To Interleave or Not To Interleave, That is The Question

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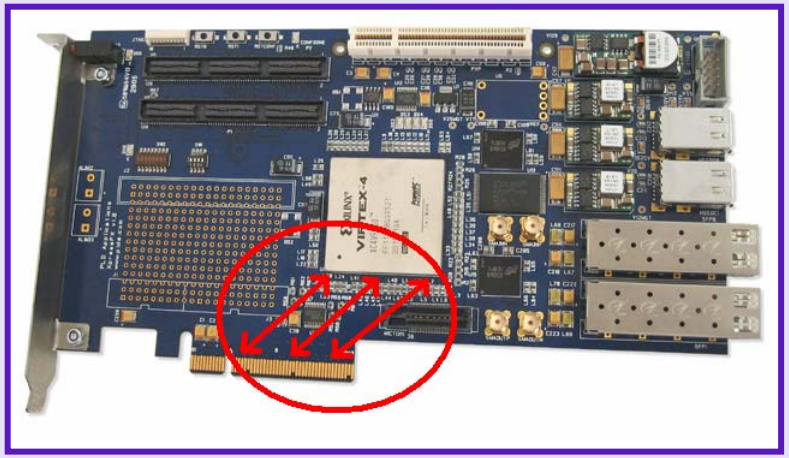
Agenda

- **The Question of Interleaving**
- Crosstalk Overview
- Microstrip Crosstalk Analysis
- Stripline Crosstalk Analysis
- Conclusion

Crosstalk in PCI Express®

- Major design concern
  - ✓ Same as in PCI and PCI-X®
    - – Large number of signals
    - – Signals need to go to the same place
    - → Large amount of parallelism

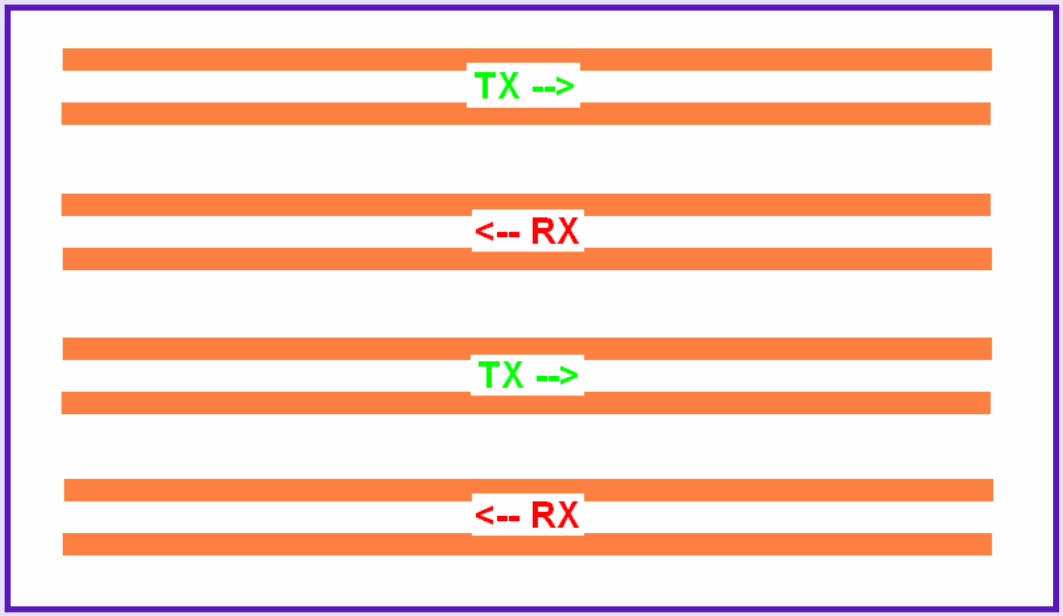


- Edge rates ~ 50ps
  - ✓ About 1/3 of an inch
  - ✓ More crosstalk for given parallelism

- Main method of control = increased spacing

Crosstalk in PCI Express

- PCI Express consists of unidirectional differential pairs
  - ✓ TX
  - ✓ RX



- Main concern is crosstalk at receiver

→ Crosstalk can ALSO be controlled by altering aggressor directionality

Crosstalk in PCI Express

- Interleave TX and RX pairs
  - ✓ Place a TX signal only next to an RX signal
  - ✓ Only crosstalk at receivers is reverse crosstalk
  - ✓ Preferred if forward crosstalk dominates
    - Forward crosstalk will go towards victim's transmitter

- Non-interleaving
  - ✓ Place TX signals next to other TX signals (same for RX)
  - ✓ Only crosstalk at receivers is forward crosstalk
  - ✓ Preferred if reverse crosstalk dominates
    - Reverse crosstalk will go towards victim's transmitter

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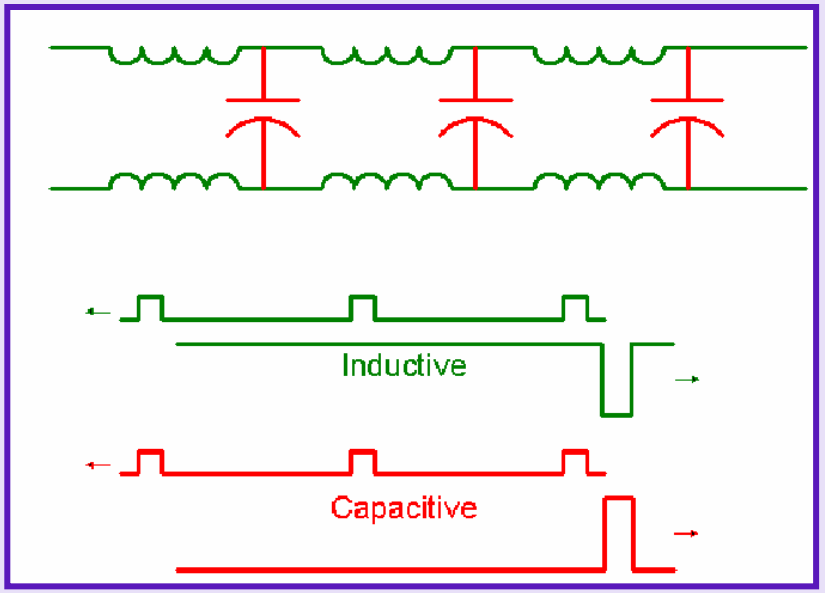
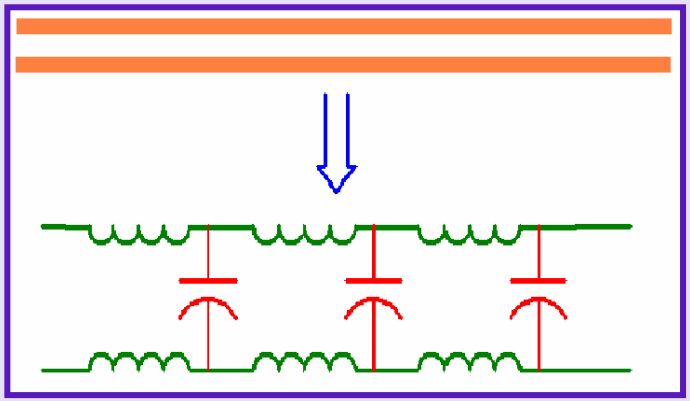
Crosstalk Overview

- Two types of crosstalk
  - ✓ Far-end crosstalk
    - A.k.a. Forward crosstalk
    - A.k.a. FEXT
  - ✓ Near-end crosstalk
    - A.k.a. Reverse crosstalk
    - A.k.a. NEXT

