Mohr on Minimizing Crosstalk in Wiring and Cabling

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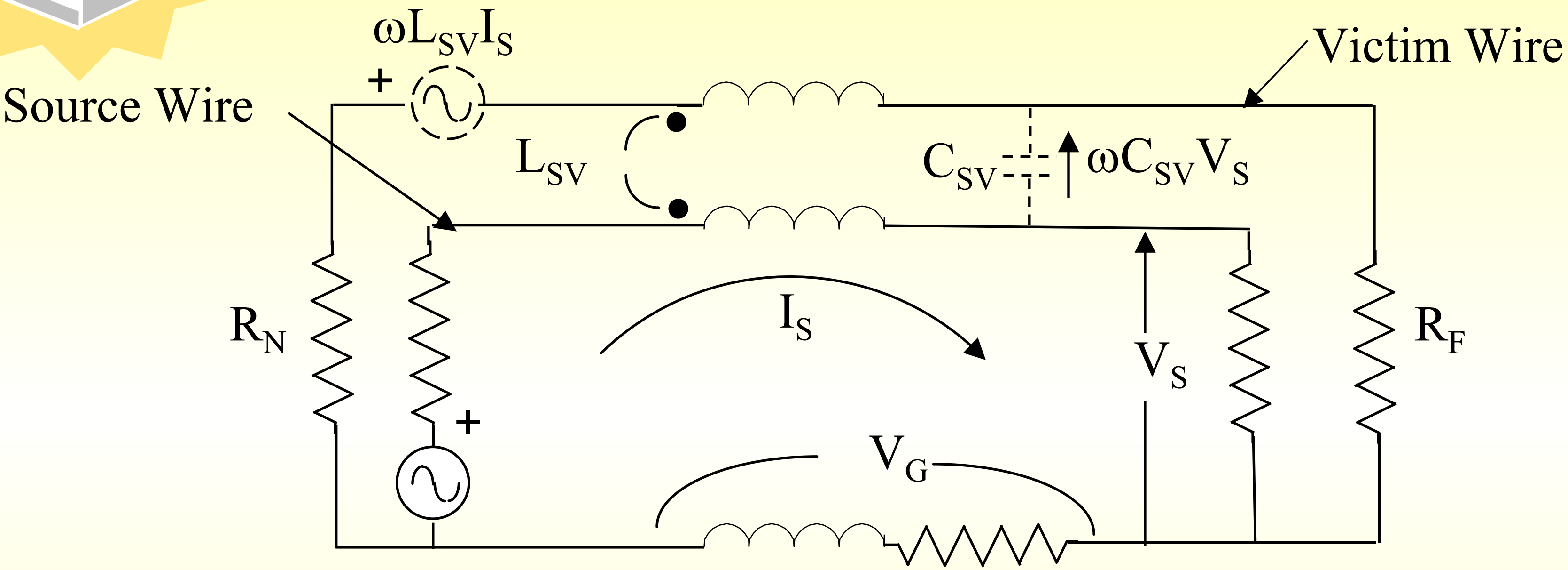
Foreword

This presentation is extracted from portions of Sections 6 and 7 of the EMC training seminar by R. J. Mohr Associates, Inc.: "Getting your product into EMC Compliance".

Introduction

- Purpose
  - Provide a solid understanding of the factors determining crosstalk in wiring and cabling, particularly of grounding and shielding. Understand where protective measures work, or may not work
- Approach
  - The basic mechanisms of crosstalk are shown
  - Representative shielded and unshielded cabling interface models are introduced
  - The models are selected to provide insight into the advantages and disadvantages of different cabling and grounding schemes
  - Extension of the models for quantitative evaluations of crosstalk is illustrated with examples

Cross Coupling Mechanisms in Interface Wiring

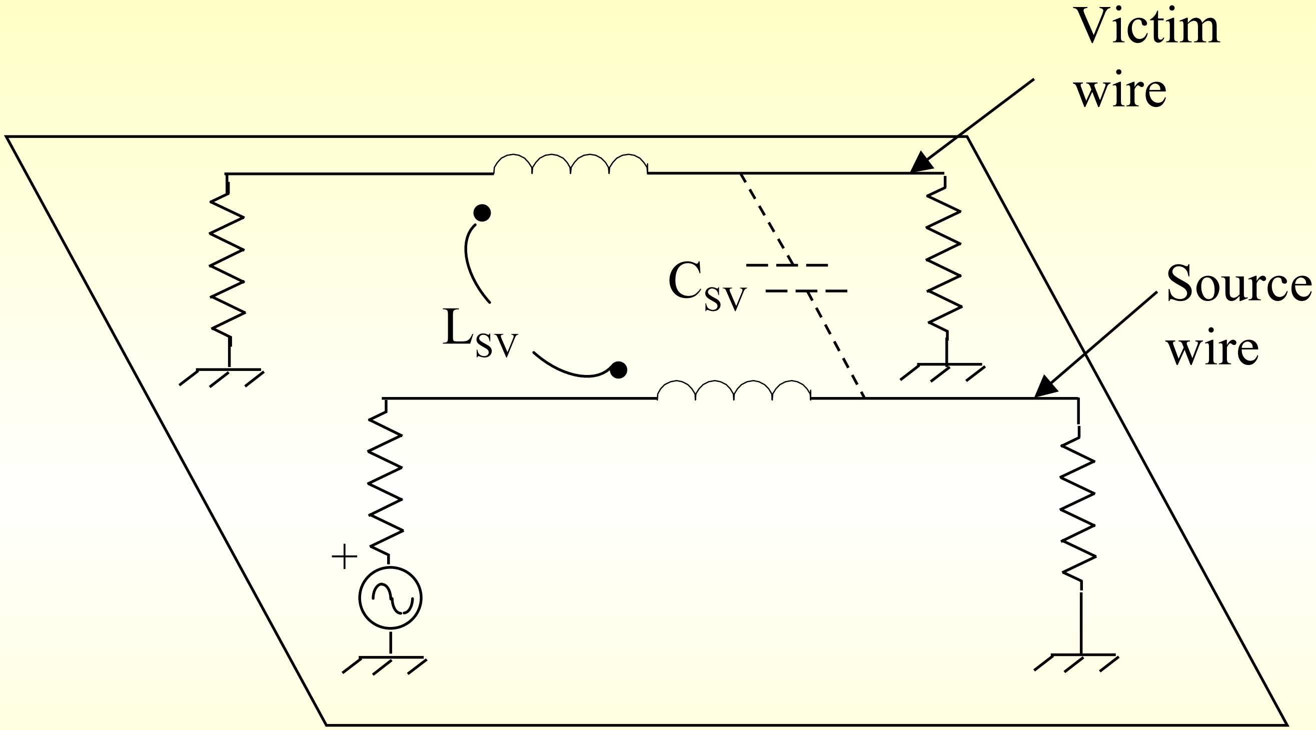


Crosstalk via.:

- Self-impedance in common return
- Mutual inductance, source to victim
- Mutual capacitance, source to victim

Cross Coupling Mechanisms in Interface Wiring (Cont'd)

Employment of Conductive Ground Reference Plane



- ***Ground plane serves as reference for analysis of crosstalk configurations***
- ***Representative of configurations on metal-frame platforms and wiring trays***
- ***Ground plane reference is standard for EMC evaluations***

General Considerations on Prevention of Crosstalk

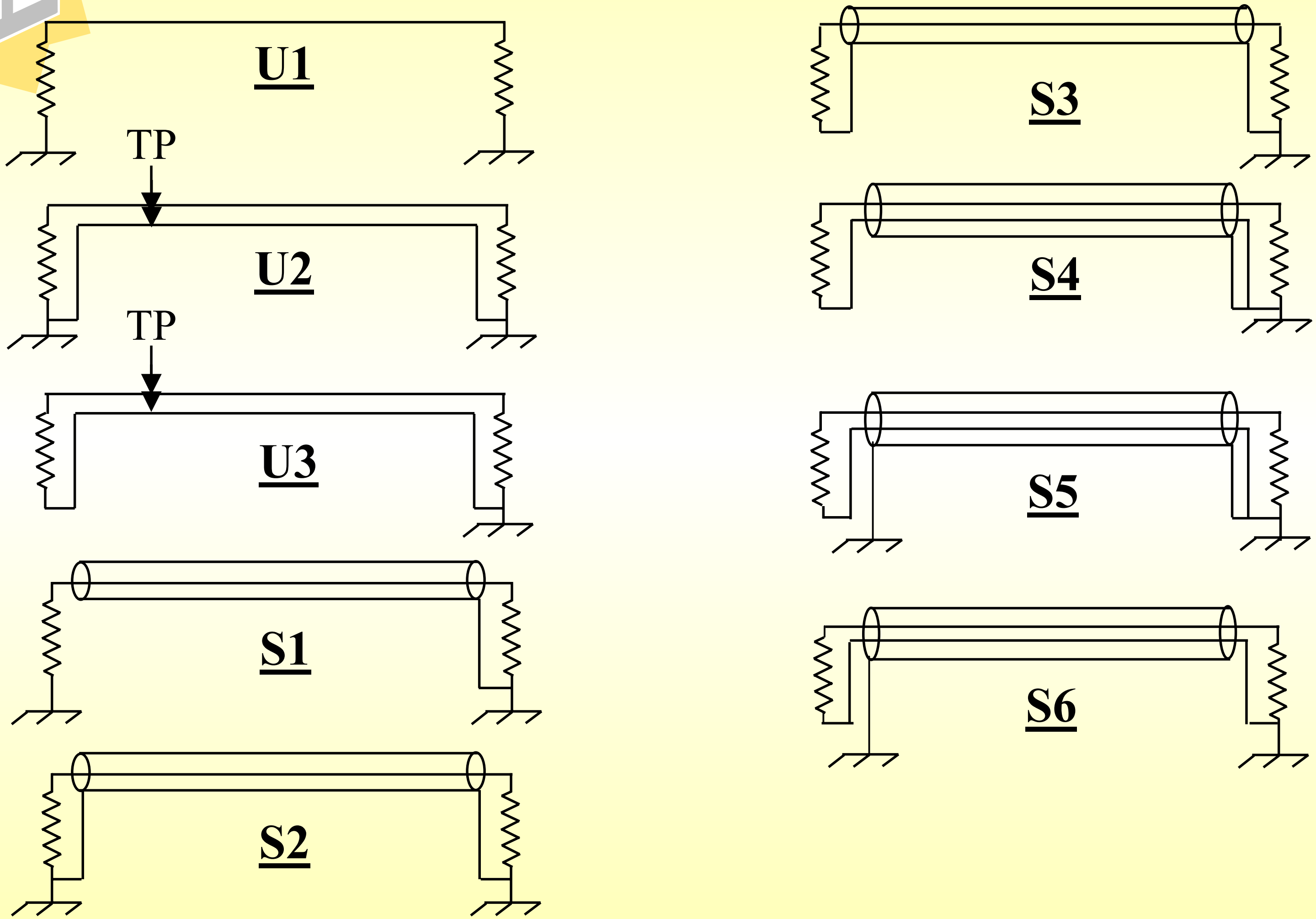
- A common return wire, as on Sheet 4 herein, should never be employed in sensitive interfaces and will not be addressed here any further
- Prevention measures are equally effective when introduced into Source or Victim interfaces
- Optimally, prevention measures should be employed in both Source and Victim circuits
- For this presentation, illustrations will address primarily the victim, it being understood that corrective approaches, and improvement realized, generally apply also to the source circuit

Balanced, differential interfaces are not treated explicitly here. For analysis they may first be treated as unbalanced interfaces, then apply an additional level of rejection due to their balance.

