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

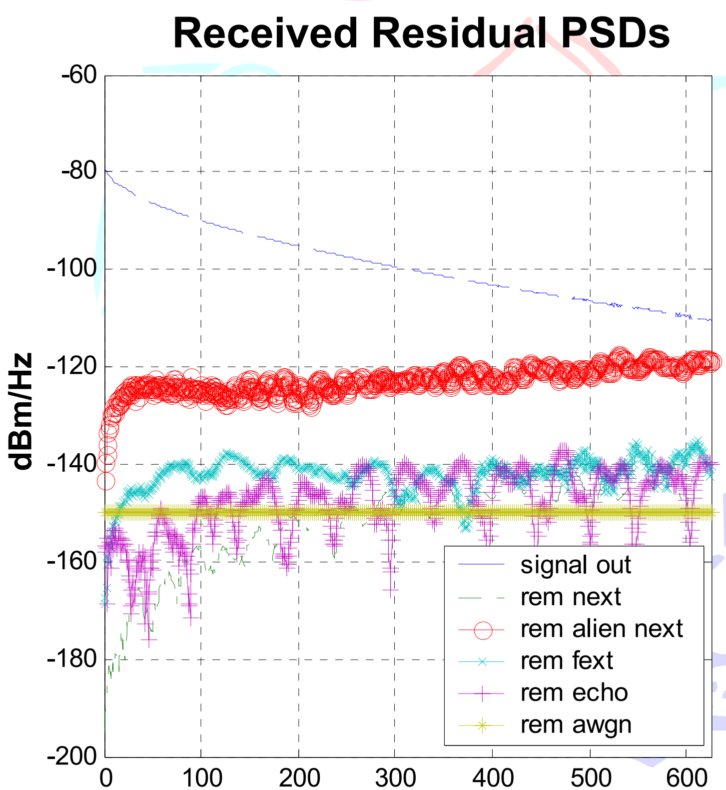
- Channel models
  - 55m Class E Objective:
    - Cabling ad hoc IL, NEXT, FEXT & RL models (http://www.ieee802.org/3/10GBT/public/material/10GBASE-T_Cat6_Model.zip)
    - Class E ad hoc ANEXT model, Class E ISO proposal (15 dB/decade)
  - 100m Class E+ Objective:
    - Class E ad hoc IL, NEXT, FEXT & 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

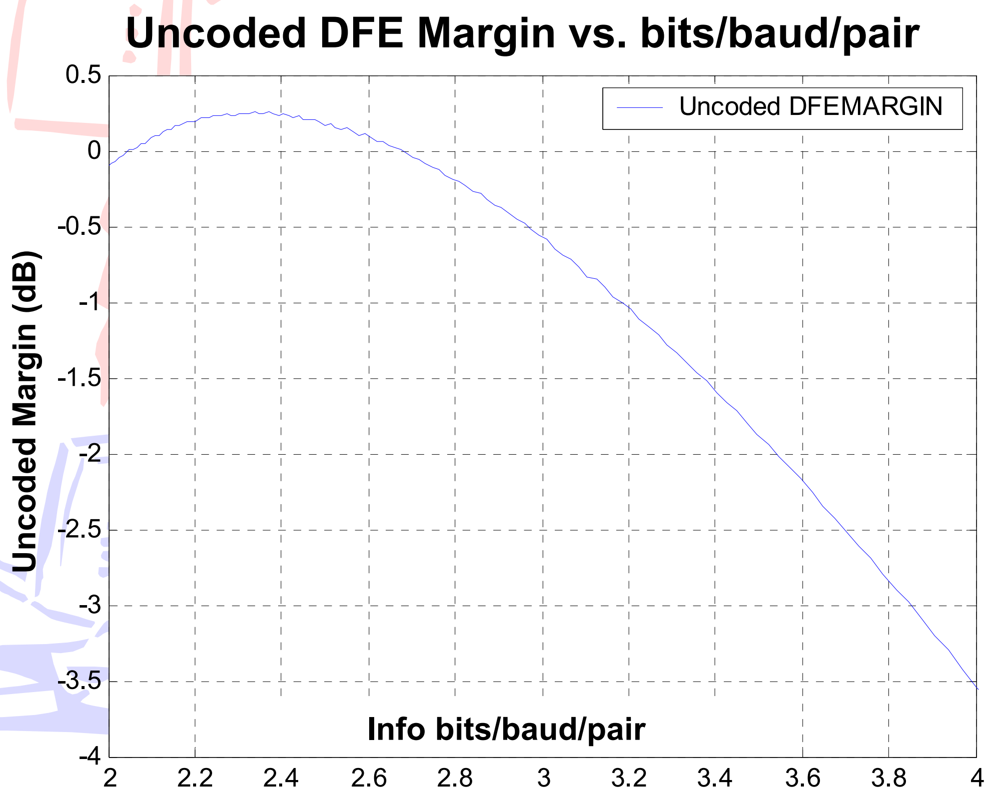
Baud Rate: Info bits/baud (/pair)

- **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

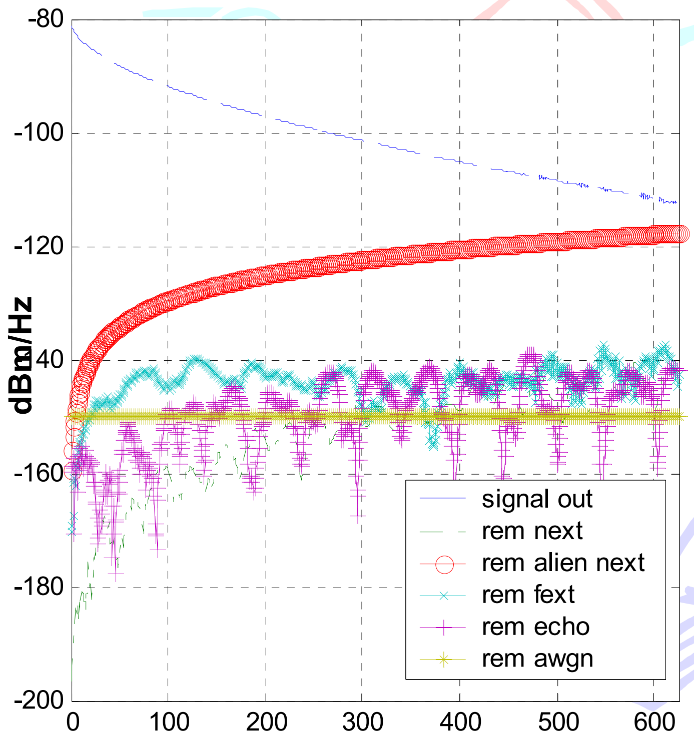




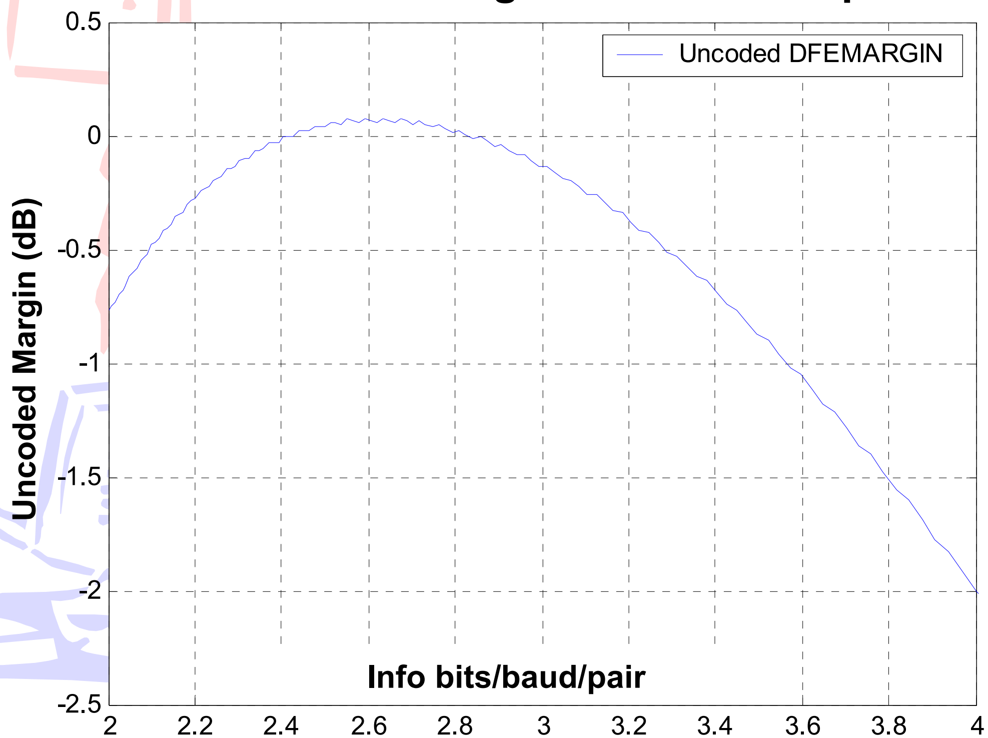
Baud Rate: 55m Class E with 15dB / decade ANEXT model