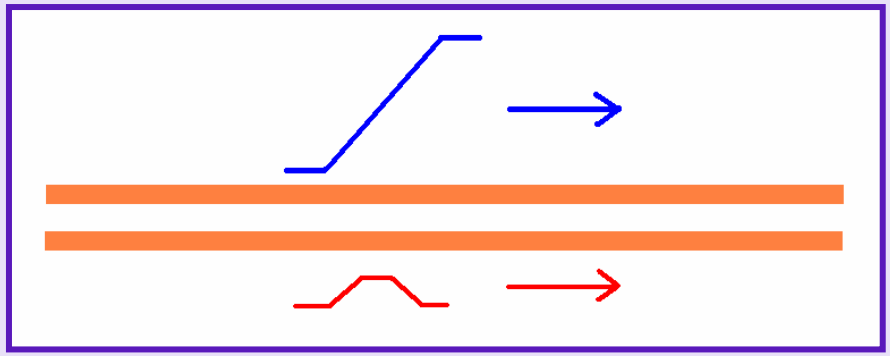


- Two types of coupling
  - ✓ Mutual Inductance
  - ✓ Mutual Capacitance



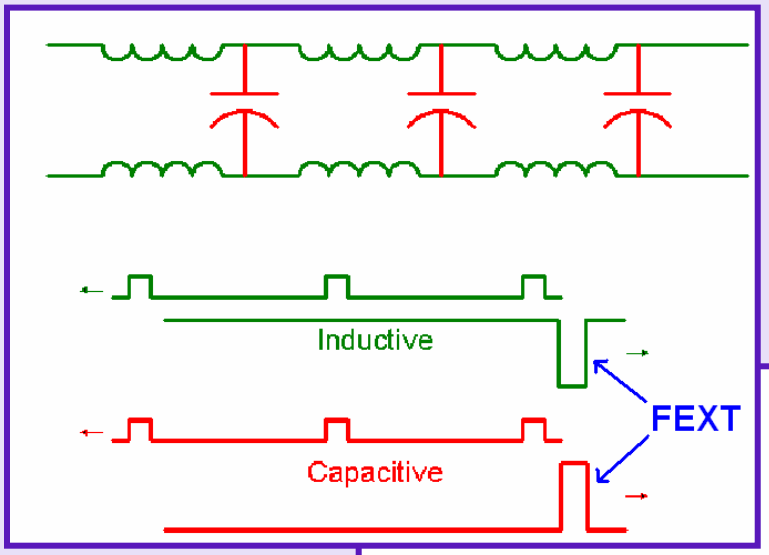
FEXT

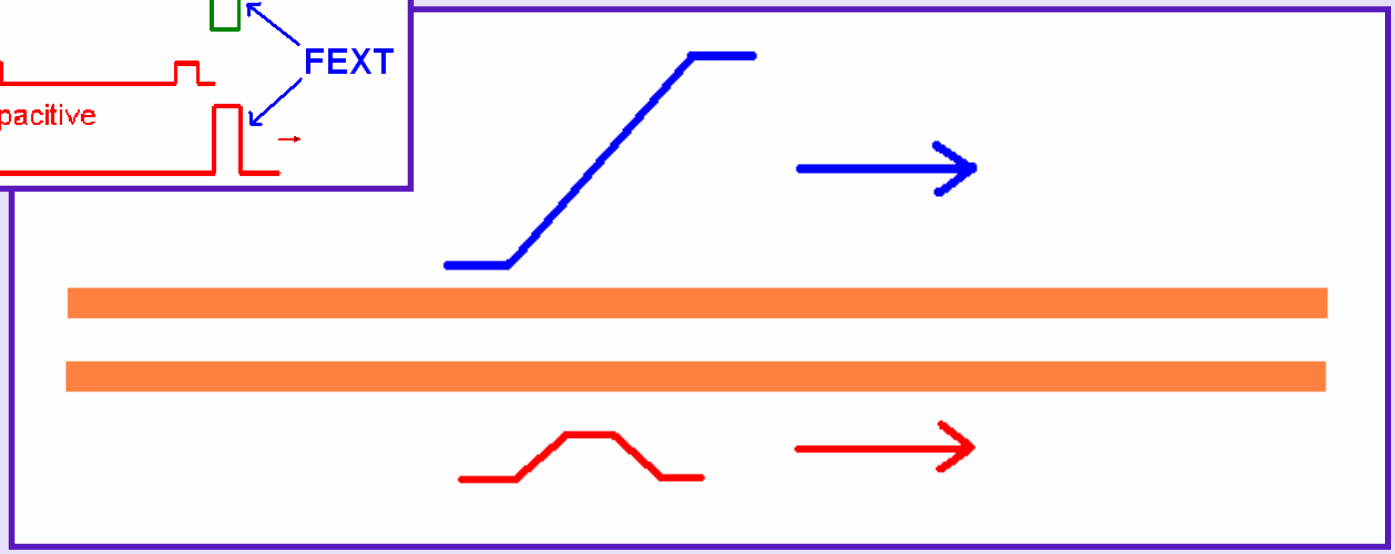
- Propagates with aggressor signal edge
- Has same edge width as aggressor signal edge
- Amplitude determined by coupling
  - ✓ Grows continuously
  - ✓ Negative coupling caused by mutual inductance
  - ✓ Positive coupling caused by mutual capacitance



FEXT

- Crosstalk pulses “stack” to form a larger pulse

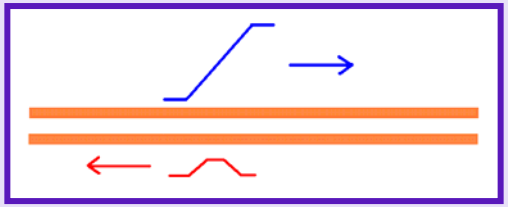




NEXT

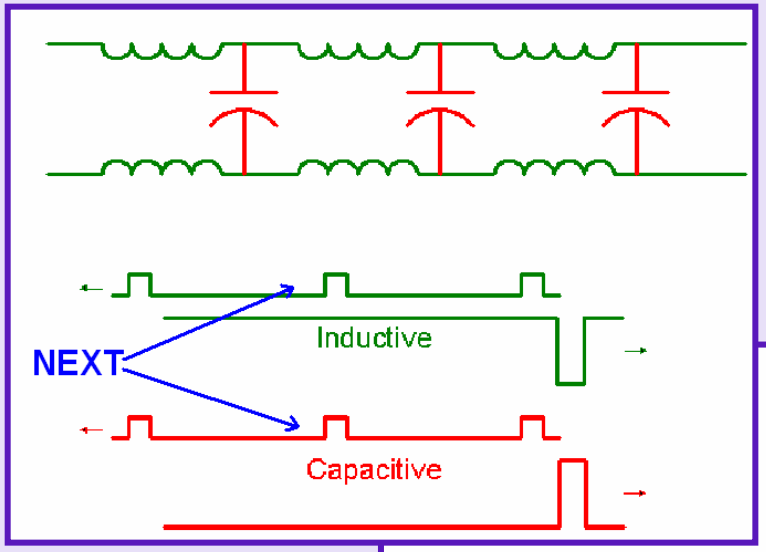
- Propagates in the reverse direction of aggressor signal edge
- Has width equal to twice the signal propagation time
- Amplitude determined by coupling
  - ✓ Saturates when

