



INSTITUTO FEDERAL
SANTA CATARINA



CEM: Estratégias de Controle e Mitigação de EMI

ELM20704 – 2014/1

Professor: Bruno Fontana da Silva





Revisão sobre dB, reflexão/refração de onda, espectro eletromagnético

ASPECTOS BÁSICOS NO ESTUDO DE CEM

“When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers your knowledge is of meagre and unsatisfactory kind; it may be the beginning of knowledge but you have scarcely progressed in your thoughts to the stage of science whatever the matter may be.”



Grandezas em decibéis



Unidades das quantidades primárias de interesse do EMC:

Tensão (**V**olts)

Campo Elétrico (**V/m**)

Corrente (**A**mpères)

Campo Magnético (**A/m**)

Potência (**W**atts)

Densidade de Potência (**W/m²**)

Grandezas em decibéis



Representação de uma larga faixa dinâmica de magnitudes

ex.: $1 \mu\text{V}/\text{m}$ a $200 \text{V}/\text{m}$ – diferença de ordem de 10^8

Em dB: $0 \text{dB}\mu\text{V}/\text{m}$ a $166.02 \text{dB}\mu\text{V}/\text{m}$

Grandezas em decibéis



Decibel de sinais de tensão/corrente:

Transformação logarítmica da razão entre um valor absoluto e um valor de referência.

$$\text{dB}\mu\text{V} \equiv 20 \log_{10} \left(\frac{\text{volts}}{1 \mu\text{V}} \right)$$

$$\text{dBmV} \equiv 20 \log_{10} \left(\frac{\text{volts}}{1 \text{mV}} \right)$$

$$\text{dB}\mu\text{A} \equiv 20 \log_{10} \left(\frac{\text{amperes}}{1 \mu\text{A}} \right)$$

$$\text{dBmA} \equiv 20 \log_{10} \left(\frac{\text{amperes}}{1 \text{mA}} \right)$$

Grandezas em decibéis



Decibel de sinais de potência:

$$\text{dB} = \text{dBW} \equiv 10 \log_{10} \left(\frac{\text{watts}}{1 \text{ W}} \right)$$

$$\text{dB}\mu\text{W} \equiv 10 \log_{10} \left(\frac{\text{watts}}{1 \mu\text{W}} \right)$$

$$\text{dBm} \equiv \text{dBmW}$$

$$\equiv 10 \log_{10} \left(\frac{\text{watts}}{1 \text{ mW}} \right)$$

Grandezas em decibéis



Decibel de sinais de campo elétrico/magnético:

$$\text{dB}\mu\text{V}/\text{m} \equiv 20 \log_{10} \left(\frac{\text{V}/\text{m}}{1 \mu\text{V}/\text{m}} \right)$$

$$\text{dB}\mu\text{A}/\text{m} \equiv 20 \log_{10} \left(\frac{\text{A}/\text{m}}{1 \mu\text{A}/\text{m}} \right)$$

Espectro em Frequência



Ferramentas matemáticas:

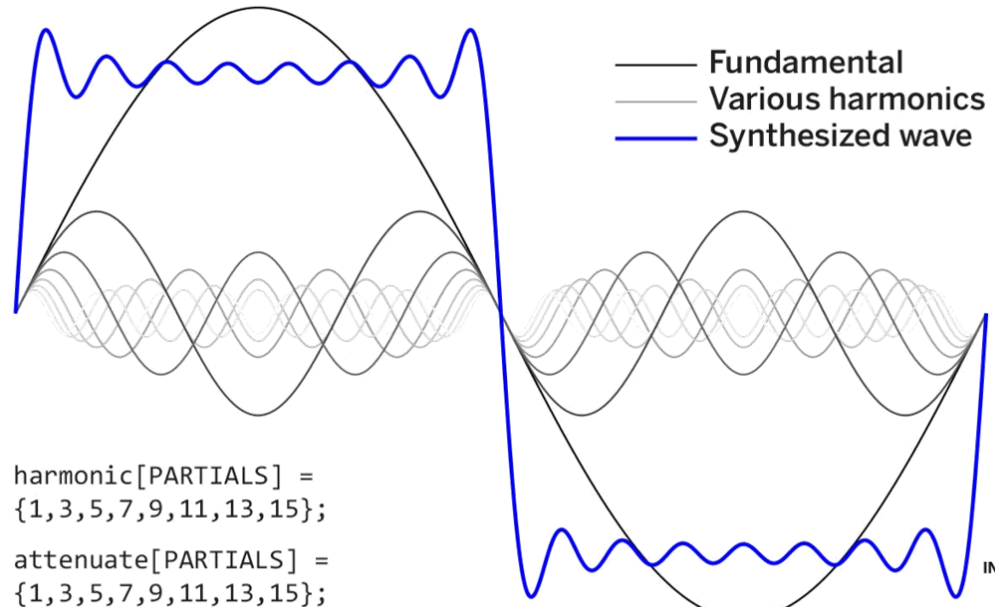
- Série de Fourier
- Transformada de Fourier (**FT**)
- Transformada de Fourier de Tempo Discreto (**DTFT**)
- Transformada Fourier Discreta (**DFT**)
- Algoritmo: transformada rápida de fourier (**FFT**)

Espectro em Frequência



Sinais digitais possuem conteúdo harmônico significativo.

▪ Série de Fourier

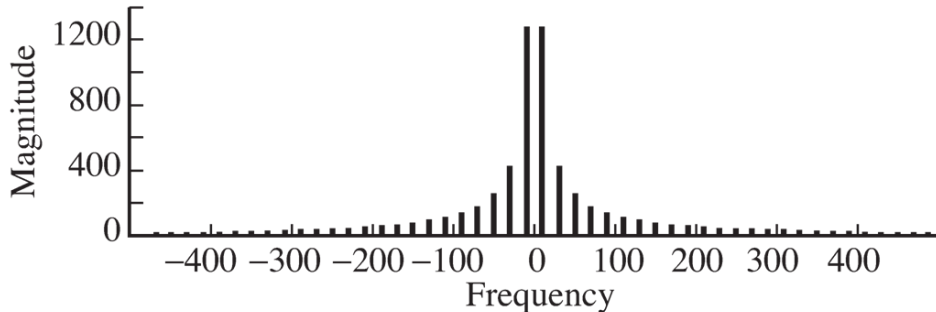
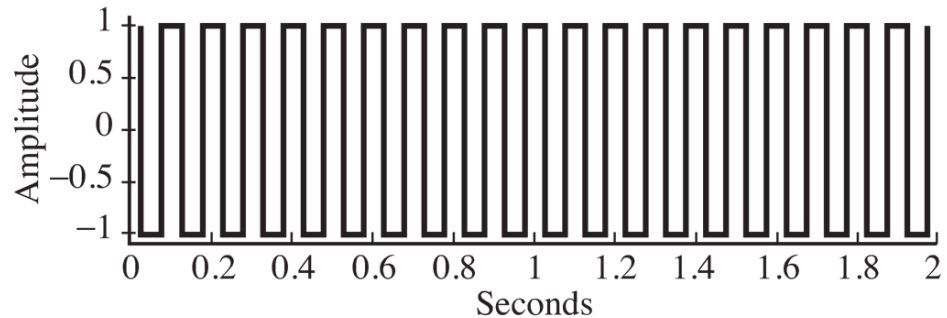


Espectro em Frequência



Sinais digitais possuem conteúdo harmônico significativo.

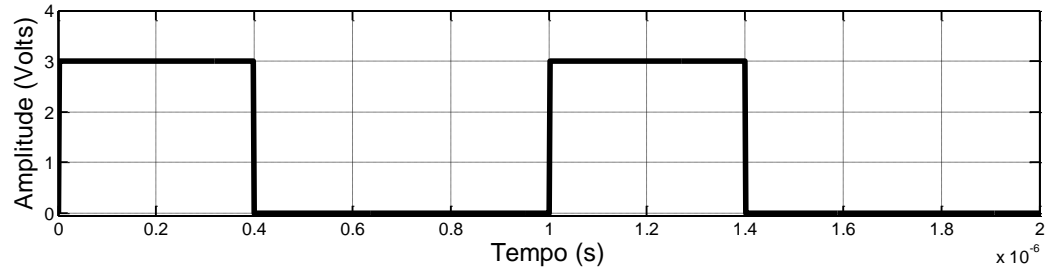
- Transformada de Fourier



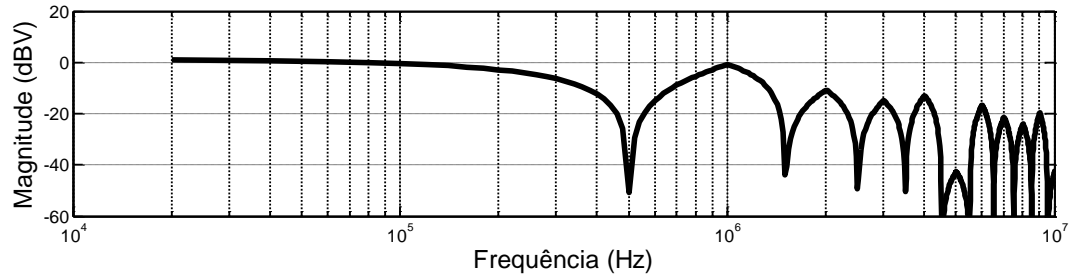
Espectro em Frequência



Sinais digitais possuem conteúdo harmônico significativo.



▪ DTFT

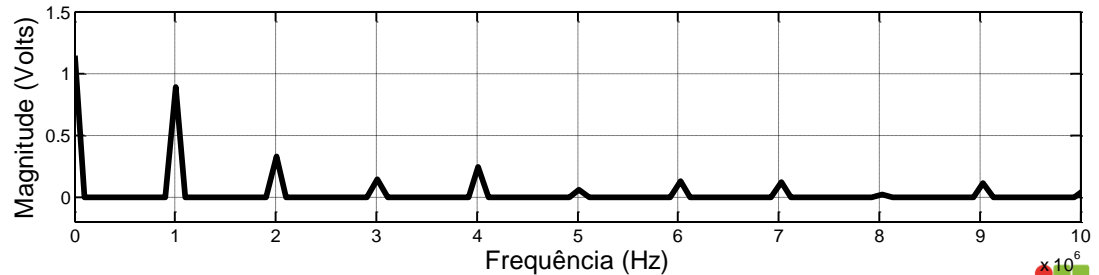
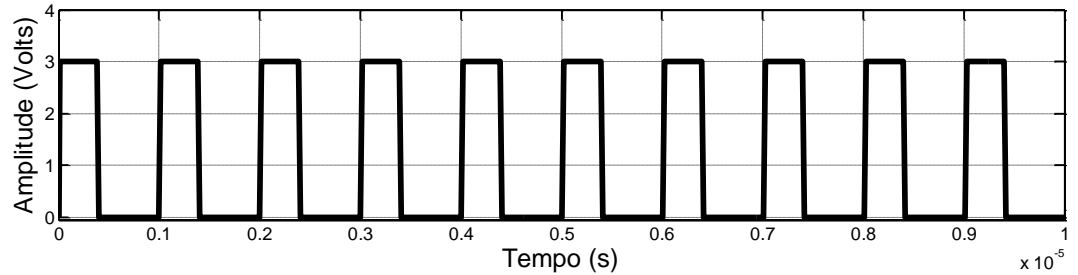


Espectro em Frequência



Sinais digitais possuem conteúdo harmônico significativo.