- 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

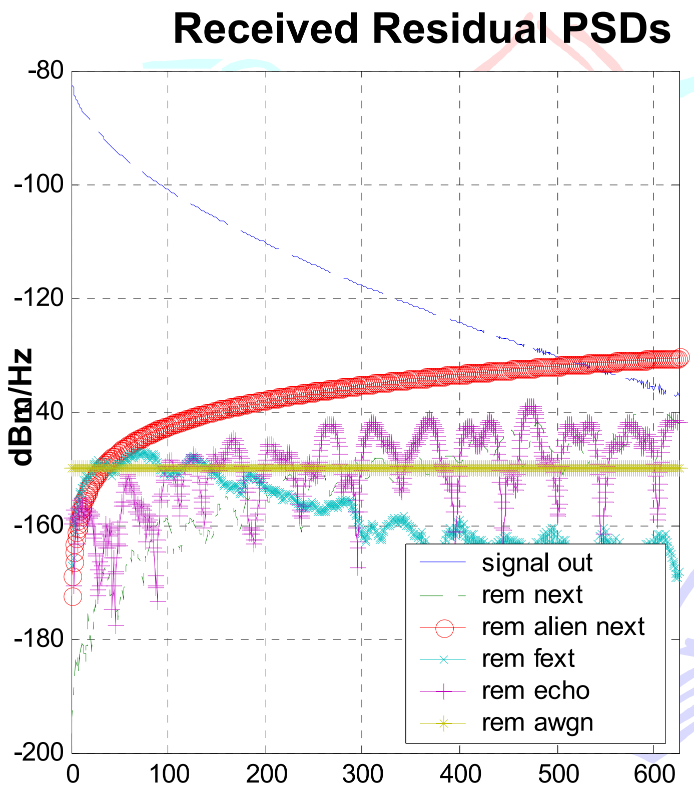


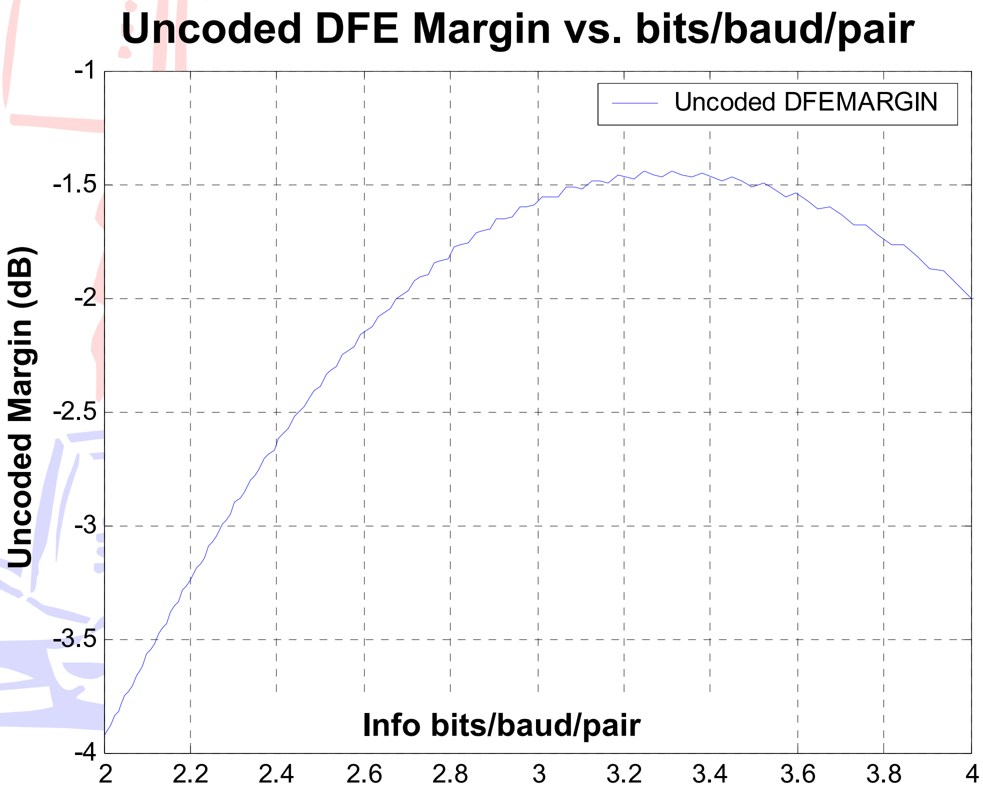
Uncoded DFE Margin vs. bits/baud/pair



Baud Rate: 100m Class E+ Example

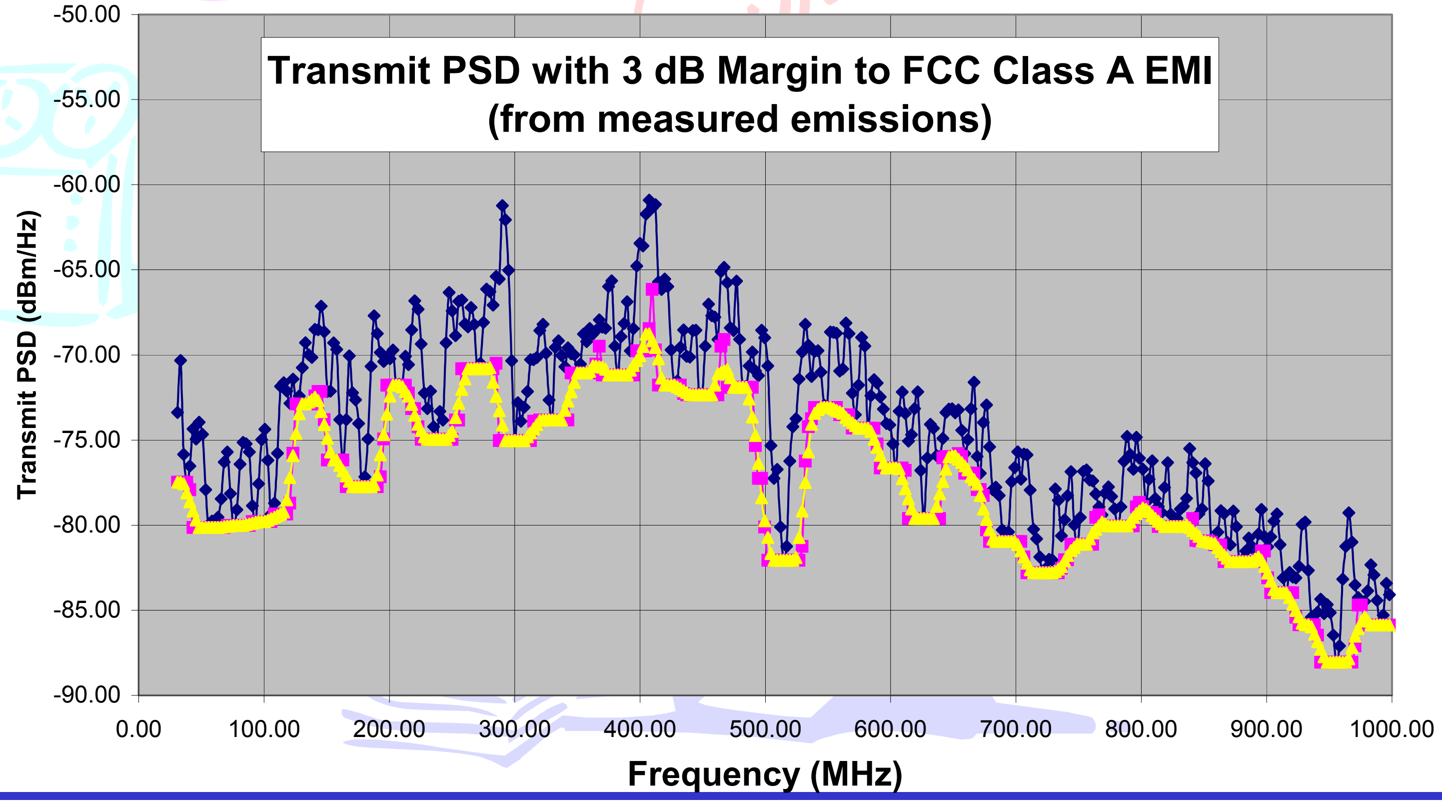
- DFE Margin vs. info bits/baud strongly favors lower baud rates
  - ANEXT Loss = 60-15*log10(f/100) + 2.5dB (limit line adj.)