Applicability of Crosstalk Models Treated Herein

- The crosstalk models presented are applicable to a wide range of crosstalk situations.
- For simplicity in the presentation and illustrative examples the following limitations apply:
  - Ground reference will be provided by a conductive ground plane, which may or may not be used as a signal return.
  - Coupled line lengths will be limited to no more than $\lambda/10$
  - R_N, the resistance in the victim line near the source in the source line is 400 Ohms
  - R_F, the resistance in the victim line opposite the far end of the source line is 400 Ohms
  - Source voltage is: 5 V; source current is: 0.0125 A
- The limitations allow lumped element models; and, in the examples, stray inductance, capacitance, and resistance of the wiring can be neglected, except where they are a primary mechanism in crosstalk.

Signal Interface Types Treated



Preview

Crosstalk Analysis Summaries

100 kHz, 10 m interface, routed at h = 0.05 m over ground plane

Configuration	**Description**	**Signal Ground End**	**Shield Ground End**	**Near End Coupling Electric/Magnetic V_E/V_H(V/V)**	**Far End Coupling Electric/Magnetic V_E/V_H(V/V)**
Unshielded U1	Single wire	Both	N/A	0.0139/0.0111	0.0139/ -0.0111
Unshielded U2	Twisted Pair (TP)	Both	N/A	0.0081/0.0074	0.0081/ -0.0074
Unshielded U3	Twisted Pair (TP)	Far	N/A	$0.0081/1.302*10^{-4}$	$0.0081/ -1.302*10^{-4}$
Shielded S1	Shielded Single wire	Both	Far	$5.766*10^{-7}/0.0111$	$5.766*10^{-7}/ -0.0111$
Shielded S2	Shielded Single wire	Both	Both	$1.442*10^{-7}/3.197*10^{-4}$	$1.442*10^{-7}/ -3.197*10^{-4}$
Shielded S3	Shielded Single wire	Far	Far	$-2.492*10^{-6}/7.09*10^{-8}$	$2.492*10^{-6}/ -7.09*10^{-8}$
Shielded S4	Shielded Twisted Pair (STP)	Far	Far	$1.355*10^{-6}/1.271*10^{-8}$	$1.355*10^{-6}/1.271*10^{-8}$
Shielded S5	Shielded Twisted Pair (STP)	Far	Both	$3.388*10^{-7}/1.553*10^{-3}$	$3.388*10^{-7}/1.553*10^{-3}$
Shielded S6	Shielded Twisted Pair (STP)	Far	Near	$1.355*10^{-6}/3.106*10^{-3}$	$1.355*10^{-6}/3.106*10^{-3}$

Summary

Parameters in Wiring and Cabling

Crosstalk Models

Wiring and Cabling Parameters Per Meter

And 100 kHz impedances in 10 meters of cable routed at h=5 cm above conducting ground plane

	Capacitance to ground, C_W		**Self-Inductance, L_W**		**Resistance, R_W**		**Mutual Inductance, L_{W-W}**		**Mutual Capacitance, C_{W-W}**	
Type	**(pF/m)**	**(Ohms/ 10m)**	**(uH/m)**	**(Ohms/ 10m)**	**(Ohms/ m)**	**(Ohms/ 10m)**	**(uH/m)**	**(Ohms/ 10m)**	**(pF/m)**	**(Ohms/ 10m)**
#24 AWG Open Wire	9.312	17,091	1.194	7.502	0.0719	0.719			-	
Shielded Wire (RG-58 Coax)	-		-		-		-		-	
• Conductor	92.08 to shield)	1728	1.0832	6.806	0.0278	0.278	0.853	5.360	-	
• Shield	13.182	12,074	0.853	5.360	0.0154	0.154	0.853	5.360	-	
#24 TP	9.312	17,091	1.159	7.282	0.080	0.8	0.386	2.425	38.16	
#24 STP	-		-		-		-			
• Conductor	111.1 (to shield)	1433	0.620 (round trip)	6.2	0.157 (round trip)	1.57	-		24.53	
• Shield	12.73	12,498	0.873	5.485	0.0307	0.193	-		-	

Series impedances in the model conductors are much less than R_N (400 Ohms) and R_F, (400 Ohms) and shunt impedances are much greater than R_N and R_F and all may be neglected in the examples.

Coupling Parameters, Source to Victim

Coupled length, *l*=10 m,
Height over ground plane, *h*= 5 cm;
Separation of source to victim *D*=2.5 cm

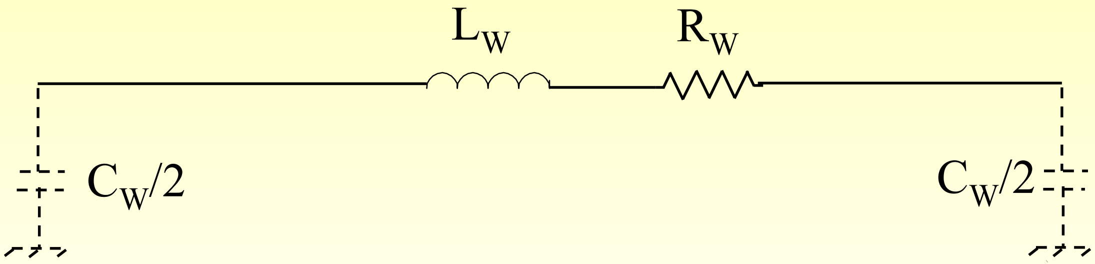
	Mutual Inductance		**Mutual Capacitance**	
Coupling from Source to:	**(uH/m)**	**(Ohms/10 m)**	**(pF/m)**	**(Ohms/10 m)**
• Open wire	$(L_{S\text{-}W})$ 0.2833	1.780	$(C_{S\text{-}W})$ 2.208	72,081
• Shield of RG-58	$(L_{S\text{-}Sh})$ 0.2833	1.780	$(C_{S\text{-}Sh})$ 3.091	51,490
• #24 TP	$(L_{S\text{-}W})$ 0.2833	1.780	2.570 ($(C_{S\text{-}W})$ 1.285 to each wire)	61,928 ($1.239*10^5$ to each wire)
• Shield of #24 TP	$(L_{S\text{-}W})$ 0.2833	1.780	$(C_{S\text{-}W})$ 3.020	52,700

The capacitive reactance of the coupling capacitance is much greater than the R_N and R_F in the victim circuits, and the injected current may be modeled as from a constant current source.

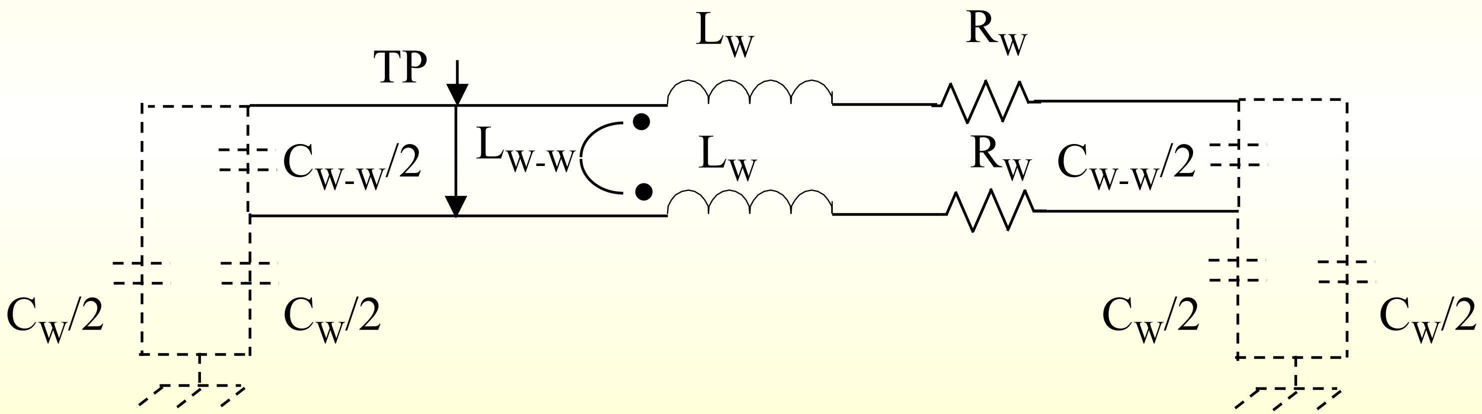
Unshielded Configurations

Unshielded Wire Models

Single Wire



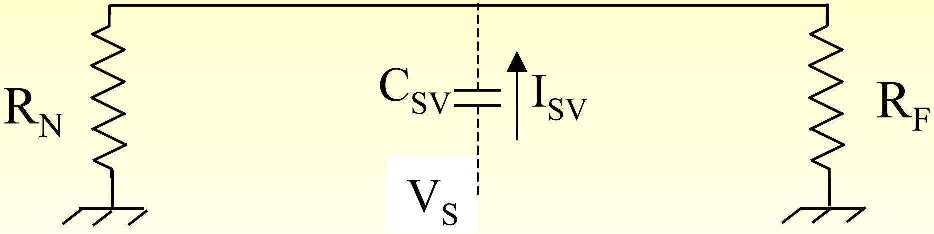
Twisted Pair



In analyses of crosstalk at low frequencies some of the parameters have only second-order effects on the net crosstalk, and may be neglected as will be indicated in the following

Model **U1**, Single Wire, Ground Plane Return

Electric Coupling



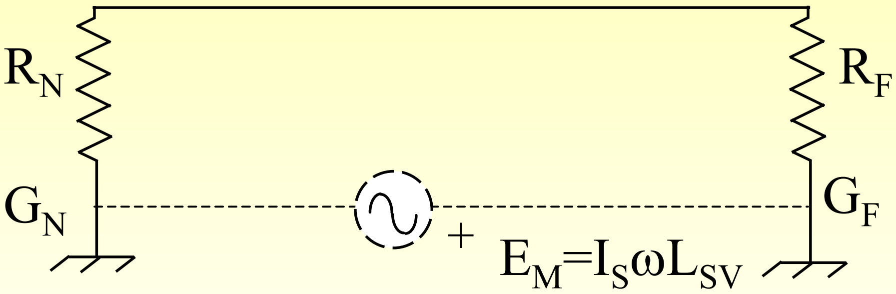
$V_N=V_F=I_{SV}*R_P=V_S\omega C_{SV}R_P$
Where, $I_{SV}=V_S\omega C_{SV}$, and R_P is the parallel resistance of R_N and R_F

Example:
$V_N=V_F=5*2\pi10^5 22.08*10^{-12}200=0.0139$ V

- ***Electrical coupled voltages at R_N and R_F are in phase***
- ***Electrical coupled crosstalk is less with small R_P, say, with a low impedance driver in the Victim***