▪ DFT/FFT



Espectro em Frequência

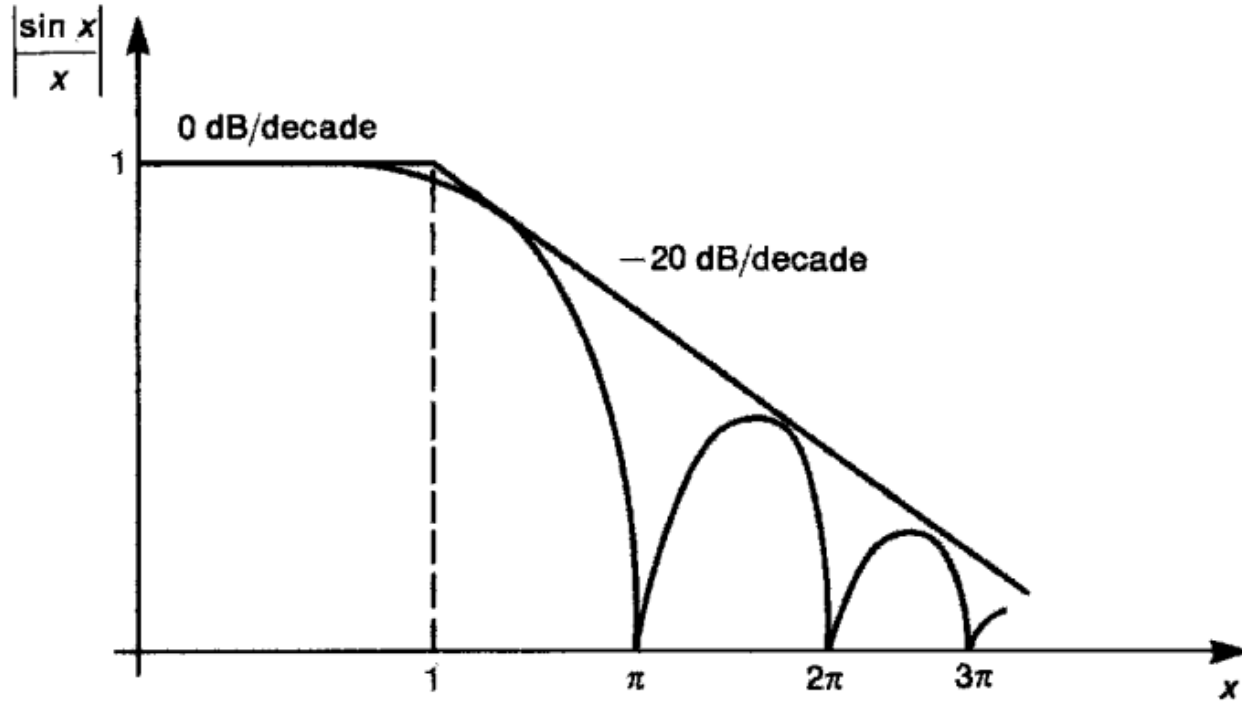
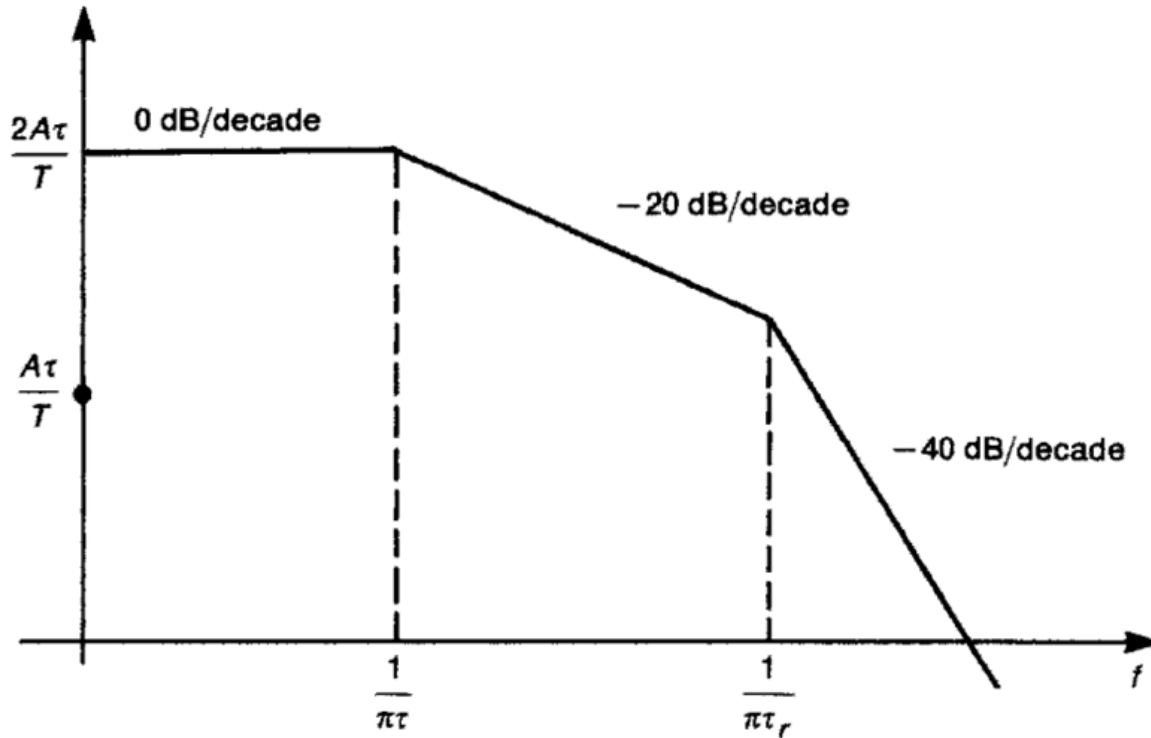


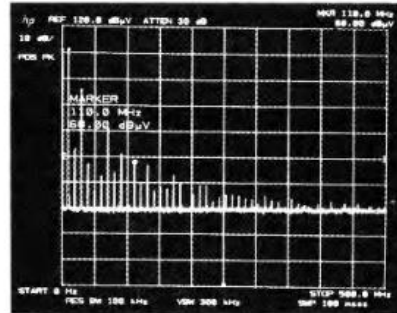
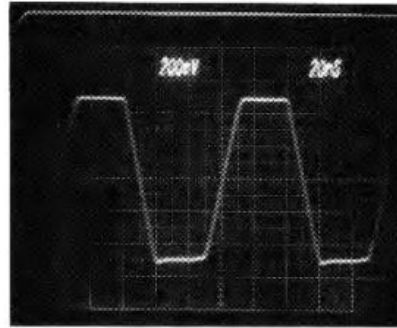
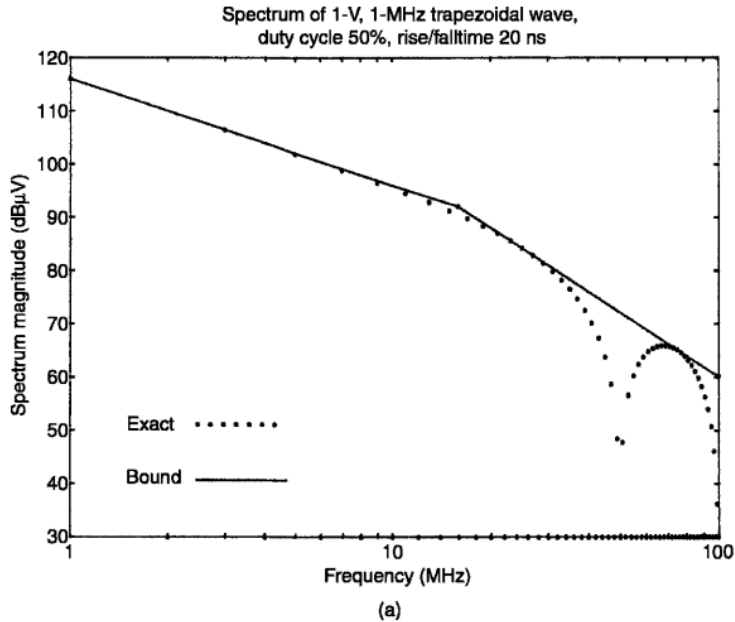
FIGURE 3.18 Bounds on the $(\sin x)/x$ function.

Espectro em Frequência



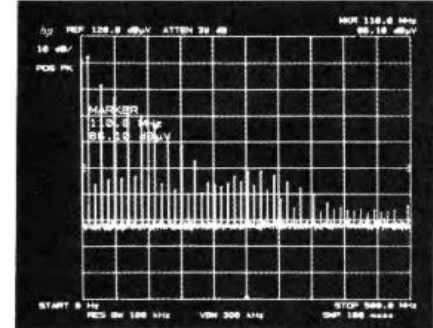
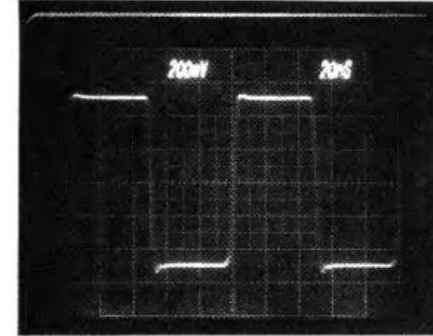
(PAUL, 2006) **FIGURE 3.19** Bounds on the one-sided magnitude spectrum of a trapezoidal pulse train.

Espectro em Frequência



rise/falltime = 20 ns

(a)



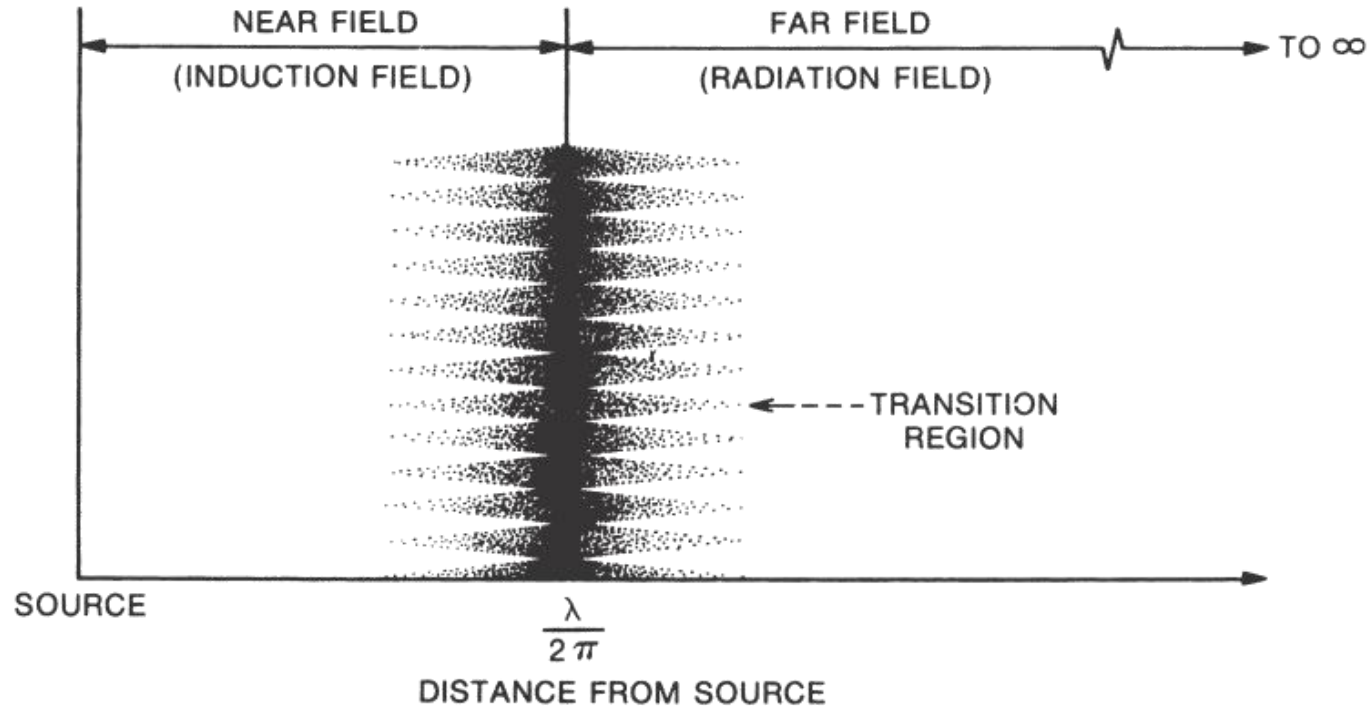
rise/falltime = 5 ns

(b)

FIGURE 3.21 Experimentally measured spectra of a 1-V, 10-MHz, 50%-duty-cycle trapezoidal pulse train for rise/falltimes of (a) 20 ns; (b) 5 ns.



