

Performance Comparison between Copper, Carbon Nanotube and Optics for On-chip Interconnects

Mar. 18. 2007

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Outline

- Motivation

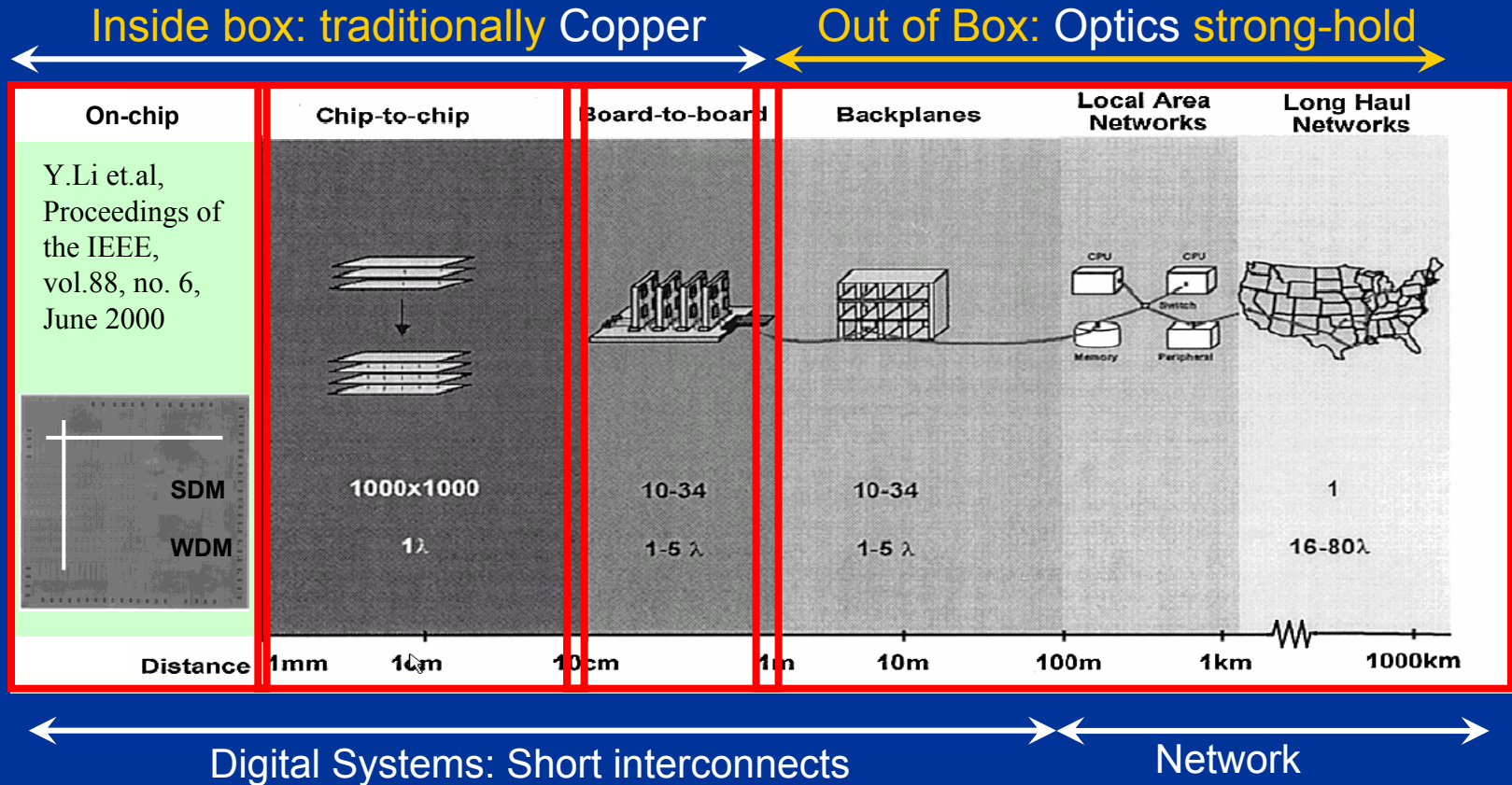
- Modeling of Cu/low-K, CNT, and Optics
 - RLC Modeling of Cu/low-K and CNT
 - Optical Interconnect Modeling

- Performance Comparison
 - Primary metrics
 - ✓ Bandwidth density
 - ✓ Latency
 - ✓ Power
 - Compound metrics
 - ✓ Bandwidth density/Latency/Power

