Modelling and Analysis of Off-Chip Optical and Electrical Interconnect and Interface

Jiang Xu
Acknowledgement

- **Current PhD students**
  - Zhehui Wang, Duong Huu Kinh Luan, Peng Yang, Zhe Wang, Haoran Li, Zhifei Wang, Rafael Kioji Vivas Maeda, Xuanqi Chen, Zhongyuan Tian

- **Past members and visitors**
  - Xuan Wang, Mahdi Nikdast, Yaoyao Ye, Xiaowen Wu, Weichen Liu, Xing Wen, Kwai Hung Mo, Yu Wang, Sébastien Le Beux, Yiyuan Xie, Huaxi Gu
Challenges of Inter/Intra-Chip Electrical Interconnect

- More communications from more cores
  - Cisco QuantumFlow (40), Intel Phi (72), Tilera Tile (72), PicoChip (300) ...
  - Blade server, micro server, disaggregated server ...
- Tighter I/O bandwidth
  - Maximum pin count of package grows slow
  - Higher packaging and PCB cost
- Larger latency
  - Multiple clock cycles are required to cross a chip
- Higher energy consumption and loss
  - Dynamic and leakage power of drivers and buffers
  - ~35dB/m @12.5G on high-quality PCB
- SerDes energy and performance bottleneck
  - ~5pJ/bit @ 100G
Optical Interconnect

- Photonic technologies have been successfully used in WAN and LAN
  - Showed strengths in multicomputer systems and Internet core routers

- Benefit from more matured silicon-based technologies
  - Micron-scale devices working at picosecond-level are widely demonstrated

- Commercialization efforts
  - IBM, Intel (Omni-Path), HP (Machine), Oracle (UNIC), STMicro, NTT, NEC, Fujitsu (PECST), Huawei ...
  - Startups: Luxtera-STMicro, Lightwire/Cisco, Kotura/Mellanox, Caliola/Huawei, Aurrion, OneChip, Skorpies ...
  - EDA: Cadence-PhoeniX-Lumerical, Mentor Graphics-Lumerical, RSoft/Synopsys ...

Off-Chip Interconnect Overview

- **Optical interconnect OI(M,N)** include
  - M electrical inputs
  - M electrical outputs
  - N optical wavelengths

- **Electrical interconnect EI(M,N)** include
  - M electrical inputs
  - M electrical outputs
  - N electrical lanes

Off-Chip Interconnect Structure Examples

- Electrical off-chip Interconnect
  - Serializer
  - 8b/10b encoder
  - Pre-Amplifier
  - Driver
  - Electrical Pin
  - Trace
  - Electrical Pin
  - Equalizer
  - Limiting Amplifier
  - Clock and Data Recovery
  - 8b/10b decoder
  -Deserializer

- Optical off-chip Interconnect
  - Serializer
  - 8b/10b encoder
  - Pre-Amplifier
  - Driver
  - Laser
  - Modulator
  - Optical Pin
  - Fiber/Waveguide
  - Optical Pin
  - Photodetector
  - Transimpedance Amplifier
  - Equalizer
  - Limiting Amplifier
  - Clock and Data Recovery
  - 8b/10b decoder
  - Deserializer

2016-03-15
Jiang Xu (OPTICS Lab)
Holistic Models and Comparisons

- Optical interconnects vs. electrical Interconnects
  - Bandwidth
  - Area and linear bandwidth density
  - Latency
  - Energy efficiency
  - Signal integrity
  - Area

- OE interfaces
- SerDes designs
- Packaging options
- Different structures
Outline

