AMI Simulation with Error Correction to Enhance BER Performance

10-WP6

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Agenda

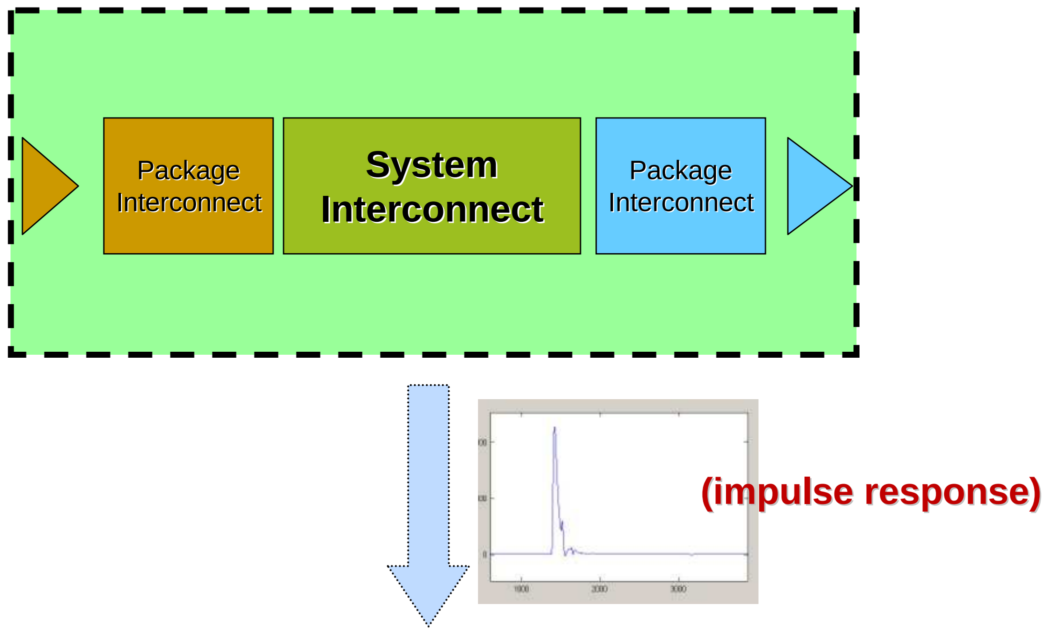
- Overview
- Serial link simulation process
- IBIS-AMI modeling
- Error correction theory and methods
- Prediction of BER improvement with FEC

Overview

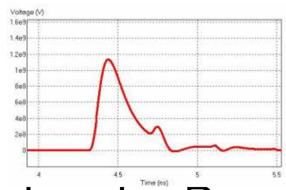
- IBIS 5.0 introduced Algorithmic Modeling Interface (AMI) for modeling advanced SerDes EQs like DFE
- DFE model operation can provide key insight into burst errors that can degrade BER
- Error correction methods have historically been used for optical links
- These methods can also be applied to electrical serial link interfaces to enhance BER
- This paper examines FEC application to serial link simulation, leveraging information from AMI simulations using adaptive DFE models

Serial Link Simulation Process

- Analog channel is exercised in Spice to produce an impulse response
- Impulse response is convolved with the bit stream to produce raw waveforms