- Conclusion



Interconnect Hierarchy



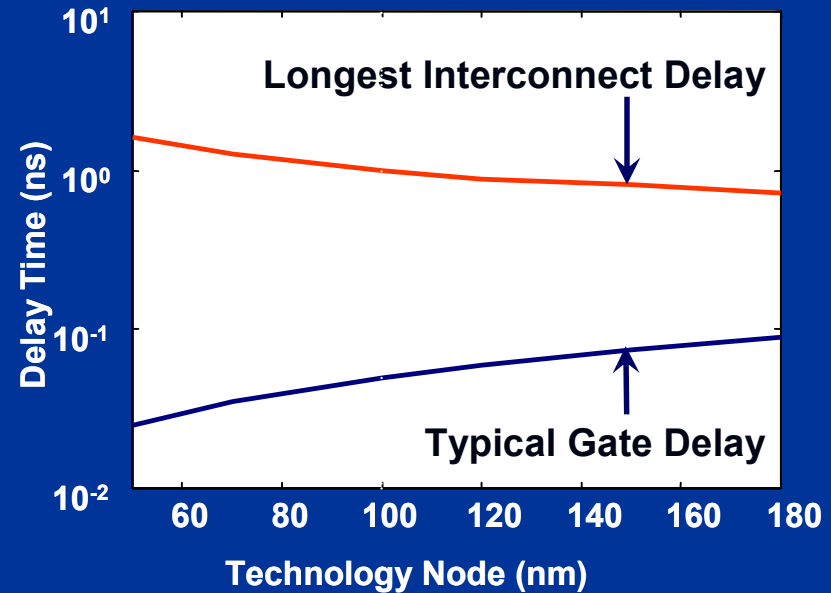
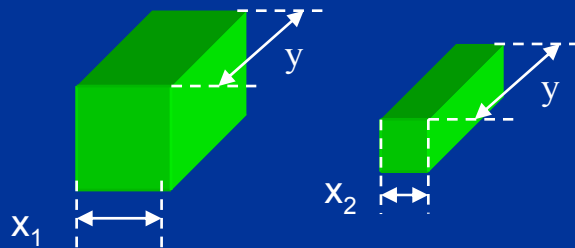
Interconnect level of this talk: On-chip global wires



Limit of On-chip Electrical Interconnect: Latency

- On-chip wires are getting slower

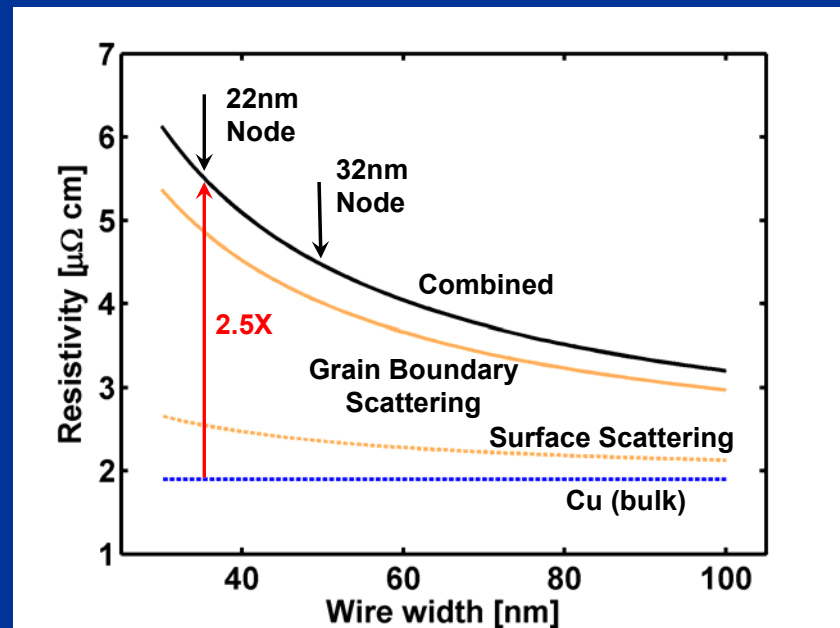
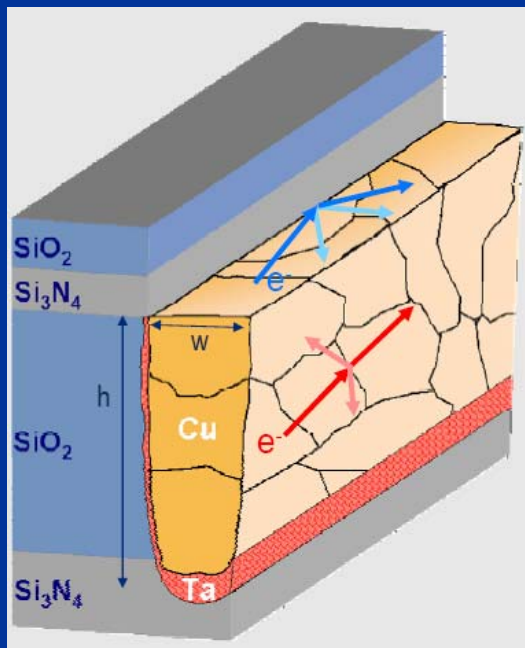
Cross-section Scaling



Wire delay is deteriorating wrt gate delay with scaling even with low-k materials