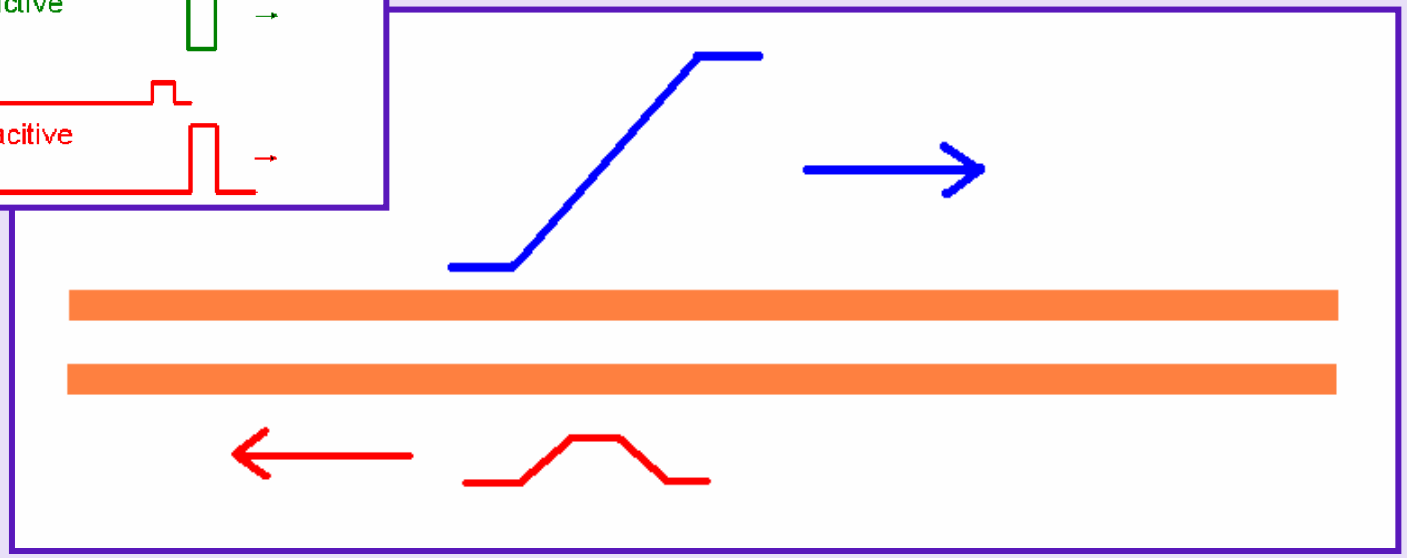
    parallelism length = aggressor edge length
  - ✓ Positive coupling caused by mutual inductance
  - ✓ Positive coupling caused by mutual capacitance



NEXT

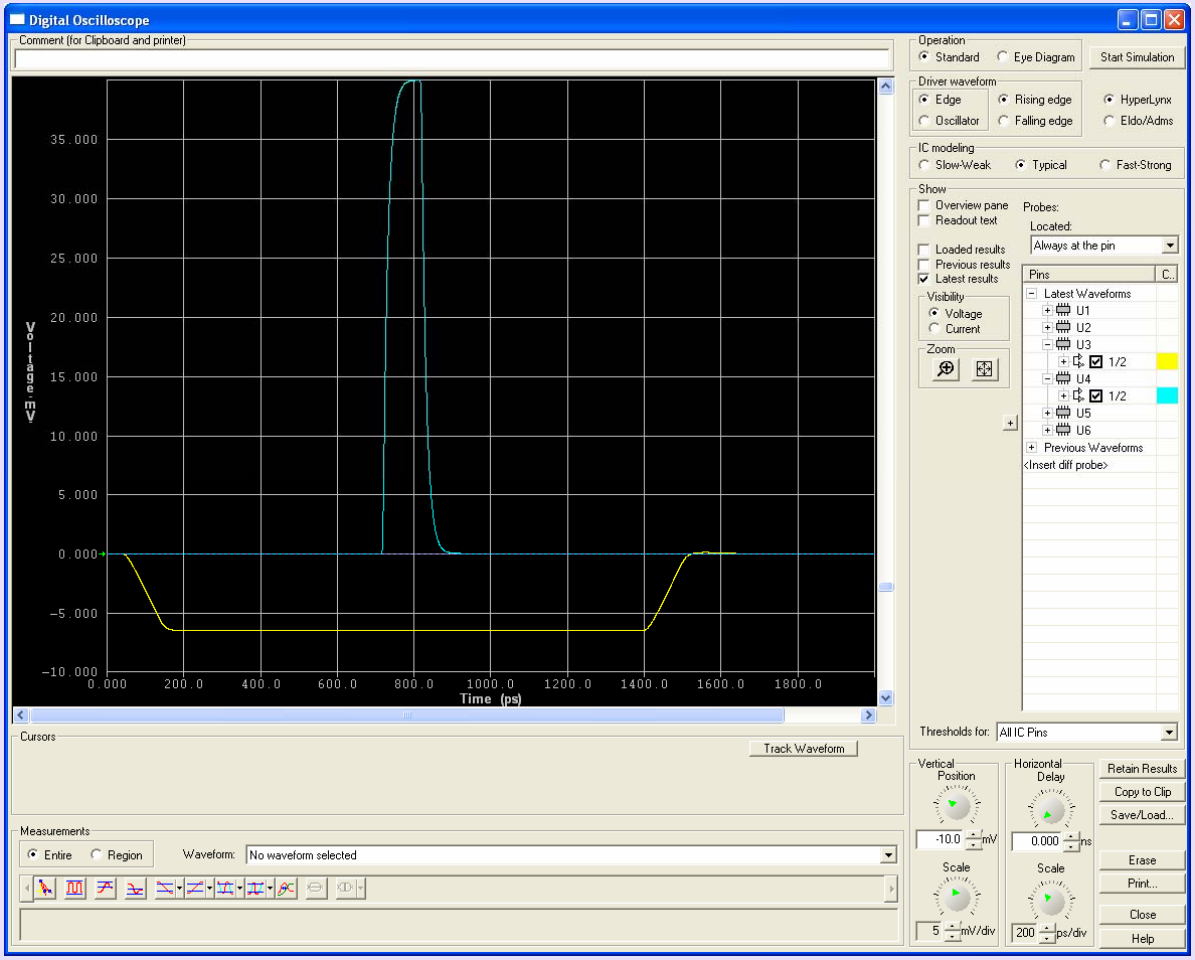
- Crosstalk pulses “line up” to form a longer pulse





