Differential Signaling is the Opiate of the Masses

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Distinguished Lecturer for the IEEE EMC Society 2012-13

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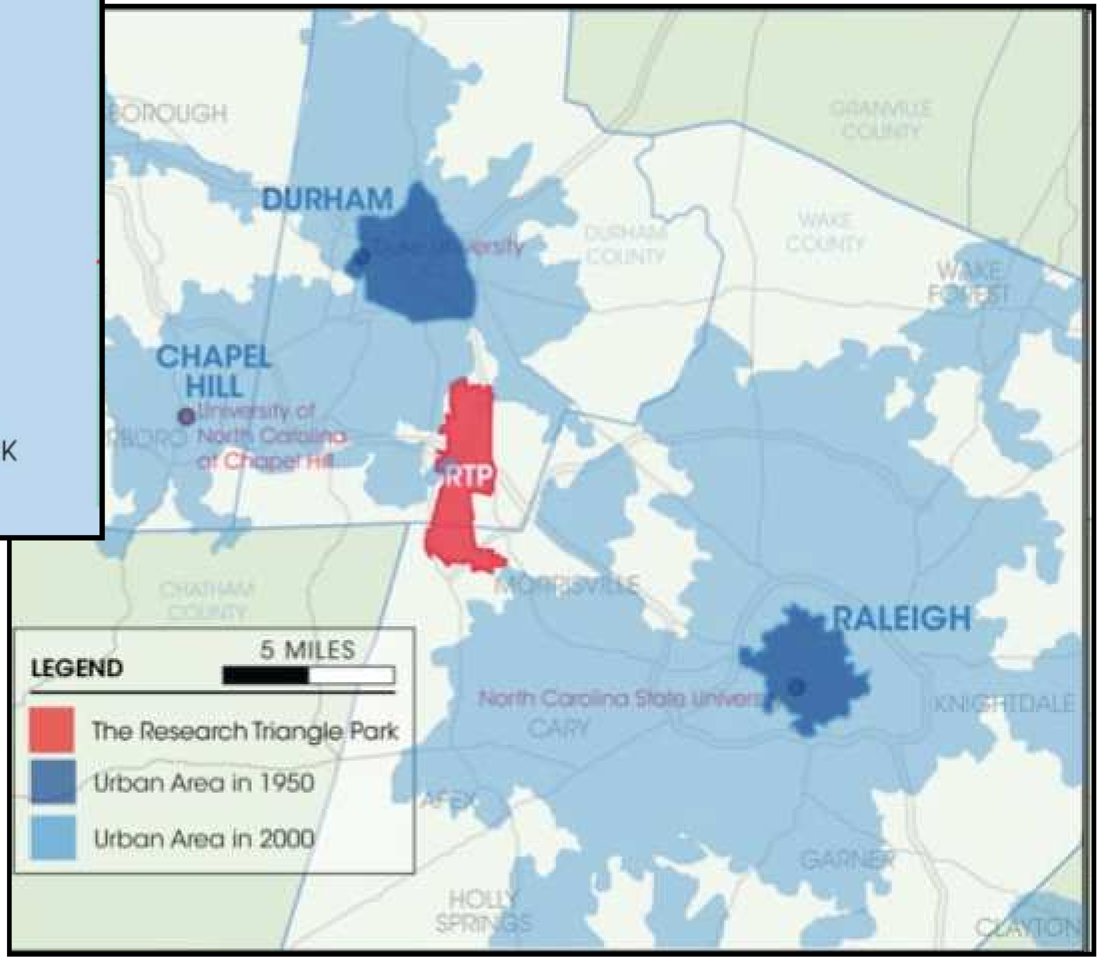
My Background

- BSEE, University of Notre Dame, 1994
- Lockheed Martin Control Systems, Johnson City, NY
  - 1994-1996
  - Systems Engineer
- IBM, Research Triangle Park, NC
  - 1996-Present
  - Timing Verification
  - Logic Verification
  - Signal Quality Analysis
  - EMC Design
    - Simulation
    - EMC Design Rule Checker development
    - Research collaboration

Location


RESEARCH TRIANGLE PARK


Chicago
Indianapolis
Cincinnati
Pittsburgh
New York
Philadelphia
Baltimore
Washington, DC
Richmond
I-95
I-40
I-85
Chapel Hill
Durham
Raleigh
Charlotte
Atlanta
THE RESEARCH
TRIANGLE PARK

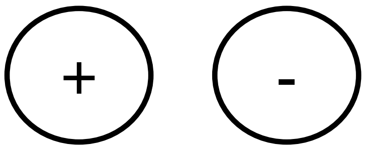

DURHAM
Duke University
DURHAM COUNTY
GRANVILLE COUNTY
WAKE COUNTY
WAKE FOREST
CHAPEL HILL
University of North Carolina at Chapel Hill
RTP
MORRISVILLE
CHATHAM COUNTY
RALEIGH
North Carolina State University
CARY
KNIGHTDALE
APEX
GARNER
HOLLY SPRINGS
CLAYTON
LEGEND
5 MILES
The Research Triangle Park
Urban Area in 1950
Urban Area in 2000

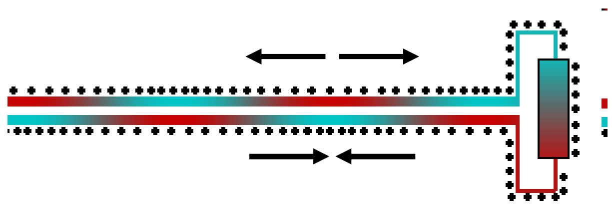
Outline

- Background
  - Differential Signaling Pros/Cons
  - Transmission line modes
- Common Mode
  - Sources of CM signals
  - S-Parameters primer
  - Causes of mode conversion
- Radiation mechanisms
  - Cables/connectors
- EMC Design Options
  - CM filtering
  - Absorbing material
- Summary

Background

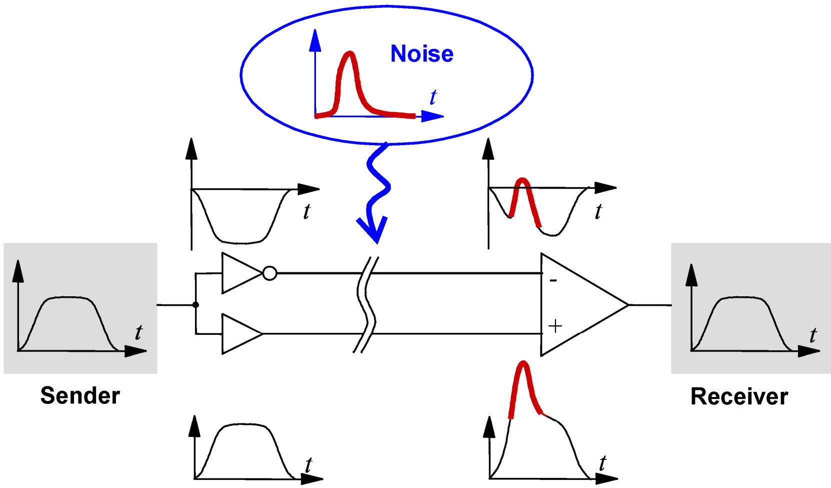
- Differential Signal
  - 2-wire transmission system
  - Signal is the voltage difference between the 2 wires
  - Current in the 2 wires is equal and opposite



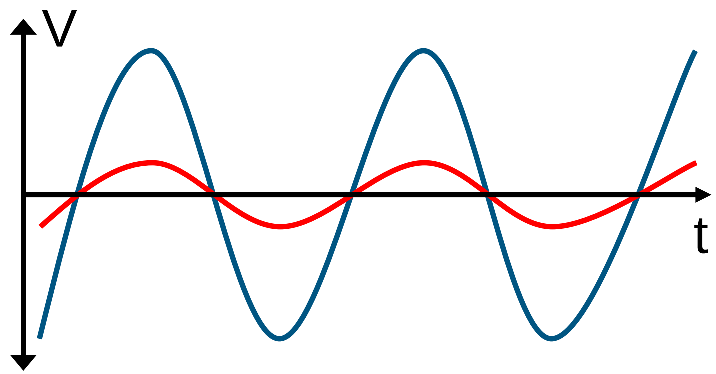


Pros/Cons of Differential Signaling

- Advantages = Noise immunity, loss tolerance (0-crossing), minimal radiated EMI*

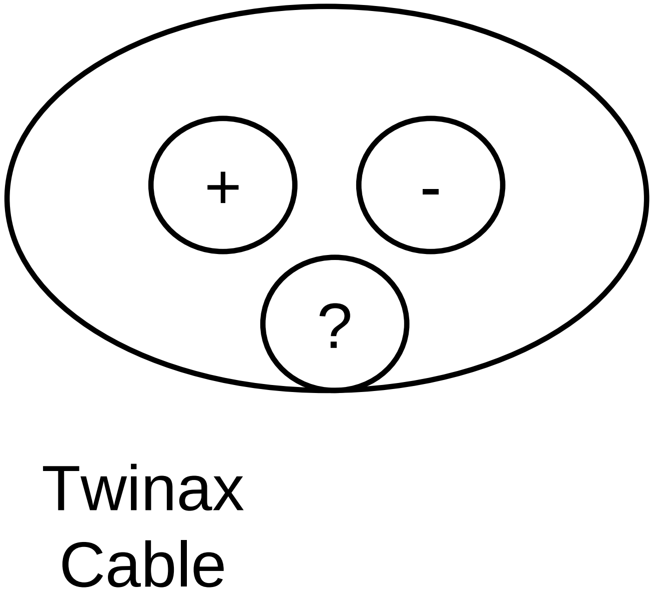


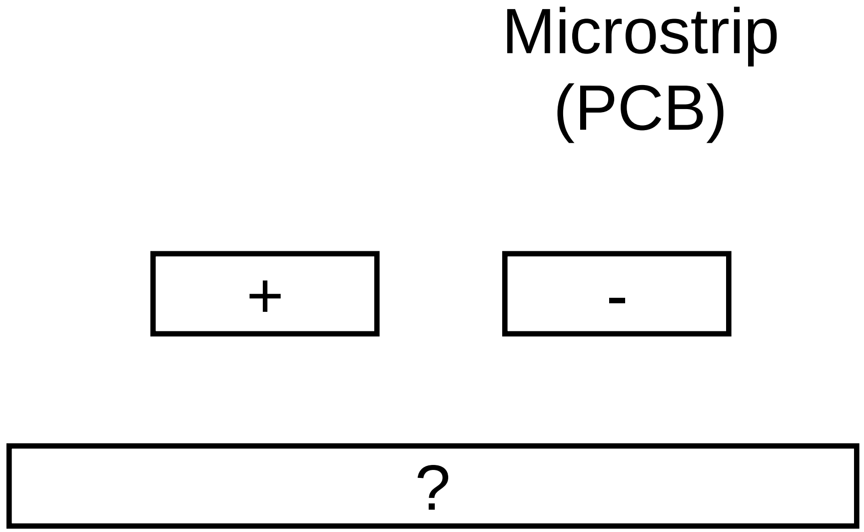
Picture from: http://en.wikipedia.org/wiki/Differential_signaling



- Disadvantages = Requires 2 wires (wiring density, weight, cost), routing challenges*

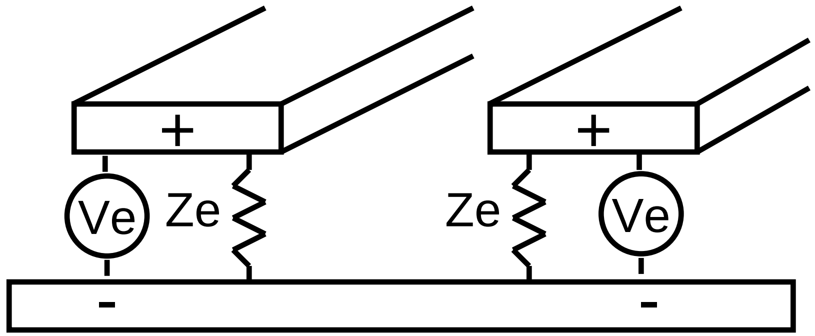
Real-World



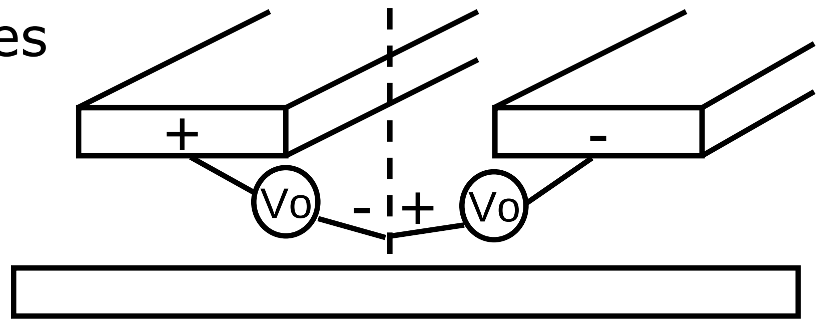


Transmission Line Modes

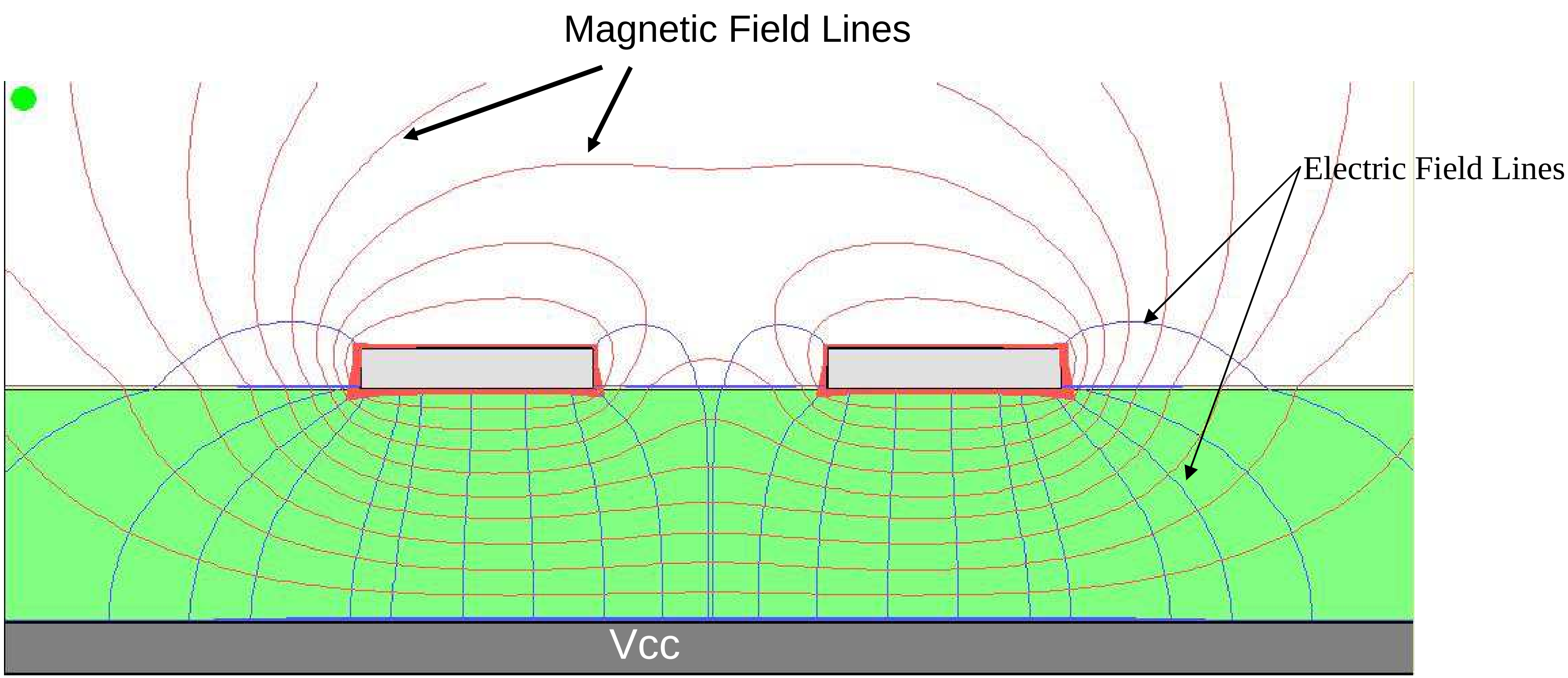
- Even Mode
  - Both signal conductors are driven with same voltage (referenced to 3rd conductor)
  - Vcomm = Veven = (Va+Vb)/2
  - Zcomm = Zeven / 2



- Odd Mode
  - Signal conductors are driven with equal and opposite voltages (referenced to “virtual ground” between conductors)
  - Vdiff = Vodd * 2 = Va - Vb
  - Zdiff = Zodd * 2