Model **U1**, Single Wire, Ground Plane Return

Magnetic Coupling



$V_N=E_M*R_N/(R_N+R_F)$, $V_F=-E_M*R_F/(R_N+R_F)$

Example:

$E_M=0.0125*2\pi10^5 2.833*10^{-6}=0.02225V$

E_M is divided among R_N and R_F in accordance with their impedances so that:

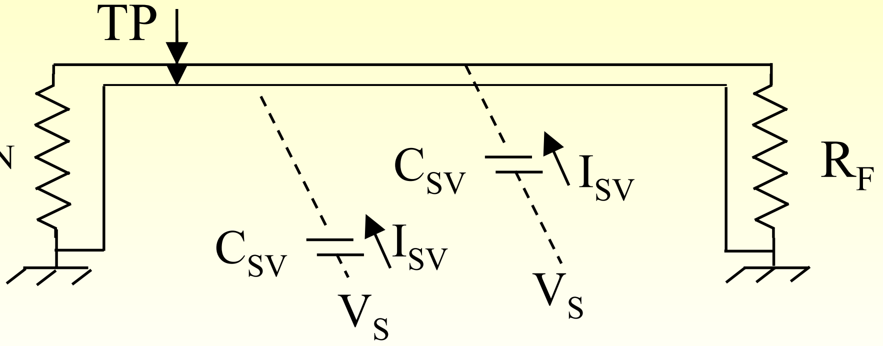
$V_N = E_M*(400/800) = 0.0111$ V

$V_F =-E_M*(400/800) =-0.0111$ V

Magnetic induced voltage, E_M, may be represented, as shown, as though it is due to a potential difference in circuit reference points, G_N, G_F

Model **U2,** Ground Plane Return, and Added Return

Electric Coupling



$V_N = V_F = I_{SV} R_P = V_S \omega C_{SV} R_P$

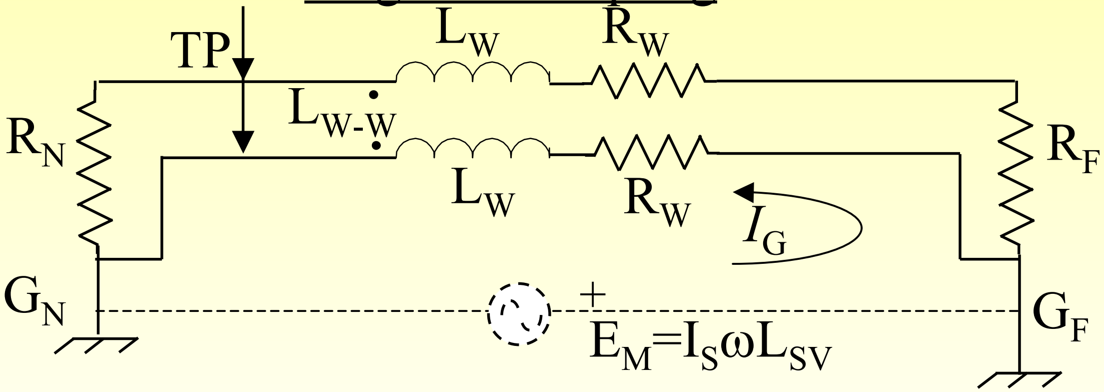
Example:

$V_N = V_F = 5 * 2\pi 10^5 * 12.85 * 10^{-12} * 200 = 0.0081$ V

Return wire decreases effective C_{SV} and acts to partially shield signal wire

Model **U2,** Ground Plane Return, and Added Return

Magnetic Coupling



Net Induction, E_i:

$$E_i = -E_M + I_G j\omega L_{W-W} = -E_M + \frac{E_M}{R_W + j\omega L_W} j\omega L_{W-W} = -E_M\left[\frac{R_W + j\omega\left(L_W - L_{W-W}\right)}{R_W + j\omega L_W}\right]$$

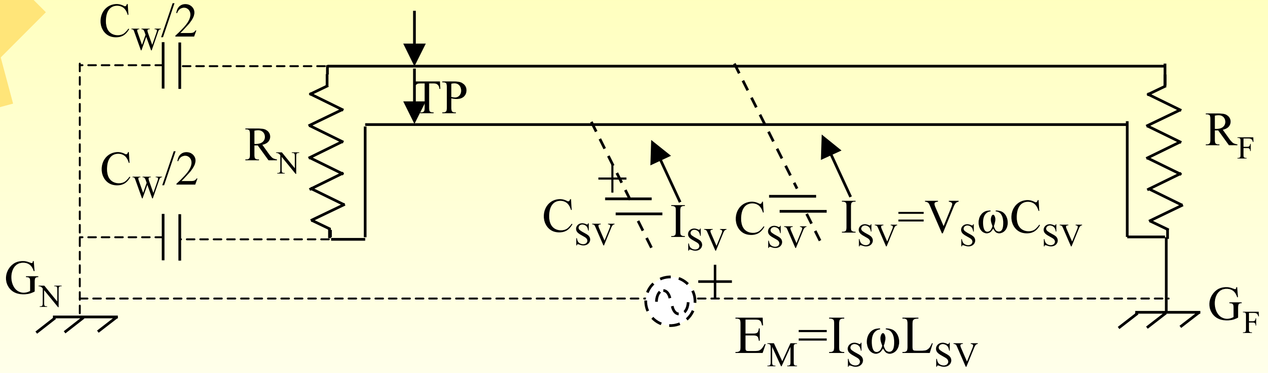
$$\text{For } \omega(L_W - L_{W-W}) >> R_W : E_i \cong -E_M\left(\frac{L_W - L_{W-W)}}{L_W}\right)$$

Example: E_i=-0.0125*2π10^5*2.833*10^{-6}*(11.59-3.86)/11.59=-0.0148V
$V_N=E_i*R_N/(R_N+R_F)=0.0074V$; $V_F=-E_i*R_F/(R_N+R_F)=-0.0074V$

- ***Return wire in addition to ground plane return provides some suppression***
- ***Is it clear that a heavy common mode choke would provide additional rejection?***

Model **U3**, Single-Ended Twisted Pair

Electric and Magnetic coupling



Electric Coupling: $V_N=V_F=V_S\omega C_{SV}$

Example: $V_N=V_F=5*2\pi10^5*12.85*10^{-12}*200=0.0081\text{V}$

Magnetic Coupling: $V_N=V_F=-E_M\omega(C_W/2)R_P=-I_S\omega L_{SV}\omega(C_W/2)R_P$

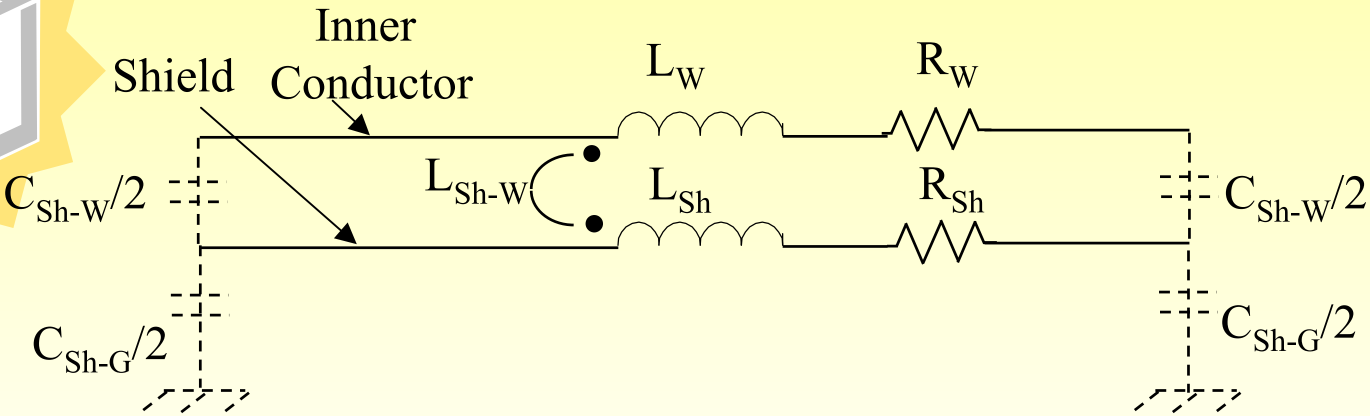
Example:

$V_N=V_F=-0.0125*2\pi10^5*2.833*10^{-6}*2\pi10^5(93.12*10^{-12}/2)*200=-1.302*10^{-4}\text{V}$

- ***Capacitive current to return is drained to ground; capacitive coupling to signal interface is reduced modestly***
- ***Large fraction of*** E_M ***is dropped across*** $C_W/2$***, big help!***

Shielded Wires

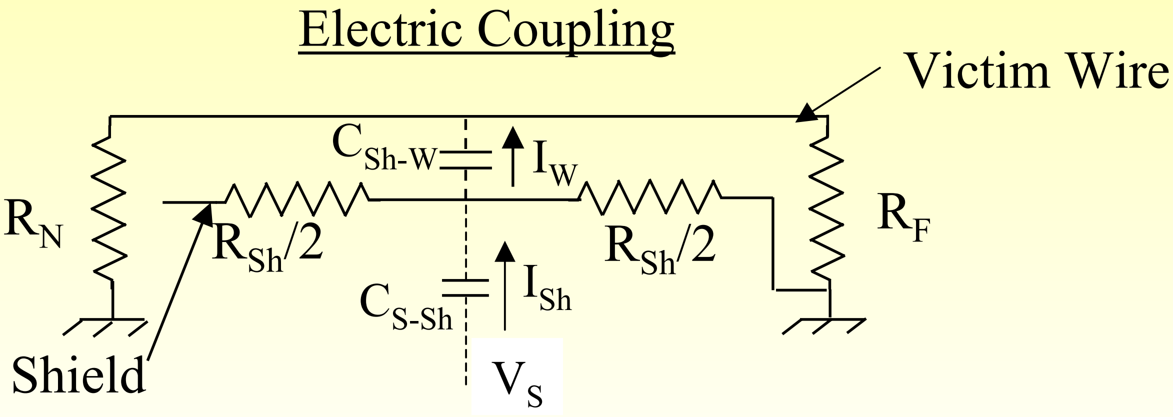
Model for Shielded Wire



$$\frac{E_i}{E_M} = \frac{1}{1+\frac{j\omega L_{Sh}}{R_{Sh}}};\ \text{for } \omega L_{Sh} >> R_{Sh};\ \frac{E_i}{E_M} \cong \frac{R_{Sh}}{\omega L_{Sh}}$$

- ***Shield inductance is equal to the mutual inductance between the shield and inner conductor: $L_{Sh}=L_{Sh-W}$ – it's why the shield is so effective against magnetic coupling***
- ***At high frequencies the shield resistance, R_{Sh}, in the expression should be replaced by the transfer impedance, Z_T, of the shield***

