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

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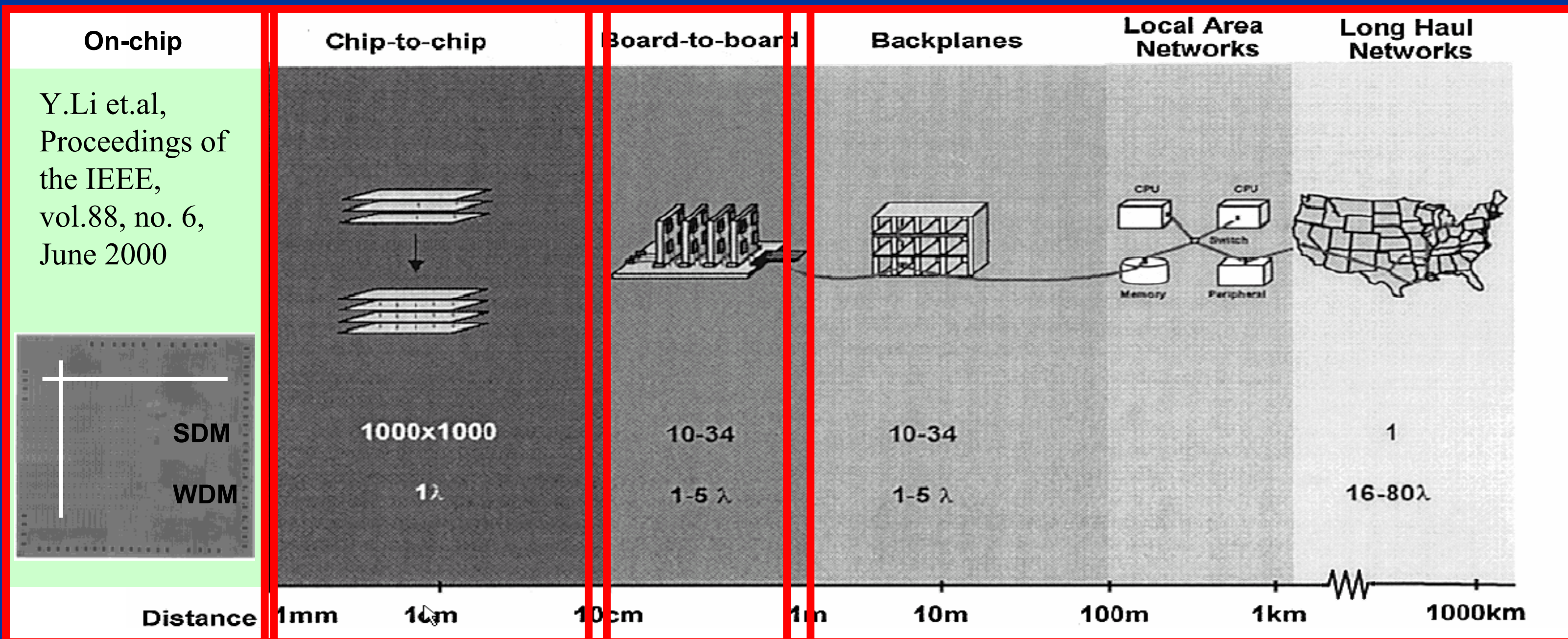
Outline