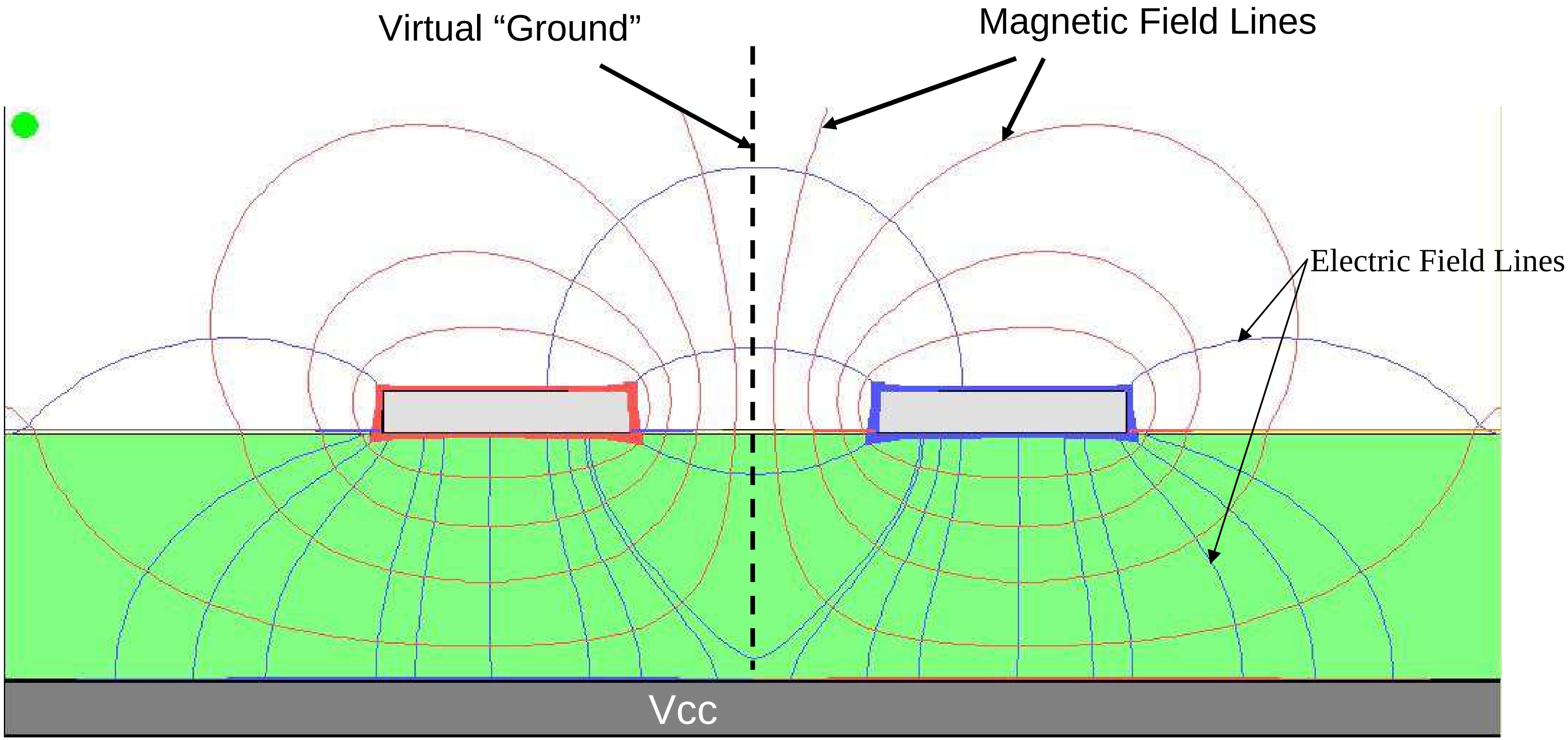


Microstrip Electric/Magnetic Field Lines
Even/Common Mode



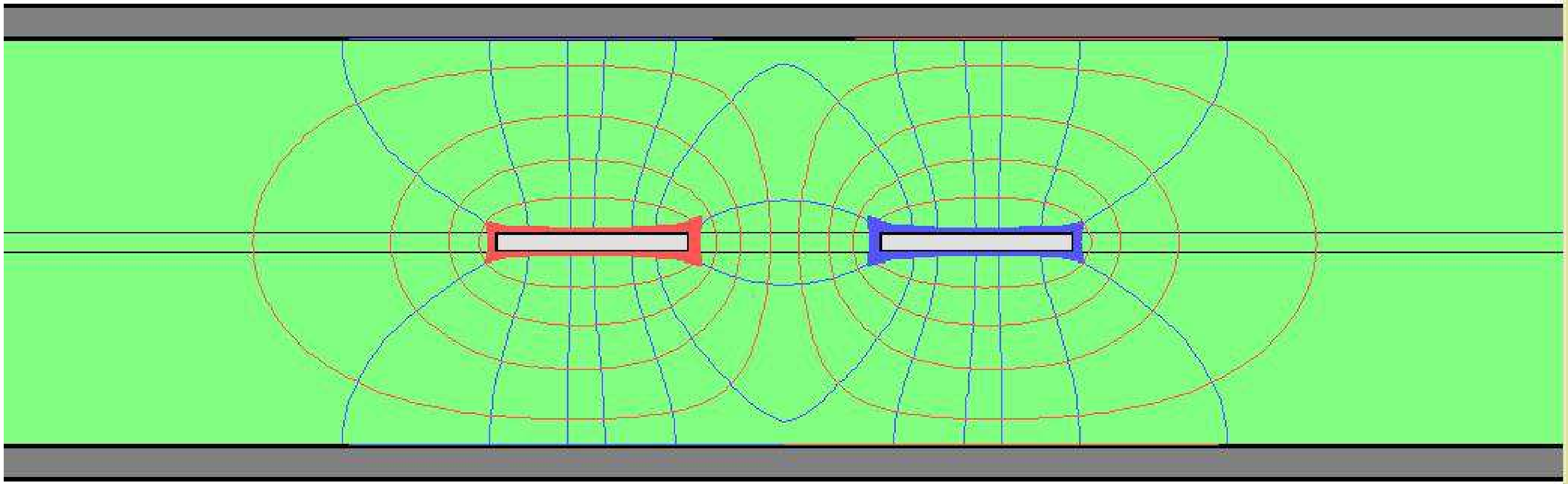
Field plot generated in Hyperlynx

Microstrip Electric/Magnetic Field Lines
Odd/Differential Mode



Field plot generated in Hyperlynx

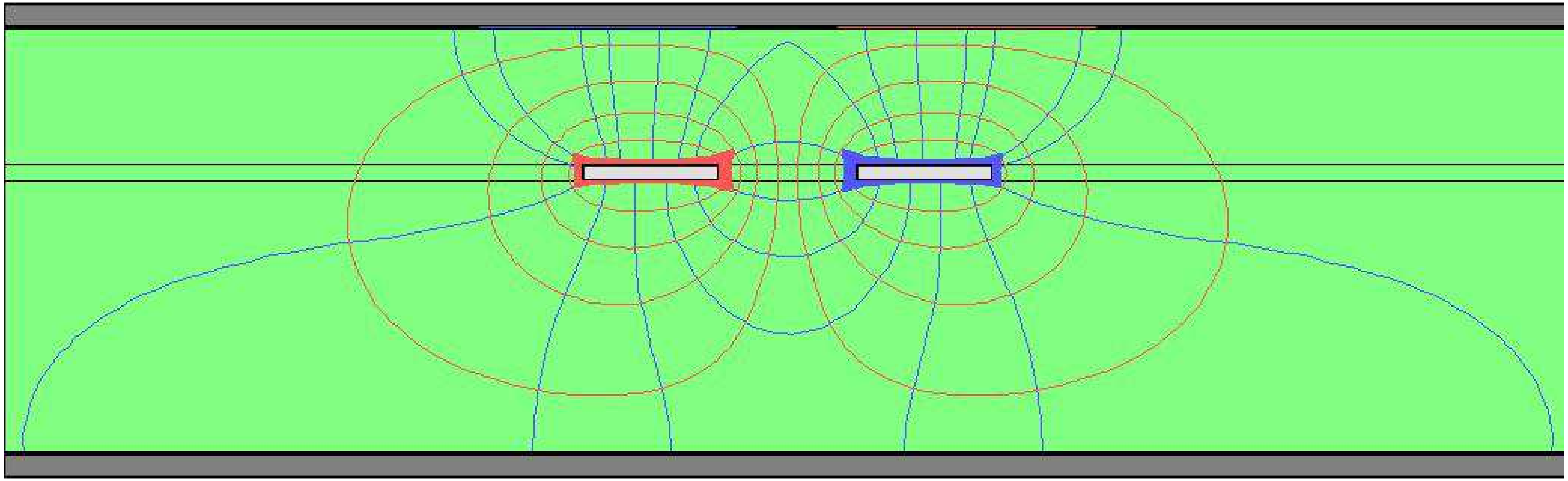
Electric/Magnetic Field Lines
Symmetrical Stripline (Differential)



Field plot generated in Hyperlynx

Electric/Magnetic Field Lines

Asymmetrical Stripline (Differential)

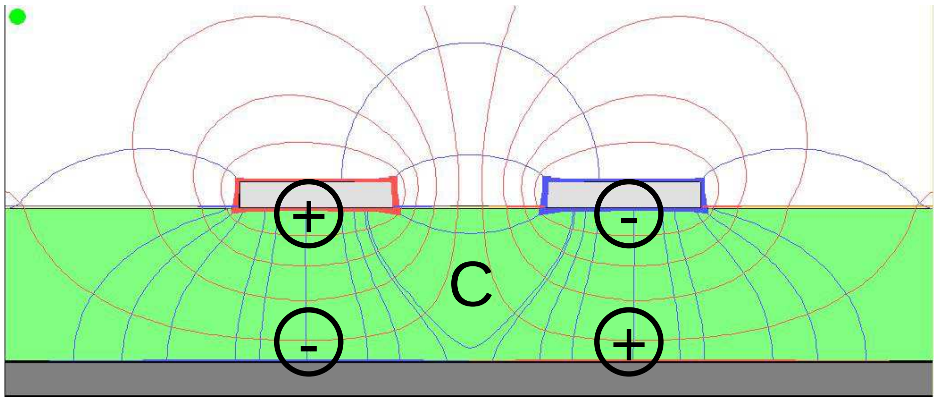


Field plot generated in Hyperlynx

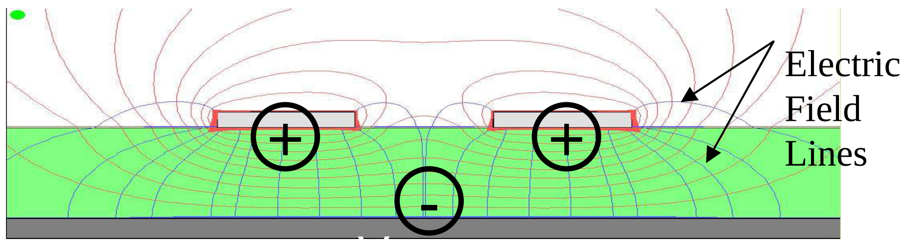
Impact on Radiated EMI

- Experiment at 2012 IEEE EMC Symposium
  - Dr. Tom Van Doren: "Electromagnetic Field Containment Using the Principle of "Self-Shielding"
  - When geometric centroids of currents are coincident, fields cancel
  - Example: twisted pair wiring reduces radiated EMI (assuming twist length is small compared to wavelength)

- Apply geometric centroid concept to differential pair
  - Common mode radiates



Differential Mode



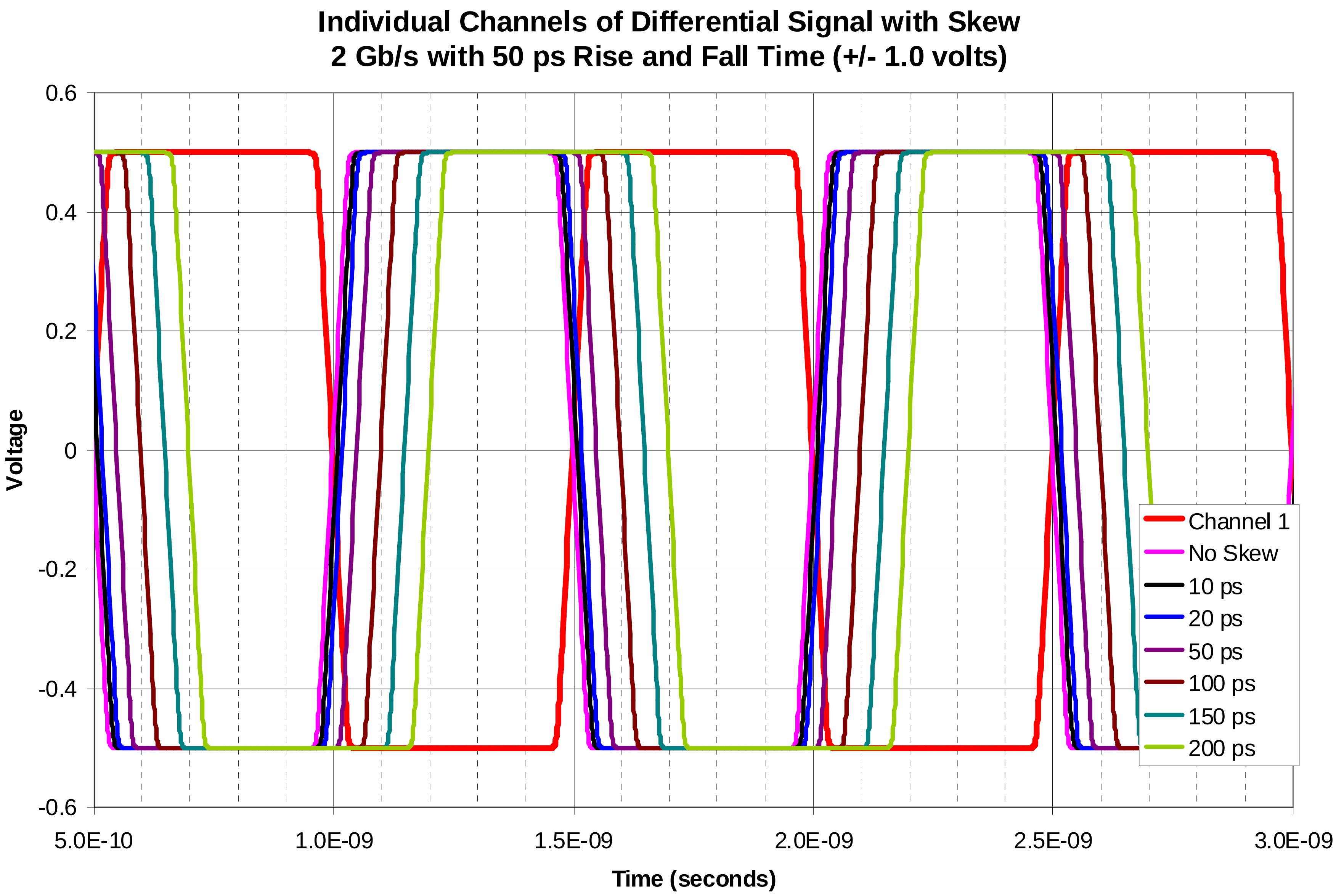
Common Mode

Sources of Common Mode Signals

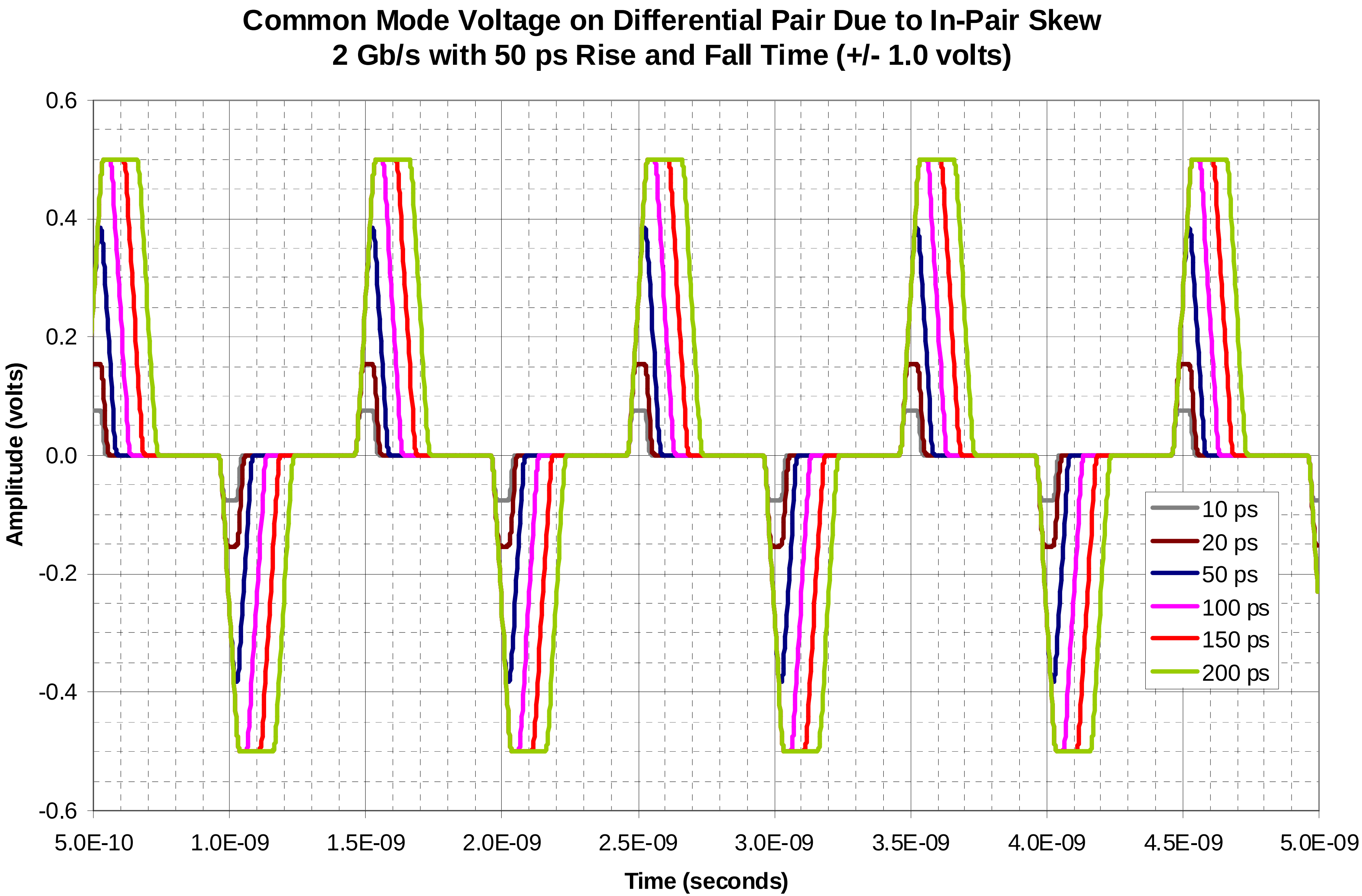
- Common Mode Noise is very difficult to avoid in real-world differential pairs
  - Driver skew (IC+Package)
  - Rise/fall time mismatch
    - Also non-50% duty cycle
  - Amplitude mismatch