Limit of On-chip Electrical Interconnect: Resistance



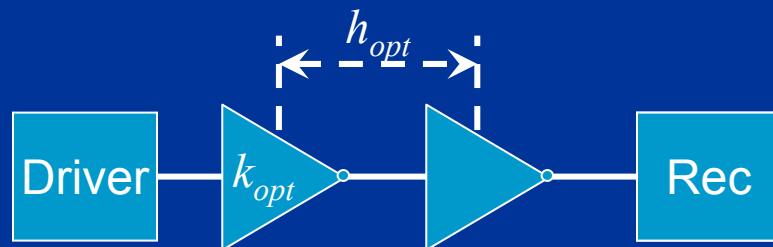
Based on W. Steinhogel et.al. Phys. Rev. B, 2002

□ Resistivity increases as wire dimensions and grain size become comparable to the bulk mean free path of electrons

- Grain boundary scattering
- Surface scattering



Limit of On-chip Electrical Interconnect: Repeaters



A long global link w/o Repeaters

$$t_{total} = 0.4R_w C_w l^2$$

□ **Delay (helps enormously)**

- Best possible interconnect delay
- Linear with length
- Scales better
- **But is it good enough?**

With Repeaters

$$t_{total} = 5l\sqrt{r_o C_{mos} R_w C_w}$$
$$= 2l\sqrt{(0.4R_w C_w)t_{FO4}}$$

**Repeaters have power and area penalty:
need new interconnect technologies...**



Alternative Candidates

	Pros	Cons
Optics	<ul style="list-style-type: none">➤ Low loss for longer wire and higher bandwidth➤ Lower power at higher bandwidth and switching activity➤ Wavelength Division Multiplexing	<ul style="list-style-type: none">➤ Larger pitch (~0.6μm) → Lower BW density
Carbon Nanotube (CNT)	<ul style="list-style-type: none">➤ Small device: ~nm diameter➤ Longer mean free path → Resistance ↓	<ul style="list-style-type: none">➤ Power

Imperative to quantify performance metrics of alternative candidates comparing with Cu/low-K



Performance Metrics

Primary Metric	Cu, CNT, Optics
Bandwidth	Level-off (10~20Gb/s) Design paradigm: Multi-core
Area	Different pitch → BW density
Latency	Core to core communication
Power	Budget: hungry at chip level
Compound Metric	BW density/Latency/Power

Extensive analysis on performance comparison between Cu, CNT and optics for on-chip levels using primary and compound metrics



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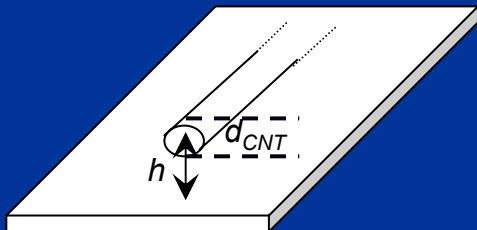
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RLC Model for Single-wall CNT: Capacitances (C_E , C_Q)

$$C_w = \frac{C_E \cdot C_Q}{C_E + C_Q}$$

□ **Electrostatic Capacitance (C_E)**



$$C_E = 2\pi\epsilon / \ln\left(\frac{d_{CNT}}{h}\right) \\ = 0.19 \text{ fF} / \mu\text{m}$$

□ **Quantum Capacitance (C_Q)**

$$C_Q = \frac{2e^2}{hv_F} \sim 0.1 \text{ fF} / \mu\text{m} (\sim C_E)$$

[P. J. Burke, Trans. on Nanotechnology, 2002]

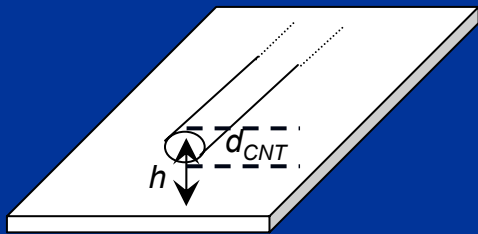
The quantum and electrostatic capacitances are in series, and have the same orders of magnitude



RLC Model for Single-wall CNT: Inductances (L_m, L_k)

$$L_w = L_m + L_k$$

□ Magnetic inductance (L_m)



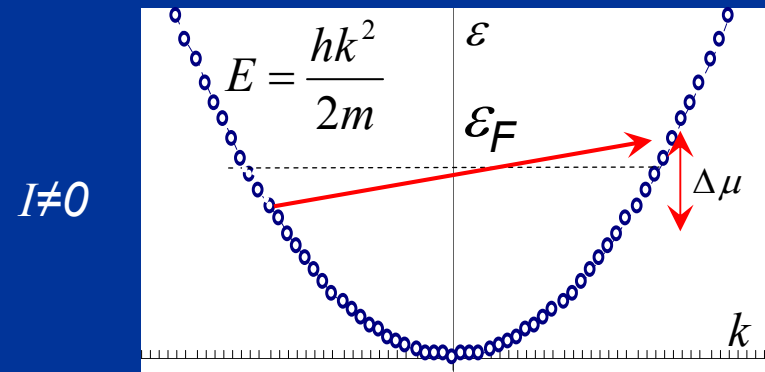
$$L_m = \frac{\mu}{2\pi} \ln\left(\frac{d_{CNT}}{h}\right) = 1.6nH / mm$$