Model **S1,** Shield Grounded Far End



$I_{Sh}=V_S\omega C_{S\text{-}Sh}$

Average voltage on shield: $V_{Av}=I_{Sh}R_{Sh}/3$

$I_W=V_{Av}\omega C_{Sh\text{-}W}$

and: $V_N=V_F=I_W{*}R_P=V_S\omega C_{S\text{-}Sh}(R_{Sh}/3)\ \omega C_{Sh\text{-}W}R_P$

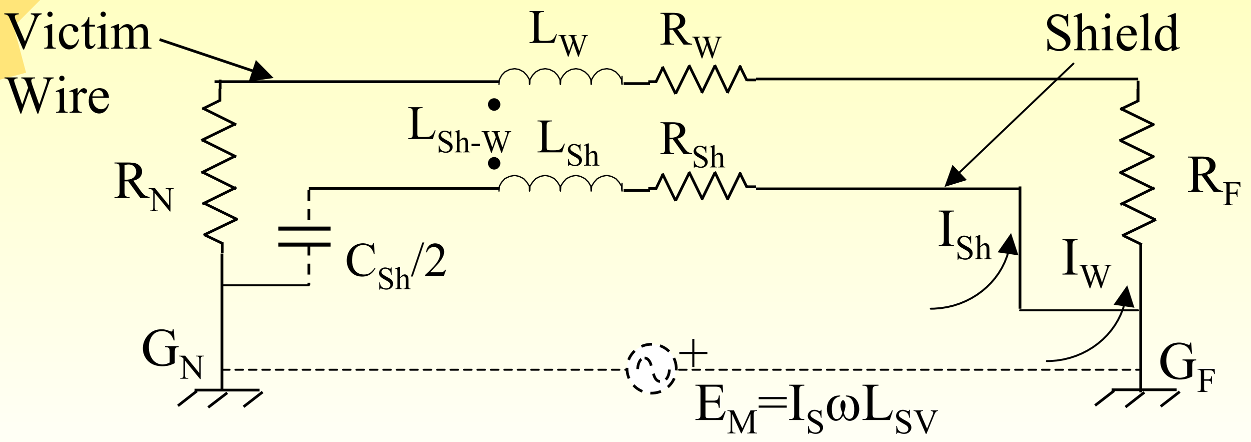
Example:

$V_N=V_F=5{*}2\pi 10^{5*}30.9{*}10^{-12}(0.154/3)\ {*}2\pi 10^5{*}920.8{*}10^{-12}{*}200=5.766{*}10^{-7}$ V

Shield provides large attenuation to electrically coupled voltage

Model **S1**, Shield Grounded Far End

Magnetic Coupling



$$I_W \cong I_S \omega L_{SV} / (R_N + R_F)$$

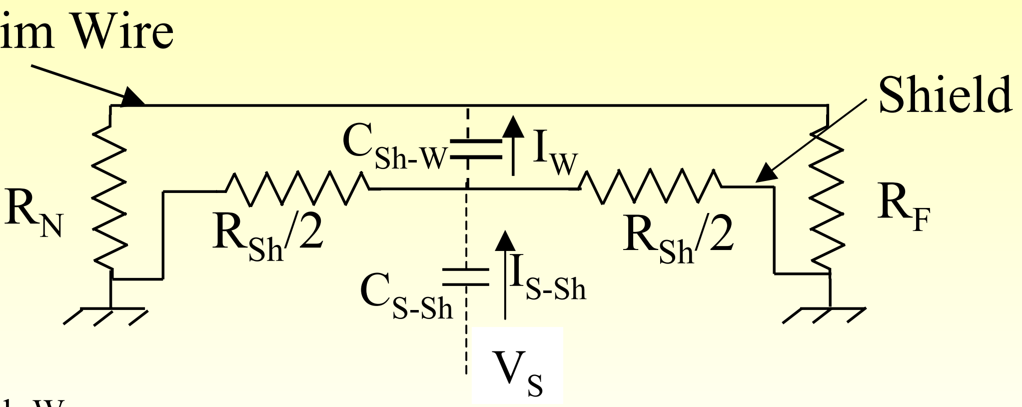
$$I_{Sh} \cong I_S \omega L_{SV} \omega (C_{Sh} / 2)$$

Example: $I_W=0.0125*2\pi 10^5*2.833*10^{-6}/800=2.781*10^{-5}$A
$I_{Sh}=0.0125*2\pi 10^5*2.833*10^{-6}2\pi 10^5(131.8*10^{-12}/2)=9.213*10^{-7}$A
$V_N=I_W*R_N=2.781*10^{-5}*400 = 0.0111$V
$V_F= -I_W*R_F= -2.781*10^{-5}*400 = -0.0111$V

- ***High reactance of C_{Sh} limits I_{Sh}; little cancellation of E_M in the signal interface***
- ***Would a common-mode choke be a good idea here? (Clue: no; why?)***

Model **S2**, Shield Grounded Both Ends

Electric Coupling



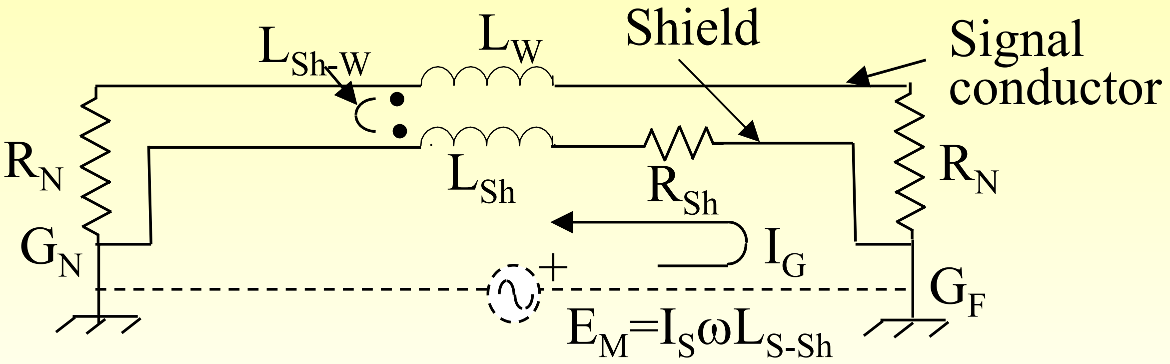
Note: $I_W=V_{Av}\omega C_{Sh\text{-}W}$
where: average Voltage on shield: $V_{Av}=I_{Sh}R_{Sh}/12$
and: $I_{Sh}=V_S\omega C_{S\text{-}Sh}$
$V_N=V_F=I_W*R_P= V_S\,\omega C_{S\text{-}Sh}\,(R_{Sh}/12)\,\omega C_{Sh\text{-}W}R_P$

Example:
$V_N=V_F=5*2\pi 10^{5}*30.9*10^{-12}(0.154/12)\ *2\pi 10^{5}*920.8*10^{-12}*200=1.442*10^{-7}V$

- ***For electrically coupled voltage, grounding shield at both ends is more effective than single-point grounding***

Model **S2**, Shield Grounded Both Ends

Magnetic Coupling



Net induced voltage, E_i, in signal interface:

$$E_i = I_G R_{Sh} \cong \frac{E_M}{R_{Sh} + j\omega L_{Sh}} R_{Sh} = E_M \frac{1}{1 + \frac{j\omega L_{Sh}}{R_{Sh}}} \quad \text{For } \omega L_{Sh} >> R_{Sh},\ E_i \cong E_M \frac{R_{Sh}}{\omega L_{Sh}}$$

Example: $\omega L_{Sh}/R_{Sh} = 2\pi * 10^5 * 8.53 * 10^{-6}/0.154 = 34.8$

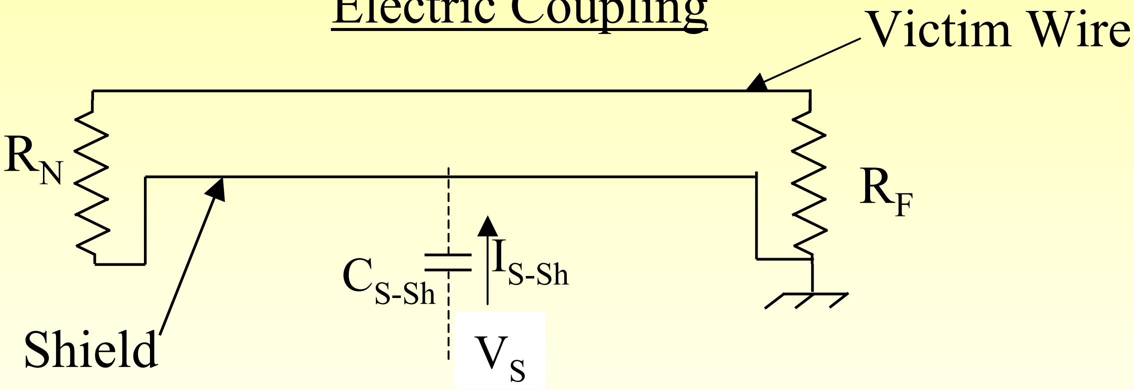
$E_i = E_M/34.8 = 0.0125 * 2\pi 10^5 * 2.833 * 10^{-6} * 0.154/34.8 = 6.393 * 10^{-4}$V

$V_N = E_i * R_N/(R_N + R_F) = 6.393 * 10^{-4}/2 = 3.197 * 10^{-4}$, $V_F = -3.197 * 10^{-4}$

- ***I_G in shield induces voltage component in signal line which opposes E_M in signal interface; shield resistance, R_{Sh}, prevents complete cancellation.***
- ***Good place for a common choke; also a current-drive signal source in the victim works great (by effectively raising the impedance of its source)***

Model **S3**, Shield Grounded at Signal Reference

Electric Coupling



Electrically-induced voltage in signal line is:

$E_i=I_{S\text{-}Sh}*R_{Sh}/3=V_S\omega C_{S\text{-}Sh}R_{Sh}/3$

$V_N=-E_iR_N/(R_N+R_F)$; $V_F=E_iR_F/(R_N+R_F)$;

Example:

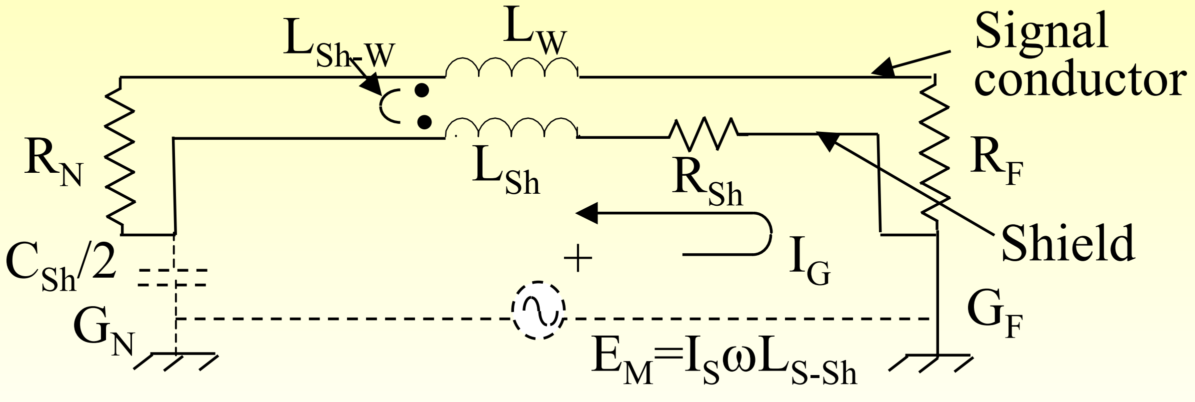
$E_i=5*2\pi 10^{5*}30.9*10^{-12}(0.154/3) =4.983*10^{-6}V$