Campos próximo e distante (da fonte)



(OTT, 2009)

Considerações de campo próximo (NF)

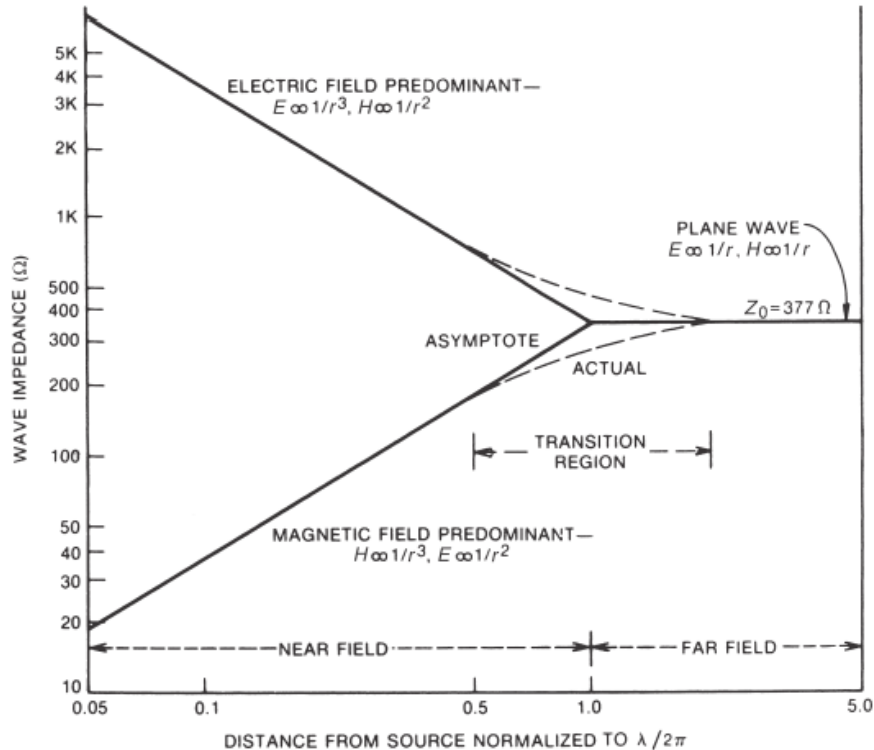


FIGURE 6-4. Wave impedance depends on the distance from the source.

- As **propriedades do campo** são definidas principalmente pelas **características da fonte**.
- Correntes altas, tensões baixas:
NF predominantemente magnético
- Correntes baixas, tensões altas:
NF predominantemente elétrico.

Considerações de campo distante (FF)

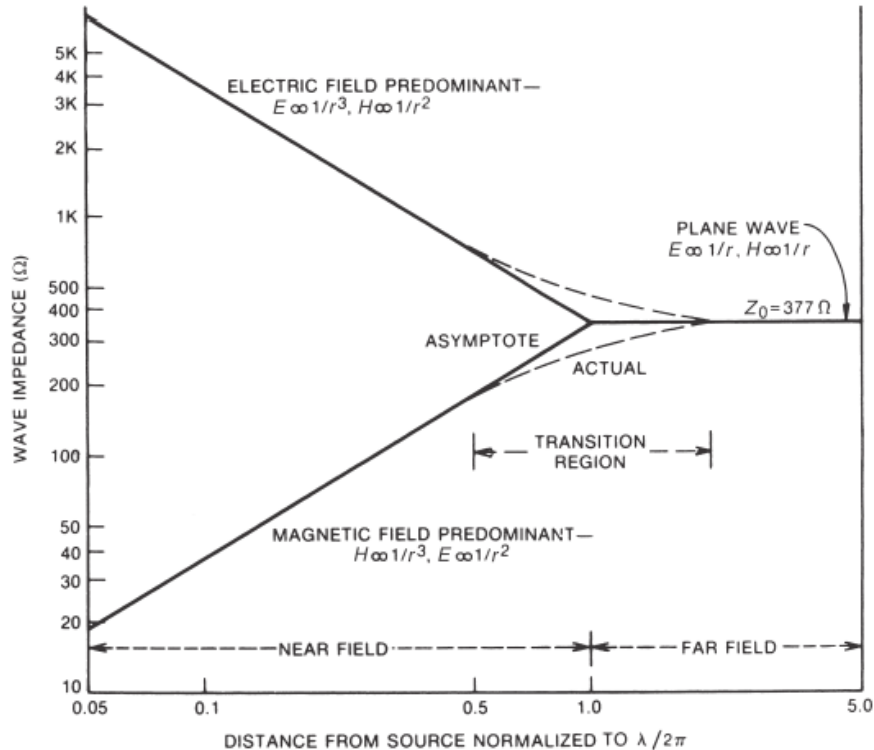
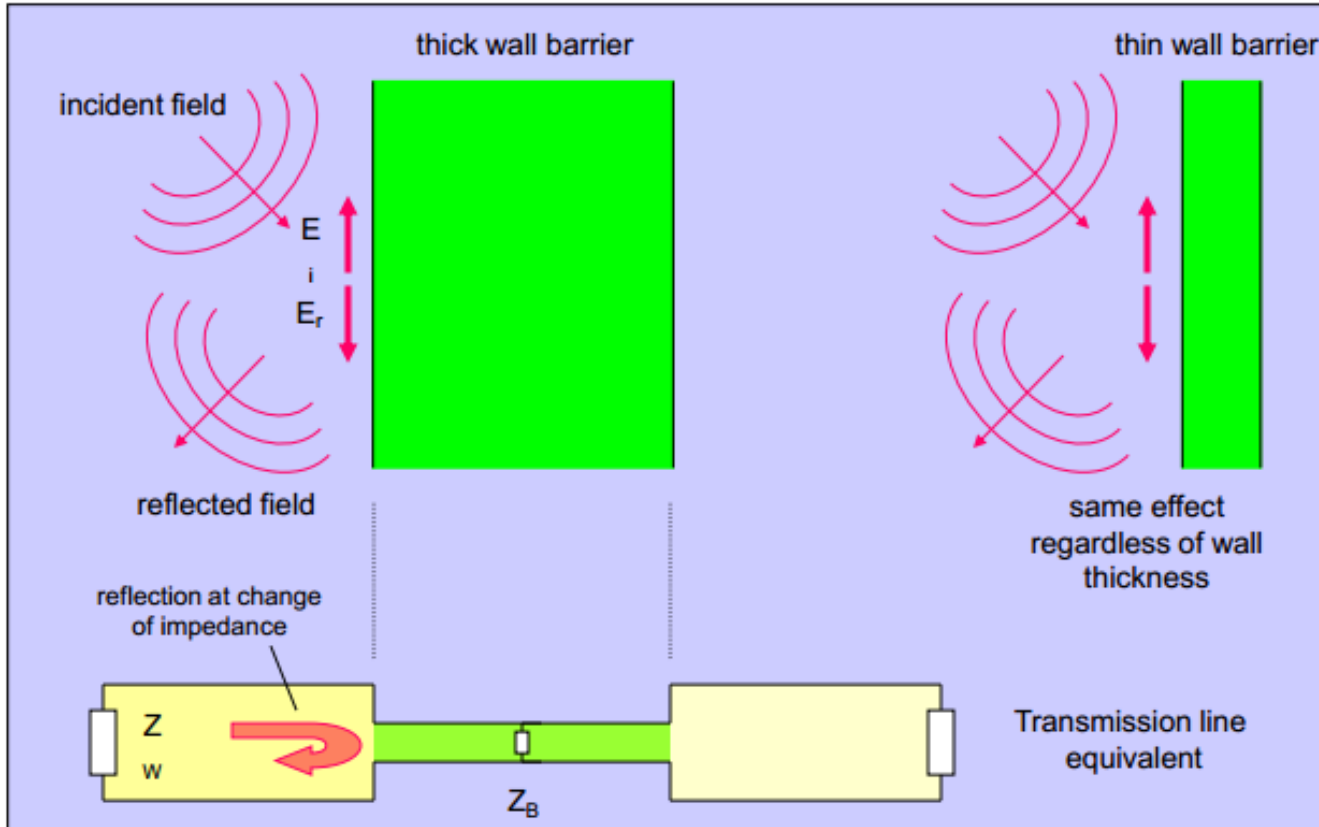


FIGURE 6-4. Wave impedance depends on the distance from the source.

- As propriedades do campo são definidas principalmente pelas características do meio de propagação.
- Onda planar uniforme: impedância da onda

$$\eta_w = \frac{\mathbf{E}_s}{\mathbf{H}_s} = \sqrt{\frac{\mu}{\epsilon}} \quad (\Omega)$$

Reflexão de Ondas



(LAWSON)

Reflexão de Ondas

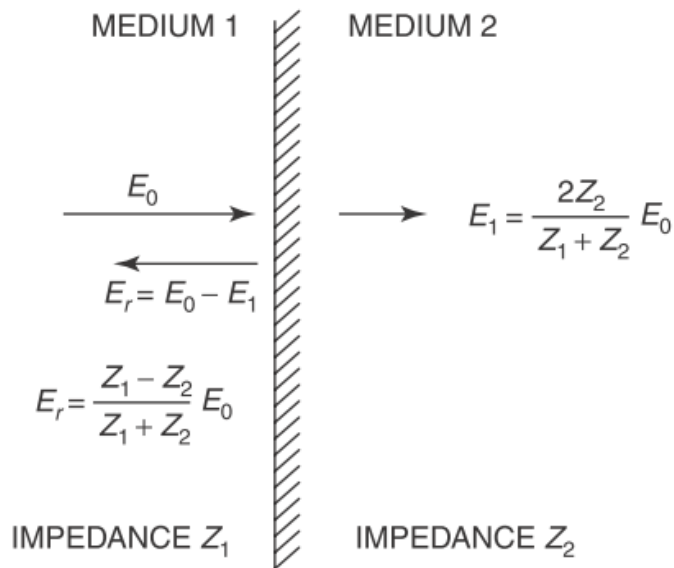


FIGURE 6-10. An incident wave is partially reflected from, and partially transmitted through, an interface between two media. The transmitted wave is E_t and the reflected wave is E_r .

Reflexão de Ondas

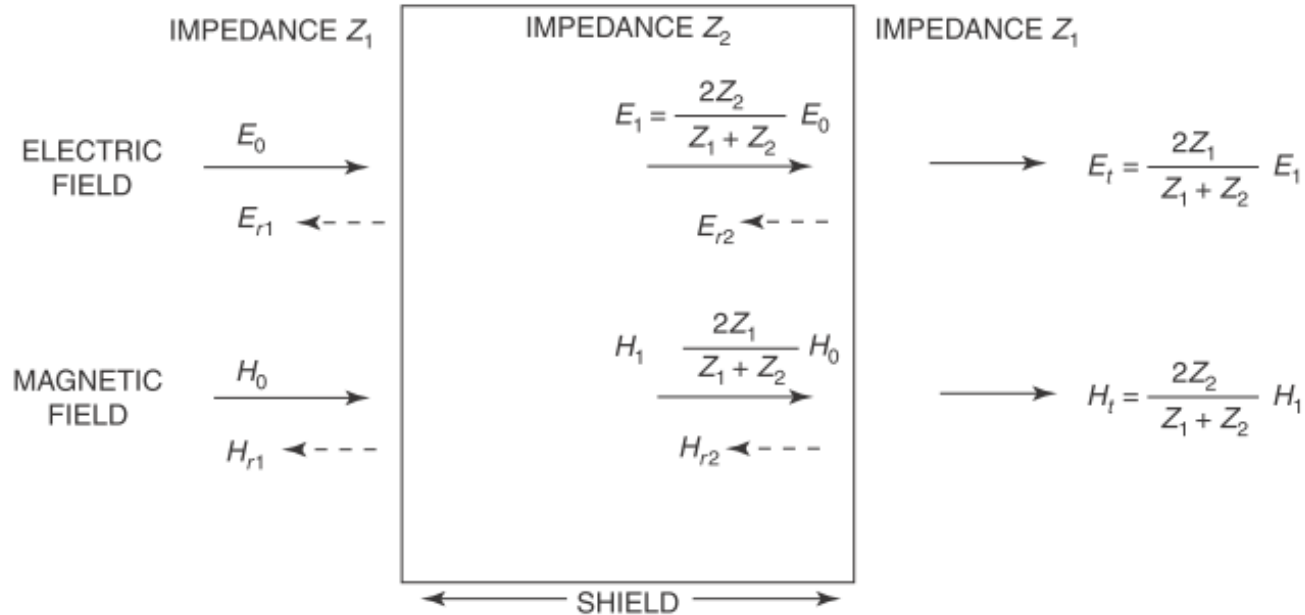
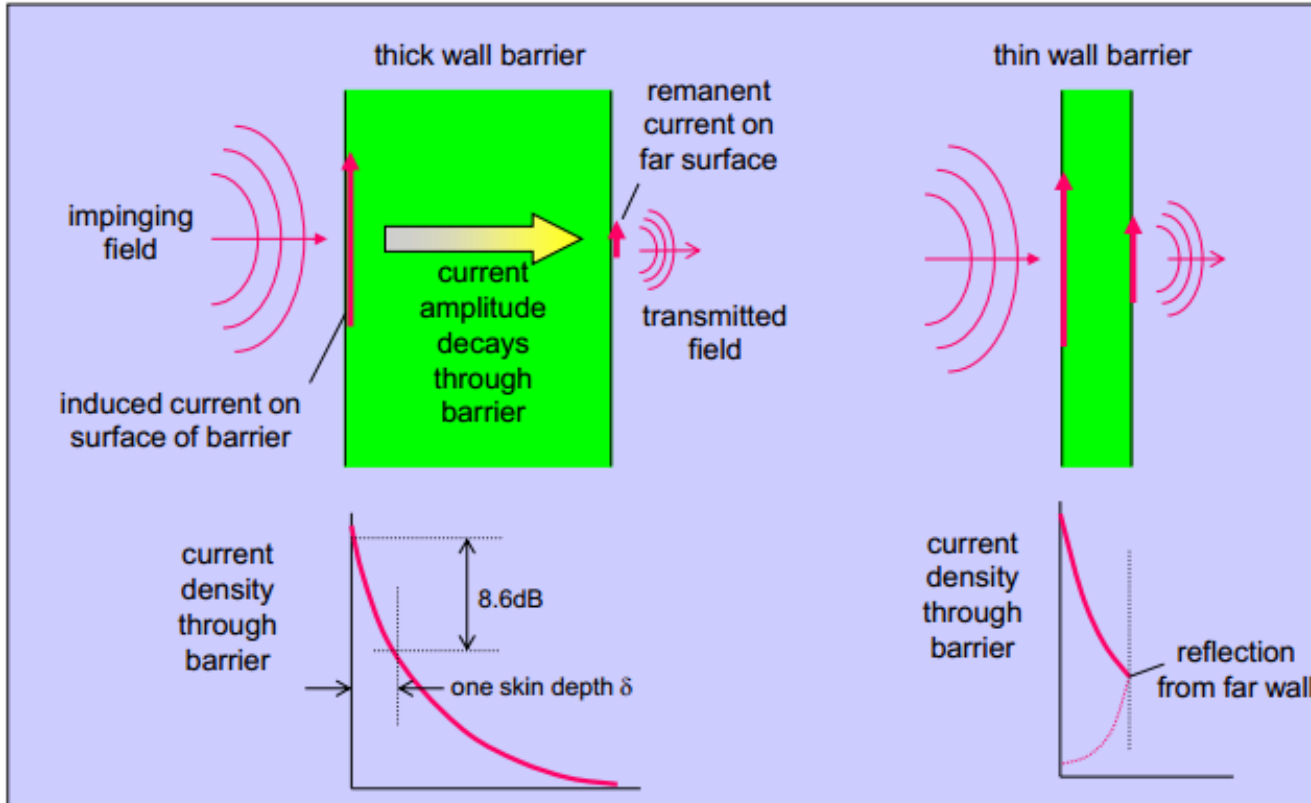


