"Radiated Field Coupling to Signal Cables"

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"Power Circuit Cross Coupling"

Presented by Senior Student
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SFSU EMC Research Projects

Overview

"Radiated Field Coupling to Signal Cables"

- Motivation
- Problem Definition
- Distributed Parameters Model
- Mechanisms of Coupling
  - o Normal H−Field
  - o Transverse E−Field
  - o Longitudinal E−Field
- Directional Coupling Modes
- Transmission Line Equations
- Lumped Parameter Model
  - o Twin Pair
    - − Electrically Short Line
    - − Electrically Long Line
  - o Twisted Pair
- Numerical Results
- Conclusions

Computer Industry

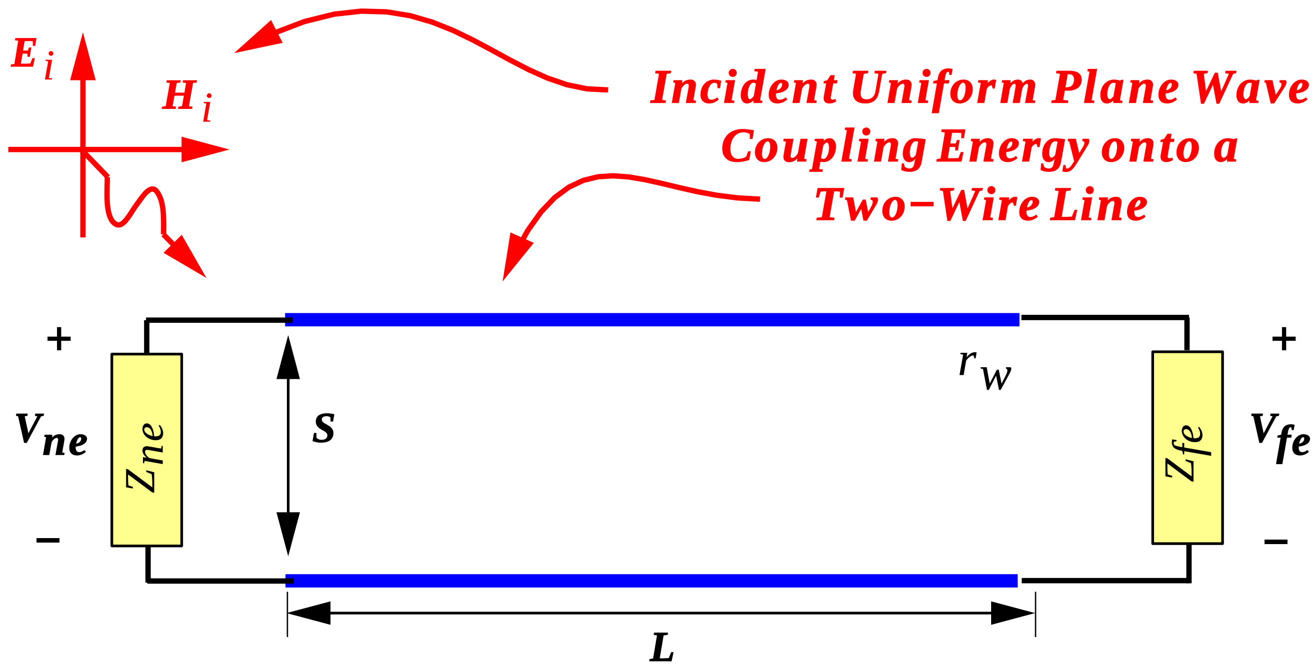
Airline Industry

Sensitive Electronics

Automotive Industry

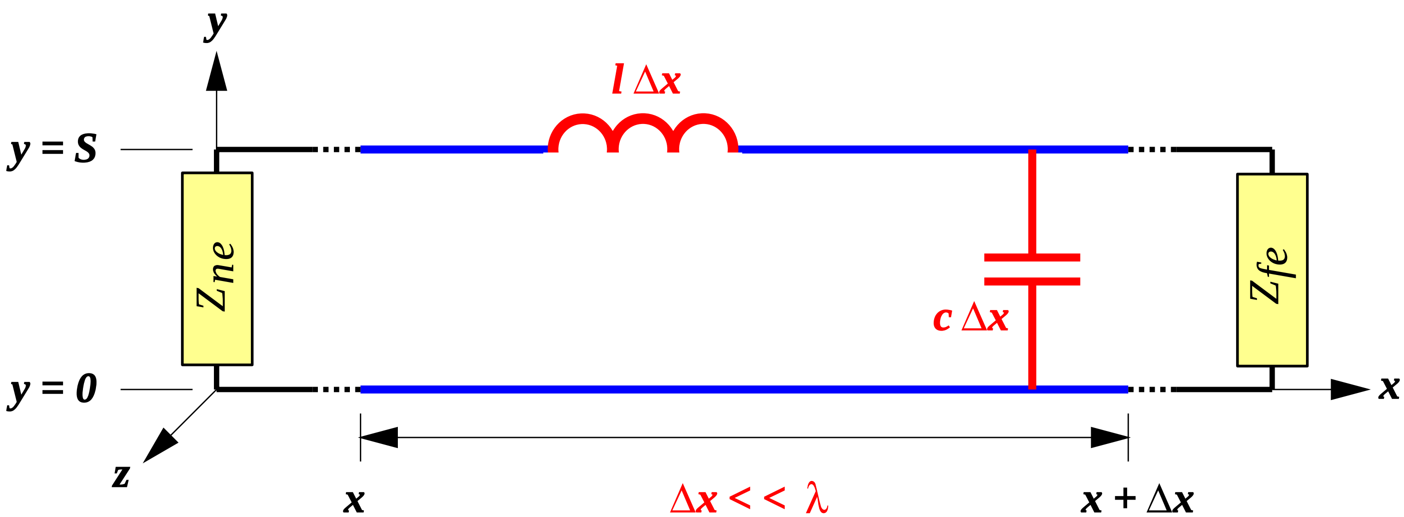
Radiated electric and magnetic fields can cause significant susceptibility problems in computer, airline or automotive industry and in sensitive electronics equipment. One of the main mechanisms of coupling is through signal and power cables. Our models will allow us to calculate the levels of induced volatges and currents in these cables.

Problem Definition



Known	E_i, H_i:	*Incident Electromagnetic Plane Wave*
	Z_{ne}, Z_{fe}:	*Near End/Far End Termination Impedance*
	S:	*Separation Distance Between Wires*
	L:	*Coupling Length*
	r_w:	*Radius of wire*
Unknown	V_{ne}, V_{fe}:	*Near End/Far End Induced Voltage*

L−Cell Equivalent Distributed Parameter Model



- ***Lossless "LC" equivalent circuit oriented in x−y plane***
- λ = ***Wavelength (in meters)***
- l = ***Per unit length inductance (H/m)***

  $= (\mu_o/\pi) \cosh^{-1}(S/2\,r_w)$

  $l\,\Delta x$ = ***Total cell inductance***
- c = ***Per unit length capacitance (F/m)***

  $= \pi\,\varepsilon_o / \cosh^{-1}(S/2\,r_w)$

  $c\,\Delta x$ = ***Total cell capacitance***

Mechanisms of Coupling

There are 3 mechanisms of coupling

1: Normal H−Fields
2: Transverse E−Fields
3: Longitudinal E−Fields

The Conventional Model takes into account 1 and 2

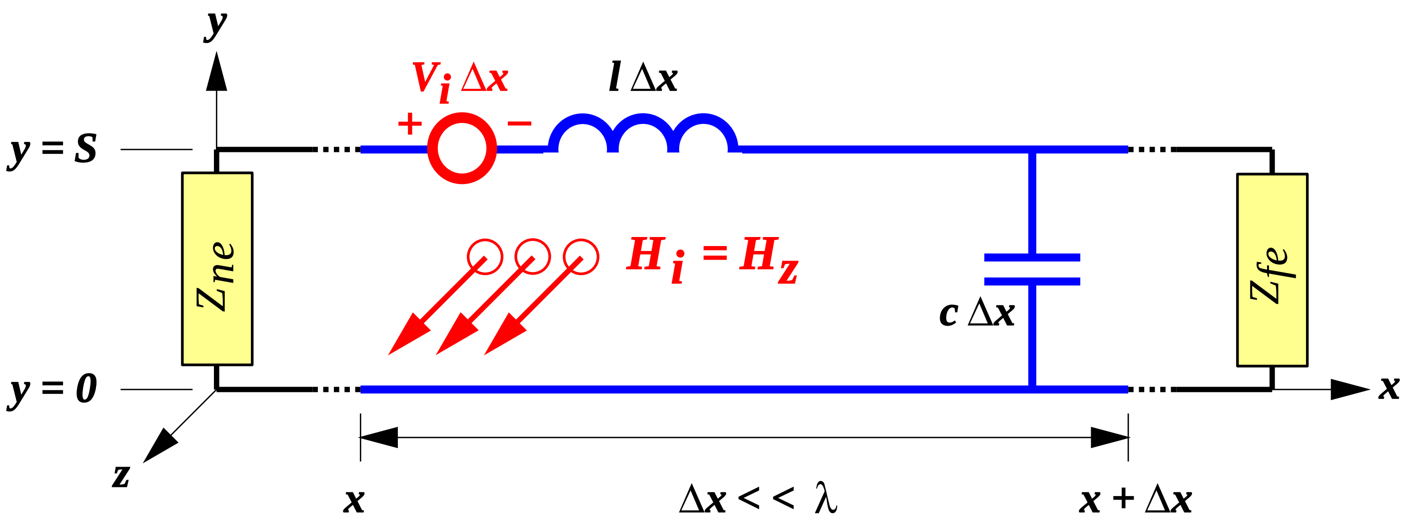
C.D. Taylor, R. S. Saterwhite and C.W. Harrison, "The Response of a Terminated Two−Wire Transmission Line Excited by a nonuniform Electromagnetic Field", AP−13, pp 987 − 989, Nov 1965

A. A. Smith , "A More Convenient Form of the Equations for the Response of a Transimssion Line excited by Nonuniform Fields", EMC−15, pp 151 − 152, Aug1973

The Modified Model takes into account all 3

Y. Kami and R. Sato, "Equivalent circuit for he Tranmission Line under the Electromagnetic Environment", Proc . 1981 IEEE Int. Sym. on EMC, Boulder, Co, Aug 18−20, 1981.

Mechanisms of Coupling (Normal Magnetic Field)



- Uniform incident H−field oriented in z−direction
- Induced voltage due to time−varying magnetic flux

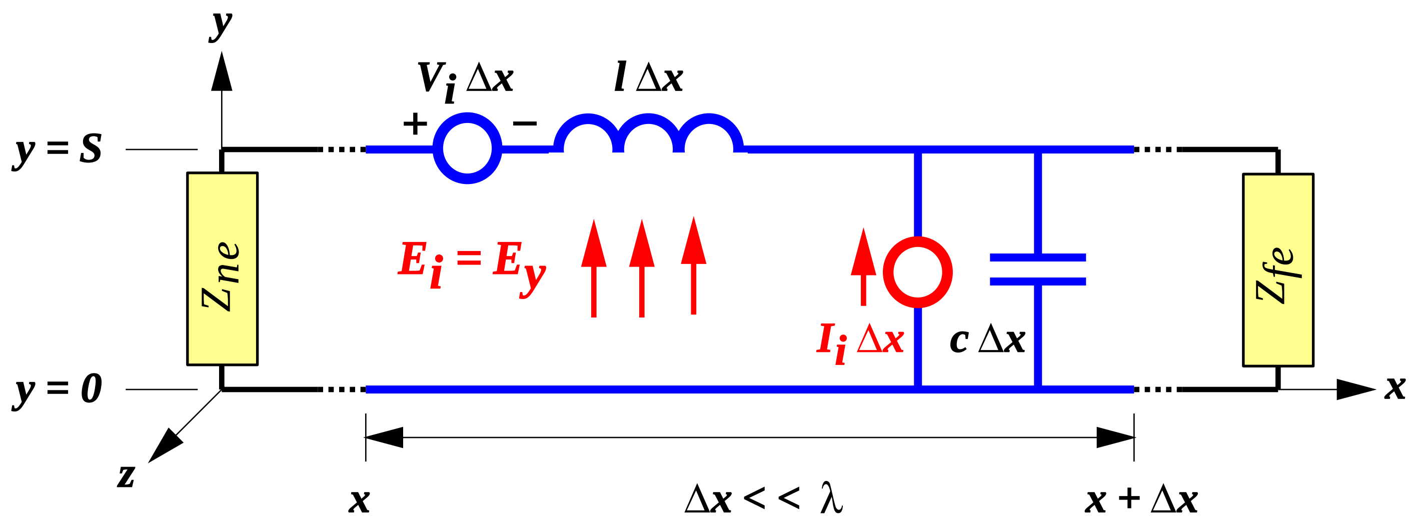
$$\Psi_i = \int_0^S H_z(x,y)\,dy$$

$$V_i = -\,d\,\Psi_i / dt = \text{per unit length voltage (V/m)}$$

$$= -\,j\,\omega\,\mu_o \int_0^S H_z(x,y)\,dy$$

$$V_i\,\Delta x = \text{Total cell induced voltage}$$

Mechanisms of Coupling (Transverse Electric Field)