$V_N= -4.983*10^{-6}*400/800=-2.492*10^{-6}$; $V_F= 4.983*10^{-6}*400/800=2.492*10^{-6}$

For electrically coupled voltage, grounding shield at one end is less effective than grounding at both ends

Model **S3**, Shield Grounded at Signal Ground Reference

Magnetic Coupling



Net induced voltage, E_i in signal interface:

$$E_i = I_G R_{Sh} \cong E_M \omega (C_{Sh}/2) R_{Sh} = I_S \omega L_{S-Sh} \omega (C_{Sh}/2) R_{Sh}$$

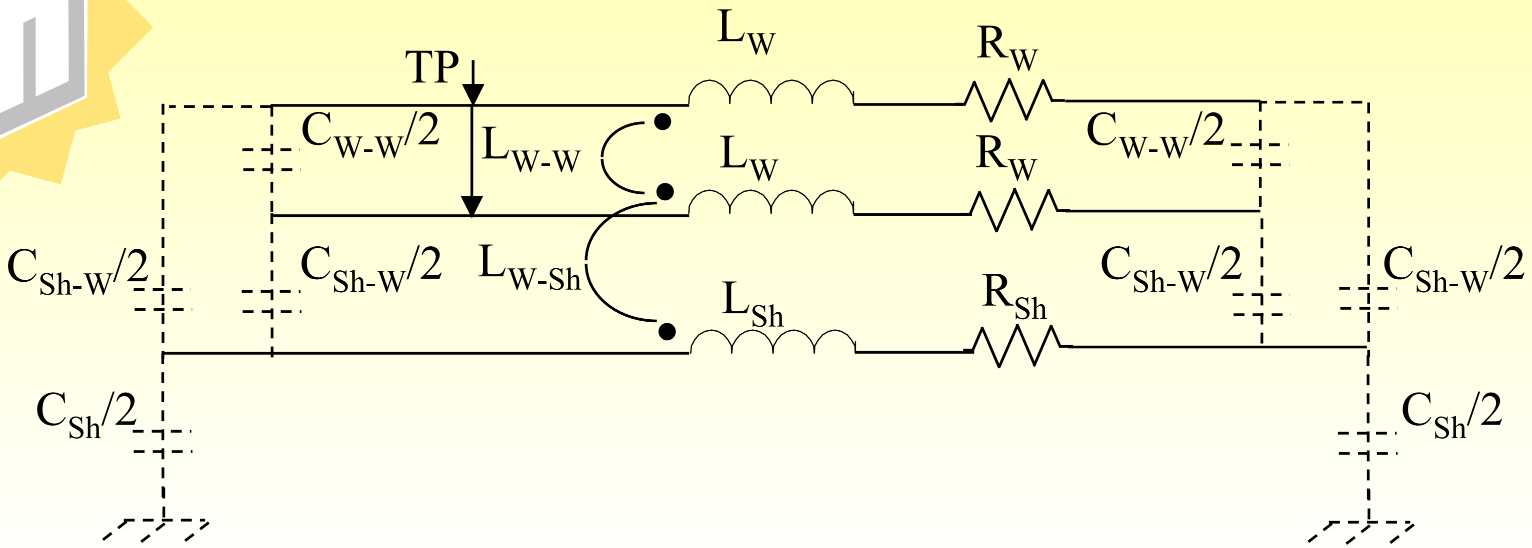
$$V_N = E_i \frac{R_N}{R_N + R_F}; V_F = -E_i \frac{R_F}{R_N + R_F}$$

Example: $E_i=0.0125*2\pi10^5*2.833*10^{-6}*2\pi10^5*(131.8*10^{-12}/2)0.154=1.419*10^{-7}$V
$V_N=E_i*R_N/(R_N+R_F)=1.419*10^{-7}/2=7.094*10^{-8}$, $V_F=-7.094*10^{-8}$

Reactance of $C_{Sh}/2$ drops large fraction of E_M; and net crosstalk is small

Shielded Twisted Pairs (STPs)

Model for Shielded Twisted Pair (STP)



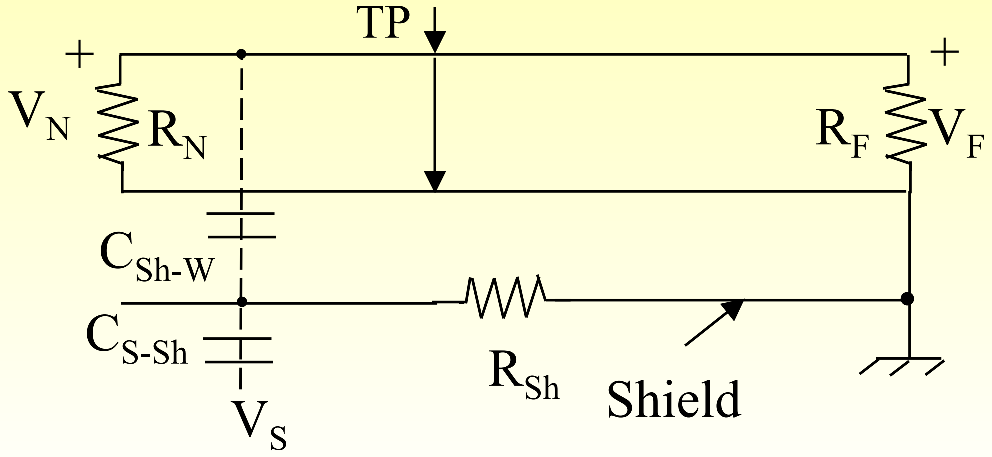
Note:

Mutual-inductance, $L_{Sh\text{-}W}$, between the shield and each wire is equal to L_{Sh}

In analyses of crosstalk some of the parameters have only second-order effects on the net crosstalk, and may be neglected as will be indicated in the following

Model **S4**, STP, Shield Grounded at Signal Reference

Electric Coupling



At LF, i.e. $1/\omega C_{Sh\text{-}W} >> R_N, R_F, R_{Sh}$, then:

$$V_N = V_F = V_S \omega C_{S\text{-}Sh} (R_{Sh}/3) \omega C_{Sh\text{-}W} R_P$$

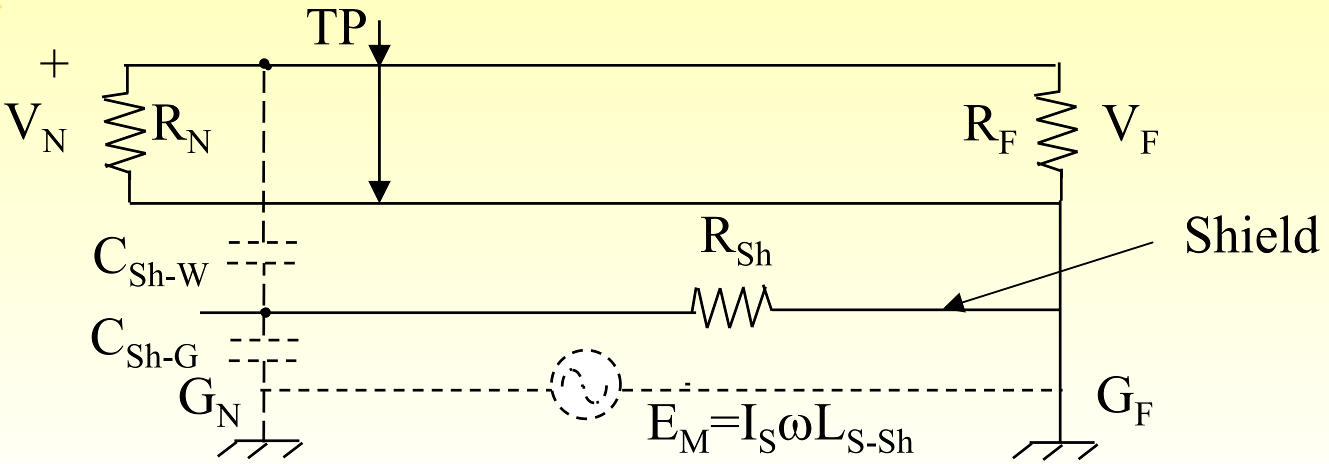
Example: $V_N = V_F =$

$5 * 2\pi 10^5 * 30.2 * 10^{-12} (0.307/3)\ 2\pi * 10^5 * 1111 * 10^{-12} * 200 = 1.355 * 10^{-6}$ V

Shield provides effective low frequency drain to ground for electrical-coupled current with small net voltage on shield and small I_w to victim

Model **S4,** STP, Shield Grounded at Signal Reference

Magnetic Coupling



At LF, i.e. where, $1/\omega C_{Sh\text{-}G}$, $1/\omega C_{Sh\text{-}W} >> R_N, R_F, R_{Sh}$:

$$V_N = V_F = I_S\omega L_{S\text{-}Sh}\omega(C_{Sh\text{-}G}/2)(R_{Sh}/3)\omega C_{Sh\text{-}W}R_P=(1/6)I_S\omega^3 L_{S\text{-}Sh}C_{Sh\text{-}G}R_{Sh}C_{Sh\text{-}W}R_P$$

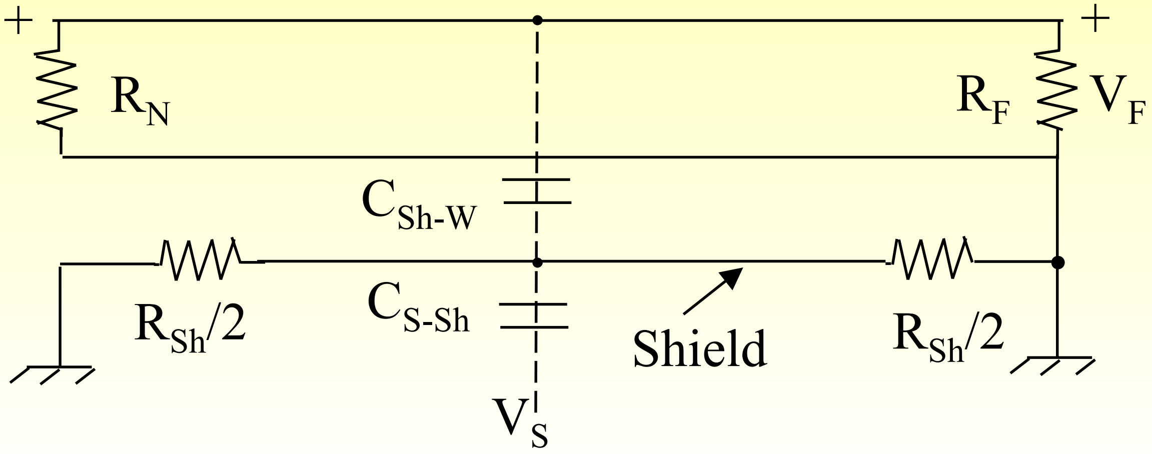
Example:

$$V_N=V_F=$$
$$(1/6)0.0125(2\pi 10^5)^3 2.833*10^{-6}*127.3*10^{-12}(0.307/2)1111*10^{-12}200$$
$$=1.271*10^{-8}V$$

