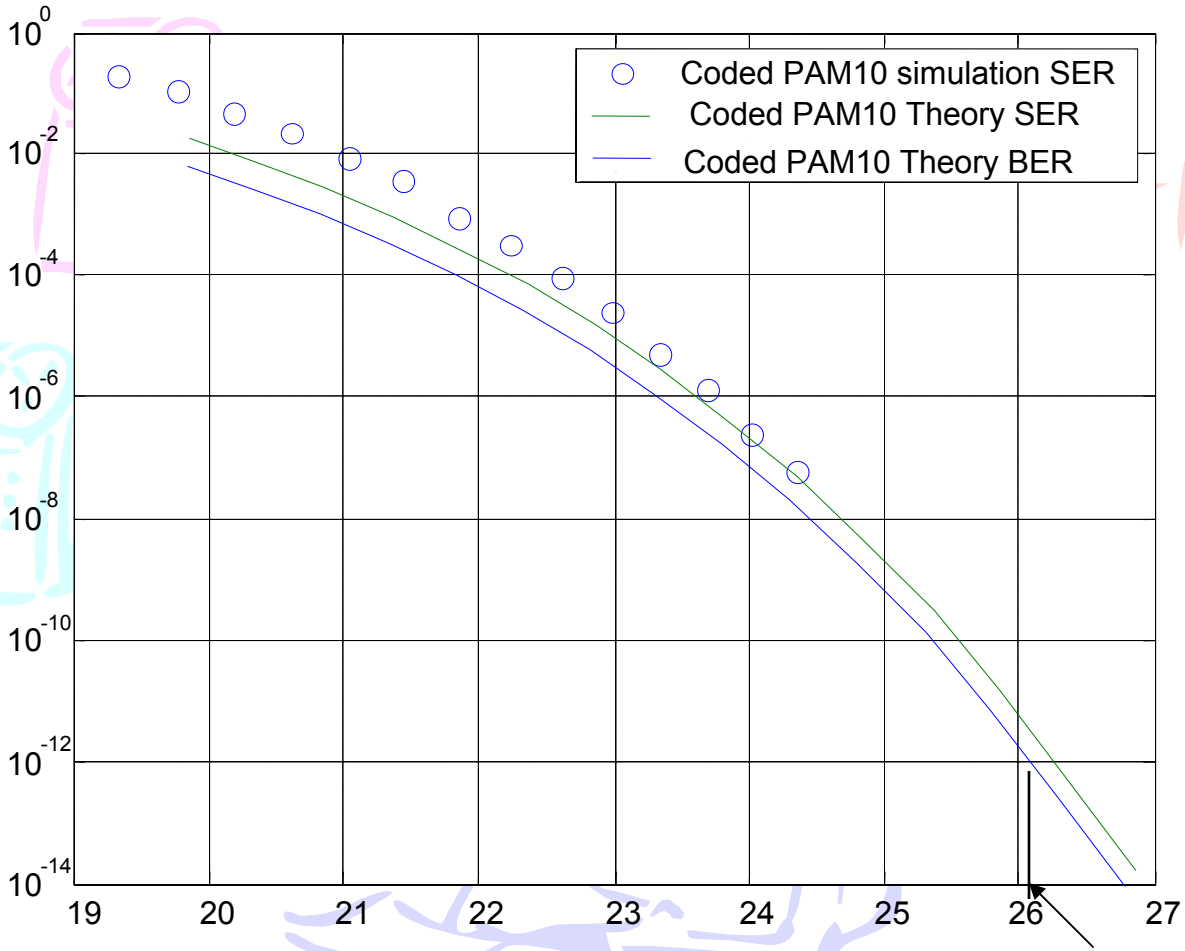
Line Code Proposal: 4D-4W-PAM10

- 8st 4D Ungerboeck code used in 1000BASE-T
  - 2^13 possible encoded symbols
  - 10,000 constellation points
  - Remaining 1808 points can be used for control symbols
- 4 Way time interleaving, code is 4D across pairs
- Balanced constellation
  - No polarity scrambler required
- Shaped constellation (0.64 dB shaping gain)

-9	-7	-5	-3	-1	+1	+3	+5	+7	+9
512	896	896	896	896	896	896	896	896	512

Table 1: 1D PAM Level Rate of Occurrence in the 4D Mapping (8192 points)