FIGURE 6-11. Partial reflection and transmission occur at both boundaries of a shield.

Refração e absorção de ondas



(LAWSON)



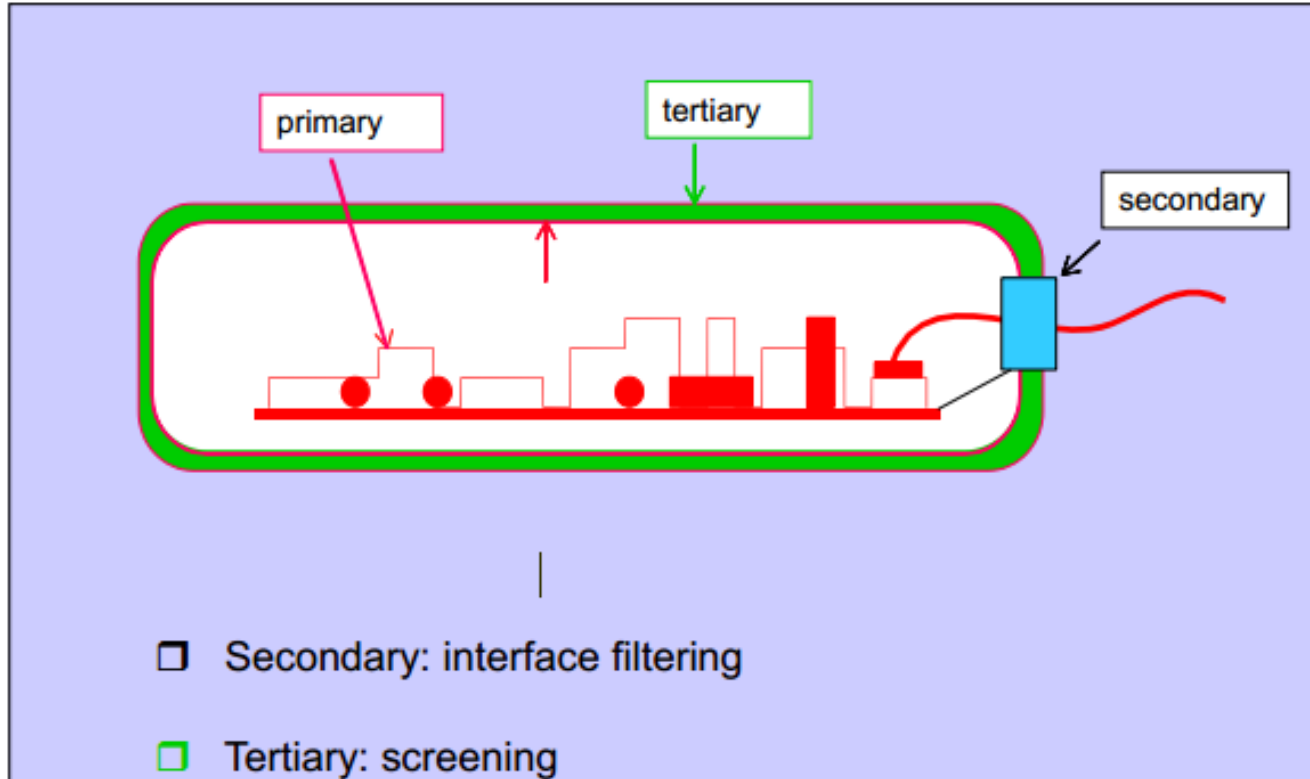
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Métodos preventivos e corretivos

TÉCNICAS DE CONTROLE DE EMI

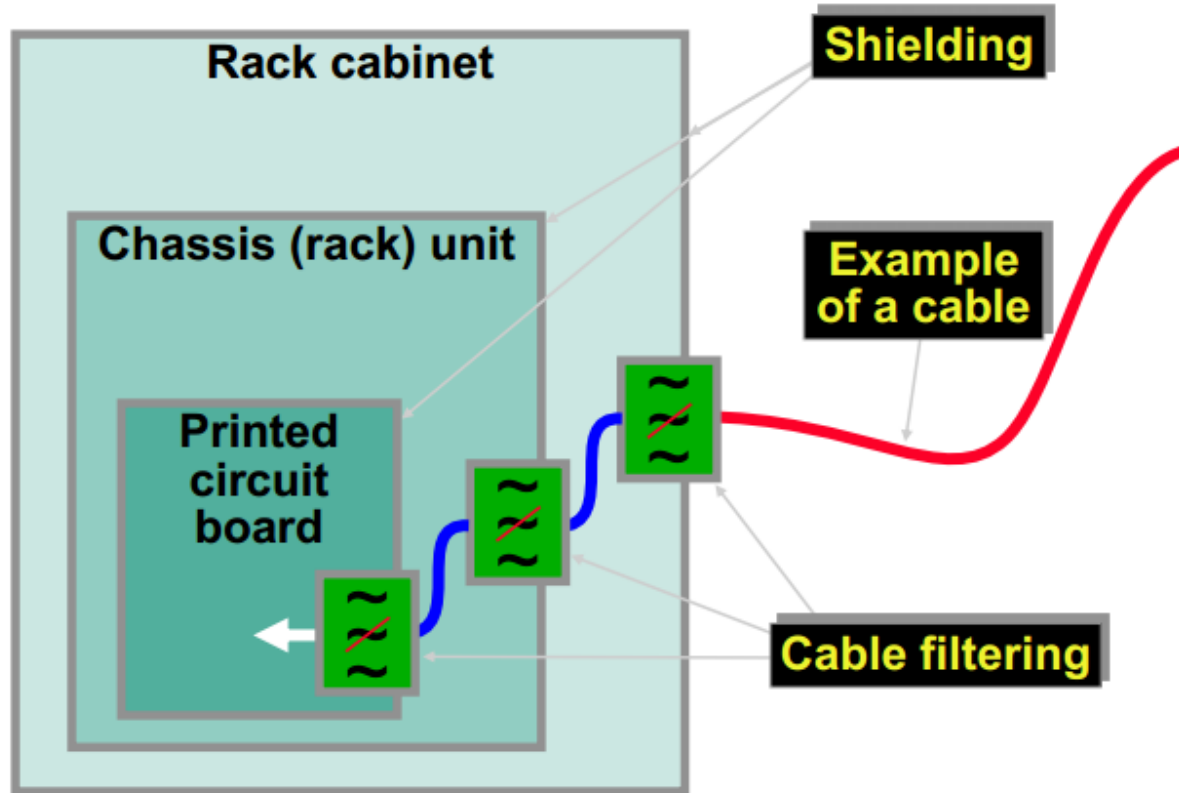


Mitigação de EMI

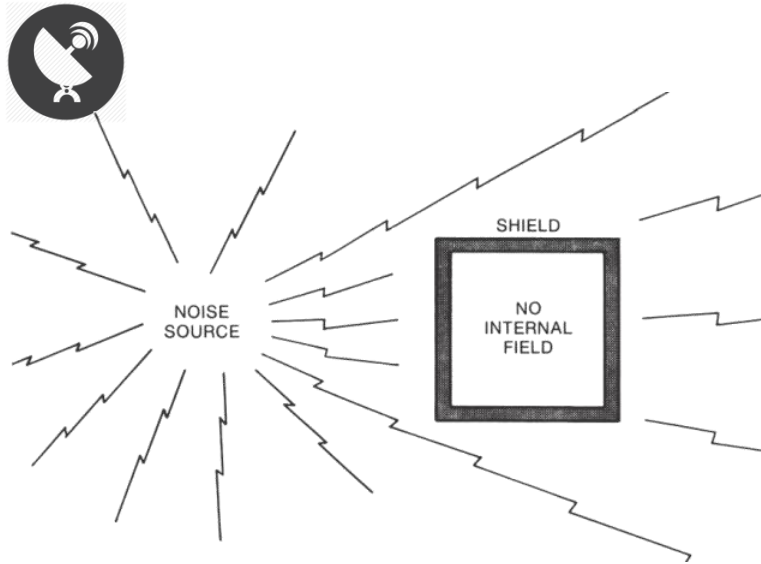


(LAWSON)

Mitigação de EMI

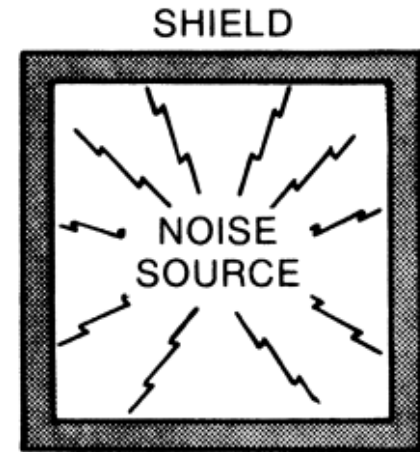


Blindagem (*Shielding*)



Caso 1: Imunidade ao ambiente

NO EXTERNAL
FIELD

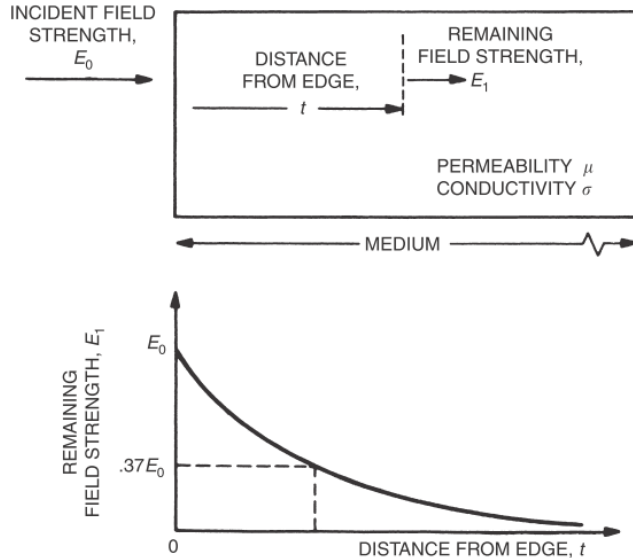


Caso 2: Contenção de interferência

Blindagem Efetiva



Blindagem efetiva (SE) é a medida da qualidade de atenuação do campo eletromagnético.



$$SE_{dB} = 20 \log_{10} \left(\frac{E_0}{E_1} \right)$$

FIGURE 6-6. Electromagnetic wave passing through an absorbing material is attenuated exponentially.