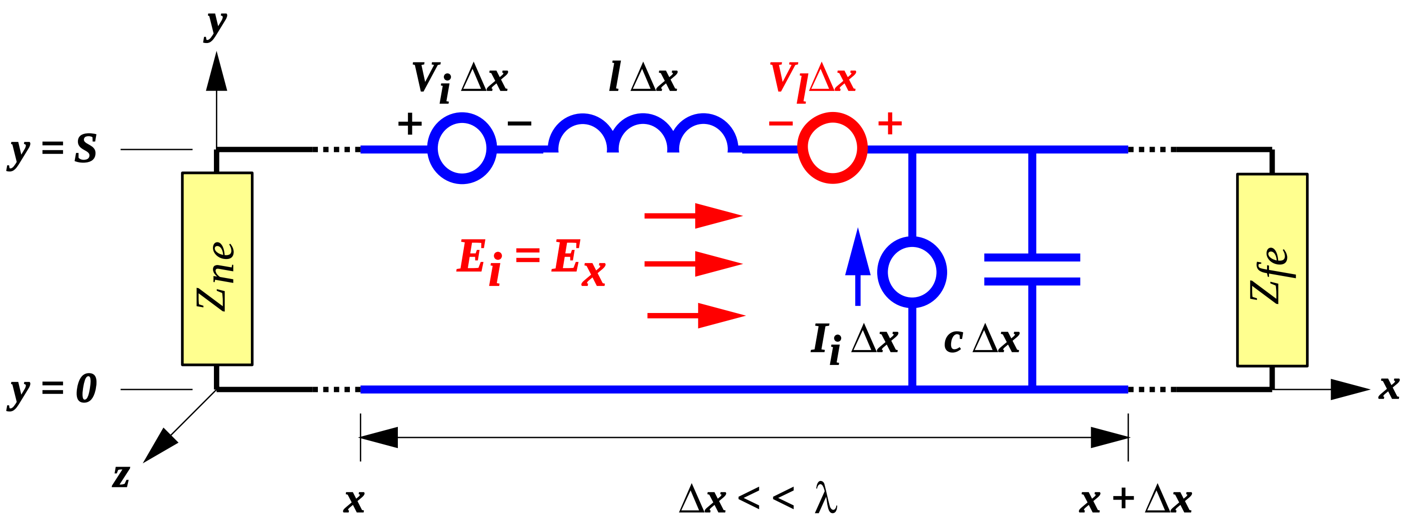
- ***Uniform incident E−field oriented in y−direction***
- ***Induced current due to a time−varying charge***

I_i = $dq / dt = c\ dv / dt$ = ***per unit length induced current (A/m)***

$$= -j\,\omega\,c \int_0^S E_y(x,y)\,dy$$

$I_i\ \Delta x$ = ***Total cell induced current***

Mechanisms of Coupling (Longitudinal Electric Field)



- *Incident E−field oriented in z−direction*
- *Based on the differences of the induced voltages in the upper and lower conductors.*

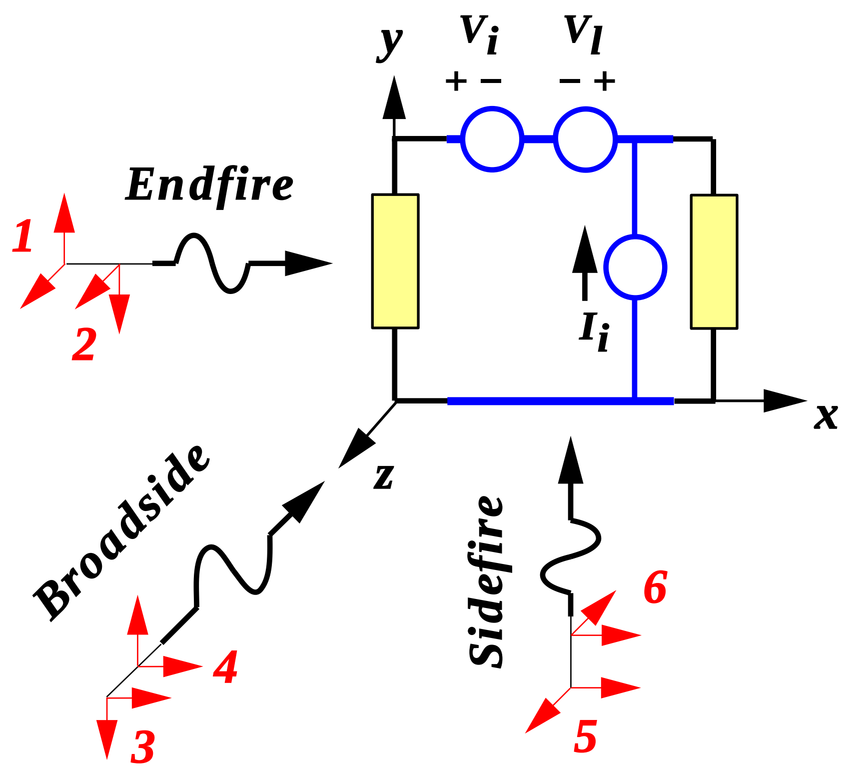
V_l = *per unit length induced voltage (V/m)*

$= E_x(x,s) - E_x(x,0)$

$V_l\,\Delta x$ = *Total cell induced voltage*

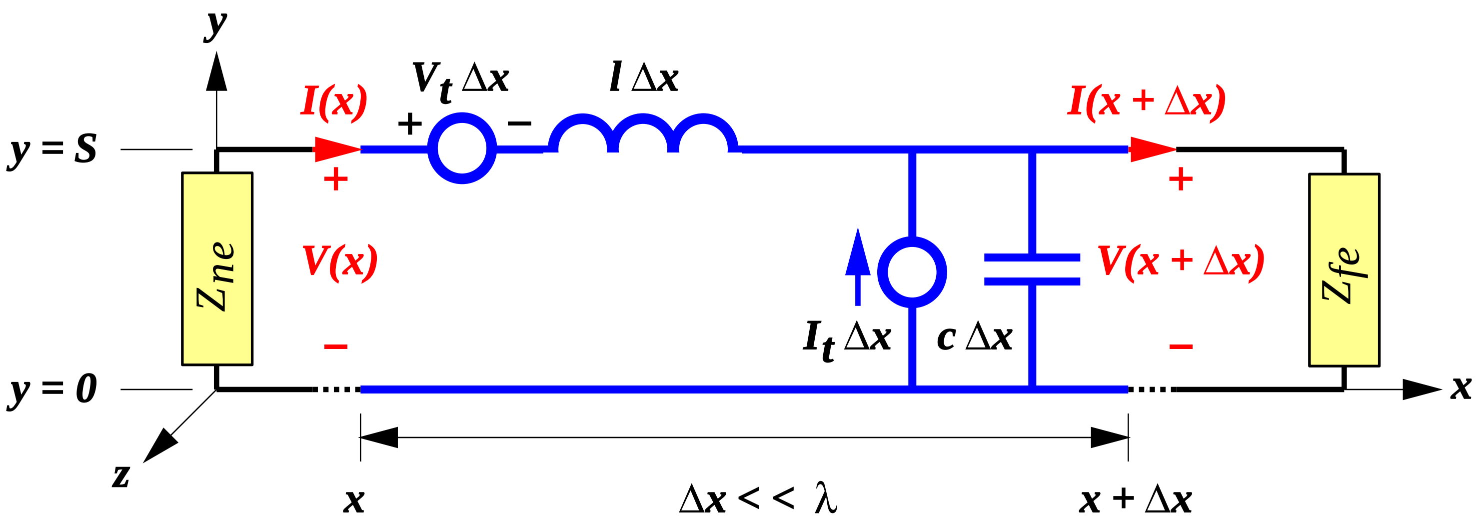
Directional Coupling Modes

1	E_y	H_z	V_i	0	I_i
2	E_z	$-H_y$	0	0	0
3	E_x	$-H_y$	0	V_l	0
4	E_y	H_x	0	0	I_i
5	E_z	H_x	0	0	0
6	E_x	$-H_z$	$-V_i$	V_l	0



- ***The coupling modes are dependent on***
  - *Wave polarization*
  - *Orientation (direction) of incoming wave and polarization*

Derivation of Transmission Line Equations



- o **_Kirchoff's voltage and current laws_**

$$V(x+\Delta x) - V(x) = -j\omega l\Delta x I(x) - V_t(x)\Delta x$$

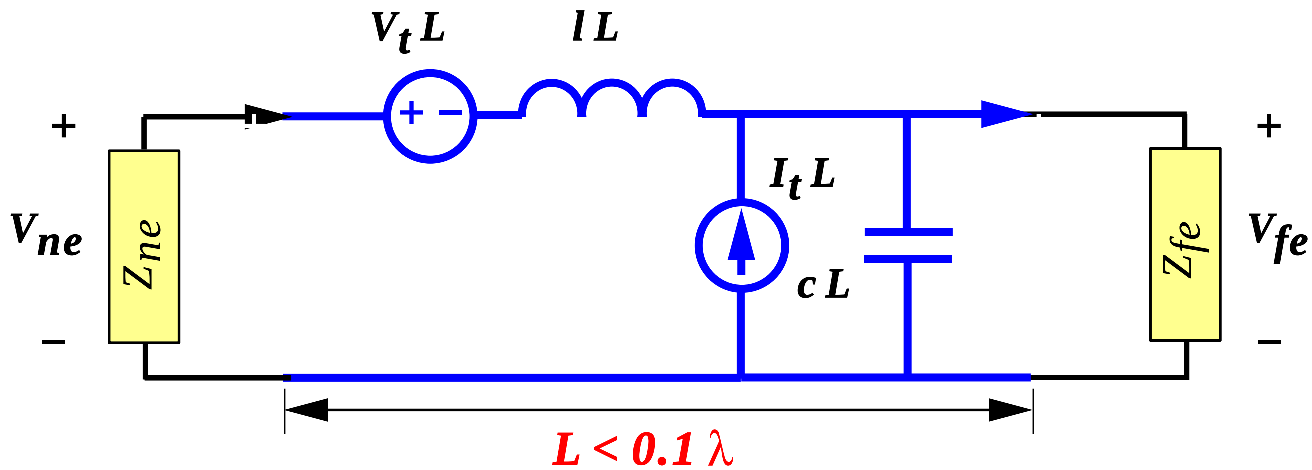
$$I(x+\Delta x) - I(x) = -j\omega c\Delta x V(x+\Delta x) - I_i(x)\Delta x$$

- o **_Dividing by $\Delta x \Rightarrow 0$ yields the transmission line equations_**

$$dV(x)/dx + j\omega l I(x) = V_t(x) = V_i(x) - V_l(x)$$

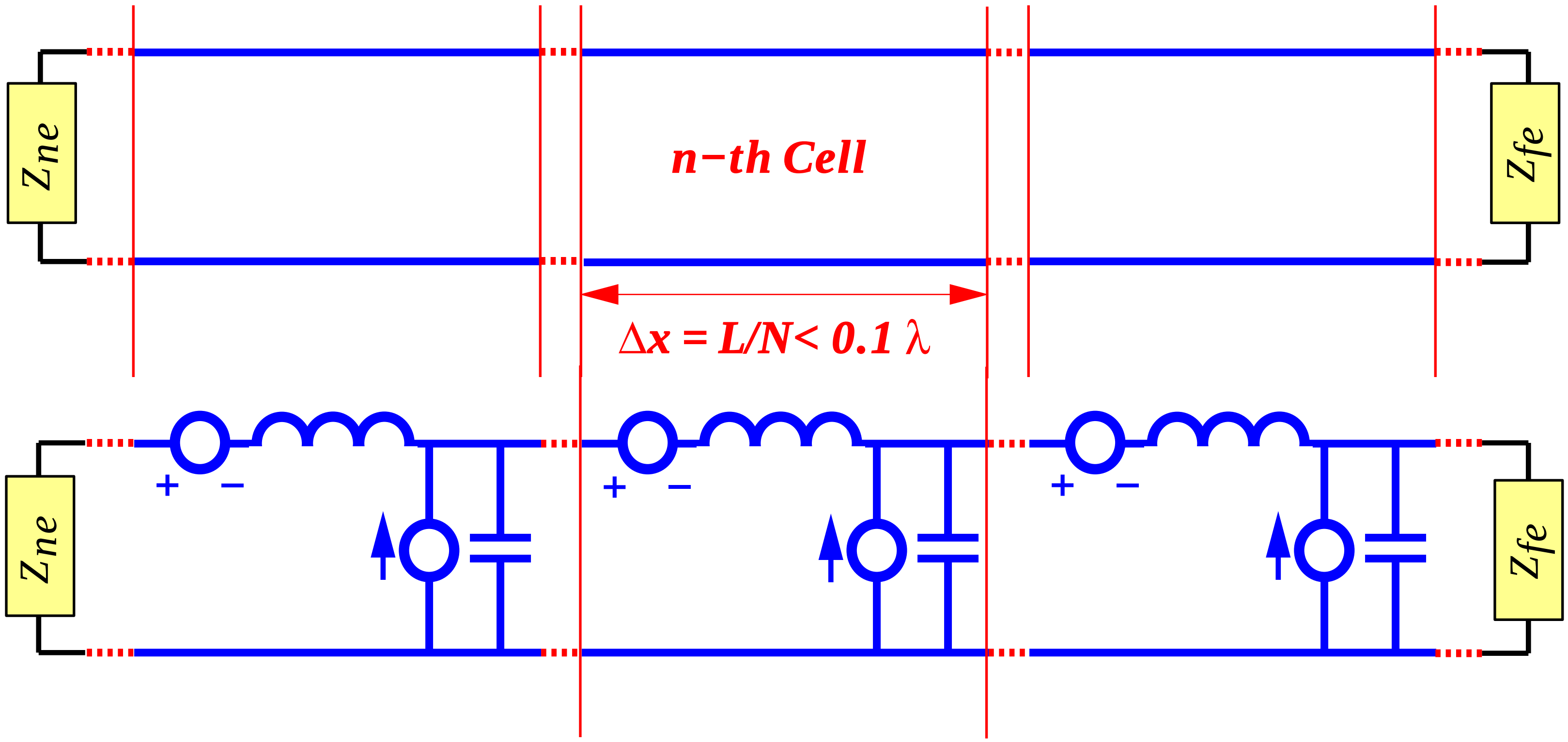
$$dI(x)/dx + j\omega c V(x) = I_t(x) = I_i(x)$$