- Introduction
- Modelling off-chip interconnects and interfaces
  - Electrical Interconnects
  - Optical Interconnects
  - SerDes and O-E interface
- A new O-E interface
- Quantitative analysis and comparisons
- Conclusions
## Basic Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Saraswat</th>
<th>Chen</th>
<th>Esener</th>
<th>OEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Energy Efficiency</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1.1 Power Consumption</strong></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.1 Transmitter Power</strong></td>
<td>✓</td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.1.1 Crosstalk Noise</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.1.1.1 Number of Wavelengths</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.1.2 Wavelength Spacing</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.1.3 MR Characteristics</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2 Optical Power Loss</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.1 Coupler Loss</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.2 Waveguide Attenuation</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.3 Interconnect Length</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.4 MR Characteristics</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3 Receiver Sensitivity</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3.1 Photodetector Responsively</strong></td>
<td>*</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3.2 Signal to Noise Ratio</strong></td>
<td>*</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3.3 Modulation Frequency</strong></td>
<td>*</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3.4 TIA Transimpedance</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.3.5 Limiting Amplifier Sensitivity</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.4 Laser &amp; Modulator Parameters</strong></td>
<td>✓</td>
<td>*</td>
<td>*</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.4.1 Threshold Current</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.4.2 Slope Efficiency</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.4.3 Power Extinction Ratio</strong></td>
<td>✓</td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Saraswat</th>
<th>Chen</th>
<th>Esener</th>
<th>OEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.1.2 Receiver Power</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.1 TIA Power</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.1.1 Photodetector Capacitance</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.1.2 Signal Frequency</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.1.3 TIA Supply Voltage</strong></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.2 LA Power</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.2.1 LA Supply Current</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.1.2.2.2 LA Supply Voltage</strong></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>1.2 Data Rate</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>2 Bandwidth Density</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.1 Data Rate per Wavelength</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.2 Number of Wavelengths</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.2.1 MR Characteristics</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.2.2 Wavelength Spacing</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.3 Optical Pin Pitch</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>2.4 Waveguide Pitch</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>3 Latency</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>3.1 RC Delay</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>3.2 Propagation Delay</strong></td>
<td></td>
<td>*</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>3.2.1 Interconnect Length</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>3.2.2 Signal Propagation Speed</strong></td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

* Mentioned but without an exact model
Electrical Crosstalk Noise

- Top/bottom layer for power/ground and inner layer for signal
- The differential traces on PCB board has the following parameters:
  - $H$ height between two panels
  - $w$ width of a trace
  - $h$ height of a trace
  - $P_e$ pitch of differential traces:

\[ C(d) \text{ is the crosstalk noise coefficient of two traces with distance } d \]

\[ c(d) = \frac{H^2}{(4d^2 + H^2)} \]
Electrical Crosstalk Noise

- $N_d(i)$ is the crosstalk noise coefficient between two differential pair $n$ and pair $n+i$

$$N_d(i) = c(|i|p_e - 2w) - 2c(|i|p_e) + c(|i|p_e + 2w)$$

- The total crosstalk noise coefficient is the summation of coefficients from neighboring pairs

$$\varepsilon_e = \ldots + N_d(-1) + N_d(1) + N_d(2) + \ldots$$
The attenuation factor of PCB trace has two terms, which are skin effect loss and dielectric loss:

- $R_{dc}$ direct current resistance
- $Z_0$ characteristic impedance
- $f_s$ frequency of half skin depth
- $C_0$ the capacitance per unit length
- $\tan\delta_D$ loss tangent in dielectric material

The total attenuation of electrical interconnects:

- $\eta_e$ coupling loss of electrical pin
- $f$ working frequency
- $L$ interconnect length

\[
\alpha_e = \frac{R_{dc}(w + h)}{2Z_0w} \left(\frac{f}{f_s}\right)^{0.5} + \pi f C_0 \tan\delta_D Z_0
\]

Skin effect loss

Dielectric loss

\[
A_e = \eta_e^2 e^{-\alpha_e L}
\]

Coupling loss

Propagation loss
Electrical Interconnect Sensitivity

- Only when this voltage difference is greater than $|V_{th}|$ of the limiting amplifier, signals can be detected
  - $A_e$ attenuation (0~1)
  - $\varepsilon_e$ crosstalk noise coefficient
  - $\varepsilon_o$ receiver offset coefficient:

- The supply current of driver
  - $V_{th}$ threshold voltage
  - $Z_d$ differential impedance

$$I_0 = \frac{2V_{th}}{(A_e - \varepsilon_e - \varepsilon_o) \cdot Z_d}$$

\[ \text{Ratio} = A - \varepsilon_e - \varepsilon_c = \Delta \varepsilon > 0 \]
In electrical interconnect, power consumption includes the power of driver, receiver and SerDes:

- $P_{sd}$ power of SerDes
- $V_c$ supply voltage
- $I_{la}$ supply current of limiting amplifier

$$P_e = P_{sd} + (2I_0 + I_{la})V_c$$
Electrical Interconnect Bandwidth

- If the signal frequency or the interconnect length is increased, trace attenuation is increased. The ratio $\Delta \varepsilon$ of the receiver amplitude over transmitter amplitude, will be decreased

\[ A - \varepsilon_e - \varepsilon_c = \Delta \varepsilon \]