(OTT, 2009)

Blindagem Efetiva



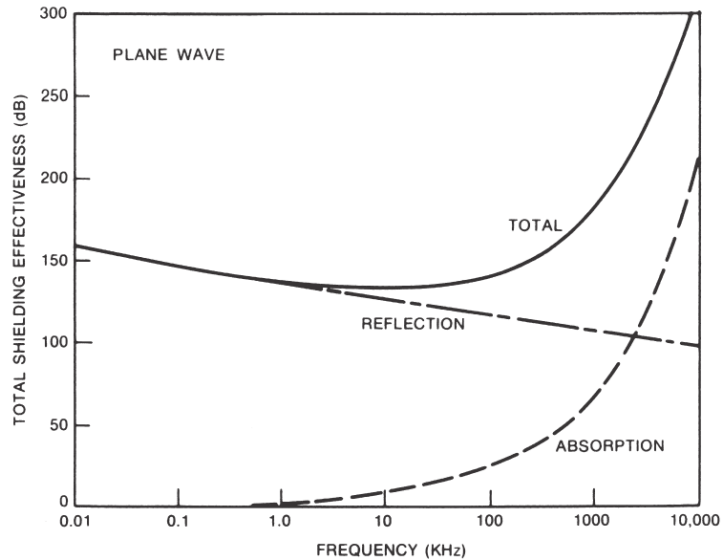
SE teórico de um material homogêneo considera:

- Perdas por reflexão, R
- Perdas por absorção, A
- Perdas por reflexão secundária, B (ignorar se $A > 8$ dB)

$$SE_{dB} = R + A + B$$

Veja exemplos de R, A e B em OTT, 2009 – Cap. 6: Shielding.

Limitações práticas da blindagem efetiva



SE é normalmente limitado por aberturas e junções:

- Coberturas removíveis
- Aberturas para controle/mostra de componentes
- Aberturas para ventilação
- Aberturas para conectores

(COLOTTI, 2003)

FIGURE 6-16. Shielding effectiveness of a 0.02-in thick copper shield in the far field.

Estratégias para melhorar o SE

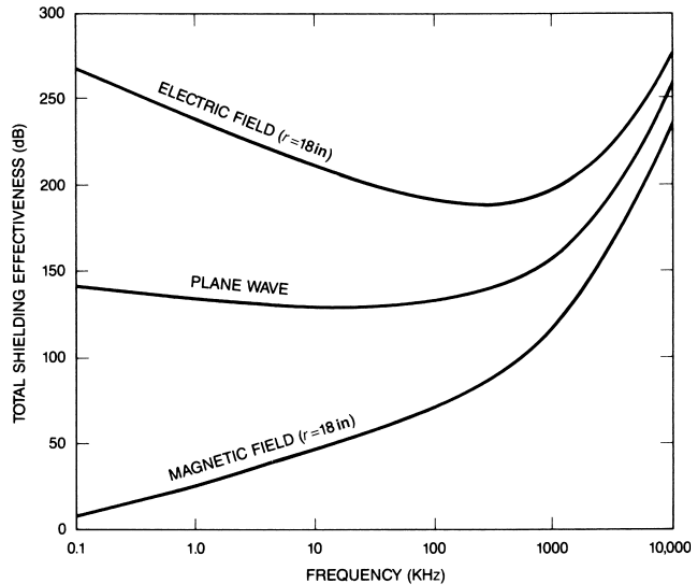


FIGURE 6-18. Electric field, plane wave, and magnetic field shielding effectiveness of a 0.02-in-thick solid aluminum shield.

Mitigação de aberturas e junções:

- Minimizar tamanho e número de aberturas de junções;
- Uso de juntas mecânicas (arruelas) para selar interfaces de metal;
- Interfaces livres de tinta
- Área de superfície adequada
- Evitar corrosão galvânica
- Usar componentes de controle de EMI

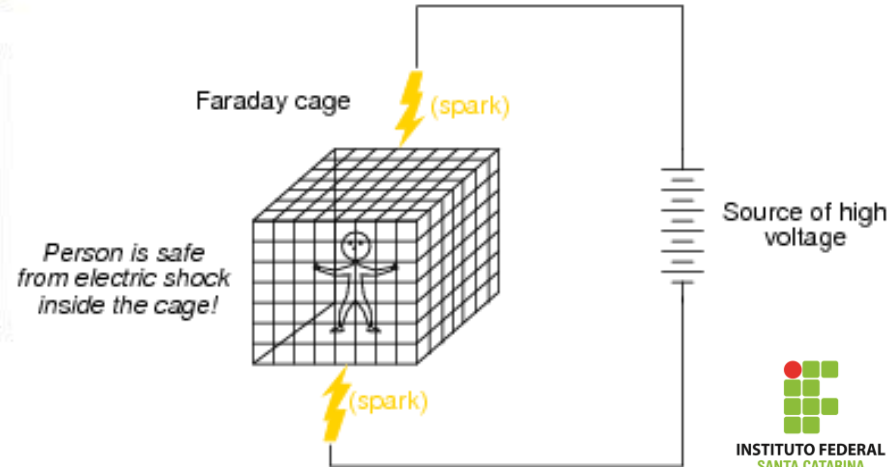
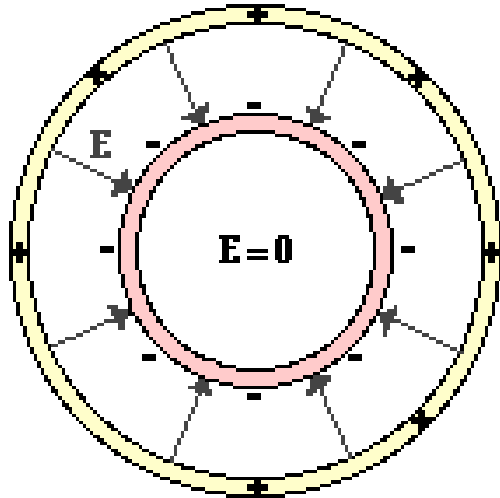
(COLOTTI, 2003)

Gaiola de Faraday



Campo elétrico (e carga total) dentro de uma superfície condutora fechada é **nulo**.

A “gaiola” é imune a passagem dos campos elétricos externos.



Gaiola de Faraday: Exemplos



O forno micro-ondas utiliza a gaiola de Faraday para conter a energia das micro-ondas dentro do forno.

Elevadores e outras salas com *frames* metálicos simulam gaiolas de faraday, causando “*zonas mortas*” para usuários de telefones celular, rádios e qualquer dispositivo que requira campo eletromagnético externo.

Cabos blindados (USB, coaxial).

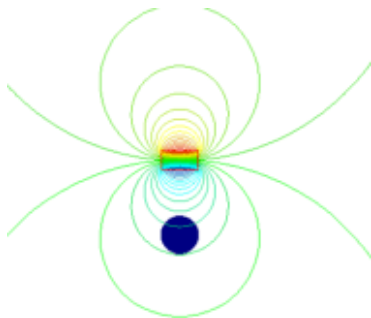
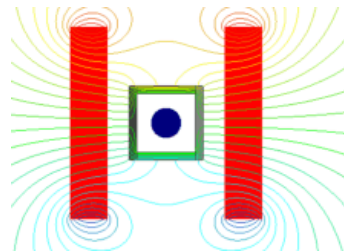
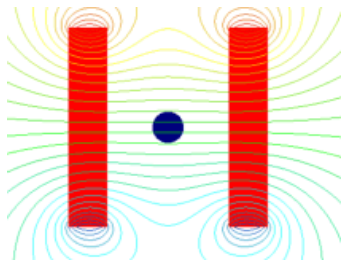
Gaiola de Faraday



“Gaiolas” Magnéticas: Ferrites



Desviam o fluxo magnético externo e concatenam o interno.



“Gaiolas” Magnéticas: Exemplos



Material “ μ -metal” (liga de níquel-ferro)

Ferrites.

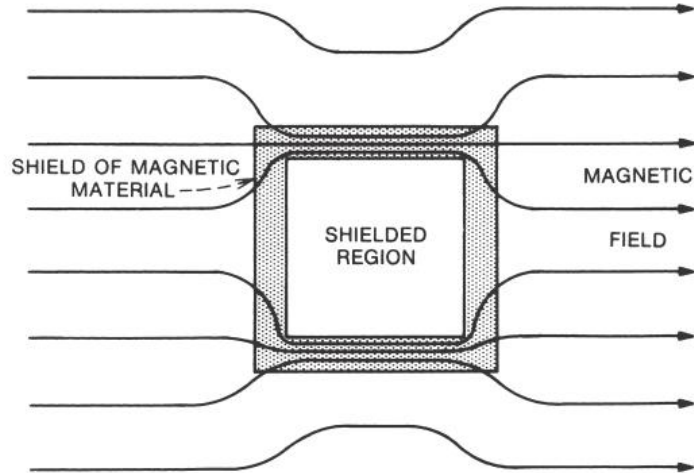
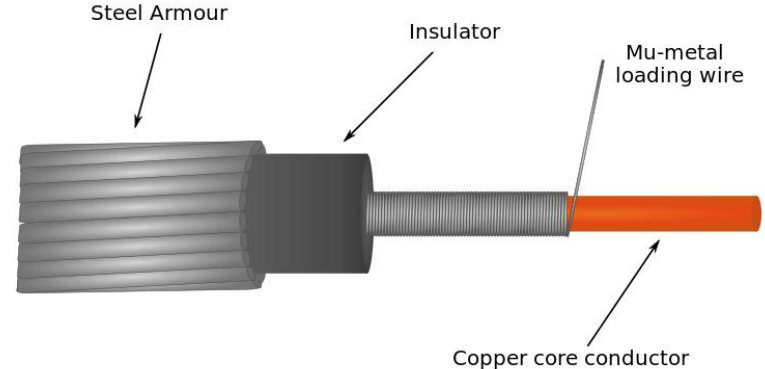


FIGURE 6-17. Magnetic material used as a shield by providing a low-reluctance path for the magnetic field, diverting it around the shielded region.



“Gaiolas” Magnéticas: Ferrites



FerriShield installation locations.



CABLING

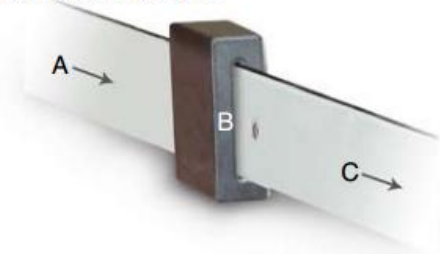
RFI suppressor functions



- A. Data signals and high frequency interference signals absorbed and conducted
- B. All high frequency interference absorbed by ferrite suppressor and thermally dissipated
- C. Low frequency data signals pass unimpeded

BUS BARS

RFI suppressor functions: bus bars



- A. Power distribution and high frequency interference signals absorbed and conducted
- B. All high frequency interference absorbed by ferrite suppressor and thermally dissipated
- C. Power distribution characteristics pass unimpeded