Common Mode from Driver Skew

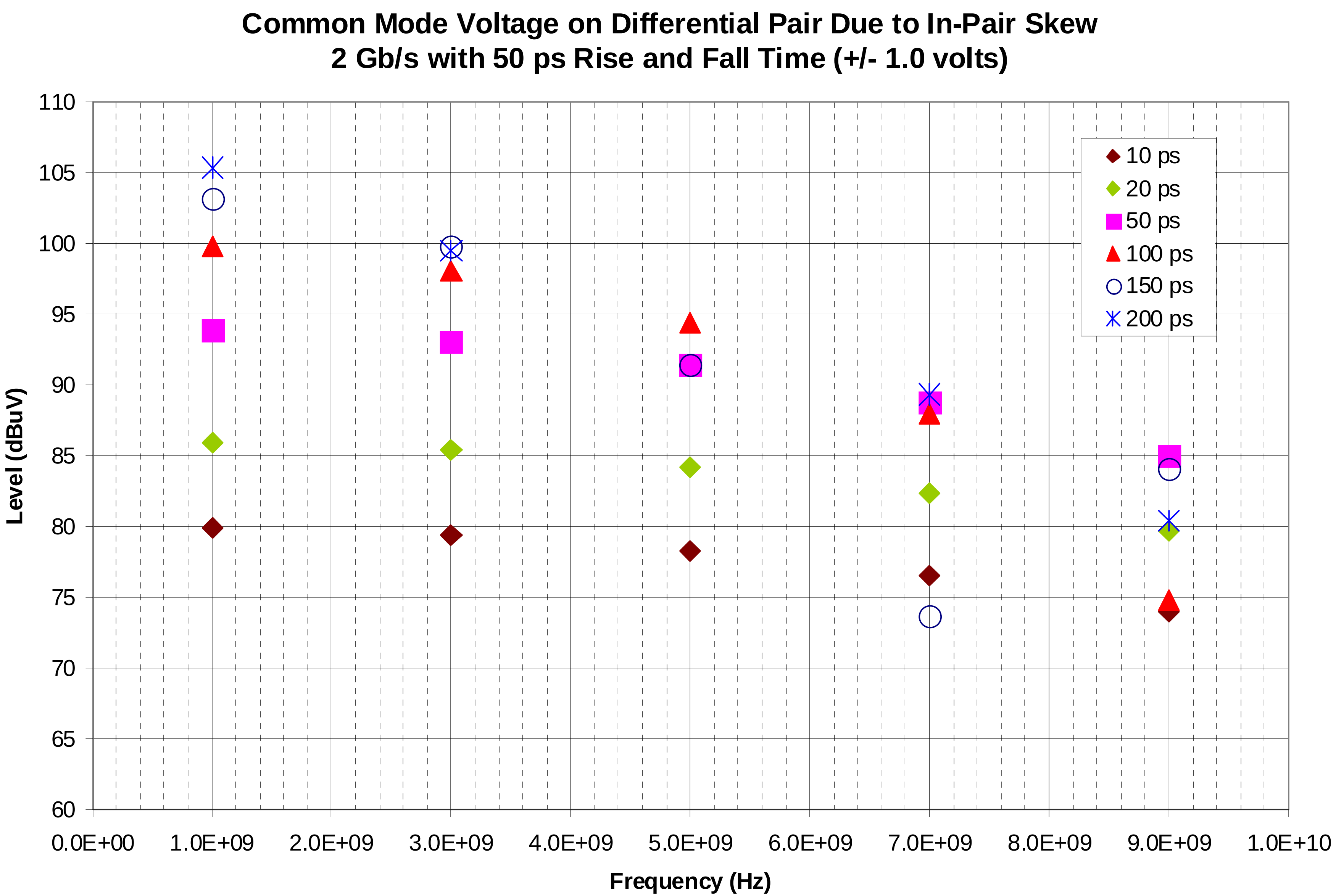
- Small amount of skew results in significant CM
  - As little as 1% of bit width (UI) for skew can have significant EMI effects
  - When Skew ~= Rise Time, CM amplitude ~= DM amplitude



Individual Channels of Differential Signal with Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Voltage
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
Time (seconds)
Channel 1
No Skew
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps



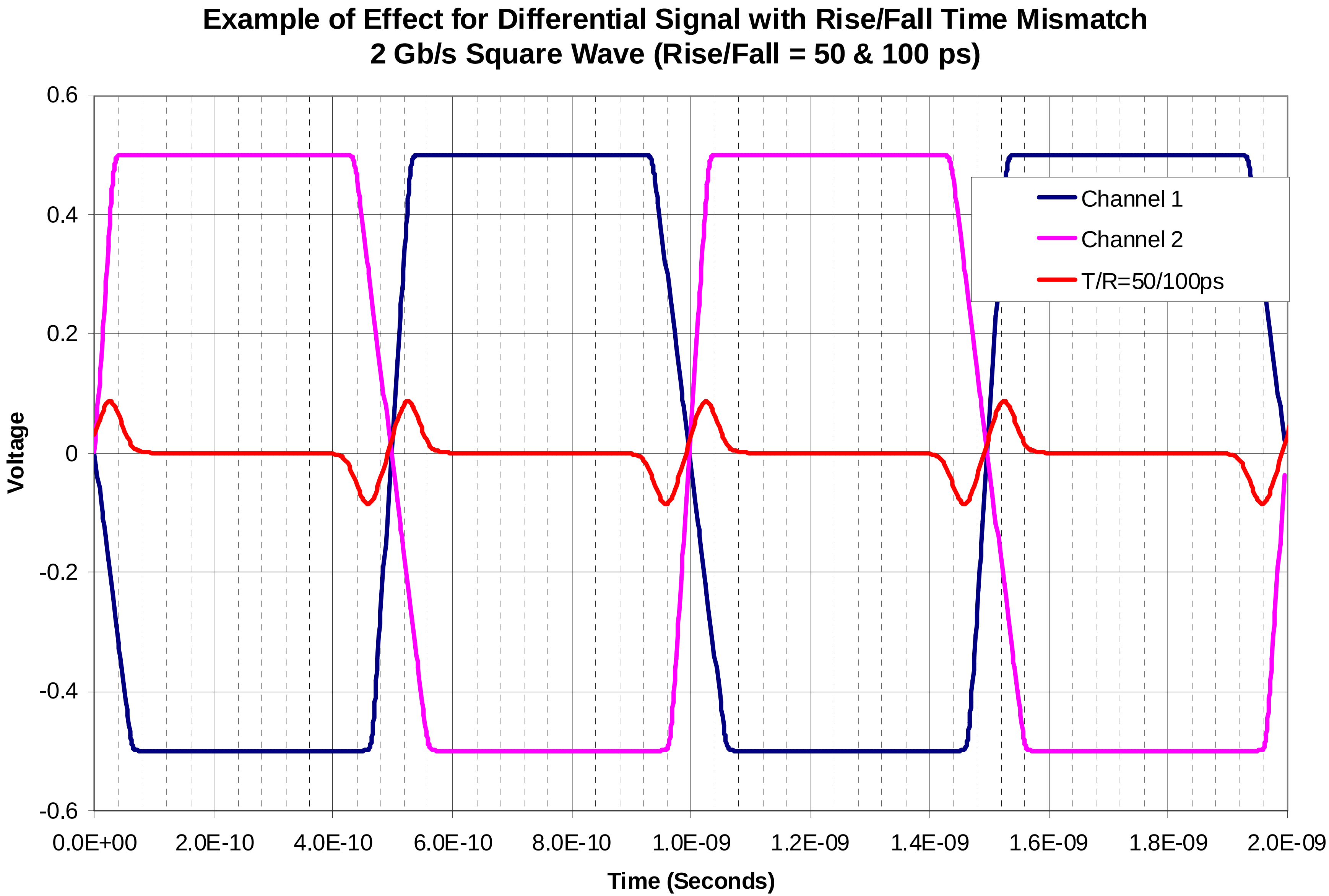
Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Amplitude (volts)
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (seconds)
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

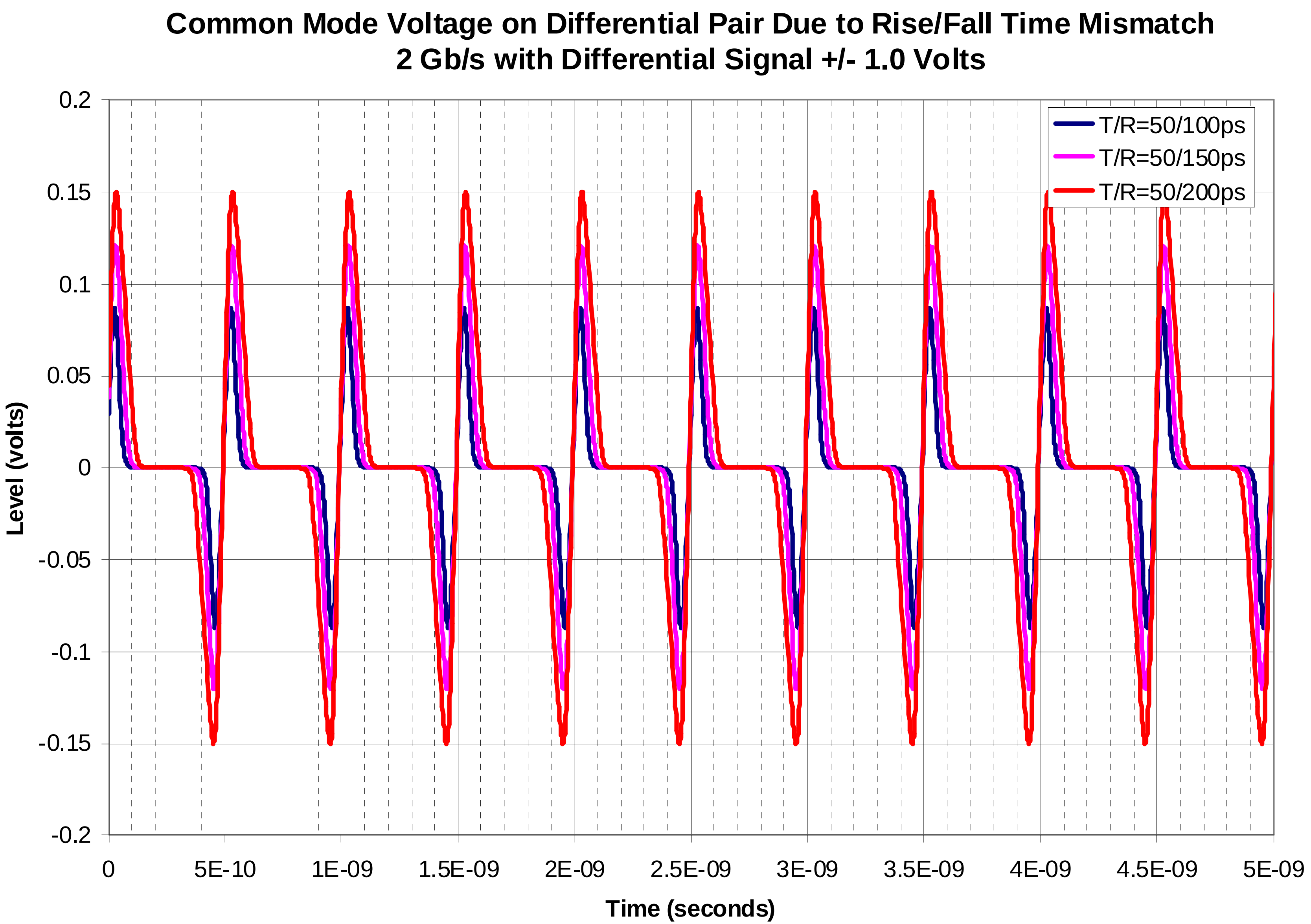


Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
110
105
100
95
90
85
80
75
70
65
60
Level (dBuV)
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

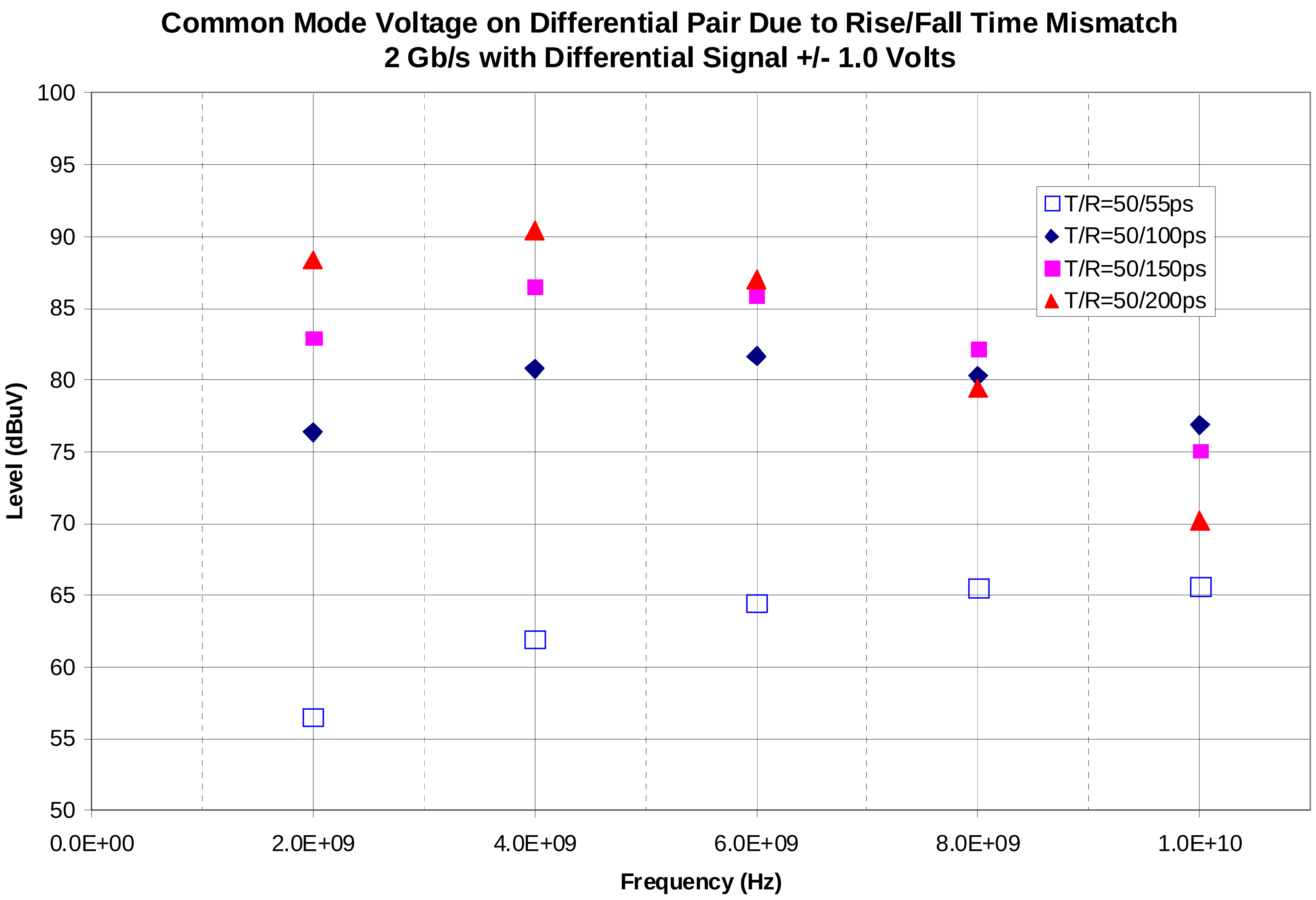
Common Mode from Rise/Fall Time Mismatch

- Small amounts of mismatch create significant CM noise
- Cause:
  - IC driver
    - Transistor sizing, parasitics
    - Process variation
- Cannot compensate on PCB


Example of Effect for Differential Signal with Rise/Fall Time Mismatch
2 Gb/s Square Wave (Rise/Fall = 50 & 100 ps)
Voltage
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0.0E+00
2.0E-10
4.0E-10
6.0E-10
8.0E-10
1.0E-09
1.2E-09
1.4E-09
1.6E-09
1.8E-09
2.0E-09
Time (Seconds)
Channel 1
Channel 2
T/R=50/100ps