- **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

Inside box: traditionally Copper

Out of Box: Optics strong-hold



Digital Systems: Short interconnects

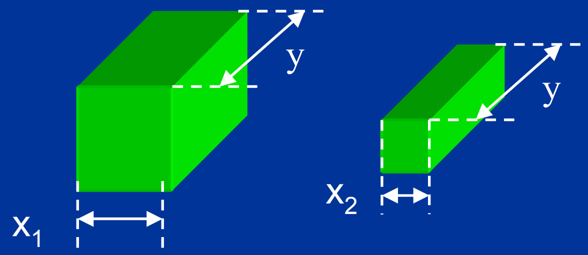
Network

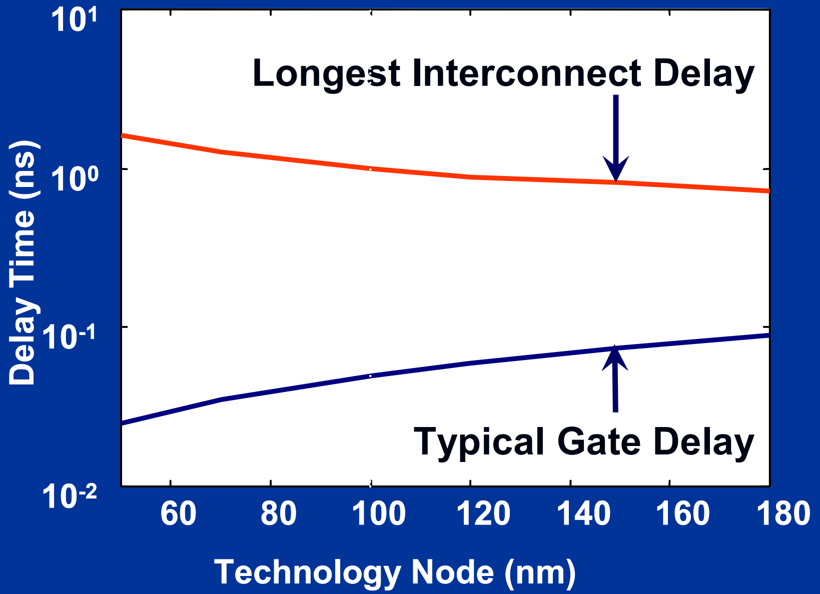
Interconnect level of this talk: On-chip global wires

Limit of On-chip Electrical Interconnect: Latency

- On-chip wires are getting slower

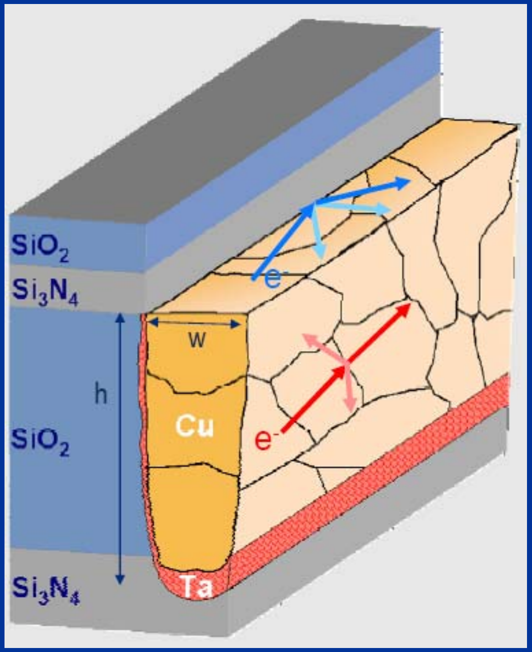
Cross-section Scaling

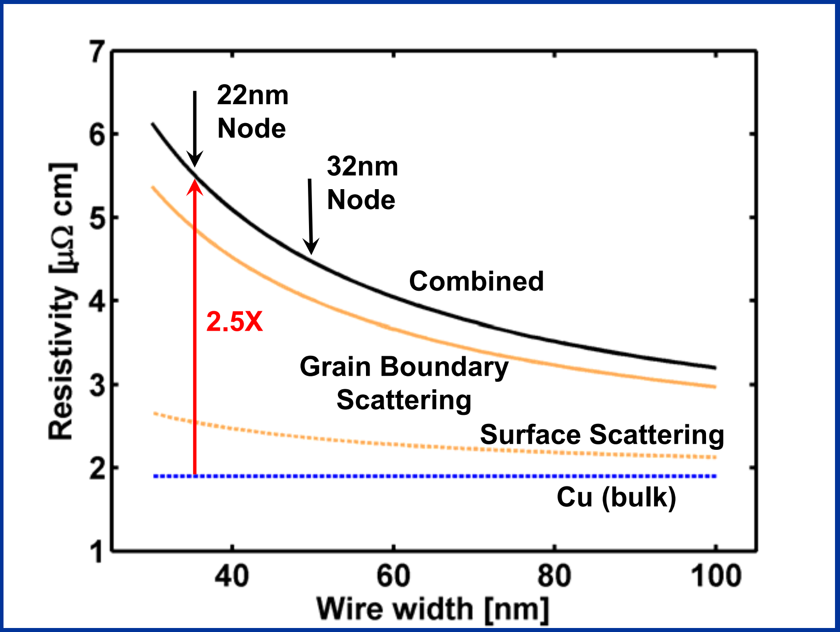




Wire delay is deteriorating wrt gate delay with scaling even with low-k materials