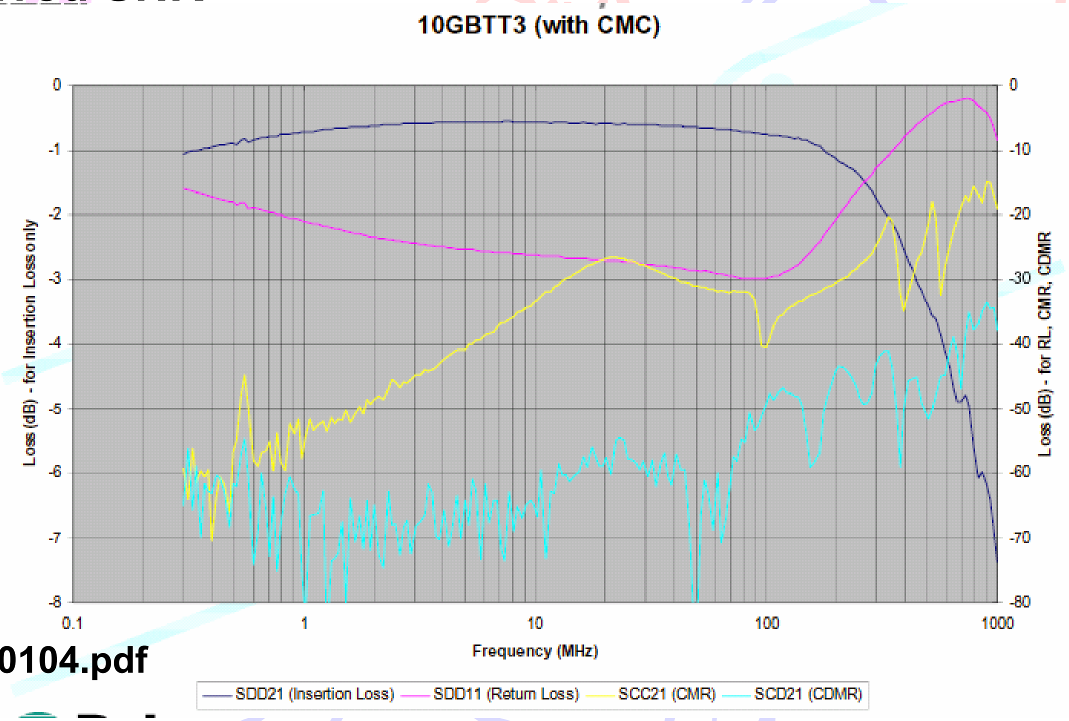
Baud Rate: EMI

- **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

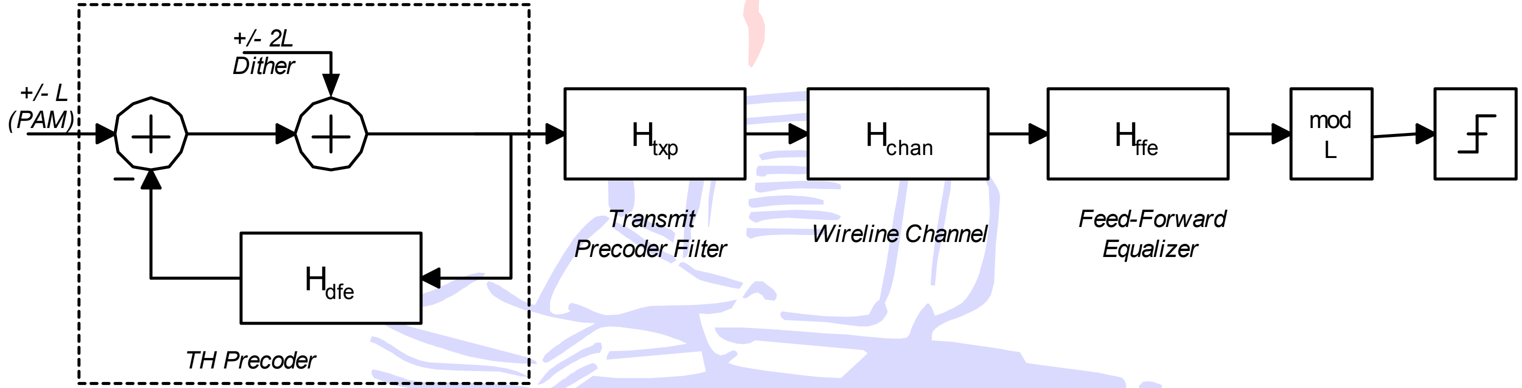
- **Timing jitter degrades SNR as baud rate increases (10*log10(fb1/fb2) relative loss in ADC quant noise PSD)**

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

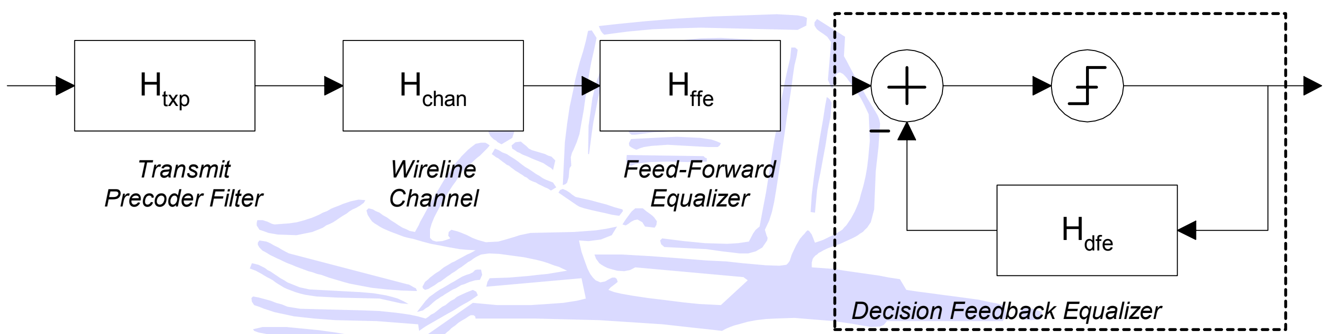
- **Alleviates DFE error propagation in coded systems**
  - **Cost is large amplitude "dither" element added to signal**
    - **Transmit power penalty is small for large # PAM levels**
  - **Problems:**
    - **Dither couples through NEXT, FEXT & Echo paths**
    - **High PAR & extra dynamic range increases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



