Surfliner: Approaching Distortionless Light-Speed Wireline Communication

Haikun Zhu, Rui Shi, Chung-Kuan Cheng
Dept. of CSE, U. C. San Diego

Hongyu Chen
Synopsys Inc.

Outline

- Motivation
- Previous Work
- Surfliner
    - Overview
    - Theory
    - Implementation
    - Simulation Results
- Applications
- Conclusions

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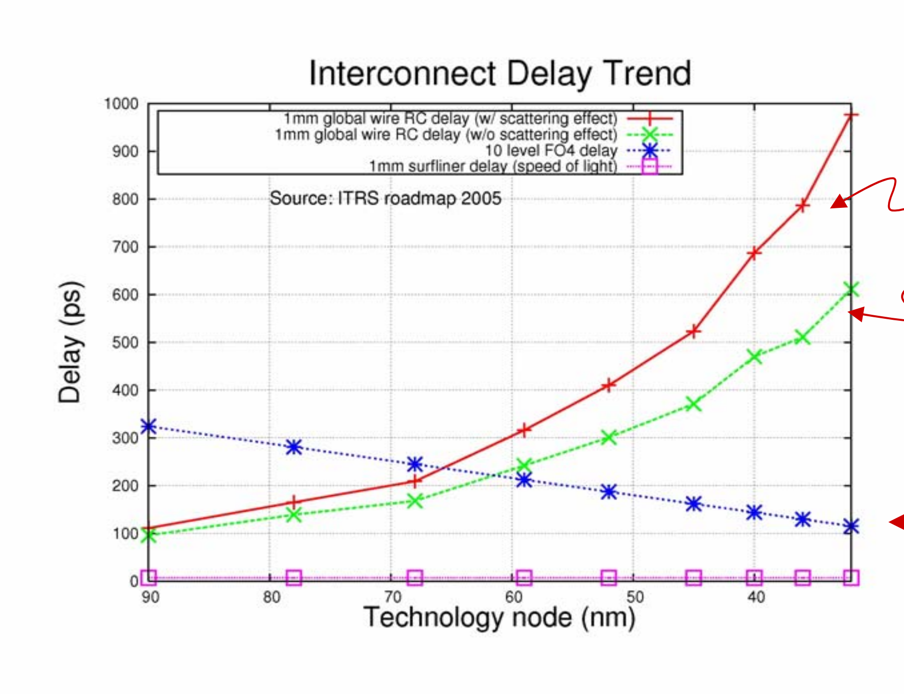
Motivation — On-chip Perspective

- On-chip global interconnect trend



Wall of global interconnects
- Delay, power, cost, reliability

Abundant transistor computing resources and capability

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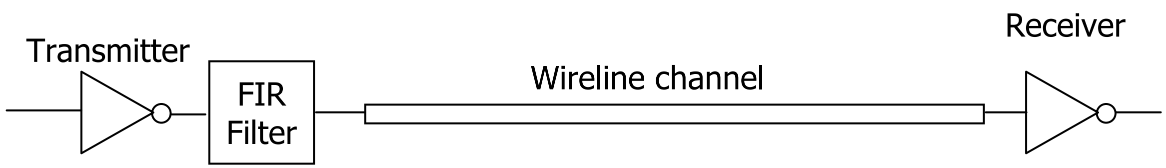
Previous Work

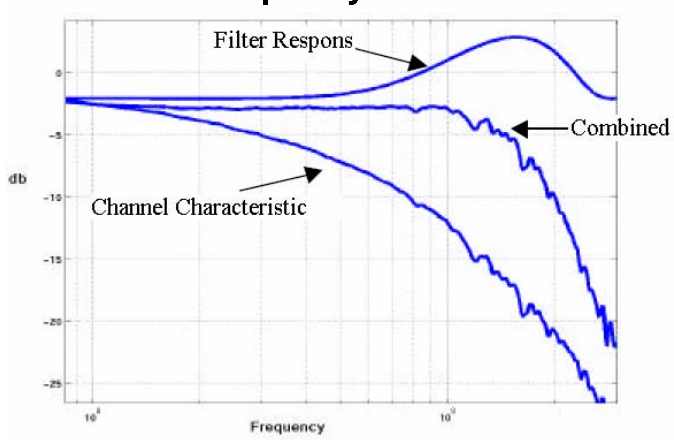
- Existing on-chip serial link signaling schemes
  - Pre-emphasis and equalization (W. Dally, ’98)
  - Clocked discharging (Horowitz, ISVLSI’03)
  - Frequency modulation (Wong, JSSC’03; Jose, ISVLSI‘05)
  - Non-linear transmission line (Hajimiri, JSSC’05, E. C. Kan, CICC’05)
  - Resistive termination (Hashimoto, EPEP’04, Tsuchiya, CICC’04, Flynn, ICCAD’05, CICC‘05)