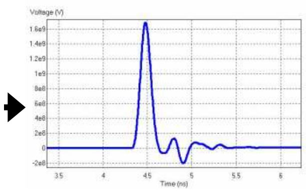
APIs in IBIS-AMI Modeling



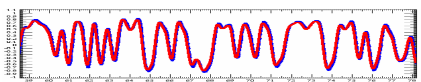
Impulse Response

Model input parameters

AMI_Init
-Initialize filter
- Setup Data Structures

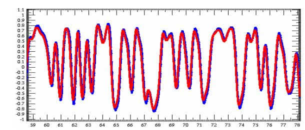


Modified Impulse Response

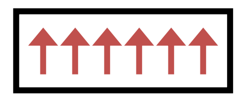


Continuous waveform

AMI_GetWave
-Waveform Processing
-Clock and Data Recovery



Equalized waveform

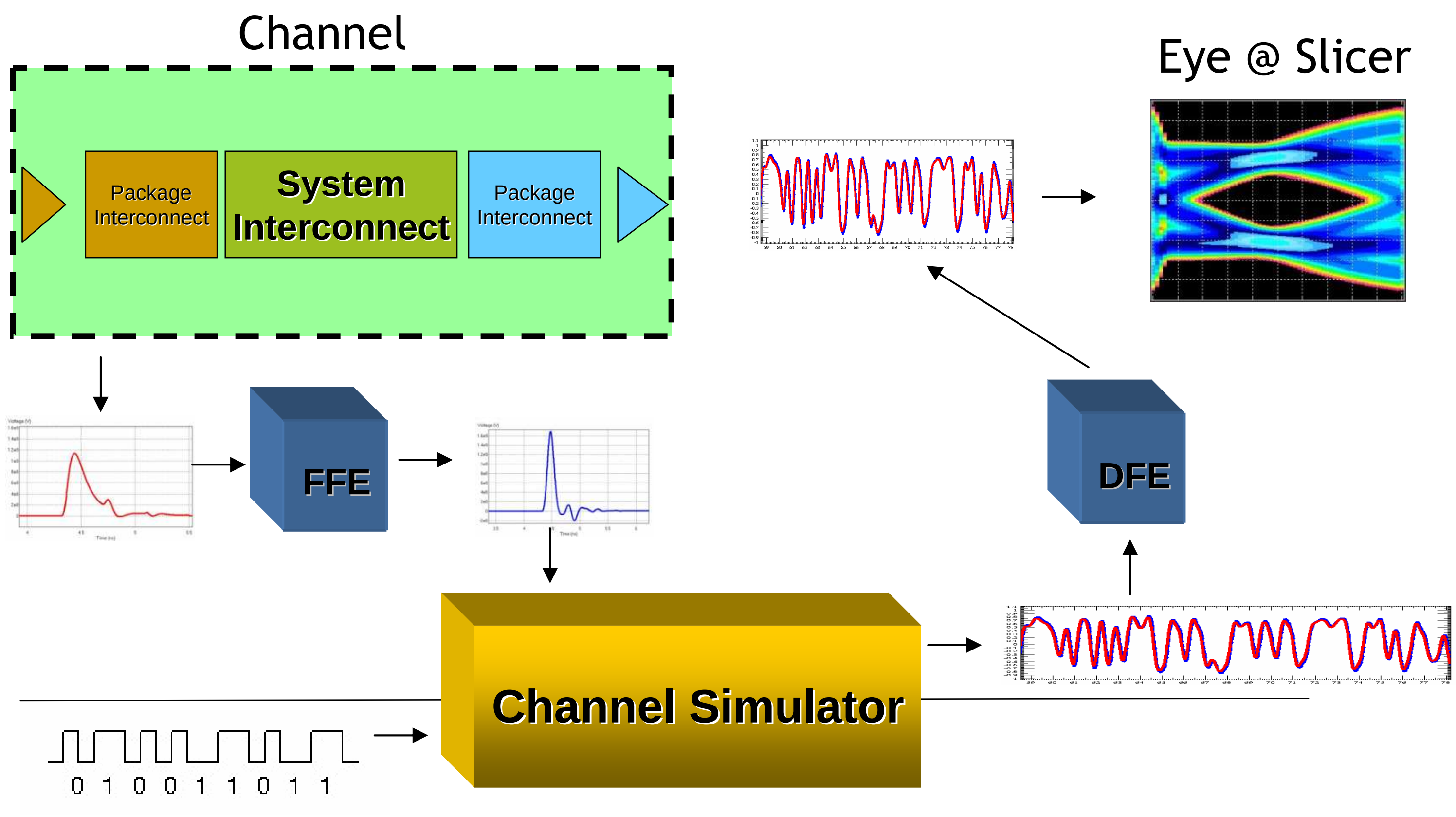


Clock tics

- AMI_Init for “one-time adaptive EQs
- AMI_GetWave for “real-time” adaptive EQs

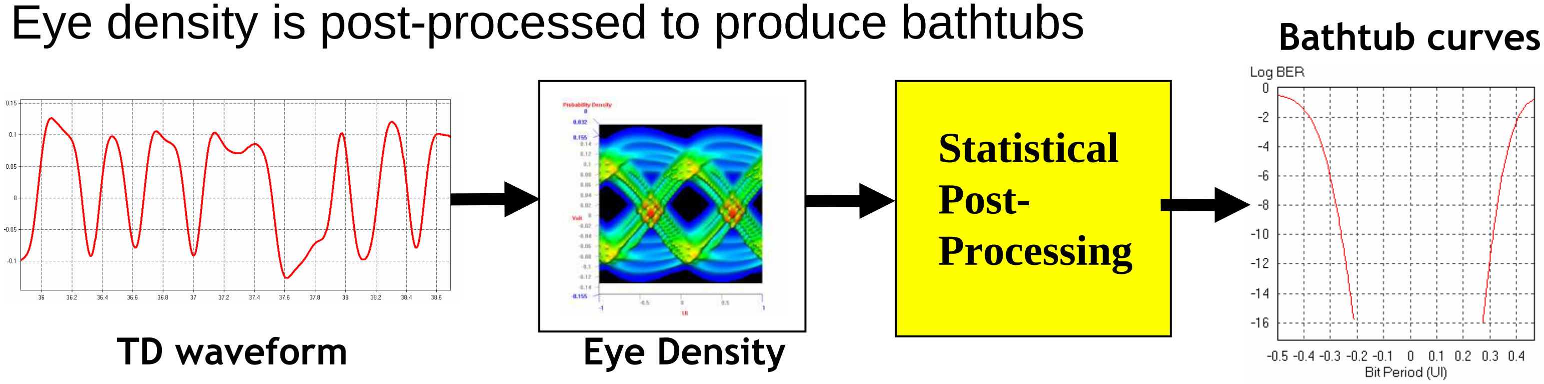
AMI_Close
-Free memory etc

IBIS-AMI in Channel Simulation



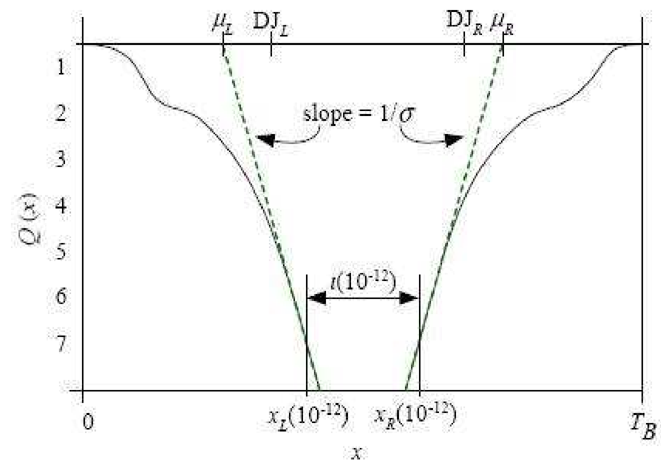
Bathtub Curve Generation

- Waveforms are used to determine the eye density
- Eye density is post-processed to produce bathtubs



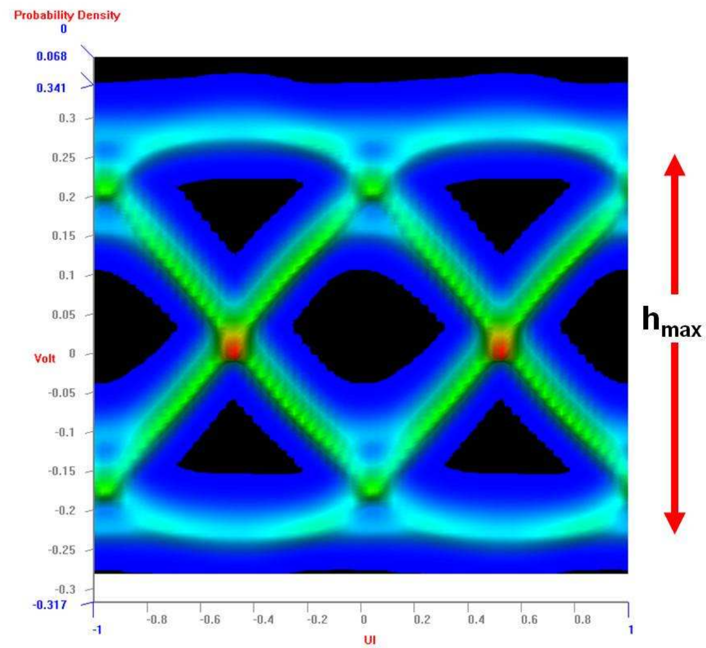
Dual Dirac Method is used for statistical post-processing:

- ➢Extrapolated “cumulative eye distribution” at center
- ➢Based on Gaussian tail extrapolation
- ➢Intersection is proportional to Dj
- ➢Slope represents Rj



Weighted Eye

- Metric to quantify the sparseness of the eye distribution
- Sparser eye is better BER
- “hmax” is the eye height at the outer envelope, used for normalization
- Excellent means to quantify the effect of equalization, as well as the effect of the various components that comprise the channel



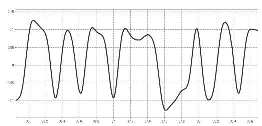
$$\text{Weighted\_eye} = \sum h(y)\,p(y)$$

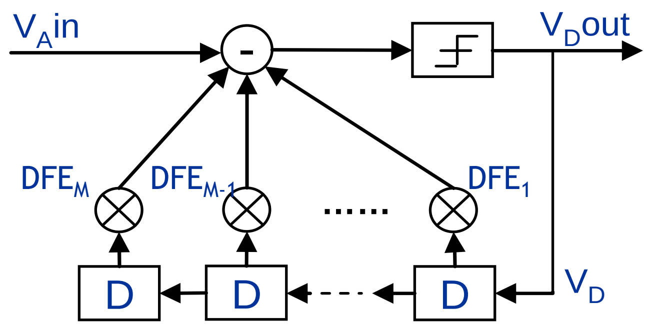
h(y) - eye height
p(y) - probability

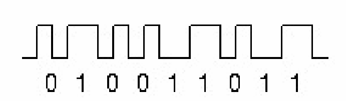
Error Mechanism in High Speed Serial Link

High speed serial links have a mixed error mechanism, random and burst errors.

- DFE can introduce burst errors due to the feedback mechanism







$$V_D out(t_0) = sign(V_A in(t_0) - DFE_1 \cdot V_D(t_{-1}) - DFE_2 \cdot V_D(t_{-2}) - \ldots - DFE_M \cdot V_D(t_{-M}))$$

$$sign(x) = \begin{cases} 1, x \geq 0 \\ 0, x < 0 \end{cases}$$

- Once errors occur, they change the output voltage and thus impact the judgments of the equalized bits that follow. A “domino effect” can result

Error Propagation Calculation Methods (1)

- Error propagation is modeled by probability calculation[3]:

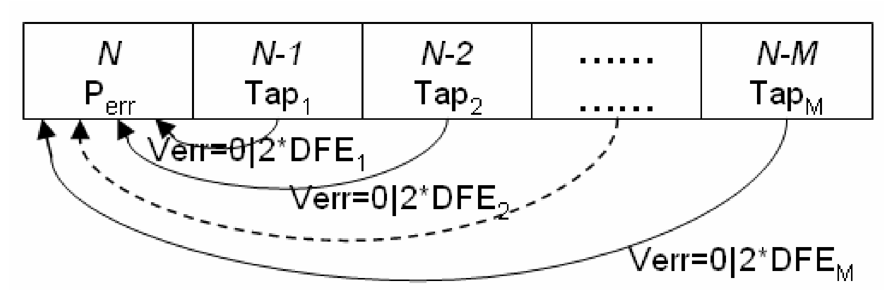
$$BER=\sum_{i=1}^{rll_{\max}}\sum_{allE} p(rll=i,E)\cdot W(E)\cdot p_1\cdot(1-p_1)^{n-rll_{\max}-i}$$

- p_1 → random error probability
- $W(E)$ → the probability that i bits in error among a n bit block
- E → all the combinations of the error pattern when error propagation length is i
- rll → maximum error propagation length

- A critical aspect in estimating BER with error propagation is to calculate the probabilities of erroneous bits due to different propagation lengths: $p(rll=1:rll_{\max})$

Error Propagation Calculation Methods (2)

- The probabilities are gleaned from the raw voltage bathtub curves, by calculating the probabilities of error pattern E



- The voltage offset from a feedback loop is represented by

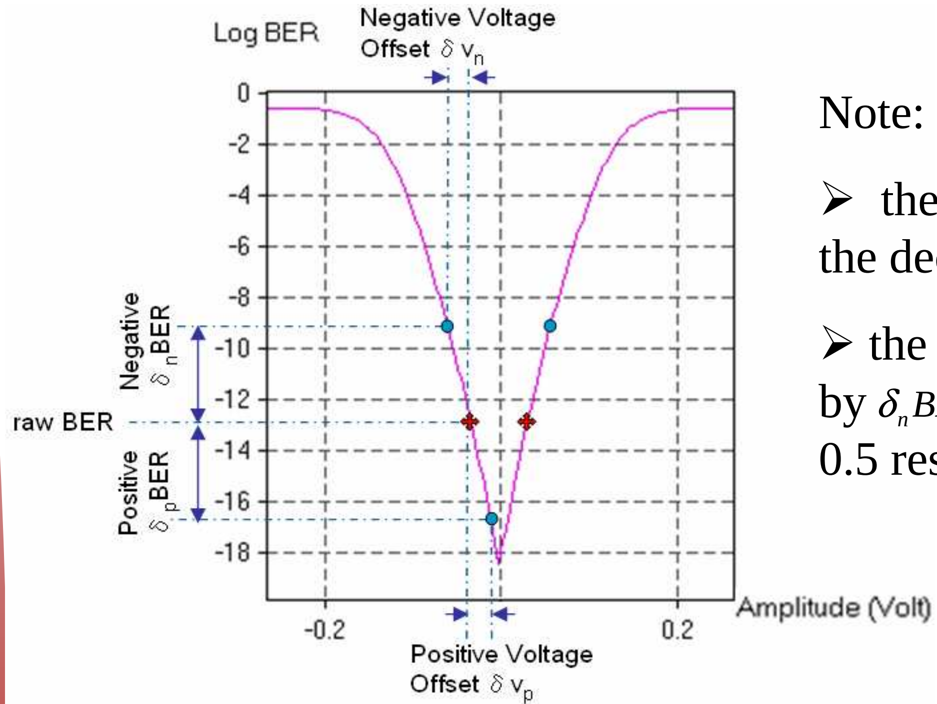
$$[V_{sum\_err_j} \mid p_j] = \sum_{i=1}^{M} Verr(i)$$

When ith bit error, $Verr(i) = 2 \cdot DFE(i)$ else $Verr(i) = 0$

$$p_j = \prod_{j=1}^{2^M} [p_i \mid (1 - p_i)]$$ When ith bit error using p_i else $(1 - p_i)$

Error Propagation Calculation Methods (3)

- A certain voltage offset due to wrong judgment can be estimated and BER due to this offset can be obtained directly from the bathtub curve.