TH Precoded Channel Equalizer Block Diagram

Equalization: Precoded DFE

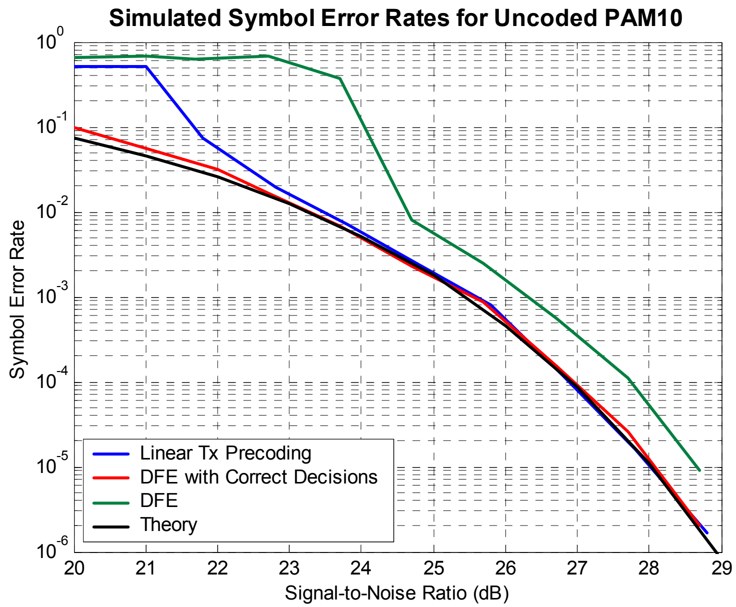
- Adaptive Linear precoding can shape DFE response to minimize error propagation
  - Small transmit power penalty for preemphasis
    - 10GBASE-T not generally transmit power limited
  - Can be combined with other transmit filtering
  - Can be combined with constellation shaping gain
  - Feedforward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