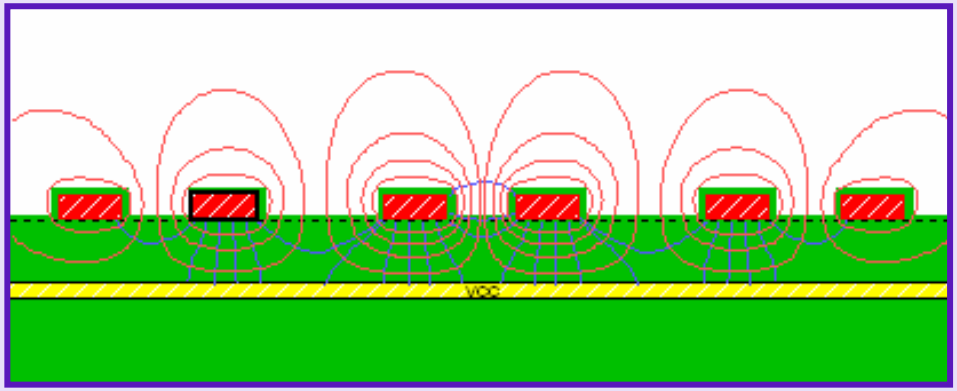
Crosstalk Examples

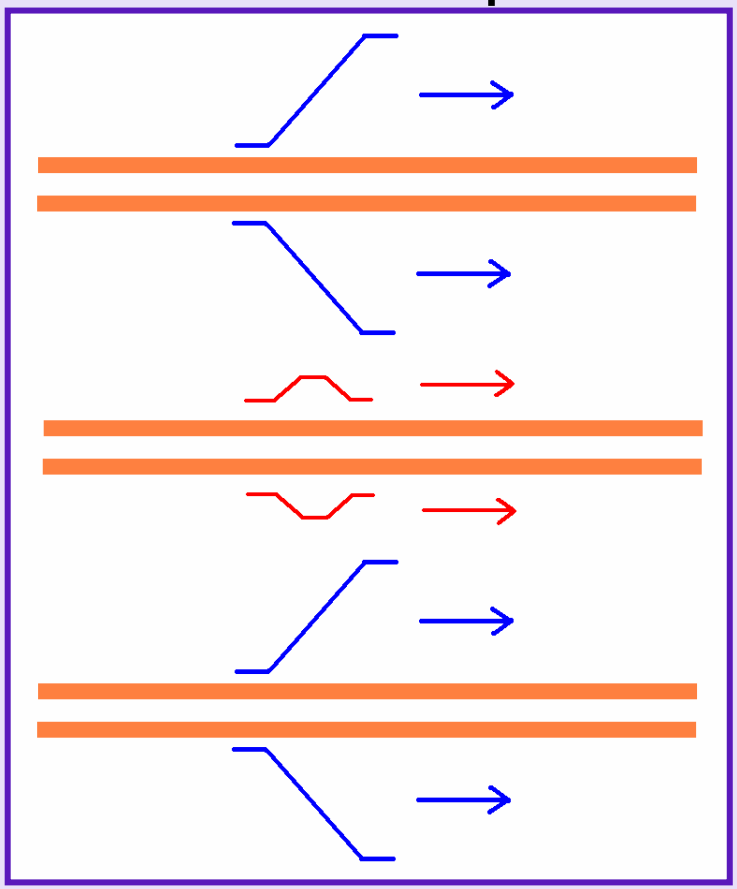
- NEXT and FEXT from real simulation
- NEXT has width equal to twice the line length (5”or 712ps)
- FEXT has same rising edge time as aggressor signal (100ps)



Differential crosstalk

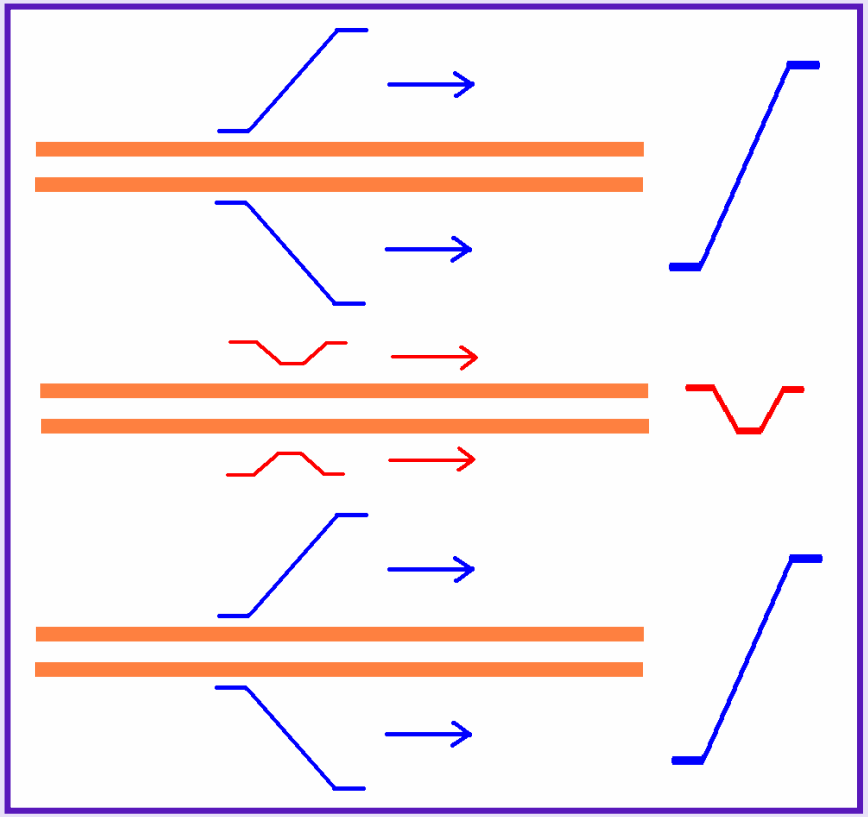
- Equal and opposite pulses of crosstalk can be induced on either side of the differential pair





Differential crosstalk

- Differential signal = DIFFERENCE of single-ended signals
- $A_{diff} = A_{plus} - A_{minus} = 2*A_{single}$
  - ✓ Both crosstalk and signal amplitude are twice their single-ended counterparts
  - ✓ Differential crosstalk just like single-ended



Reflected crosstalk

- PCI Express TX/RX Impedance = 100ohms +/- 20%

- Assuming interconnect impedance of 100+/-20 ohms, worst-case reflection =

  (120-80)/(120+80) = 20%

→ Reflected crosstalk (NEXT or FEXT) cannot exceed more than 1/5th original crosstalk voltage

$Z_{TX\text{-}DIFF\text{-}DC}$	DC Differential TX Impedance	80	100	120	Ω

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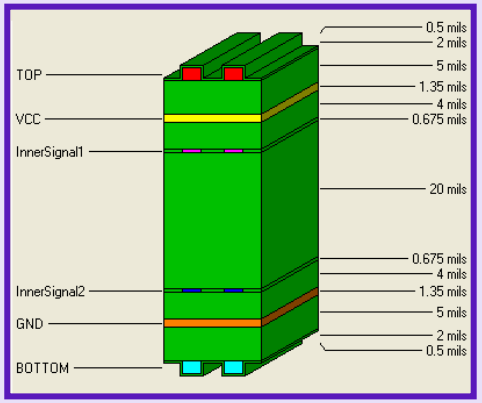
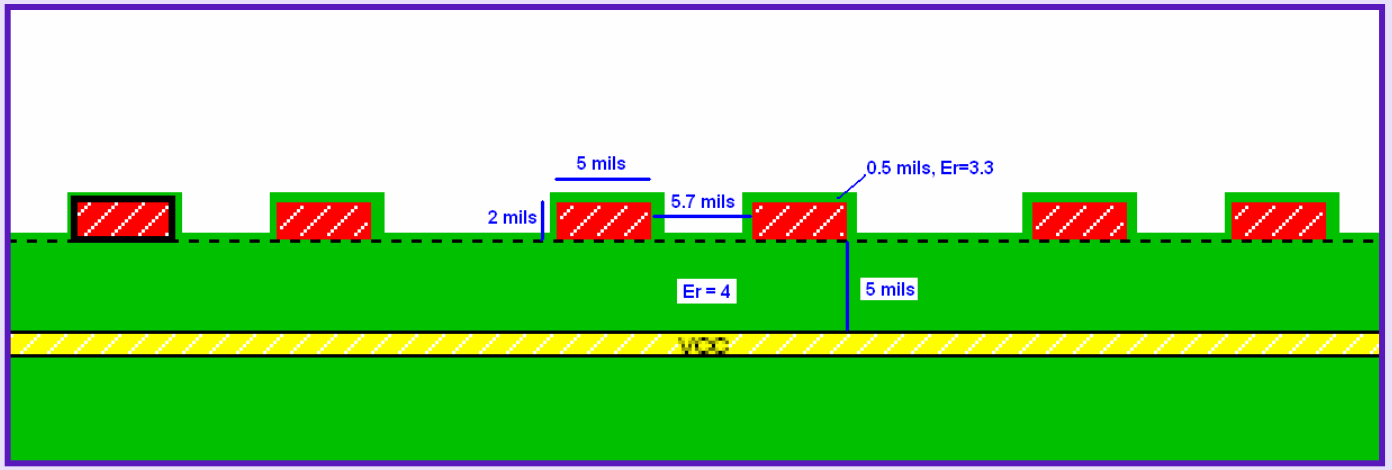
MS Analysis Setup