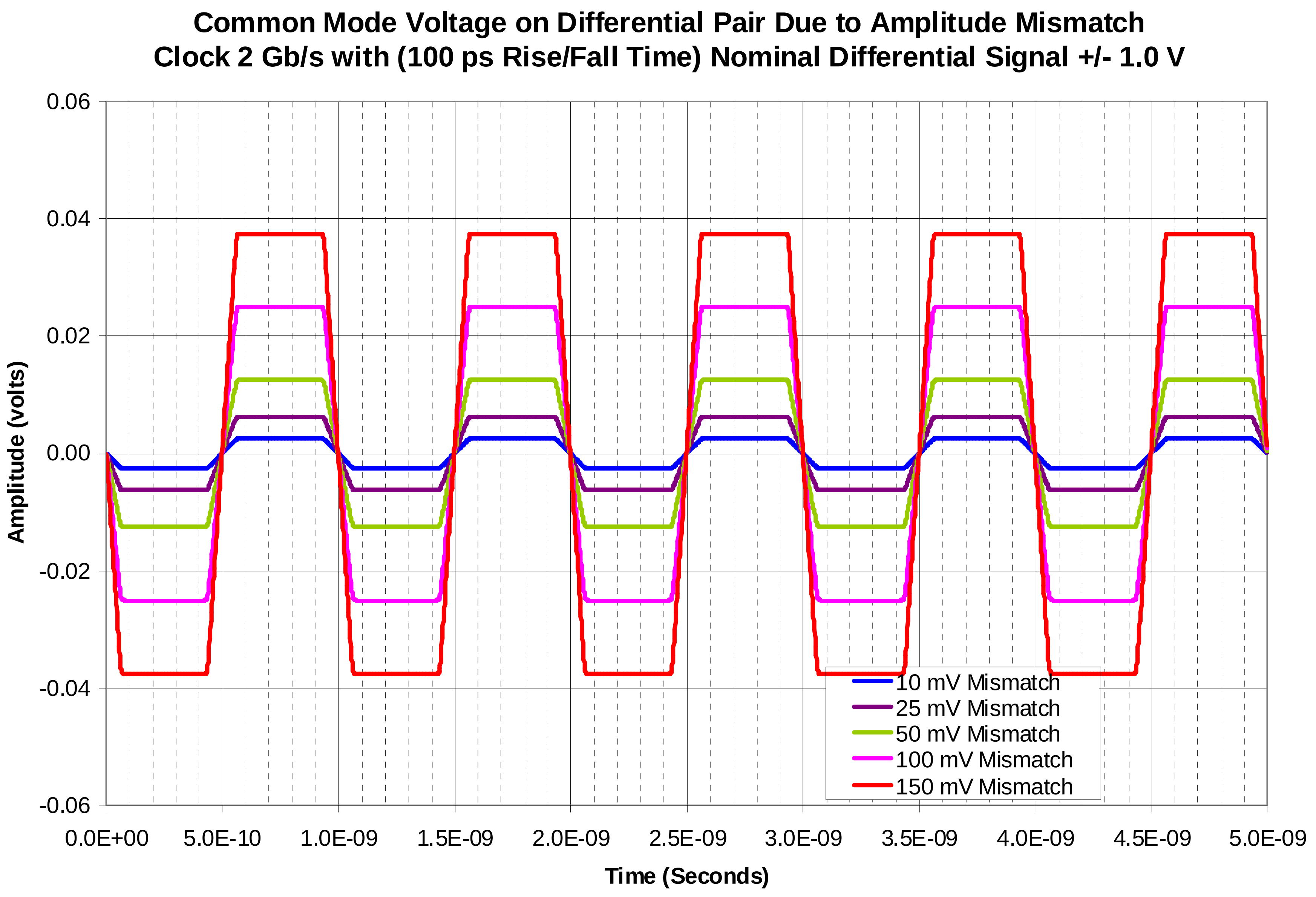


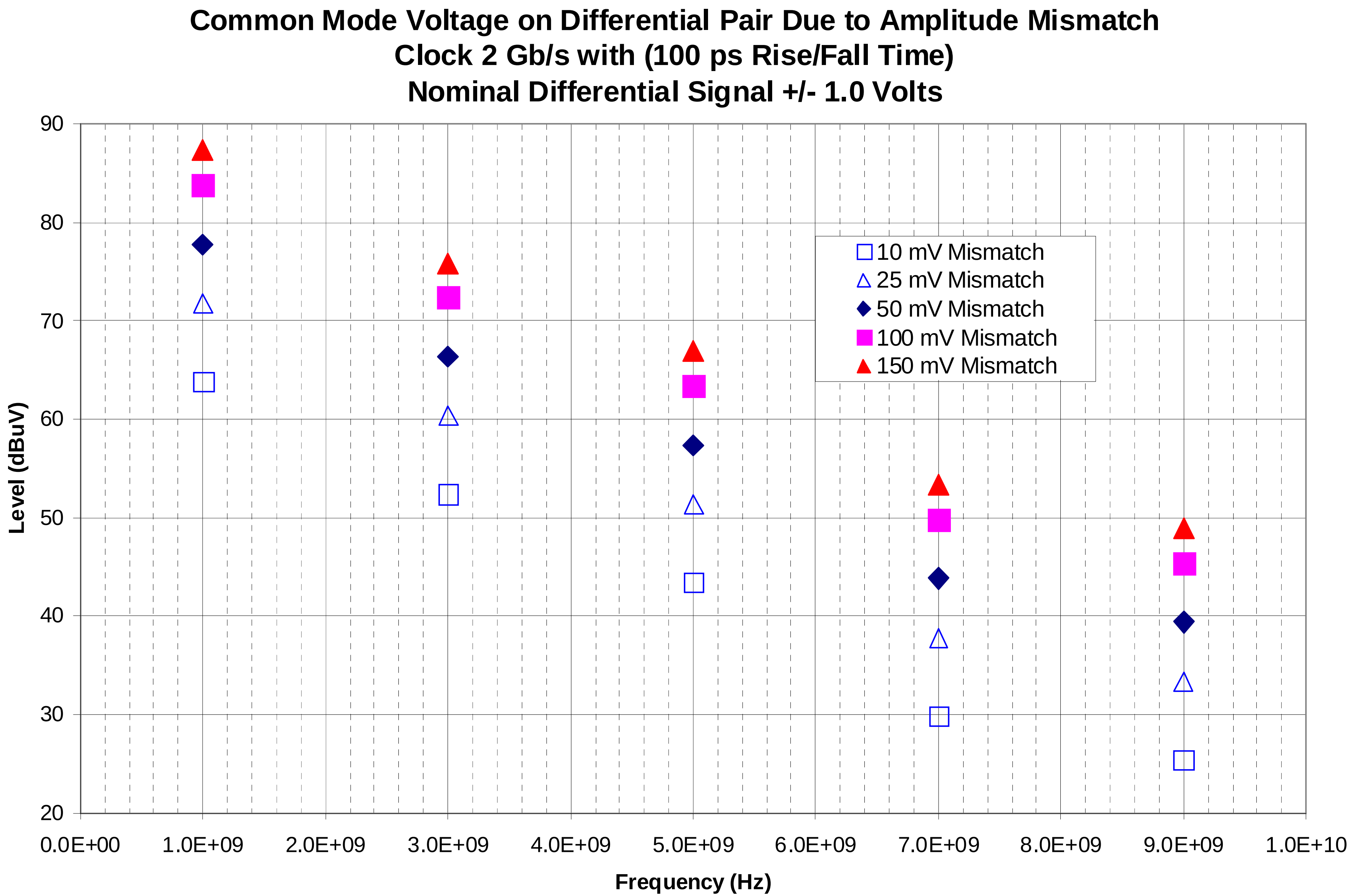
Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Level (volts)
0
5E-10
1E-09
1.5E-09
2E-09
2.5E-09
3E-09
3.5E-09
4E-09
4.5E-09
5E-09
Time (seconds)


Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
Level (dBuV)
100
95
90
85
80
75
70
65
60
55
50
0.0E+00
2.0E+09
4.0E+09
6.0E+09
8.0E+09
1.0E+10
Frequency (Hz)
T/R=50/55ps
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps

Common Mode from Amplitude Mismatch

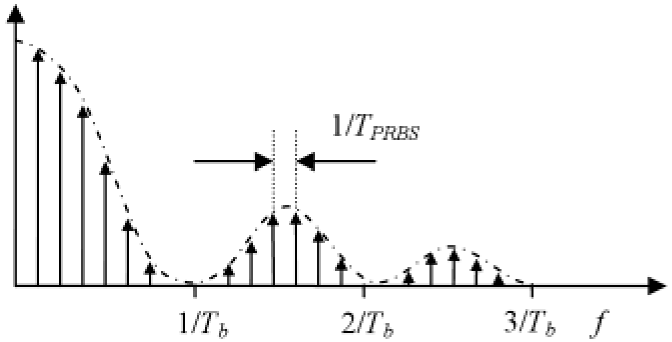
- A small mismatch can result in large harmonics in source spectrum
- Harmonics are additive with other sources of CM noise
- Causes
  - Imbalance within IC

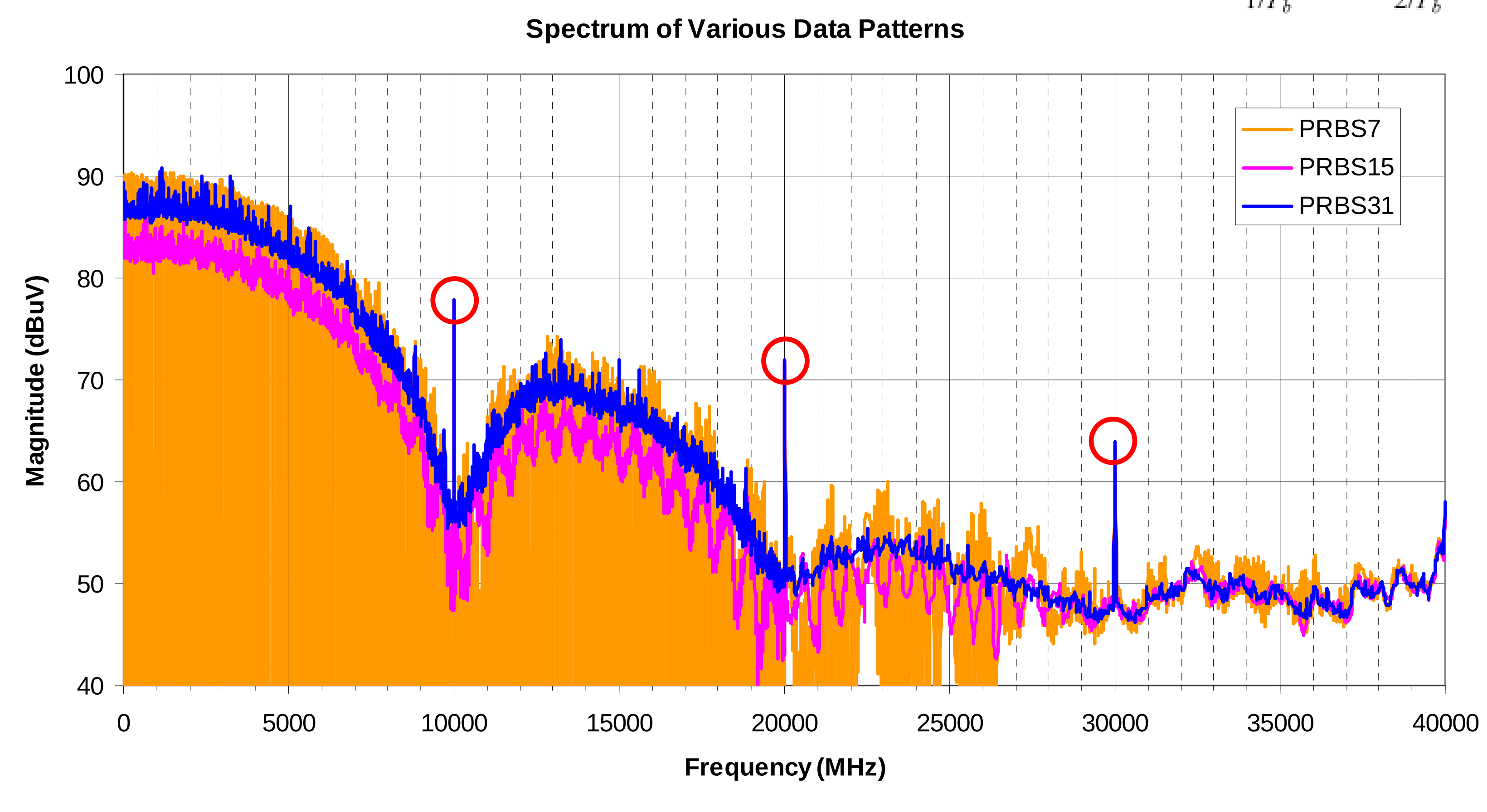

Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time) Nominal Differential Signal +/- 1.0 V
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
Amplitude (volts)
0.0E+00
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (Seconds)
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch



Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time)
Nominal Differential Signal +/- 1.0 Volts
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch
Level (dBuV)
90
80
70
60
50
40
30
20
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)

PRBS Source Spectrum
Real-World vs Theory



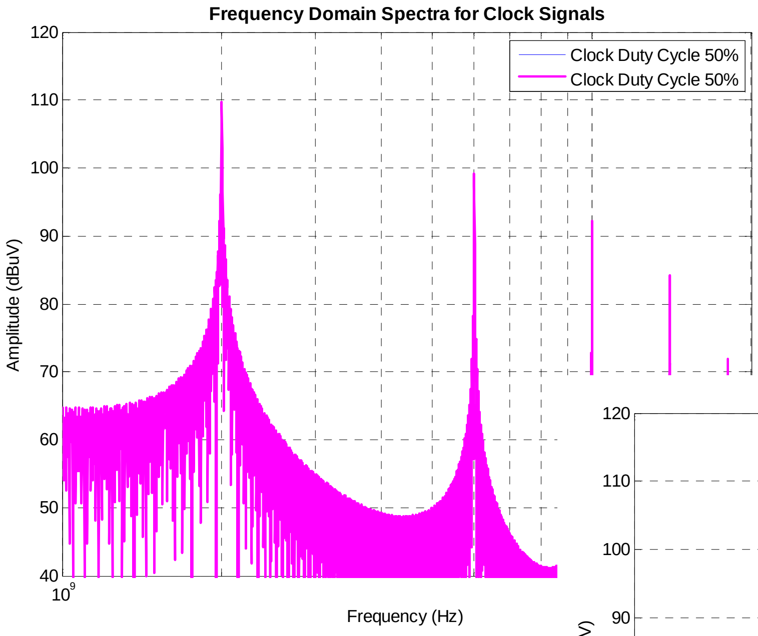


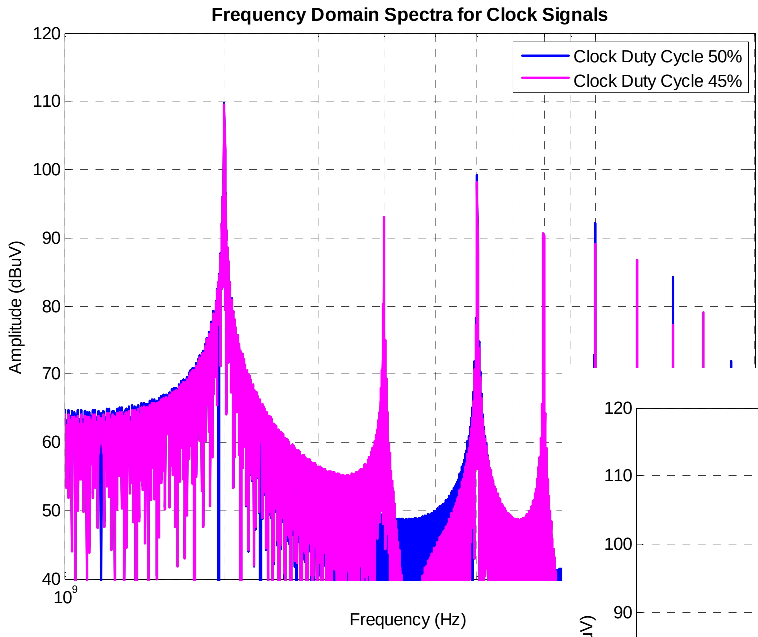
Data Rate = 10 Gbps

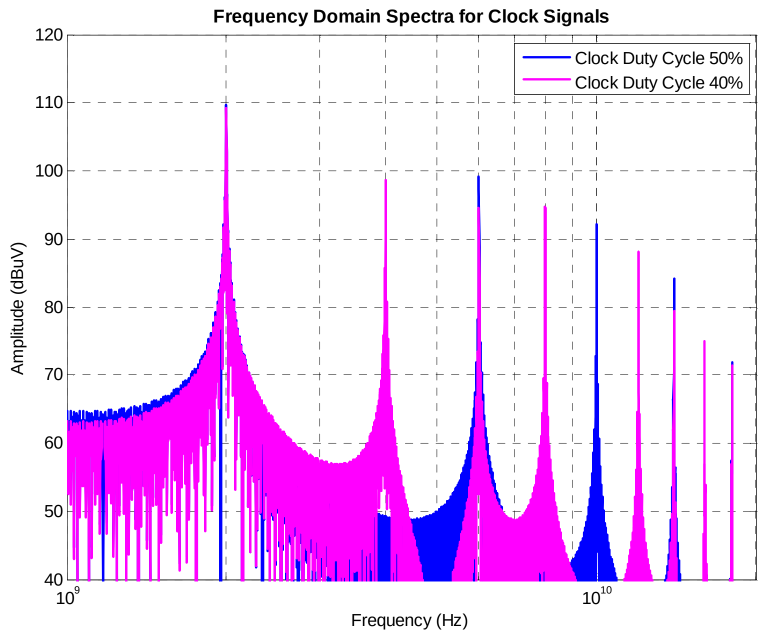
Practical Takeaways

- Differential pairs will have CM noise on them
- Skew and Amplitude Mismatch create CM noise with odd harmonics of data rate
  - 2 Gbps -> 1, 3, 5, 7, 9… GHz
- Rise/Fall Time Mismatch creates CM noise with even harmonics of data rate
  - 2 Gbps -> 2, 4, 6, 8, 10… GHz

Duty Cycle Effects on Spectral Content



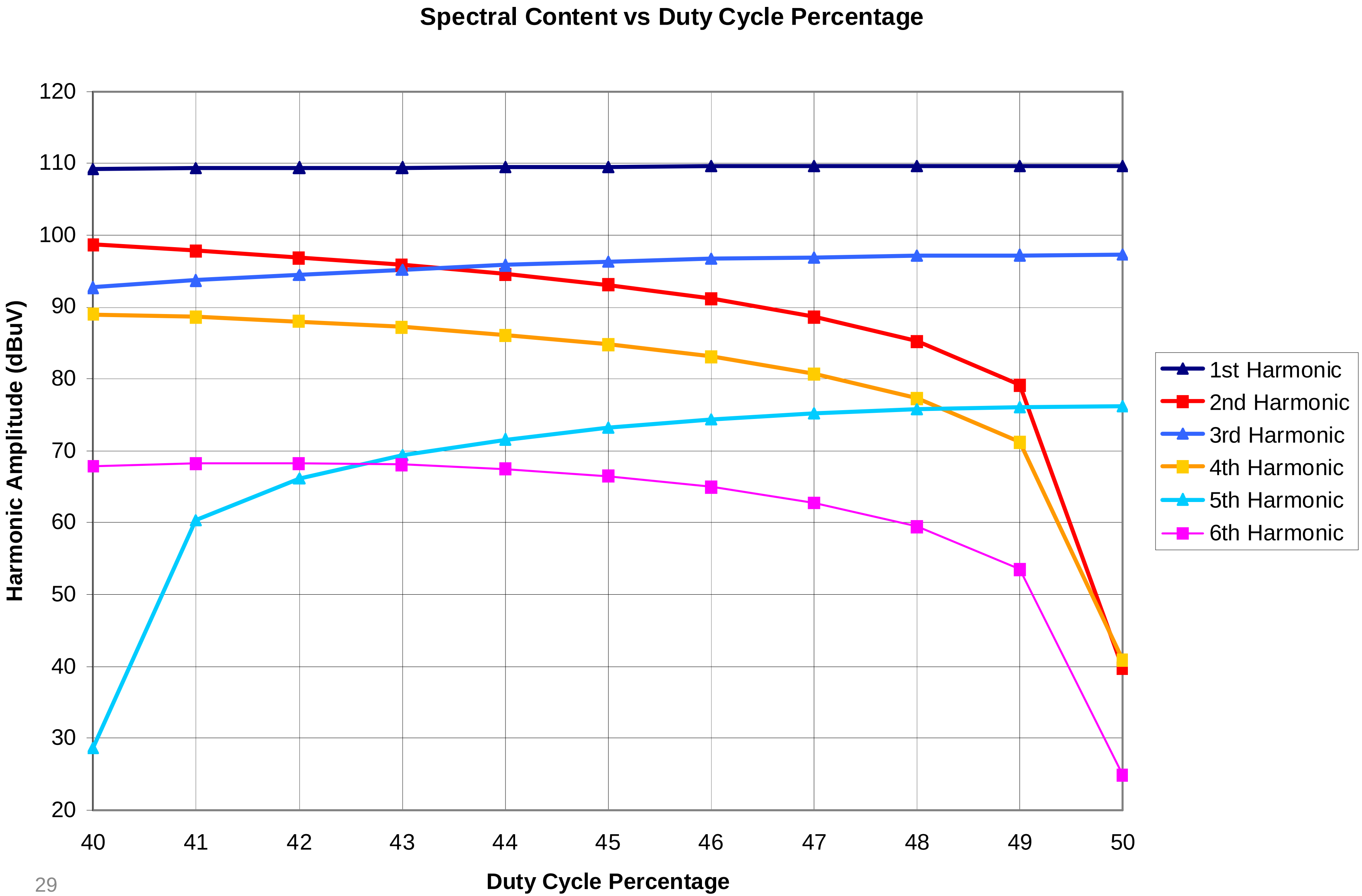




Data Rate = 4 Gbps

Rise/Fall Time = 50 ps

Plot of Harmonic Amplitude Trends



Note about Even Harmonics

- Even harmonics can be caused by intentional differential signal with non-50% duty cycle
- Non-50% duty cycle can be caused by rise/fall time mismatch
- Need to measure signals as single-ended and look at both Vdiff and Vcomm