Limit of On-chip Electrical Interconnect: Resistance

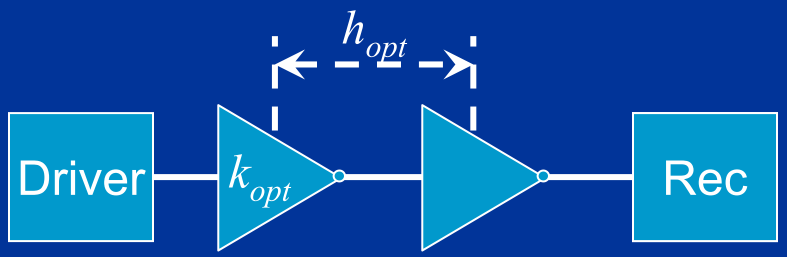




Based on W. Steinhogl et.al. Phys. Rev. B, 2002

- **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

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

With Repeaters

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

- **Delay (helps enormously)**
  - Best possible interconnect delay
  - Linear with length
  - Scales better
  - **But is it good enough?**

Repeaters have power and area penalty: need new interconnect technologies…

Alternative Candidates

	Pros	Cons
Optics	➢ Low loss for longer wire and higher bandwidth ➢ **Lower power** at higher bandwidth and switching activity ➢ Wavelength Division Multiplexing	➢ Larger pitch(~0.6μm) → Lower BW density
Carbon Nanotube (CNT)	➢ Small device: ~nm diameter ➢ Longer mean free path → Resistance ↓	➢ 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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  - **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
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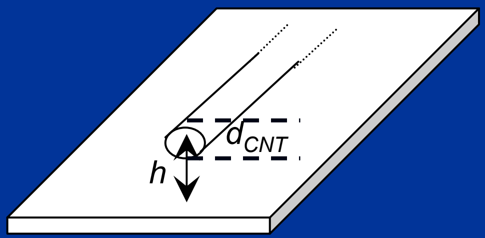
RLC Model for Single-wall CNT: Capacitances (C_E, C_Q)

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

- **Electrostatic Capacitance (C_E)**



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

- **Quantum Capacitance (C_Q)**

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

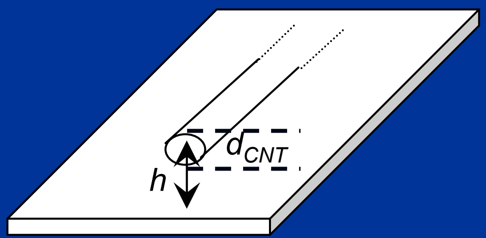
[P. J. Burke, Trans. on Nanotechnology, 2002]

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)



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

$$= 1.6 nH / mm$$

4 orders higher magnitude

→ Inductance effects becomes important

❑ Kinetic inductance (L_k)

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

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

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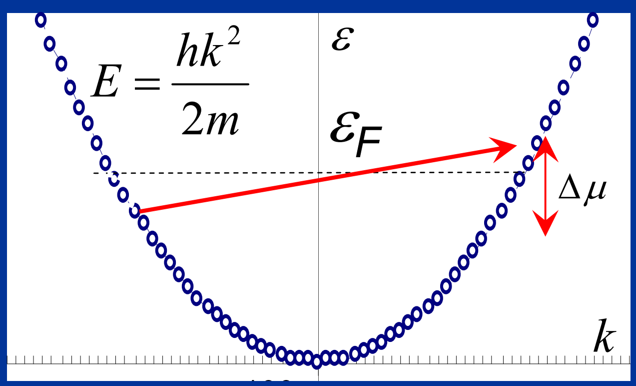


RLC Model for Single-wall CNT: Resistance

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

- **Contact resistance (R_C)**
  - 120KΩ → ~KΩ per nanotube [H. Dai, Applied Phys. A, 2004]