Cabos: acoplamento capacitivo

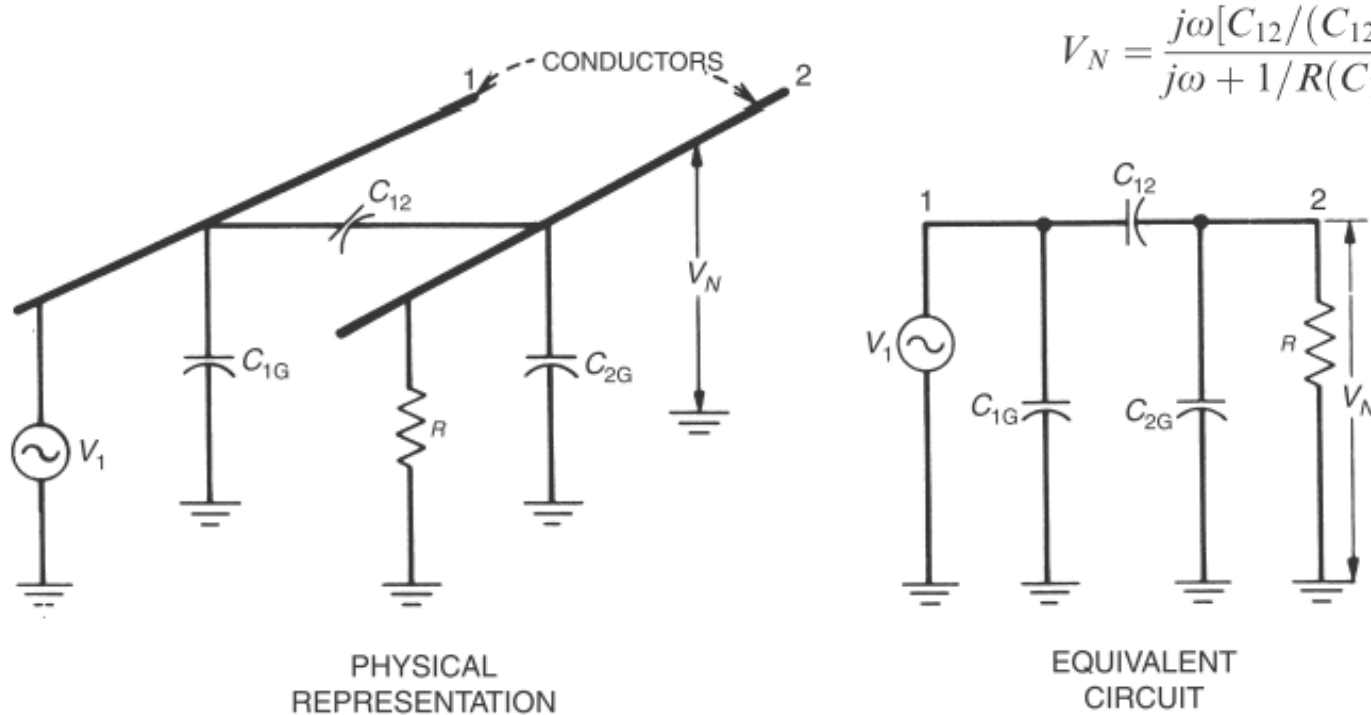


FIGURE 2-1. Capacitive coupling between two conductors.

Cabos: acoplamento capacitivo

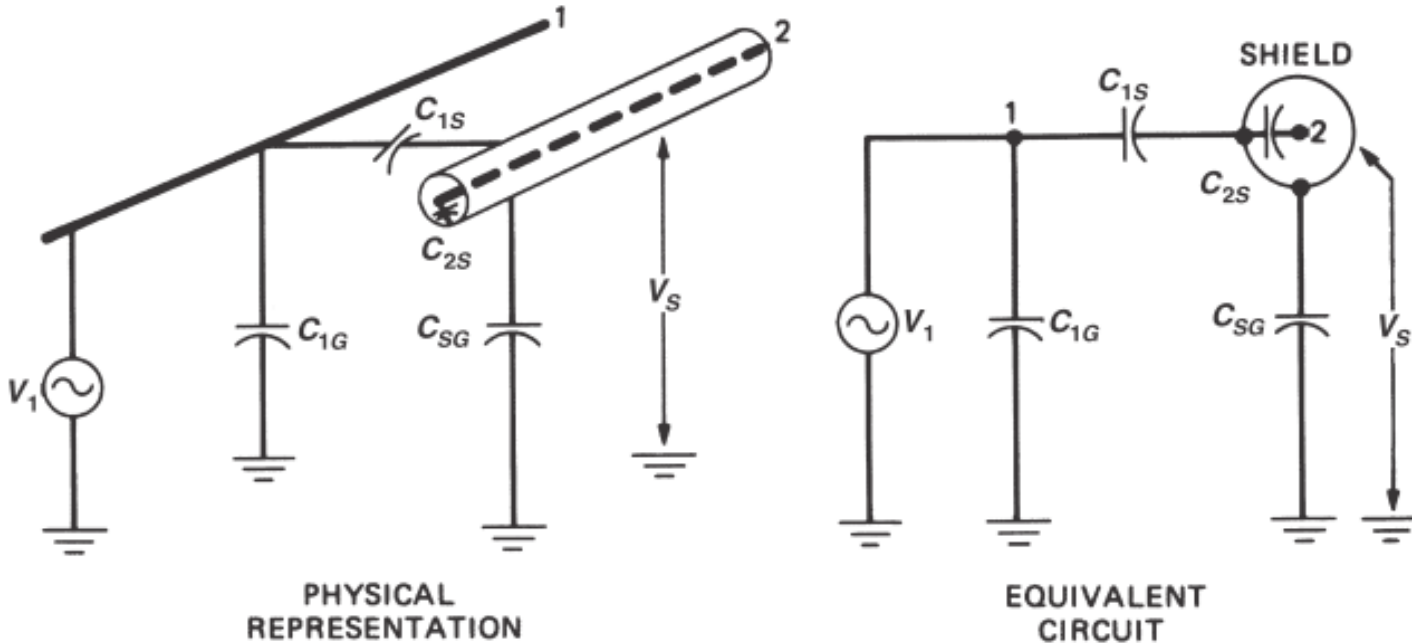


FIGURE 2-4. Capacitive coupling with shield placed around receptor conductor.

Cabos: acoplamento indutivo

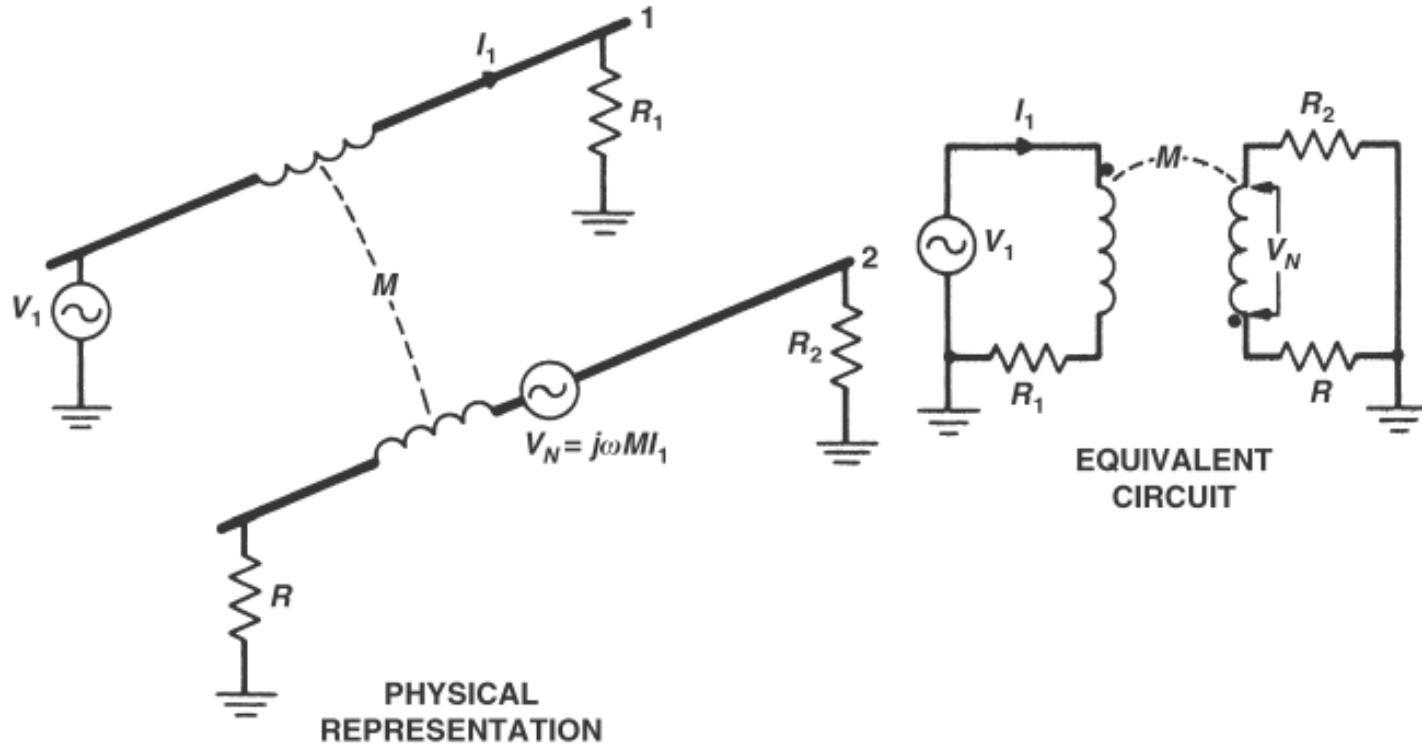


FIGURE 2-8. Magnetic coupling between two circuits.

Cabos: ruído de campos elétrico x magnético

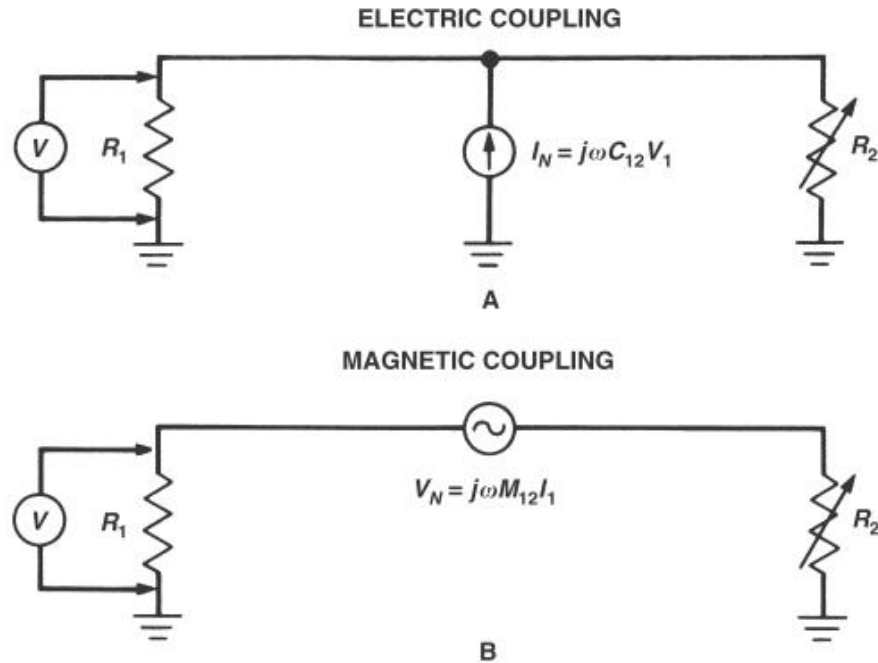


FIGURE 2-9. (A) Equivalent circuit for electric field coupling; (B) equivalent circuit for magnetic field coupling.

Cabos: blindagem na terminação



Manter a qualidade do SE e da impedância de transferência depende da **terminação efetiva em cada ponta dos absorvedores** (blindagem):

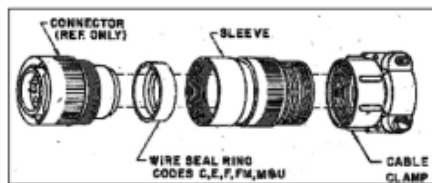
- Acessório do conector (**backshell**) 360 graus
- Se isolação de alta frequência é necessária, evite usar trilhas longas para finalizar as blindagens.