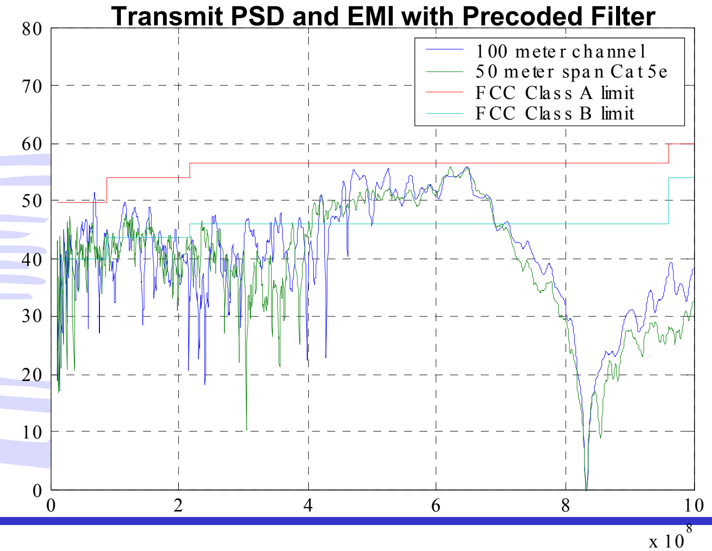


DFE-based Channel Equalizer Block Diagram

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**

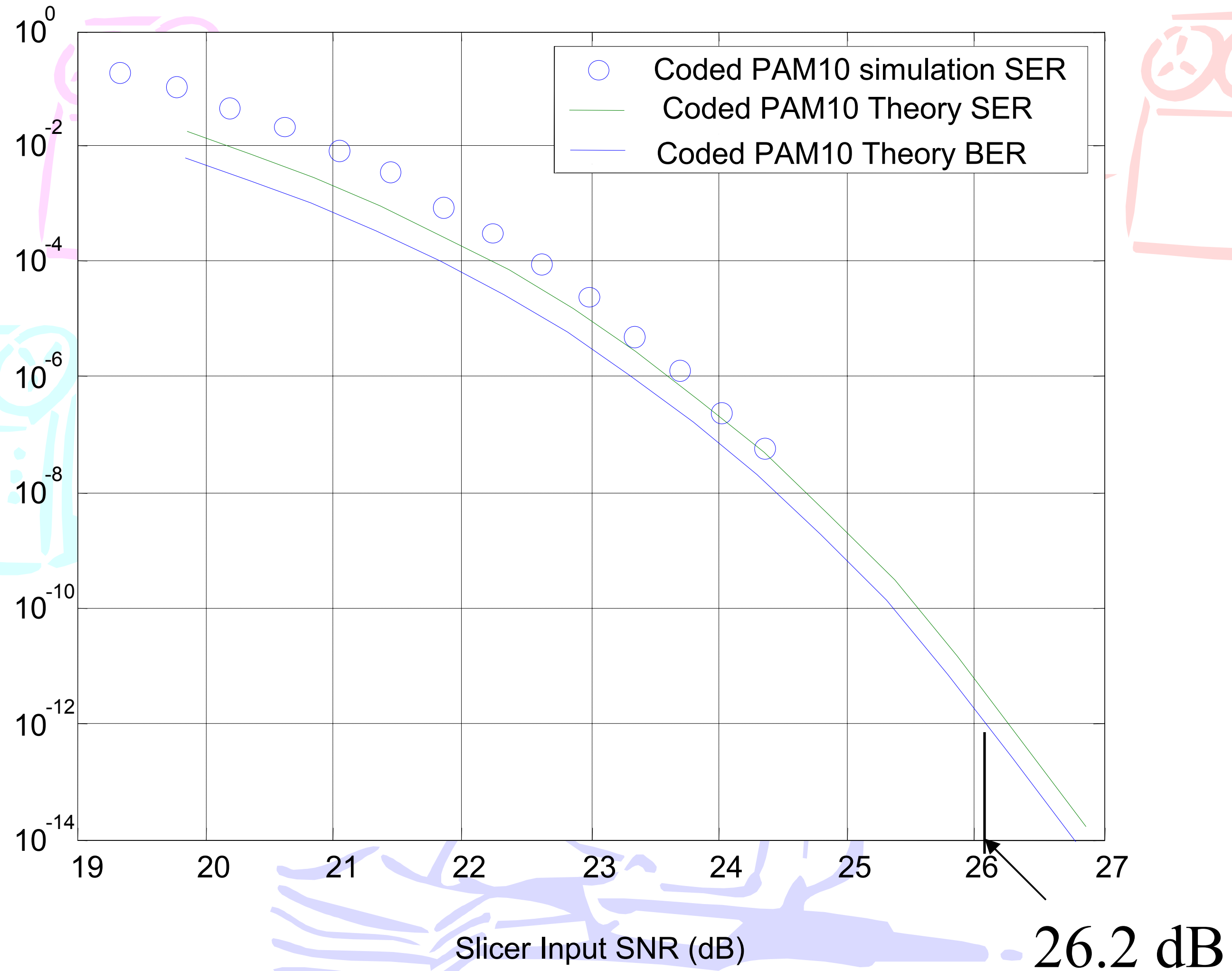
Line Code Proposal: 4D-4W-PAM10

- **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

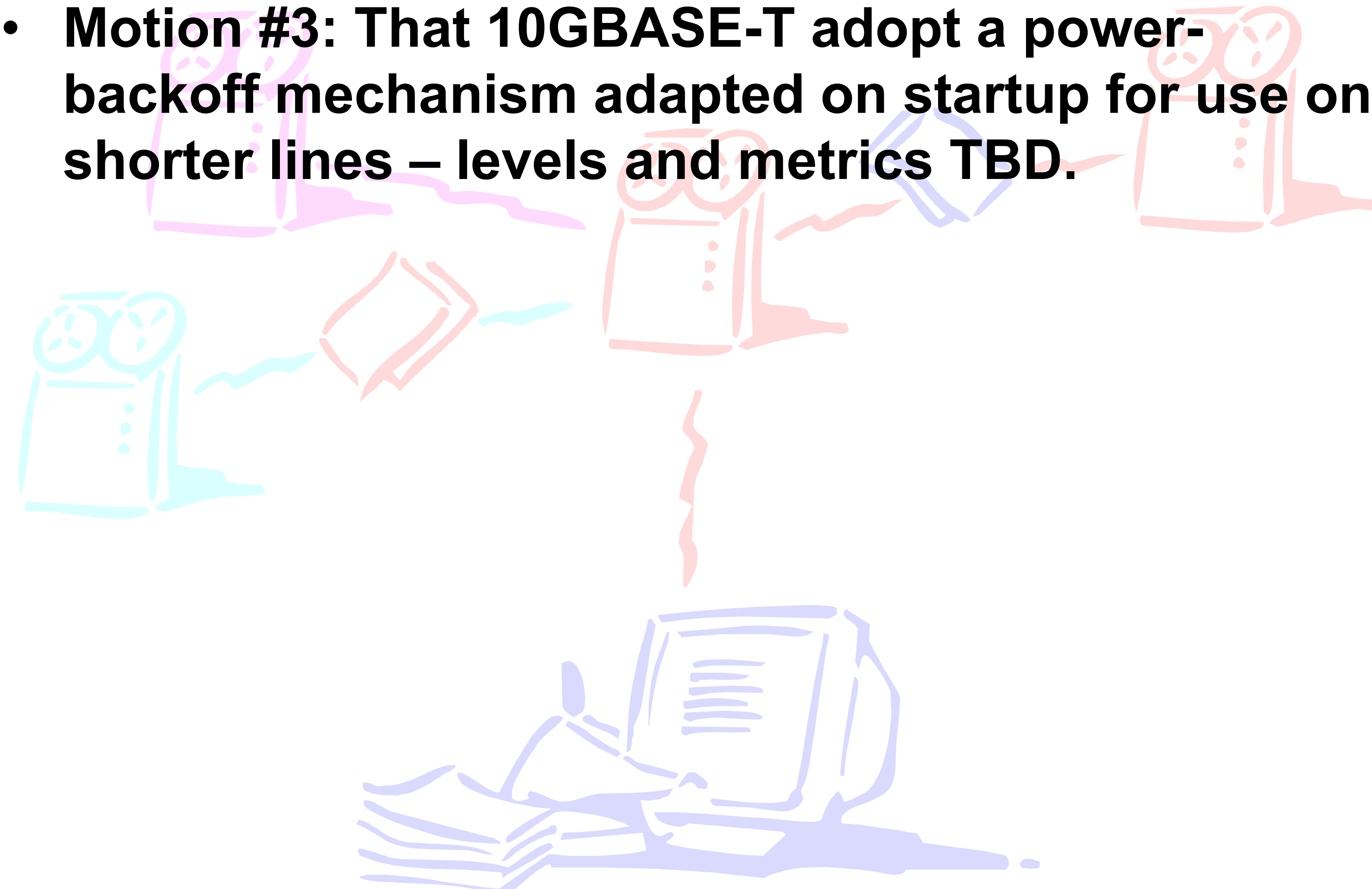
- **Motion #1: That 10GBASE-T baseline baud rates consistent with 3 information bits/baud/pair**