- **Quantum resistance (R_Q)**

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

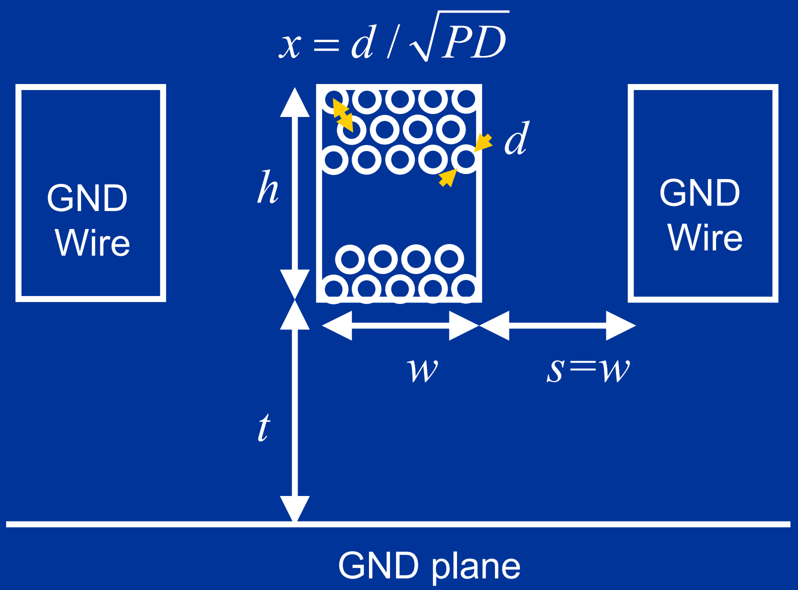
[P. J. Burke, Trans. on Nanotechnology, 2002]

- **Wire resistance (R_w)**
  - **linear model** [J.Y. Park, *Nano Letters*, 2004]
  - Good quality CNT: l_o=1.6μm

