



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/m<sup>2</sup>**)

# 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:

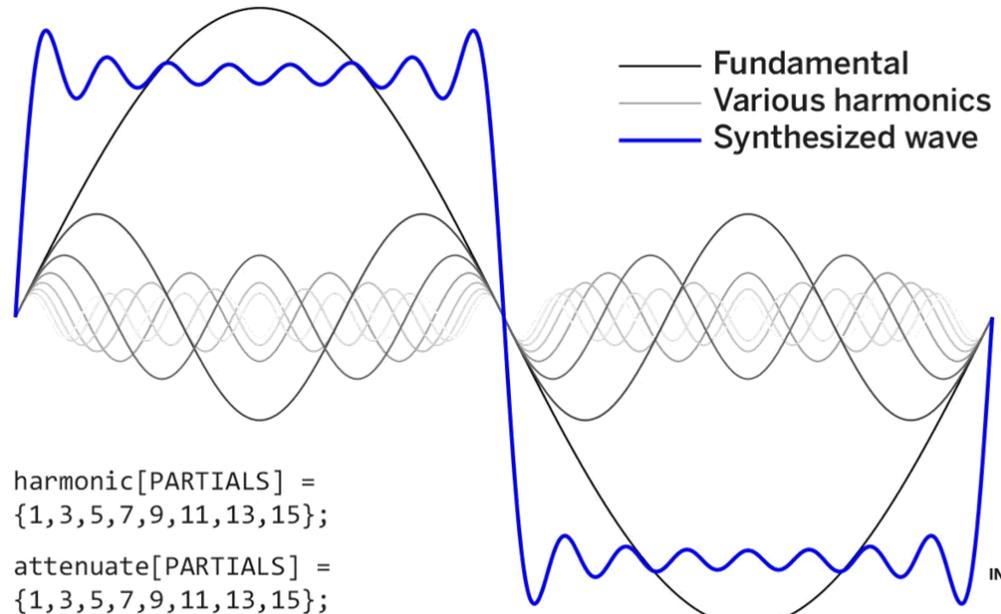
- Série de Fourier
- Transformada de Fourier (**FT**)
- Transformada de Fourier de Tempo Discreto (**DTFT**)
- Transformada Fourier Discreta (**DFT**)
- Algoritmo: transformada rápida de fourier (**FFT**)

# Espectro em Frequência



**Sinais digitais** possuem conteúdo harmônico significativo.

▪ Série de Fourier



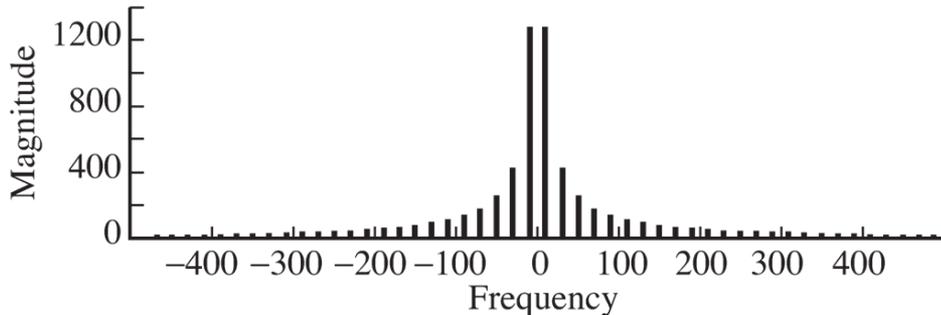
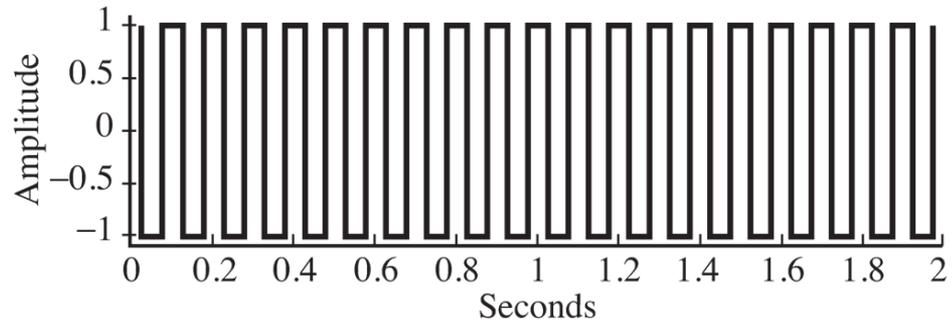
```
harmonic[PARTIALS] =  
{1, 3, 5, 7, 9, 11, 13, 15};  
attenuate[PARTIALS] =  
{1, 3, 5, 7, 9, 11, 13, 15};
```

# Espectro em Frequência



**Sinais digitais** possuem conteúdo harmônico significativo.

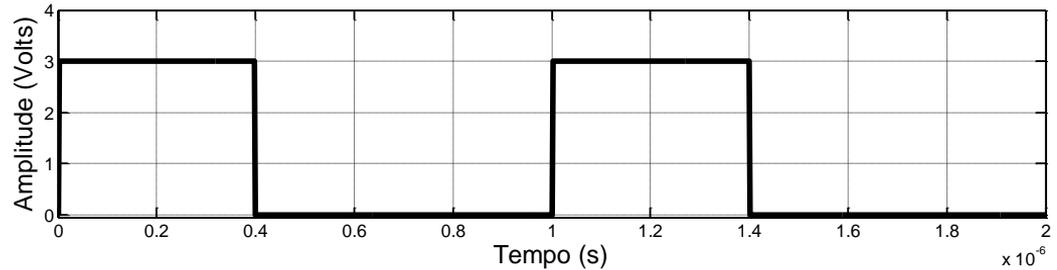
- Transformada de Fourier



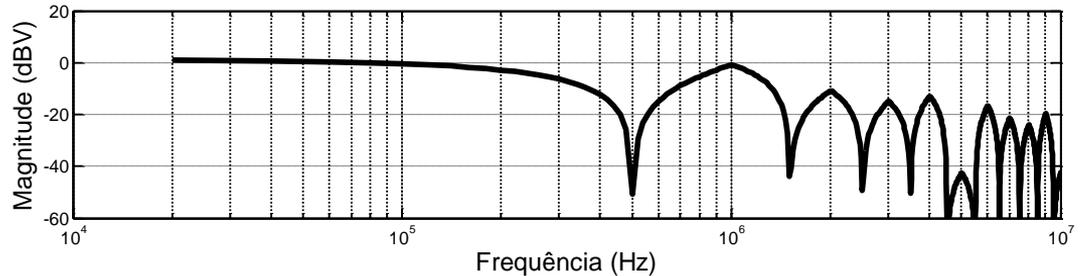
# Espectro em Frequência



**Sinais digitais possuem conteúdo harmônico significativo.**



■ DTFT

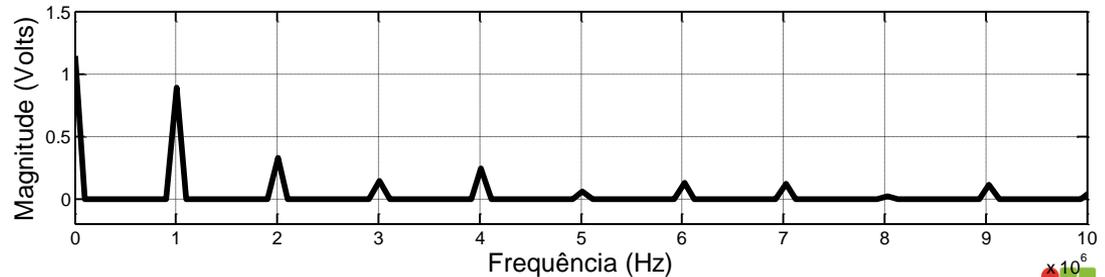
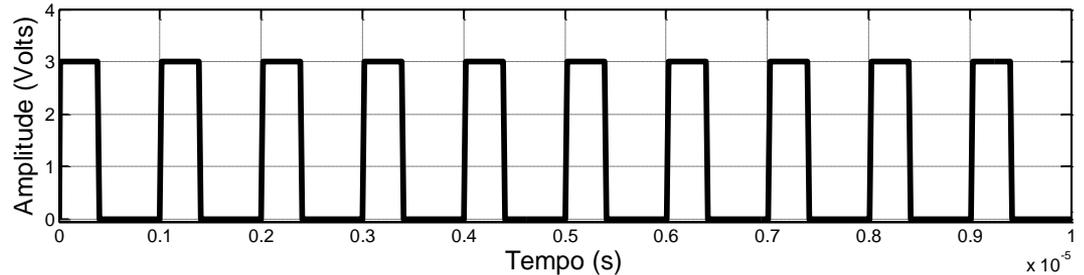


