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Global Optimization of Wireline Transceivers for Minimum Post-FEC vs. Pre-FEC BER

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   b. DFE Error Propagation
3. Pre-FEC and Post-FEC BER as Criteria for Optimizing Wireline Transceivers
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Motivation

- Common receiver DSP equalizer blocks in 100Gb/s+ wireline applications:
  - Feed-forward Equalizer (FFE)
    - Noise amplification
    - High speed operation
    - No error propagation
  - Decision-Feedback Equalizer (DFE)
    - Error propagation
    - Speed limited by critical feedback path
    - No noise amplification
  - Forward-Error Correction (FEC) code have also become an integral part of the DSP
    - Standard Reed-Solomon (RS) to mitigate DFE error propagation
    - Ex: RS(544,514,15) KP4 code to achieve a targeted post-FEC BER <10^{-15}
Motivation

- Three performance metrics for optimizing equalizer coefficients in wireline transceivers:
  - SNR (Implicitly the optimization criteria when using LMS adaptation)
  - Pre-FEC BER
  - Post-FEC BER

<table>
<thead>
<tr>
<th>Metric</th>
<th>FFE Noise Amplification</th>
<th>DFE Error Propagation</th>
<th>Sensitivity to Long Burst Errors at very low BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Pre-FEC BER</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Post-FEC BER</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>
Motivation

- FFE and DFE tap coefficients are typically optimized to maximize signal-to-noise ratio (SNR) or to minimize the mean-squared error (MMSE) or pre-FEC BER [1-3]
- Equalizer parameters found by conventional methods do not necessarily minimize post-FEC BER
- This work presents an accurate and efficient methodology for finding transceiver parameters using Genetic Algorithm, based on post-FEC BER
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Transceiver Model – System Overview

- Equalized pulse response $\alpha(z)$ is generated by convolving the physical channel’s pulse with the impulse response of other components in the link, such as the TX FFE, TX driver, CTLE and RX FFE.

- Additive white Gaussian noise (AWGN) assumed at CTLE input, creating correlated noise samples after CTLE filtering.
Example of a 2-tap DFE represented by a simplified 4-state Markov model

Time-unrolling the Markov DFE model to generate PAM trellis

Apply trellis dynamic programming to the PAM trellis to efficiently collect all error patterns
Statistical Model – DFE Error Propagation
[Yang, TCAS-I, 2020]
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A channel model with 30 dB insertion loss for a link communicating 4-PAM symbols at 56 GBaud/s subject to 0.55 VP-P swing at TX, 4.58 mV_{rms} integrated rms noise

A simplified CTLE model provides 12 dB peaking gain with 0 dB gain at DC

A 1-tap DFE and a 7-tap FFE with 2 pre-cursor and 4 post-cursor taps at RX

The post-FEC BER is calculated assuming the standard KP4 RS(544,514, 15) code
Pre-FEC vs Post-FEC BER Optimum

- Vastly different optimal point with proposed optimization approach
- Tradeoff between FFE noise amplification and DFE error propagation

<table>
<thead>
<tr>
<th></th>
<th>Pre-FEC BER</th>
<th>Post-FEC BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-FEC</td>
<td>$2.38 \times 10^{-8}$</td>
<td>$4.88 \times 10^{-7}$</td>
</tr>
<tr>
<td>Post-FEC</td>
<td>$3.51 \times 10^{-16}$</td>
<td>$1.06 \times 10^{-39}$</td>
</tr>
</tbody>
</table>

Significant improvement in post-FEC BER using proposed optimization approach
Simulation Results: 1-Tap DFE

- More extensive simulation results using six measured channel responses to validate our methodology using post-FEC BER
- TX has a 2-tap FFE providing 5 dB pre-emphasis, and the RX FFE has 15 taps, including 3 pre-cursor taps and 11 post-cursor taps
- An 8th-order CTLE model was applied to equalize all six channels having 30–40 dB insertion loss
- The equalized pulse responses including TX FFE, CTLE and PHY channel are tabulated in Table I of the paper
Simulation Results: 1-Tap DFE

- Plot both the pre-FEC BER and post-FEC BER as a function of DFE tap weight $\alpha_1/\alpha_0$ for the 36 dB channel
- Simulated at two integrated rms noise levels: 1.62 mV$_{\text{rms}}$ (low noise) and 2.42 mV$_{\text{rms}}$ (high noise)
- Different DFE coefficients at pre-FEC and post-FEC optimal
  - Post-FEC BER is minimized at a lower $\alpha_1/\alpha_0$ than pre-FEC
Simulation Results: 1-Tap DFE

- Repeating the same analysis for all six measured channels
- The optimal post-FEC BER obtained by post-FEC optimization is always superior
A wireline transceiver model incorporating 1/(1+D) pre-coding to mitigate DFE error bursts

1/(1+D) decoder removes burst errors because the error \( d_k - b_k \) in the current received symbol is added to the error \( d_{k-1} - b_{k-1} \) in the previously received symbol

Isolated individual symbol errors give rise to two consecutive symbol errors after decoding

Method in [8] is used to generate the post-FEC BER results including 1/(1+D) pre-coding
### Prior FFE+DFE equalization strategy:

- Only use the \( N \)-tap DFE to equalize the first \( N \) post-cursor ISIs, the first \( N \) FFE post-cursor taps are set to zero. Here we denote the FFE-equalized pulse response as \( \alpha_k^{\text{intrinsic}} \).