Pre-emphasis

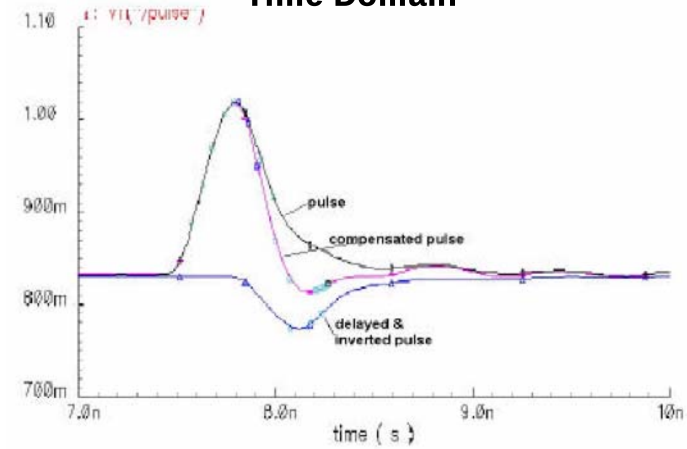
- A high-pass filter at the transmitter side to compensate the channel characteristic



Frequency Domain

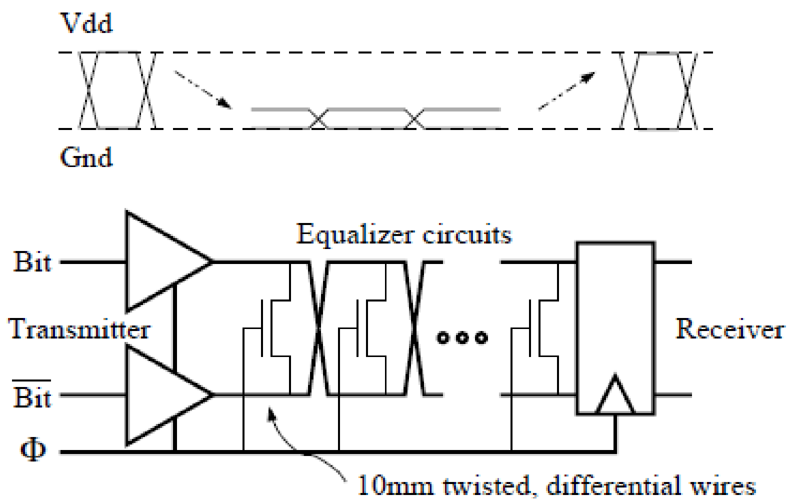


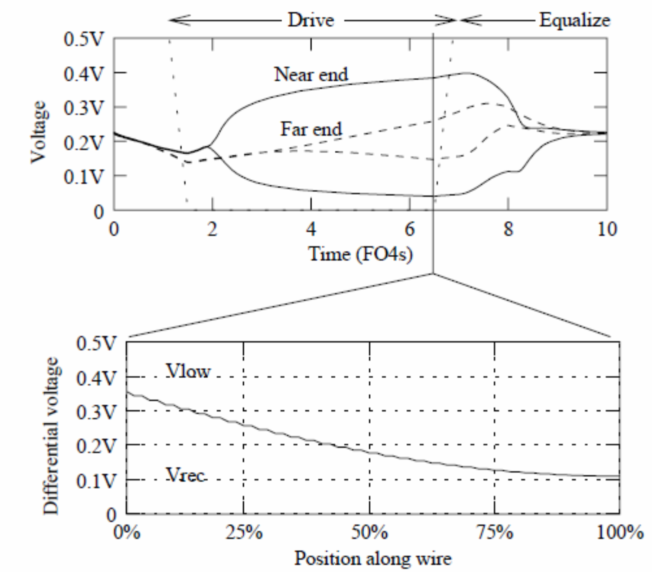
Time Domain



Pictures courtesy of Johnny Zhang and Zhi Wang, "White paper on transmit pre-emphasis and receive equalization"

Clocked Charge Recycling





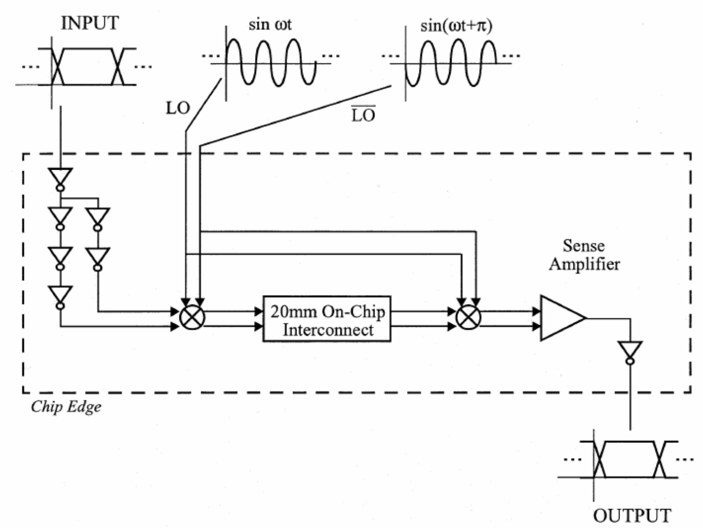
- Essentially time-domain equalization directly implemented on the wire