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

$$C_w \sim C_E$$

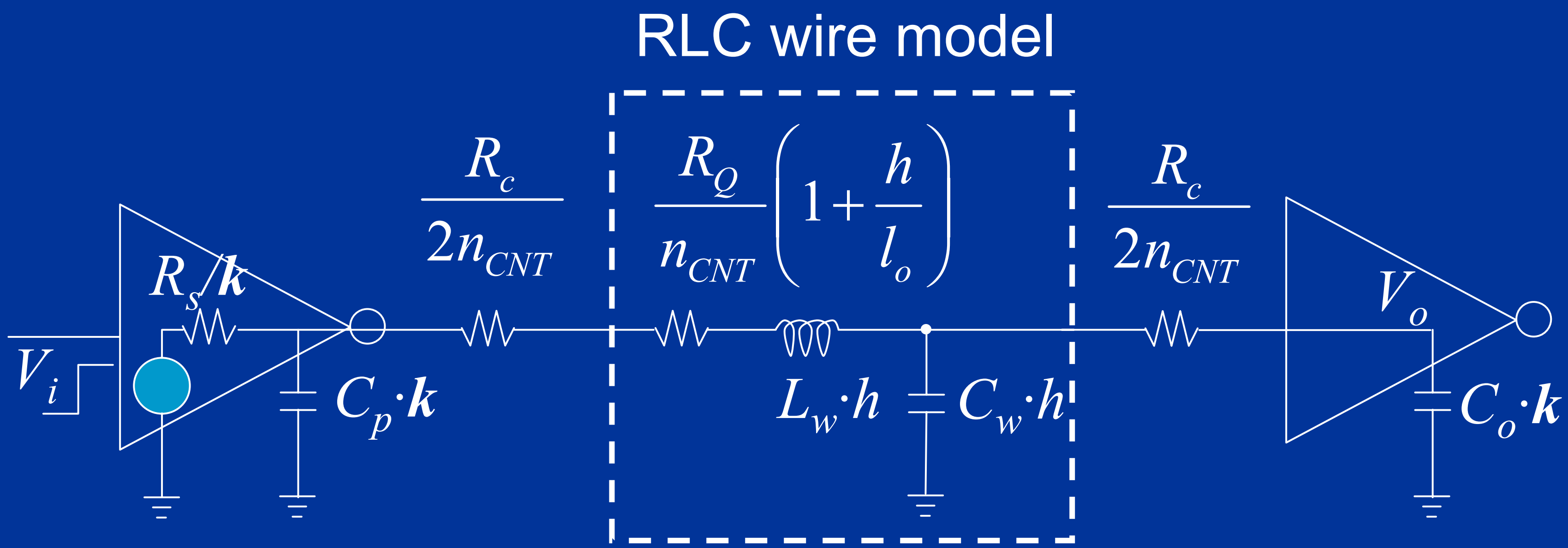
$$L_w \sim L_k / 4n + L_m$$

$$R_C \sim 0$$

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

Repeater Model: RLC

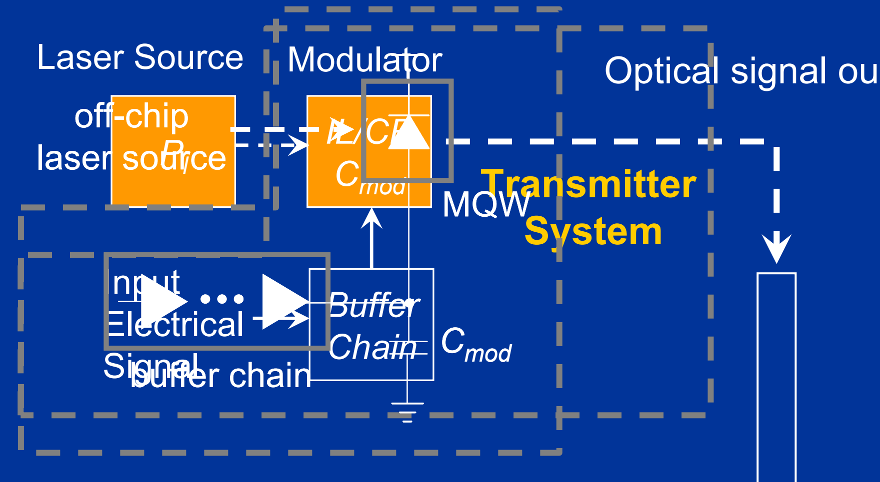
- **RLC model**
  - No closed form solution: k (driver size) and h (repeater spacing)
  - Newton-Raphson numerical iteration method
  - Increase in the inductance ratio to resistance
    - ✓ $k \downarrow$ **and** $h \uparrow$
    - ✓ the total repeater capacitance reduces resulting in a **lower power: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