4D-4Way PAM-10 Code Performance

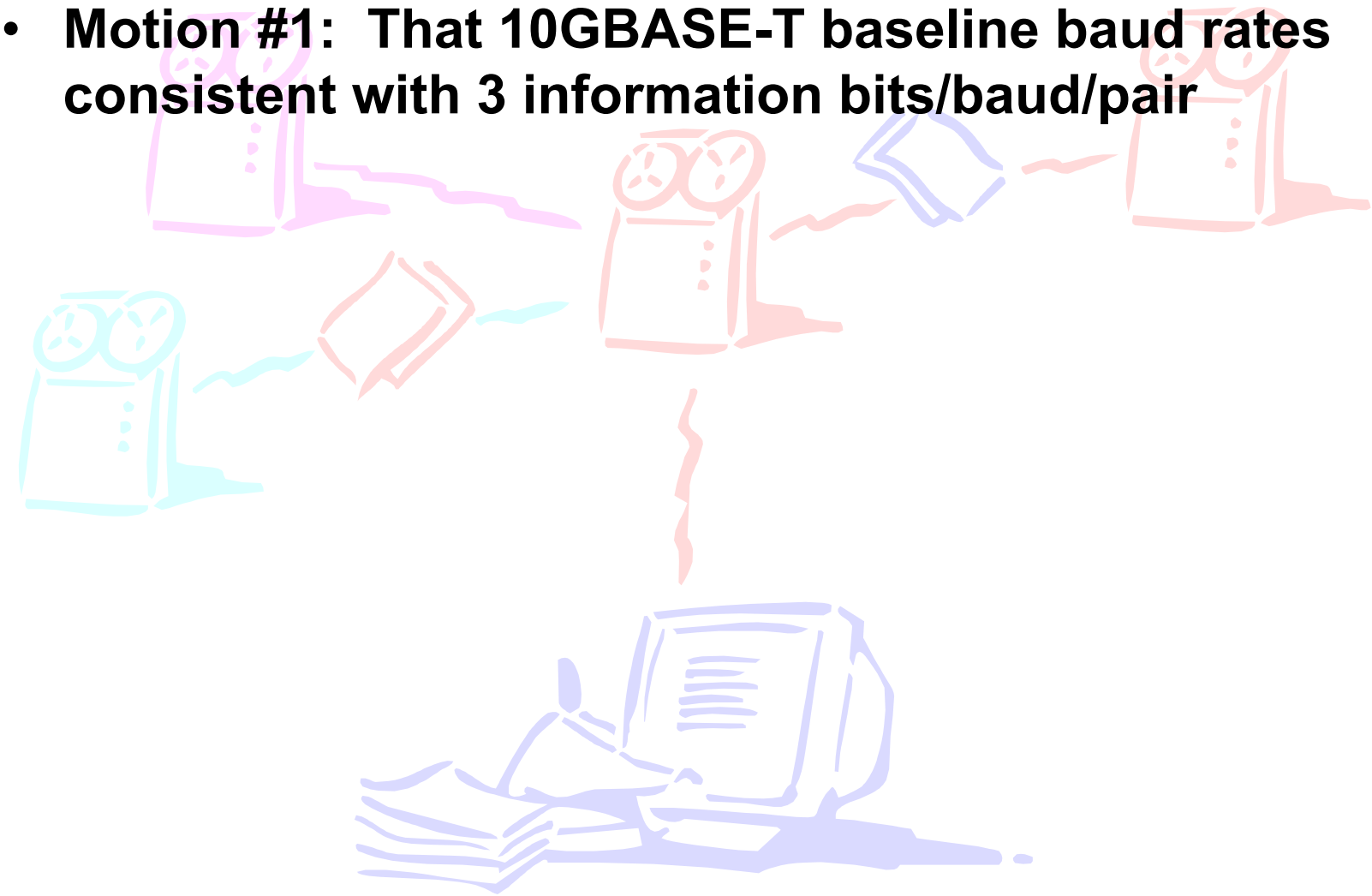


Launch Power Tradeoffs

- Launch power < 10 dBm due to EMI constraints
- Long line launch power > 6 dBm due to 1000BASE-T ANEXT constraints
- Negotiated launch power backoff
  - Widely used in deployed DSL standards to mitigate asymmetric link near/far problem
  - Lines less than 50m
  - Negotiated at Startup, based on SNR and/or attenuation
  - Minimum backoffs to be specified in the standard