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

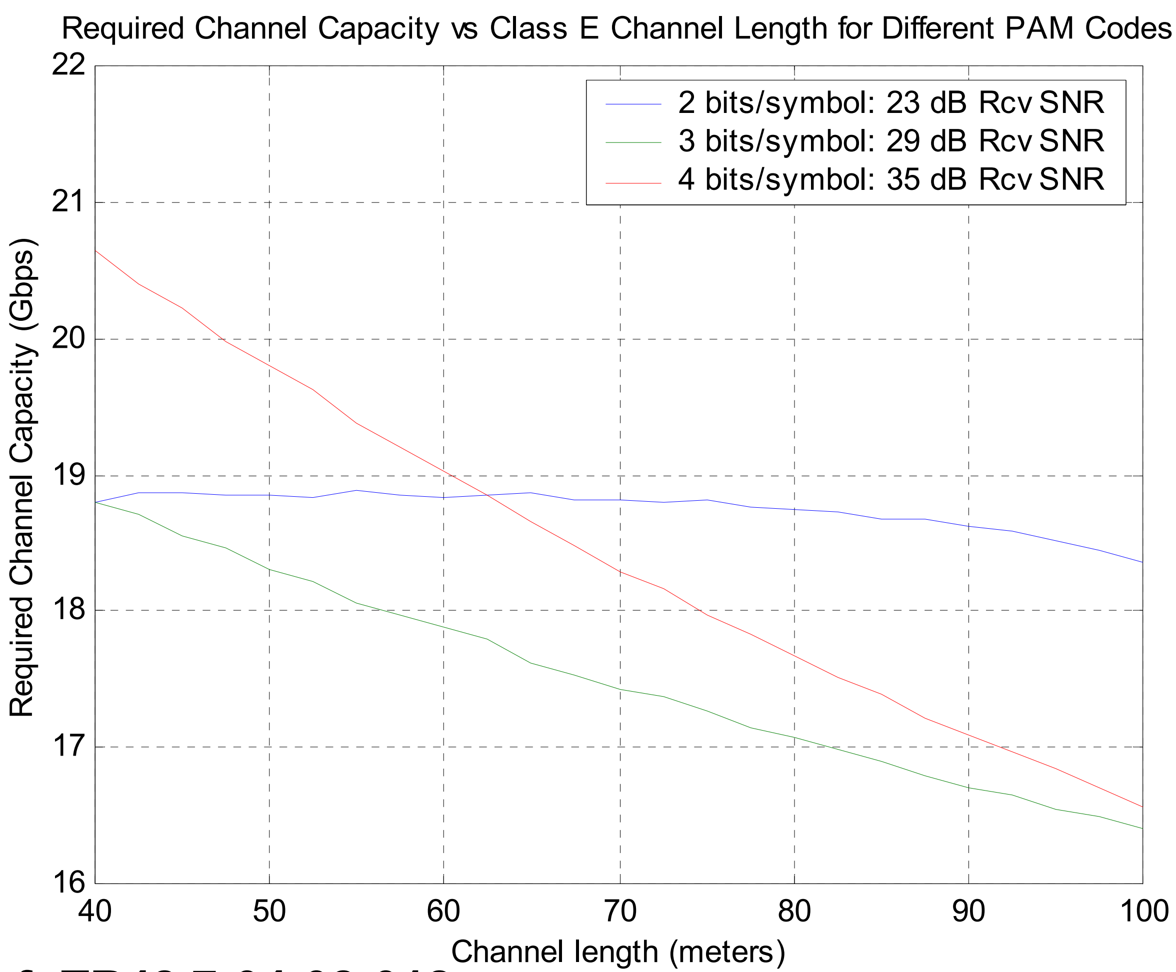
- **Optimum DFE Result:**

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

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

- **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**

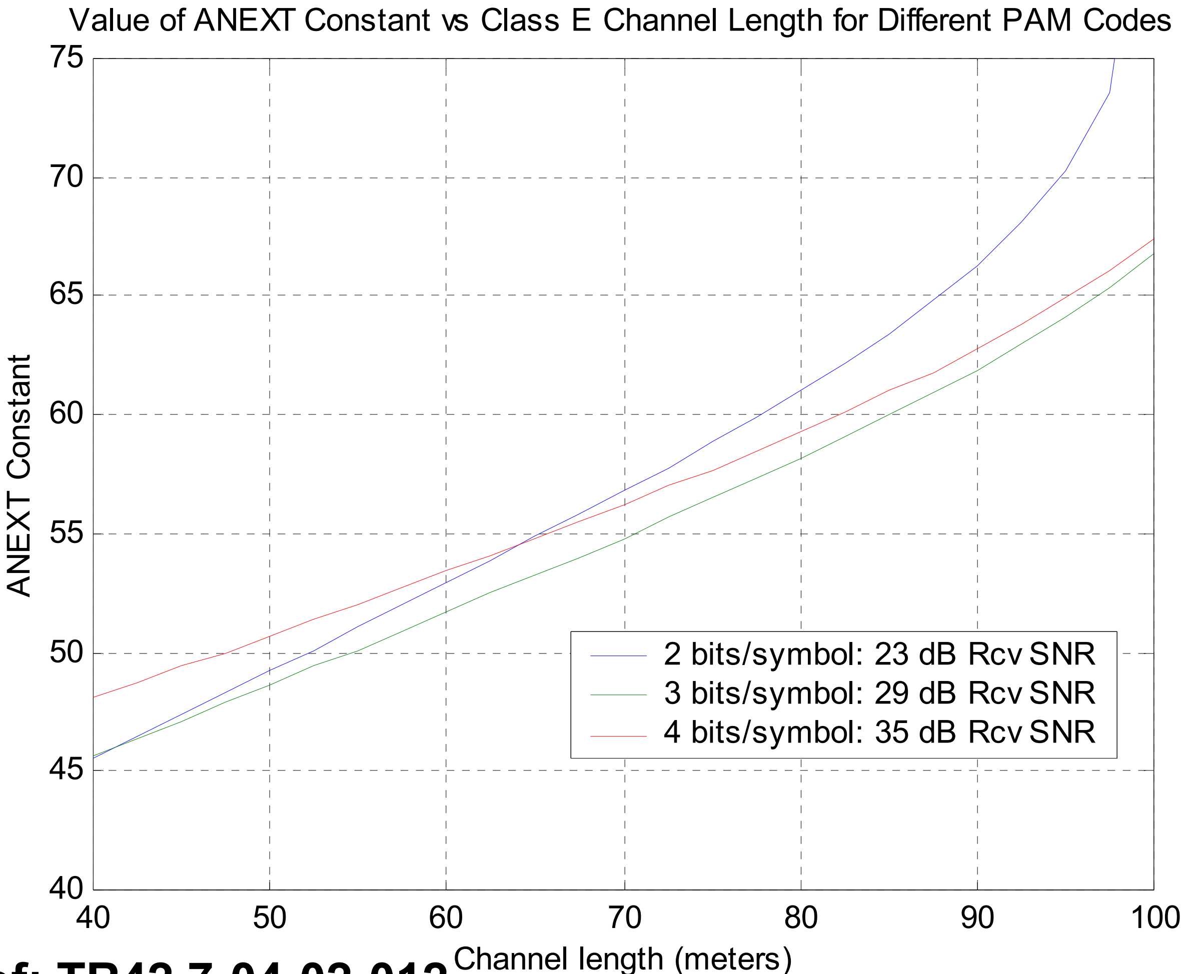
ANEXT Robustness: Variability of Required Channel Capacity with Constant SNR Constraint