□ Kinetic inductance (L_k)

$$L_k \equiv \frac{h}{2v_F e^2} \sim 16\mu H / mm$$

[P. J. Burke, Trans. on Nanotechnology, 2002]

4 orders higher magnitude
→ Inductance effects
becomes important



RLC Model for Single-wall CNT: Resistance

$$R_w = R_C + R_Q \left(1 + \frac{l}{l_o} \right)$$

□ Contact resistance (R_C)

- 120K Ω \rightarrow ~K Ω per nanotube [H. Dai, Applied Phys. A, 2004]

□ Quantum resistance (R_Q)

$$R_Q = \frac{h}{4e^2} = 6.45K\Omega$$

[P. J. Burke, Trans. on Nanotechnology, 2002]

□ Wire resistance (R_w)

- **linear model** [J.Y. Park, *Nano Letters*, 2004]
- Good quality CNT: $l_o = 1.6\mu\text{m}$

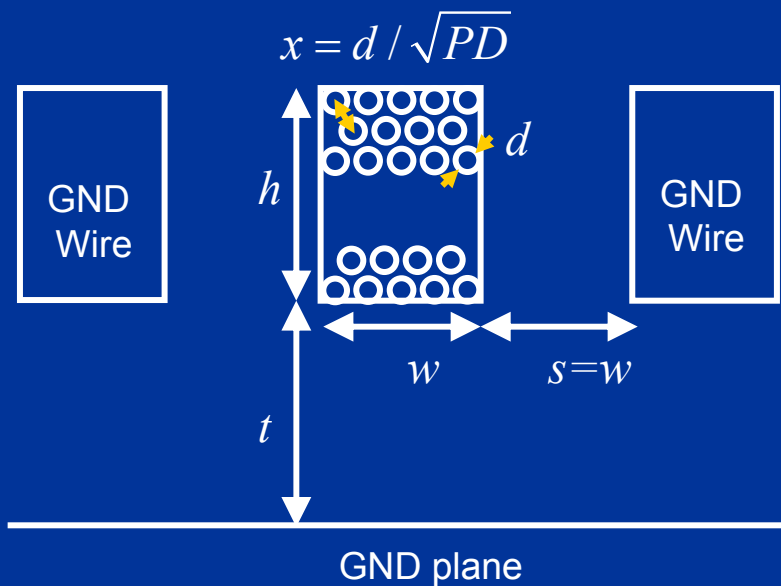
Resistance is linear dependence with wire length multiplied by Quantum resistance