# Espectro em Frequência

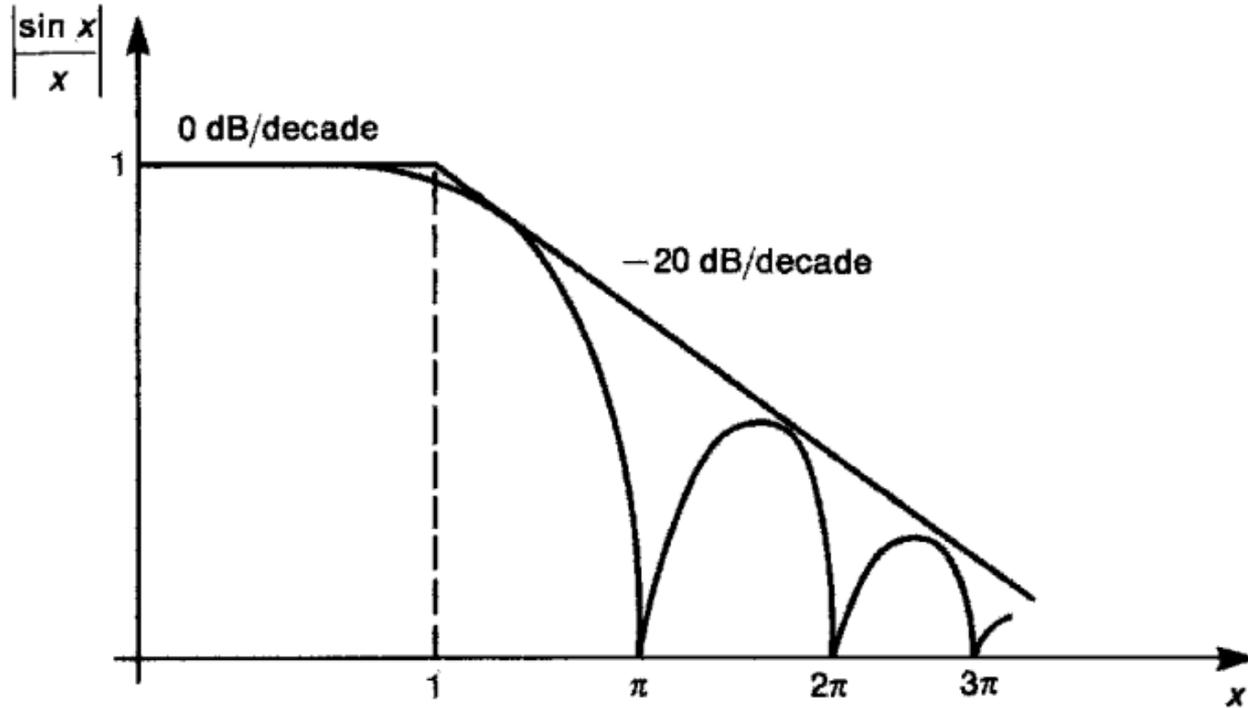


**Sinais digitais** possuem conteúdo harmônico significativo.

▪ DFT/FFT

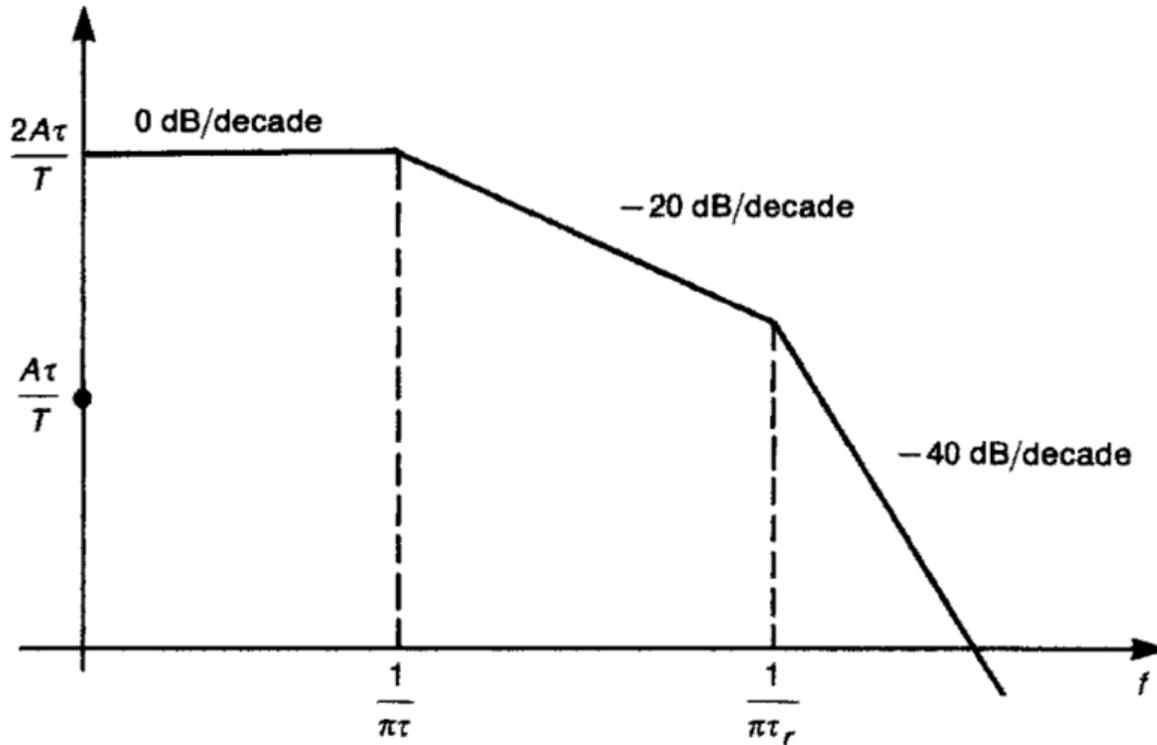


# Espectro em Frequência



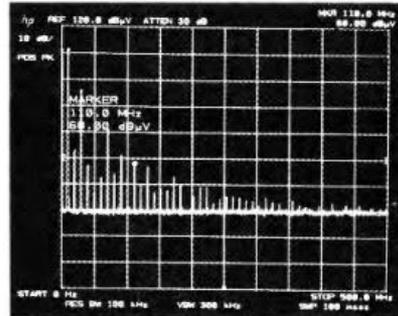
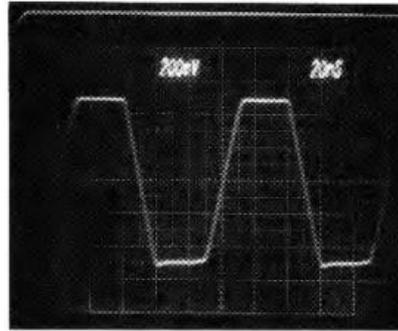
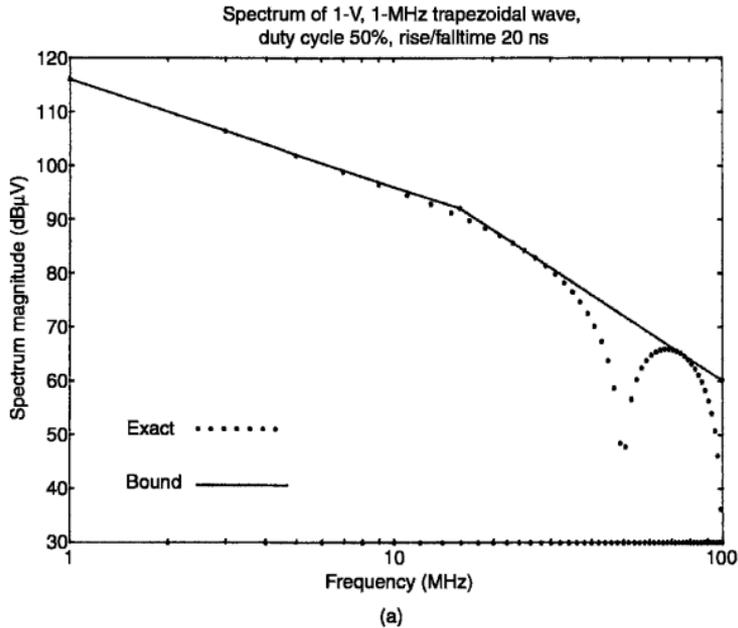
**FIGURE 3.18** Bounds on the  $(\sin x)/x$  function.

# Espectro em Frequência



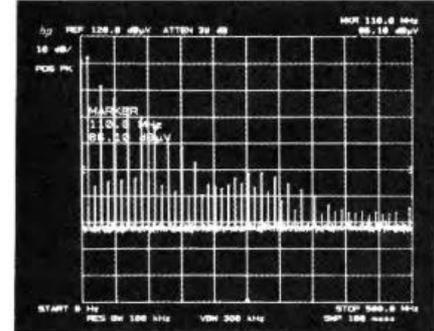
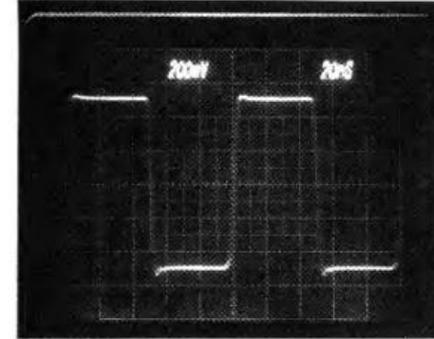
(PAUL, 2006) **FIGURE 3.19** Bounds on the one-sided magnitude spectrum of a trapezoidal pulse train.

# Espectro em Frequência



rise/falltime = 20 ns

(a)



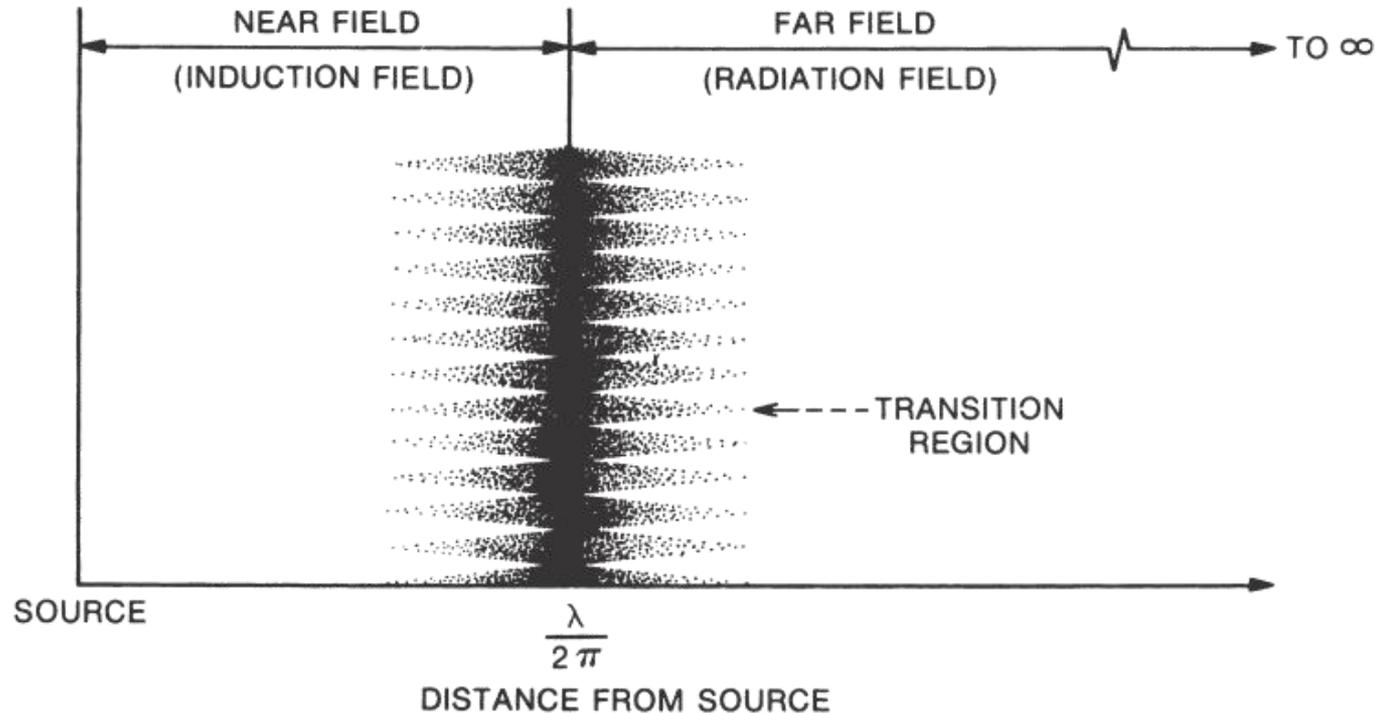
rise/falltime = 5 ns

(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)

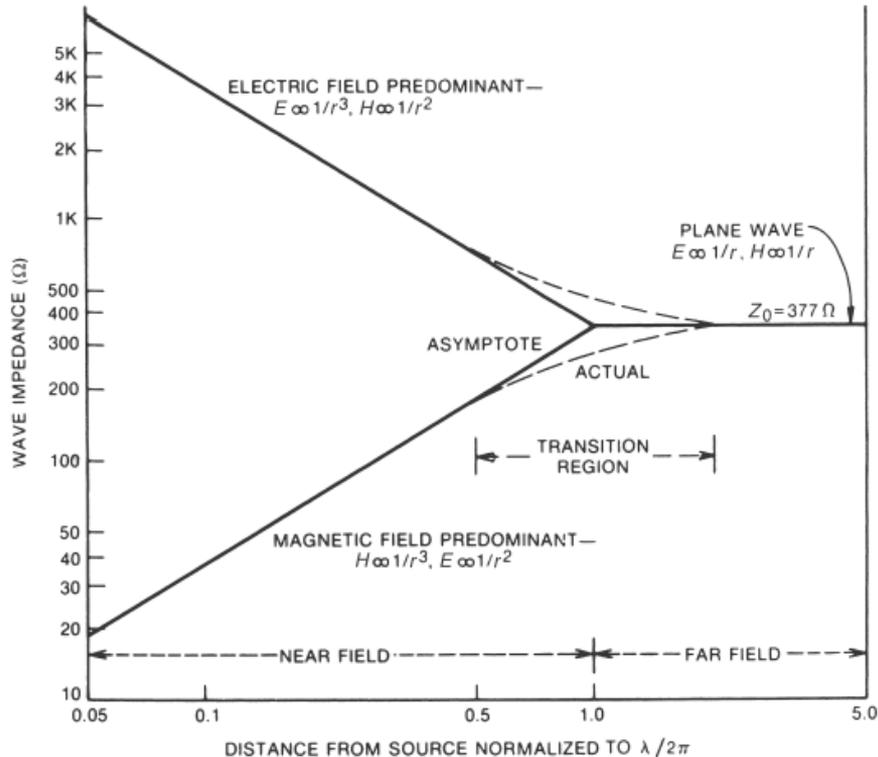


FIGURE 6-4. Wave impedance depends on the distance from the source.