Electrically Short Line: Single L − Cell Model



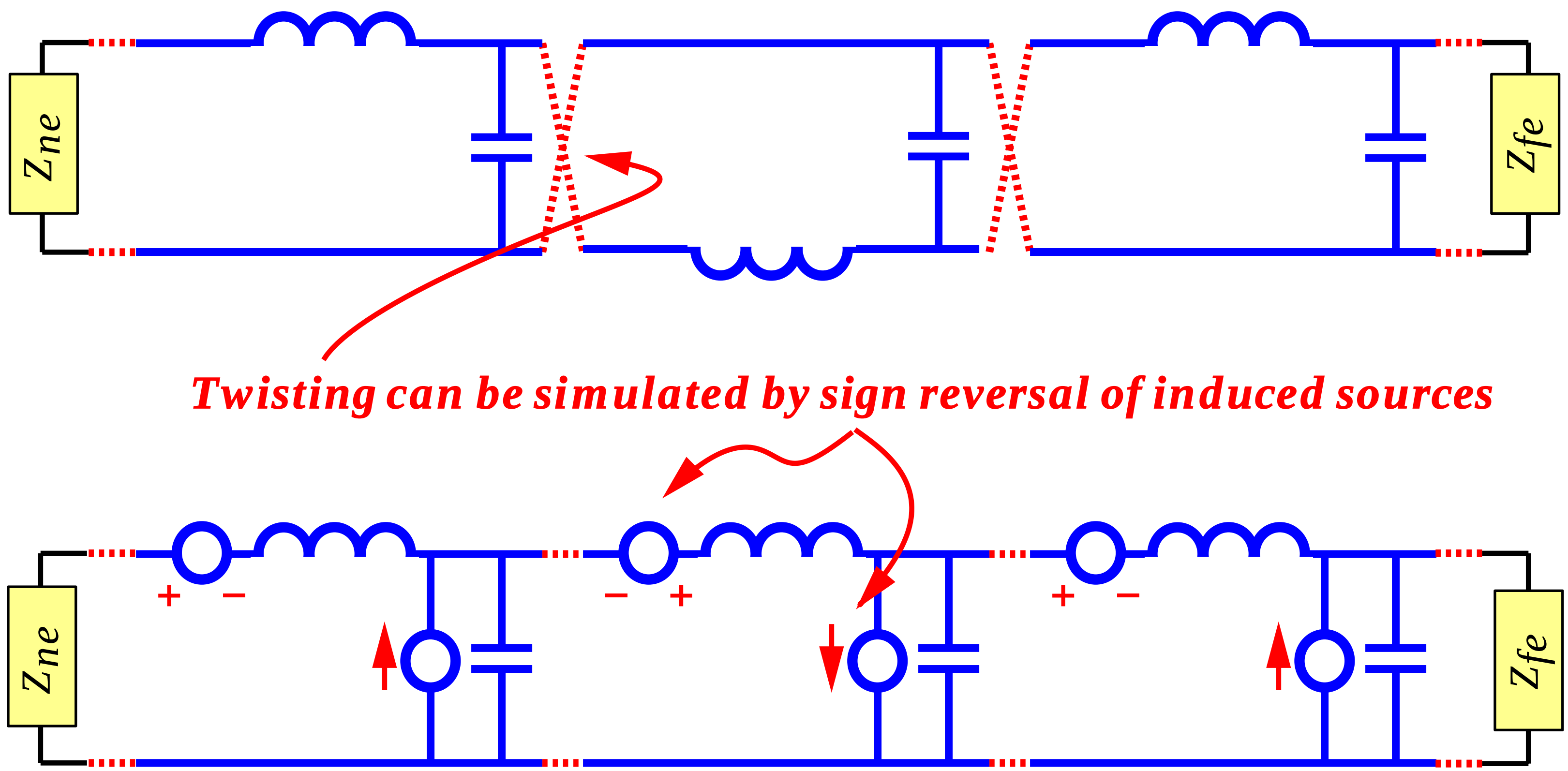
- o $\Delta x = L$ (Cell length = Cable length)
- o Only valid for electrically short lines ($L < 0.1\ \lambda$)
- o Well suited for Spice−like circuit solvers

Electrically Long Line: Cascaded L − Cell Model



- o N = Number of Cells
- o Δx = L/N < 0.1 λ (Cell length = Cable length/N)
- o Valid for electrically long lines (L > 0.1 λ)
- o Well suited for Spice−like circuit solvers

Twisted Pair Lines



Each twist is modeled by a single lumped parameter L−cell

Numerical Results Overview

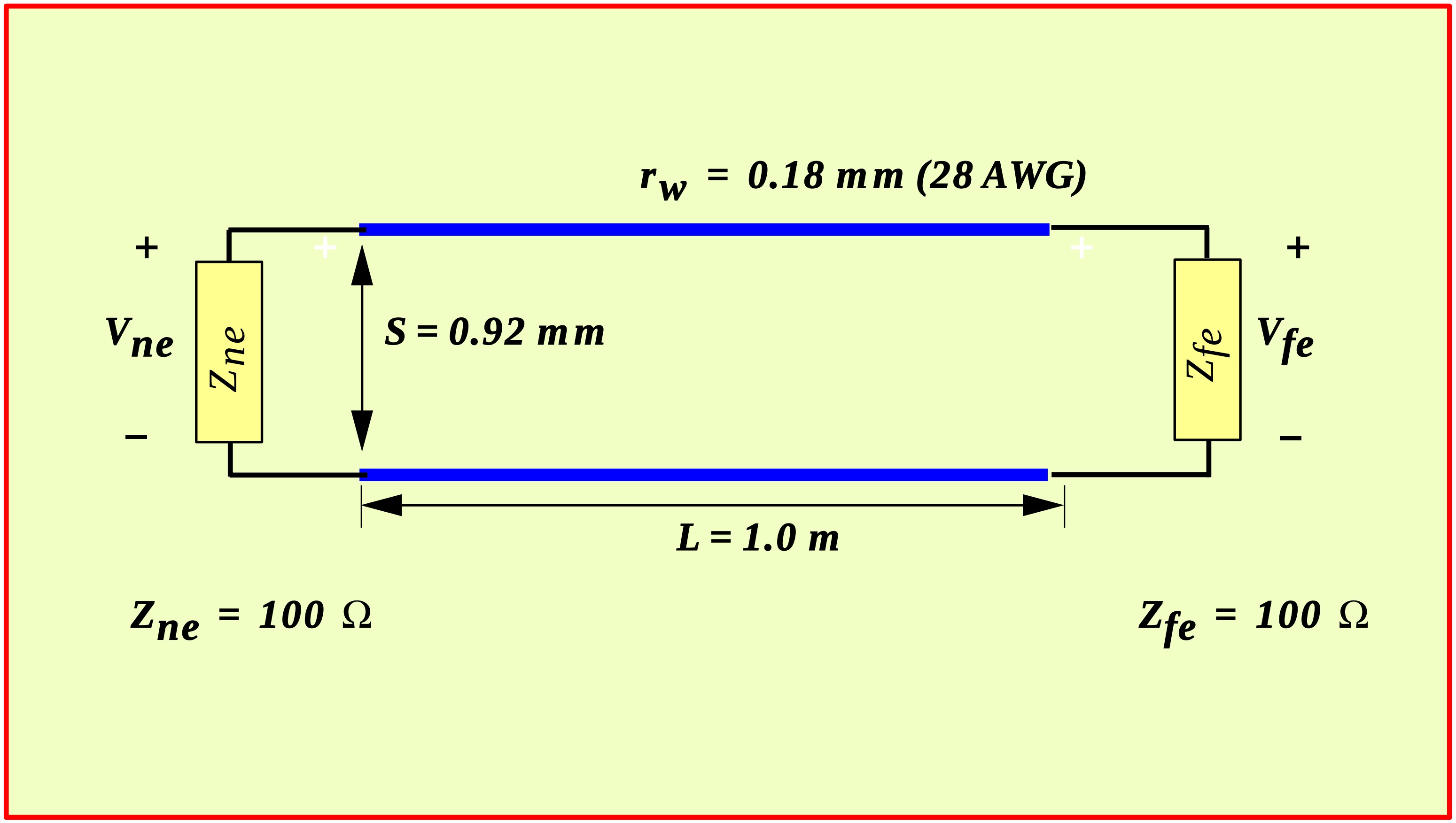
Twin Pair

- o **Endfire Excitation**
  - – **Lumped Parameter Model**
  - – **Partially Distributed Cascaded 5−Cell Model**
  - – **Partially Distributed Cascaded 35−Cell Model**
- o **Sidefire Excitation**
  - – **Lumped Parameter Model**
  - – **Partially Distributed Cascaded 5−Cell Model**
  - – **Partially Distributed Cascaded 35−Cell Model**

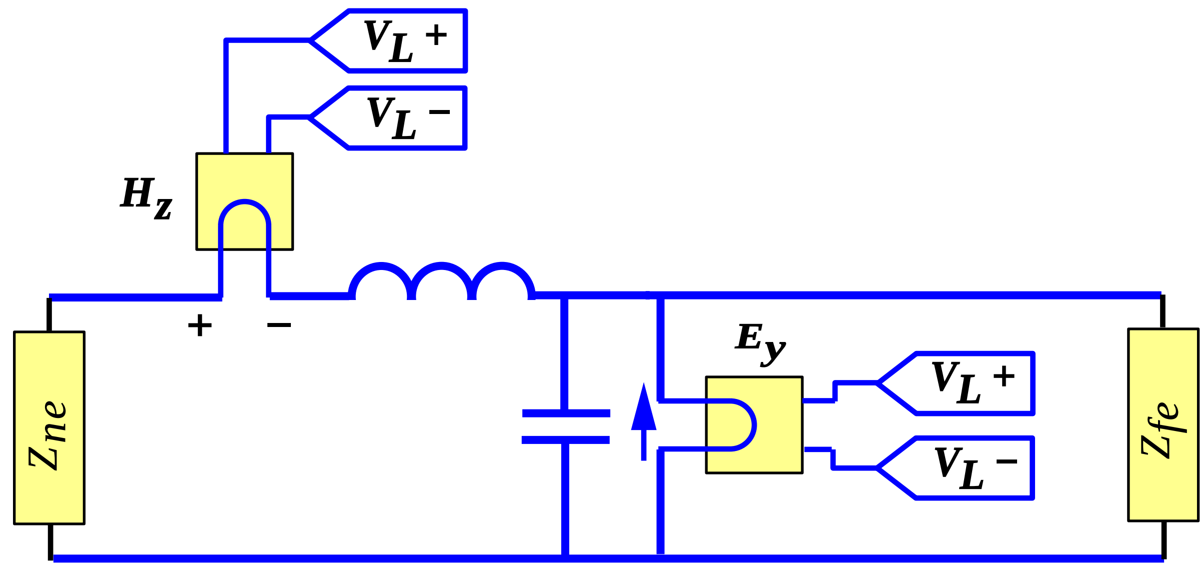
Twisted Pair

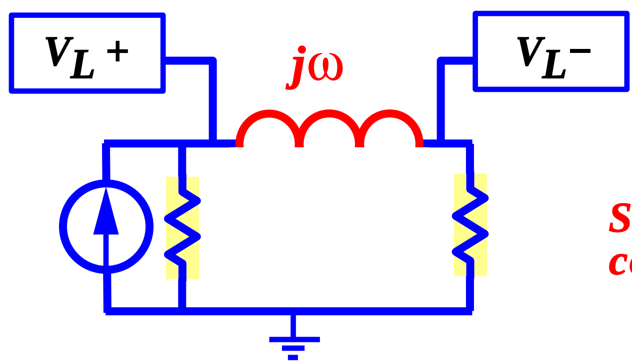
- o **35 −Cell Model**

Twin−pair Model Geometry



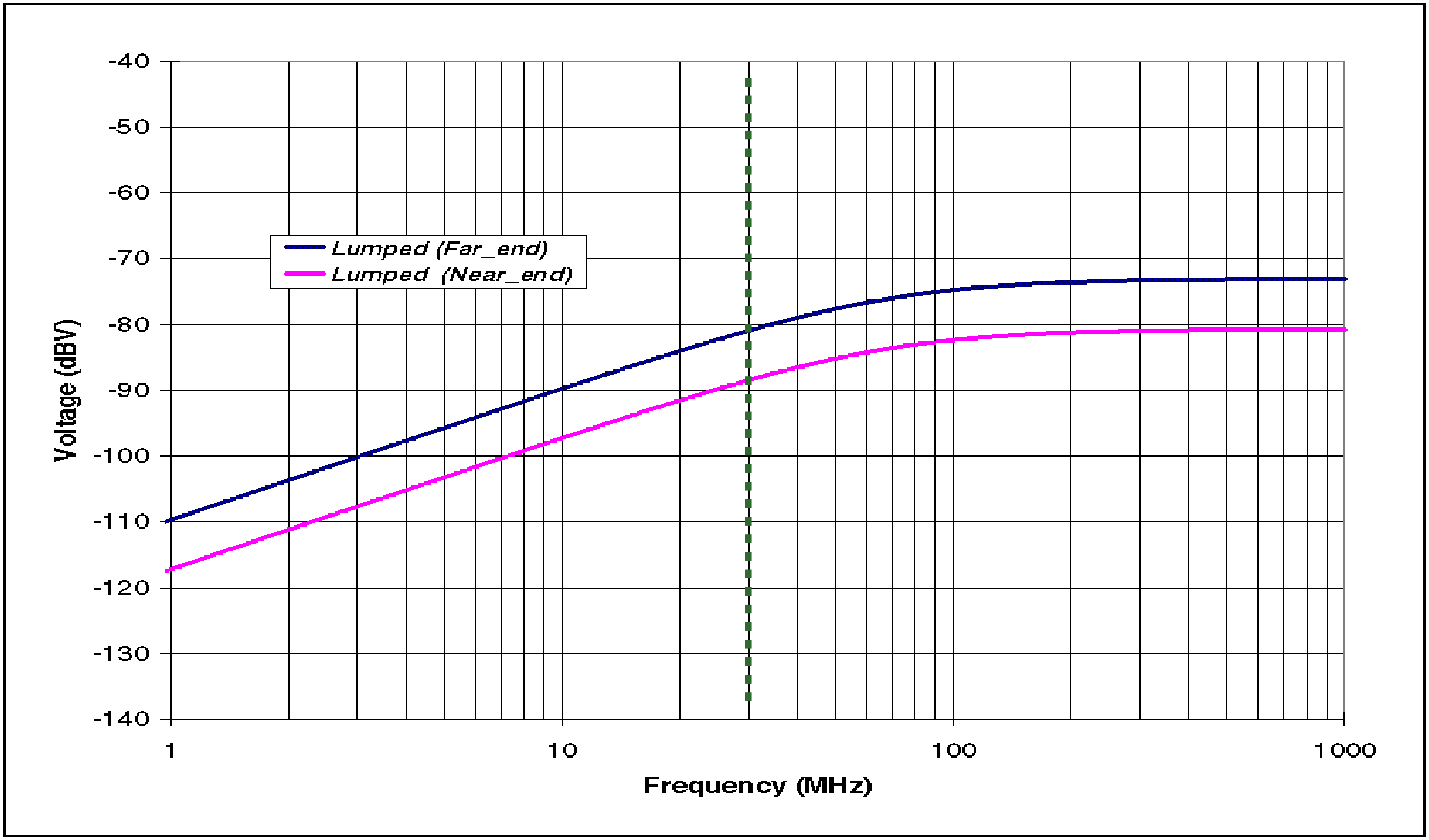
Lumped Parameter Model − Endfire Excitation