RLC Model for Bundled CNT

□ CNT bundle

- Same wire dimension with Cu
- Packing density



Equiv. RLC for CNT Bundle

$$C_w \sim C_E$$

$$L_w \sim L_k / 4n + L_m$$

$$R_C \sim 0$$

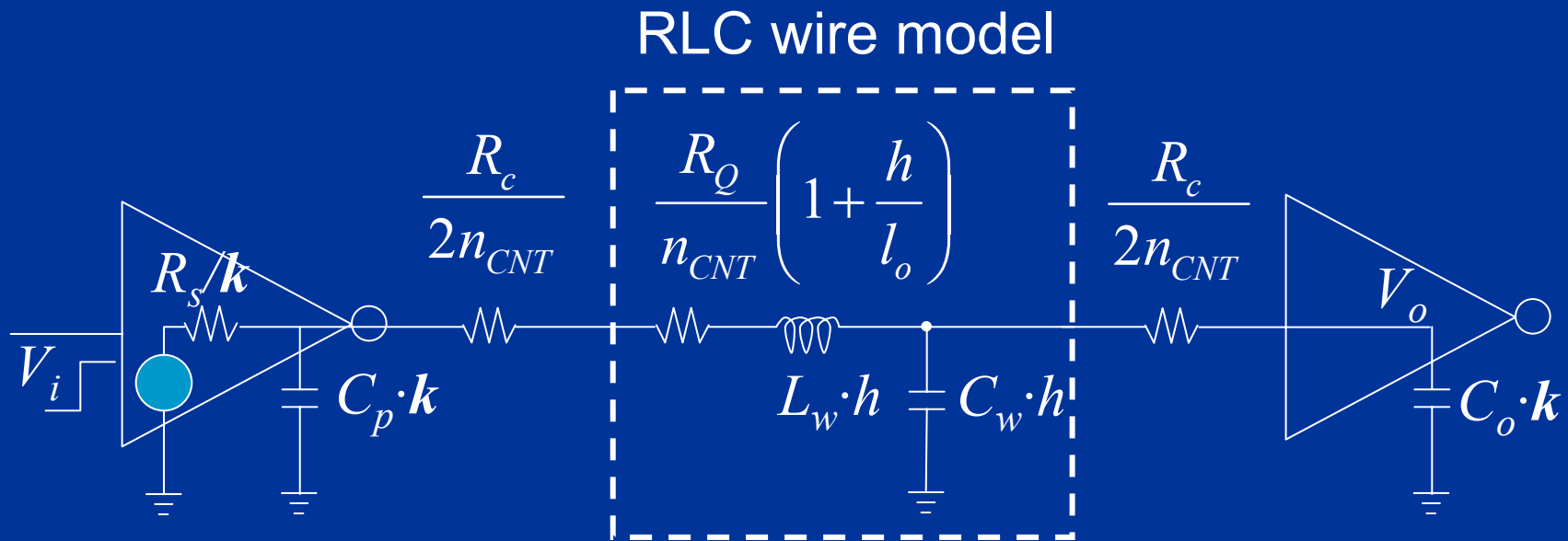
$$R_w = \frac{R_Q}{n} (1 + l/l_o)$$



Repeater Model: RLC

□ RLC model

- No closed form solution: k (driver size) and h (repeater spacing)
- Newton-Raphson numerical iteration method
- Increase in the inductance ratio to resistance
 - ✓ $k \downarrow$ and $h \uparrow$
 - ✓ the total repeater capacitance reduces resulting in a **lower power: inductance effect**

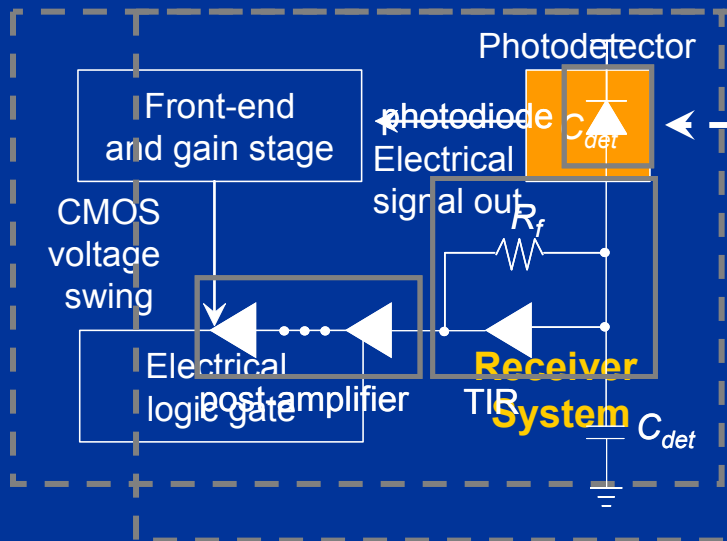
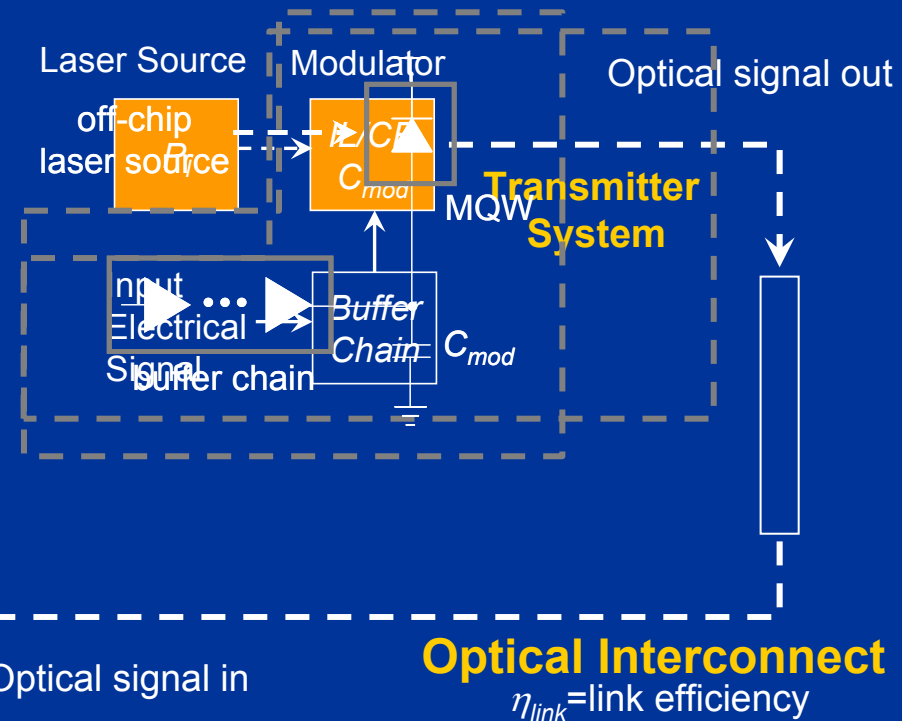


K. Banerjee, Trans. on CAD of Int. Circuits and Systems, vol. 21, 2002.



Optical Interconnect: Modeling

- Off-chip laser power source with 1.3 μm wavelength
- On-chip quantum well modulators/Photodiode
- Trans-impedance receiver (TIR)
- Subsequent amplifier stage