- 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)

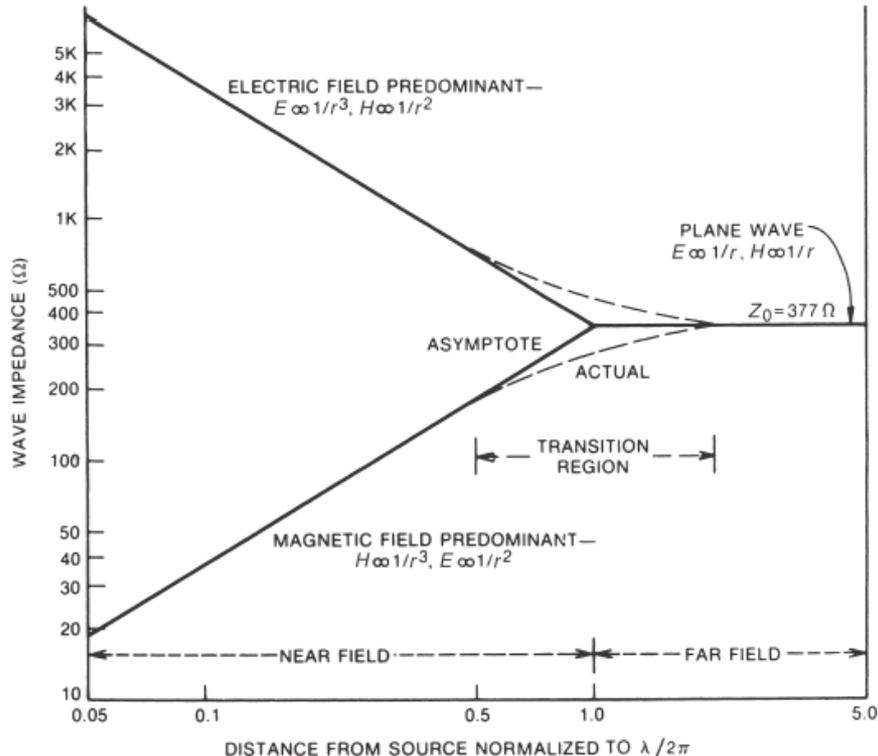
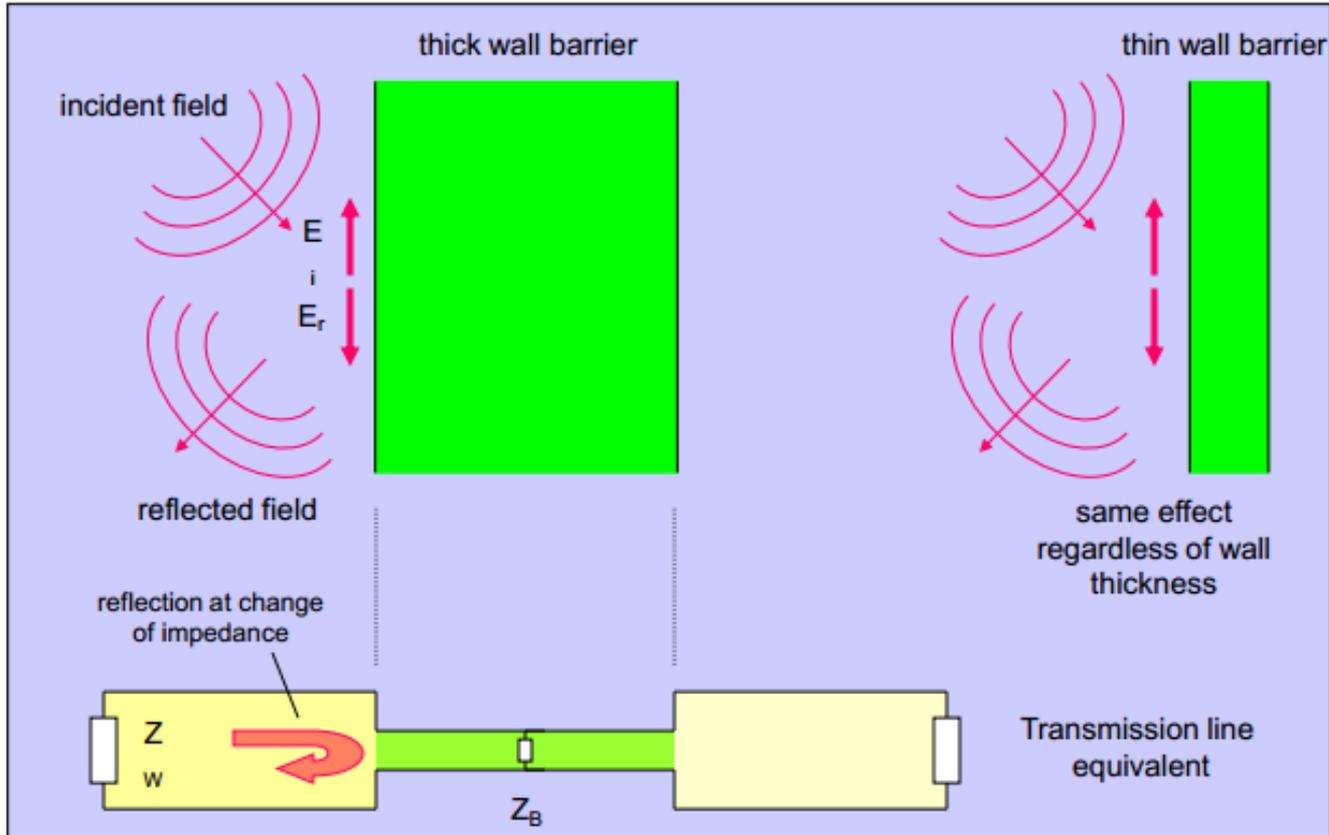


FIGURE 6-4. Wave impedance depends on the distance from the source.

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

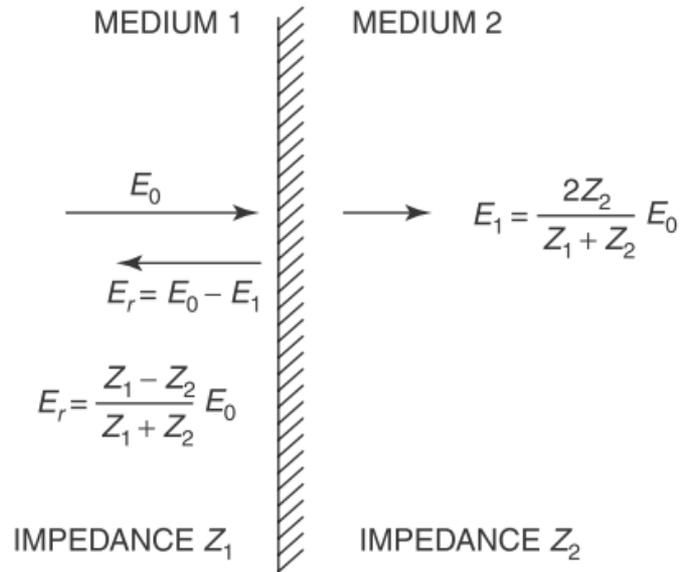
$$\eta_w = \frac{\mathbf{E}_s}{\mathbf{H}_s} = \sqrt{\frac{\mu}{\epsilon}} \quad (\Omega)$$