Ron Ho, M. Horowitz, ISVLSI '03

Frequency Modulation

- Modulate the data to high-frequency (LC region) to achieve speed-of-light, low distortion transmission

Richard T. Chang, Simon Wong, JSSC '03

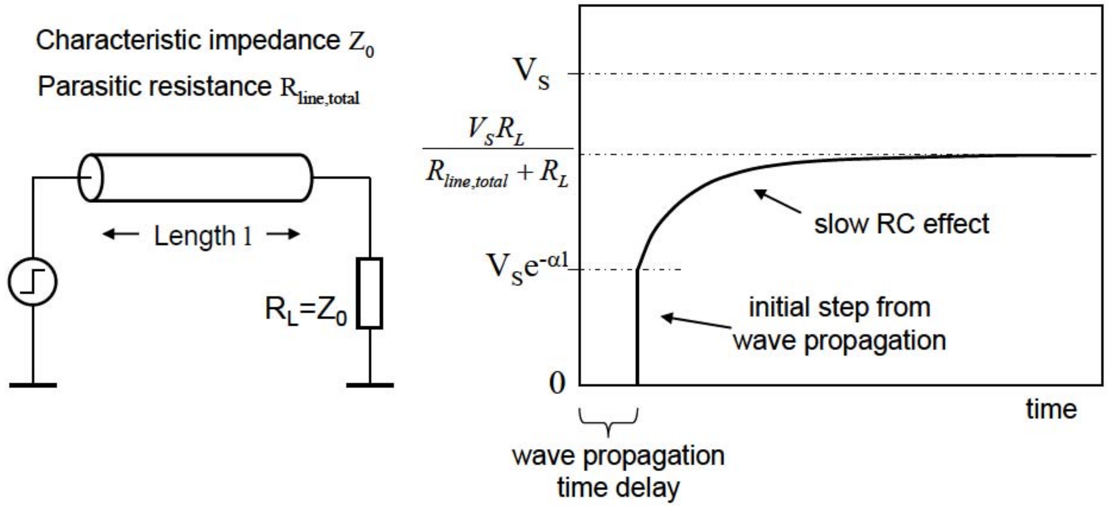


- Use RZ bit piece instead of NRZ, and reduce the duty cycle to push more frequency content to the higher spectrum (Jose et al., ISVLSI '05)

Resistive Termination

- Use resistive termination to cut the slow RC top

Michael Flynn, ICCAD '05



- Tsuchiya et al. developed an analytical model for eye opening with resistive termination (CICC '05)

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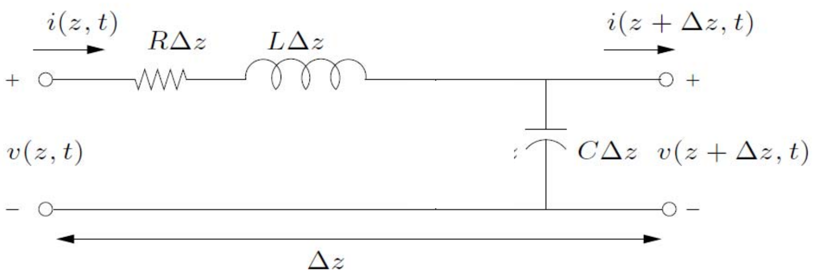
Surfliner — Overview

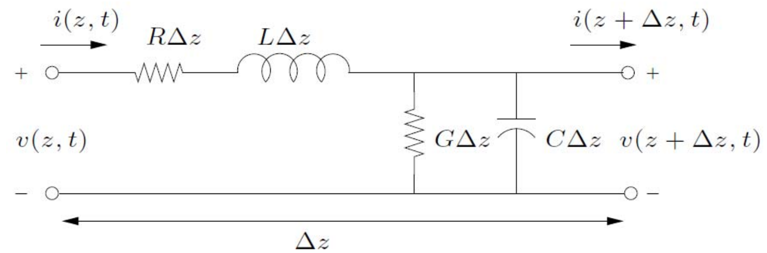
- Single-ended case

Typical on-chip Transmission Line



- negligible leakage conductance
- Frequency dependent phase velocity (speed) and attenuation

Distortionless Transmission Line



- Intentionally make leakage conductance satisfy R/G=L/C
- Frequency response becomes flat from DC mode to Giga Hz

Telegrapher's Equations

- Telegrapher's equations

$$\frac{\partial V(z,t)}{\partial z} = -RI(z,t) - L\frac{\partial I(z,t)}{\partial t}$$
$$\frac{\partial I(z,t)}{\partial z} = -GV(z,t) - C\frac{\partial V(z,t)}{\partial t}$$

- Wave Propagation

$$V(z) = V_0 e^{-\alpha z - j\beta z} \qquad I(z) = V(z)/Z_0$$

- Propagation Constant

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

- Characteristic Impedance

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

- α and $v = \omega/\beta$ correspond to attenuation and phase velocity. Both are frequency dependent in general.