Note:

➢ the diamond markers are located at the decision slicer levels

➢ the raw BER degrades or improves by $\delta_n BER$ or $\delta_p BER$ at the probability of 0.5 respectively.

- The BER due to error propagation should be the mean value of the BERs taken from the left and right bathtub curves.

Enhancing BER with Error Correction (1)

Assuming:

Err_DFE is the probability vector of a burst length, and contains rll probability values

Err_rand is the random error rate

N is the packet length

The total BER including the error propagation is calculated by

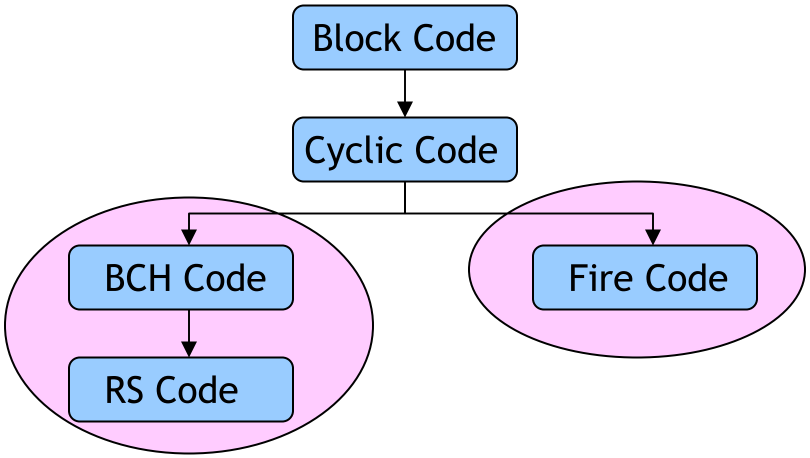
$$BER_{total} = \frac{1}{N} \sum_{allP} \sum_{i=0}^{H} \underline{P_{pkt}(i+1 \mid i)}$$

- a function of the vector Err_DFE.
- The $(i+1)th$ burst error rate in a packet under the condition that the ith burst error occurs in the same packet
- When i equals to 0, P_{pkt} is simply the probability vector of the 1st burst error in the packet.

- ➢ Note that H is a customized number that is determined by Err_DFE , and the value of H should be picked by the user.
- ➢ Different probability levels can be subtracted from BER_{total} to get the enhanced BER values.

Enhancing BER with Error Correction (2)

Common error correction codes: block codes and convolution codes

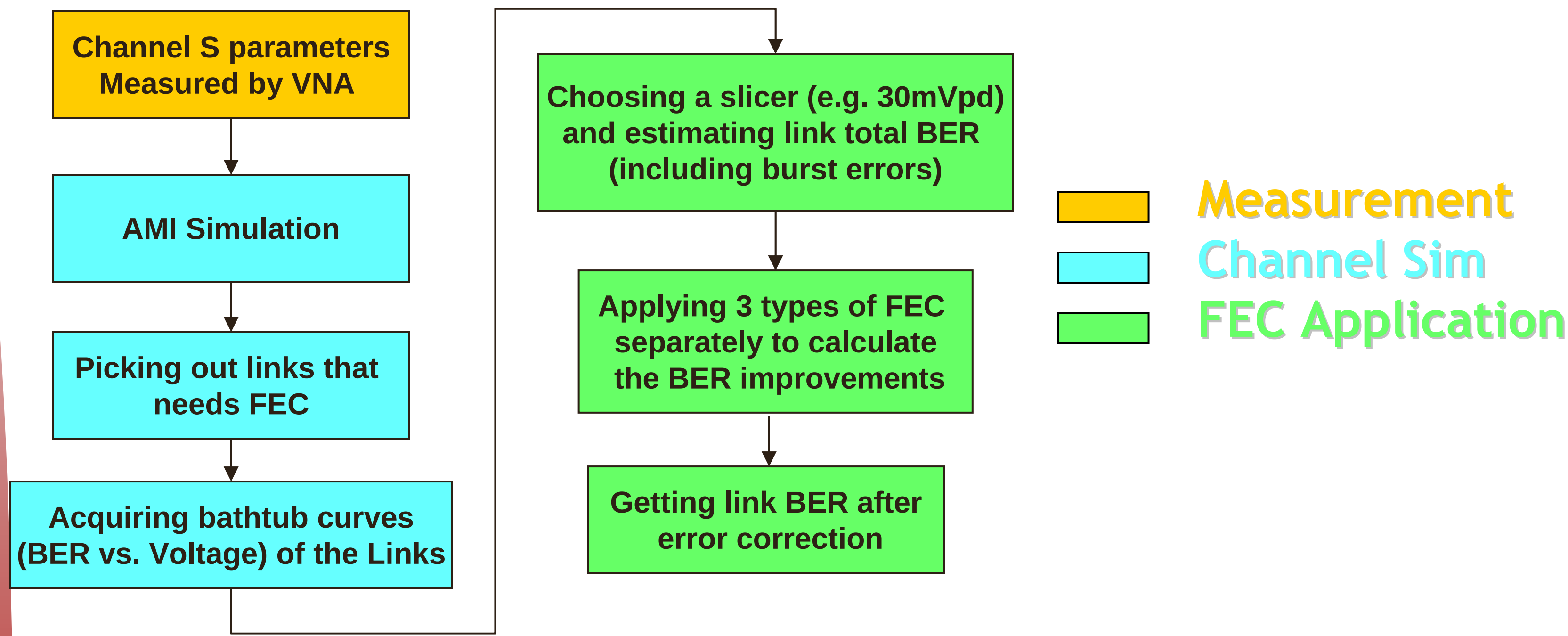


In the following experiment, 3 kinds of block codes are interested:

1. BCH codes that deal with random errors
2. Fire codes that deal with single burst errors (burst length with 7 and 11 bits are investigated separately)
3. RS code that can deal with multiple burst errors (8-symbol errors are considered)

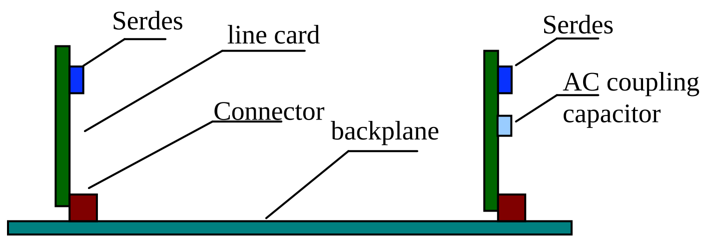
AMI Simulation Flow Incorporated with FEC

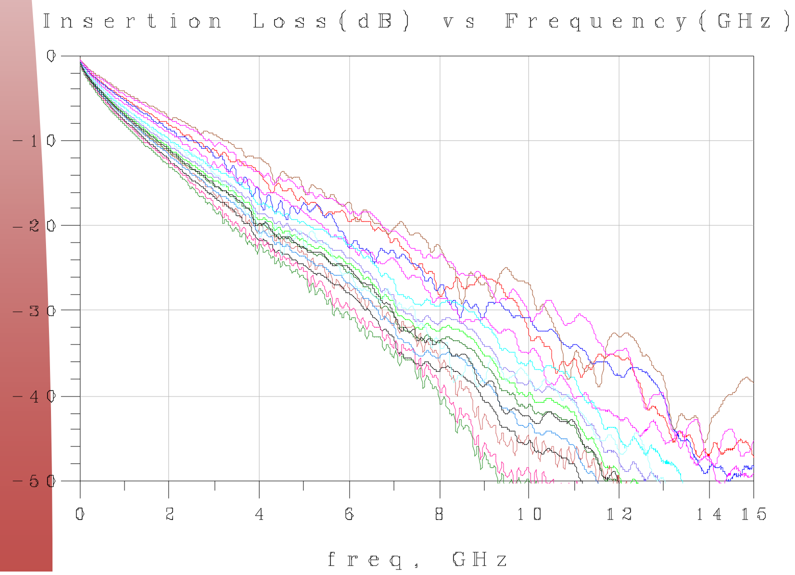
The following flow was utilized in the case study:

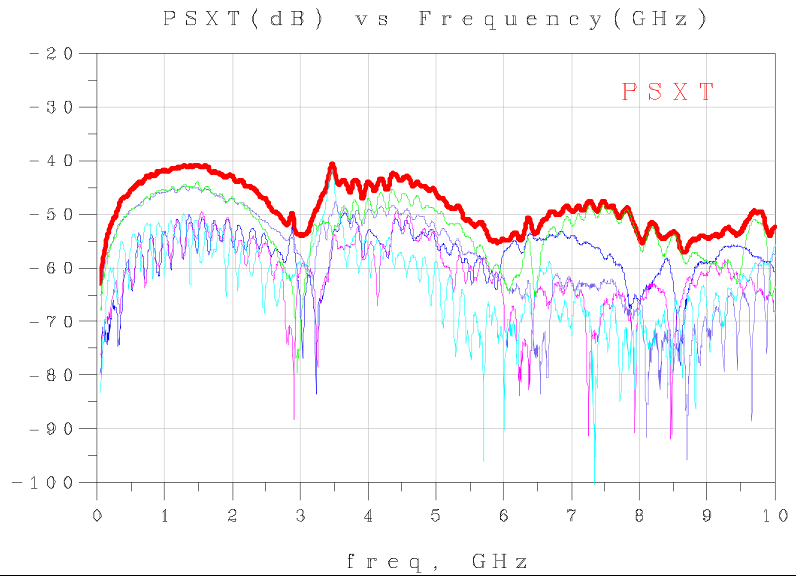


System Configuration

- SerDes IP: HSS12, Worst case, 3-tap emphasis and 5-tap DFE
- SerDes package: User defined
- Data Rate: 10.3125Gbps
- Coding: PRBS23+64B/66B
- Target BER: 1e-17
- Simulation bit number: 2000000
- Channel: Experimental backplane system, with 5 crosstalk channels

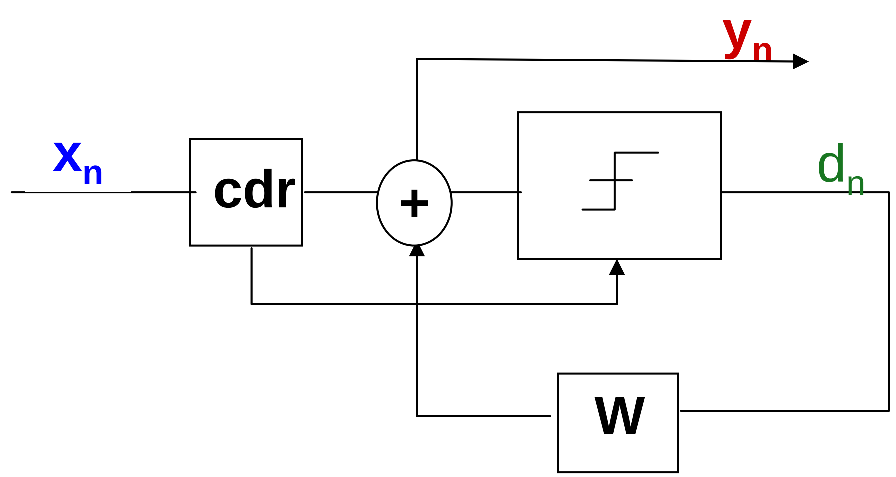






IBM HSS12 Rx AMI Model

- Multi-phase, 5-tap Decision Feedback Equalizer (DFE)
- Integrated CDR (clock/data recovery)
- Real time, adaptive equalization
- Signal processing of time domain waveforms