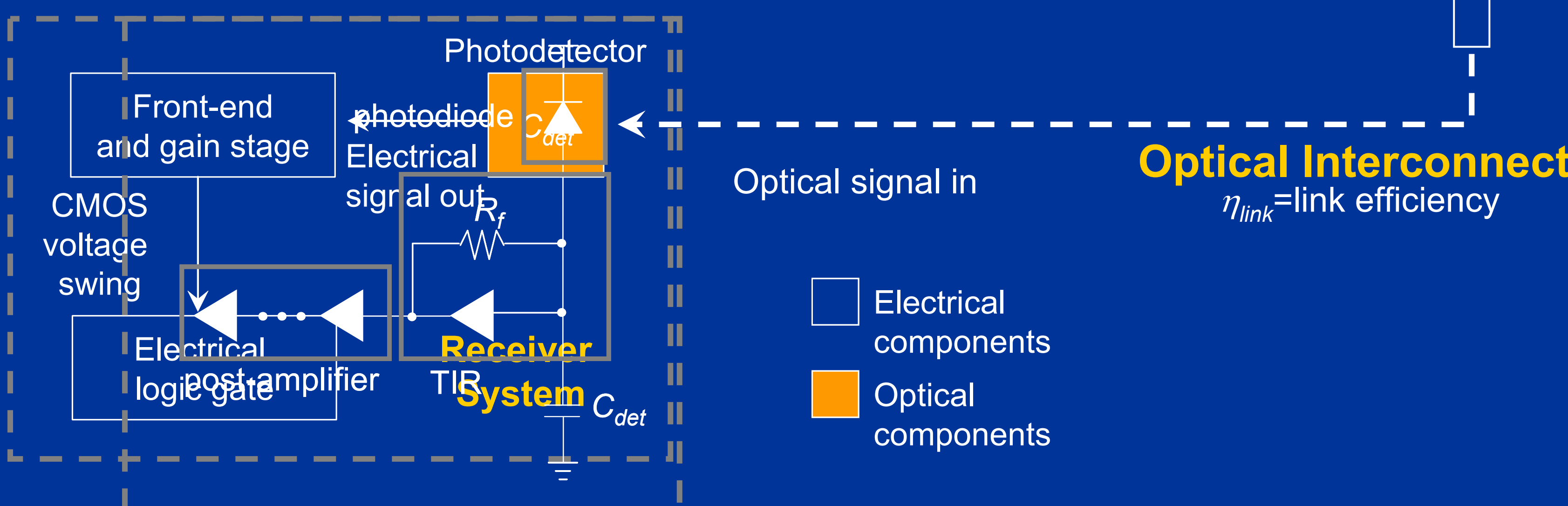


K. Banerjee, Trans. on CAD of Int. Circuits and Systems, vol. 21, 2002.

Optical Interconnect: Modeling

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





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

    } **Optimize design parameters**
  - **Receiver power dramatically decreases with the detector capacitance**: P. Kapur, IITC, 2002
    - ✓ Device Capacitance: 50fF → 10fF

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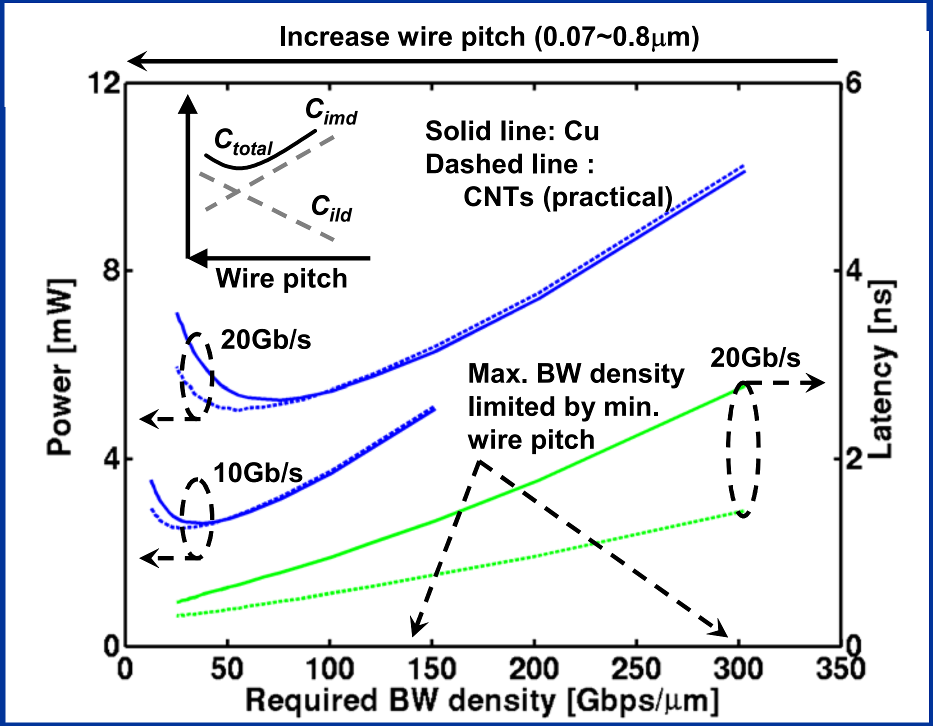
Performance Comparison: Power and Latency for Cu/low-K and CNT