Unassembled 360 Degree Backshell for D Connector



Circular D38999 Mil Connector with 360 Degree Backshell

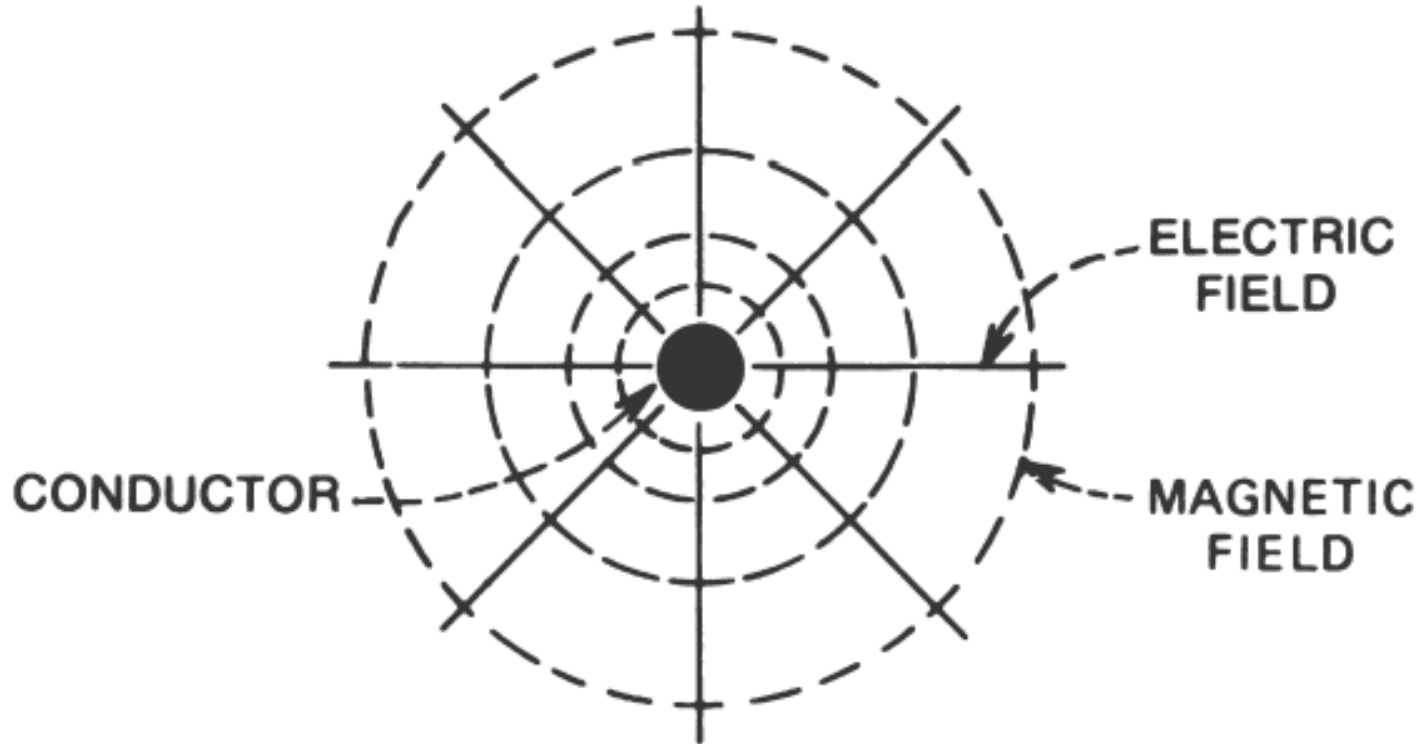


Exploded View of 360 Degree Backshell for D38999 Connector



Coax Shield Terminated with Excessive Lead Length

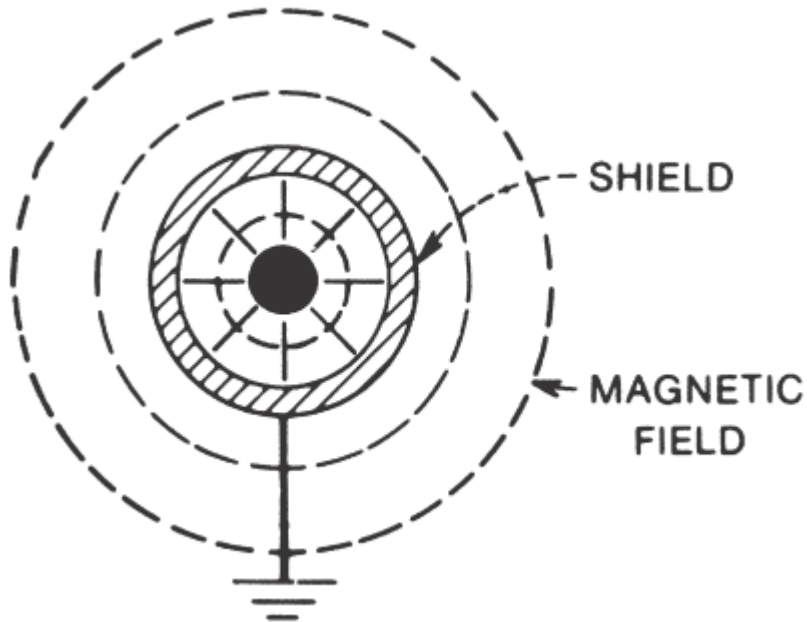
Cabos: campos ao redor



(OTT, 2009)

Fields surrounding a current-carrying conductor.

Cabos: aterramento da blindagem



Fields around shielded conductor;
shield grounded at one point.

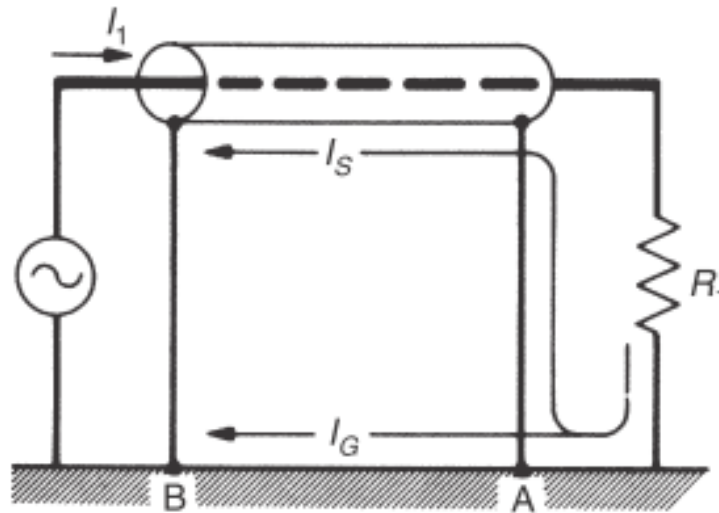


Fields around shielded conductor;
shield grounded and carrying a
current equal to the conductor current
but in the opposite direction.

Modelo do cabo coaxial blindado



Considere um circuito aterrado nas duas pontas, conduzindo corrente i_1 com blindagem coaxial.

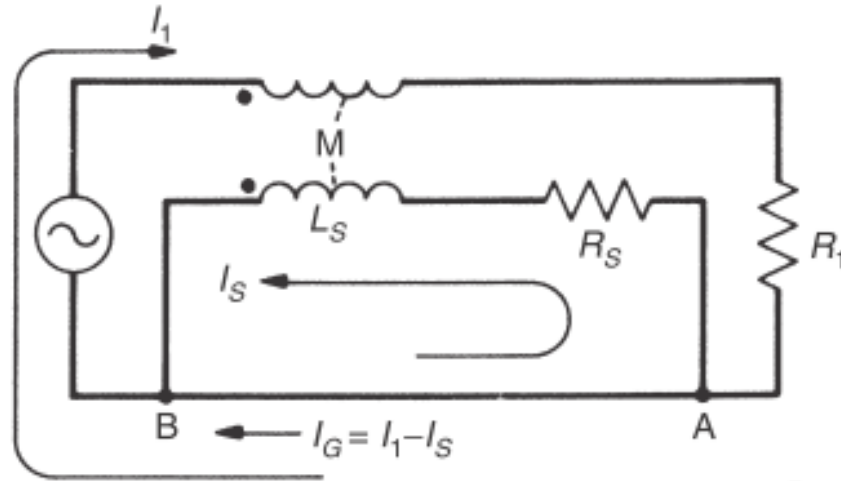


PHYSICAL REPRESENTATION

Modelo do cabo coaxial blindado



Em alta frequência um cabo coaxial consiste na verdade de três condutores isolados; o condutor central, a superfície interna do escudo e a superfície externa do escudo.



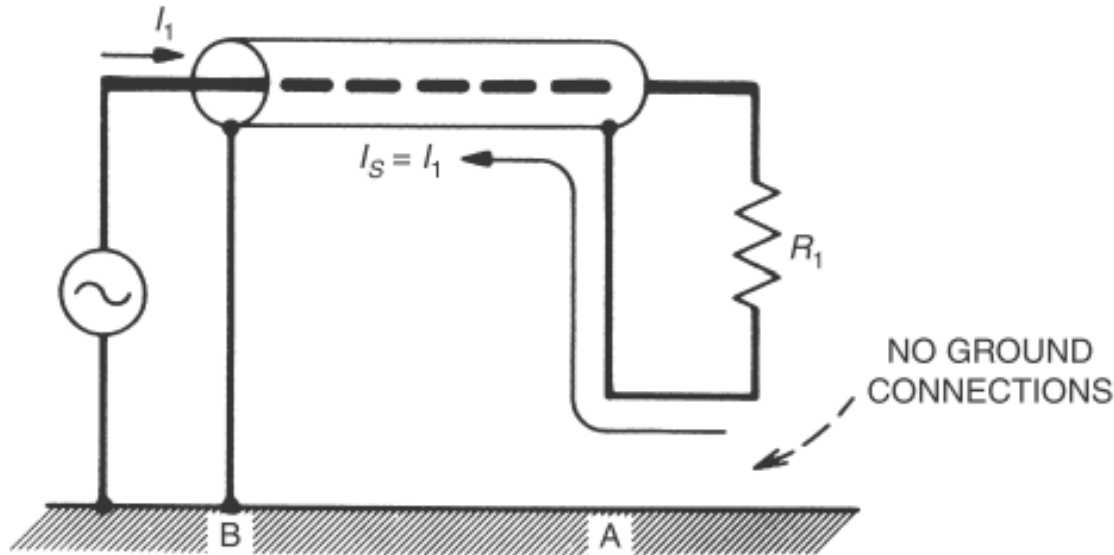
EQUIVALENT CIRCUIT

$$I_S = I_1 \left(\frac{j\omega}{j\omega + R_S/L_S} \right) = \left(\frac{j\omega}{j\omega + \omega_c} \right) I_1$$

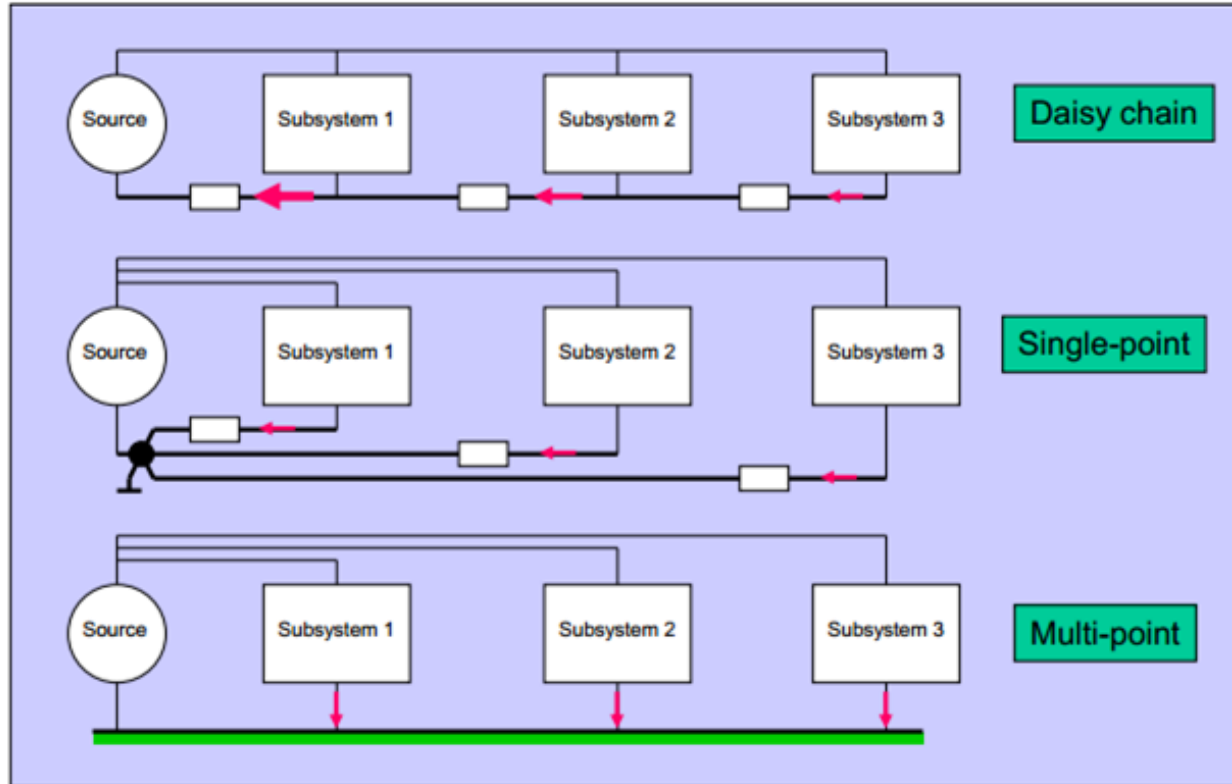
Modelo do cabo coaxial blindado



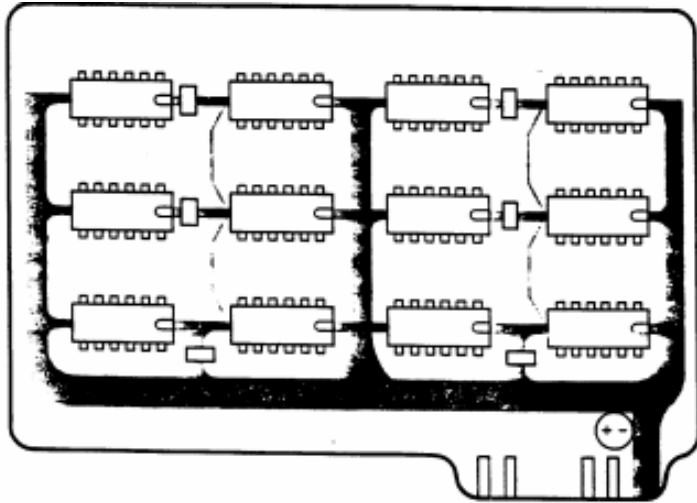
A corrente de retorno pela blindagem reduz (*tenta cancelar*) o campo magnético gerado pelo condutor central.