# 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

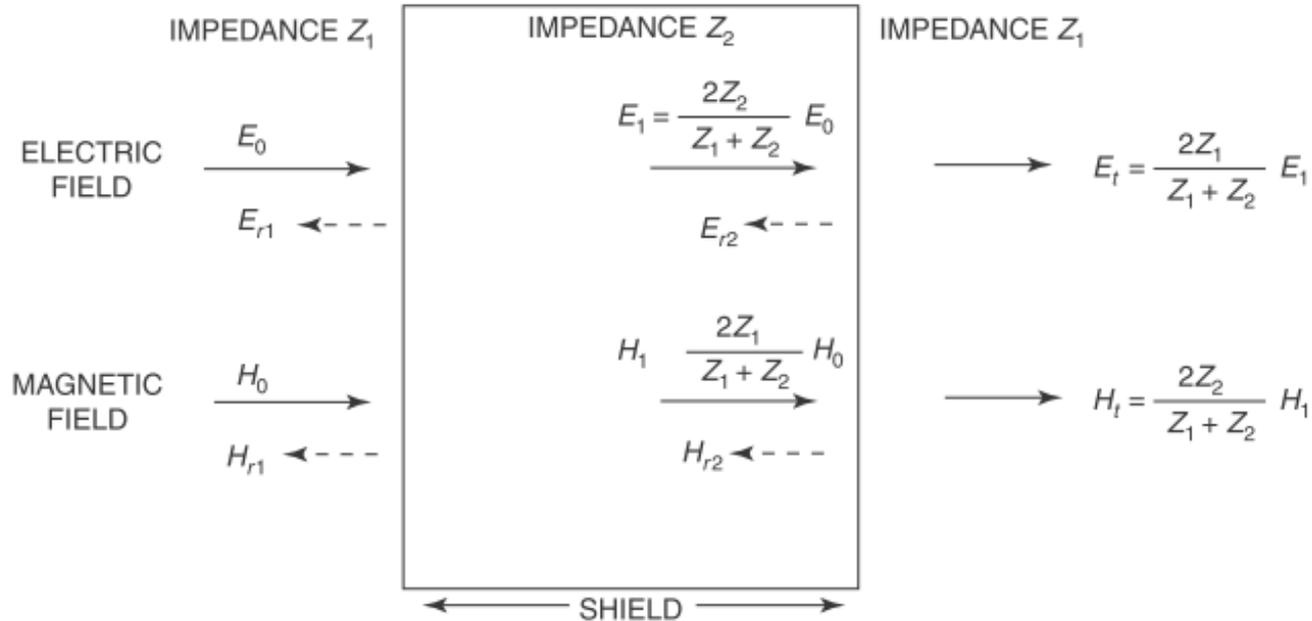
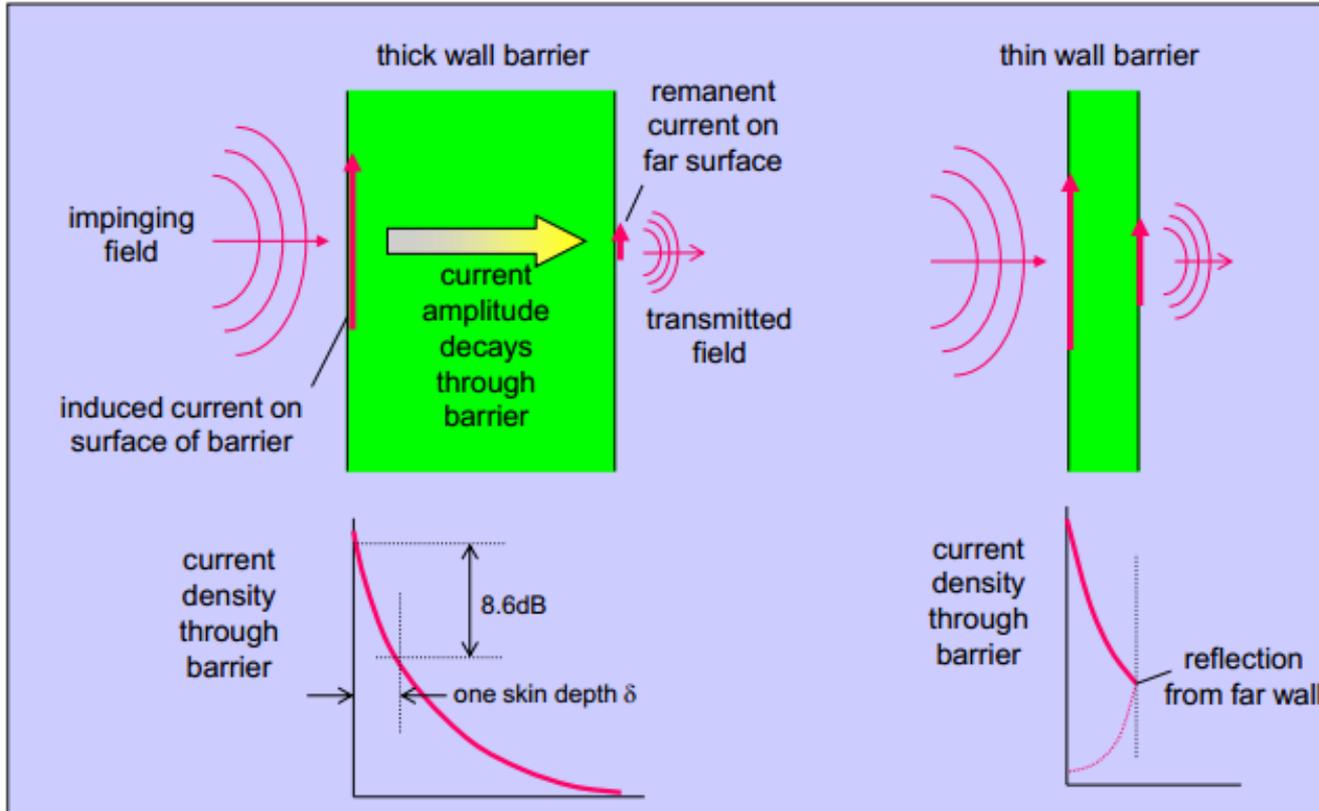


FIGURE 6-11. Partial reflection and transmission occur at both boundaries of a shield.

# Refração e absorção de ondas



(LAWSON)



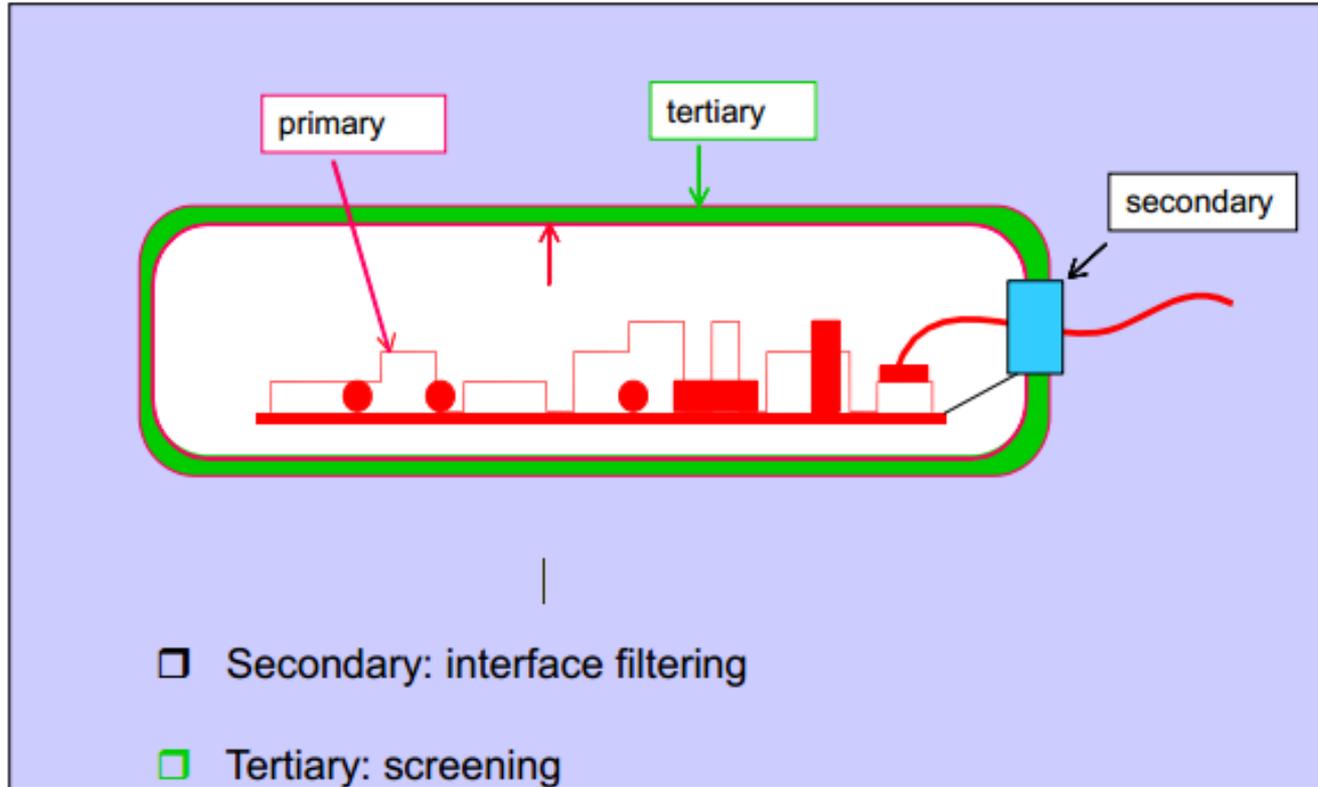
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Métodos preventivos e corretivos

# TÉCNICAS DE CONTROLE DE EMI

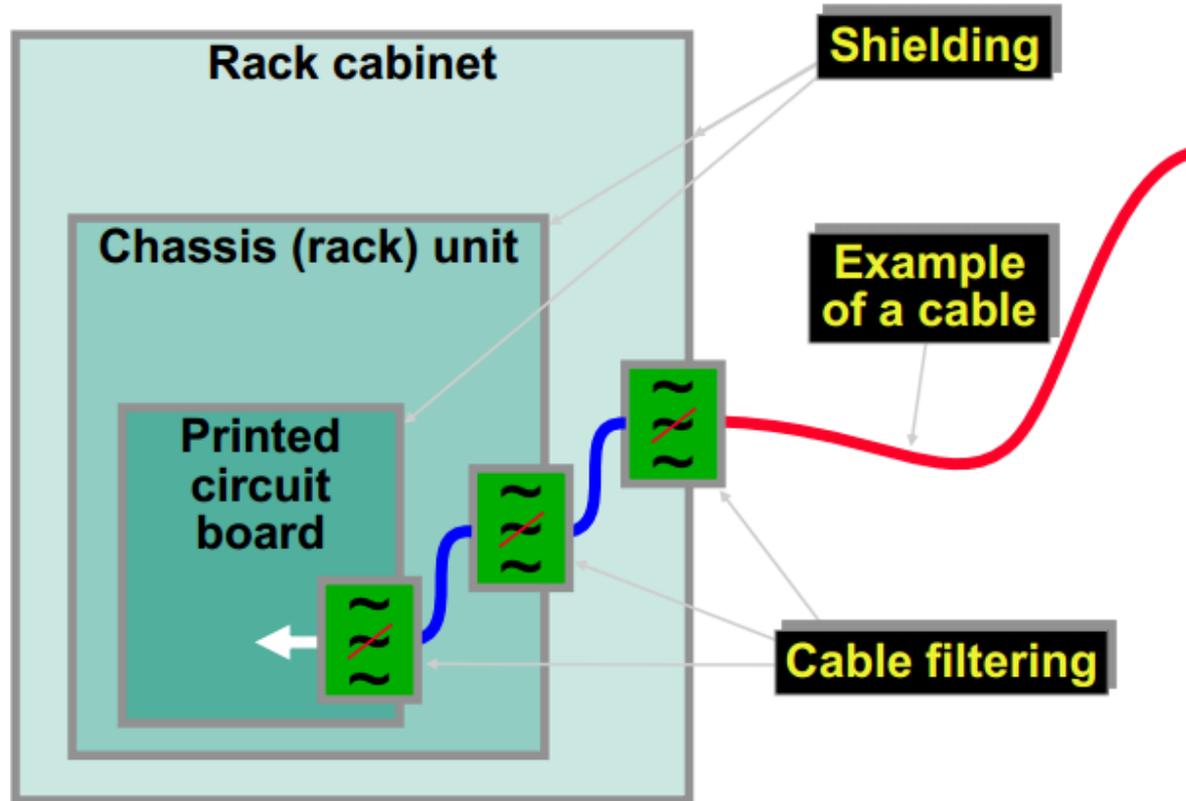


# Mitigação de EMI

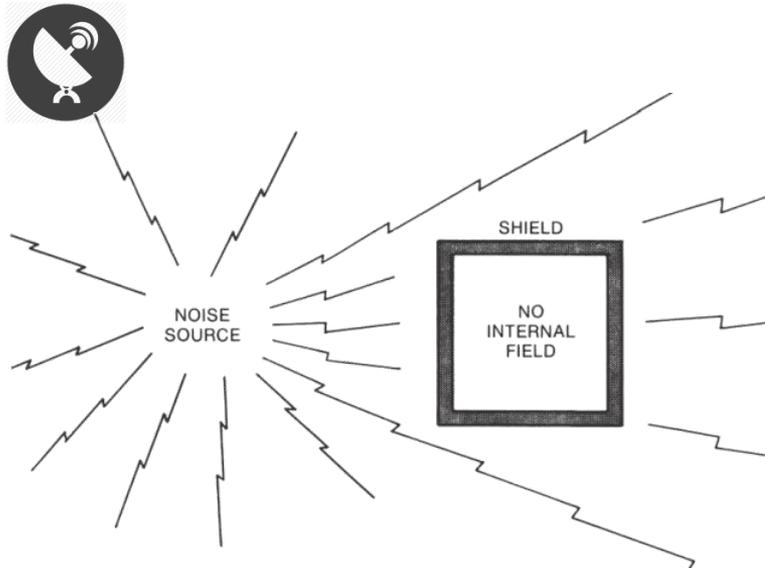


(LAWSON)

