ECEN720: High-Speed Links
Circuits and Systems
Spring 2019

Lecture 1: Introduction

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University
Class Topics

• System and design issues relevant to high-speed electrical (and optical) signaling

• Channel properties
  • Modeling, measurements, communication techniques

• High-Speed link circuits
  • Drivers, receivers, equalizers, timing systems

• Link system design
  • Modeling and performance metrics

• Link system examples
Administrative

- **Instructor:**
  - Sam Palermo
  - 315E WEB, 845-4114, spalermo@ece.tamu.edu
  - Office hours: Th 10:30am-12:00pm, F 1:00pm-2:30pm

- **Lectures:** TR 2:20pm-3:35pm, ETB 1035

- **Lab:** M 10:20pm-1:10pm, CVLB 324
  - Lab begins on January 30

- **Class web page**
  - http://www.ece.tamu.edu/~spalermo/ecen720.html
Class Material

• Textbook: Class Notes and Technical Papers

• Key References

• Class notes
  • Will post online before class
Grading

• Exams (50%)
  • Two midterm exams (25% each)

• Homework & Labs (25%)
  • Labs (Prelab + Report) and homeworks weighted equally
  • Collaboration is allowed, but independent simulations and write-ups
  • Need to setup CADENCE simulation environment
  • Due at beginning of lab or 5PM (HW)
  • No late homework will be graded

• Final Project (25%)
  • Groups of 1-3 students
  • Report and PowerPoint presentation required
Prerequisites

- This is a circuits AND systems class

- Circuits
  - ECEN474 or approval of instructor
  - Basic knowledge of CMOS gates, flops, etc...
  - Circuit simulation experience (HSPICE, Spectre)

- Systems
  - Basic knowledge of s- and z-transforms
  - Basic digital communication knowledge
  - MATLAB experience
Simulation Tools

- Matlab
- ADS (Statistical BER link analysis)
- Cadence
- 90nm CMOS device models
  - Can use other technology models if they are a 90nm or more advanced CMOS node
- Other tools, schematic, layout, etc... are optional
Desktop Computer I/O Architecture

- Many high-speed I/O interfaces
- Key bandwidth bottleneck points are memory (FSB) and graphics interfaces (PCIe)
- Near-term architectures
  - Integrated memory controller with serial I/O (>5Gb/s) to memory
  - Increasing PCIe from 2.5Gb/s (Gen1) to 8Gb/s (Gen3)
- Other serial I/O systems
  - Multi-processor systems
  - Routers
Serial Link Applications

- Processor-to-memory
  - RDRAM (1.6Gbps), XDR DRAM (7.2Gbps), XDR2 DRAM (12.8Gbps)

- Processor-to-peripheral
  - PCIe (2.5, 5, 8Gbps), Infiniband (10Gbps), USB3 (4.8Gbps)

- Processor-to-processor
  - Intel QPI (6.4Gbps), AMD Hypertransport (6.4Gbps)

- Storage
  - SATA (6Gbps), Fibre Channel (20Gbps)

- Networks
  - LAN: Ethernet (1, 10Gbps)
  - WAN: SONET (2.5, 10, 40Gbps)
  - Backplane Routers: (2.5 – 12.5Gbps)
Chip-to-Chip Signaling Trends

<table>
<thead>
<tr>
<th>Decade</th>
<th>Speeds</th>
<th>Transceiver Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980’s</td>
<td>&gt;10Mb/s</td>
<td>Inverter out, inverter in</td>
</tr>
<tr>
<td>1990’s</td>
<td>&gt;100Mb/s</td>
<td>Termination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Source-synchronous clk.</td>
</tr>
<tr>
<td>2000’s</td>
<td>&gt;1 Gb/s</td>
<td>Pt-to-pt serial streams</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pre-emphasis equalization</td>
</tr>
<tr>
<td>Future</td>
<td>&gt;10 Gb/s</td>
<td>Adaptive Equalization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advanced low power clk.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternate channel materials</td>
</tr>
</tbody>
</table>

Slide Courtesy of Frank O’Mahony & Brian Casper, Intel
Increasing I/O Bandwidth Demand