S-Parameter Primer

- Single-ended (unbalanced)
- Transfer function between ports
  - S11,S22,S33,S44 = Return Loss (gray boxes)
  - S13,S31,S24,S42 = Insertion Loss (green boxes)
  - Example with 4 ports (2 input, 2 output)

Rcv \ Drv	1	2	3	4
1	S11	S12	S13	S14
2	S21	S22	S23	S24
3	S31	S32	S33	S34
4	S41	S42	S43	S44

S-Parameter Primer (2)

- Mixed-mode (balanced)
- Transfer function between balanced ports
  - Example with 2 ports (1 input, 1 output), 2 transmission modes (DM and CM)

Drv / Rcv	D1	D2	C1	C2
D1	Sdd11	Sdd12	Sdc11	Sdc12
D2	Sdd21	Sdd22	Sdc21	Sdc22
C1	Scd11	Scd12	Scc11	Scc12
C2	Scd21	Scd22	Scc21	Scc22

S-Parameter Primer (3)

Drv / Rcv	D1	D2	C1	C2
D1	Sdd11	Sdd12	Sdc11	Sdc12
D2	Sdd21	Sdd22	Sdc21	Sdc22
C1	Scd11	Scd12	Scc11	Scc12
C2	Scd21	Scd22	Scc21	Scc22

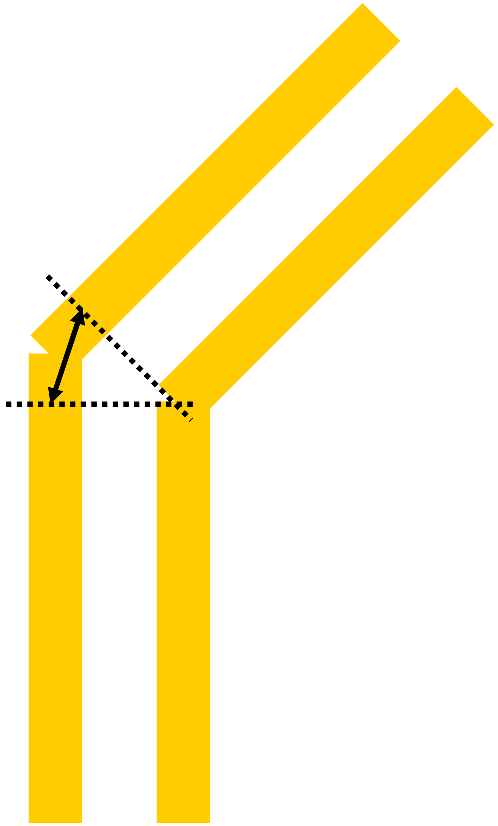
How much of the differential signal driven at Port 1 is converted to CM signal by the time it reaches Port 2

1 – Sdc11 – Sdc21 – Scc11 – Scc21 = ?
Absorption, Multiple Reflection,
Radiation

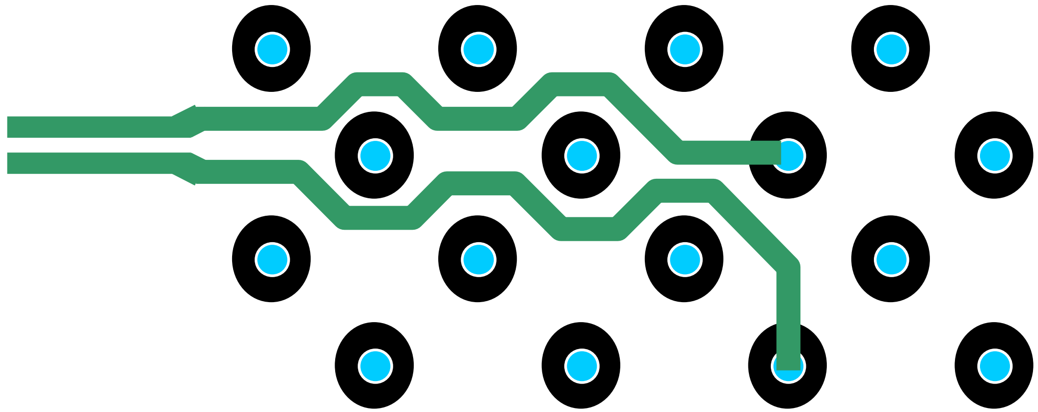
Sources of Mode Conversion

- Routing asymmetries cause in-pair skew
  - Length mismatch
  - Diff Pair near edge of reference plane
  - Return via placement
  - Weave effects in dielectric material
  - Reference plane interruptions
  - Line width variation
  - Unequal stub lengths

Skew from Length Mismatch

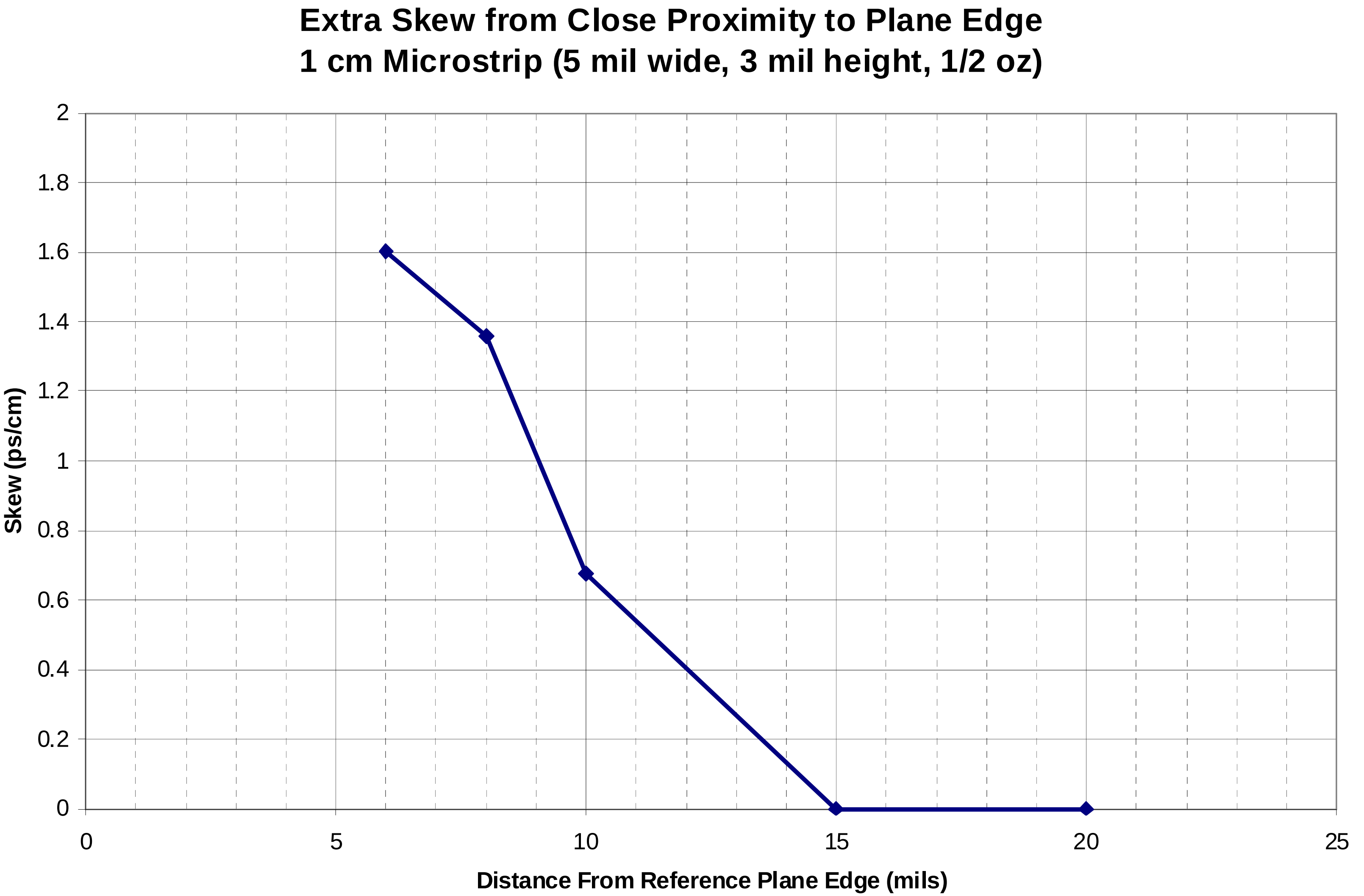


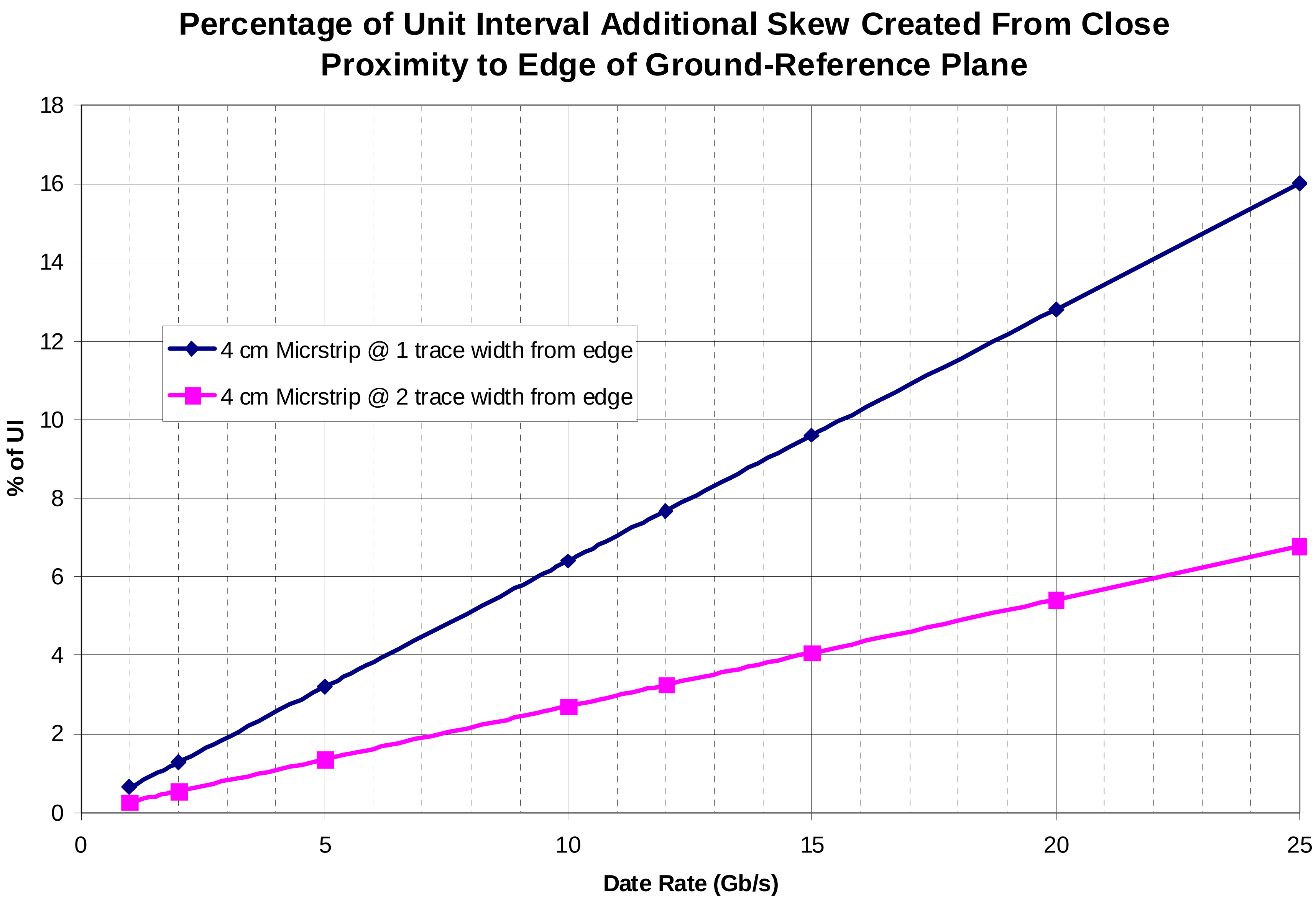
Turns add length
to outside line



Escapes from pin fields
often require one line to
be longer

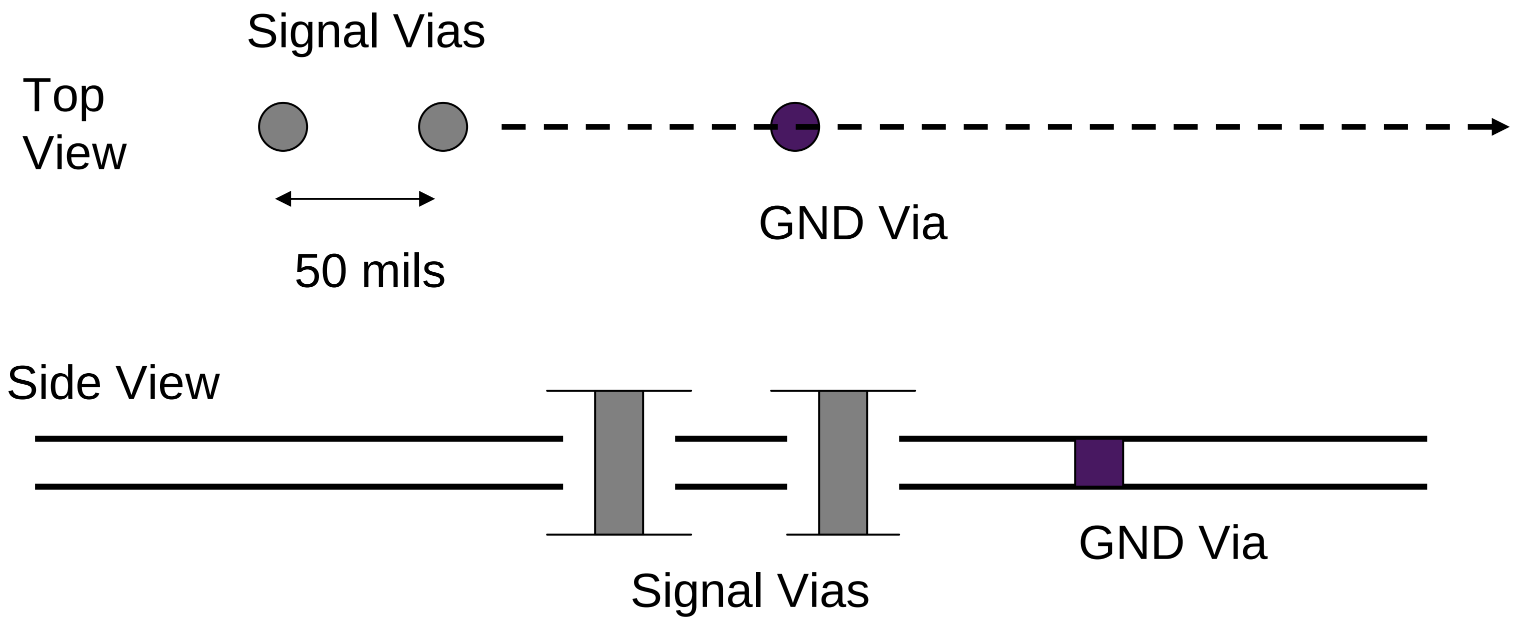
Skew from Pair Near Edge of Reference Plane



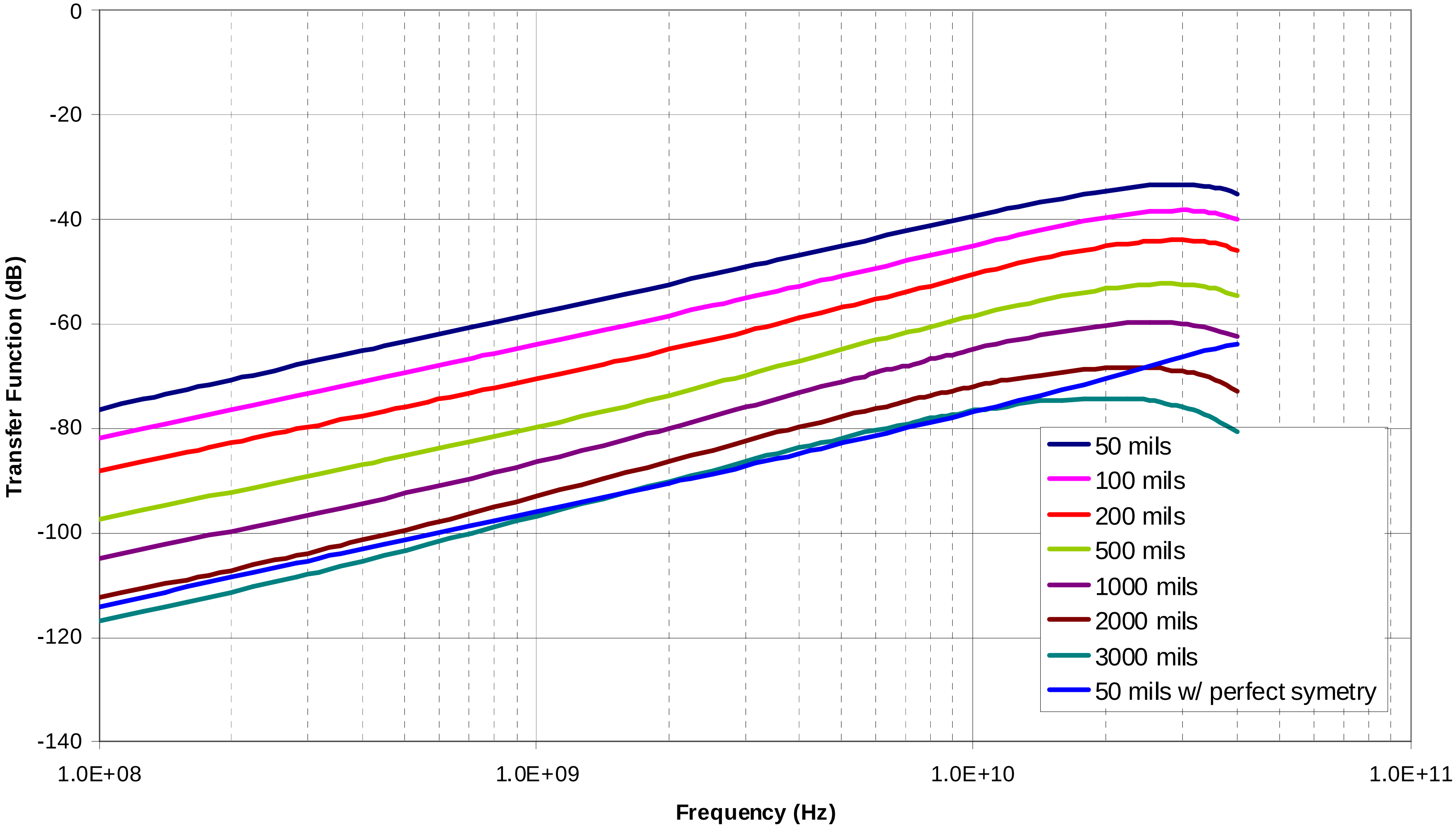

Percentage of Unit Interval Additional Skew Created From Close Proximity to Edge of Ground-Reference Plane
% of UI
Date Rate (Gb/s)
4 cm Micrstrip @ 1 trace width from edge
4 cm Micrstrip @ 2 trace width from edge
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25