# Mitigação de EMI

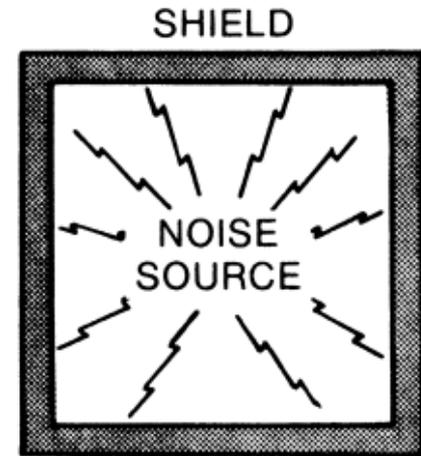


# Blindagem (*Shielding*)



**Caso 1:** Imunidade ao ambiente

NO EXTERNAL  
FIELD



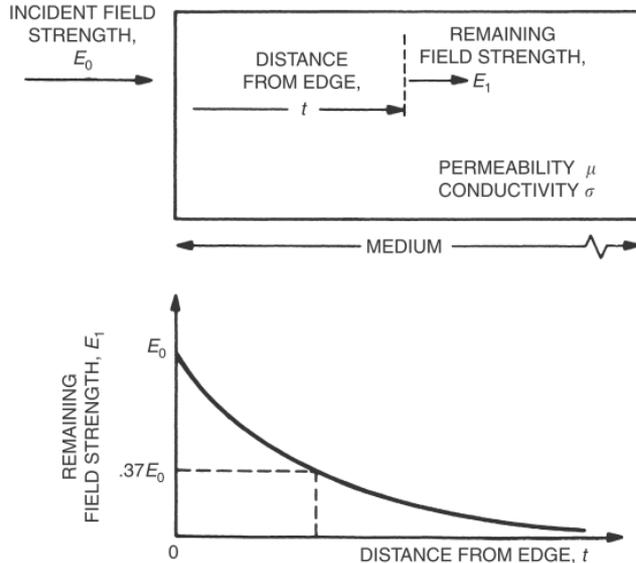
**Caso 2:** Contenção de interferência

(OTT, 2009)

# 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



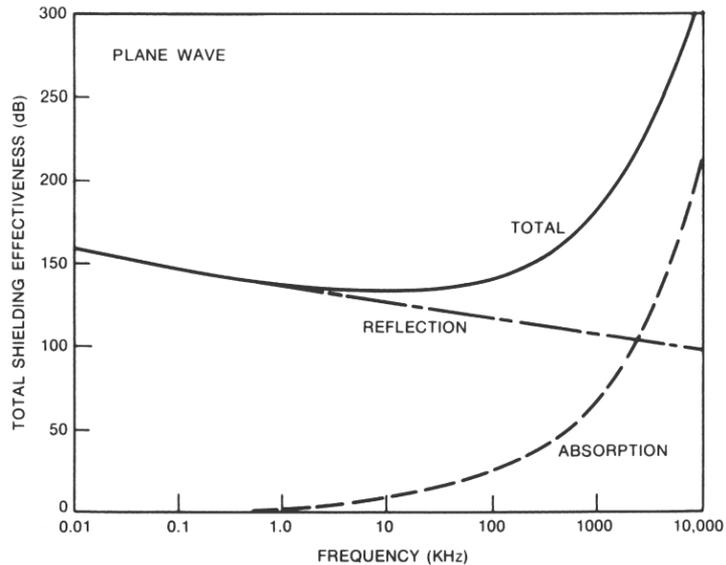
**SE** teórico de um material homogêneo considera:

- 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

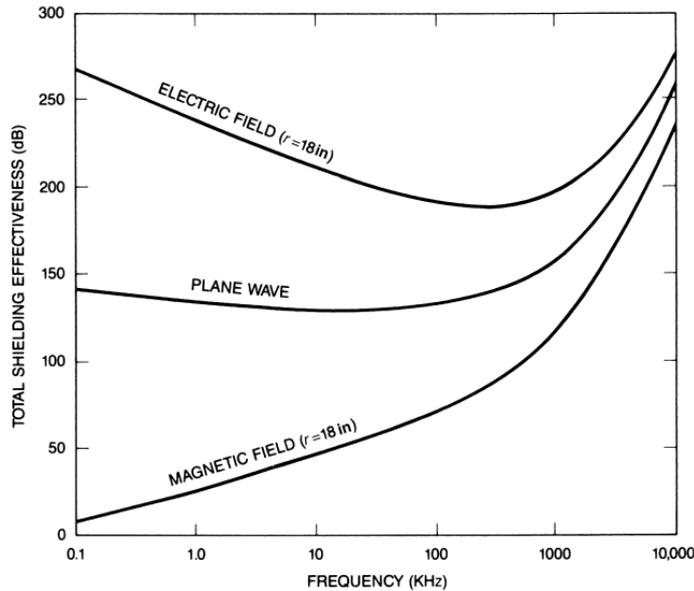


FIGURE 6-18. Electric field, plane wave, and magnetic field shielding effectiveness of a 0.02-in-thick solid aluminum shield.

## 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

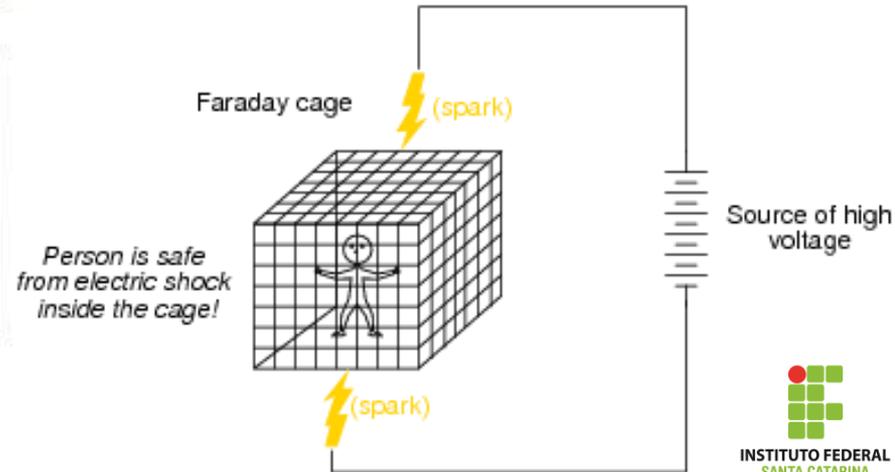
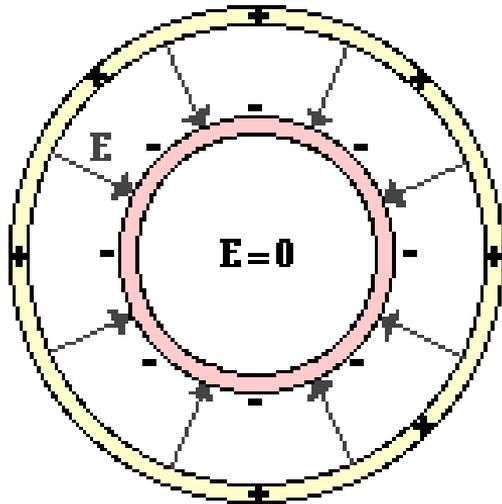
(COLOTTI, 2003)

# 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).

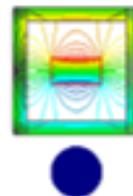
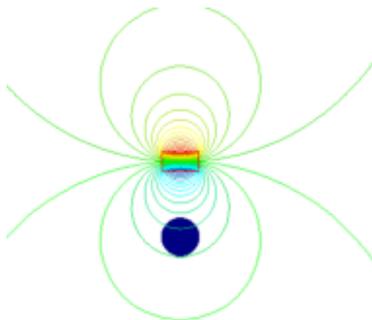
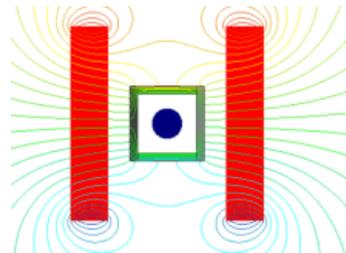
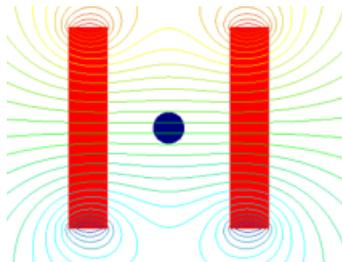
# Gaiola de Faraday



# “Gaiolas” Magnéticas: Ferrites



Desviam o fluxo magnético externo e concatenam o interno.



# “Gaiolas” Magnéticas: Exemplos



Material “ $\mu$ -metal” (liga de níquel-ferro)

Ferrites.

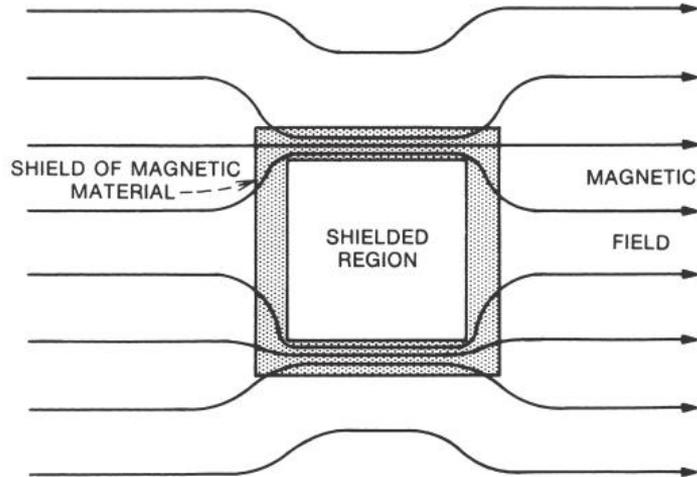
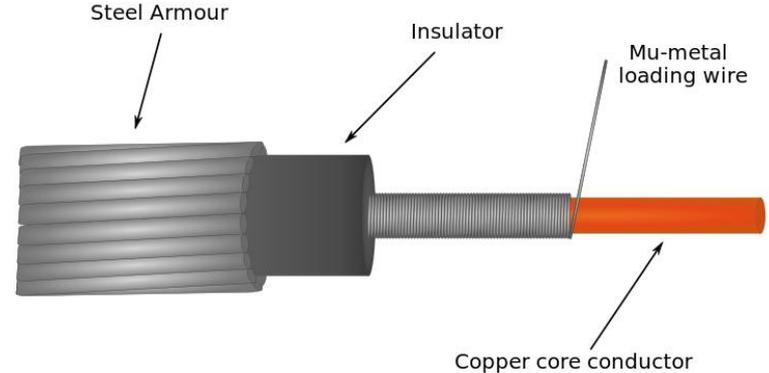


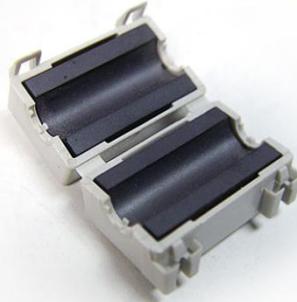
FIGURE 6-17. Magnetic material used as a shield by providing a low-reluctance path for the magnetic field, diverting it around the shielded region.