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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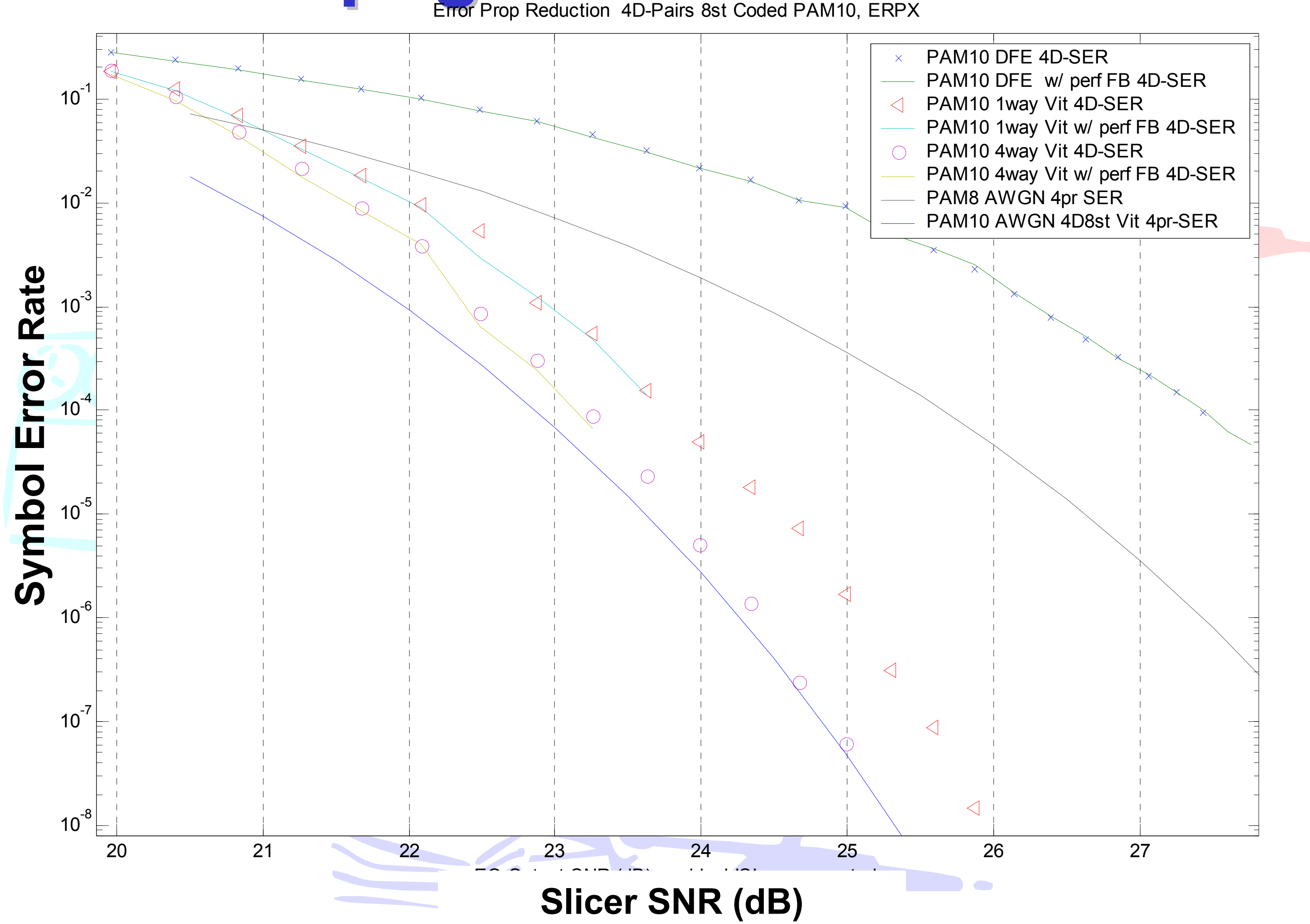
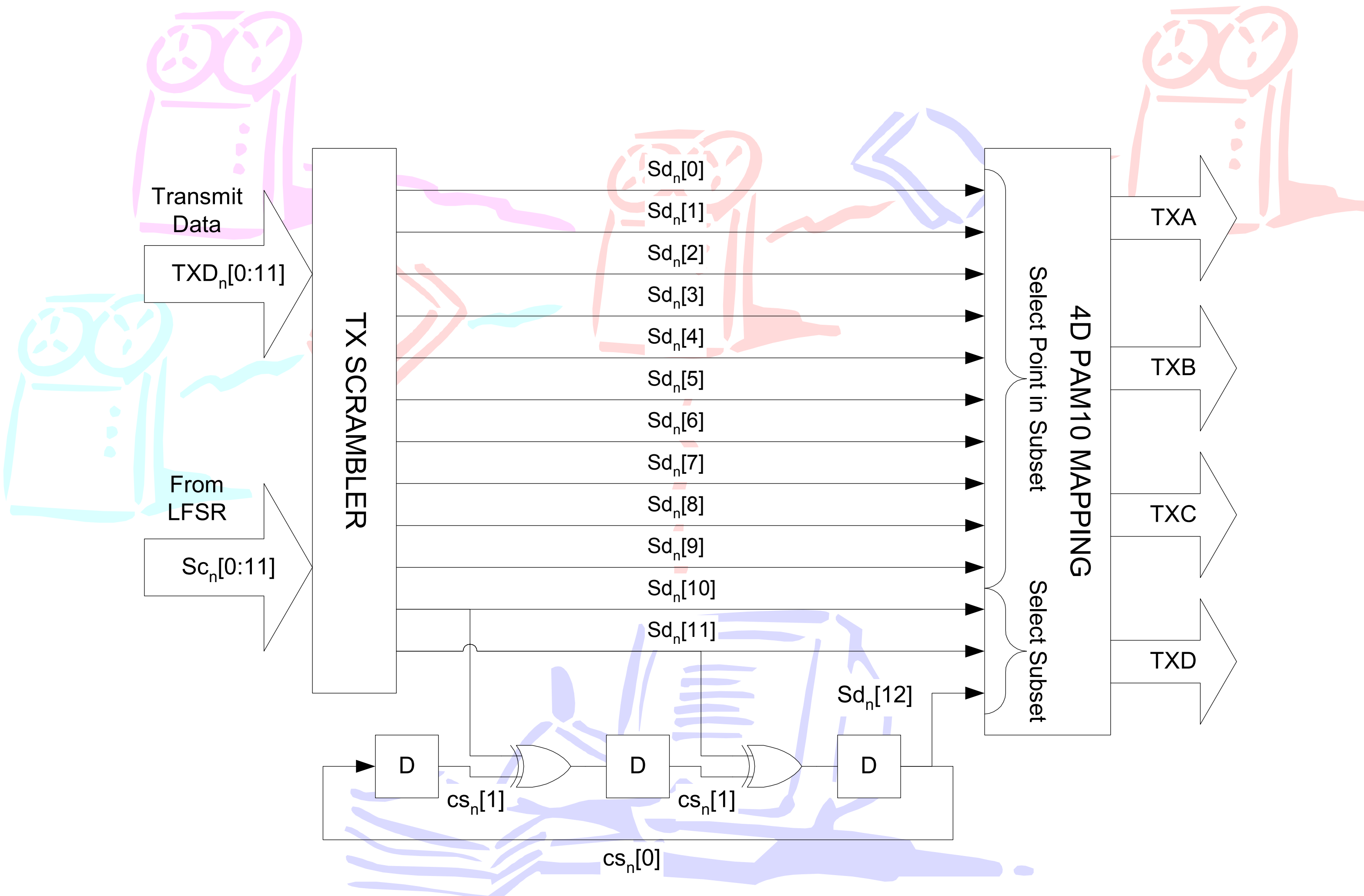
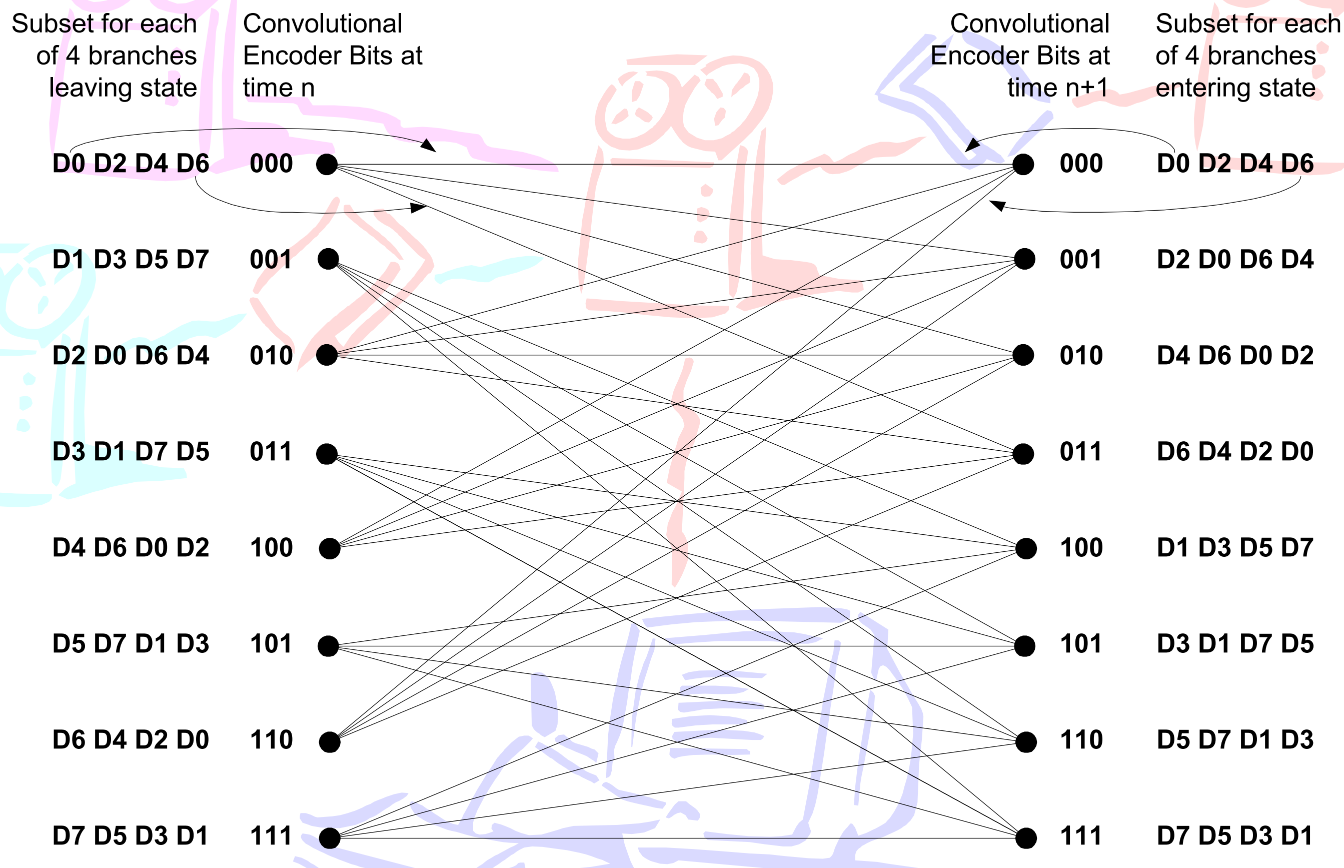
Error Propagation Performance