### This work:

- FFE-equalized pulse response is \((1+\alpha_1 \cdot D+\alpha_2 \cdot D^2+\ldots)\) where \( \alpha_k > \alpha_k^{\text{intrinsic}} \) for \( 1 \leq n \leq N \). Extra SNR margin can be obtained by reducing FFE noise amplification. DFE taps are selected to cancel the new \( \alpha_n \) and \( 1/(1+D) \) pre-coding is then applied to remove large DFE error propagation.
Simulation Results: 1-Tap DFE with $1/(1+D)$ Pre-Coding

- Post-FEC BER of the previous 36dB channel case with and without $1/(1+D)$ pre-coding
- With pre-coding, both post-FEC and pre-FEC BER are minimized with the same equalizer coefficients
Pre-FEC BER performance surface of the 36dB loss channel at 2.42 mV<sub>rms</sub> noise level

The 2-tap DFE affords the FFE post-cursor taps with one more degree of freedom to low-pass filtering the noise

- significant BER improvement
Simulation Results: 2-Tap DFE

- Vastly different optimal points identified on each performance surface
Contrary to the 1-tap DFE example, with precoding enabled the post-FEC BERs optimized for post-FEC is better than the post-FEC BERs optimized for pre-FEC.

The post-FEC BERs optimized for post-FEC with precoding are optimal.
Although $N$ is typically limited to 1-2 due to the critical timing path in the DFE feedback loop, in this example near optimal results can be achieved using a 2-tap DFE.

- Suggests that we should optimize for $1 + \alpha_1 \cdot D + \alpha_2 \cdot D^2$ equalized pulse response in this example.
- Only true if the post-cursor residual ISIs cancelled by the RX FFE are small.
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Although LMS adaptation and other gradient-descent methods are commonly employed for optimizing FFE and DFE coefficients, they are ill-suited to CTLE optimization which has a non-unimodal performance surface.

- The time required to accurately evaluate each CTLE setting through an exhaustive search grows exponentially as the number of CTLE control parameters increases.

- A genetic algorithm (GA) is combined with the statistical model to obtain the best candidate settings for each transceiver block.
Genetic Algorithm – Initial Condition Generation

Step 1: Random Initial Conditions

- Global Optima
- 2 Elite Children
- Local Minima
- Random Children
Genetic Algorithm – Parent Selection

Step 2: Parent Selection

- Survived Parents
- Local Minima
- Global Optima
- New Parents
Genetic Algorithm – Crossover

Step 3: Crossover

🌟 Crossover Children
Genetic Algorithm – Mutation

Step 4: Mutation

Δ Mutated Children
Genetic Algorithm – Next Generation

Step 5: Children Used in Next Generation

Repeat Step 2-5
The optimization framework shown in the diagram includes:

- (1) a statistical model
- (2) a genetic algorithm optimizer

The FFE-DFE co-optimization method is employed by assuming the FFE equalized pulse response has taken the form \((1 + \alpha_1 \cdot D + \alpha_2 \cdot D^2 + \ldots)\)

- (1) reduce search-space complexity and (2) achieve optimal noise filtering
Simulation Setup

- A 14-inch orthogonal backplane channel from TE Connectivity [16] as the PHY channel model
  - Channel model has 35 dB insertion loss at 28 GHz
- A simple RC-degenerated differential pair reported in [17] is used as the reference CTLE design
  - A 5-bit digital control code is assigned to each CTLE component value
Non-Unimodal Performance Surface

- Pre-FEC BER surface plots are generated by sweeping $C_s$ and $C_p$
- $R_s$ and $R_D$ set to global optimal (left) and suboptimal (right)
## Simulation Results

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>CTLE Settings</th>
<th>TX FIR</th>
<th>DFE</th>
<th>Pre-FEC BER</th>
<th>Post-FEC BER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_s$</td>
<td>$C_s$</td>
<td>$R_d$</td>
<td>$C_p$</td>
<td>$\beta_1$</td>
</tr>
<tr>
<td>Pre-FEC</td>
<td>18</td>
<td>8</td>
<td>6</td>
<td>10</td>
<td>-0.06</td>
</tr>
<tr>
<td>Post-FEC</td>
<td>17</td>
<td>9</td>
<td>4</td>
<td>14</td>
<td>-0.06</td>
</tr>
<tr>
<td>Pre-Coded Post-FEC</td>
<td>20</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

- Link communicates 4-PAM symbols at 56 GBaud/s subject to 1 V\(_{P\text{P}}\) swing at TX
- The transmitter has a 3-tap FIR filter equalizing only pre-cursor ISIs
- A 2-tap DFE and a 13-tap FFE with 1 pre-cursor and 11 post-cursor taps at RX
- GA is used to optimize 8 parameters
  - 4 CTLE component values, 2 TX FIR pre-cursor and 2 DFE tap weights
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- Using SNR or pre-FEC BER as performance metrics may not be effective in minimizing post-FEC BER when architecting and optimizing wireline links
  - Links attain their minimum post-FEC BER with equalizer coefficients very different from those that minimize pre-FEC BER
  - The introduction of pre-coding mitigates the impact of error bursts, ensuring that both pre-FEC and post-FEC BER are minimized with the same equalizer coefficients for the 1-tap DFE example
  - Vastly different optimal equalizer settings with/without pre-coding for multi-tap DFE cases

- An optimization framework using Genetic Algorithm to find equalizer settings for minimum post-FEC BER on non-unimodal performance surfaces
  - 1+alpha-D type of partial responses are optimized by the GA to achieve optimal noise filtering and reduced search-space complexity
References


5. Transcoding/FEC Options and Trade-offs for 100 Gb/s Backplane and Copper Cable, IEEE Standard 802.3bj, Nov. 2011.

6. FEC Codes for 400 Gbps 802.3bs, IEEE Standard 802.3bs, Nov. 2014.


References

Thank you!

QUESTIONS?