# “Gaiolas” Magnéticas: Ferrites



FerriShield installation locations.



## CABLING

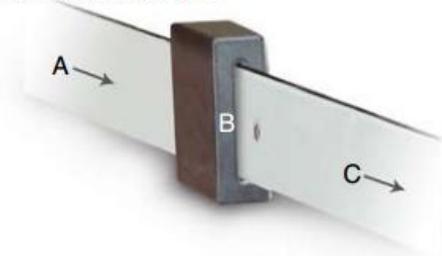
RFI suppressor functions



- 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

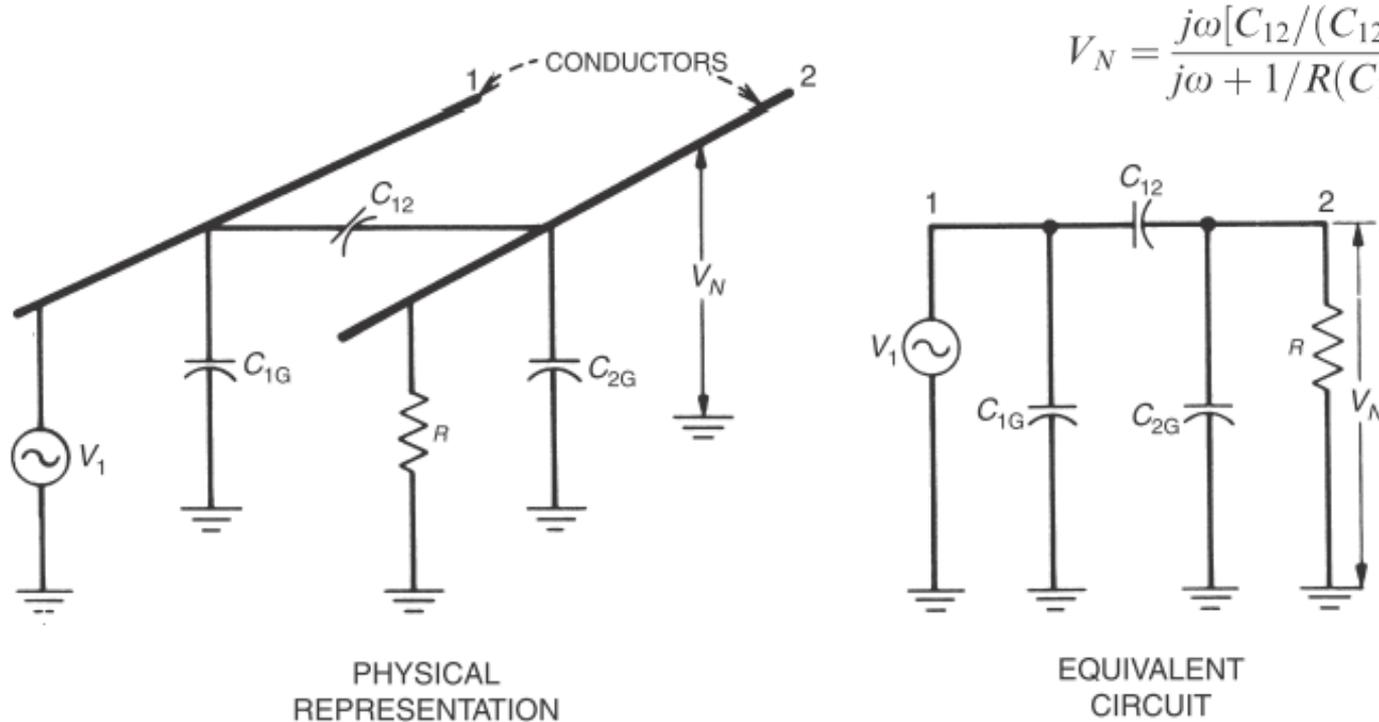


FIGURE 2-1. Capacitive coupling between two conductors.

# Cabos: acoplamento capacitivo

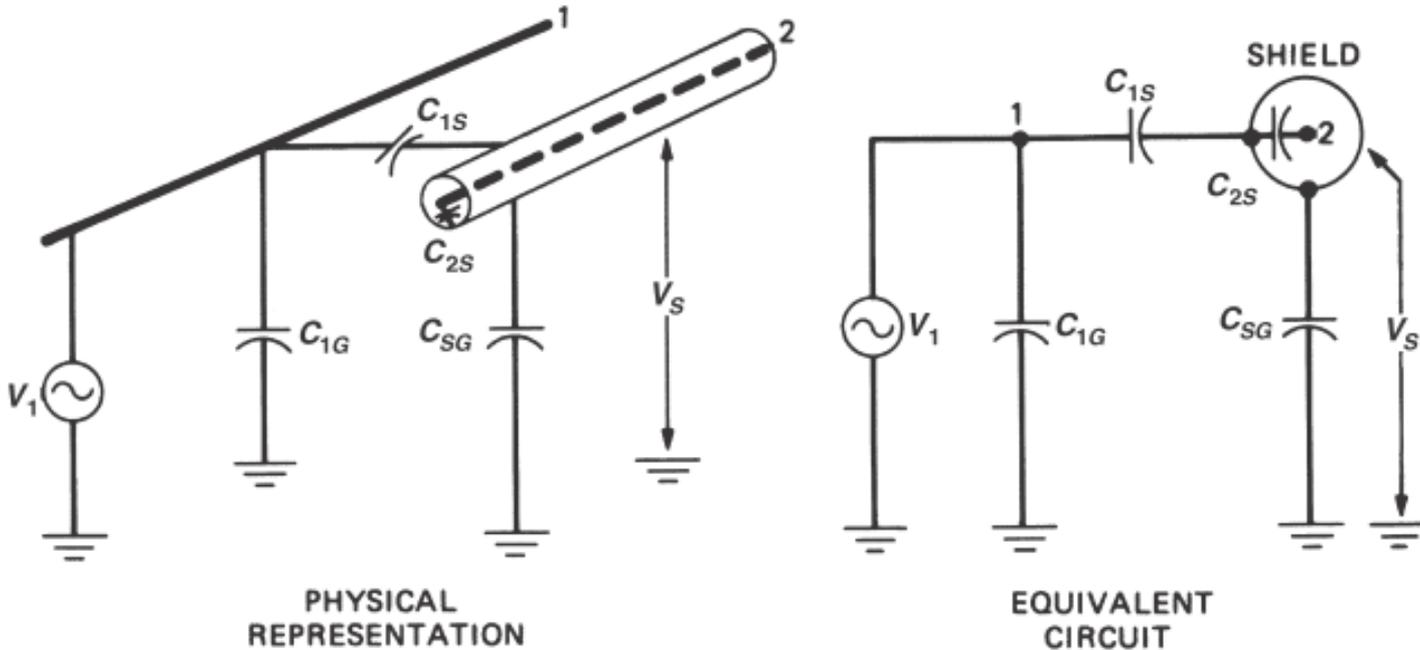


FIGURE 2-4. Capacitive coupling with shield placed around receptor conductor.

# Cabos: acoplamento indutivo

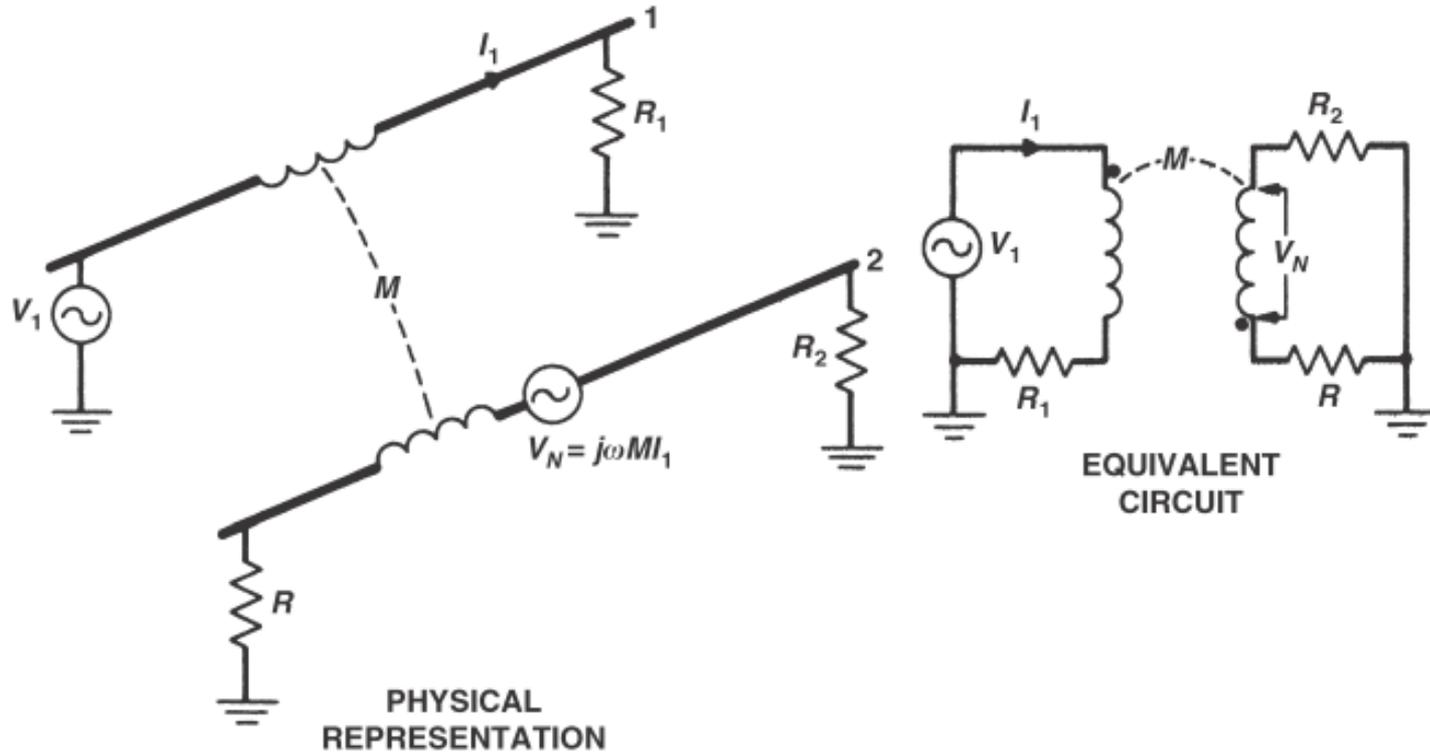
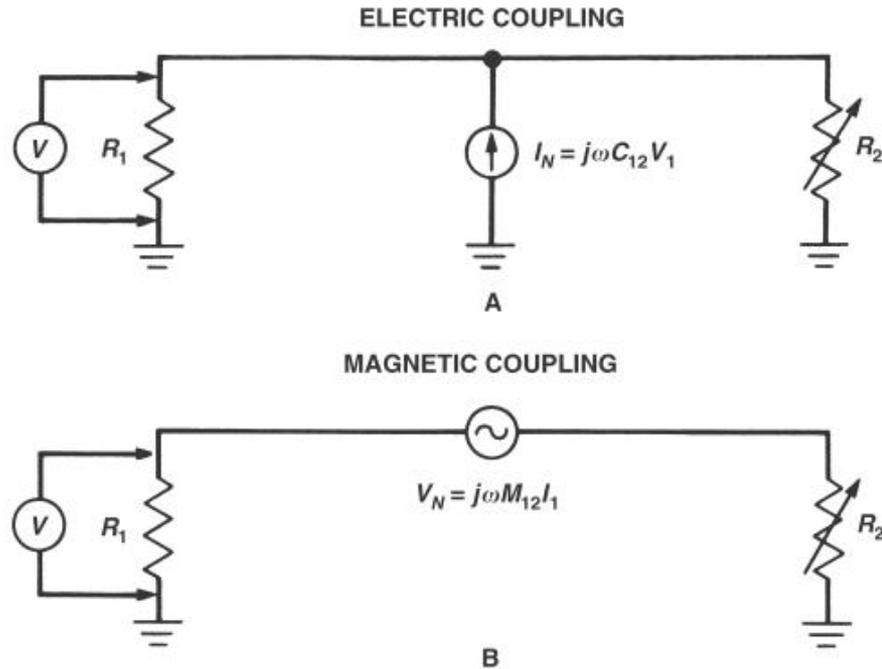


FIGURE 2-8. Magnetic coupling between two circuits.