Skew from Return Via Asymmetry

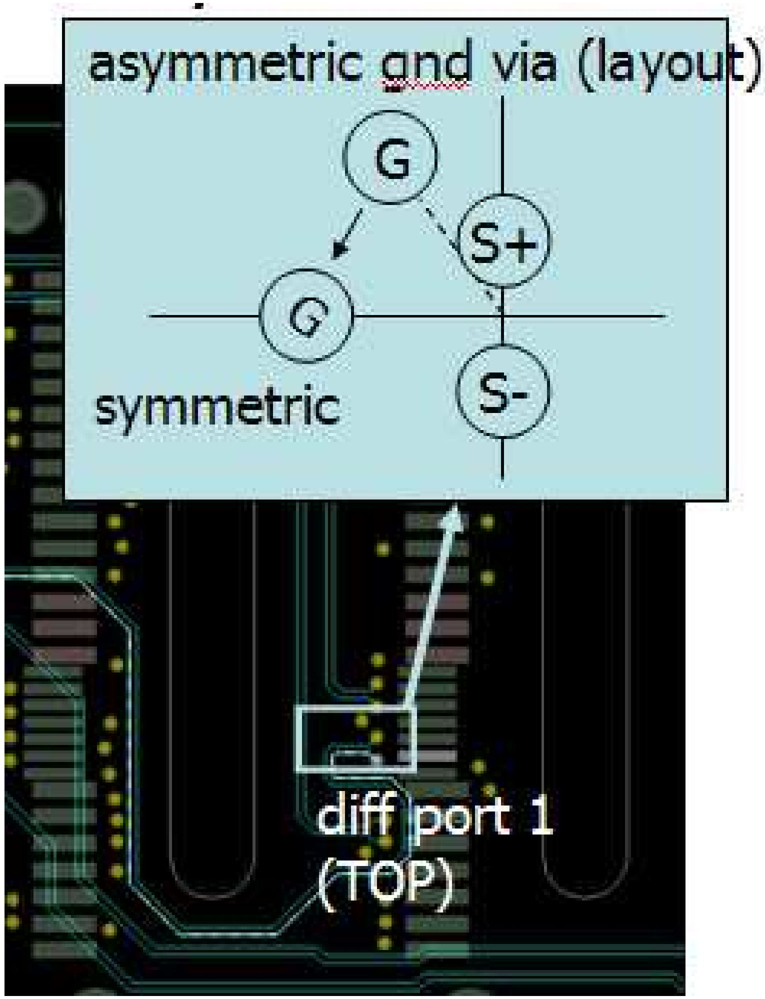
- Significant CM created!