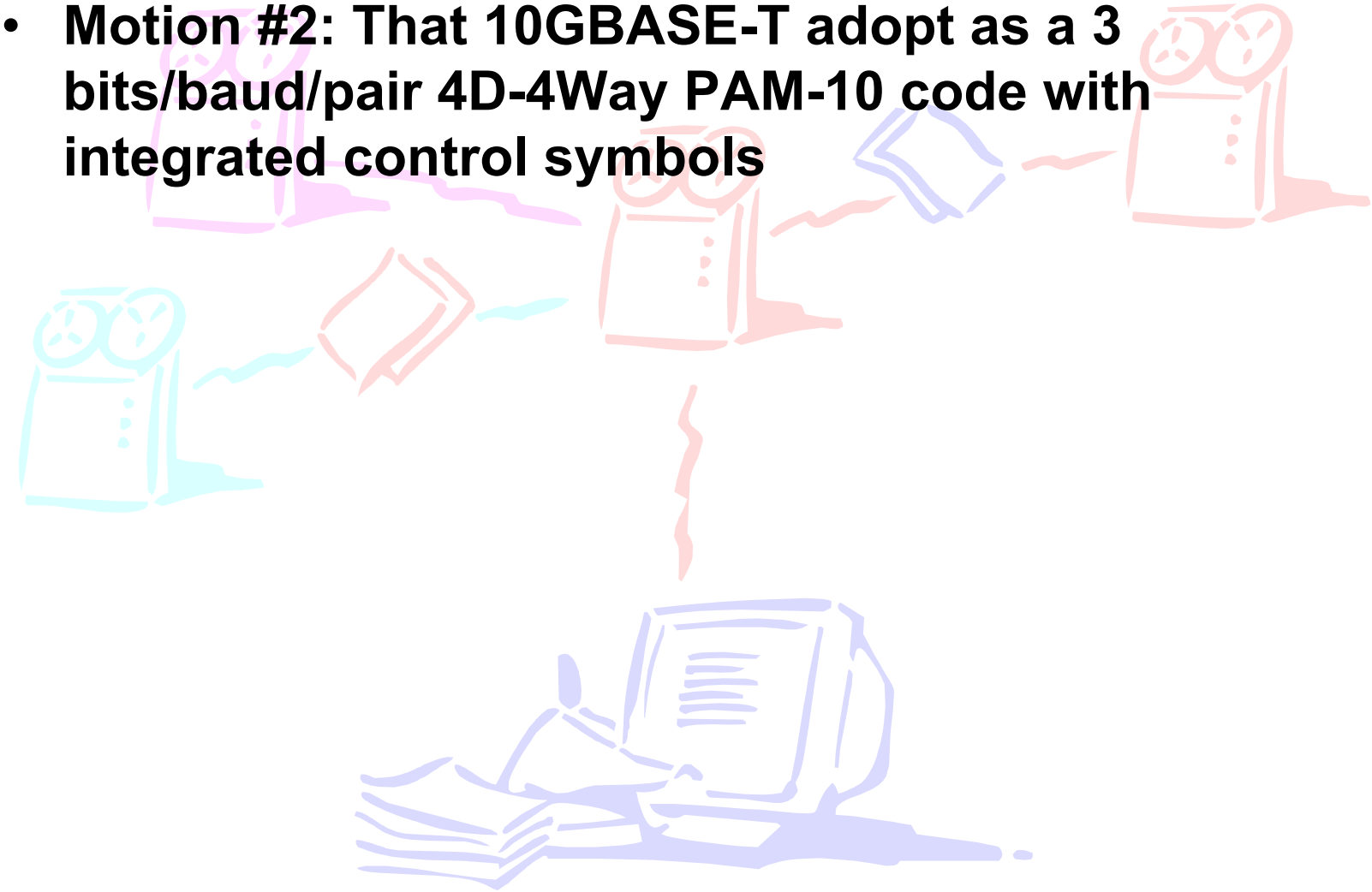
Baud Rate Proposal

- **Motion #1: That 10GBASE-T baseline baud rates consistent with 3 information bits/baud/pair**