# 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):

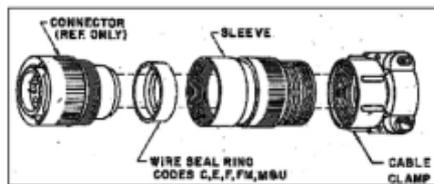
- Acessório do conector (**backshell**) 360 graus
- Se isolação de alta frequência é necessária, evite usar trilhas longas para finalizar as blindagens.



Unassembled 360 Degree Backshell for D Connector



Circular D38999 Mil Connector with 360 Degree Backshell

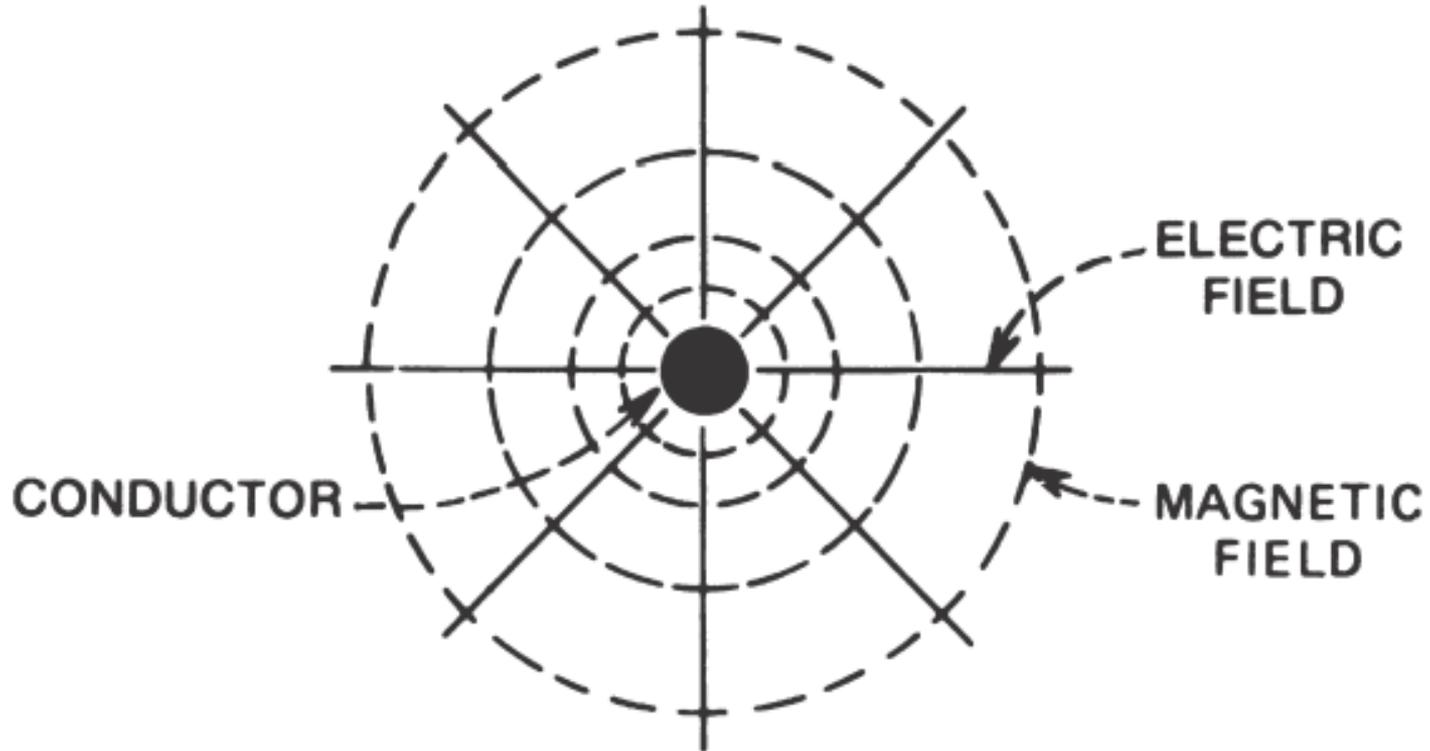


Exploded View of 360 Degree Backshell for D38999 Connector



Coax Shield Terminated with Excessive Lead Length

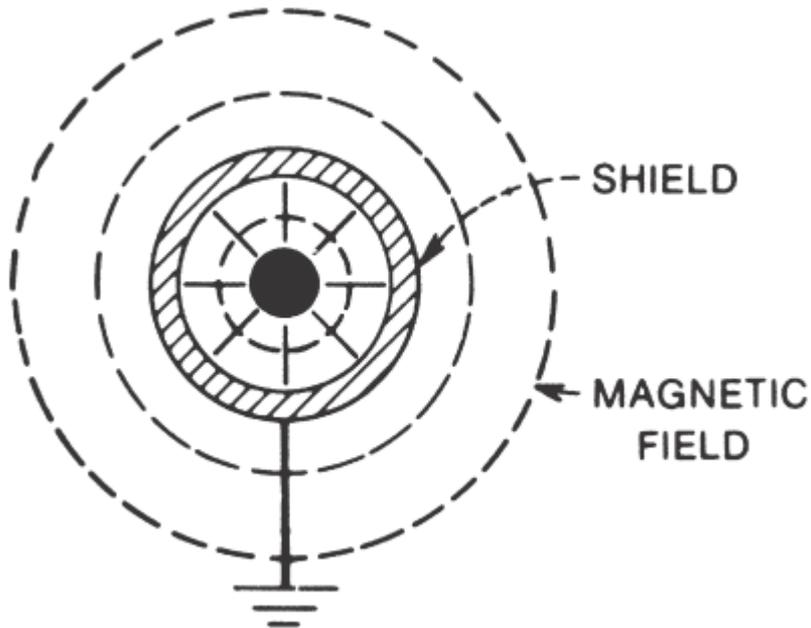
# Cabos: campos ao redor



(OTT, 2009)

Fields surrounding a current-carrying conductor.

# Cabos: aterramento da blindagem



Fields around shielded conductor; shield grounded at one point.

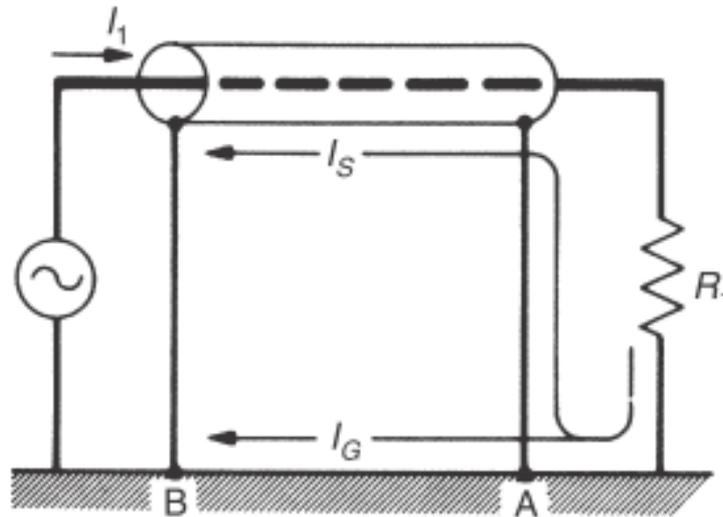


Fields around shielded conductor; shield grounded and carrying a current equal to the conductor current but in the opposite direction.