- Electrical components
- Optical components



Optical Interconnect: Power Dissipation

❑ Optical Modulator Power (QWM)

- Dynamic power: capacitance of modulator and the driving gates
- Static power: optical absorption in QWs

❑ Receiver Power

- Criteria
 - ✓ Bit rate (BR)
 - ✓ Bit error rate (BER) = 10^{-15}
 - ✓ Output voltage swing equal to the supply voltage
- **Receiver power dramatically decreases with the detector capacitance:** P. Kapur, IITC, 2002
 - ✓ Device Capacitance: 50fF → 10fF

} **Optimize design parameters**



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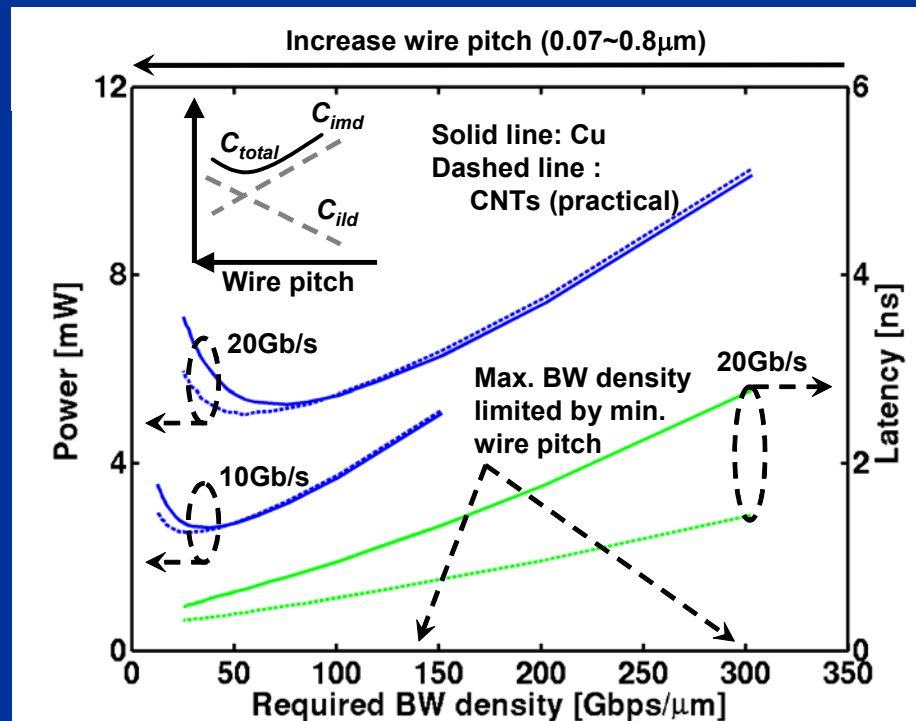
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Performance Comparison: Power and Latency for Cu/low-K and CNT



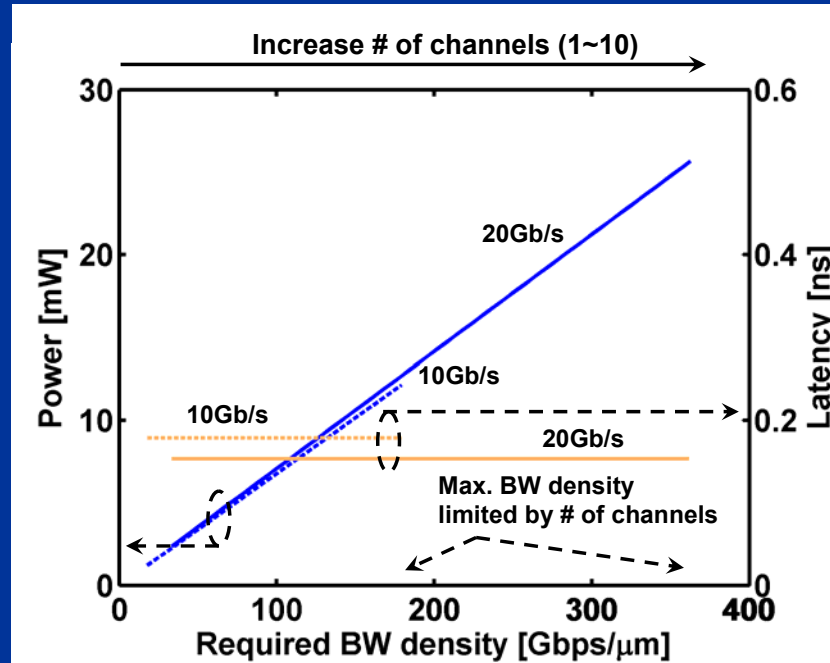
Wire length=10mm, 22nm technology node

- ❑ **BW density** limited by Min. pitch of ITRS: $\sim 150 \text{ Gbps}/\mu\text{m}$ for $f_{ck}=10 \text{ Gbps}$
- ❑ **Further limited by repeater area**
- ❑ **Power:** Wide wire pitch exhibits inductance effect