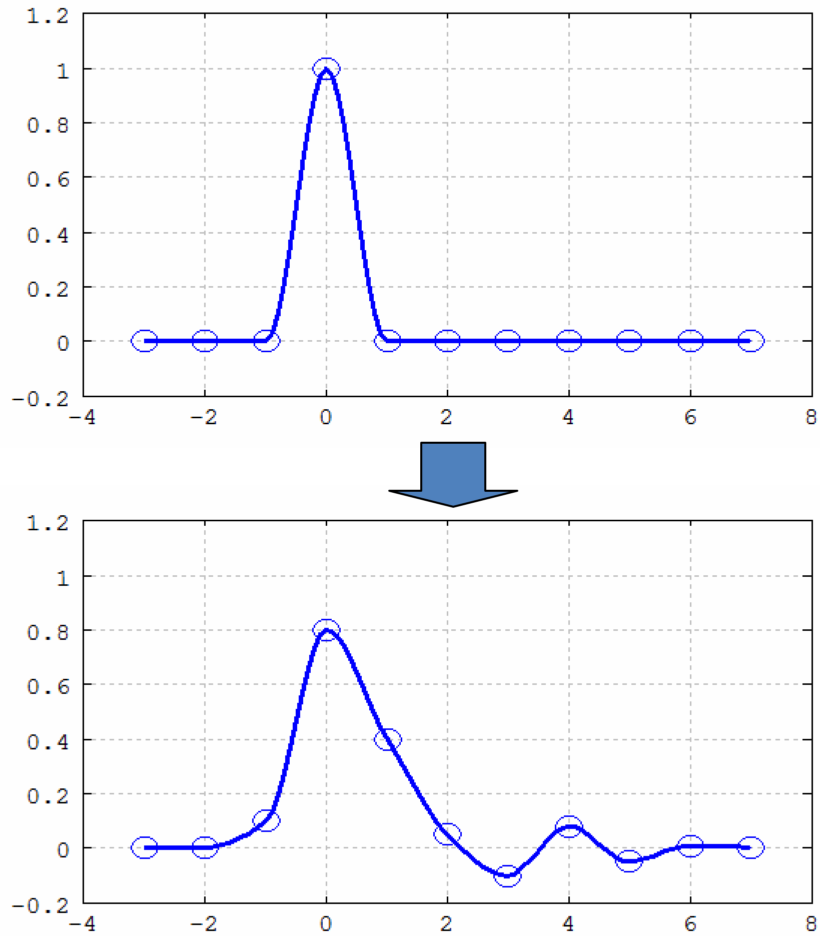


$y_n = x_n + \Sigma\, w_i * d_i$

- y_n - output
- x_n - input
- d_i - previous 'i_{th}' decision
- w_i - i_{th} tap weight

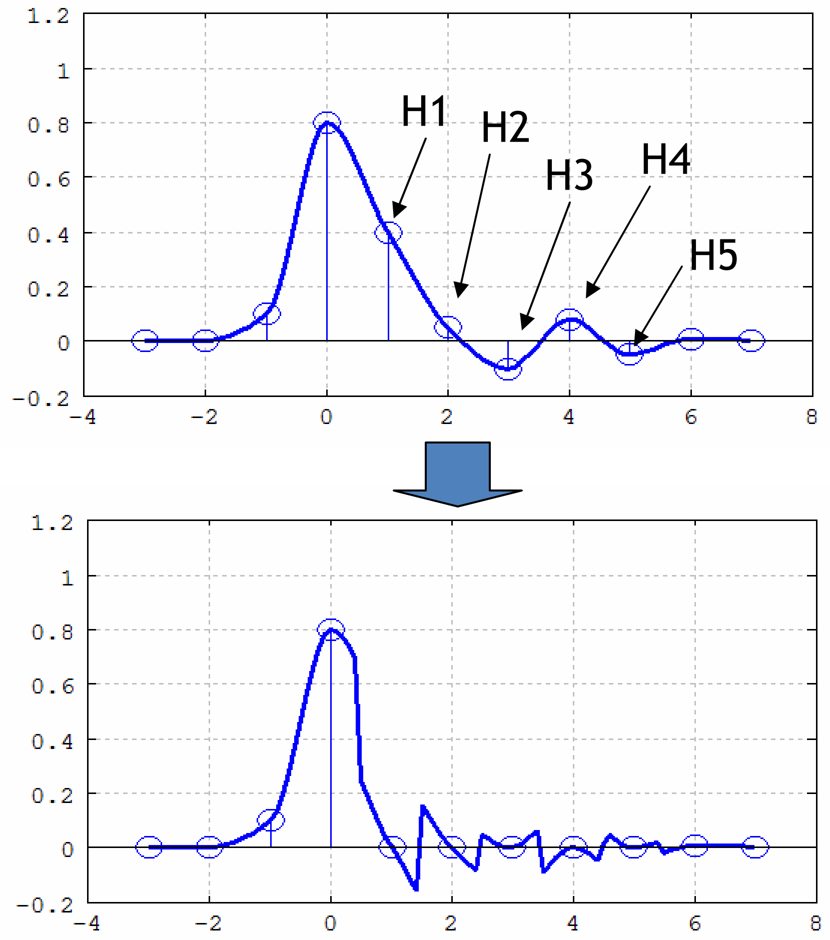
Decision Feedback Equalization (1)

- Inter-Symbol Interference (ISI) introduced by channel
- Each bit's signal value influences the following few bits
- DFE compensates for a 'decided' value
- IBM HSS12 Rx, 5-tap DFE used