Subcircuit for frequency dependent coupling mechanism

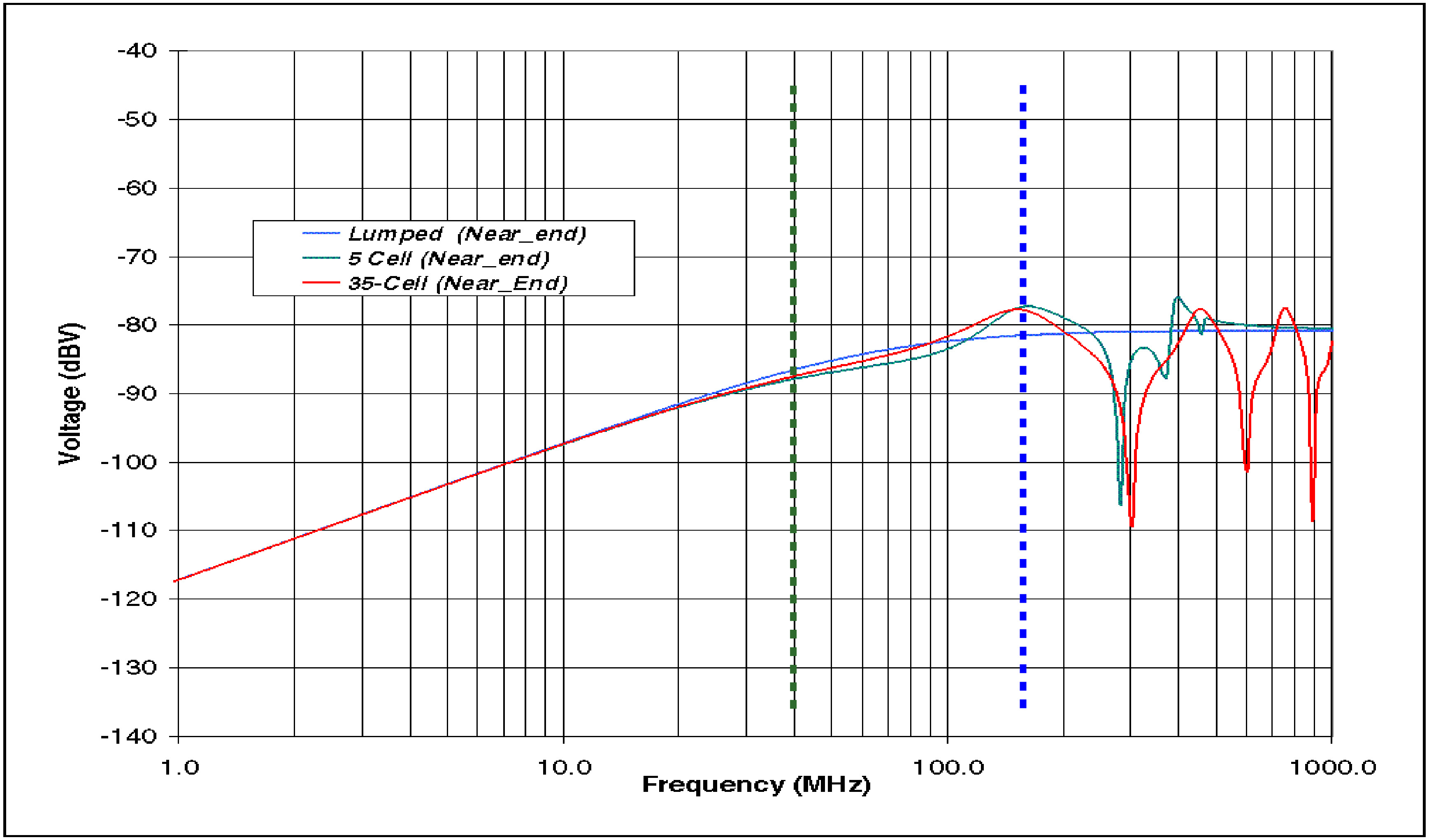
Results for Lumped Parameter Model – Endfire Excitation



Induced voltages at the near and far ends versus frequency for lumped single cell model

Upper Freq limit for lumped cell model

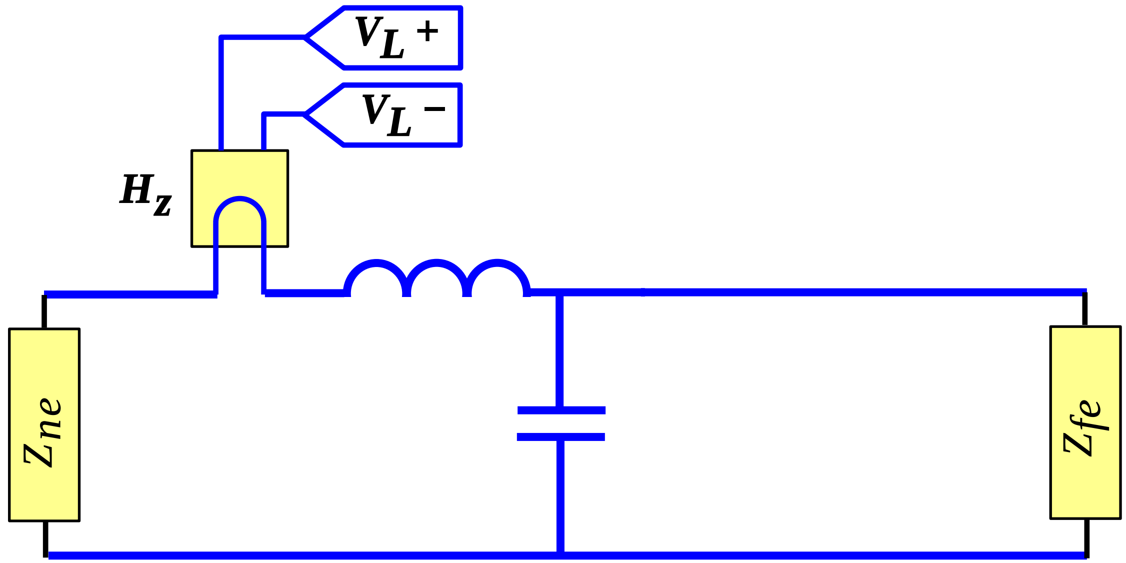
Results Summary – Endfire Excitation



Induced voltages at the near end versus frequency for lumped single cell, 5-cell, and 35-cell model

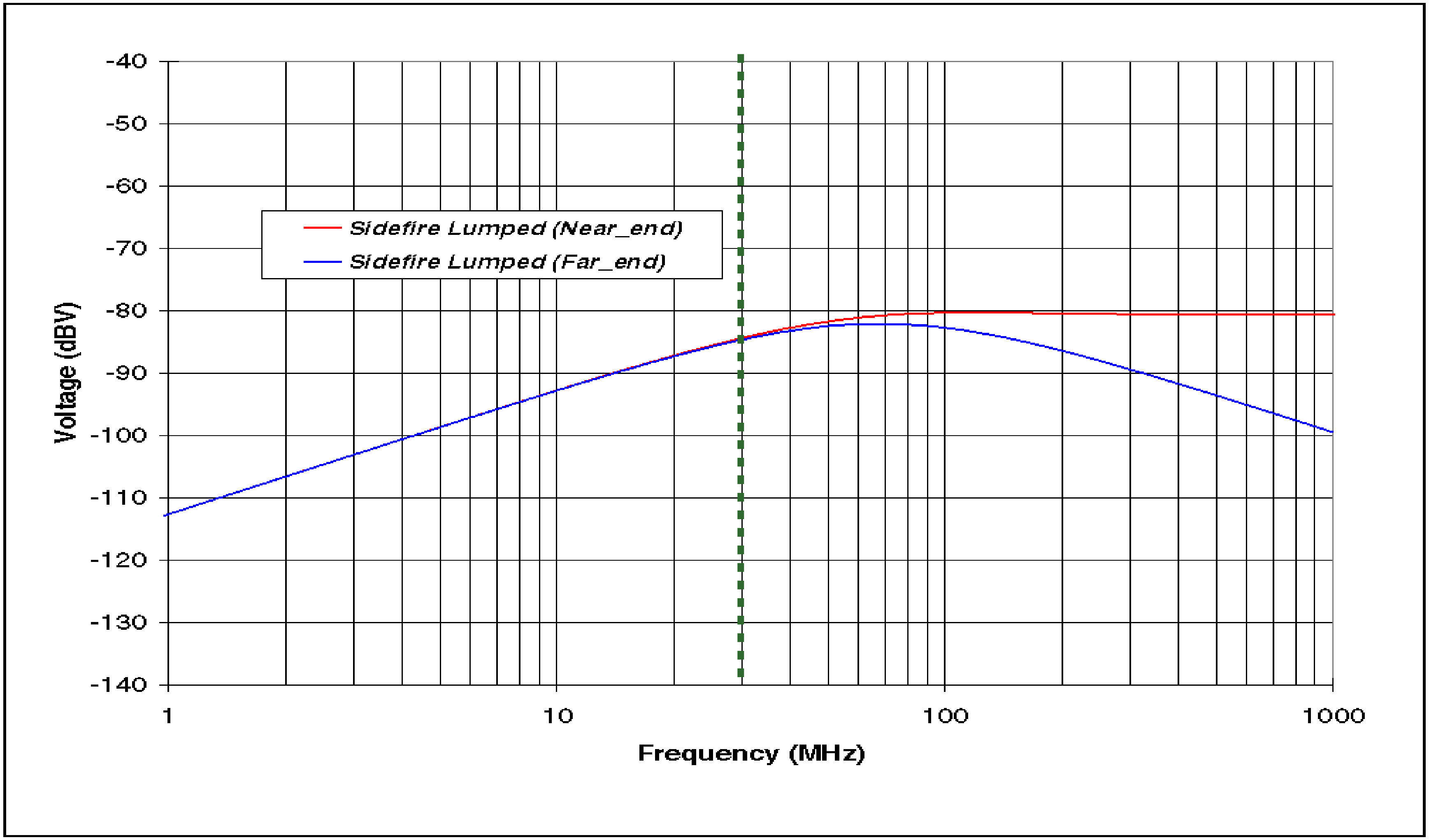
Upper Freq limit for lumped cell model *Upper Freq limit for lumped cell model*

Lumped Parameter Model − Sidefire Excitation



- *Parameters are the same as the Endfire lumped model*
- *Only the V source is present because only the H−field is oriented in such a way to cause coupling*

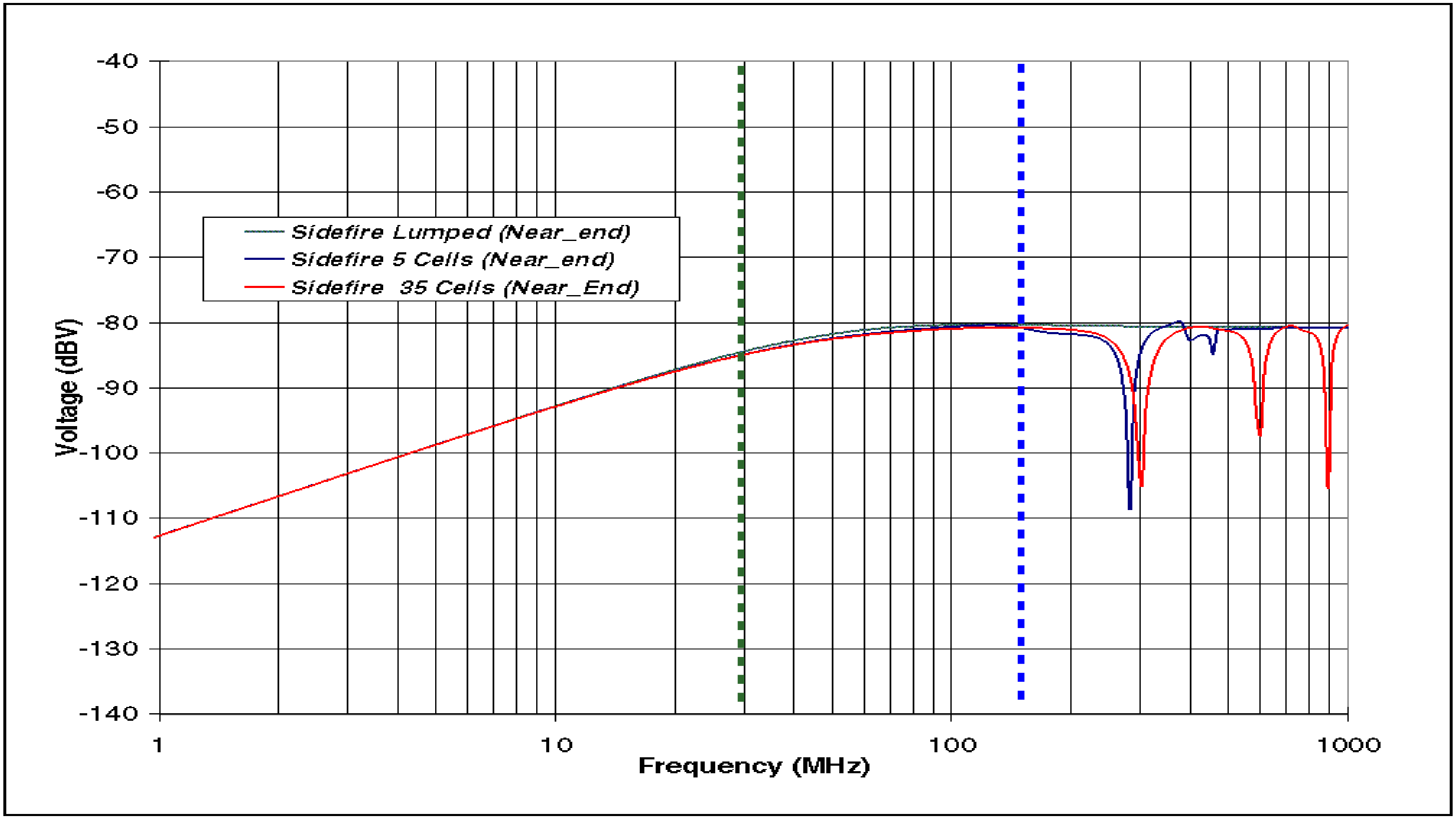
Results for Lumped Parameter Model – Sidefire Excitation