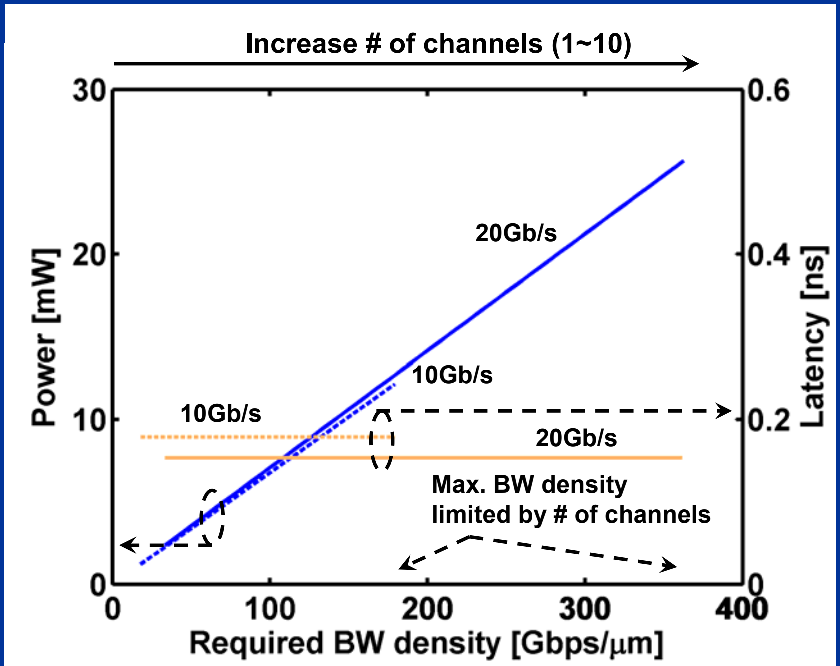


Wire length=10mm, 22nm technology node

- **BW density** limited by Min. pitch of ITRS: ~150Gbps/μm for f_{ck}=10Gbps
- **Further limited by repeater area**
- **Power:** Wide wire pitch exhibits inductance effect

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

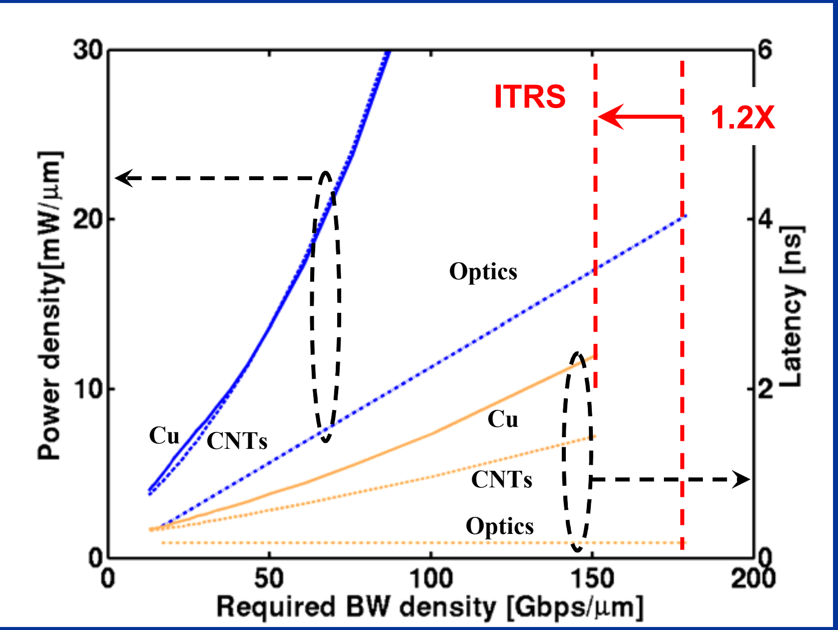
Performance of Optics: Power and Latency