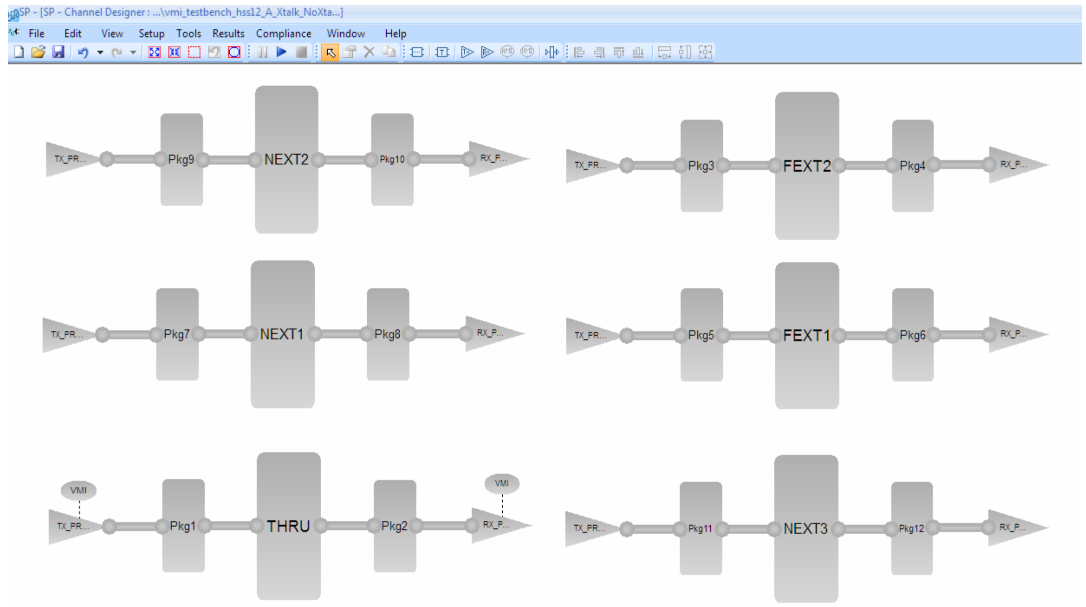
Decision Feedback Equalization (2)

- DFE adds weighted +/- value of previous 5 bits
- Weights determined by adaptation/feedback
- H1 decision 'speculative'
- Pre-cursor ISI not affected
- ISI reduction dependent on 'decision' being correct!



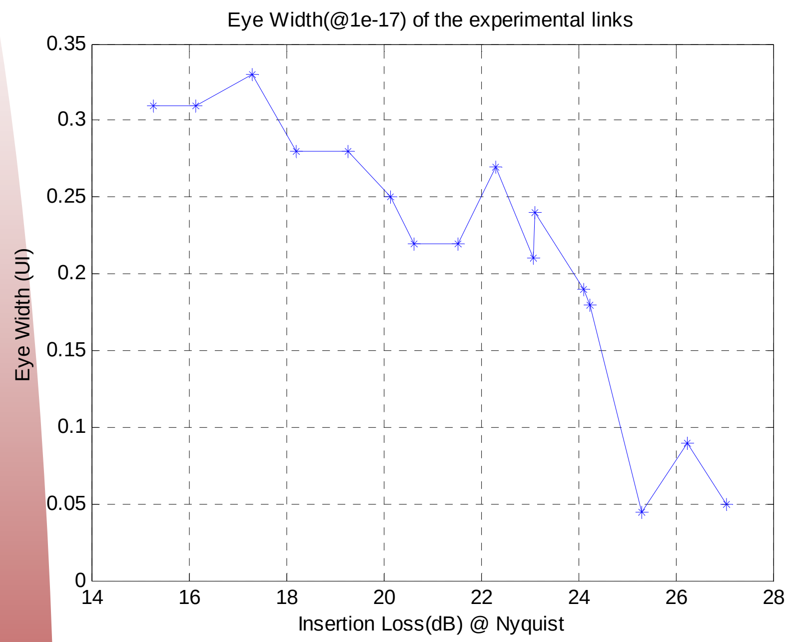
Simulation Topology

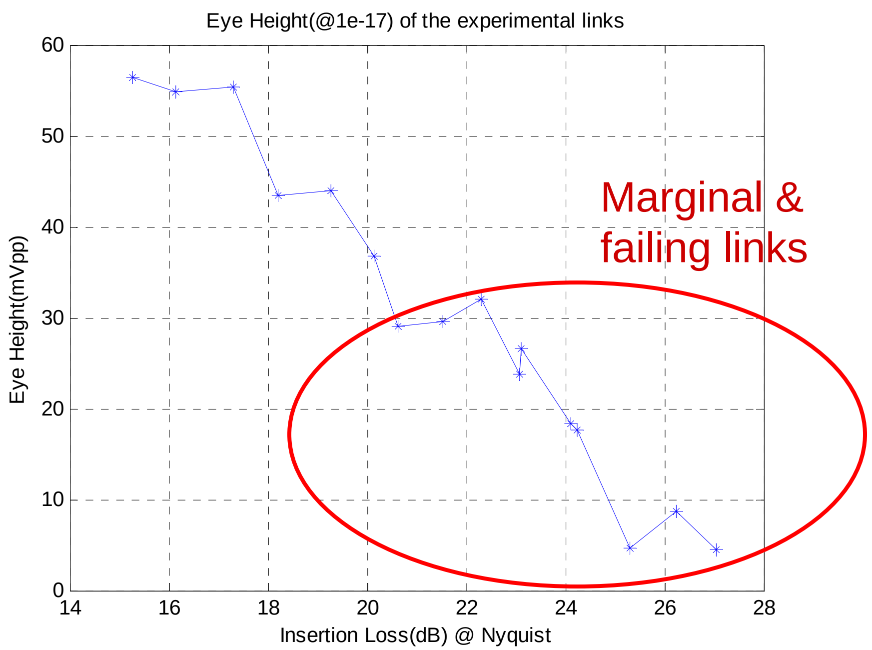
- “Through” channel with multiple crosstalk channels
  - 3 “NEXT” near-end crosstalk
  - 2 “FEXT” far-end crosstalk
- All channels taken from measured S-parameters



- Through channel swept for insertion loss of 15 to 30dB (at 5GHz)
- IBM IBIS-AMI models for Tx and Rx