Induced voltages at the near/far ends versus frequency for lumped single cell model

Upper Freq limit for lumped cell model

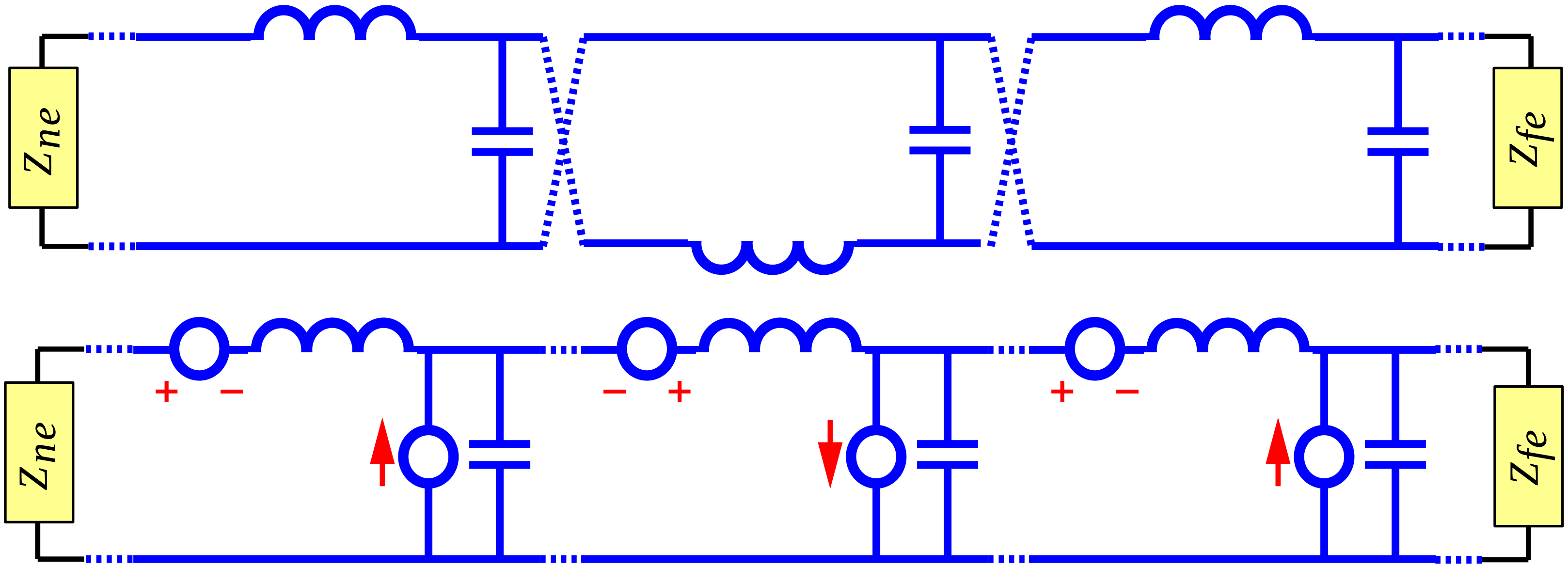
Results Summary – Sidefire Excitation



Induced voltages at the near end versus frequency for lumped single cell, 5-cell, and 35-cell model

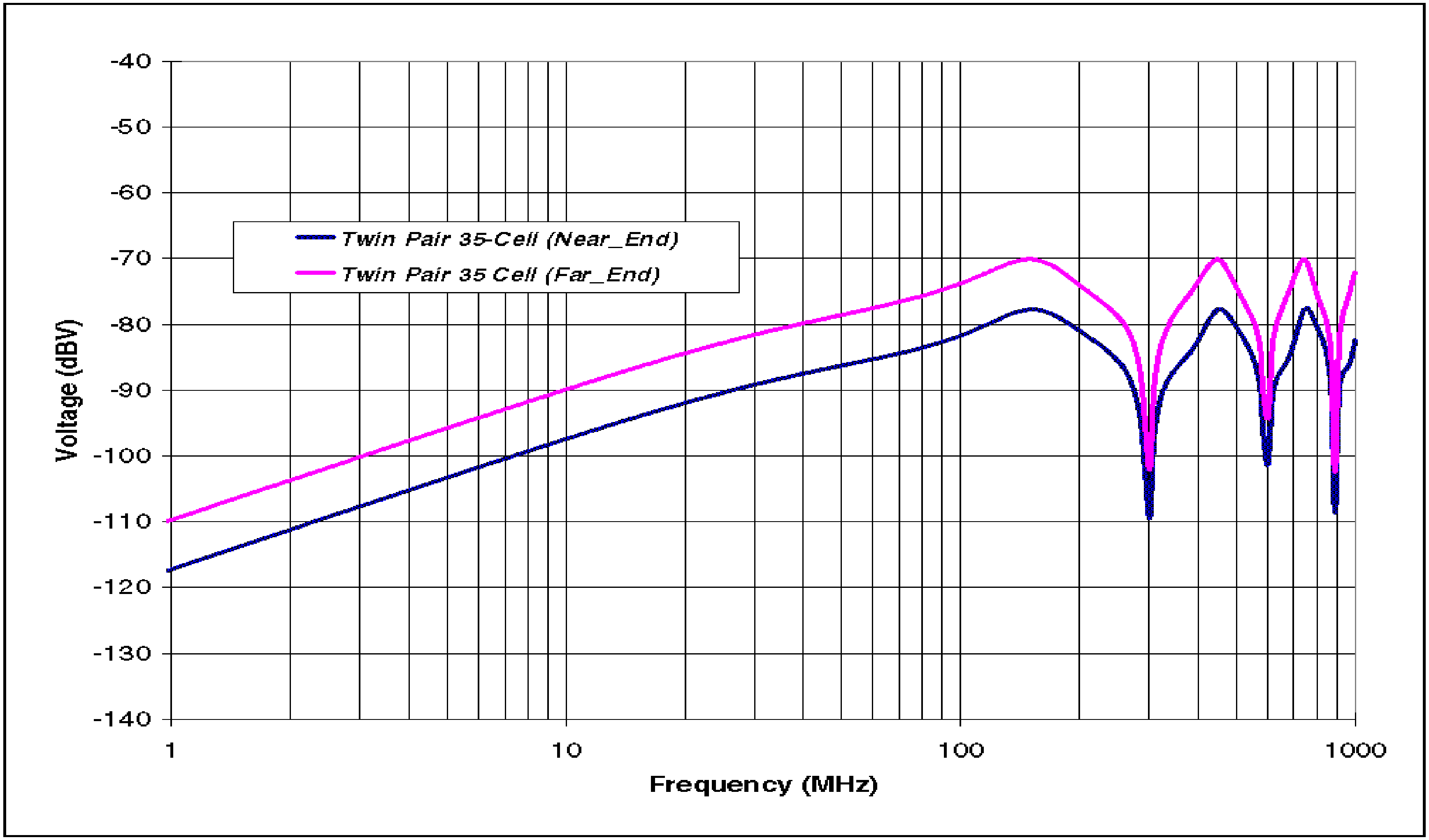
Upper Freq limit for lumped cell model *Upper Freq limit for lumped cell model*

Twisted Pair Model



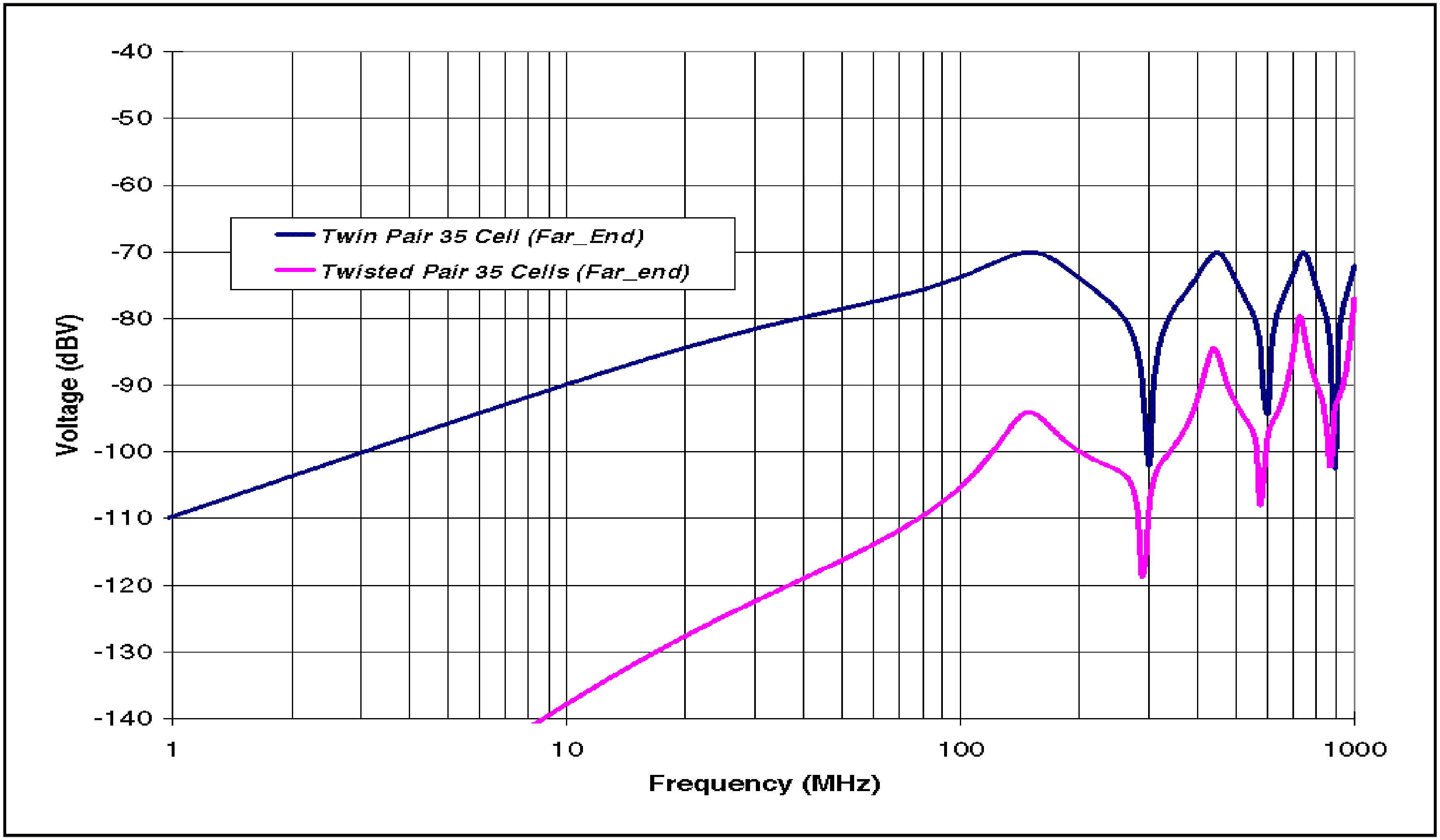
- Twisting simulated by sign reversal of induced sources
- 1 meter long line divided into 35 twists

Results for Twisted Pair Model − Endfire Excitation



Induced voltages at the near/far ends versus frequency for lumped 35 −cell twisted pair model

Twisted and Twin Pair Model Results − Endfire Excitation



Comparison of induced voltages at the near end versus frequency for lumped 35 −cell twisted and twin pair models

Conclusions

- Three mechanisms of coupling were investigated
- Theoretical models were developed to utilize conventional circuit analysis software
- Numerical results for sidefire and endfire are presented for twin and twisted pair configurations
- The results show:
  - Increasing the number of cells improves the accuracy at high frequencies
  - Twisted pair is less susceptible than twin pair

Overview

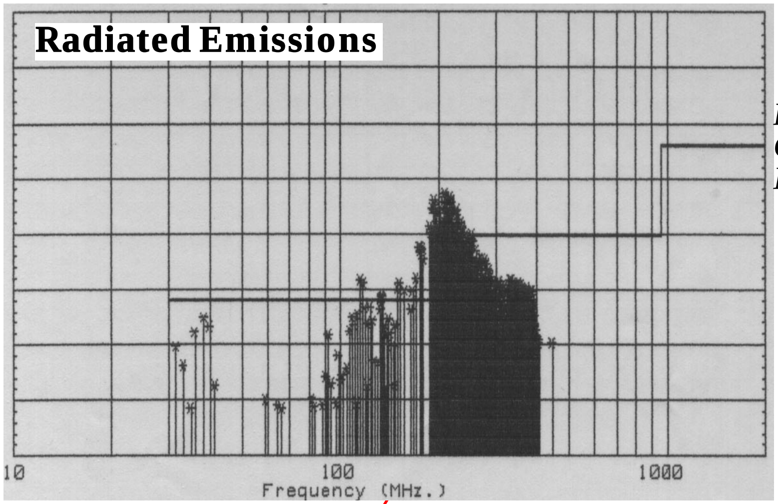
"Power Circuit Cross Coupling"

- **Motivation**
- **Problem Definition**
- **Distributed Parameters Model**
- **Mechanisms of Coupling**
  - o Capacitive Crosstalk
  - o Inductive Crosstalk
  - o Crosstalk Model
- **Crosstalk Model Results**
  - o Unmatched Terminations
  - o Increasing Separation Distance
  - o Increasing Source Frequency
  - o Filtering
- **Conclusions**

Motivation

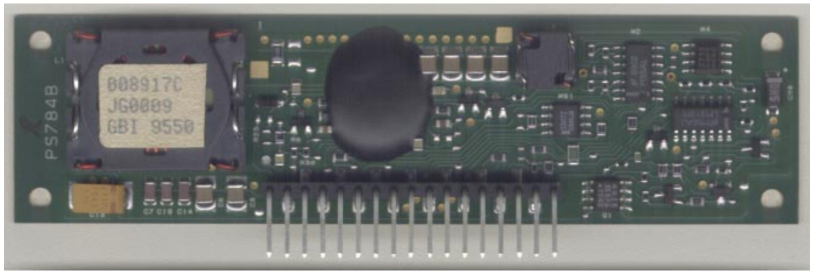
- Microprocessors and ASICs are powered by on−board DC − DC converters
- The DC − DC converters produce high frequency noise that couples onto low level signal traces routed adjacent to power distribution traces in printed circuit boards (PCBs).
- The noise can also have substantial harmonic content that can excite resonant structures within a system, causing it to exceed EMC conducted and radiated emission limits.