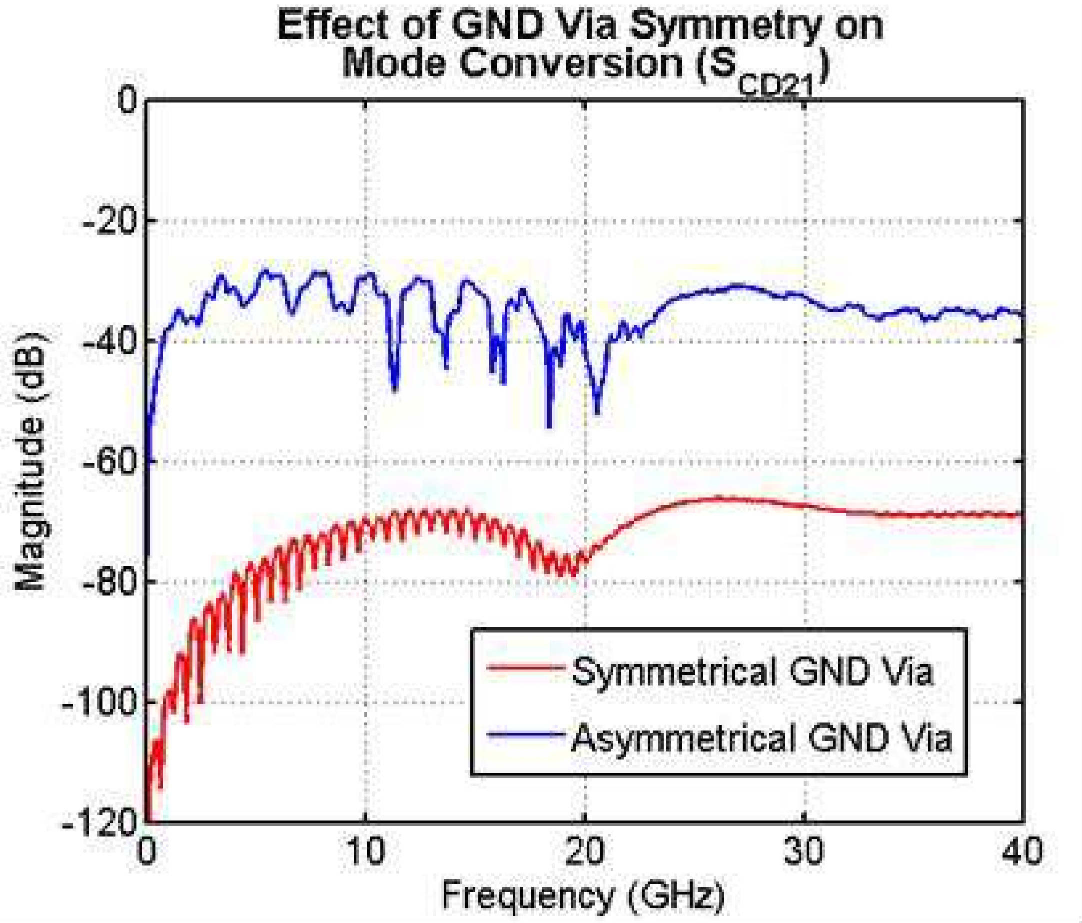


Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes

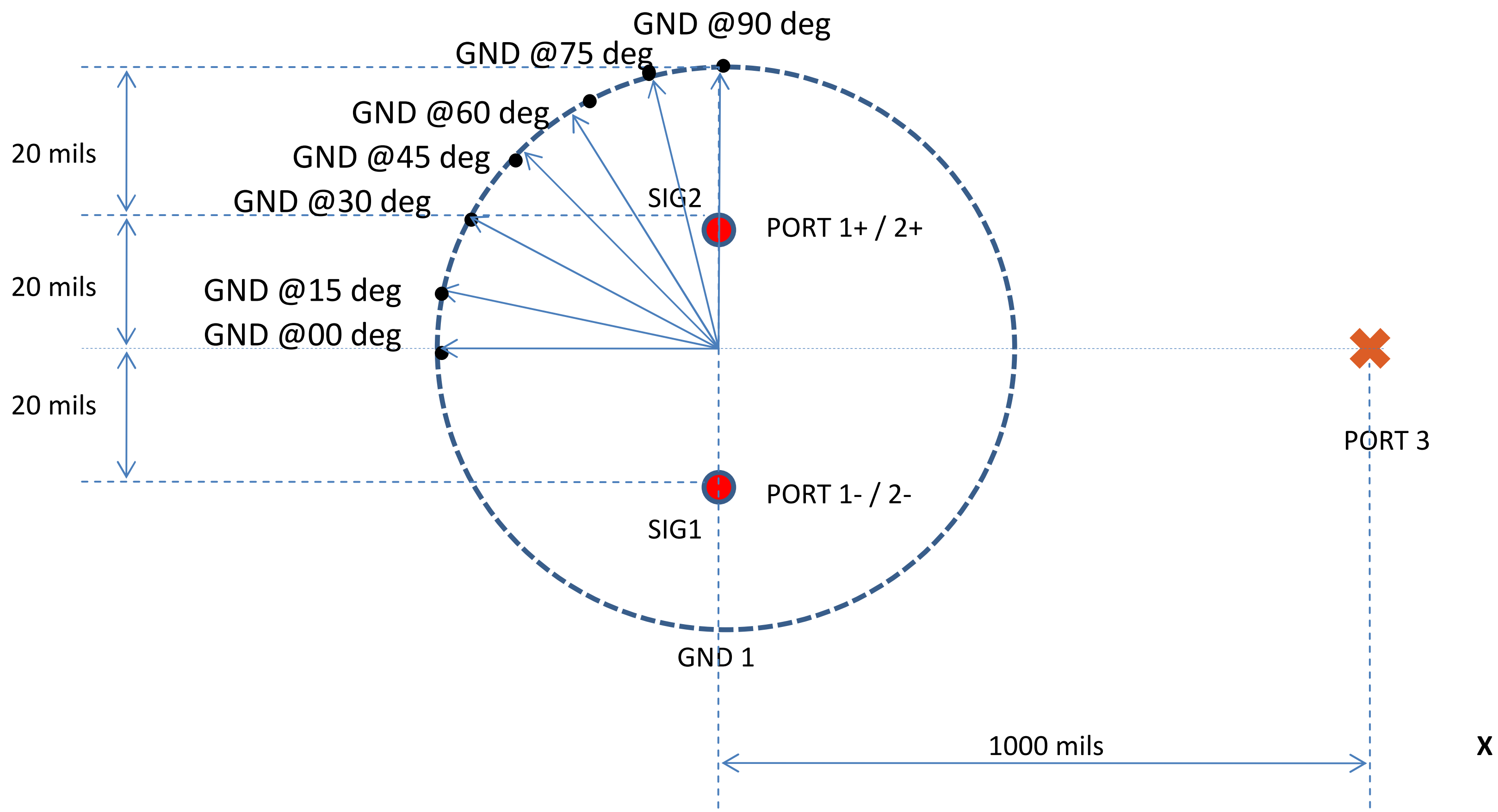


Return Via Symmetry Effect – Escape from SAS Connector

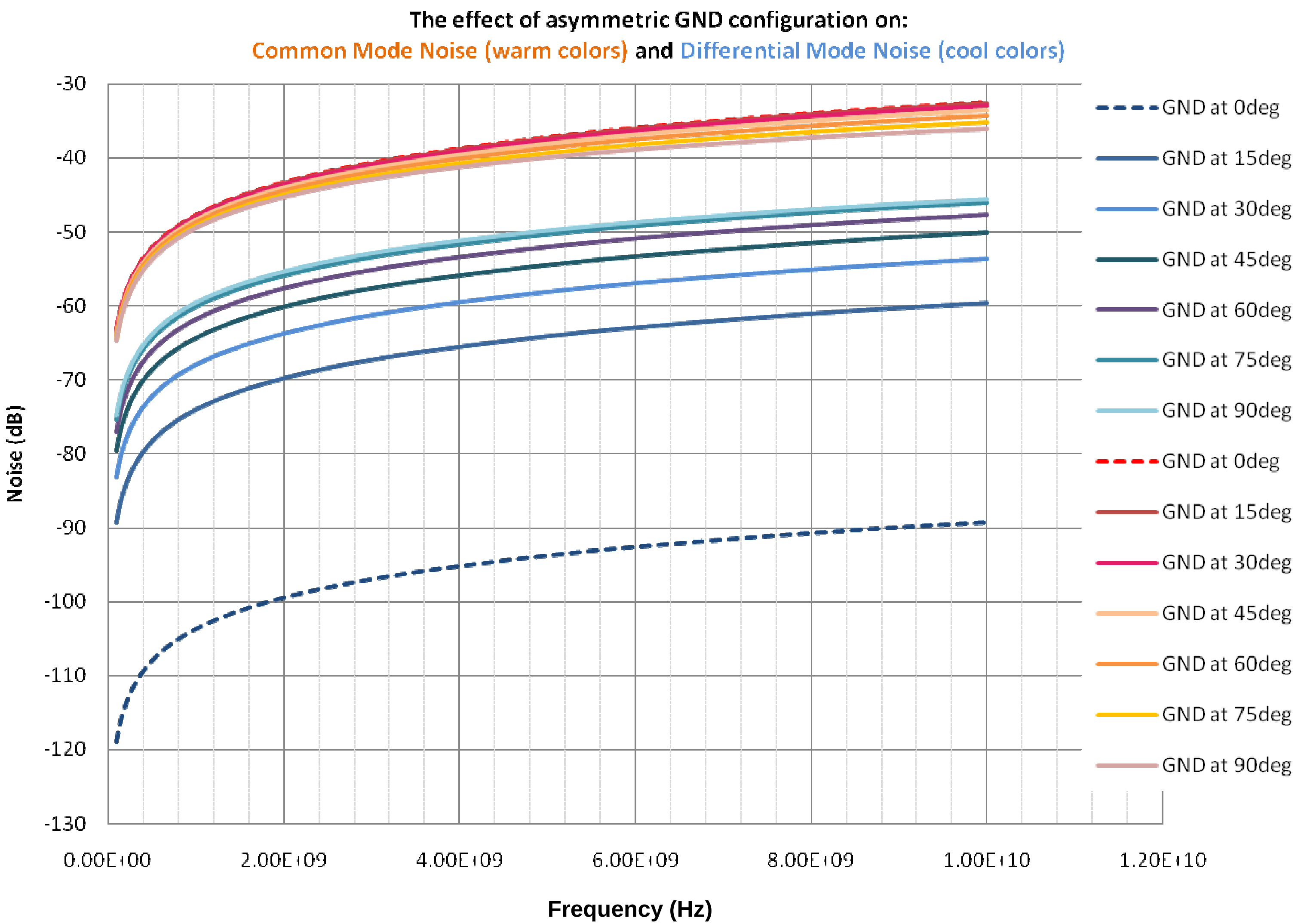




Top View of the Board: Different GND configurations



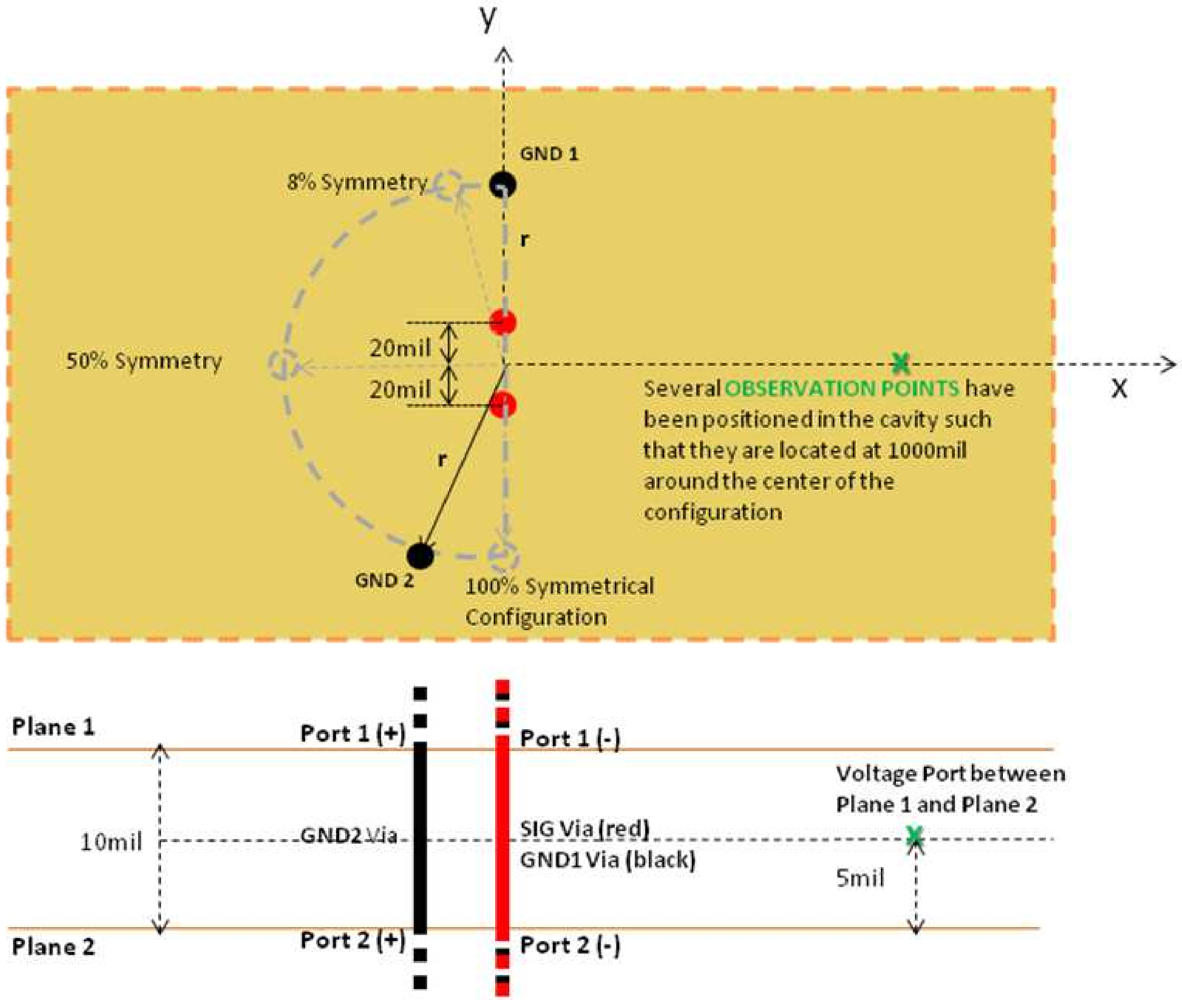
Asymmetric Ground Via Effects



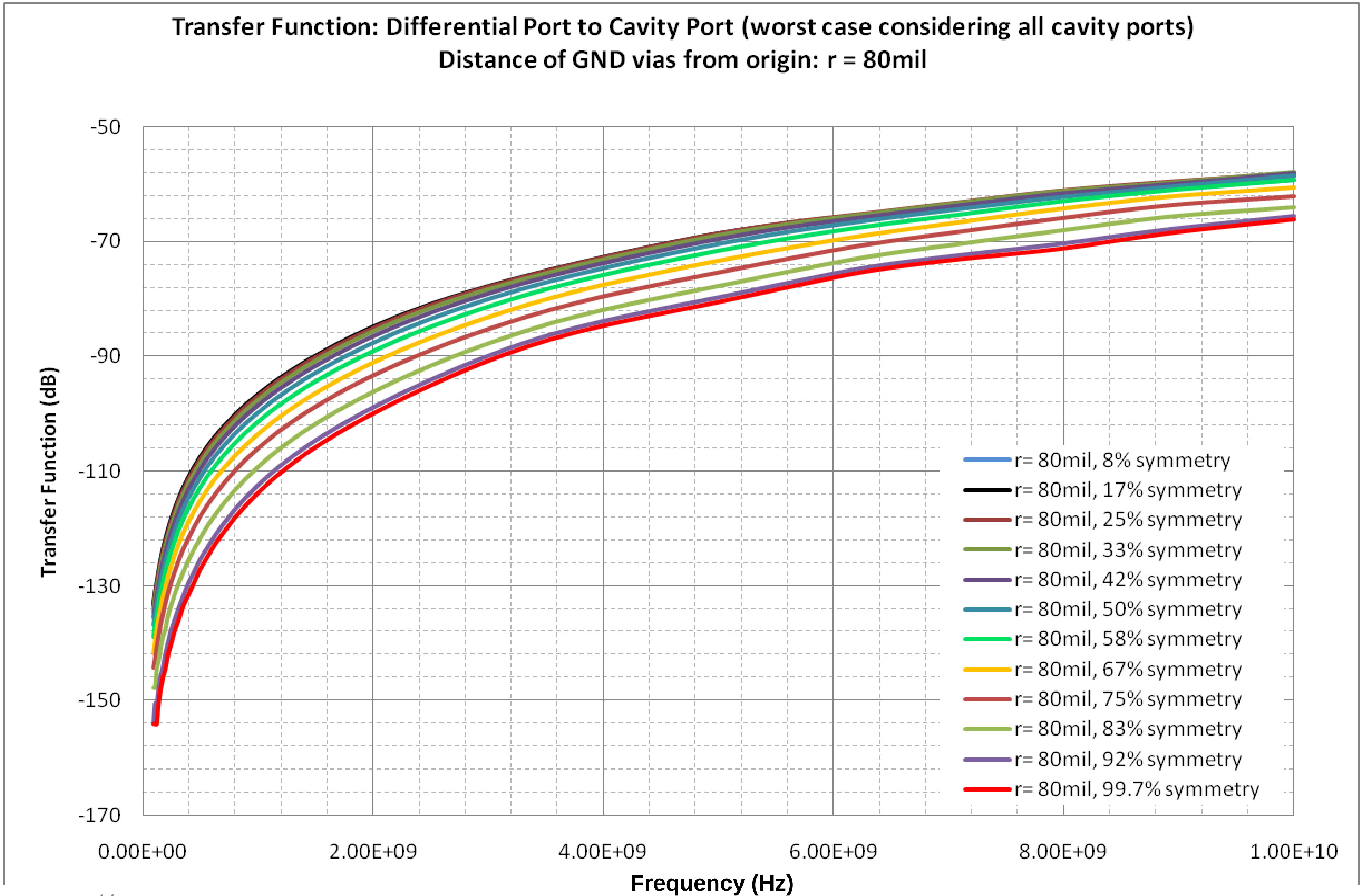
Asymmetry with Two GND Vias

TOP VIEW

PROFILE VIEW



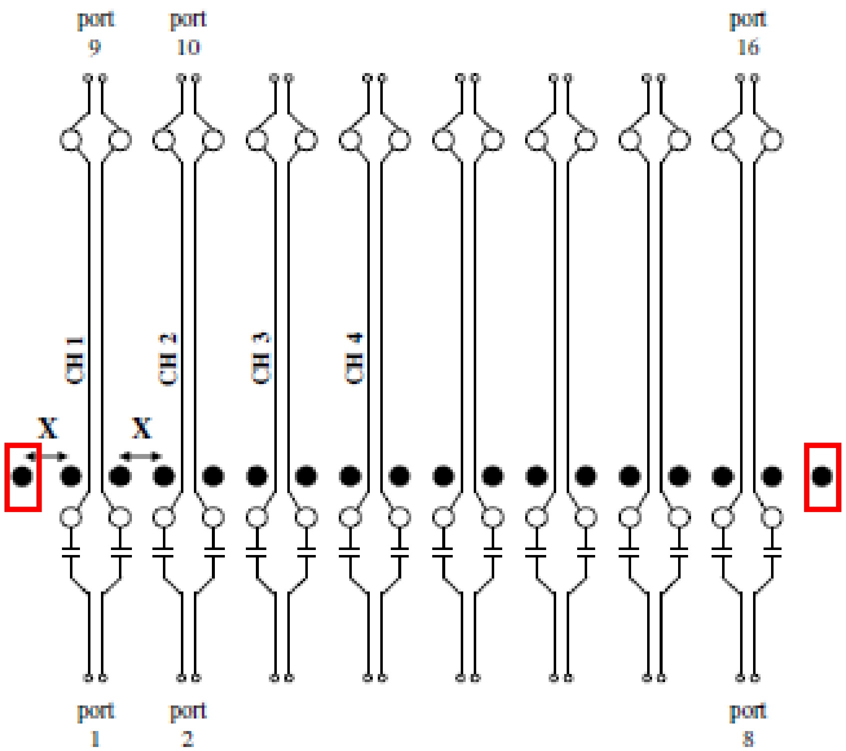
Dielectric Constant, Metal Thickness: 4.3, 1mil
Antipad, Pad, Via Drill Diameter: 35 mil, 20mil, 12 mil

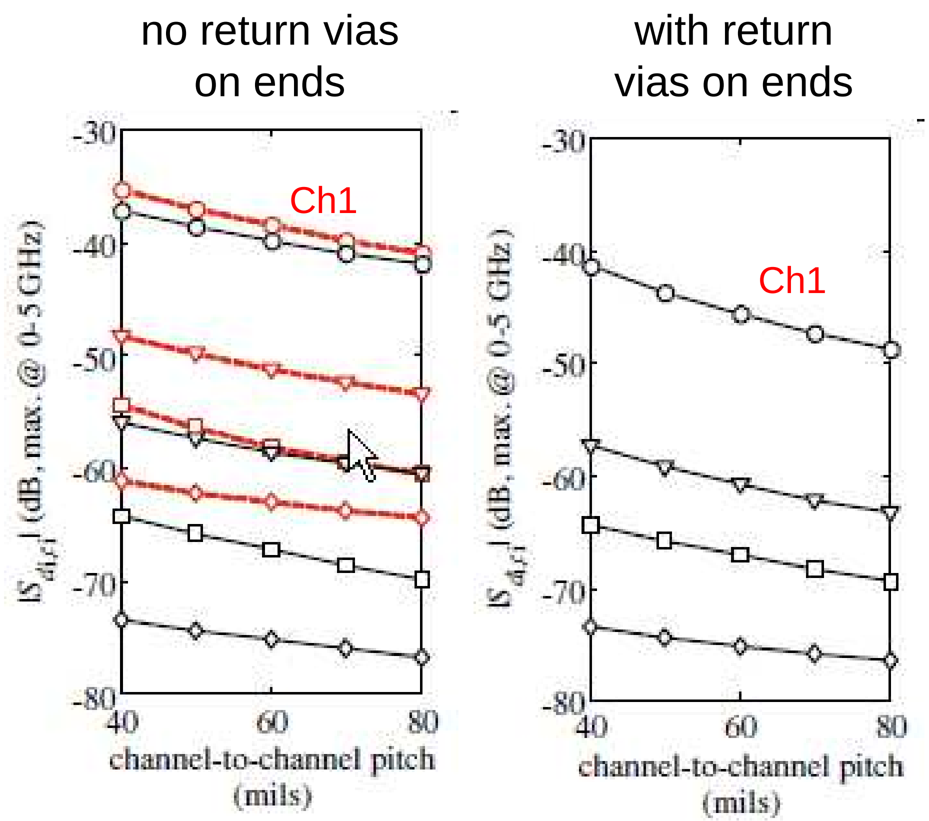


Transfer Function: Differential Port to Cavity Port (worst case considering all cavity ports)
Distance of GND vias from origin: r = 80mil
-50
-70
-90
-110
-130
-150
-170
Transfer Function (dB)
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
r= 80mil, 8% symmetry
r= 80mil, 17% symmetry
r= 80mil, 25% symmetry
r= 80mil, 33% symmetry
r= 80mil, 42% symmetry
r= 80mil, 50% symmetry
r= 80mil, 58% symmetry
r= 80mil, 67% symmetry
r= 80mil, 75% symmetry
r= 80mil, 83% symmetry
r= 80mil, 92% symmetry
r= 80mil, 99.7% symmetry

Return Via Symmetry Effect – Bus of Diff Pairs with DC Blocking Caps

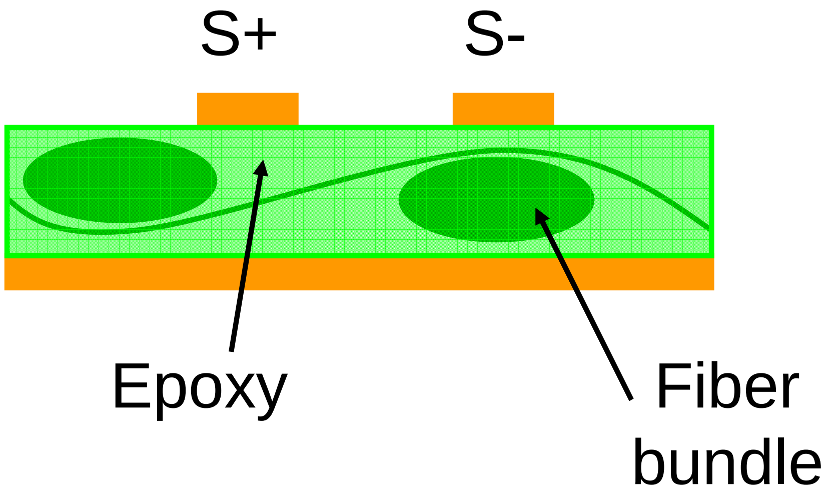
Mode Conversion (Scd21)





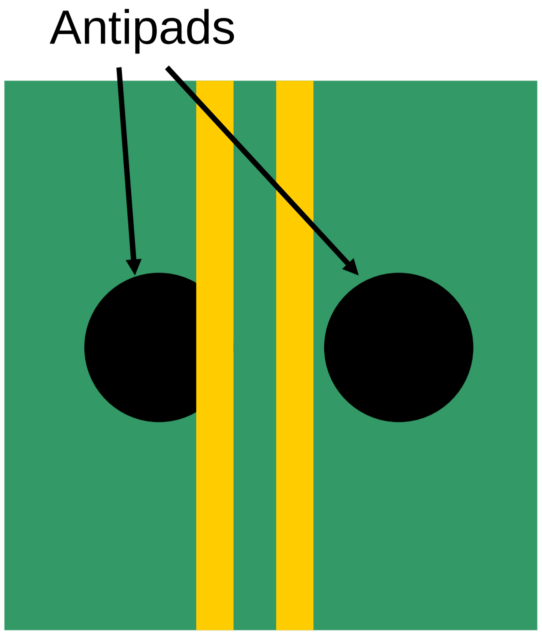
K.J. Han, X. Gu, Y. Kwark, Z. Yu, D. Liu, B. Archambeault, S. Connor, J. Fan, "Parametric Study on the Effect of Asymmetry in Multi-Channel Differential Signaling," in Proceedings of IEEE International Symposium on EMC 2011.

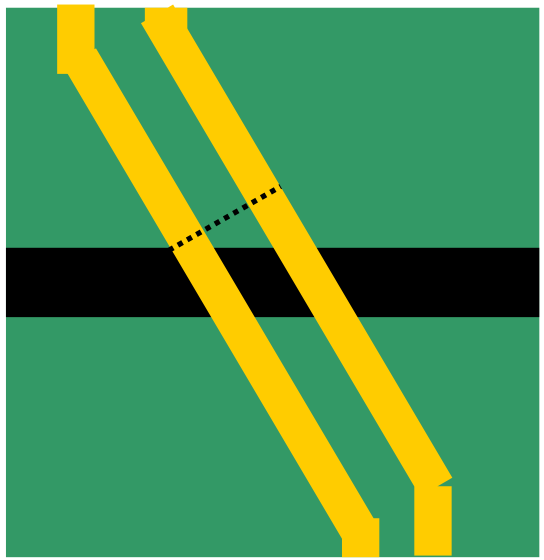
Skew from Weave Effects



- Effective dielectric constant is different under S+ and S-
  - Propagation velocities will vary
  - Skew of 5-10 ps/in is common

Skew from Reference Plane Interruptions

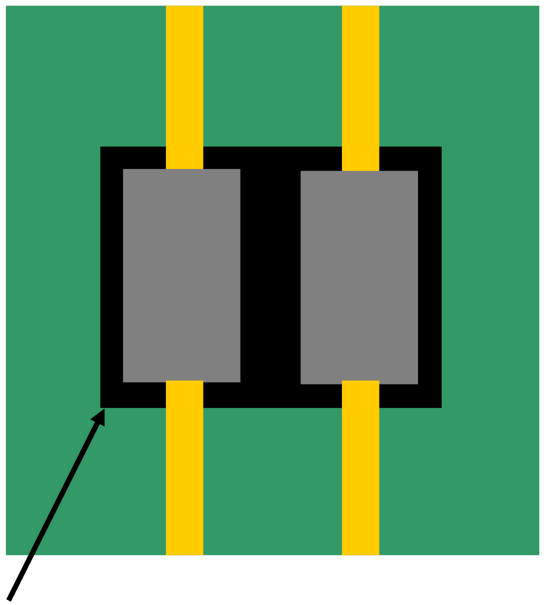




Split between power islands

Other Issues with Reference Plane Interruptions

Where does CM return current flow?

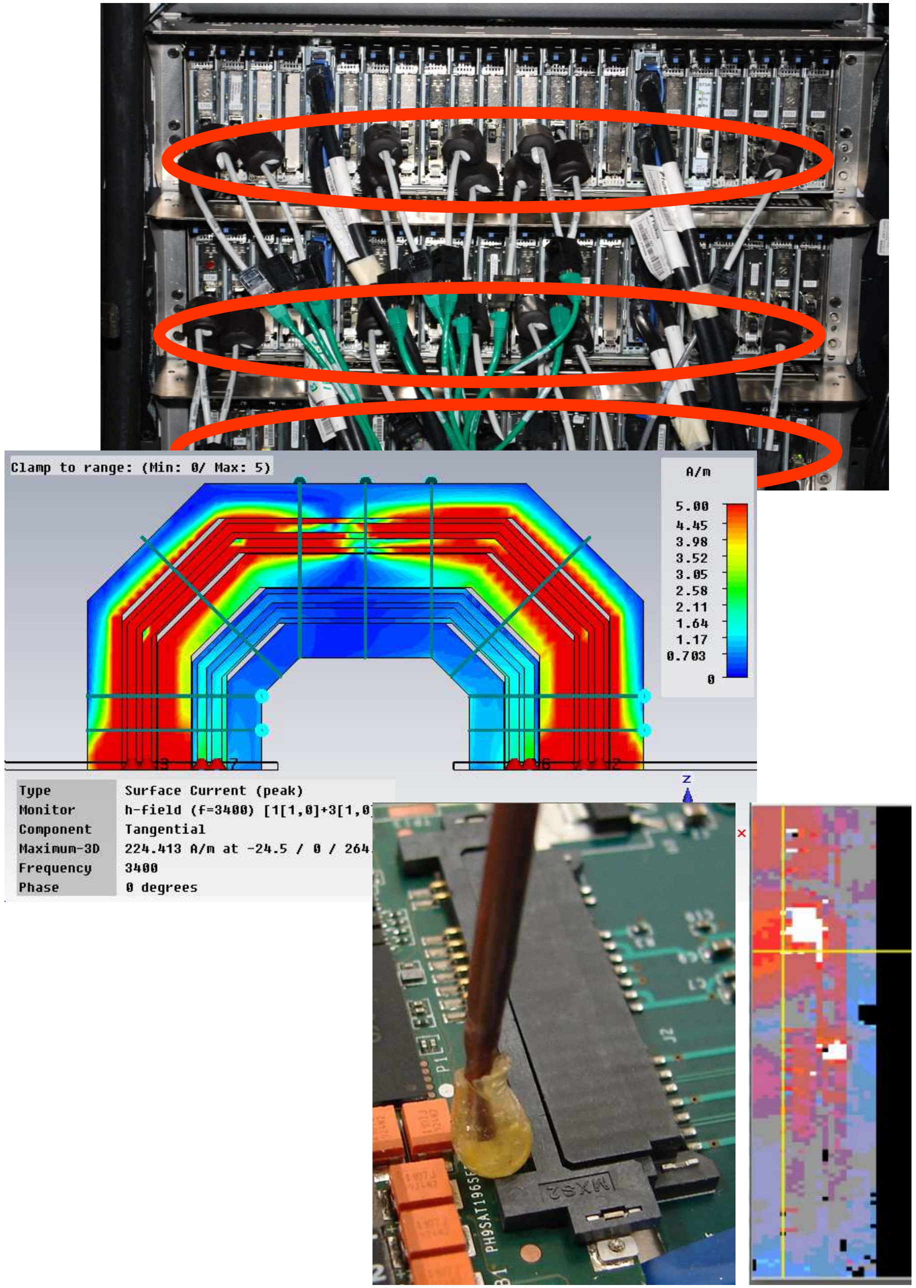


Cutout area under DC blocking caps

- Lowers parasitic capacitance
- Improves differential insertion loss (Sdd21)
- What about common mode (Scc11, Scc21)?