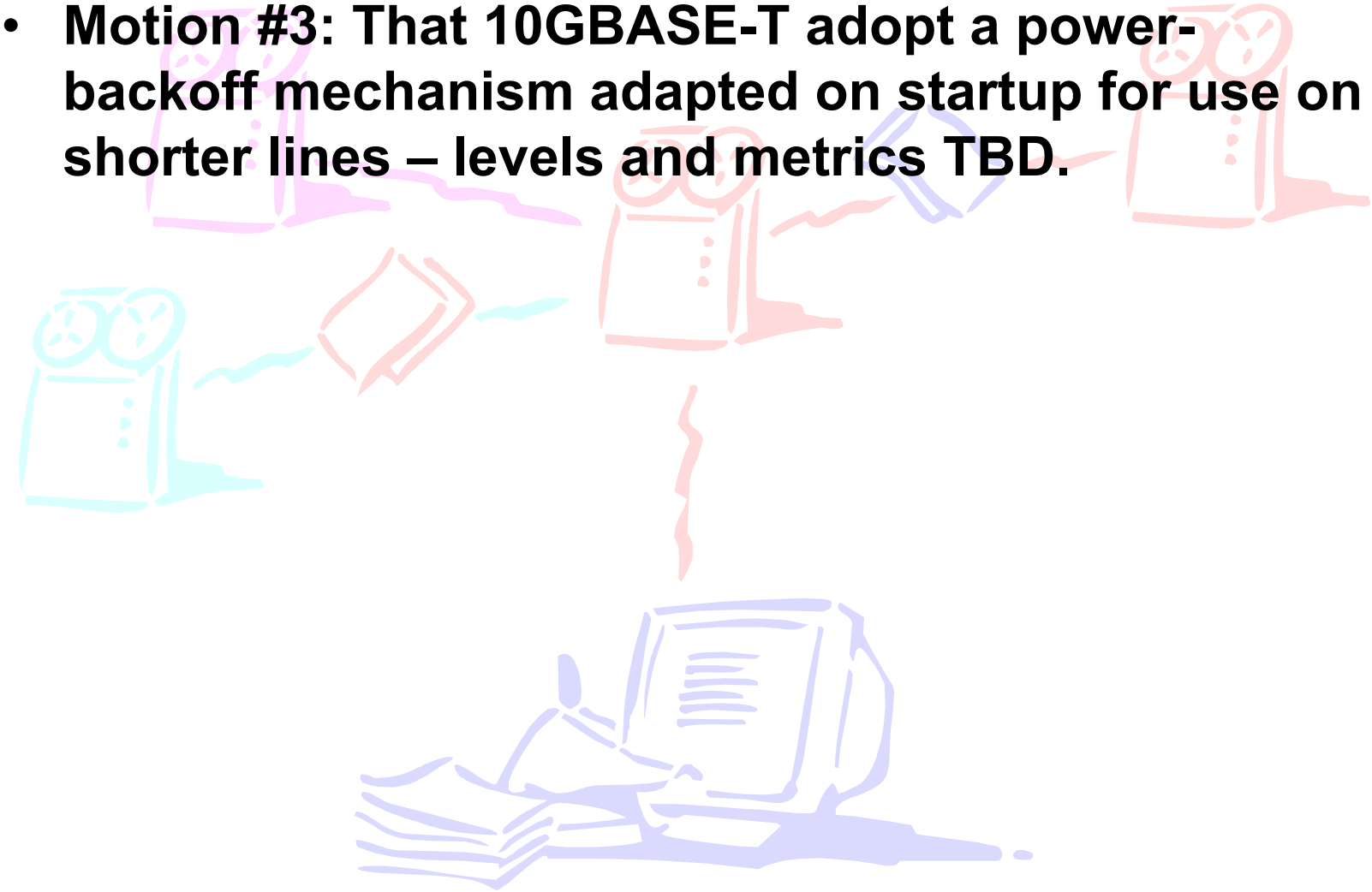
Coding proposal

- **Motion #2: That 10GBASE-T adopt as a 3 bits/baud/pair 4D-4Way PAM-10 code with integrated control symbols**