Note how $C_{Sh\text{-}G}$ and R_{Sh} act together to divide down E_M at shield, and result in minimum coupling to the signal lines

Model **S5,** STP, Shield Grounded Both Ends

Electric coupling



At LF, i.e. $1/\omega C_{Sh-W} >> R_N, R_F, R_{Sh}$, then:

$$V_N = V_F = V_S \omega C_{S-Sh}(R_{Sh}/12)\omega C_{Sh-W} R_P$$

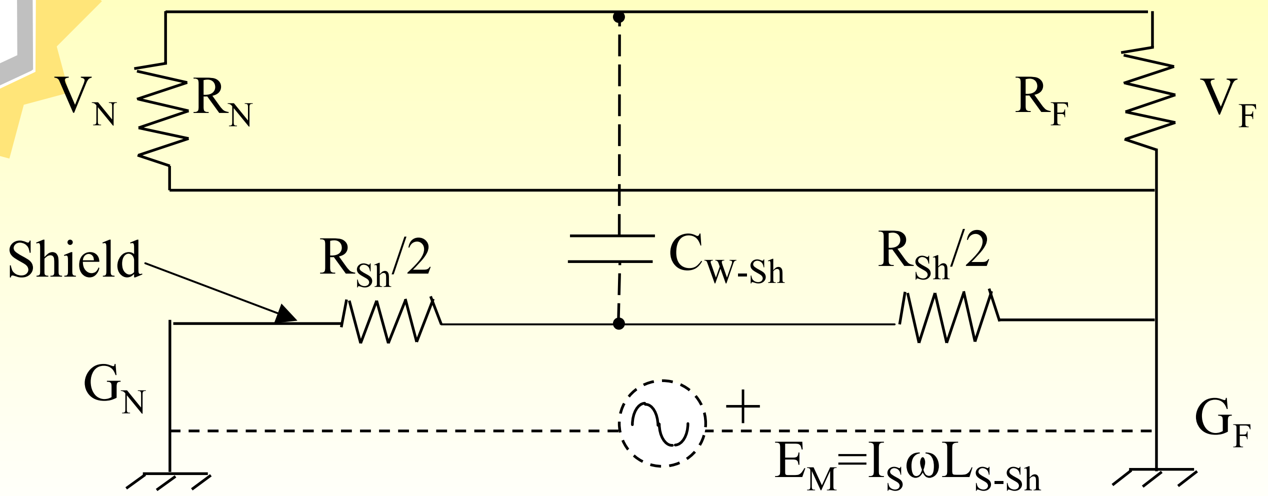
Example:

$V_N=V_F=5*2\pi 10^5*30.2*10^{-12}(0.307/12)\ 2\pi*10^5*1111*10^{-12}*200=3.388*10^{-7}V$

With shield grounded at both ends, cross-coupling of electrically-induced interference is 1/4th that with the shield grounded at only one end

Model **S5,** STP, Shield Grounded Both Ends

Magnetic Coupling



At LF, i.e. where $1/\omega C_{Sh\text{-}W} >> R_N, R_F, R_{Sh}$:

$$V_N = V_F = (E_M/2)\omega C_{Sh\text{-}W} R_P = (I_S \omega L_{S\text{-}Sh}/2)\omega C_{Sh\text{-}W} R_P$$

Example:

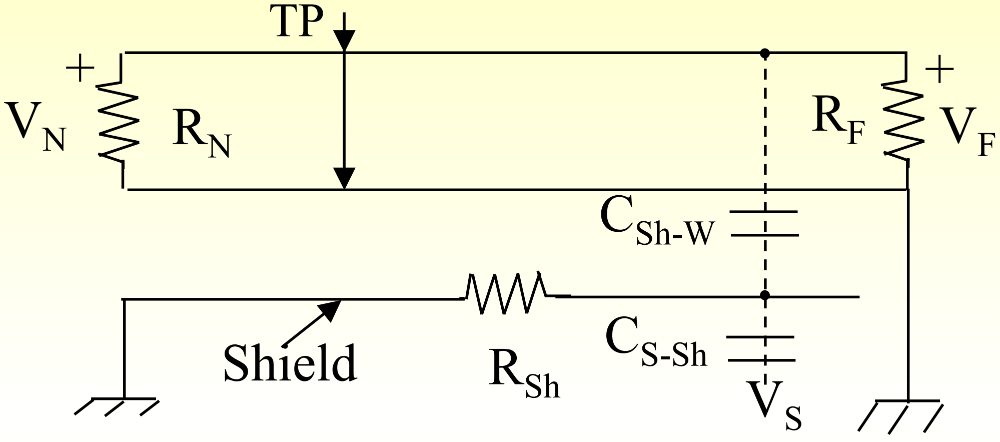
$V_N = V_F =$

$(0.0125 * 2\pi 10^5 * 2.833 * 10^{-6}/2) 2\pi * 10^5 * 1111 * 10^{-12} /2 * 200 = 1.553 * 10^{-3} V$

Entire E_M is across the shield and performance is much poorer than when grounding at signal ground reference only

Model **S6,** STP, Shield Grounded Opposite Signal Reference

Electric Coupling



At LF, i.e. $1/\omega C_{W-Sh} >> R_N, R_F, R_{Sh}$, then:

$$V_N = V_F = V_S \omega C_{S-Sh}(R_{Sh}/3)\omega C_{Sh-W} R_P$$

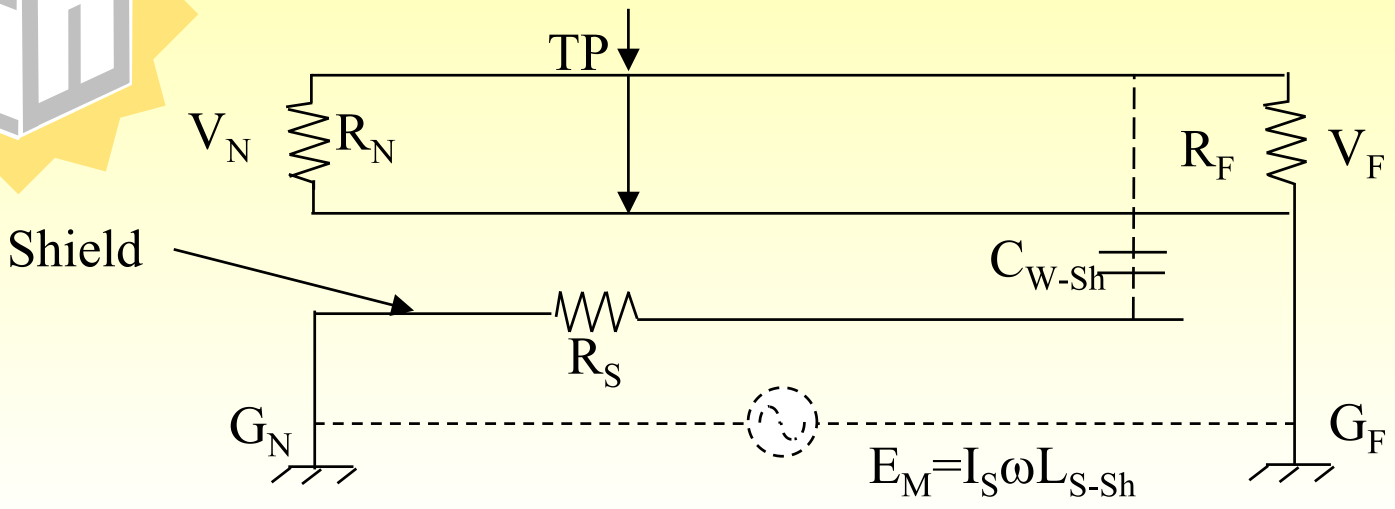
Example:

$V_N=V_F=5*2\pi 10^5*30.2*10^{-12}(0.307/3)\ 2\pi*10^5*1111*10^{-12}*200=1.355*10^{-6}$ V

<u>Result the same as with the shield grounded at the ground reference-electric coupling is independent of the end at which the shield is grounded</u>

Model **S6**, STP, Shield Grounded Opposite Signal Reference

Magnetic Coupling



At LF, i.e. where, $1/\omega C_{WSh} >> R_L, R_R, R_{Sh}$, the net voltage across R_N and R_F is:

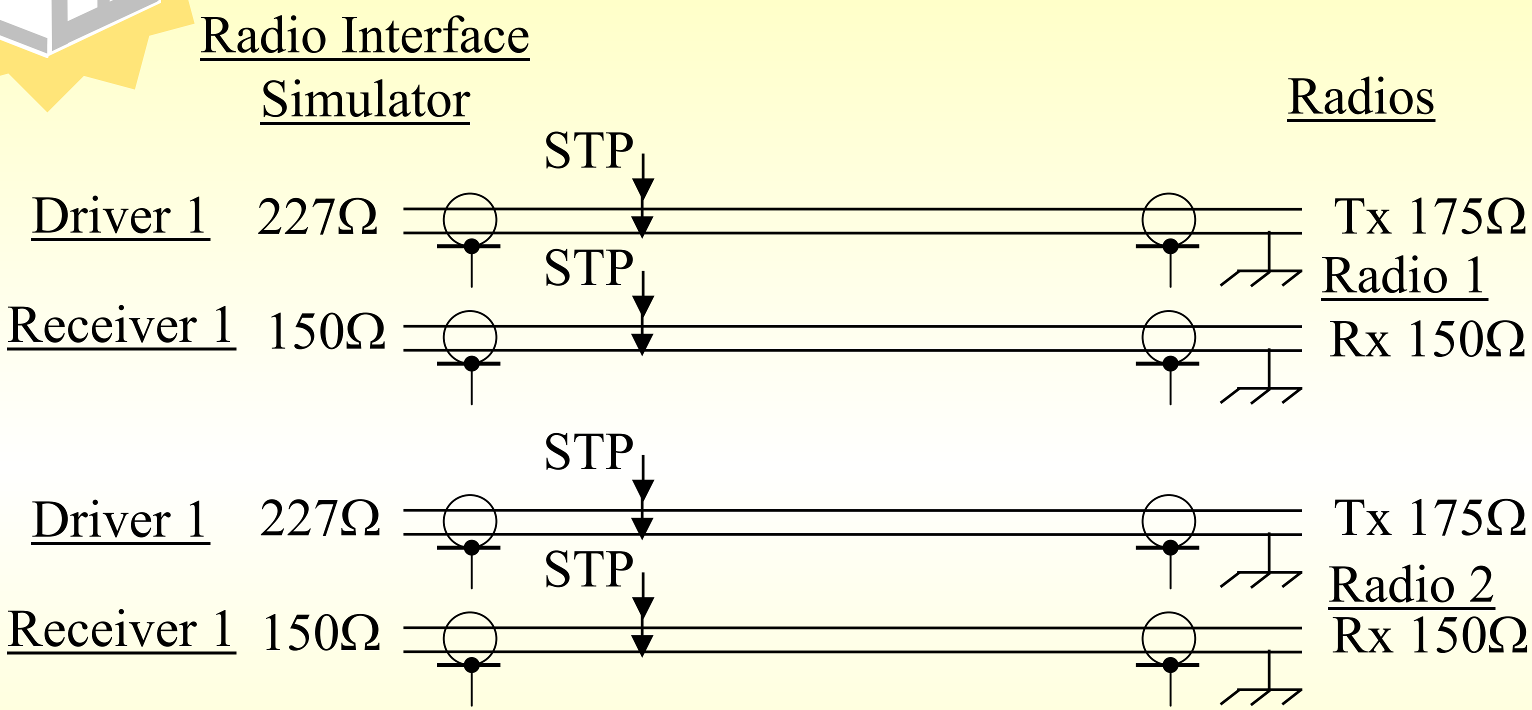
$$V_N=V_F=E_M\omega C_{Sh\text{-}W}R_P=I_S\omega L_{S\text{-}Sh}\omega C_{Sh\text{-}W}R_P$$