On-Chip Wires

- RC Region $\omega L << R, G \approx 0$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$
$$\approx \sqrt{j\omega RC}$$
$$= \sqrt{\frac{\omega RC}{2}} + j\sqrt{\frac{\omega RC}{2}}$$

$$Z = \sqrt{\frac{R}{j\omega C}} \qquad v = \sqrt{\frac{2\omega}{RC}}$$

Typical on-chip wire: R = 2 Ω/μm (A=0.01 μm^2)
L = 0.3 pH/μm, C = 0.2fF/μm
R/L = 0.67E+12

LC Region

- If $\omega L \gg R, G \approx 0$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$
$$= \sqrt{(R + j\omega L) j\omega C}$$
$$= \frac{R}{2\sqrt{L/C}} + j\omega\sqrt{LC}$$

$$Z_0 = \sqrt{\frac{L}{C}} \qquad \alpha = \frac{R}{2Z_0} \qquad v = \frac{1}{\sqrt{LC}}$$

This is the premise of the frequency modulation approaches

Surfliner — Theory

- Distortionless transmission line

If $\dfrac{R}{G} = \dfrac{L}{C}$

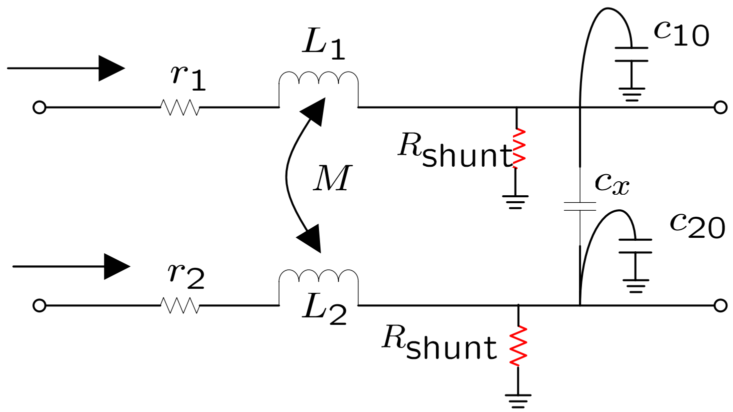
$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$
$$= \frac{R}{\sqrt{L/C}} + j\omega\sqrt{LC}$$

$$Z_0 = \sqrt{\frac{L}{C}} \qquad \alpha = \frac{R}{Z_0} \qquad v = \frac{1}{\sqrt{LC}}$$