Radiation Mechanisms

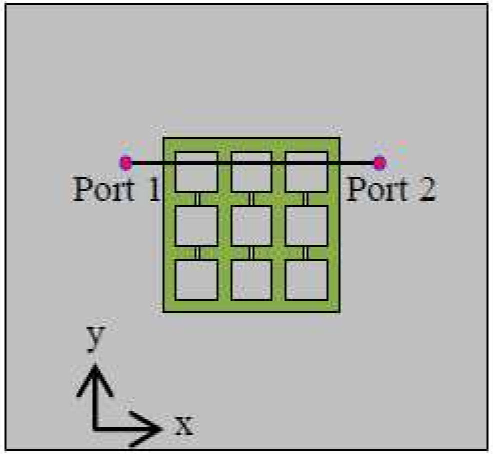
- Cables
  - Electrically long
  - Weakness in outer shield or backshell connection causes problem
  - Consider SE + |Scd21| performance
- Connectors
  - Many are longer than 1” (half wavelength between 5-6 GHz)
- Microstrip traces

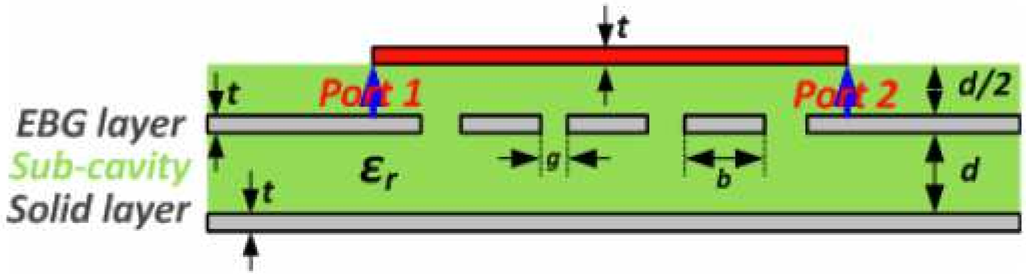


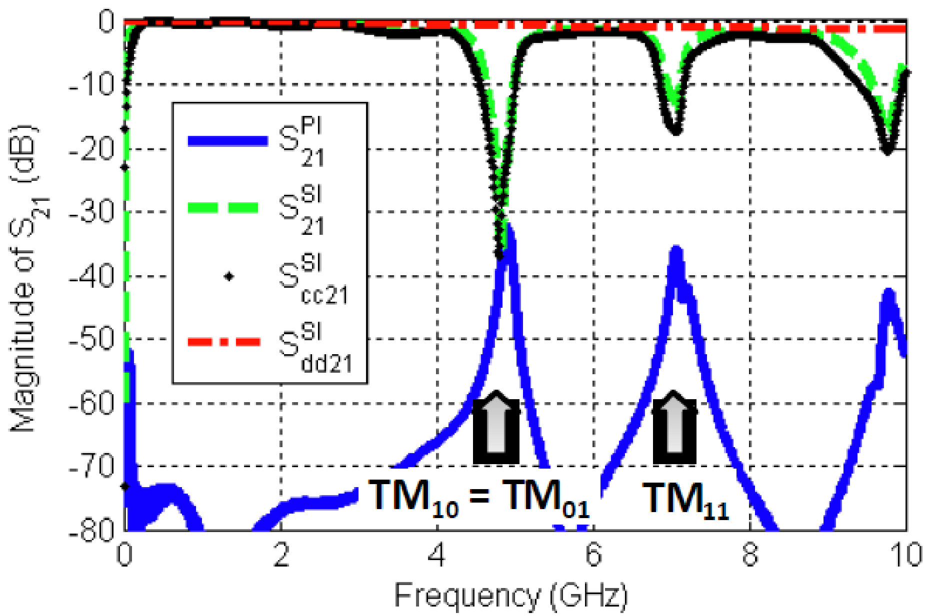
EMC Design Options

- Common mode filtering
  - Common mode choke coils work for lower-speed interfaces
  - Integrated magnetics in RJ-45 connectors
  - Looking at planar EBG structure for higher-speed (5-10 GHz) signals
- Absorbing materials
  - Absorption reduces radiation from cables
  - Proper placement could add loss to even mode fields without affecting odd mode field

Common Mode Filtering - EBGs

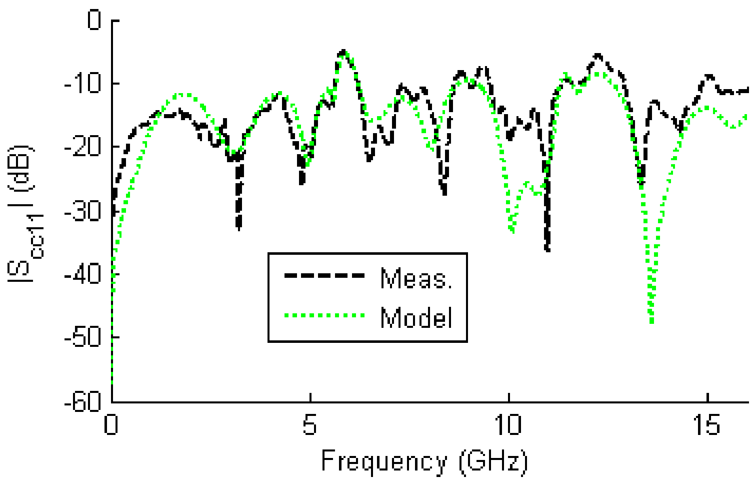


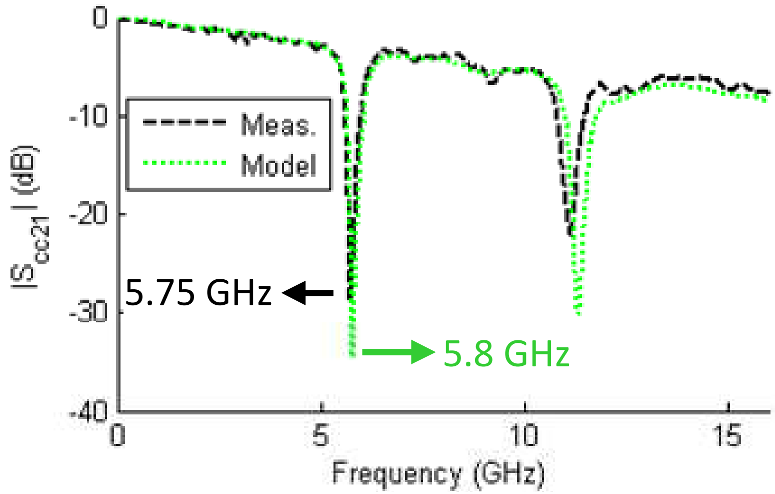


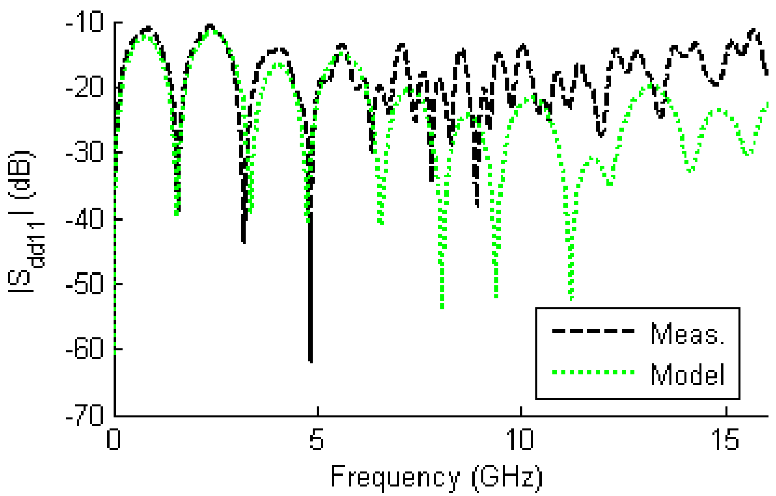


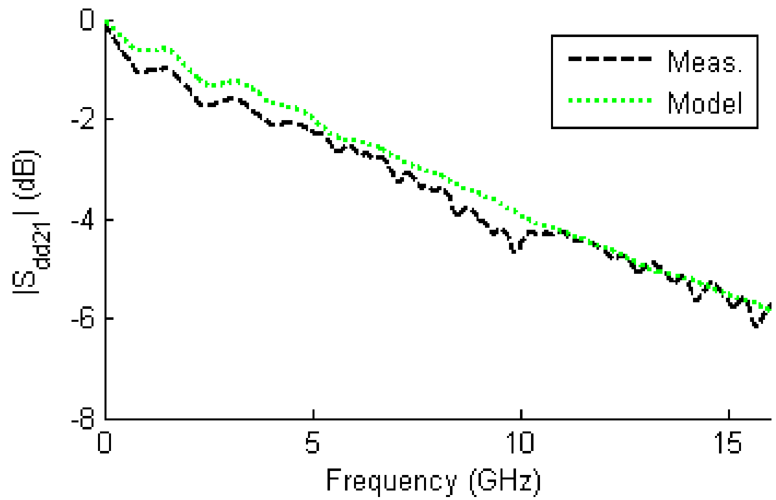
Ref.: Publications by F. De Paulis (L'Aq) at DesignCon and IEEE EMCS

Model-to-Hardware Correlation (S-Parameters - 5.8-GHz EBG)

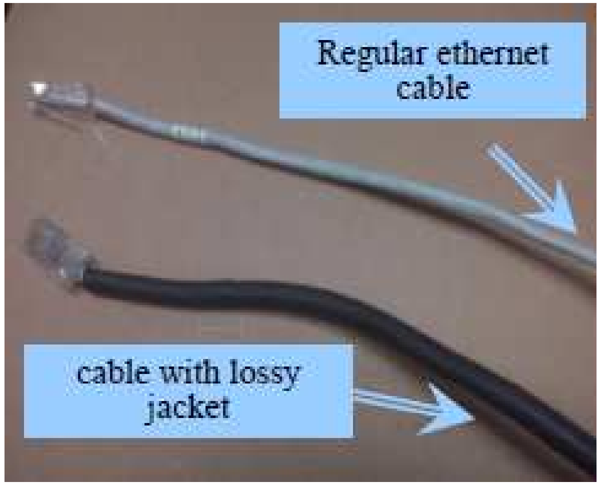




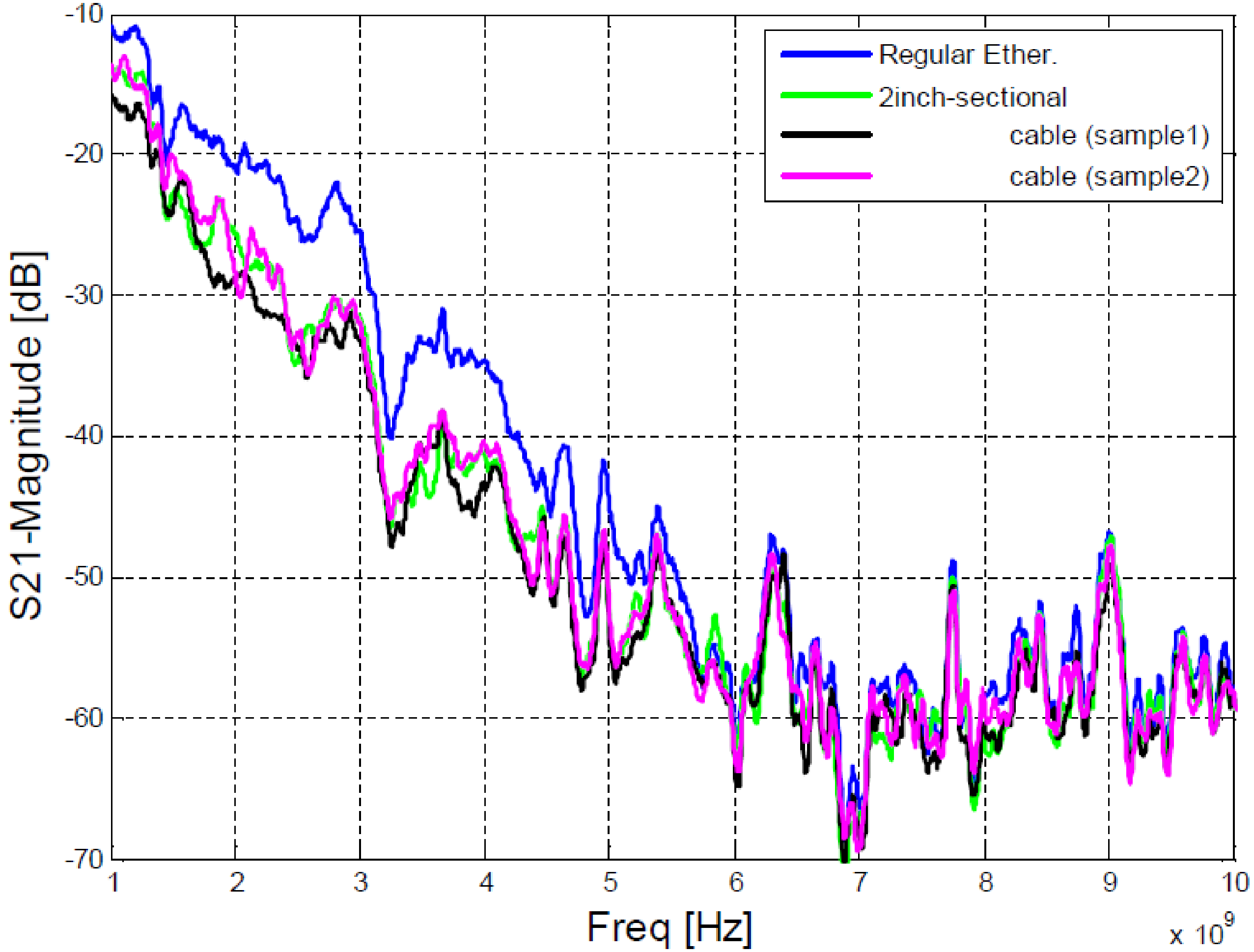




Absorbing Material on Cables

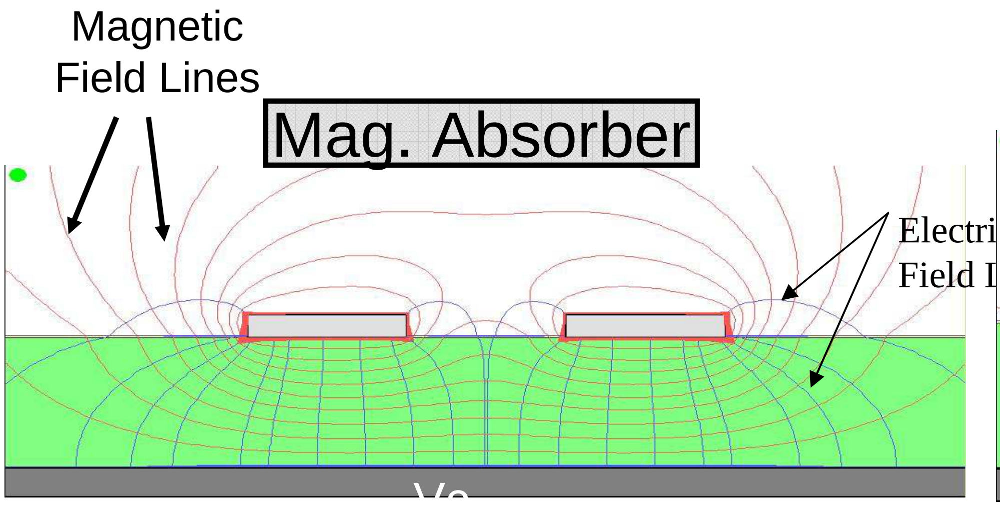


Measurements of lossy material on cables

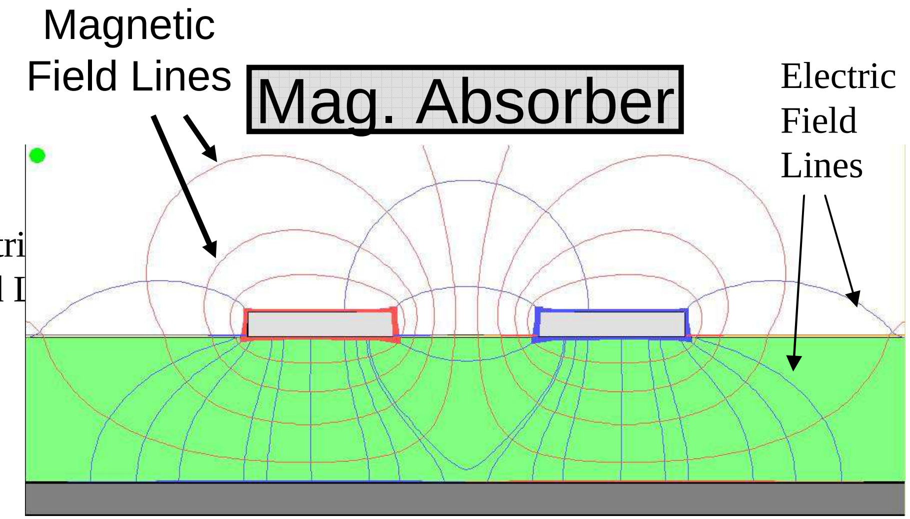


Absorbing Material near Differential Pairs

- Minimal impact to differential mode signal
- Some attenuation of common mode signal



Common Mode



Differential Mode

Summary

- The differential signals in our circuit boards, connectors, and cables all support even (common) mode transmission
- Driver skew, rise/fall time mismatch, and amplitude mismatch all create common mode noise on differential pairs
- Physical channel asymmetries create common mode noise through mode conversion
  - Asymmetries must be eliminated when possible and be minimized when unavoidable
- Common mode noise radiates
- Need to assign CM noise budget to parts of system
- CM filtering and absorption are effective at reducing radiation from differential pairs