Power Backoff Proposal

- **Motion #3: That 10GBASE-T adopt a power-backoff mechanism adapted on startup for use on shorter lines – levels and metrics TBD.**



Backup Slides

Relation of Rate Loss in DFE systems under pinch-off

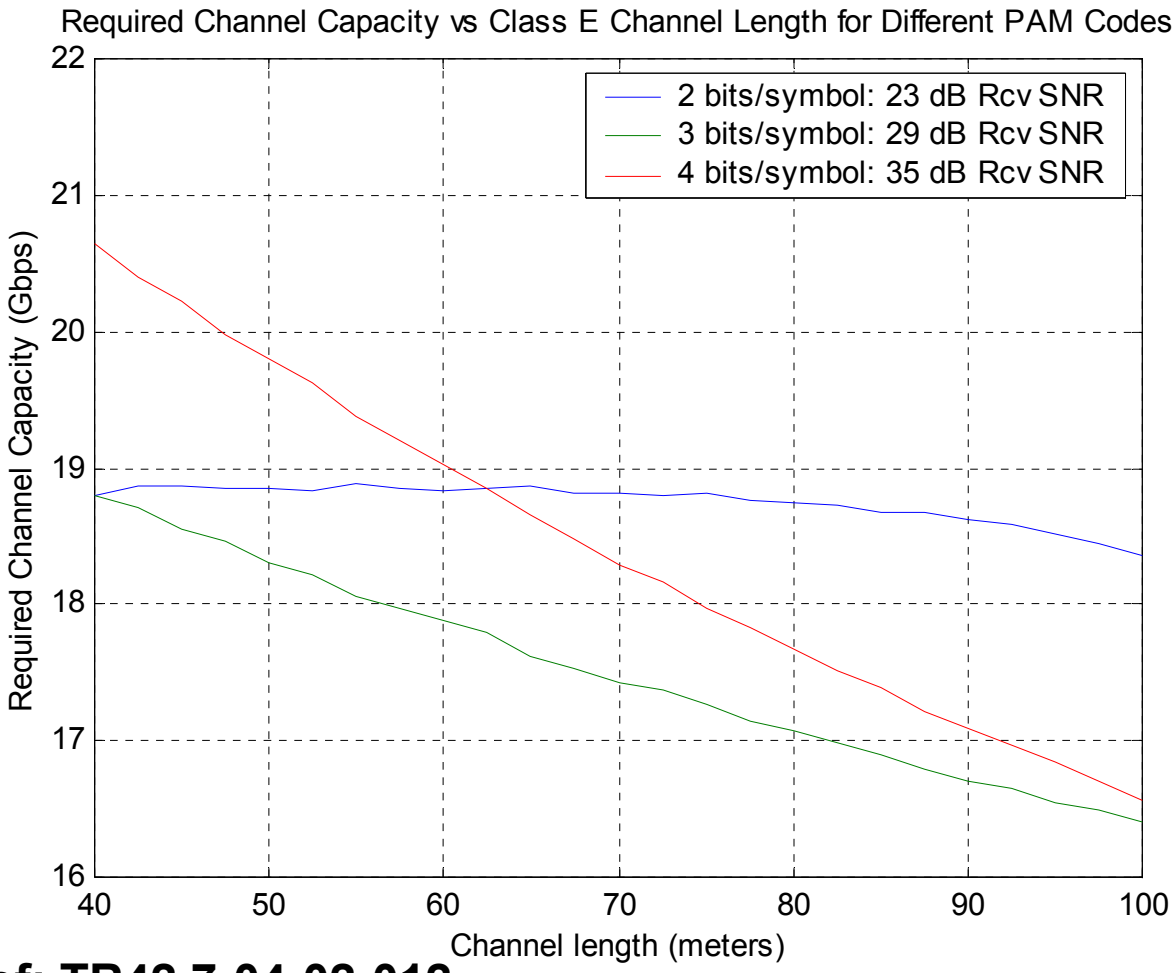
- **Optimum DFE Result:**

$$SNR(dB) = 10 * \log 10\left[\exp\left(\frac{1}{fbaud}\int_0^B \ln(1 + f\_SNR(f))df\right)\right]$$

$$= \frac{10}{fbaud}\log 10(\exp(1)) * \int_0^B \ln(1 + f\_SNR(f))df)$$

- **When f_SNR(f) is small for f>fbaud, increasing the baud rate does not change the value of the integral as in an AWGN channel**