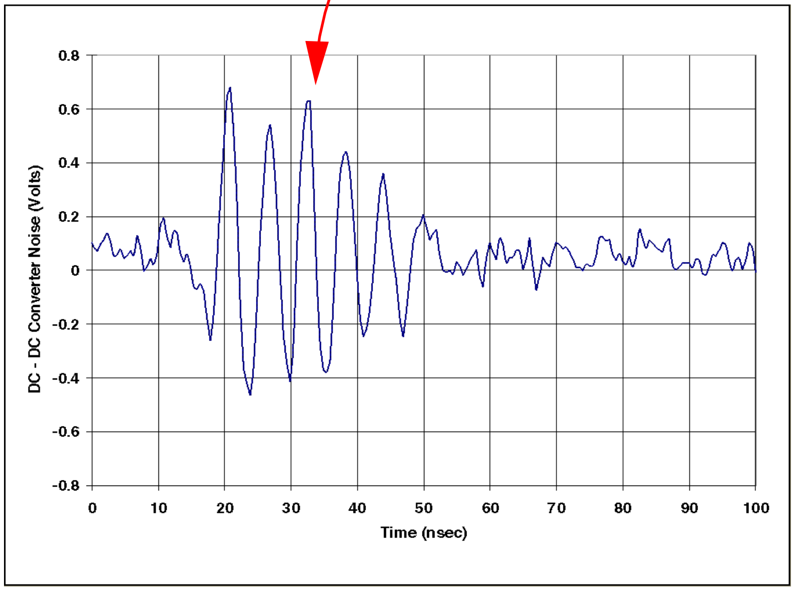
Problem Definition

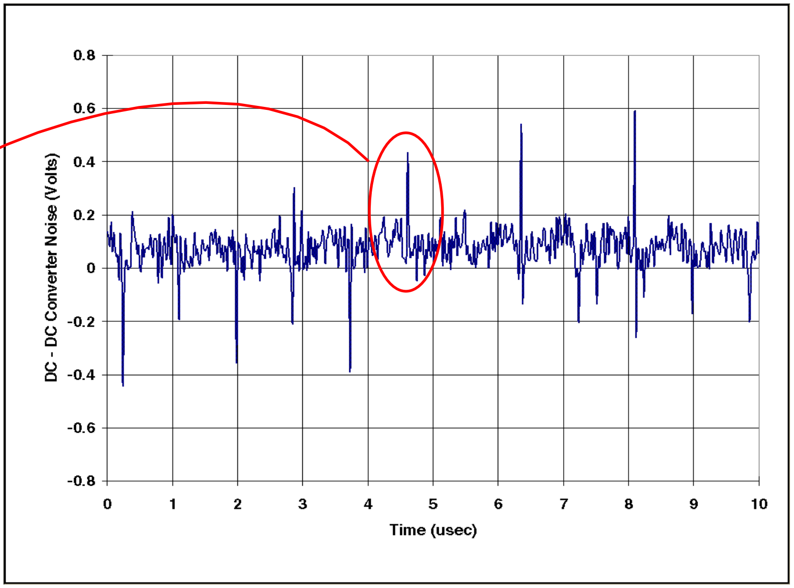


FCC Class B Limit

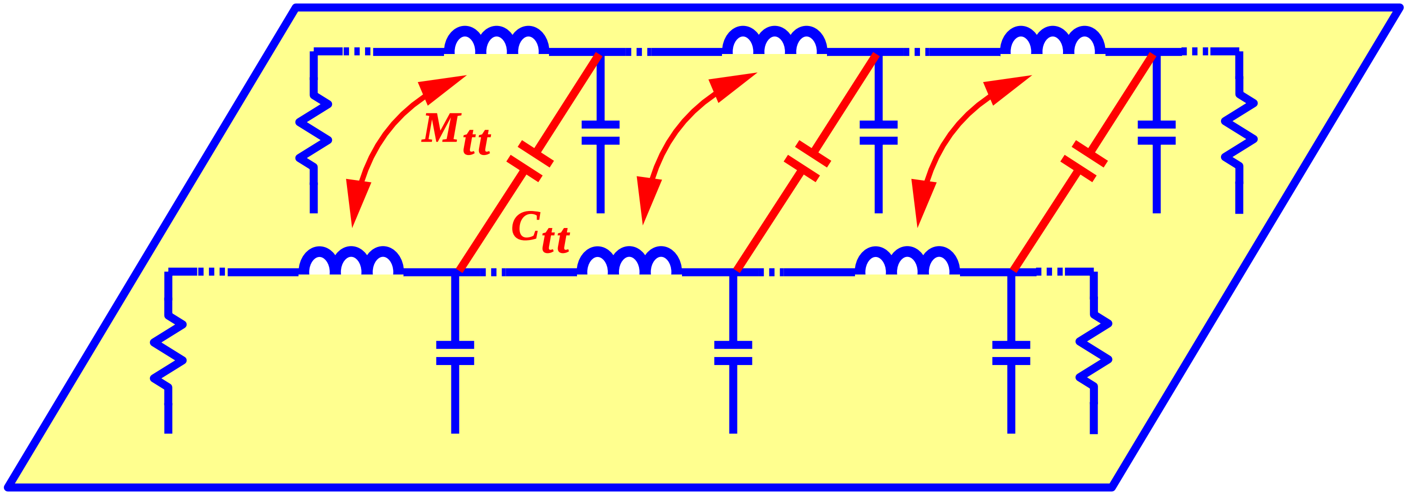
DC − DC Converter





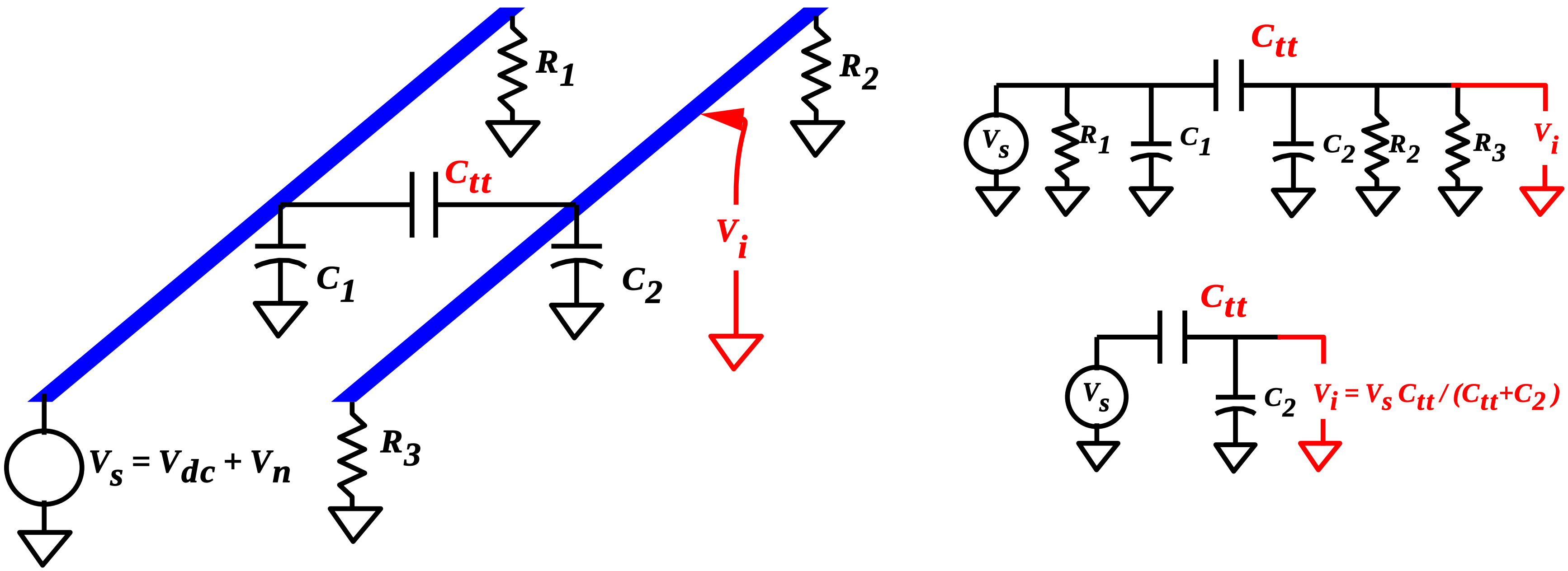


Distributed Parameters Model



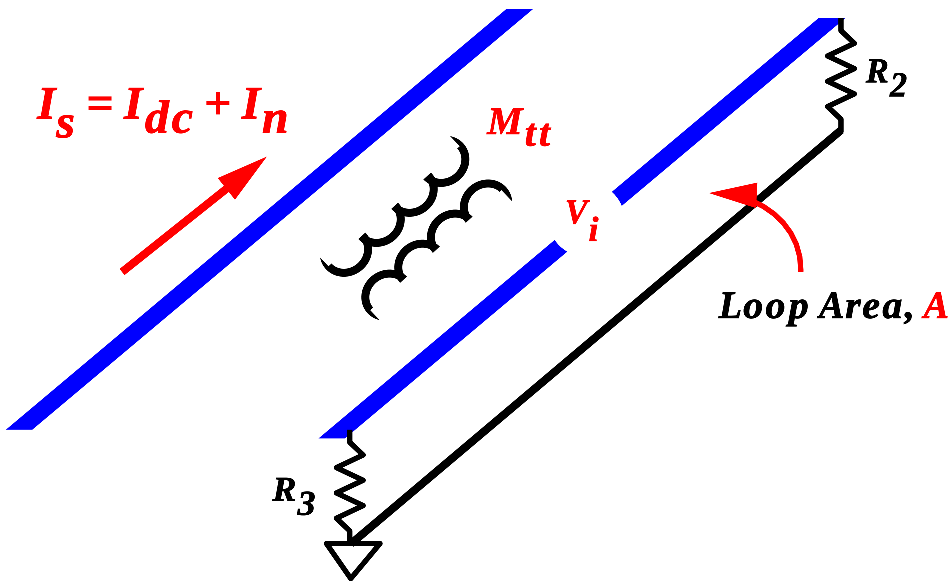
- *Placing two conductors adjacent to each other introduces two additional coupling components to the distributed transmission line model*
  - *Capacitive Crosstalk via trace−to−trace capacitance,* C_{tt}
  - *Inductive Crostalk via trace−to−trace mutual inductance,* M_{tt}

Mechanisms of Coupling − Capacitive Crosstalk



- If V_s is an "ideal" voltage source $\Rightarrow$ R_1 and C_1 can be neglected
- For high frequencies
  - $Z_{C_2} << R_2$ and R_3 $\Rightarrow$ R_2 and R_3 can be neglected
  - The equivalent circuit reduces to a simple capacitive voltage divider
- To minimize capacitive crosstalk, minimize V_s and C_{tt}, maximize C_2

Mechanisms of Coupling – Inductive Crosstalk



$V_i = j\,\omega\, B\, A = j2\,\pi\, f\, M_{tt}\, I_n$

B = Magnetic Flux Density

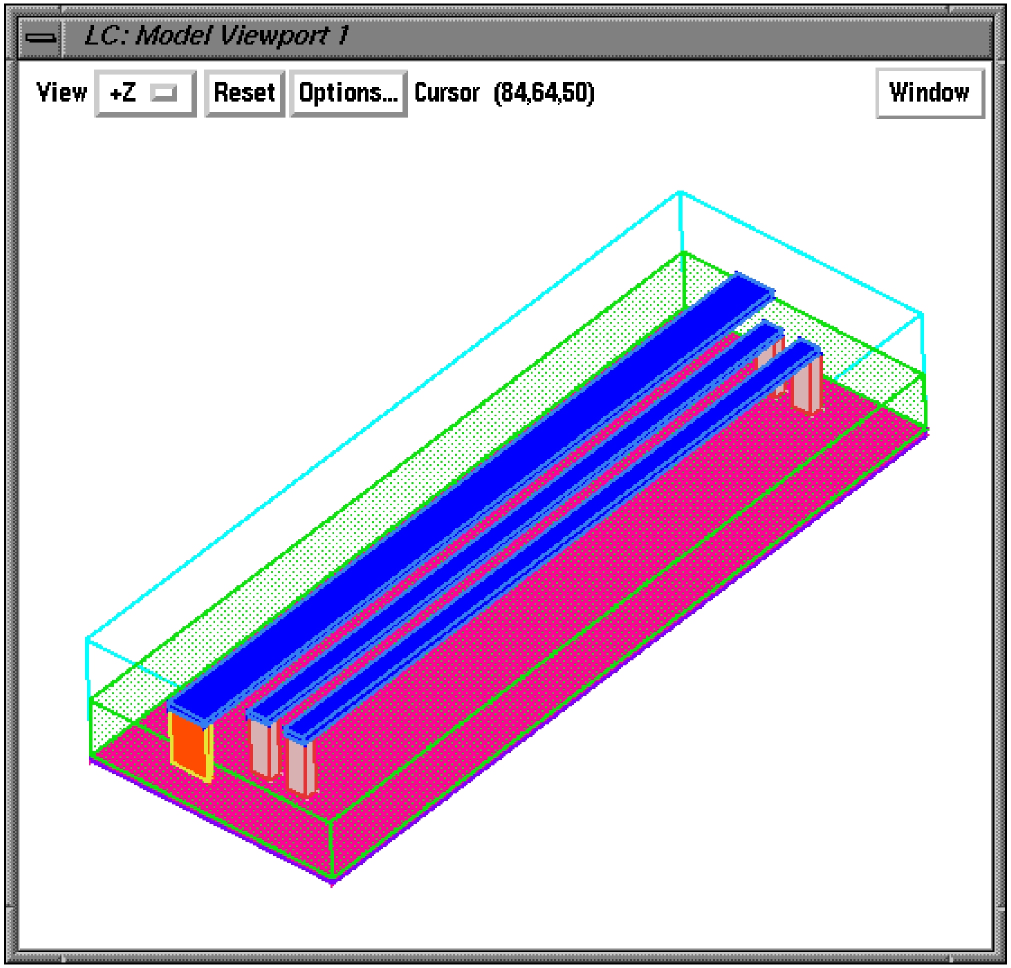
f = Frequency

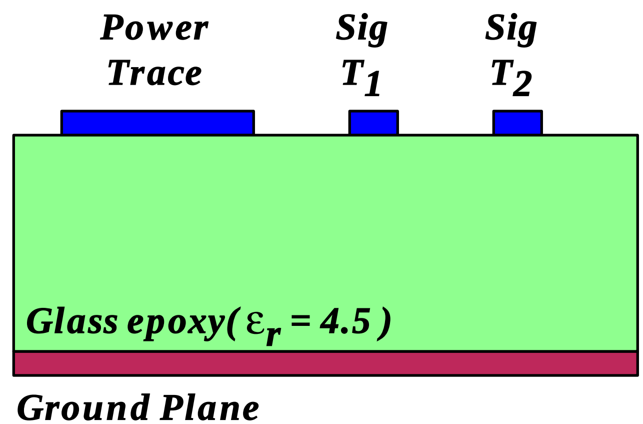
M_{tt} = Mutual Inductance

To reduce inductive crosstalk:

- *Minimize frequency (limit high frequency harmonics)*
- *Minimize mutual inductance (increase separation)*
- *Minimize loop area*
  - *bring trace closer to ground*
  - *reduce coupling length*

Crosstalk Model



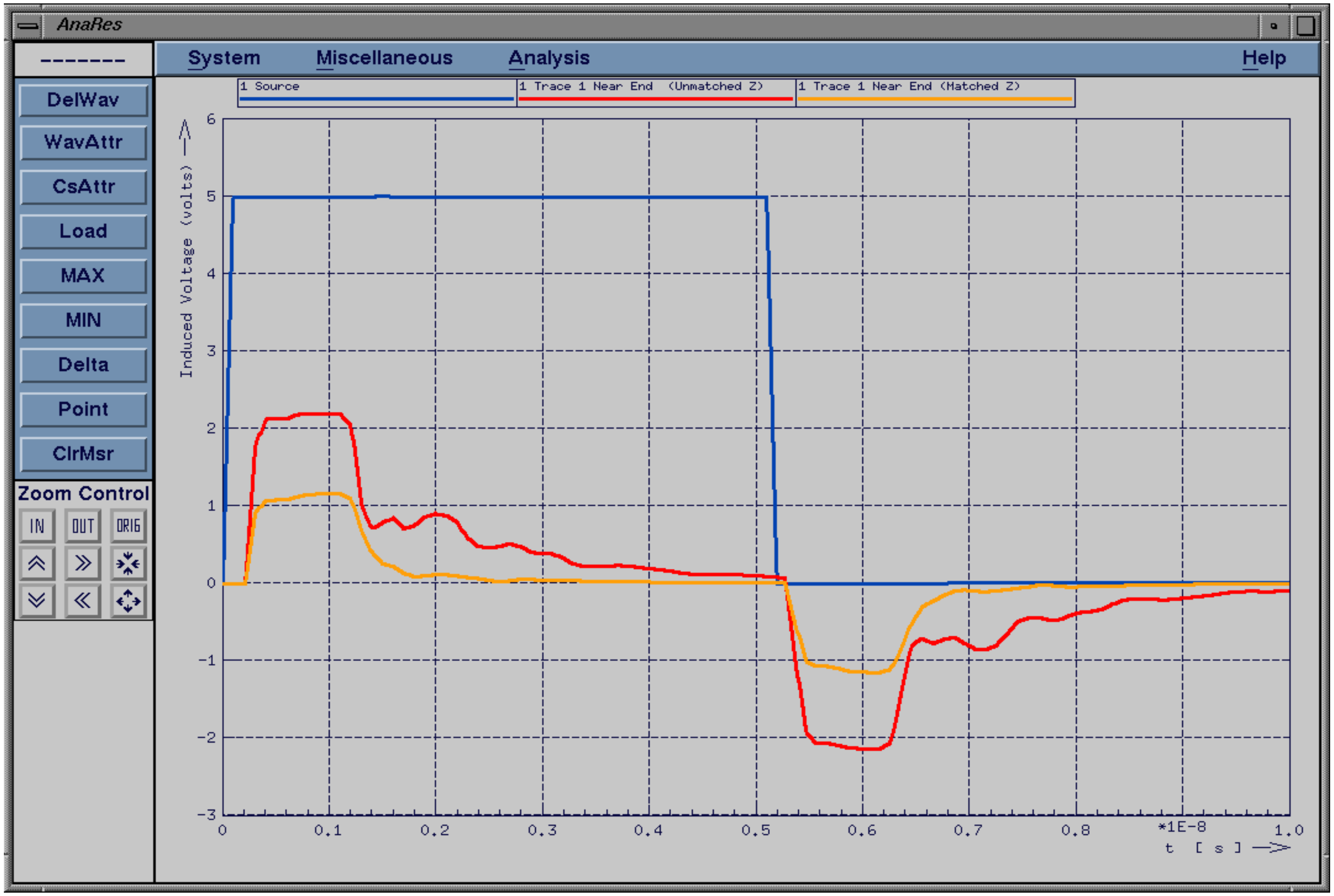


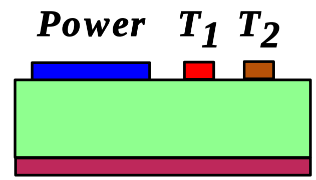
Default Parameters

Substrate Thickness:	*0.060"*
Power Trace Width:	*0.050"*
Sig Trace Widths:	*0.010"*
Separation (power to T_1):	*0.010"*
Separation (T_1 to T_2):	*0.010"*

(Load impedances matched to applicable trace characteristic impedance)

Crosstalk Model Results – Unmatched Terminations

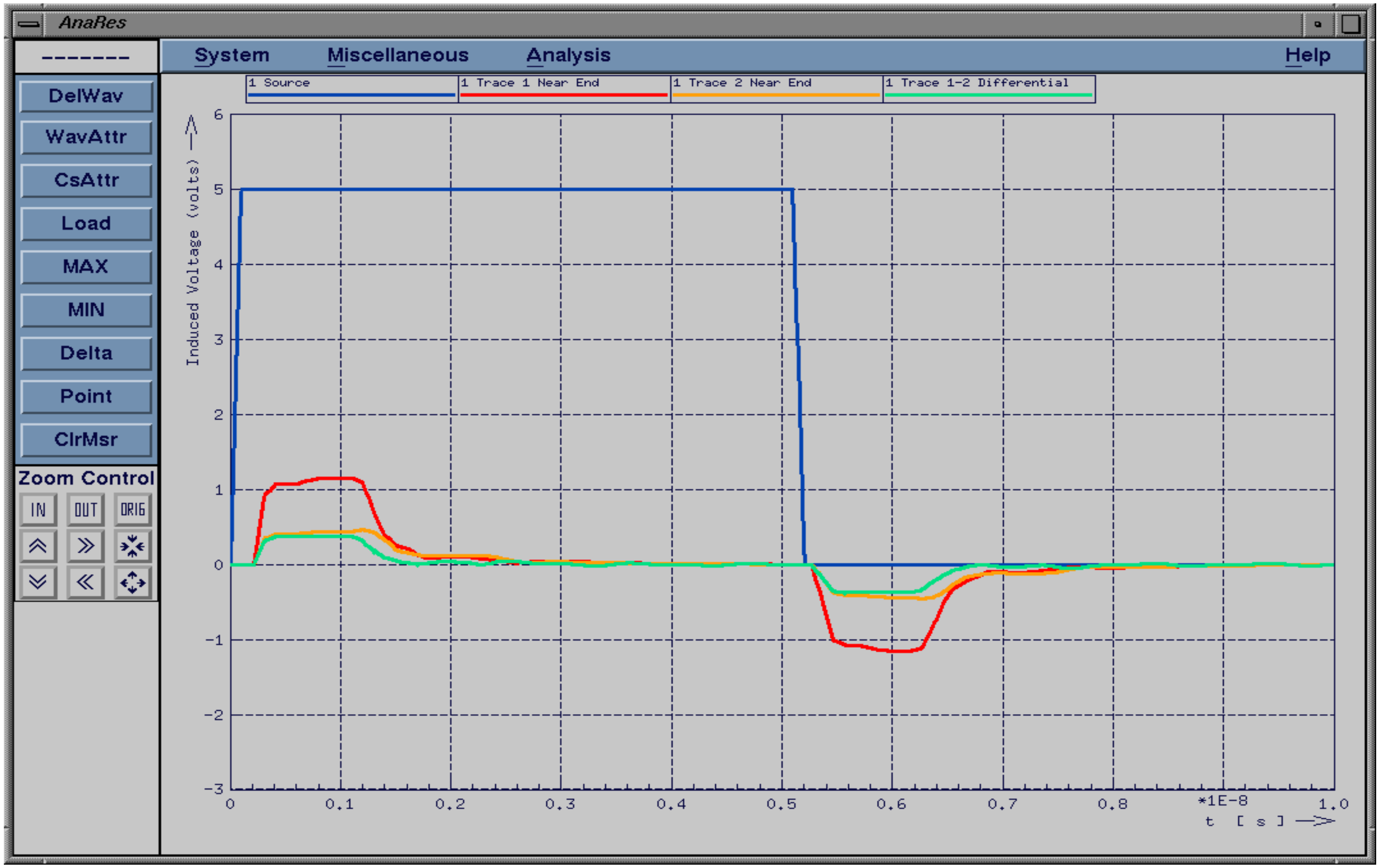


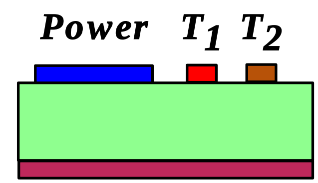


- ***Simple trapezoidal pulse used to illustrate concept***
- ***Noise Coupled onto signal traces can "ring" back and forth along "transmission line" if $Z_{ne}, Z_{fe} \neq Z_0$***

Blue: Source *Red : T_1 $Z_{ne} = Z_{fe} \neq Z_0$* *Orange: T_1 $Z_{ne} = Z_{fe} = Z_0$*

Crosstalk Model Results − Increasing Separation Distance

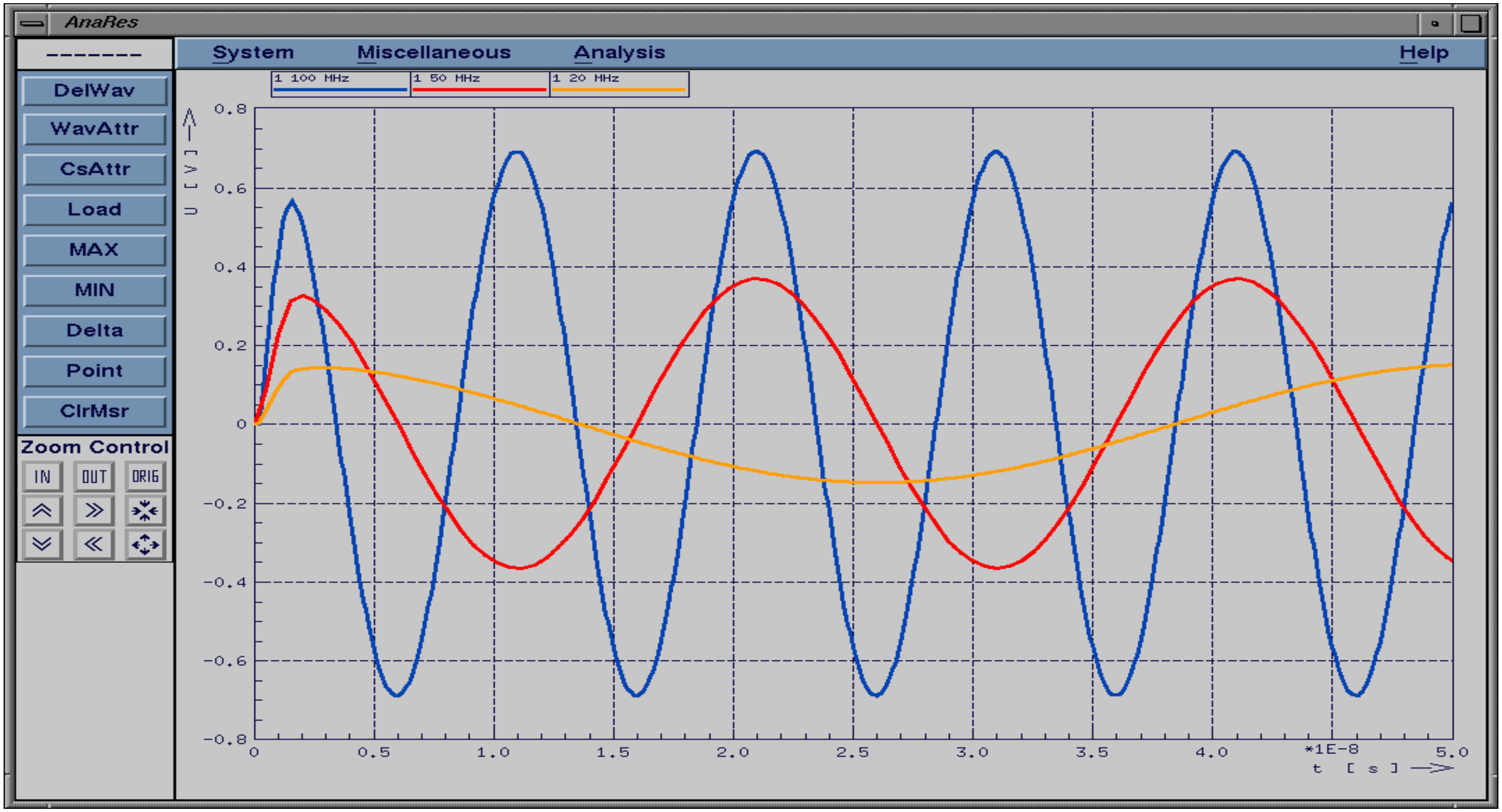




- *Simple trapezoidal pulse used to illustrate concept*
- *Coupled noise decreases with increasing source − victim separation*
- *Coupled noise also decreases when differential signal pairs are used*

Blue: Power Red : T_1 (0.010") Orange: T_2 (0.030") Green: Differential ($T_1 - T_2$)