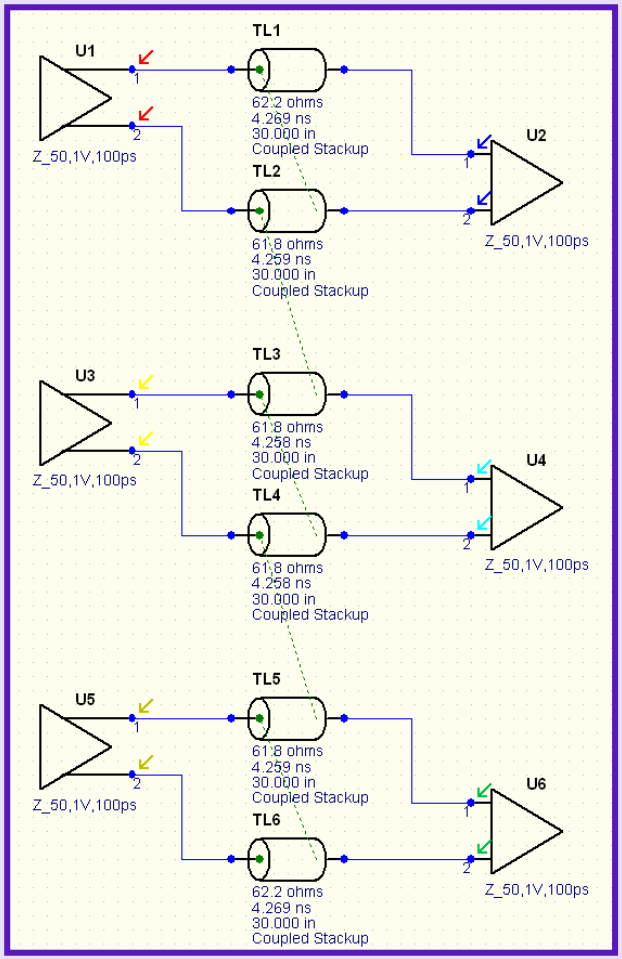
- Dielectric Height = 5 mils
- Dielectric constant = 4.0
- Trace width/spacing = 5/5.7 mils
- Trace height = 2 mils
- Soldermask = 0.5mils thick, Er = 3.3
- Differential pair spacing = 1H, 2H, 3H, 5H
- Parallel Trace length = 1, 2, 5, 10, 20, 30 inches





MS Analysis Setup

- Driver
  - ✓ 100-ohm output impedance
  - ✓ 1V differential swing
  - ✓ 100ps edge
- Receiver
  - ✓ 100-ohm input impedance
- 2 aggressor diff pairs
  - ✓ Rising edge



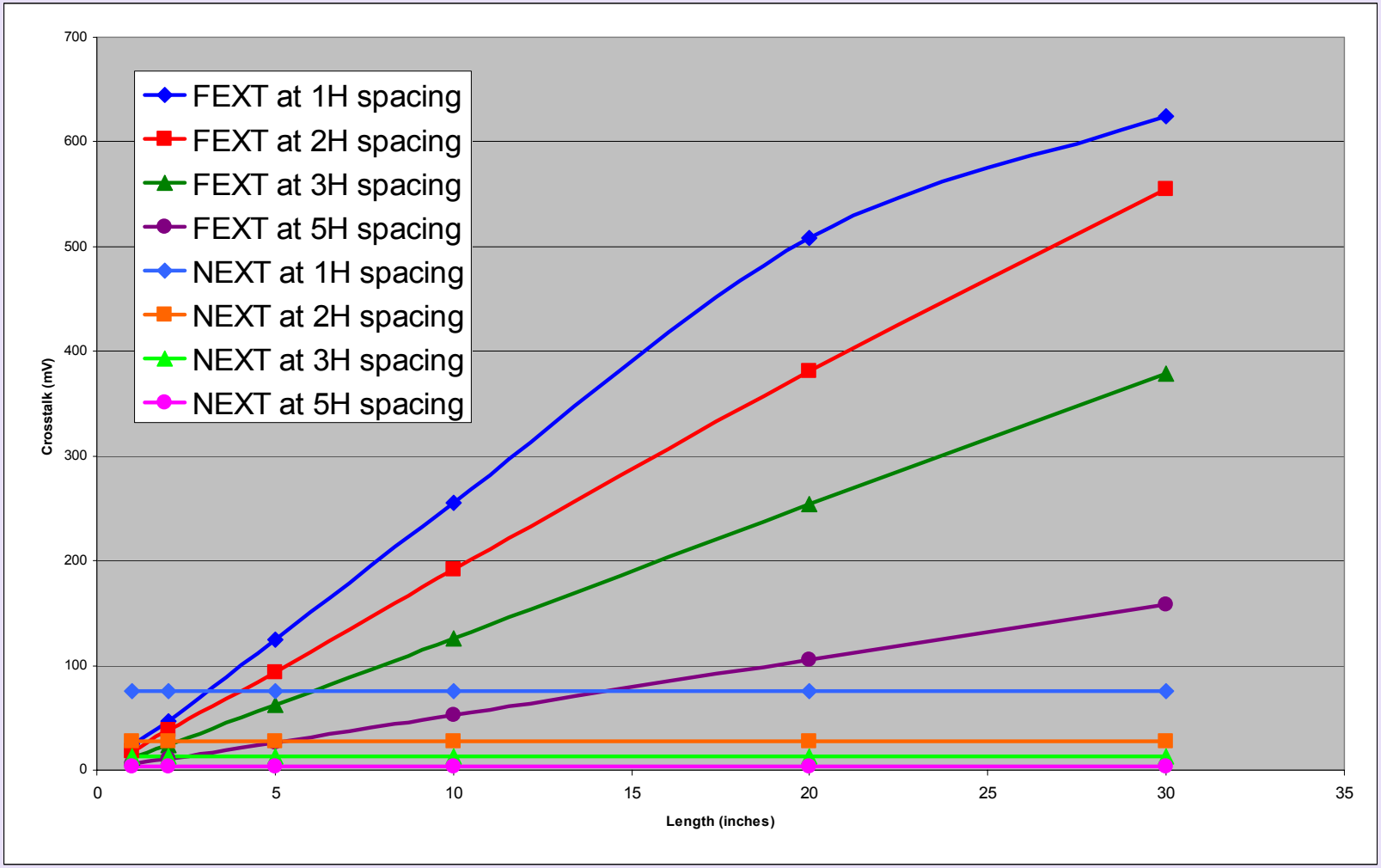
- Simulator: HyperLynx from Mentor Graphics