Both attenuation and phase velocity become frequency independent

Surfliner — Differential Case

Common Mode – Current flowing in the same direction

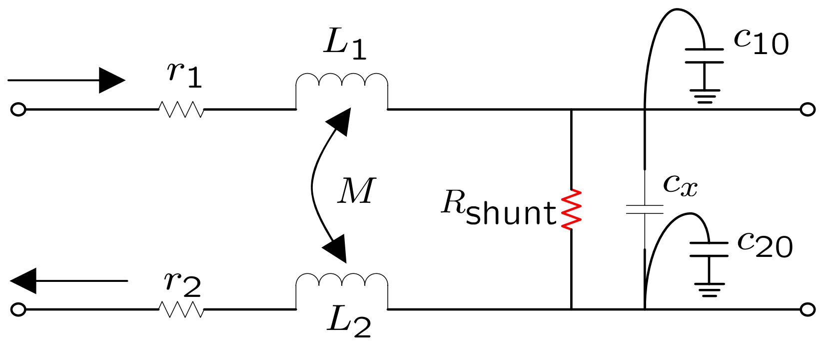


Shunt between each line to ground

$$R_{\text{shunt}} = Z^2_{\text{even}}/R_{\text{series}}$$

$$Z_{\text{even}} = \frac{(1+M)L_1}{C_{10}}$$

Differential Mode – Current flowing in the opposite direction



Shunt between the two lines

$$R_{\text{shunt}} = 2Z^2_{\text{odd}}/R_{\text{series}}$$

$$Z_{\text{odd}} = \frac{(1-M)L_1}{C_{10}+2C_x}$$

Surfliner — Implementation

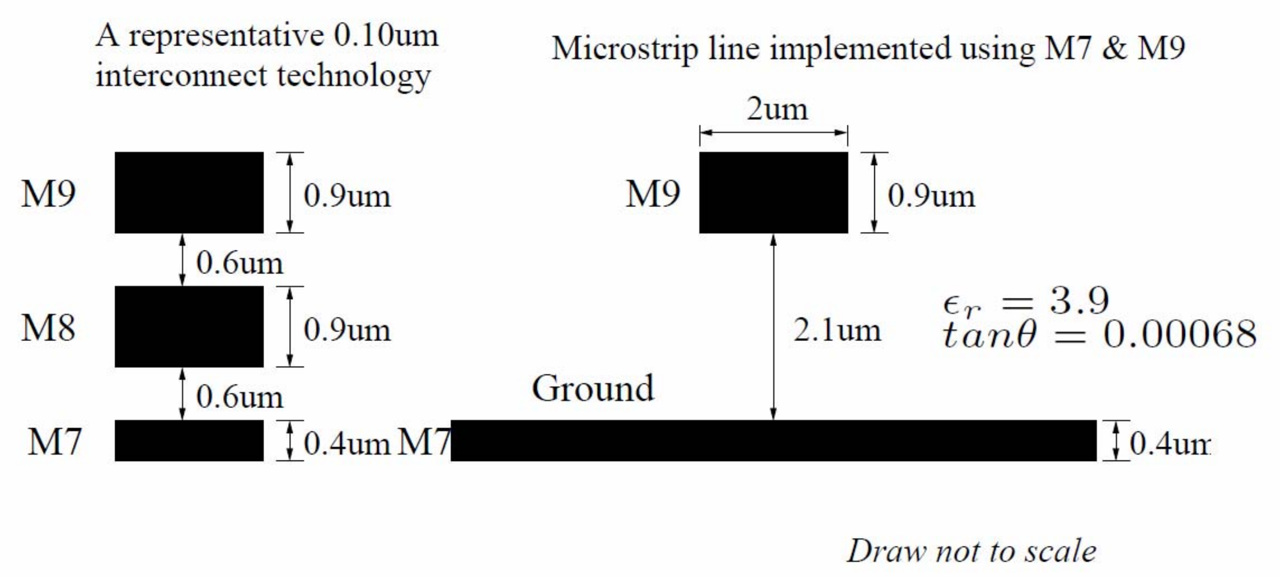
- Evenly add shunt resistors between the signal line and the ground

- Non-ideality

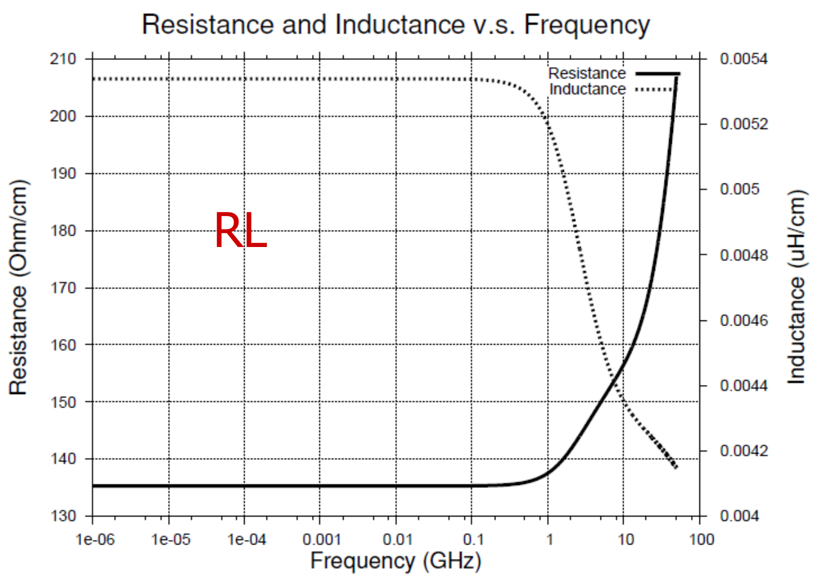
Ideal Surfliner	In Practical	Implication
Homogeneous and distributive	Discrete	What's the optimal spacing? Are the shunt resistors realizable?
RLGC are frequency independent	RLGC vary over frequency	What's the optimal frequency to do the matching?