CNT have 1.5X lower latency compared to Cu/low-K



Performance of Optics: Power and Latency

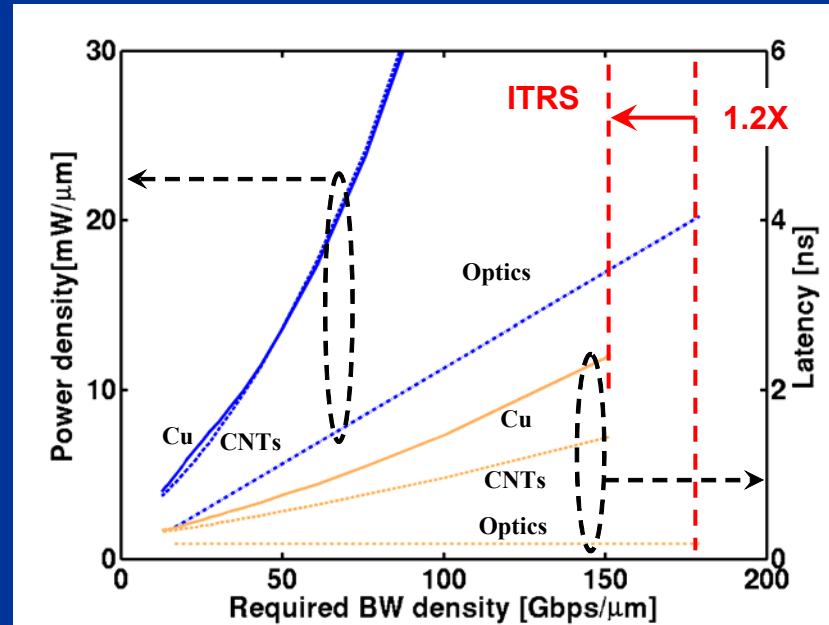


Wire length=10mm, $C_{det}=C_{mod}=10$, 22nm technology node

- ❑ **Max. BW density limited by # of channels** > Cu, CNTs @10 channels
- ❑ **Power:** linear with BW density
- ❑ **Latency:** constant



Performance Comparison: Power density and Latency



Wire length=10mm, CNT: $mfp=0.9\mu m$, $PD=1/3$, $C_{det}=C_{mod}=10fF$,
 $f_{ck}=10Gbps$, 22nm technology node

- ❑ **Power density:** Fundamentally low power for optics
- ❑ **Latency:** Optics ~4X faster than CNTs, CNTs ~1.5X faster than Cu
- ❑ **BW Density:** Optics~1.2X higher than CNTs and Cu



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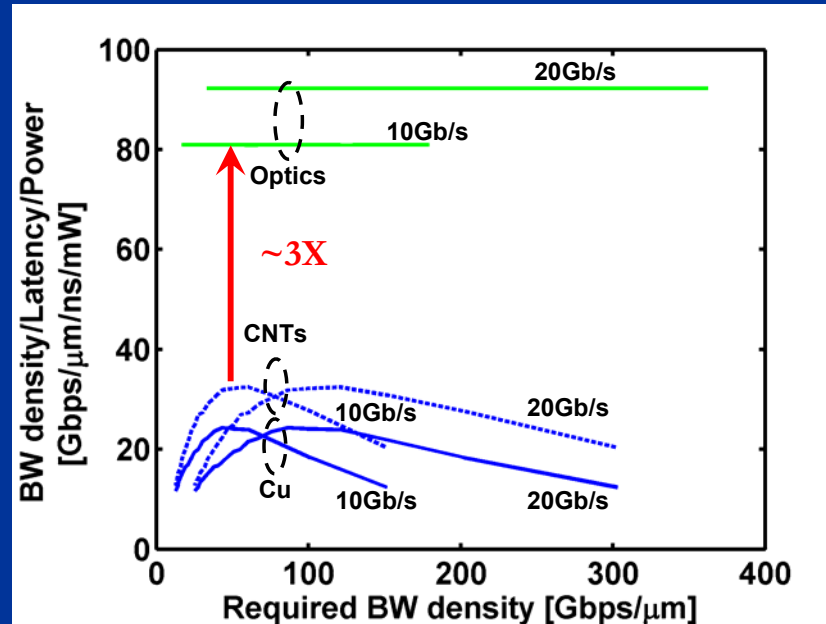
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Performance Comparison: Compound metric