MS Analysis Results

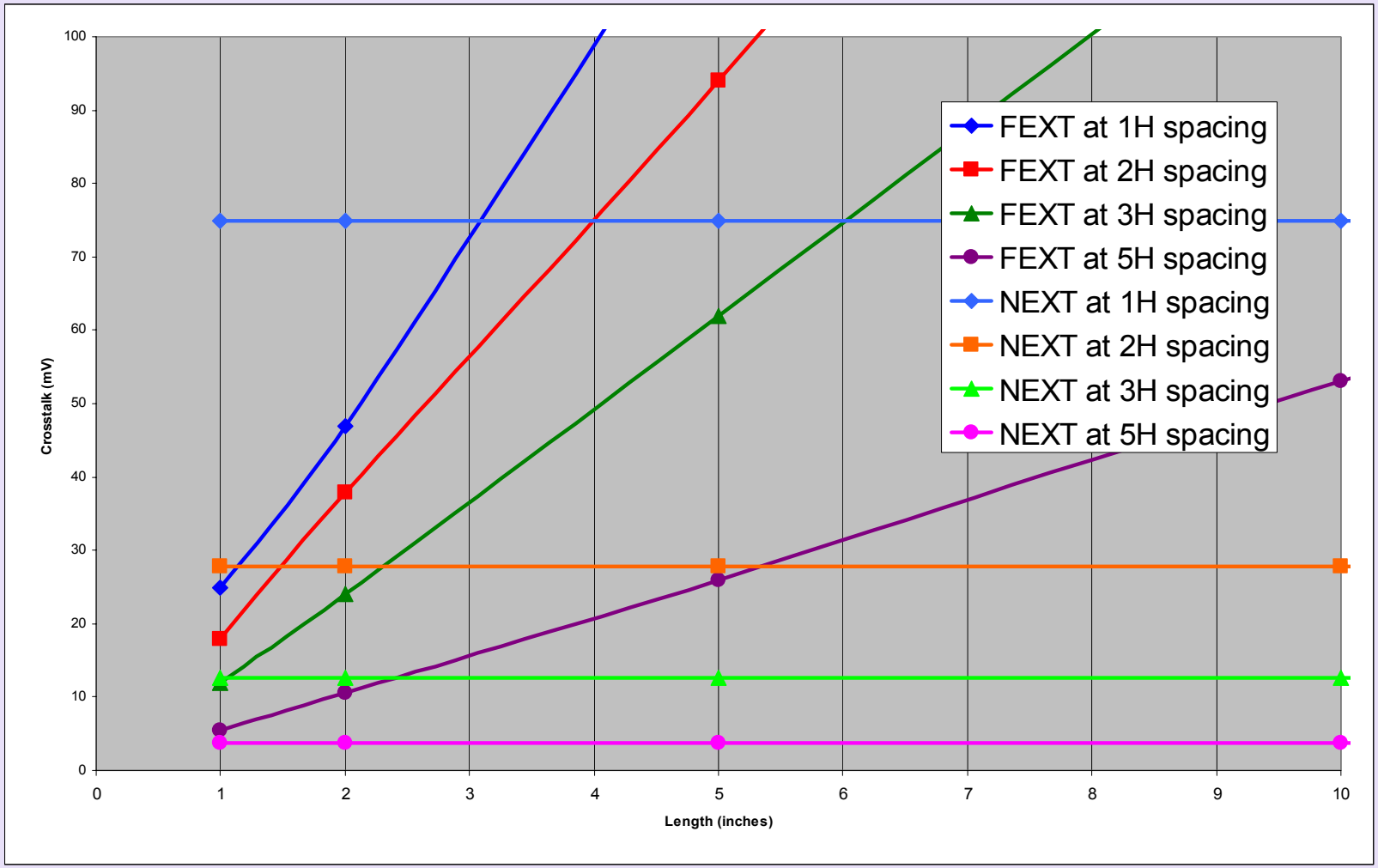
	1H	2H	3H	5H
1in.	NEXT = 75mV, FEXT = 25mV	NEXT = 27.9mV, FEXT = 18mV	NEXT = 12.7mV, FEXT = 12mV	NEXT = 3.7mV, FEXT = 5.4mV
2 in.	NEXT = 75mV, FEXT = 47mV	NEXT = 27.9mV, FEXT = 37.8mV	NEXT = 12.7mV, FEXT = 24mV	NEXT = 3.7mV, FEXT = 10.5mV
5 in.	NEXT = 75mV, FEXT = 125mV	NEXT = 27.9mV, FEXT = 94mV	NEXT = 12.7mV, FEXT = 62mV	NEXT = 3.7mV, FEXT = 26mV
10 in.	NEXT = 75mV, FEXT = 255mV	NEXT = 27.9mV, FEXT = 192mV	NEXT = 12.7mV, FEXT = 126mV	NEXT = 3.7mV, FEXT = 53mV
20 in.	NEXT = 75mV, FEXT = 508mV	NEXT = 27.9mV, FEXT = 381mV	NEXT = 12.7mV, FEXT = 254mV	NEXT = 3.7mV, FEXT = 105mV
30 in.	NEXT = 75mV, FEXT = 625mV	NEXT = 27.9mV, FEXT = 555mV	NEXT = 12.7mV, FEXT = 379mV	NEXT = 3.7mV, FEXT = 158mV

- FEXT exceeds NEXT for all but short length & tight spacing

MS Analysis Results



MS Analysis Results



MS Analysis Results

- FEXT primarily dominates
- Interleaving should be used on Microstrip routing
  - ✓ FEXT dominates in almost all cases
- Exception: short lengths in combination with tight spacing
  - ✓ Not recommended due to high crosstalk anyway

	1H	2H	3H	5H
1in.	NEXT = 75mV, FEXT = 25mV	NEXT = 27.9mV, FEXT = 18mV	NEXT = 12.7mV, FEXT = 12mV	NEXT = 3.7mV, FEXT = 5.4mV
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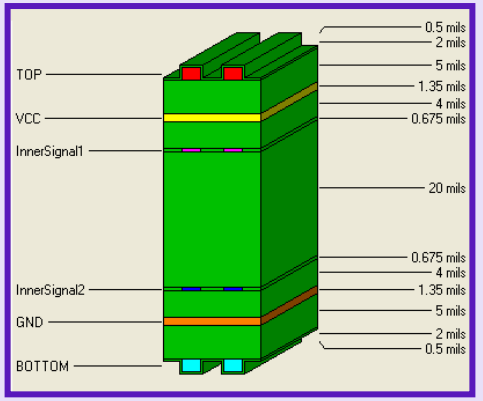
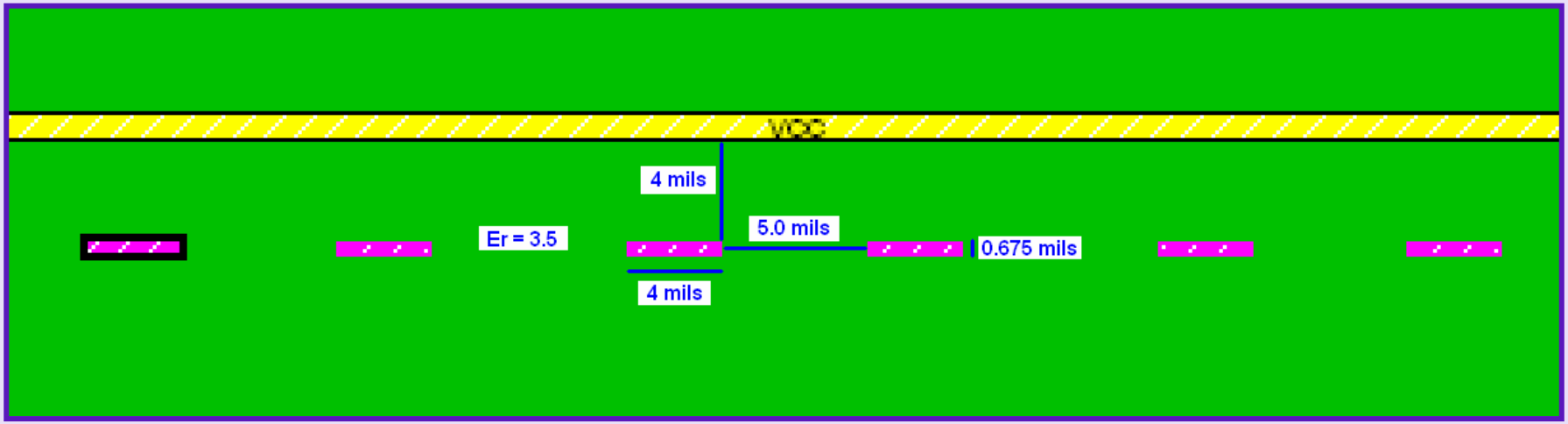
Homogenous SL Analysis Setup

- Dielectric Heights = 4 mils/20mils/4mils (dual stripline)
- Dielectric constant = 3.5
- Trace width/spacing = 4/5.0 mils
- Trace height = 0.675 mils