- Single ⇒ Multi ⇒ Many-Core μProcessors
- Tera-scale many-core processors will aggressively drive aggregate I/O rates

Intel Teraflop Research Chip
- 80 processor cores
- On-die mesh interconnect network w/ >2Tb/s aggregate bandwidth
- 100 million transistors
- 275mm²


*2006 International Technology Roadmap for Semiconductors*
High-Speed Electrical Link System

 Serializer

 TX data

 PLL

 ref clk

 TX clk

 TX

 TX data

 Channel

 RX

 RX clk

 CDR

 RX data

 Deserializer
Electrical Backplane Channel

- Frequency dependent loss
  - Dispersion & reflections

- Co-channel interference
  - Far-end (FEXT) & near-end (NEXT) crosstalk
Channel Performance Impact

Channel Responses

10Gb/s Pulse Responses

10Gb/s Eye - Desktop Channel

10Gb/s Eye - Refined BP Channel

10Gb/s Eye - Legacy BP Channel
Channel Performance Impact

Channel Responses

10Gb/s Equalized Pulse Responses

10Gb/s Eye - Desktop Channel w/ Eq

10Gb/s Eye - Refined BP Channel w/ Eq

10Gb/s Eye - Legacy BP Channel w/ Eq
A 10Gb/s 5-tap DFE / 4-Tap FFE Transceiver in 90nm CMOS Technology

Mounir Meghelli, Sergey Rylov, John Bulzacchelli, Woogeun Rhee, Alexander Rylyakov, Herschel Ainspan, Ben Parker, Michael Beakes, Aichin Chung, Troy Beukema, Petar Pepeljugoski, Lei Shan, Young Kwark, Sudhir Gowda and Dan Friedman

IBM T. J. Watson Research Center, Yorktown Heights, NY
Transmission Channel Impairments

![Diagram of the channel with various components labeled: Tx IC, Pkg, Line card trace, Edge connector, Backplane trace, Edge connector, Line card trace, Pkg, Rx IC.]

- Packaged SerDes
- Backplane trace
- Line card trace
- Edge connector
- Via stub

[S21 Channel Response: -24.6dB @ 5GHz]

[Eye FFE1 10.0Gb/s [OPEN,1e-8] No Xtalk]

[INPUT]

[OUTPUT]

[0Hz 10GHz 2.0GHz 4.0GHz 6.0GHz 8.0GHz]

[|SDD21|, |S11|, |S22|]

[-24.6dB @ 5GHz]

[Meghelli (IBM) ISSCC 2006]
10Gb/s SerDes Main Features

- Tx with 1 baud-spaced 4-tap FFE
- Rx with 5-tap adaptive DFE and digital clock recovery
- LC-VCO based PLL for low noise clock generation
- 90nm CMOS technology

[Meghelli (IBM) ISSCC 2006]
Transmitter Architecture

Key Features:
- Half-rate CML design
- 4-tap FFE
- Tap polarity control
- ESD protection
- 70mW (24mA main tap, no FFE)

<table>
<thead>
<tr>
<th>FFE Taps</th>
<th>Full Scale</th>
<th>DAC bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-cursor</td>
<td>25%</td>
<td>4</td>
</tr>
<tr>
<td>Cursor</td>
<td>100%</td>
<td>6</td>
</tr>
<tr>
<td>1st Post-cursor</td>
<td>50%</td>
<td>5</td>
</tr>
<tr>
<td>2nd Post-cursor</td>
<td>25%</td>
<td>4</td>
</tr>
</tbody>
</table>

![Diagram of the transmitter architecture](image)

[Meghelli (IBM) ISSCC 2006]
Tx Output Eye Diagram @ 10Gb/s

No FFE, 24mA on main tap

FFE 4=[0, 85%, -15%, 0, 0]

[Meghelli (IBM) ISSCC 2006]
Receiver Architecture

Key Features:
- Half-rate design
- 5-tap continuously adaptive DFE
- Variable gain amplifier
- Digital CDR
- ESD protection (HBM & CDM)
- 130mW (with DFE and CDR logic)