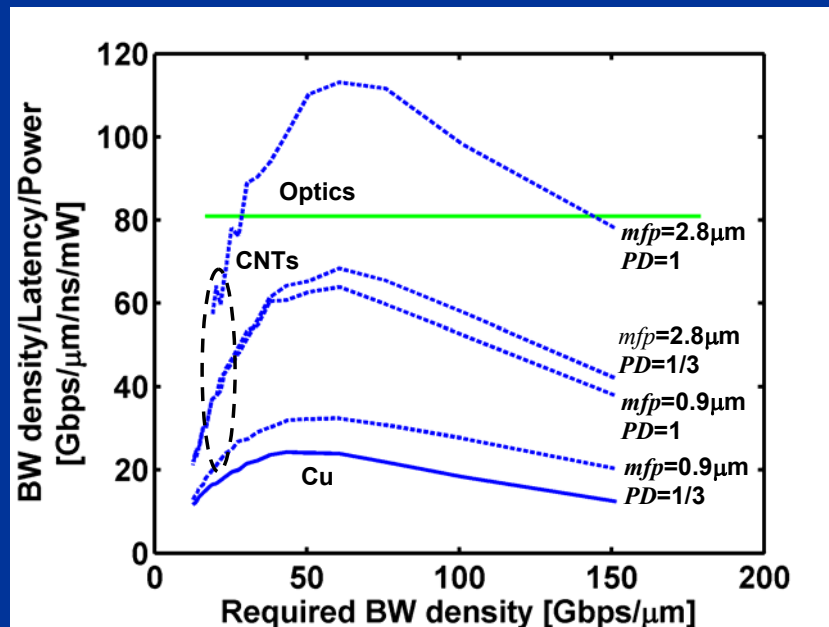


Wire length=10mm, CNT: $mfp=0.9\mu\text{m}$, $PD=1/3$, $C_{det}=C_{mod}=10\text{fF}$,
 $f_{ck}=10\text{Gbps}$, 22nm technology node

- ❑ Optics ~3X higher CNTs @Maximum
- ❑ CNT, Cu: optimum wire pitch, maximizing metric: $3\sim 5 \times W_{min}$



Impact of CNT Parameters on Compound Metric

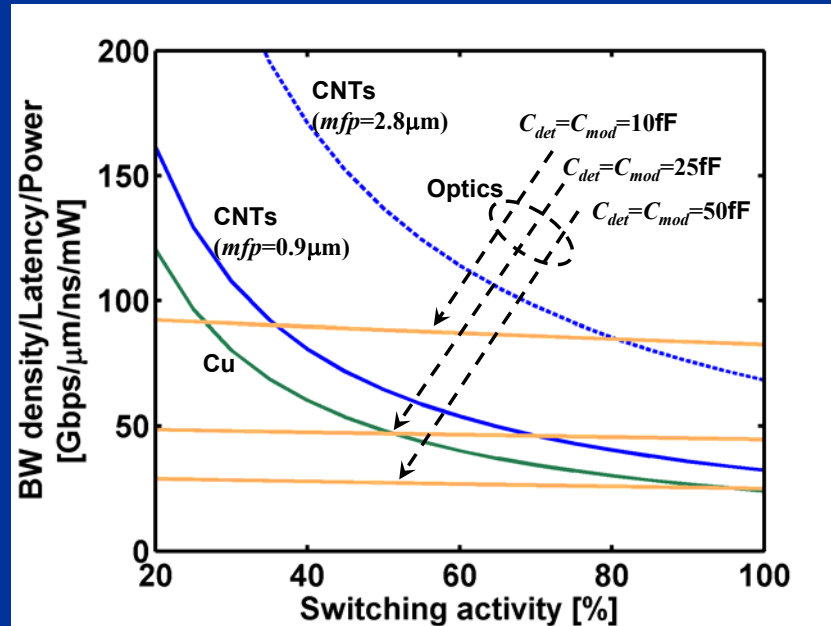


Wire length=10mm, CNT: $mfp=0.9\mu m$, $PD=1/3$, $C_{det}=C_{mod}=10fF$,
 $f_{ck}=10Gbps$, 22nm technology node

- ❑ **CNTs: ~1.4X better performance for Improving both mfp and PD**
- ❑ **Optics: device capacitances $<10fF$** → enable optics have better performance



Impact of Switching Activity on Compound Metric



Wire length=10mm, CNT: $mfp=0.9\mu m$, $PD=1/3$, $C_{det}=C_{mod}=10fF$, $f_{ck}=10Gbps$, 22nm technology node

□ **Cu, CNTs: dynamic power $\propto SA$ whereas Optics: static power $\sim SA$**

- Optics (10fF) vs. CNTs ($mfp=0.9\mu m$): cross-over $SA \sim 40\%$
- Optics (10fF) vs. CNTs ($mfp=2.8\mu m$): cross-over $SA \sim 80\%$

Optics is favorable for high SA



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Conclusion

- ❑ **Quantification of the circuit models (R, L, and C) of Cu and CNT**
- ❑ **Comparison with primary metrics**
 - Power: CNTs (practical) ~ Cu < Optics
 - Latency: Optics < CNTs (practical) < Cu
- ❑ **Comparison with compound metric:** BW density/latency/power
 - Optics > CNTs (practical) > Cu
- ❑ **Evaluation of the impact of device/material/system parameters**
 - System: global clock frequency (f_{ck}), SA
 - Material (CNT): mfp and PD
 - Device Capacitance for Optics
- ❑ **Comparison framework gives the insight to system/device engineers which interconnect technology is proper to their system application**