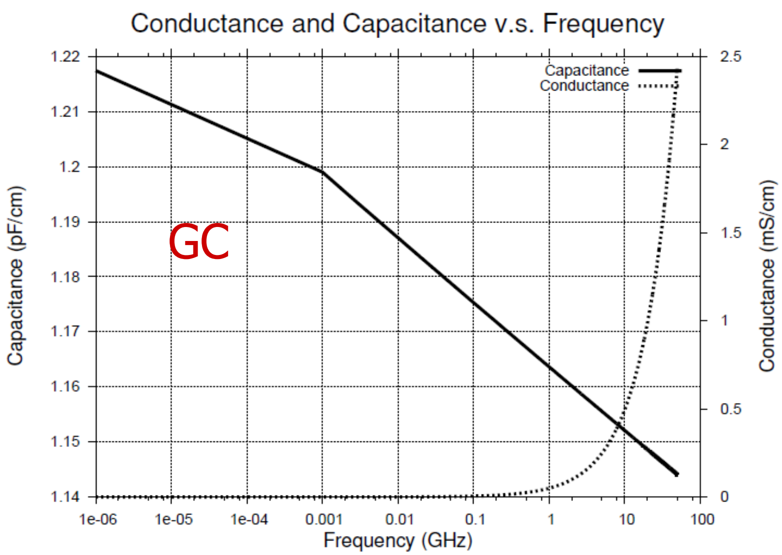
Surfliner — Simulation

- On-chip single-ended stripline, 10 mm



RLGC parameters





Z0 = 54.7 Ω, speed = 65.87 ps/cm

- Match at DC
  - Boost up low frequency traveling speed
  - Balance low frequency attenuation and high frequency attenuation

R_{1MHz}=135.4 Ω/cm, L_{1MHz}=5.34E-3 μH/cm, C_{1MHz} =1.217 pF/cm

$G=R_{1MHz}C_{1MHz}/L_{1MH}$ = 32.41 Ω/cm

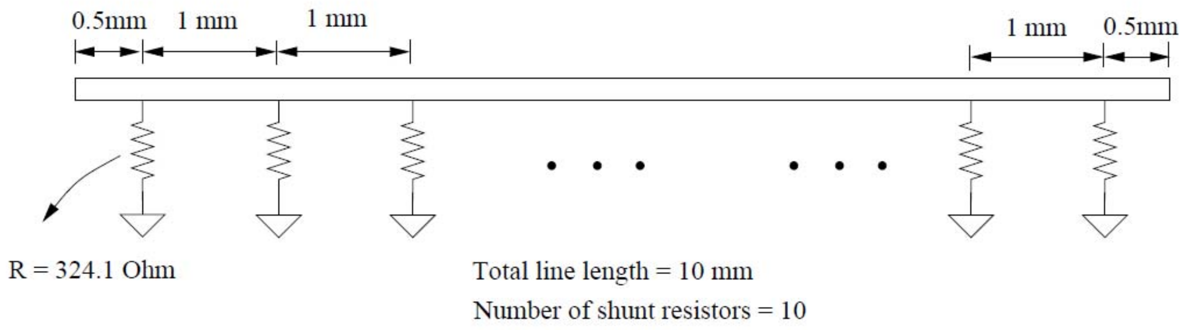
Shunt Resistor Spacing

- Assuming insert N shunt resistors

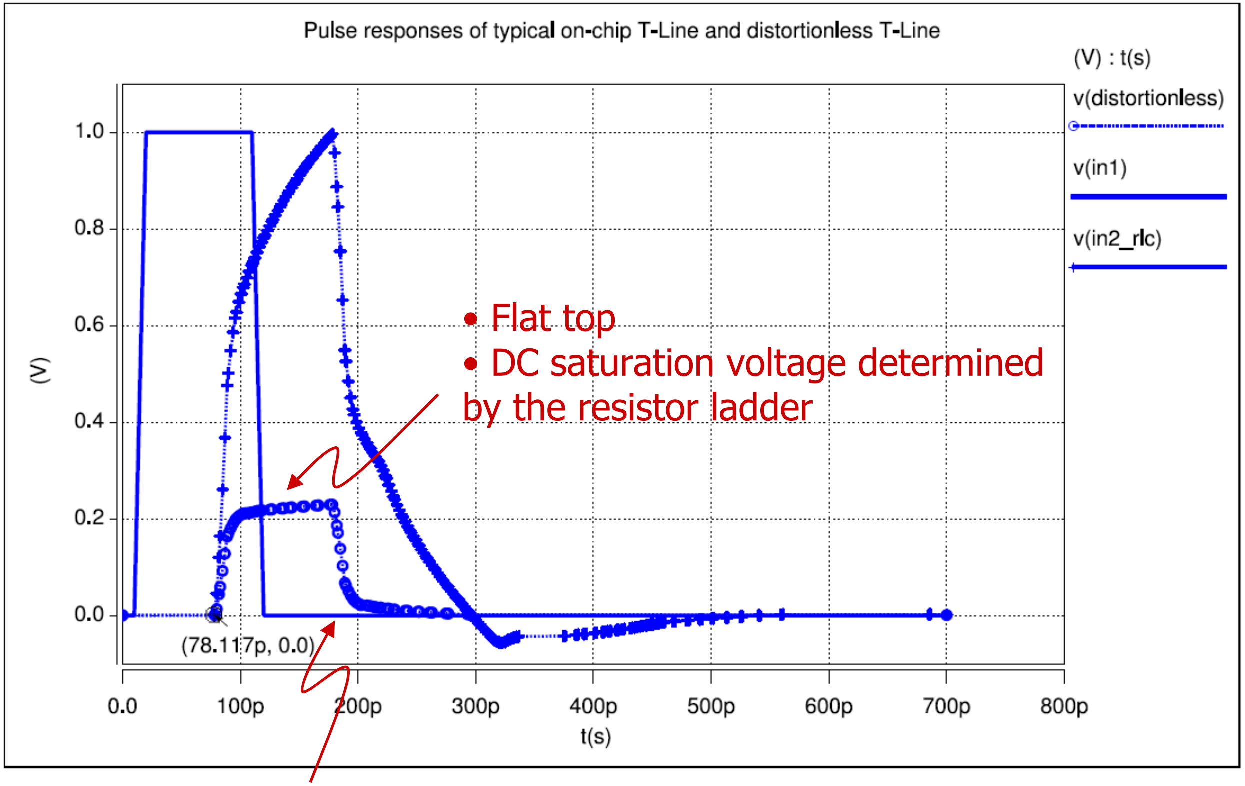
$$R_{\text{single}} = N \cdot R_{\text{shunt,total}}$$