Example: $V_N=V_F=$
$0.012*2\pi10^5*2.833*10^{-6}2\pi*10^5 1111*10^{-12}*200=3.106*10^{-3}$V

The entire shield is raised to the potential: E_M.
Much poorer than when grounding shield at signal reference, and 6 dB poorer than grounding at both ends

Sample Test Results, STP to STP Crosstalk

Test Setup for Crosstalk Among Shielded Twisted Pairs



Radio Interface Simulator

Radios

STP

Driver 1 227Ω

Tx 175Ω

Radio 1

STP

Receiver 1 150Ω

Rx 150Ω

STP

Driver 1 227Ω

Tx 175Ω

Radio 2

STP

Receiver 1 150Ω

Rx 150Ω

4 pairs, 100 ft #22 AWG STP. Bundle coiled in 18 inch diameter loop.

Measured Crosstalk, Transmitter-Receiver Pairs

Radio 1 Driver to Radio 2 Receiver, Isolation (dB)

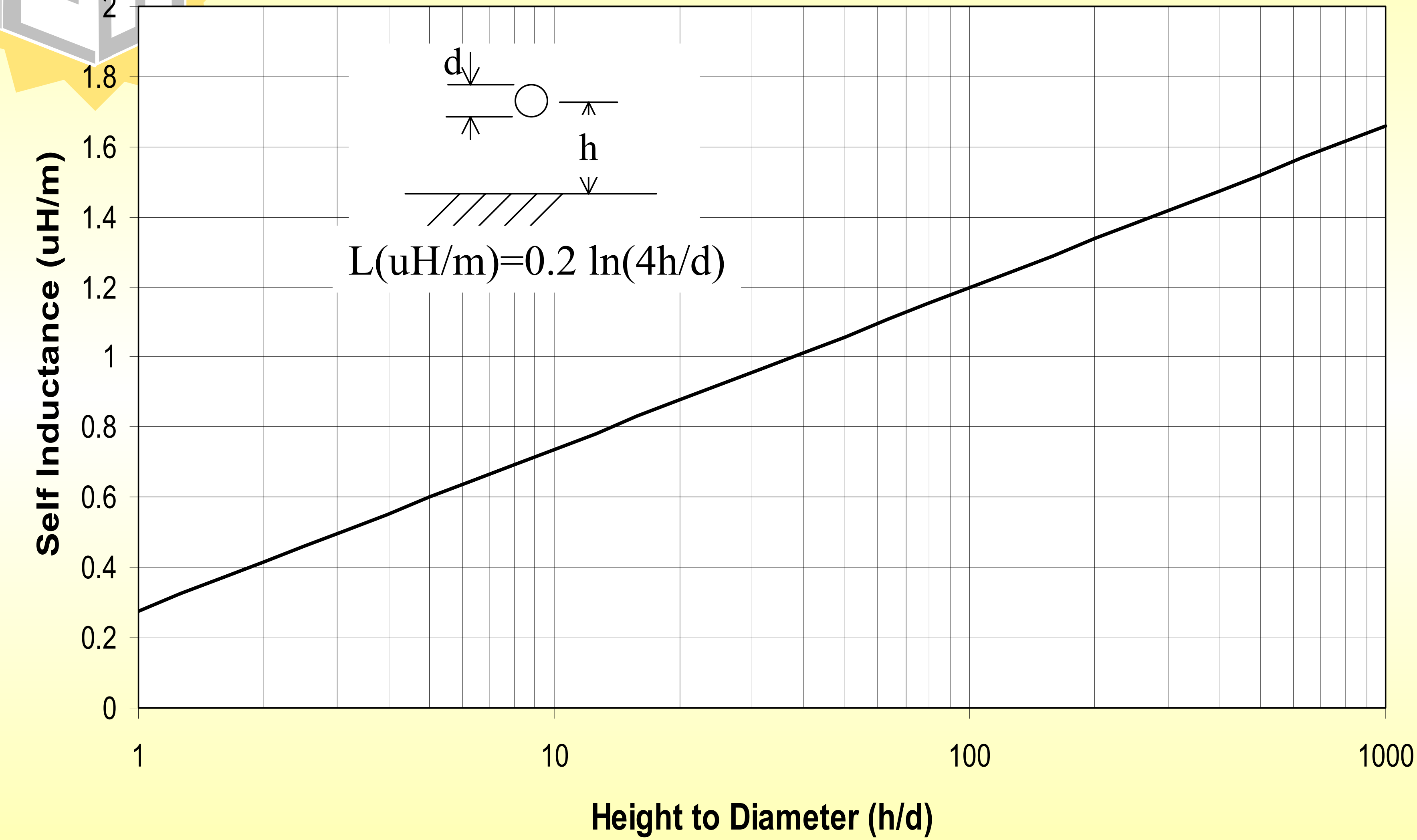
Frequency (Hz)	Shield Ground at Radio (S4)	Shield Ground at Driver and Radio (S5)	Shield Ground at Driver (S6)
100	>117.9	>117.9	115.5
1 k	117.6	117.6	115.4
10 k	107.9	107.9	79.6
30 k	99.3	99.3	48.2
100 k	91.6	91.9	6.6

Radio 1 Receiver to Radio 2 Transmitter, Isolation (dB)

Frequency (Hz)	Shield Ground at Radio (S4)	Shield Ground at Driver and Radio (S5)	Shield Ground at Driver (S6)
100	>117.3	>117.3	117.3
1 k	117.1	117.3	116.3
10 k	111.3	111.1	80.1
30 k	104.2	102.7	48.9
100 k	105.5	94.6	6.4

Parameters Of Open Wires Over A Ground Plane

Self Inductance of Conductor Over a Ground Plane



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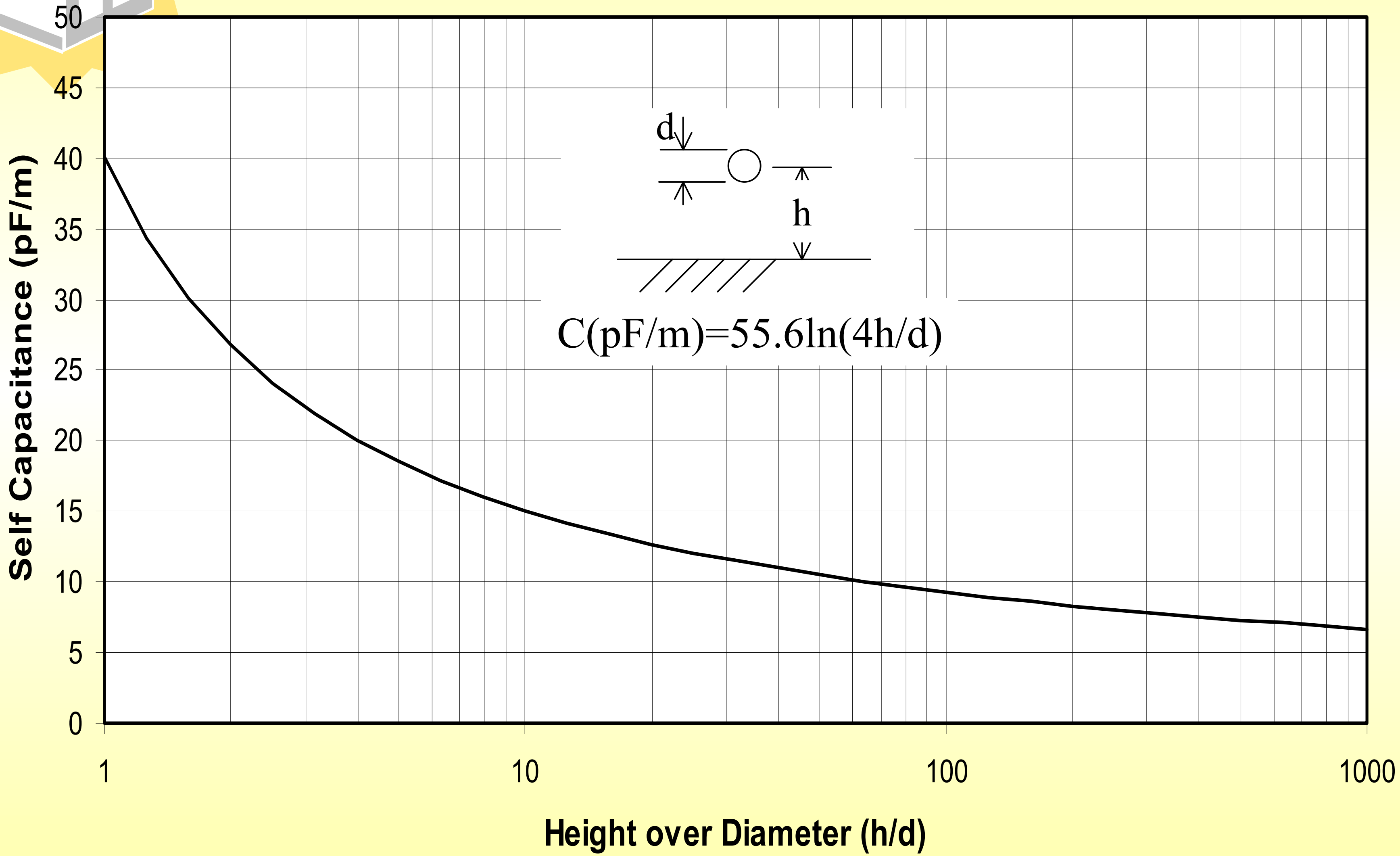
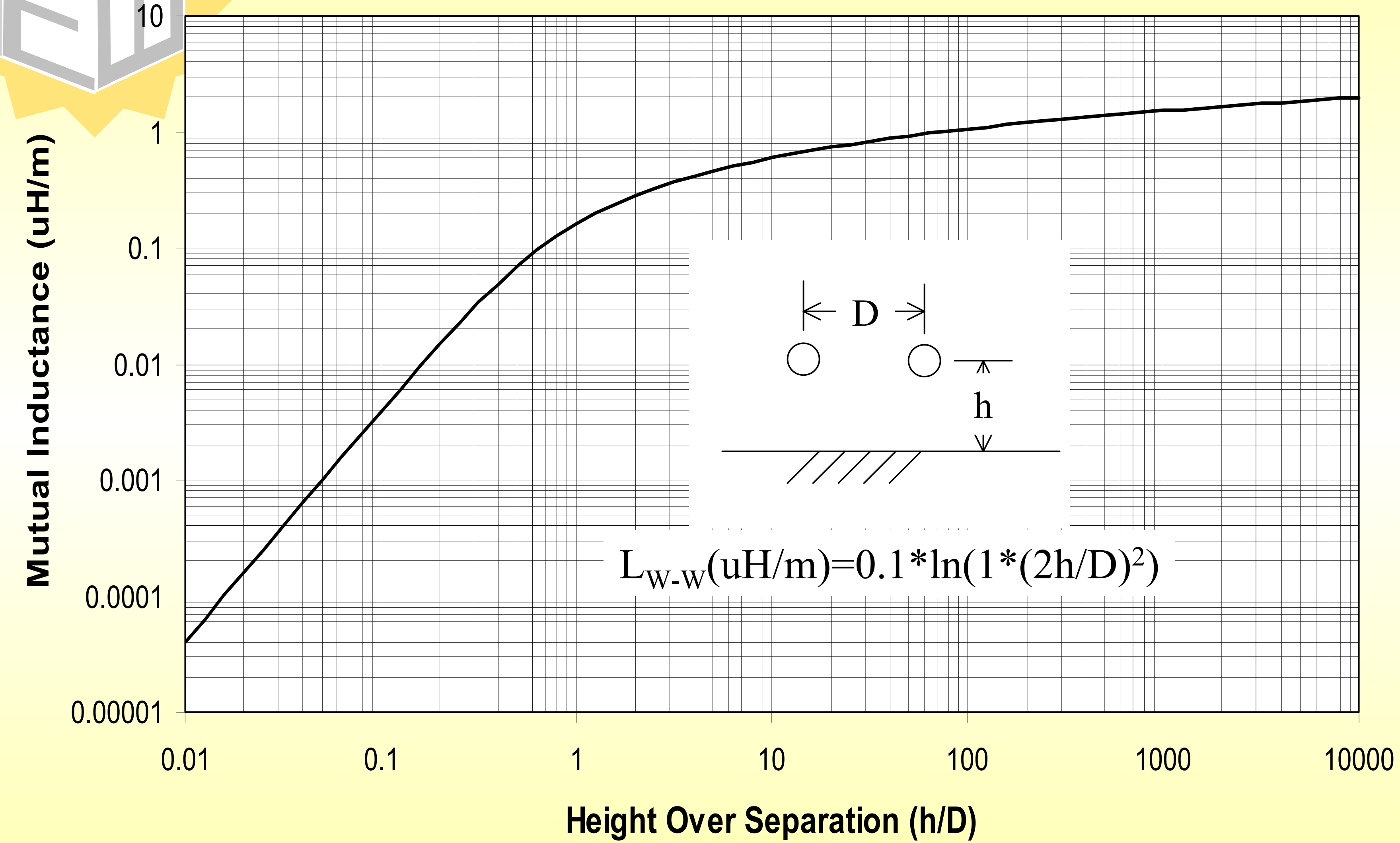
Self Capacitance of Conductor Over a Ground Plane