PCBs: Planos de Terra



PCBs: Planos de Terra



O circuito de terra de **um sistema digital com clock alto** deve **garantir pequena indutância parasita** na conexão entre componentes digitais que **se comunicam entre si**.

Isso é conseguido providenciando vários caminhos paralelos de retorno da corrente.

-Uma abordagem é usar um **plano de terra “sólido”**.

- Outra opção são sistemas com **matrizes (grades) de aterramento** (figura ao lado).

(PAUL, 2006)

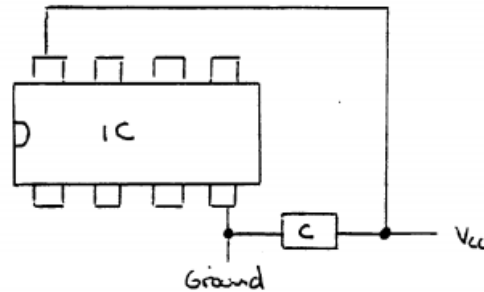
(EM research group at Michigan)

PCBs: Planos de Terra

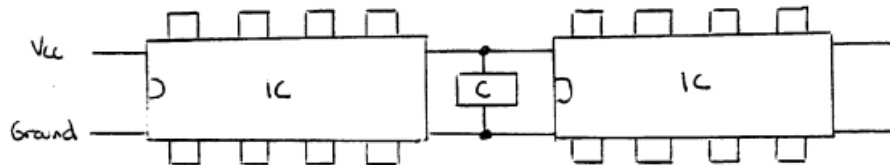


As trilhas que conectam o capacitor de V_{cc} e o CI devem ser tão curtas quanto possível e colocadas próximas entre si para minizar a área de loop.

Um capacitor também pode alimentar mais de um CI (usando um bom *layout*).



Poor placement of
decoupling capacitor



better placement
of decoupling
capacitor

(PAUL, 2006)

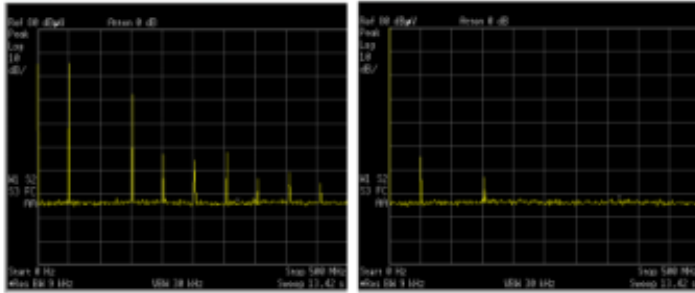
(EM research group at Michigan)

PCBs: Planos de Terra

Radiation Example, 50 MHz Clock



- Adding ground plane reduces emission of fundamental ≈ 40 dB



No Ground Plane

With Ground Plane
(Micro-Strip)

PWB: 2" x 6" x 0.060" (FR4)
Trace: 5" x 0.050"
E-Field Probe Spacing: 2"
(Emco 7405-004)
Source: 50 MHz, 4 ns rise/fall,
3 Vp

One and Two Layer



- Inexpensive
- Difficult to control EMI without external shield
- Difficult to control impedance



- Inexpensive (slightly more than 1 sided)
- EMI mitigation with ground plane
- Impedance control simplified with ground plane

Multi-Layer Stack Up Examples



- High Speed Digital PWB
- High Density
 - Ten Layers
 - Two Micro-Strip Routing Layers
 - Four Asymmetrical Strip-Line Routing Layers
 - Single Supply Plane
 - Two Sided

- High Speed Digital PWB
- Moderate Density
 - Six Layers
 - Two Micro-Strip Routing Layers
 - Two Buried Micro-Strip Routing Layers
 - Single Supply Plane
 - Two Sided

- Mixed Analog/RF/Digital PWB
- Moderate Density
 - Ten Layers
 - Two Micro-Strip Routing Layers
 - Four Asymmetrical Strip-Line Routing Layers
 - Single Digital Supply Plane
 - Analog supplies on inner layers
 - Routing Clearance Considerations
 - Improved Isolation
 - Two Sided

PCBs: Disposição de componentes



Os **componentes mais rápidos** devem ser colocados em uma seção da placa a qual está o **mais longe possível de conectores externos**.

Isso aproveita a vantagem da perda natural sobre o material da placa, o qual atenua sinais de ruído.

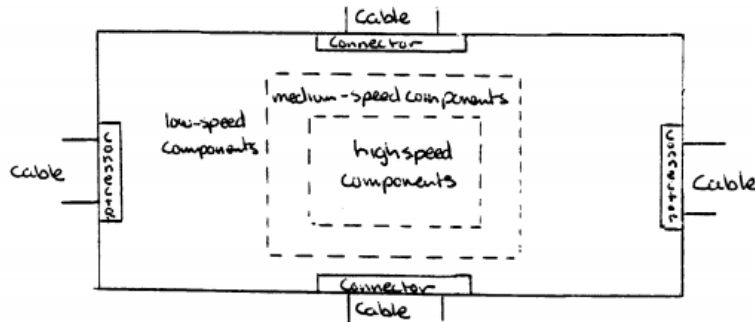


Figure 13. Placement of various-speed components on PC board.

(PAUL, 2006)

(EM research group at Michigan)

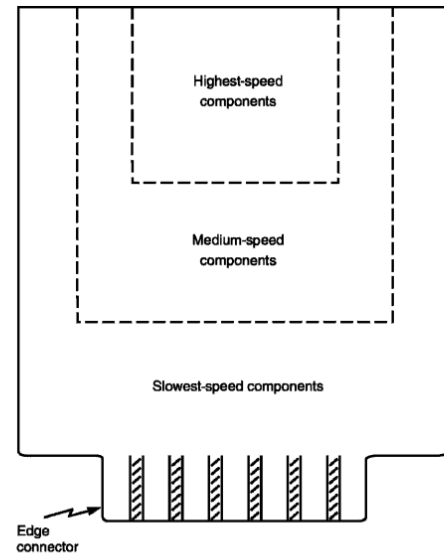


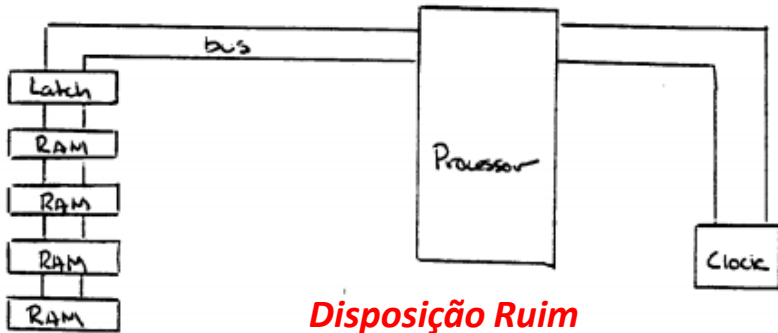
FIGURE 11.34 Keeping the highest-speed components away from offboard connectors.

PCBs: Disposição de componentes



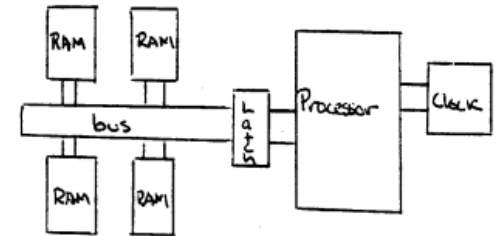
Conexões entre osciladores e CIs que usam o sinal dos osciladores devem ser feitas o mais curto possível. A fim de minizar as áreas de loop, o sinal e caminhos de retorno do clock devem ser paralelizados próximos.

Conexões de endereços, dados e portas I/O devem ser feitas o mais curto possíveis, com sinais e caminhos de retorno o mais próximo possíveis, a fim de minimizar áreas de loop.



Disposição Ruim

Poor component placement



Disposição mais adequada

better component placement

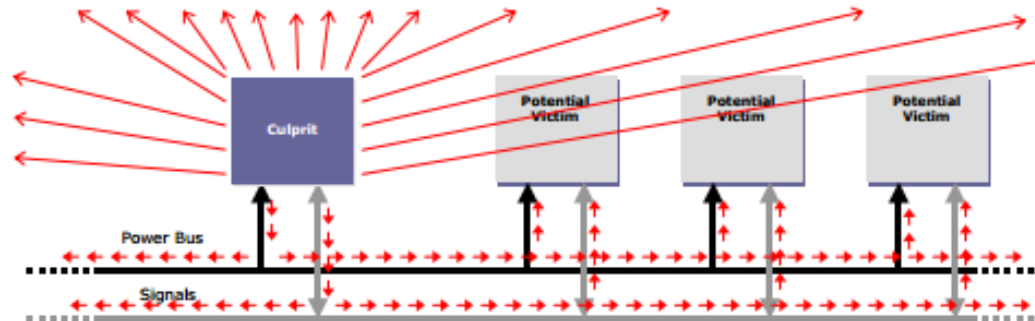
Figure 12. PC board component configurations.

Integração de Sistemas

System Partitioning/Guidelines



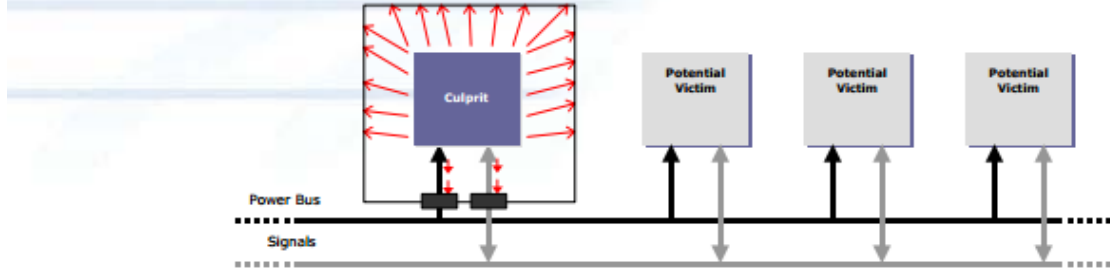
- ◆ Minimize interconnections between WRAs/LRUs
- ◆ Minimize the distribution of analog signals
- ◆ Control interference at the source



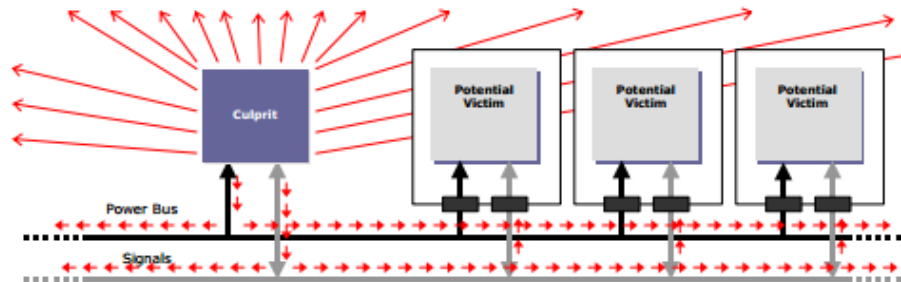
Integração de Sistemas

Control Interference at the Source

- ◆ Preferred Approach – Shield/Filter the Source (Culprit)



- ◆ Alternate Approach – Shield/Filter Potential Receivers (Victims)



Referências Bibliográficas



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“For every difficult problem there is always a simple answer and most of them are wrong.”