- Optimal spacing depends on the target data rate

$$L_{\text{crit}} = \frac{c}{\sqrt{\epsilon_r}} \cdot t_r$$



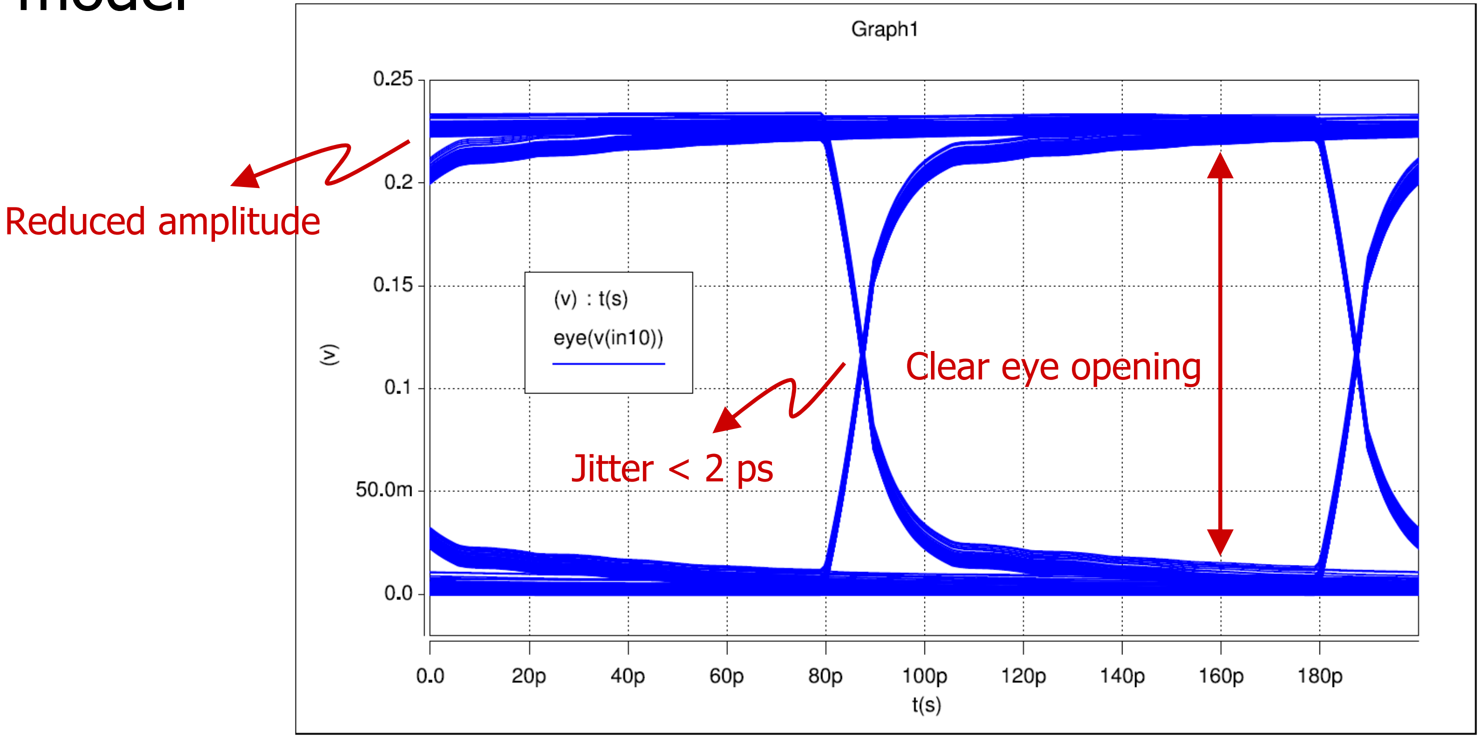
Pulse Response



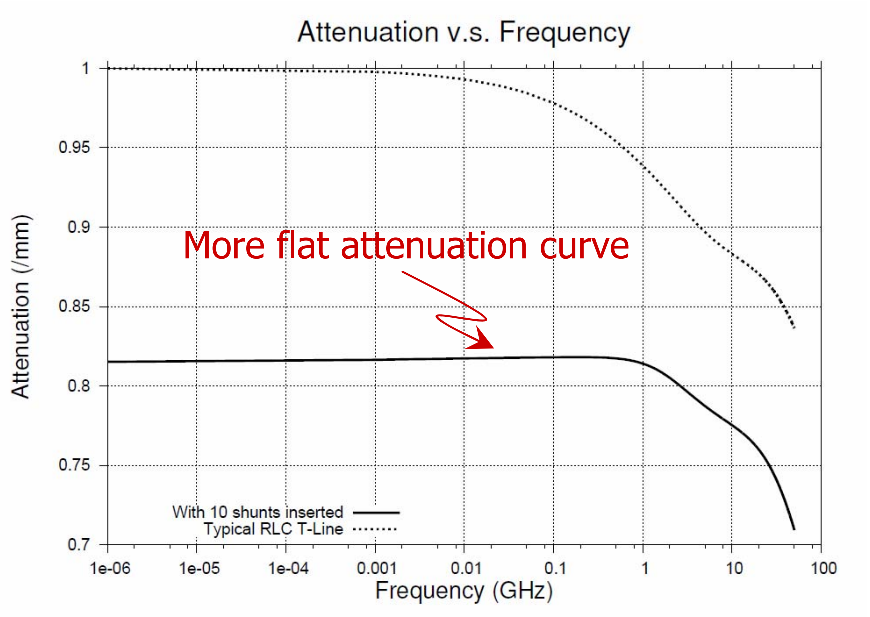
• ISI effect greatly suppressed

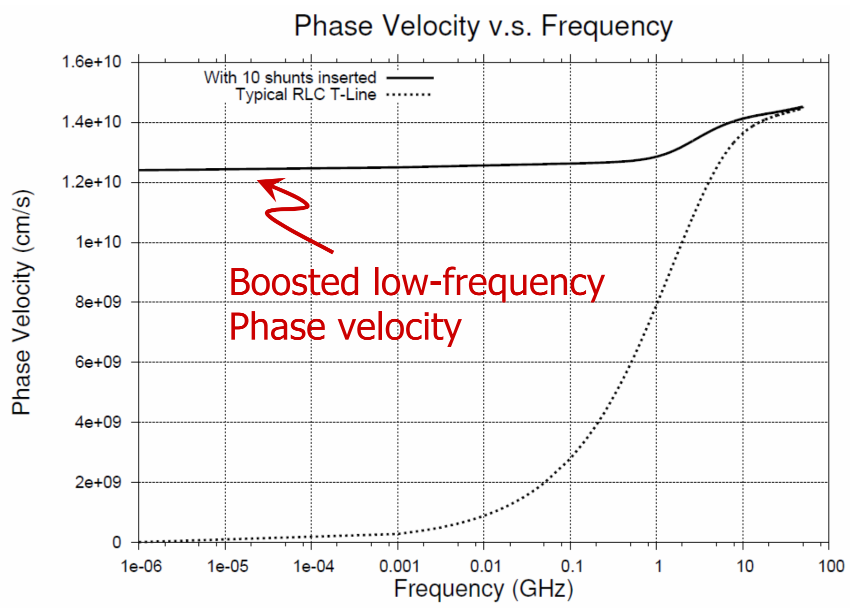
Eye Diagram

- 1000 bit PRBS at 10Gbps
- Simulated in Hspice using W-element + tabular RLGC model



A Frequency Domain Perspective





Power Consumption

- Would static power consumption through shunt resistors kill Surfliner?
  - Measured P_{avg}
  - Calculate $E_{bit}=P_{avg}*T_{cycle}$

Bit Rate (Gbps)	5	10	20	40
P_{avg} (mW)	2.5624	2.5754	2.6544	2.7612
E_{bit} (pJ)	0.5125	0.2575	0.1327	0.0690

Conclusions

- Demonstrated feasibility and superiority of Surfliner scheme
- Test chip fabrication (joint with Osaka)
  - Waiting for testing results
- Furture work
  - More applications: clock tree, etc.
  - Model data-dependent jitter
  - Incorporate transmitter/receiver design

The End

Thank you!