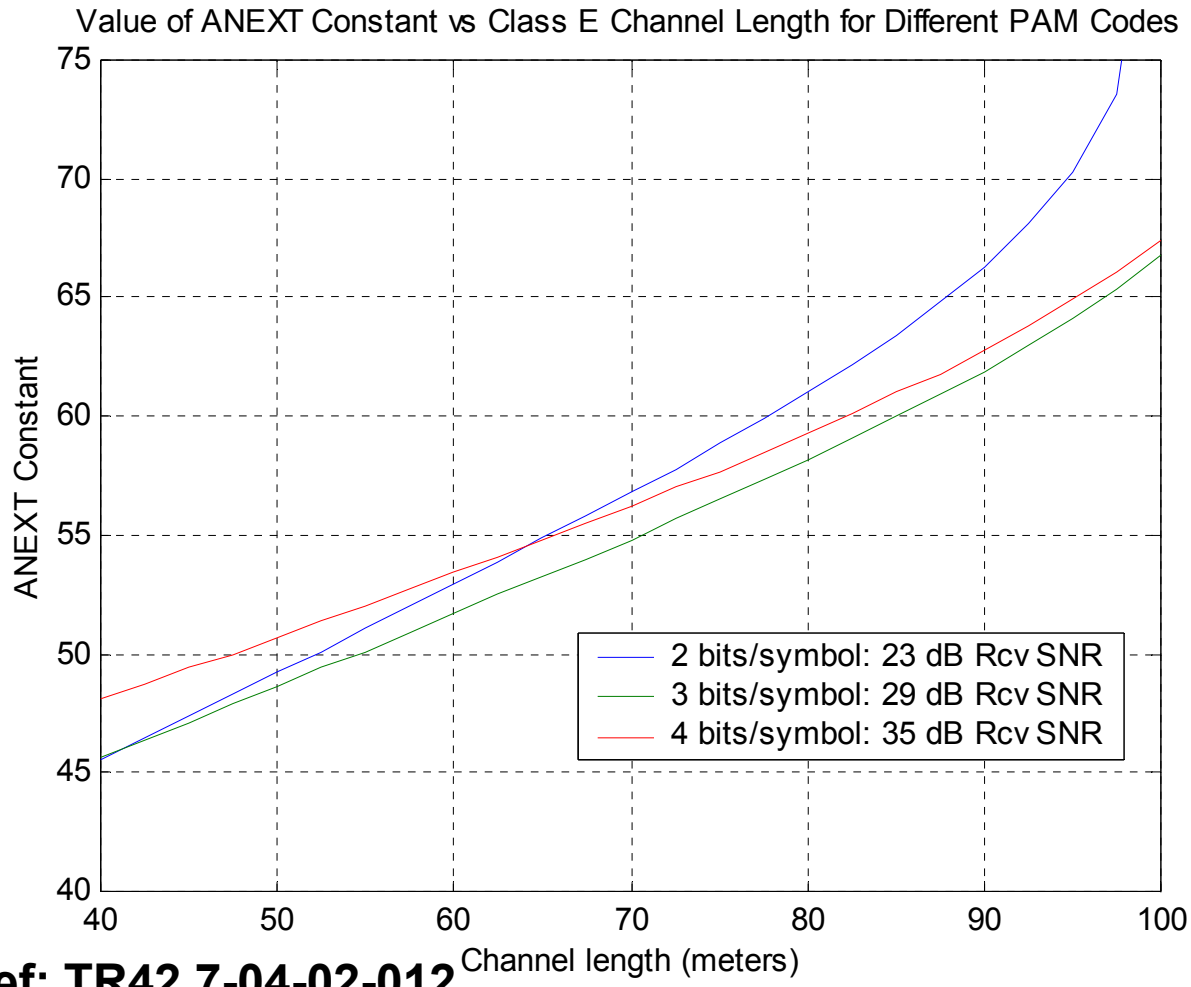
ANEXT Robustness: Variability of Required Channel Capacity with Constant SNR Constraint



ref: TR42.7-04-02-012

- ANEXT = Y + 15*log10(f/100), where Y is adjusted to produce target receive SNR
- Channel contains 4 connectors + 10 m patch cords; length adjusted with horizontal cable span only
- Target SNR includes
  - BER = 10e-12
  - 5.5 dB coding gain
  - 3 dB margin
- Impairments (Class E):
  - Echo = 55 dB
  - NEXT = 40 dB
  - FEXT = 25 dB
  - Noise = -150 dBm/Hz
- Transmit power = 8 dBm