Link Margin Identification

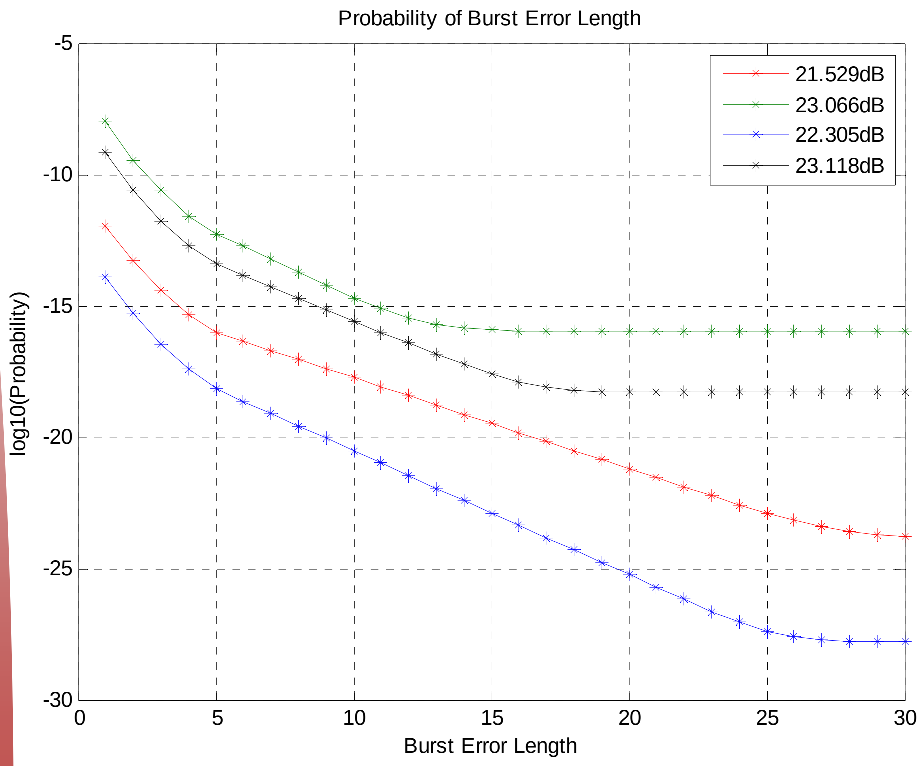




- Requirements for IBM HSS12 core:
  - 10~15% UI of horizontal eye opening
  - 20~30mVpd of vertical eye opening required
- 10 out of 16 channels were deemed “marginal” or failing and selected for FEC

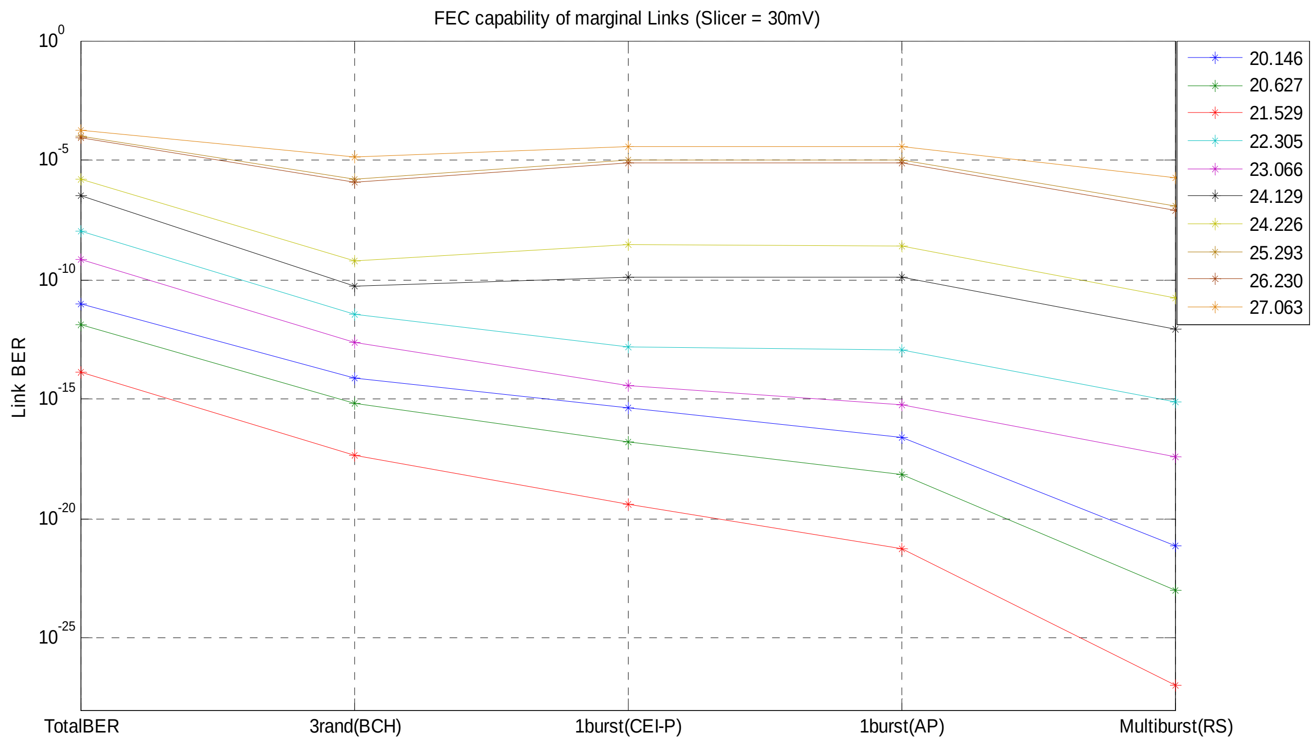
Error Propagation Calculation

Error propagation probabilities of 4 sample links:



➢ Note that the error propagation probability levels are not only related to the DFE coefficients, but also related to the error nature of the links.

BER Enhancement



- The 3-random correcting BCH can improve the BER approximately by 10^3;
- The 1-burst error correcting Fire codes can improve the BER by at least 10^4;
- The RS code (correcting 8 symbols) can achieve a BER enhancement of 10^8.

Summary

- A methodology has been presented to quantify BER improvement of electrical serial links, using error correction codes (FEC)
- Proof-of-concept has been achieved on an experimental Huawei backplane system
- Standard IBIS-AMI modeling and simulation can be used as the basis of this analysis
- FEC has shown capability to improve BER performance for marginal serial links

References

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[3] Cathy Ye Liu and Joe Caroselli, “Modeling and Mitigation of Error Propagation of Decision Feedback Equalization in High Speed Backplane Transceivers.” Proceedings of DesignCon 2006.

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