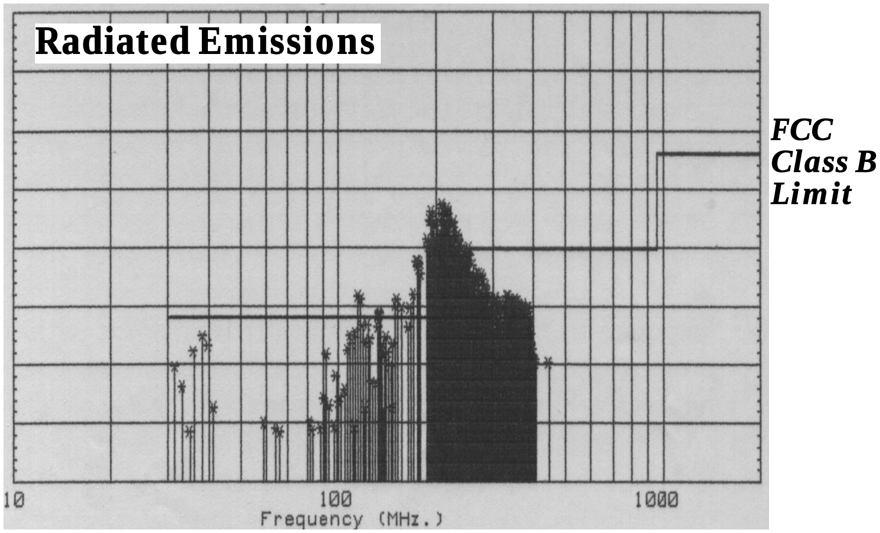
Crosstalk Model Results – Increasing Source Frequency

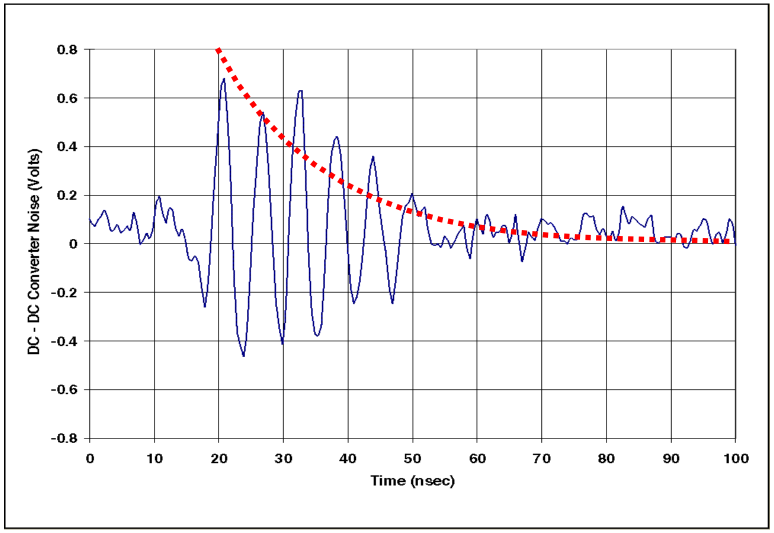


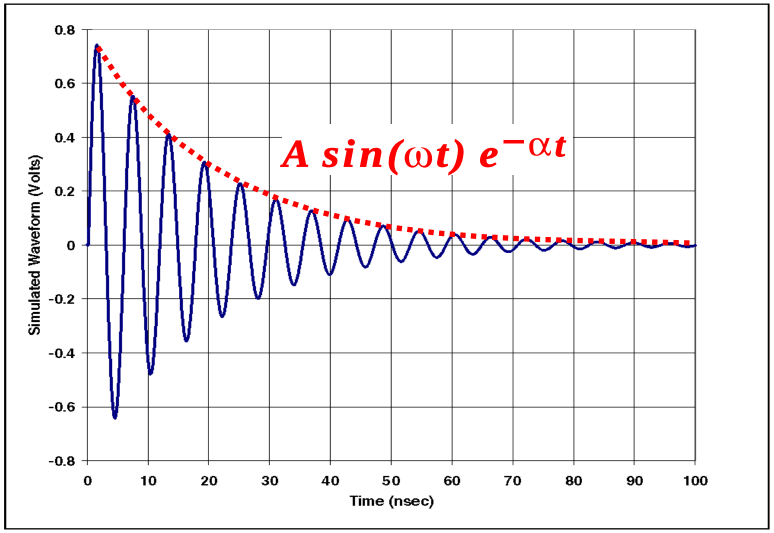
- ***Simple sine wave source used to illustrate concept 1(0 V p–p)***
- ***Coupled noise increases with increasing frequency***

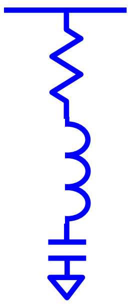
  Orange: 20 MHz Red : 50 MHz Blue: 100 MHz

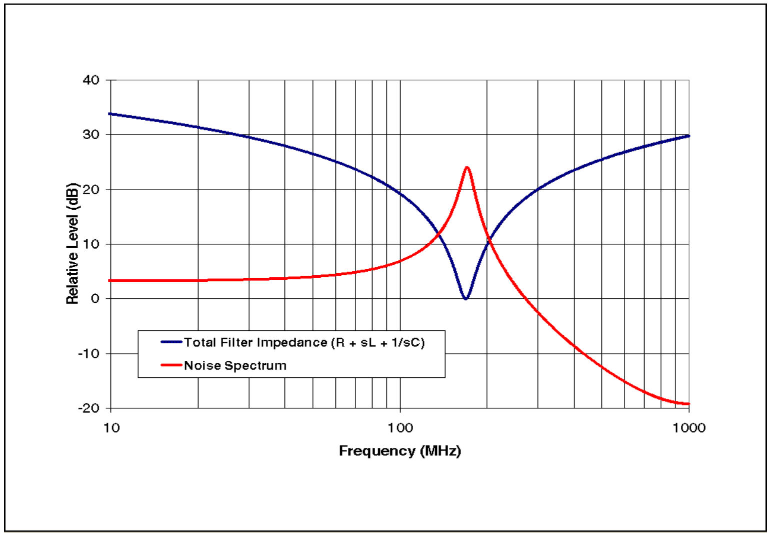
Crosstalk Model Results – Power Supply Filtering





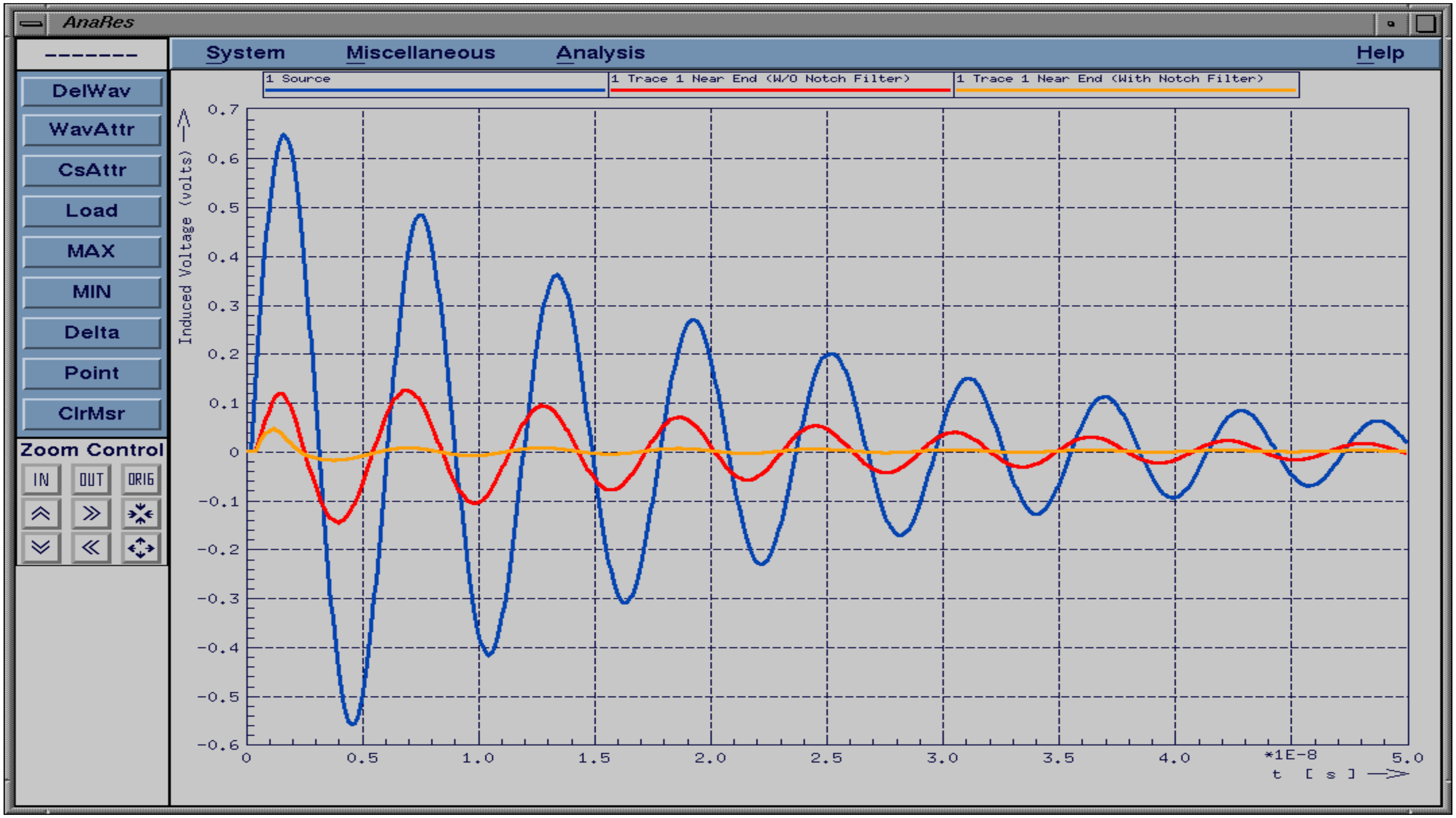






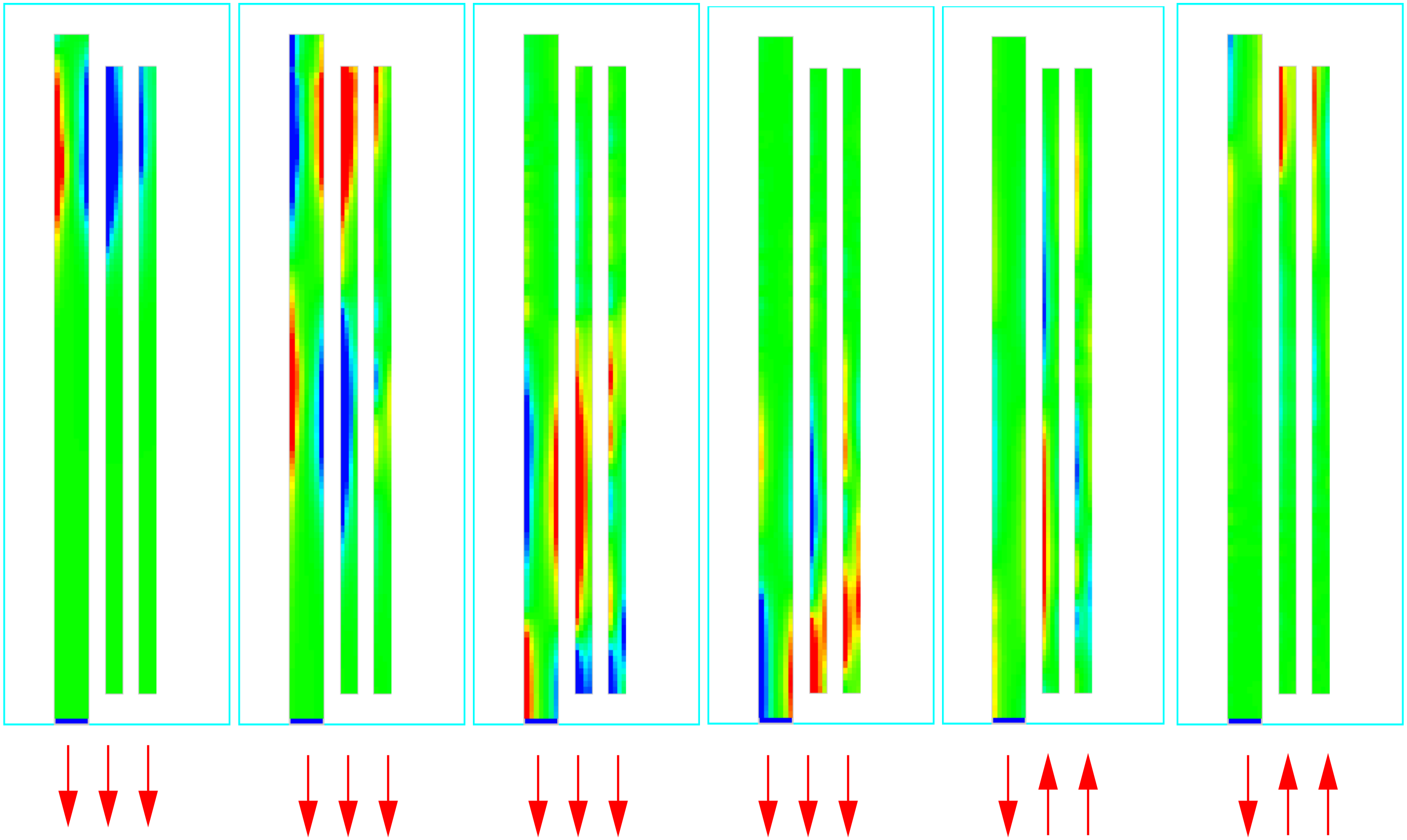
- *A shunt RLC "Notch Filter" between the power trace and ground that is "tuned" to ω can be used to filter out the damped sinusoid noise*

Crosstalk Model Results – Power Supply Filtering



- *Effect of a shunt RLC "Notch Filter" on crosstalk levels*
  Blue: noise on power trace *Red : no notch filter* *Orange: with notch filter*

LC FDTD Modeling Results



- *Time sequence of crosstalk into mismatched loads*
- *Arrows show direction of current flow*
- *Increasing time "snapshots" from left to right*

- o Capacitive and Inductive Crosstalk can be reduced by
  - – Matching source and load termination impedances
  - – Increasing source–to–susceptor separation distance
  - – Route signals using differential pairs
  - – Decreasing coupling length
  - – Band–limiting the frequency of the noise source
  - – Filtering before the crosstalk can take place