ANEXT Robustness: Value of ANEXT Coupling Constant (Y) with Constant SNR Constraint



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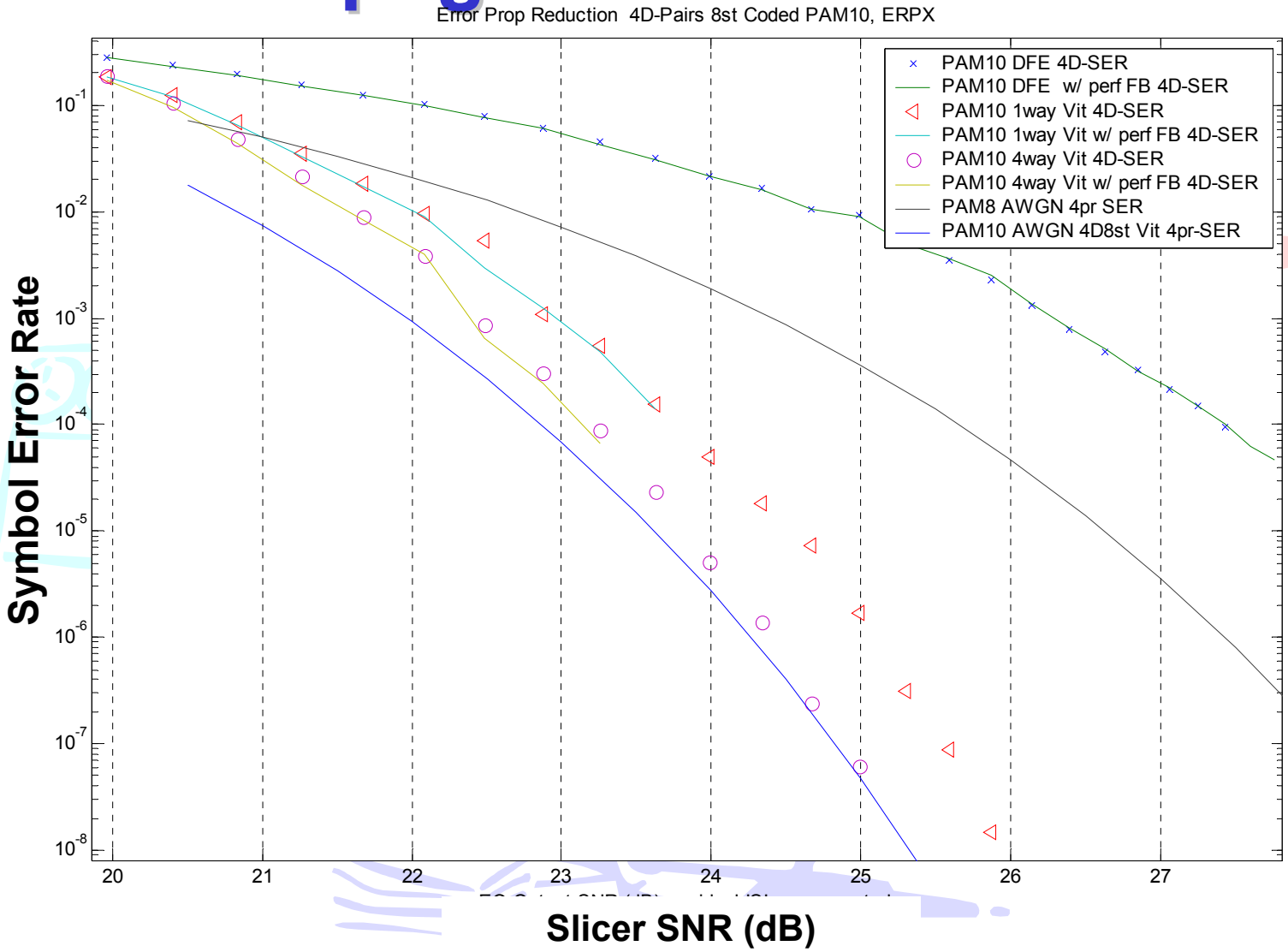