- Differential pair spacing = 1H, 2H, 3H, 5H
- Parallel Trace length = 1, 2, 5, 10, 20, 30 inches



SL Analysis Setup

- Driver
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- Receiver
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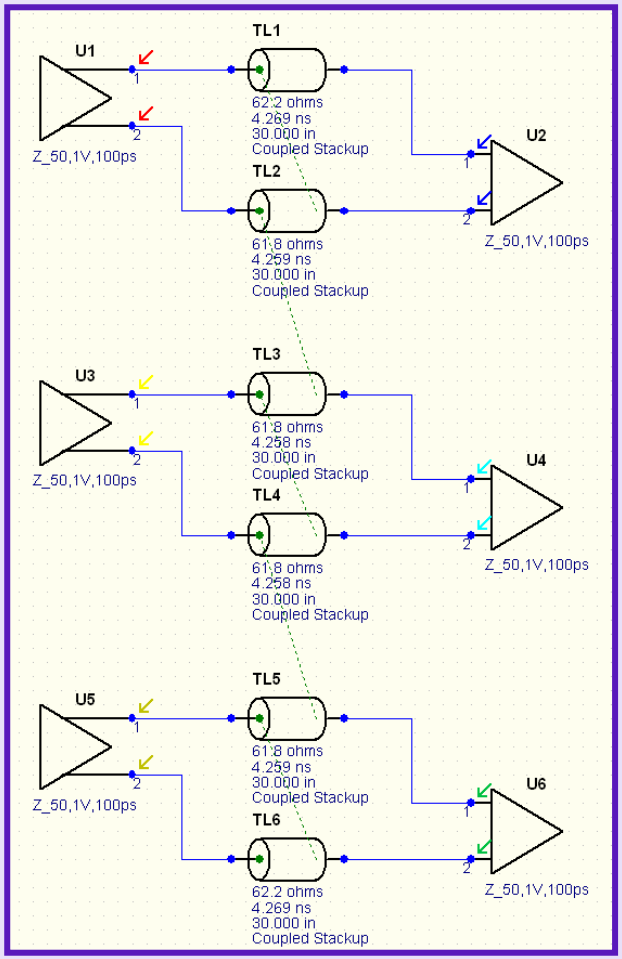
  - ✓ Rising edge



- Simulator: HyperLynx from Mentor Graphics

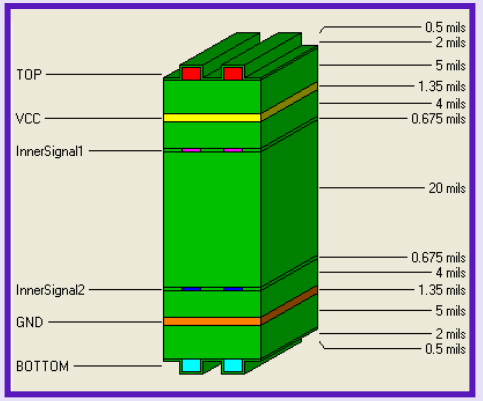
SL Analysis Results

	1H	2H	3H	5H
1in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV
2 in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV
5 in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV
10 in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV
20 in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV
30 in.	NEXT = 72.1mV, FEXT = 0mV	NEXT = 29.9mV, FEXT = 0mV	NEXT = 14.5mV, FEXT = 0mV	NEXT = 4.5mV, FEXT = 0mV

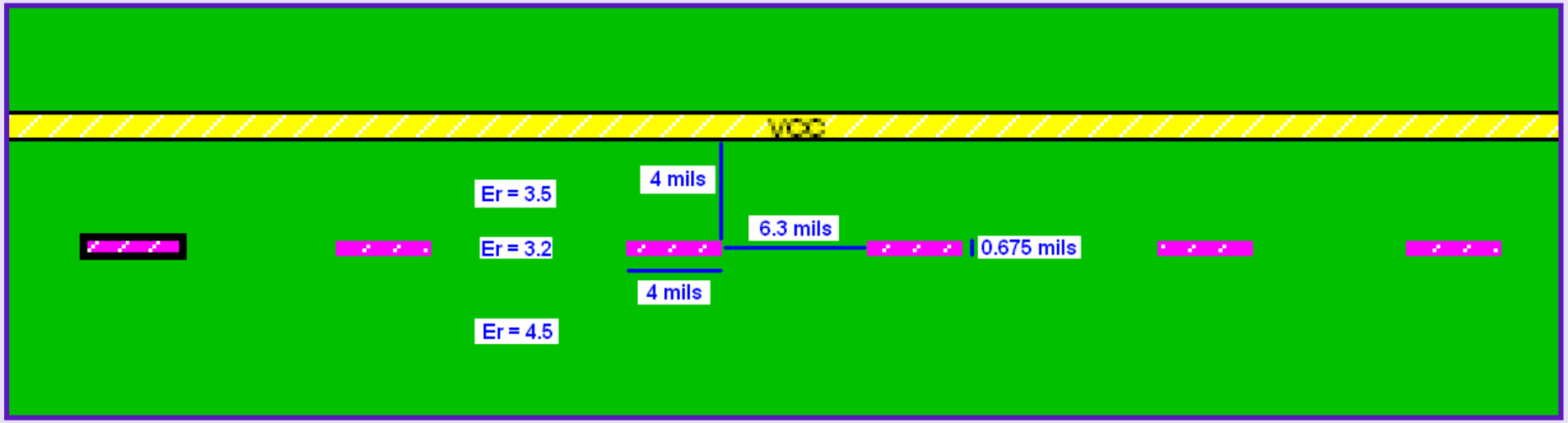
- With SL modeled as completely homogenous, FEXT is 0
  - ✓ All dielectric constants equal
  - ✓ Very rare case
    - Core/prepreg variations
    - Resin-rich areas on signal layers

Real SL Analysis Setup

- Dielectric Heights = 4 mils/20mils/4mils (dual stripline)
- Dielectric constants = 3.5, 3.2, 4.5, 3.2, 3.5
- Trace width/spacing = 4/6.3 mils
- Trace height = 0.675 mils



- Differential pair spacing = 1H, 2H, 3H, 5H
- Parallel Trace length = 1, 2, 5, 10, 20, 30 inches