- The maximum bandwidth of electrical interconnect

\[ B_e = 2A^{-1}\left(-\frac{\ln(\varepsilon_e + \varepsilon_c + \Delta \varepsilon)}{L}\right) \]
Microresonator

- Power of driver $P_d$: each time the voltage level of the PN junction is reversed, it is charged or discharged by the driver
  - $C_m$ input capacitance
  - $V_m$ supply voltage

- Power of microresonator $P_m$: when the voltage level of the PN junction is high, it is forward biased
  - $I_m$ static current

$$P_d = f \cdot C_m \cdot V_m^2$$

$$P_m = I_m \cdot V_m$$
Optical Crosstalk Noise

- At the receiver side, there are multiple optical signals in different wavelengths:
  - $\lambda_0, \lambda_1, \lambda_2, \ldots, \lambda_n$

- Part of the signal power in wavelength $\lambda_0$, $\lambda_2$ and $\lambda_3$ will also appear on the drop port.
Optical Crosstalk Noise

- In micro-resonator with working wavelength $\lambda_1$, the drop port transfer function is
  - $\cos \theta(\lambda)$ function of working frequency $\lambda$
  - $r$ power splitting ratio
  - $a$ round trip attenuation

- The optical crosstalk noise coefficient is the summation of unwanted signals whose wavelength is not $\lambda_1$
  - $m_o$ number of wavelengths in optical interconnect
  - $\Delta \lambda$ wavelength spacing

$$T_d(\lambda) = \frac{(1 - r^2)^2 a}{1 - 2r^2 a \cos \theta(\lambda) + r^4 a^2}$$

$$\varepsilon_o = 2 \sum_{i=1}^{[m_o/2]} T_d^N(\lambda_1 + i\Delta \lambda)$$
Optical Interconnect Attenuation

- Before $\lambda_0$ reaches the filter, it will pass by other micro-resonators with working wavelength
  - $\lambda_1$, $\lambda_2$, ..., $\lambda_n$

- The attenuation of optical path is the product of:
  - Coupler efficiency
  - Propagation attenuation
  - Passing-by loss of MR
  - Insertion loss of MR
Optical Interconnect Attenuation

- In microresonator with working frequency $\lambda_1$, the through port transfer function is

$$T_p(\lambda) = \frac{r^2a^2 - 2r^2a\cos\theta + r^2}{1 - 2r^2a\cos(\theta(\lambda)) + r^4a^2}$$

- The attenuation of optical path is the product of four terms
  - $\eta_o$ coupling efficiency of optical pin
  - $a_o$ attenuation of waveguide
  - $A_o = \eta_o^2 e^{-\alpha_o L} L_p(m_o - 1) T_d^2(\lambda_n)$

- Coupler loss
- Passing loss
- Propagation loss
- Insertion loss
Optical Interconnect Sensitivity

- In optical interconnect, the sensitivity OMA is the difference between two optical power levels $P_1$ and $P_0$
  - $BER$ bit error rate
  - $SNR$ signal to noise ratio
  - $i_n$ input referred RMS noise density
  - $Z_{tia}$ transimpedance of TIA
  - $\rho$ responsivity of photodetector

$$OMA = \frac{i_n f^{0.5} \cdot SNR + 2V_{th}Z_{tia}^{-1}}{\rho}$$
Optical Interconnect Sensitivity

- Only when this voltage difference is greater than OMA, signals can be detected by the limiting amplifier
  - $\varepsilon_o$ crosstalk noise coefficient
  - $r_e$ extinction ratio $P_1/P_0$
  - $\eta_s$ slope efficiency of laser
  - $I_{th}$ threshold current of laser

$$I_{mod} + I_{bias} = \frac{OMA}{A_o(1 - \varepsilon_o - r_e)\eta_s} + I_{th}$$

Ratio = $1 - \varepsilon_o - r_e > 0$
Optical Interconnect Bandwidth

- FSR is the spacing between two successive resonance peaks in spectrum
  - $n_e$ MR effective refractive index
  - $R$ MR radius of ring
  \[
  \text{FSR} = \frac{\lambda^2}{2\pi n_e R}
  \]
- $\Delta\lambda$ is the wavelength spacing between two neighboring wavelengths
  \[
  B_o = 2\left[\frac{\text{FSR}}{\Delta\lambda}\right] f
  \]
Optical Interconnect Power Consumption