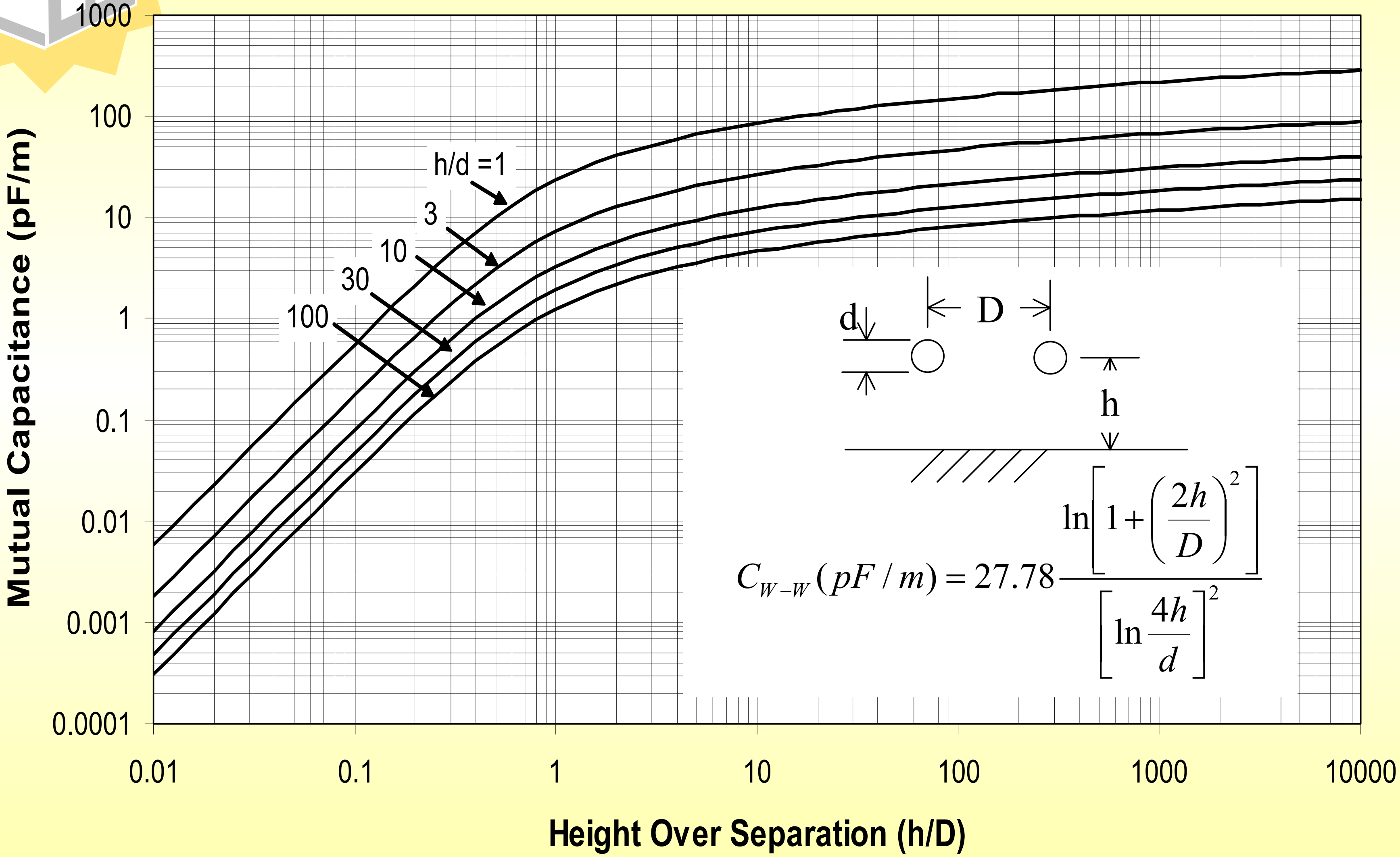


Mutual Inductance Between Conductors Over a Ground Plane



$L_{W-W}(uH/m)=0.1*\ln(1*(2h/D)^2)$

Mutual Capacitance Between Conductors Over a Ground Plane



$$C_{W-W}(pF/m) = 27.78\frac{\ln\left[1+\left(\frac{2h}{D}\right)^2\right]}{\left[\ln\frac{4h}{d}\right]^2}$$

Significant Conclusions

- General
  - Interface control provisions do not affect electric and magnetic coupling components equally
  - Typically, coupling increases as integral powers of frequency and coupled line-lengths
- Electric Coupling
  - Independent of position of signal ground reference point
  - Shielding always provides good suppression of electric-coupled interference
  - Shielding effectiveness is independent of position of single-point ground for shield - multipoint grounding of shield is best
  - Low R_P in victim is typically best
- Magnetic Coupling
  - Independent of position of signal ground reference point
  - Dedicated return with single-point ground is very important
  - Strongly dependent on position of ground point for shield; shield grounding at position of signal ground reference is best
  - Common-mode choke is effective in most configurations
  - High impedance driver (current drive) in victim is best

Crosstalk Bibliography

Over the years, much has been written on this important topic, and a reasonably comprehensive list would easily double the size of this package. A good starting point for researching the topic would be a review of the IEEE Transactions on Electromagnetic Compatibility, and the Records of IEEE EMC Symposiums. Following is a brief list of references I have found useful and that have formed the basis for this presentation.

1. "Crosstalk between Coaxial Transmission Lines" by S. A. Schelkunoff and T. M. Odarenko, Bell Systems Technical Journal, Vol. 26, April, 1937, pp144-164. A classic to be consulted when considering crosstalk in lines comparable to, or exceeding, a wavelength.
2. Paul, Clayton R.: "Introduction to Electromagnetic Compatibility," John Wiley & Sons, Inc., New York, 1992. A full chapter is devoted to the subject and includes a comprehensive treatment of the factors in multiconductor configurations, including coupling parameters, shielding, and grounding considerations.
3. "Crosstalk (Noise) in Digital Systems", Ivor Catt, IEEE Trans. Electronic Computers, Vol. EC-16, No. 6, December 1967, pp.743-763. Good coverage of digital crosstalk where delay time is comparable or greater than transition times of the source signals.
4. The following three (3) references show t he derivations, and experimental backup, for the expressions used here
    1. a. "Coupling between Open Wires over a Ground Plane," R. J. Mohr, 1968 IEEE Symposium on EMC
    2. b. "Coupling between Open and Shielded Wire Lines over a Ground Plane," R. J. Mohr, IEEE Trans. Electromagnetic Compatibility, Vol. EMC-9, September 1967, pp34-45
    3. c. "Coupling between Lines at High Frequencies," R. J. Mohr, IEEE Trans. On EMC, Vol. EMC-9, No.3, December 1967 pp. 127-219

"Mohr on Minimizing Crosstalk in Wiring and Cabling"

SPEAKER BIOGRAPHY

Richard J. Mohr, PE

Richard Mohr has over 30 years in his specialization in Electromagnetic Compatibility (EMC). In 1984 he formed R. J. Mohr Associates, Inc. and currently is its President and Chief Consultant. The company provides design support to client companies in EMC and in related areas. He has published widely on design, prediction, and test techniques in EMC disciplines. His original papers on cross-coupling between shielded and unshielded wiring in the mid 60's has provided the basis for follow-on efforts by others for the decades since. He has conducted a series of well-received technical training seminars in the EMC discipline.

He is a Professional Engineer registered in NY State, and a NARTE-Certified EMC Engineer. The EMC Society presented him with the Richard R. Stoddart award for his contributions to EMC modeling. In 1996, he was elected to the grade of Fellow of the IEEE, and cited by the Board of Directors of the IEEE "For the advancement of practical models for application in the electromagnetic compatibility design of electronic equipment". In 2004 the EMC Society of the IEEE elevated him to the grade of Honorary Life Member.