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=0.9μm, 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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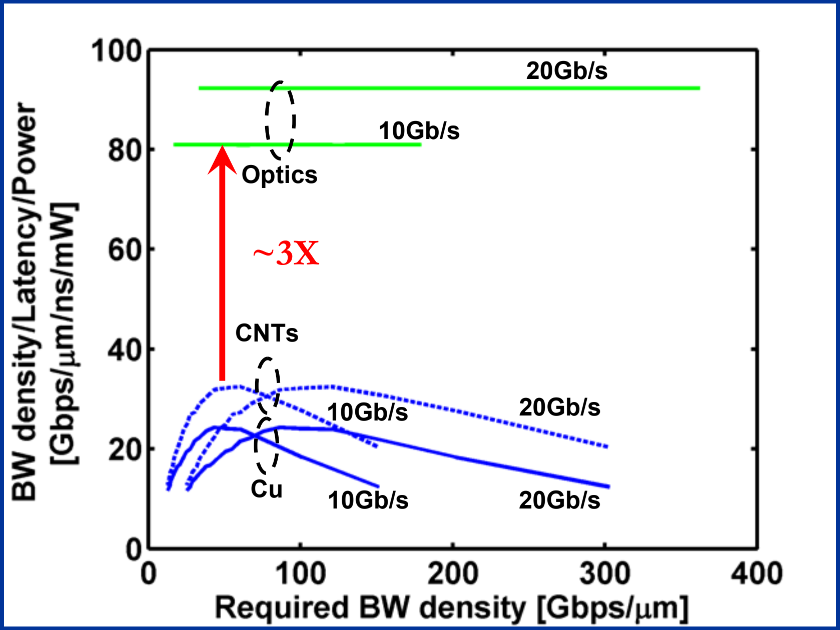
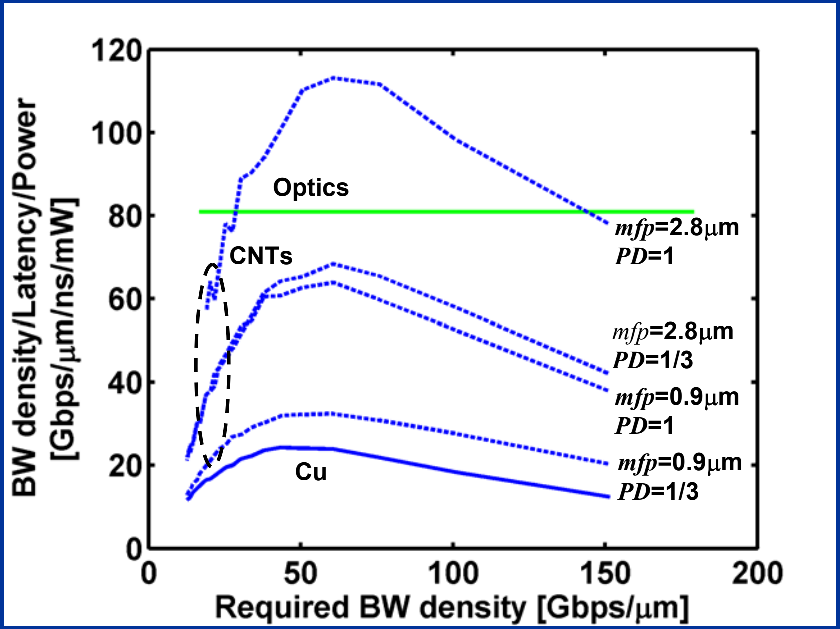
Performance Comparison: Compound metric



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

- **Optics ~3X higher CNTs @Maximum**
- **CNT, Cu: optimum wire pitch, maximizing metric: 3~5×W_{min}**

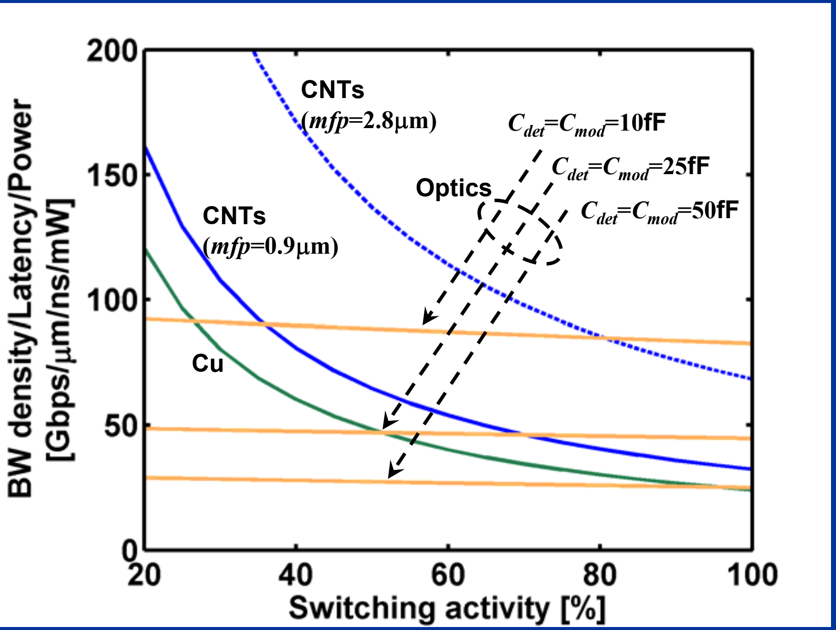
Impact of CNT Parameters on Compound Metric



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

- **Cu, CNTs: dynamic power ∝ SA whereas Optics: static power ~ SA**
  - Optics (10fF) vs. CNTs (mfp=0.9μm): cross-over SA ~ 40%
  - Optics (10fF) vs. CNTs (mfp=2.8μm): cross-over SA ~ 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**