- In optical interconnect, power consumption includes the power of laser sources, receiver, SerDes and modulator
  - \( V_L \) laser supply voltage
  - \( I_{tia} \) TIA supply current
  - Direct modulation
    \[
    P_o = P_{sd} + (I_{mod} + I_{bias})V_l + (I_{tia} + I_{la})V_c
    \]
  - Indirect modulation
    \[
    P_o = P_{sd} + (I_{mod} + I_{bias})V_l + (I_{tia} + I_{la})V_c + P_m + P_d
    \]
Optical Interconnect Power Consumption and Area

- The power consumptions of the electrical funneling interface and optical weaving interface

\[ P_{feo} = 5 \log_2 R P_e + P_c + \frac{1}{4} P_d + \frac{1}{2} P_m + P_t + \frac{P_o}{L_i} \]
\[ P_{weo} = P_e + P_c + \frac{1}{2} P_d + R P_m + R P_t + \frac{P_o}{L_i^R} \]

- The areas of the electrical funneling interface and optical weaving interface

\[ S_{feo} = 5 \log_2 R S_e + S_c + S_m + S_l \]
\[ S_{weo} = \frac{M}{2N} S_e + S_c + \frac{M}{N} S_m + S_l \]
Area and Linear Bandwidth Density

- Area bandwidth density
  - Bandwidth in a unit area
  - Important to package pin, socket *et c.*

\[
\text{Area Density} = \frac{\text{Bandwidth } B}{\text{Area } S}
\]

- Linear bandwidth density
  - Bandwidth in a unit width
  - Important to PCB, substrate, interposer *et c.*

\[
\text{Linear Density} = \frac{\text{Bandwidth } B}{\text{Pitch } p}
\]
Electrical and Optical Interconnect Latency

- Propagation delay is proportional to the interconnect length, and inverse proportional to the propagation speed
  - $v_e$ speed in electrical interconnect
  - $\varepsilon_r$ relative dielectric constant
  \[
  v_e = \frac{c}{\sqrt{\varepsilon_r}}
  \]
  - $v_c$ speed in optical interconnect
  - $n_g$ group reflection index
  \[
  v_o = \frac{c}{n_g}
  \]
Serializer and Deserializer

- SerDes consist of multiple stages of multiplexers or demultiplexers
  - With a large number of latches
- A bottleneck in inter-chip interconnect
  - Large power consumption, large area, additional latency
Our analytical models match experiment results well.
Traditional OE Interface: Electrical Funneling

- Electrical SerDes plus O-E conversion
New OE Interface: Optical Weaving

- Optical-electrical SerDes

2016-03-15  Jiang Xu (OPTICS Lab)
Outline

- Introduction
- Modelling of off-chip interconnects and interfaces
  - Electrical Interconnects
  - Optical Interconnects
  - SerDes and O-E interface
- A new O-E interface
- Quantitative analysis and comparisons
- Conclusions
Optical vs. Electrical Interconnect: Energy Efficiency

- Electrical interconnect has an energy cliff
- Optical interconnect favorite high data rate
Optical vs. Electrical Interconnect: Energy Efficiency

- 8:1 SerDes
- Electrical funneling
Optical vs. Electrical Interconnect: Area Bandwidth Density

- Two orders of magnitude higher than micro-FBGA package
- Three orders of magnitude higher than FBGA package
Optical vs. Electrical Interconnect: Pin Count

- Reduce >92% signal pins with 25cm interconnects
- Reduce >97% signal pins with 50cm interconnects
Optical vs. Electrical Interconnect: Latency

- 5Gbps
- Corning SMF-28 optical fiber
- Rogers RO4003
- Electrical funneling
Optical Weaving vs. Electrical Funneling: Energy Efficiency

- 50cm long
- 2Gbp per input
- $I_0 = 0.2\text{mA/Gbps}$
Optical Weaving vs. Electrical Funneling: Latency

- $I_0 = 0.2\text{mA/Gbps}$
Optical Weaving vs. Electrical Funneling: Area

- 50cm long
- 2Gbp per input
- 22nm node
- Differences in circuit design details, technology nodes, and foundry processes are reflected by unit current $I_0$.
OEIL: Optical and Electrical Interfaces and Links

- A comprehensive device library for off-chip interconnects
- Publicly released and available at www.ece.ust.hk/~eexu/OEIL.html
Conclusions

- Analytical models for optical and electrical interconnects and interfaces
- Holistic comparisons in terms of bandwidth, bandwidth density, latency, energy efficiency, signal integrity, and area
- Proposed a new O-E interface, optical weaving
- Publicly released a R&D tool, OEIL
References


References