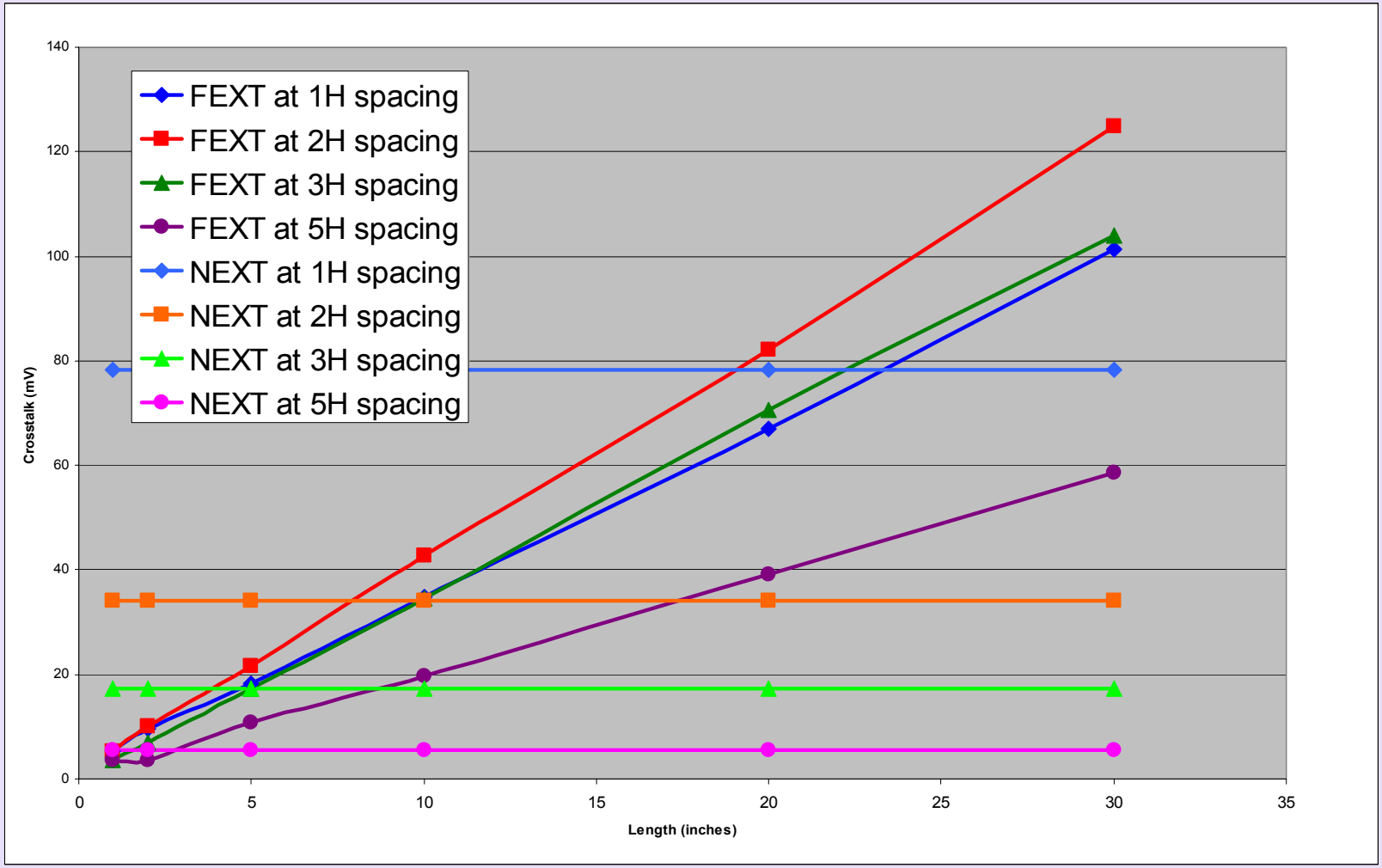


SL Analysis Results

	1H	2H	3H	5H
1in.	NEXT = 78.4mV, FEXT = 5.2mV	NEXT = 34mV, FEXT = 5.2mV	NEXT = 17.2mV, FEXT = 3.5mV	NEXT = 5.6mV, FEXT = 3.6mV
2 in.	NEXT = 78.4mV, FEXT = 9.5mV	NEXT = 34mV, FEXT = 10.1mV	NEXT = 17.2mV, FEXT = 7mV	NEXT = 5.6mV, FEXT = 3.6mV
5 in.	NEXT = 78.4mV, FEXT = 18.2mV	NEXT = 34mV, FEXT = 21.5mV	NEXT = 17.2mV, FEXT = 17.4mV	NEXT = 5.6mV, FEXT = 10.8mV
10 in.	NEXT = 78.4mV, FEXT = 34.8mV	NEXT = 34mV, FEXT = 42.8mV	NEXT = 17.2mV, FEXT = 34.6mV	NEXT = 5.6mV, FEXT = 19.7mV
20 in.	NEXT = 78.4mV, FEXT = 67.1mV	NEXT = 34mV, FEXT = 82.1mV	NEXT = 17.2mV, FEXT = 70.5mV	NEXT = 5.6mV, FEXT = 39.2mV
30 in.	NEXT = 78.4mV, FEXT = 101.4mV	NEXT = 34mV, FEXT = 124.8mV	NEXT = 17.2mV, FEXT = 104mV	NEXT = 5.6mV, FEXT = 58.6mV

- With SL modeled as non-homogenous, FEXT is nonzero and can dominate over NEXT
  - ✓ Imbalance of capacitive/inductive couplings
  - ✓ Increases with longer lengths
  - ✓ Takes more length at tighter spacing for FEXT to dominate

SL Analysis Results



SL Analysis Results

- Interleaving should be used on long routes on stripline
  - ✓ FEXT dominates over NEXT at longer lengths
- Crossover point for NEXT and FEXT varies
  - ✓ Varies with length
  - ✓ Varies with spacing
  - ✓ Varies with stackup parameters (height, width, Er)
- Non-interleaving is better for short routes with very tight spacing

	1H	2H	3H	5H
1in.	NEXT = 78.4mV, FEXT = 5.2mV	NEXT = 34mV, FEXT = 5.2mV	NEXT = 17.2mV, FEXT = 3.5mV	NEXT = 5.6mV, FEXT = 3.6mV
2 in.	NEXT = 78.4mV, FEXT = 9.5mV	NEXT = 34mV, FEXT = 10.1mV	NEXT = 17.2mV, FEXT = 7mV	NEXT = 5.6mV, FEXT = 3.6mV
5 in.	NEXT = 78.4mV, FEXT = 18.2mV	NEXT = 34mV, FEXT = 21.5mV	NEXT = 17.2mV, FEXT = 17.4mV	NEXT = 5.6mV, FEXT = 10.8mV
10 in.	NEXT = 78.4mV, FEXT = 34.8mV	NEXT = 34mV, FEXT = 42.8mV	NEXT = 17.2mV, FEXT = 34.6mV	NEXT = 5.6mV, FEXT = 19.7mV
20 in.	NEXT = 78.4mV, FEXT = 67.1mV	NEXT = 34mV, FEXT = 82.1mV	NEXT = 17.2mV, FEXT = 70.5mV	NEXT = 5.6mV, FEXT = 39.2mV
30 in.	NEXT = 78.4mV, FEXT = 101.4mV	NEXT = 34mV, FEXT = 124.8mV	NEXT = 17.2mV, FEXT = 104mV	NEXT = 5.6mV, FEXT = 58.6mV

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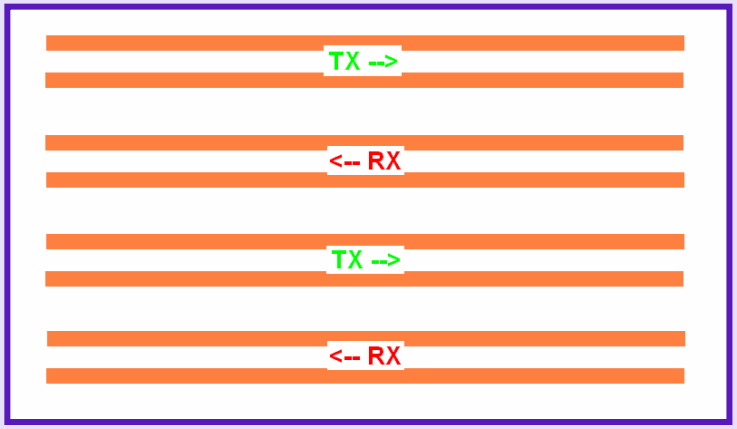
Conclusion

- On Microstrip Routing
  - ✓ Interleave TX and RX differential pairs



- On Stripline Routing
  - ✓ Interleave RX and TX pairs for long routes
  - ✓ Do not interleave RX and TX pairs for short routes
  - ✓ Use simulation to determine NEXT/FEXT crossover point
    - Can vary based on length, spacing, stackup
    - Model different dielectric layers with appropriate dielectric constants
    - FEXT is not zero

Thank you for attending the
PCI-SIG Developers Conference 2006.

For more information please go to
www.pcisig.com

References

- Johnson, Howard and Graham, Martin,
  "High-Speed Digital Design,"
  Prentice Hall, 1993.
  - ✓ I really like the explanation of crosstalk contained in this book.

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