[Meghelli (IBM) ISSCC 2006]
DFE Approach

Key Features:
- Half-rate DFE with H1 speculation and dynamic H2-H5 feedback allows 2UI for settling
- DFE algorithm maximizes vertical eye opening at the data slicing instant
- Offset adjustment at all the slicer inputs

DFE Taps | Resolution
--- | ---
H1 | 6 bits
H2 | 5 bits
H3, H4, H5 | 4 bits

[Received eye]

Tap-feedback and weighting

On-chip DFE Logic

Data

Amplitude

Offset

Deven

Tap weights

Dodd

Offset adjustment at all the slicer inputs

DFE Taps Resolution

- H1 6 bits
- H2 5 bits
- H3, H4, H5 4 bits

[Deven (IBM) ISSCC 2006]
Key Features:
- Fully digital loop
- Can handle up to +/- 4000ppm frequency offset
- Independent I,Q control

[Meghelli (IBM) ISSCC 2006]
Chip-to-Chip Link Experiments

<table>
<thead>
<tr>
<th>Trace Length</th>
<th>5GHz losses (Tx module + board trace + Rx module)</th>
<th>Number of vias 3.8mm via stub / 1.8mm via stub / 1.8mm via through</th>
</tr>
</thead>
<tbody>
<tr>
<td>10” (#1)</td>
<td>12dB</td>
<td>2 / 0 / 0</td>
</tr>
<tr>
<td>10” (#2)</td>
<td>10dB</td>
<td>0 / 2 / 0</td>
</tr>
<tr>
<td>15”</td>
<td>25dB</td>
<td>4 / 2 / 0</td>
</tr>
<tr>
<td>20”</td>
<td>15dB</td>
<td>0 / 0 / 2</td>
</tr>
</tbody>
</table>

[Meghelli (IBM) ISSCC 2006]
Chip-to-Chip Measurement Results

Horizontal eye opening of the equalized eye at the receiver slicer input

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<th>Trace Length</th>
<th>5GHz losses (Tx module + board trace + Rx module)</th>
<th>Number of vias</th>
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<tr>
<td>10” (#1)</td>
<td>12dB 2 / 0 / 0</td>
<td>3.8mm via stub / 1.8mm via stub / 1.8mm via through</td>
</tr>
<tr>
<td>10” (#2)</td>
<td>10dB 0 / 2 / 0</td>
<td></td>
</tr>
<tr>
<td>15”</td>
<td>25dB 4 / 2 / 0</td>
<td></td>
</tr>
<tr>
<td>20”</td>
<td>15dB 0 / 0 / 2</td>
<td></td>
</tr>
</tbody>
</table>

[Meghelli (IBM) ISSCC 2006]
Preliminary Schedule

<table>
<thead>
<tr>
<th>Topic</th>
<th>Week</th>
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<tbody>
<tr>
<td>I. Channels</td>
<td>Week 1-7</td>
</tr>
<tr>
<td>II. Communication Techniques</td>
<td></td>
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<tr>
<td>III. Equalizers</td>
<td></td>
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<tr>
<td>IV. Transmitter/Receiver Circuits</td>
<td></td>
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<tr>
<td>First Exam</td>
<td>March 5</td>
</tr>
<tr>
<td>V. Equalizer Circuits</td>
<td>Week 8-14</td>
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<tr>
<td>VI. Clocking Circuits</td>
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<tr>
<td>VII. Clocking Systems</td>
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<tr>
<td>VIII. Link Modeling</td>
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<td>IX. Link Examples</td>
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<tr>
<td>Second Exam</td>
<td>April 25</td>
</tr>
<tr>
<td>Project Report Due</td>
<td>April 30</td>
</tr>
<tr>
<td>Project Presentations</td>
<td>May 7 (1:00PM-3:00PM)</td>
</tr>
</tbody>
</table>

- Dates may change with reasonable notice
Next Time

• Channels
  • Components
    • Chip packages, PCBs, Wires, Connectors
  • Modeling
    • Wires, Transmission Lines