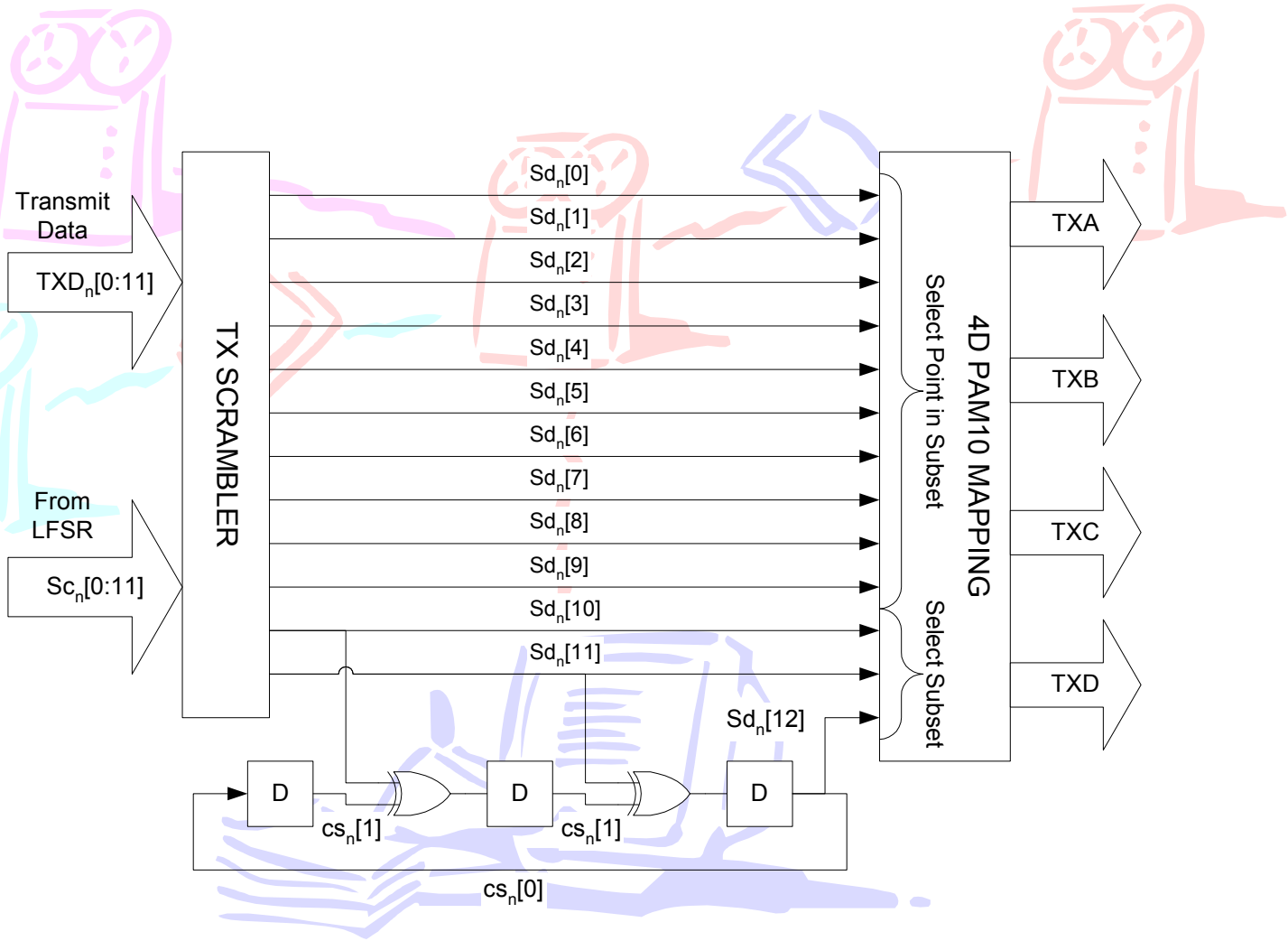
Error Propagation Performance



Coding Description: Encoder



Coding Description: Trellis Diagram