Coding Description: Encoder

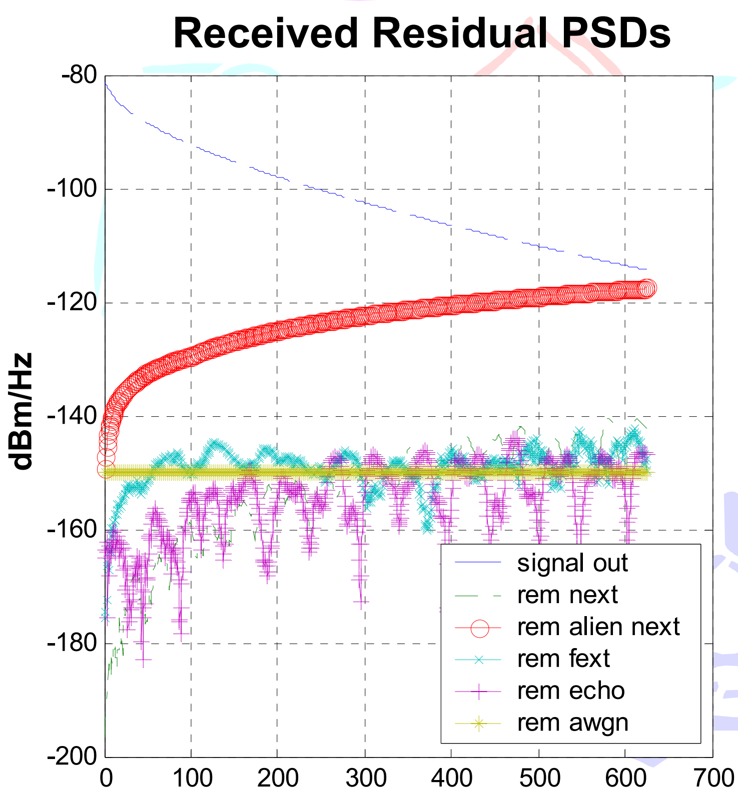


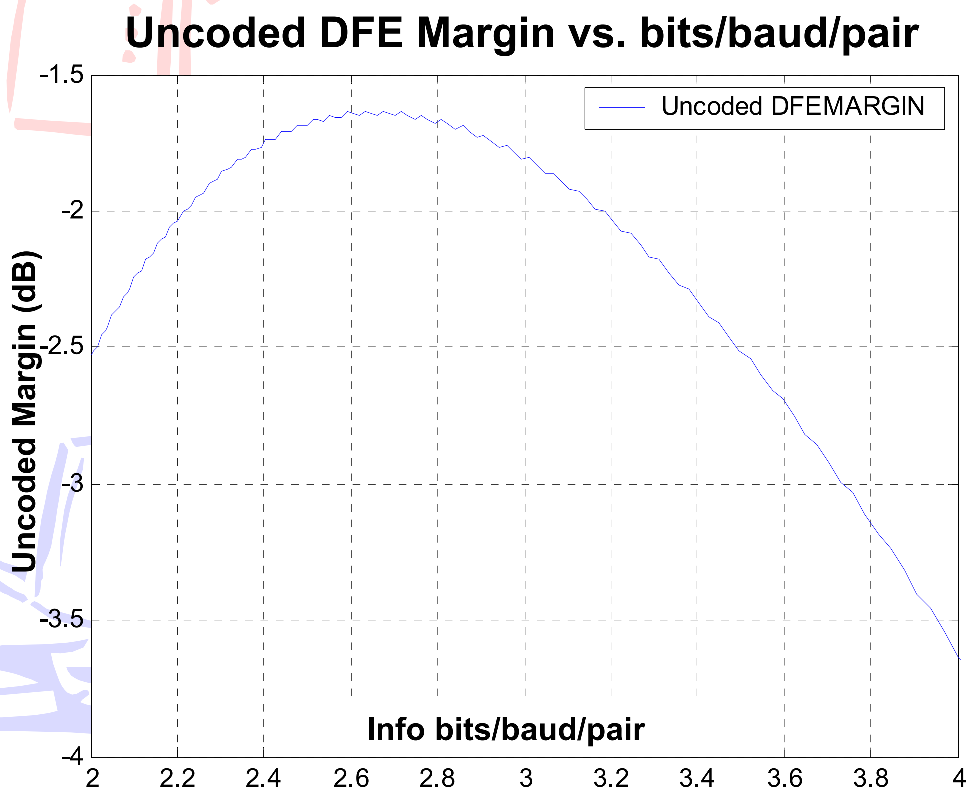
Coding Description: Trellis Diagram



Baud Rate: 55m Class E with split ANEXT model

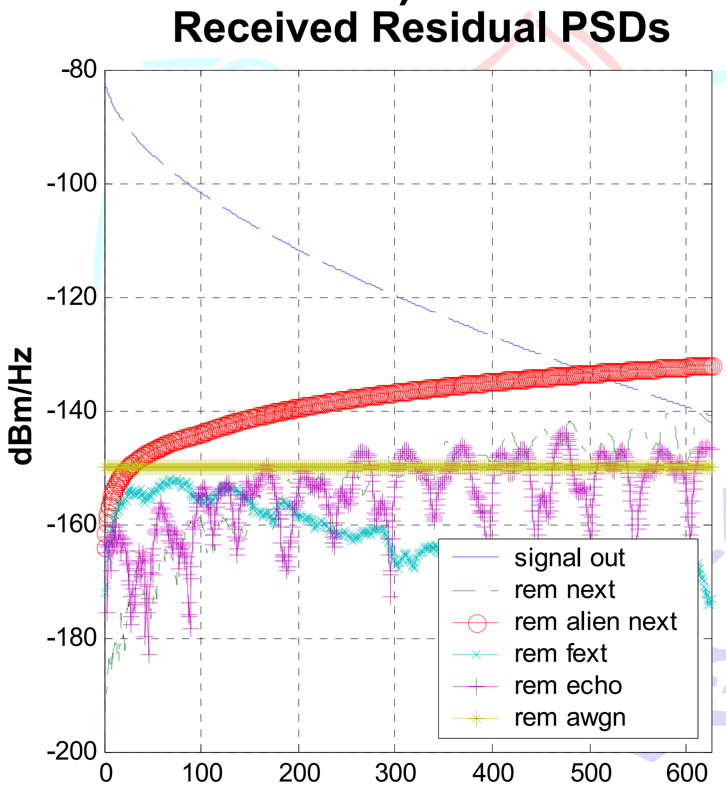
- Optimum shifts towards 3 bits/baud & steepens
- Class E IL
  - ANEXT Loss = 49-X*log10(f/100) (X=15, f>100, X=10, f<=100)

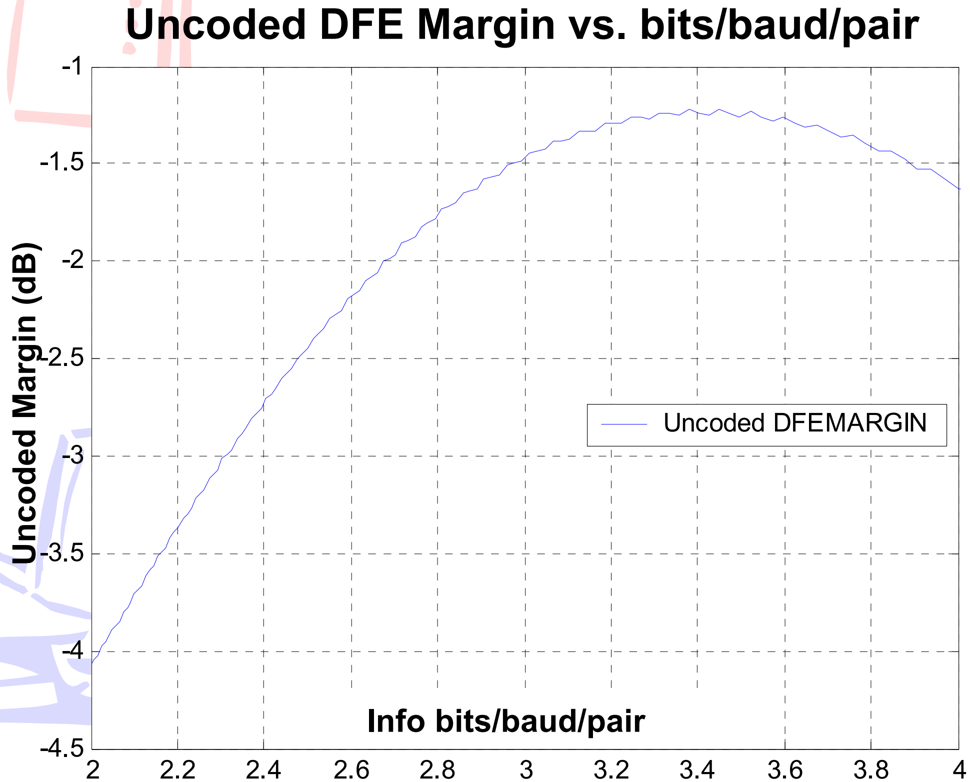




Baud Rate: 100m Class E+ Example

- **DFE Margin vs. info bits/baud strongly favors lower baud rates (Class E IL)**
  - **ANEXT Loss = 64-X*log10(f/100) (X=15, f>100, X=10, f<=100)**

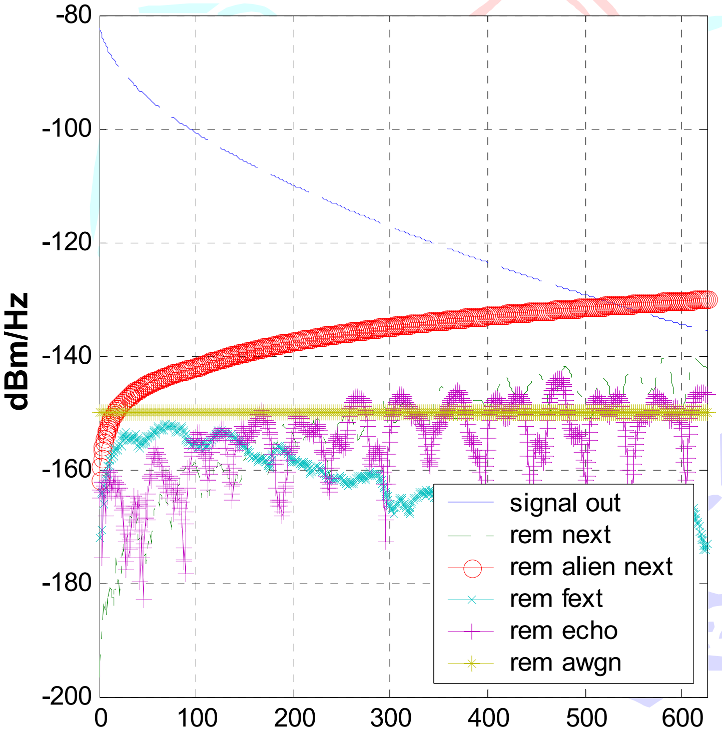




Baud Rate: 100m Class E+ Example

- DFE Margin vs. info bits/baud strongly favors lower baud rates (Class F IL)
  - ANEXT Loss = 62-X*log10(f/100) (X=15, f>100, X=10, f<=100)

Received Residual PSDs



Uncoded DFE Margin vs. bits/baud/pair