Equalizer Modeling for IBIS-AMI

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Introduction to High-Definition Multimedia Interface (HDMI)

- HDMI is provided for transmitting digital television audiovisual signals from DVD players, set-top boxes and other audiovisual sources to television sets, projectors and other video displays.

<table>
<thead>
<tr>
<th>Version</th>
<th>Year</th>
<th>Transmission bandwidth</th>
</tr>
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<tbody>
<tr>
<td>HDMI 2.0</td>
<td>2013</td>
<td>6 Gbps/channel X 3 channels</td>
</tr>
<tr>
<td>HDMI 2.1</td>
<td>2018</td>
<td>12 Gbps/channel X 4 channels</td>
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</tbody>
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Signal Integrity (SI) Issues on HDMI Channels and eye diagram

4 channels in parallel

Differential signaling

Channel #1

Channel #2

Voltage (V)

Time (UI)

ISI noise

Xtalk

Voltage

Time

Voltage

Time

Bit

Bit

bit

bit

3
What is the Signal Integrity at System-level?

Power noise: DBI encoding

Crosstalk: Transition-minimized differential signaling (TMDS)

Equalizer:
- Continuous-time linear equalizer (CTLE)
- Decision Feedback Equalizer (DFE)
- Feedforward Equalizer (FFE)

ISI: Pre-/de-emphasis

EMI: Data scrambling

Multi-level signaling: PAM-N

Multi-level signaling: PAM-N

Pseudo-random test: Linear Feedback Shift Register (LFSR)

Buffer’s reliability:
- 8B/10B encoding
- 64B/66B encoding

Signal Integrity:
- Power noise
- Crosstalk
- Equalizer
- ISI
- EMI
- Multi-level signaling
- Pseudo-random test
- Buffer’s reliability

Data Integrity:
- Error-correction code: BCH, RS code

Signal level

Data level
Introduction to an Equalizer

- Definition: A component makes the channel have the same performance
  - in **time** domain
  - in **frequency** domain

- **Feedback equalizer**
  - Decision feedback equalizer (DFE)
  - Feedforward equalizer (FFE)

- **Emphasis**
  - Pre-emphasis
  - De-emphasis

- **Continuous time linear equalizer (CTLE)**
  - Active equalizer
  - Passive equalizer
IBIS Algorithmic Modeling Interface (IBIS-AMI)

- IBIS-AMI provides not only the analog model but also the digital signal processing (DSP) for the equalizer
Comparison between IBIS and IBIS-AMI

Tx IBIS-AMI
  Algorithmic modeling
  Analog modeling
  High-speed channel
  Rx IBIS-AMI
    Analog modeling
    Algorithmic modeling

Tx IBIS
  Analog modeling
  High-speed channel
  Rx IBIS
    Analog modeling
Equations for the Frequency-domain Equalizer: CTLE

- The received waveform when $S_{21}$ is given:

$$r(t) = \mathcal{F}^{-1}[\mathcal{F}\{p(t)\} \times S_{21}(f)]$$

- The insertion loss ($S_{21}$) of the equalized channel by a CTLE:

$$S_{21,eq\_ch}(f) = \left[\{S_{21,ch}(f)\}_{S \rightarrow T} \times \{S_{21,eq}(f)\}_{S \rightarrow T}\right]_{T \rightarrow S}$$

- the received pulse for the equalized channel by the CTLE:

$$r_{eq\_CTLE}(t) = \mathcal{F}^{-1}\left[\mathcal{F}\{p(t)\} \times S_{21,eq\_ch}(f)\right]$$
Equations for the Time-domain Equalizers

- A **DFE** can be expressed with the following equation:

\[ r_{e,i}(t) = r_i(t) \times \{1 - e_i\} \]

, where \( r_{e,i}(t) \) is the i-th interval of the equalized SBR

- If \( p(t) \) denotes the pulse to be transmitted, the behavior of the **pre-emphasis** is expressed with following equations:

\[ p_{pre}(t) = p(t) + \alpha \times p(\beta t) \]

, where \( \alpha, \beta \) denote the weight factor for the amplitude and time

- A **de-emphasis** behavior can be expressed in form of following equation:

\[ p_{de}(t) = p(t) - \alpha \times p(\beta t - T) \]
Equalized Single Bit Responses

- **w/o DFE**
- **DFE**
- **Pre-emphasis**
- **De-emphasis**
- **CTLE**
Transient Simulation with Equalizers

- w/o DFE
- DFE
- Pre-emphasis
- De-emphasis
- CTLE
Channels’ Another Expression: Finite Impulse Response (FIR) Filter

\[ y(t) = \mathcal{L}^{-1}\left\{ \sum_{j=1}^{\infty} a_j s^{j-1} \times X(s) \right\} \]

\[ y(t) = \sum_{k=1}^{\infty} f_k \times x(t - kT) \]

\[ = f_0 \times x(t) + f_1 \times x(t - T) + \cdots \]

< FIR filter >

< RLCG model >
DFE equalizes the ISI noise for the next bits
Behavior Model for DFE

- Single bit response (SBR) \( r(t) \)
  
  SBR with \( i \)-th tap DFE
  \[ r_{i}^{'}(t) = r_{i}(t) \times \{1 - c_{i}\} \]

- When \( C = \overline{0} \), the DFE would be disabled

- Equalizing ISI noise

\[ r_{i}^{'}(t) = r_{i}(t) \times \{1 - c_{i}\} = r_{i}(t) - c_{i} \times r_{i}(t) \]
Experimental Verification for N-tap DFE

< Statistical eye diagram >

< Transient simulation >
DFE’s Wrong Cases Depending on Threshold Voltage

- **Case #1:** Although the received bit is 1, the DFE is OFF

- **Case #2:** Although the received bit is 0, the DFE is ON
The threshold voltage determines the DFE’s behavior.
Overall Procedure to Predict eye diagram Including non-ideal DFE

- Amplitude PDF for the equalized bit 0

\[
PDF(a|0) \rightarrow PDF(a|0, DFE) \times \{P_{\text{wrong}}\}^c \\
\hat{PDF}(a|0) \rightarrow PDF(a|0, wDFE) \times P_{\text{wrong}} \\
\rightarrow PDF(a|0)' 
\]

- Amplitude PDF for the equalized bit 1

\[
PDF(a|1) \rightarrow PDF(a|1, DFE) \times \{P_{\text{wrong}}\}^c \\
\hat{PDF}(a|1) \rightarrow PDF(a|1, wDFE) \times P_{\text{wrong}} \\
\rightarrow PDF(a|1)' 
\]

- Amplitude PDF for the equalized bit at sampling time \( \tau \)

\[
\{P(0) \cdot PDF(a|0)' + P(1) \cdot PDF(a|1)\}'|\tau 
\]
Amplitude PDF when the DFE Makes Wrong Decision

With above PDFs, the DFE is defined within the statistical eye diagram.

- Probability of wrong decision
- Effect on amplitude by wrong DFE

With above PDFs, the DFE is defined within the statistical eye diagram.
Application: Shmoo Plot for Semiconductor Test

- Origin: from animation

- Definition: semiconductor performance evaluation depending on operating condition
  - General test
  - Memory test (DDR)

Diagram:

- Frequency [Hz]
- Threshold voltage [V]
- Time [UI]
Conversion From BER eye diagram to Shmoo Plot

- Shmoo plot is the set of the timing bathtub curves depending on the threshold voltage

\[
\bigcup_{v=-0.2}^{1.2} BER(\tau|v)
\]
The obtained shmoo plot is determined by the following:

Channel performance ($S_{21}$), functioning DFE, malfunctioning DFE
Thank you

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