# Modelo do cabo coaxial blindado



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

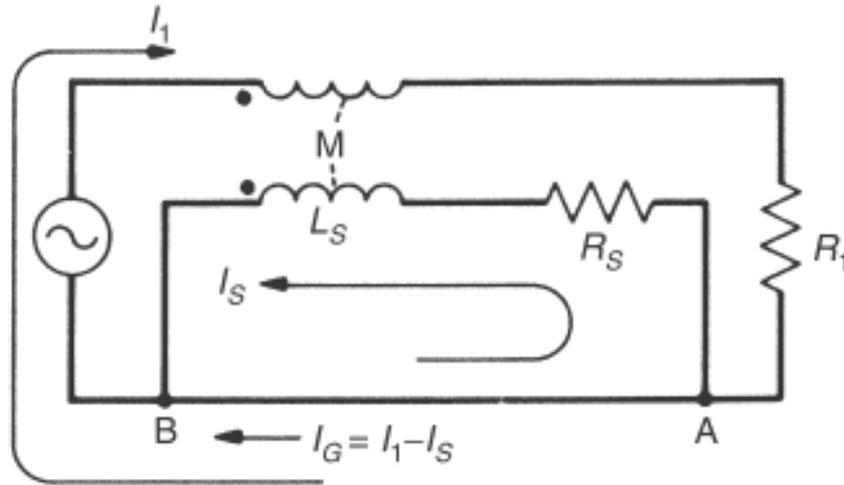


PHYSICAL REPRESENTATION

# 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.



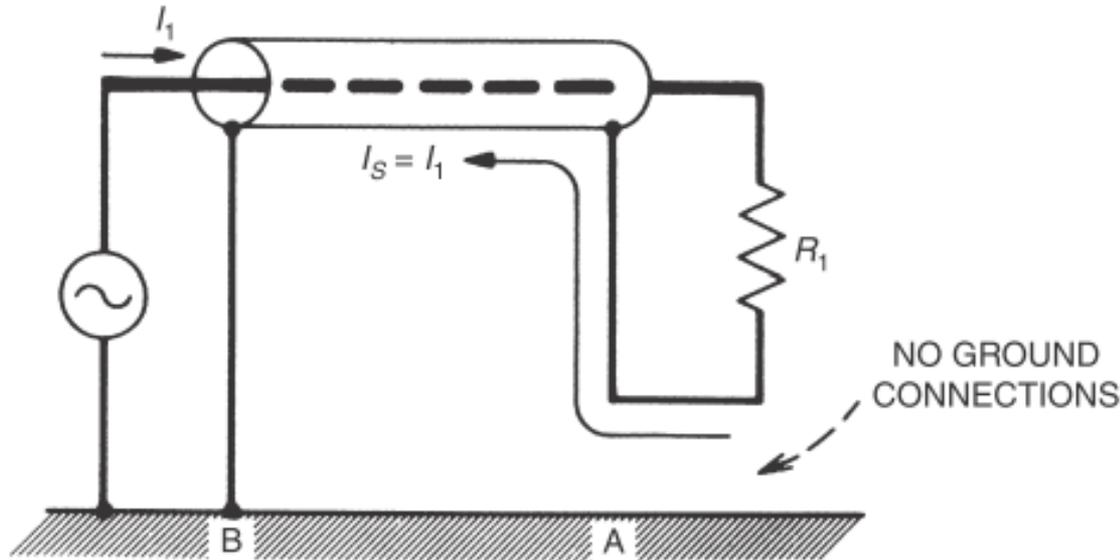
EQUIVALENT CIRCUIT

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

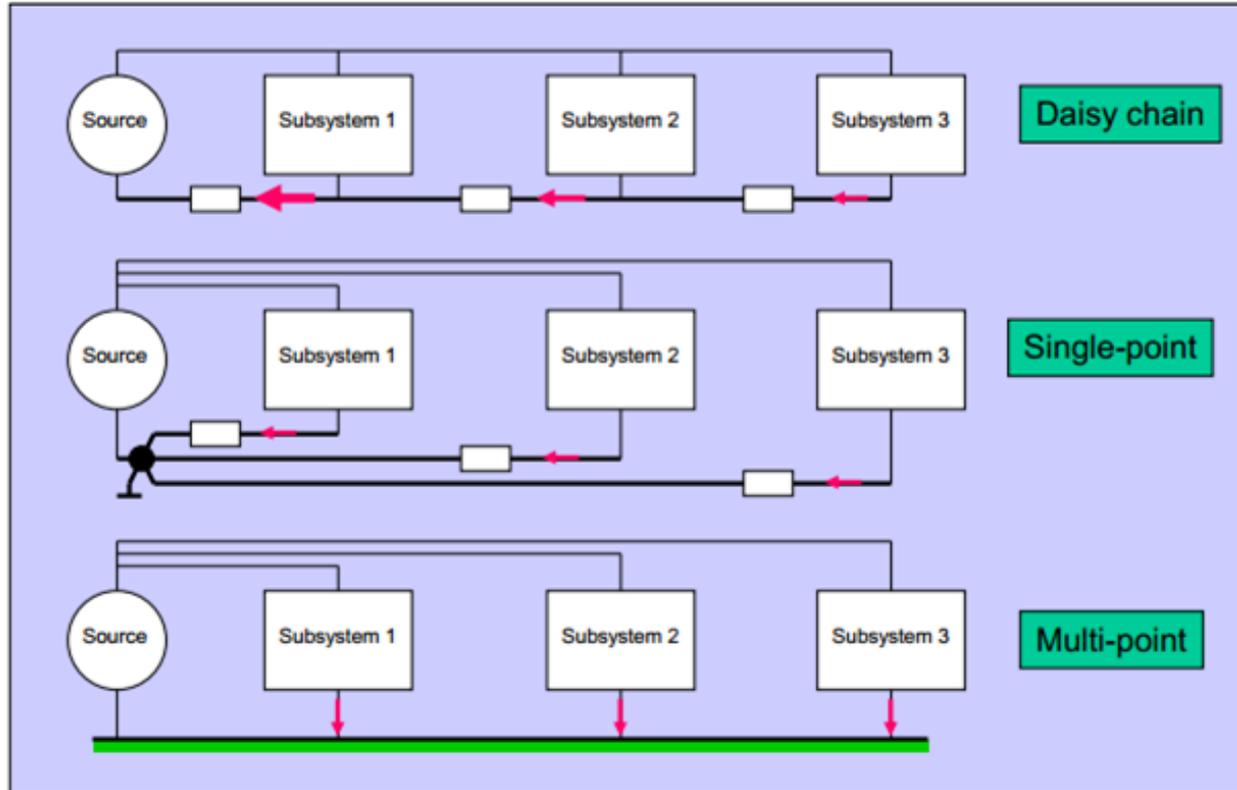
# Modelo do cabo coaxial blindado



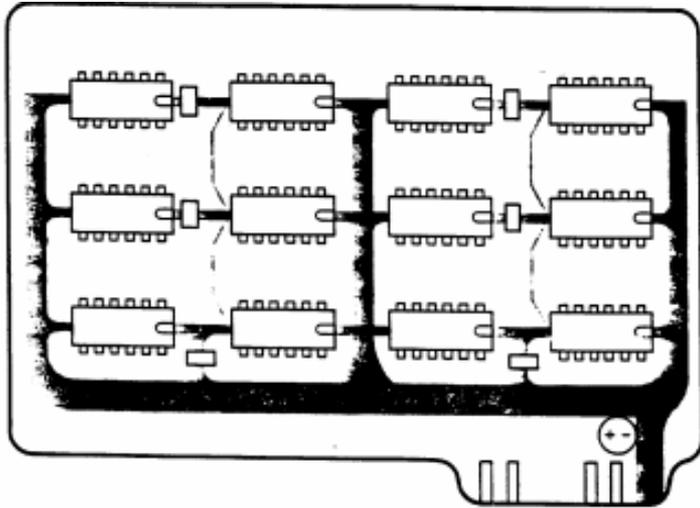
A corrente de retorno pela blindagem reduz (*tenta cancelar*) o campo magnético gerado pelo condutor central.



# 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)

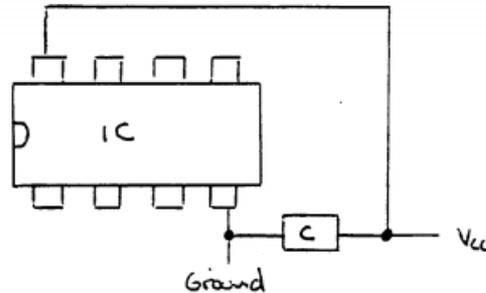
(EM research group at Michigan )

# PCBs: Planos de Terra

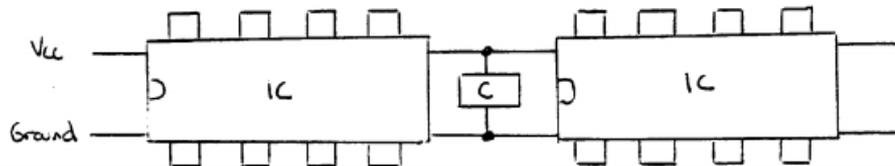


As trilhas que conectam o capacitor de  $V_{cc}$  e o CI devem ser tão curtas quanto possível e colocadas próximas entre si para minizar a área de loop.

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



Poor placement of  
decoupling capacitor



better placement  
of decoupling  
capacitor

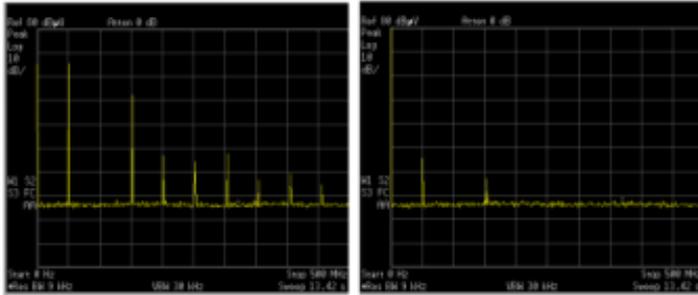
(PAUL, 2006)  
(EM research group at Michigan )

# PCBs: Planos de Terra

## Radiation Example, 50 MHz Clock



- Adding ground plane reduces emission of fundamental  $\approx 40$  dB



No Ground Plane

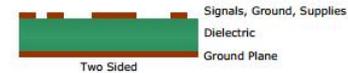
With Ground Plane  
(Micro-Strip)

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.

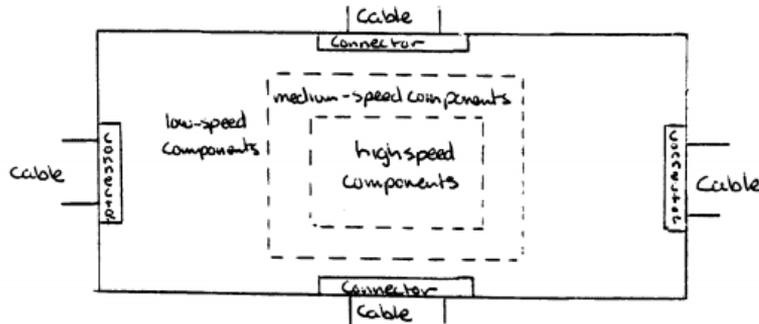


Figure 13. Placement of various-speed components on PC board.

(PAUL, 2006)

(EM research group at Michigan)

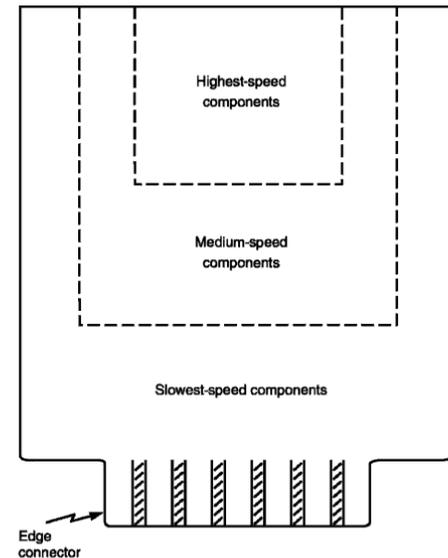


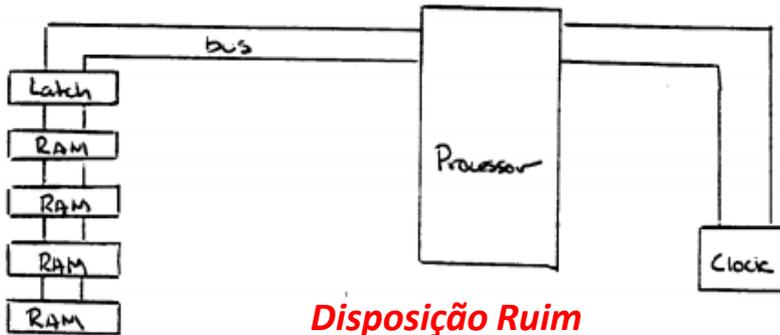
FIGURE 11.34 Keeping the highest-speed components away from offboard connectors.

# PCBs: Disposição de componentes



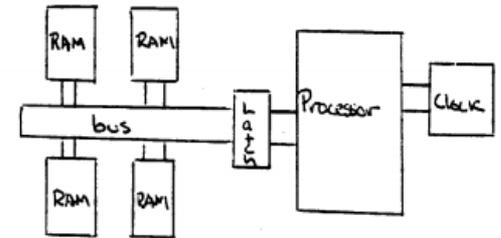
Conexões entre osciladores e CIs que usam o sinal dos osciladores devem ser feitas o mais curto possível. A fim de minizar as áreas de loop, o sinal e caminhos de retorno do clock devem ser paralelizados próximos.

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

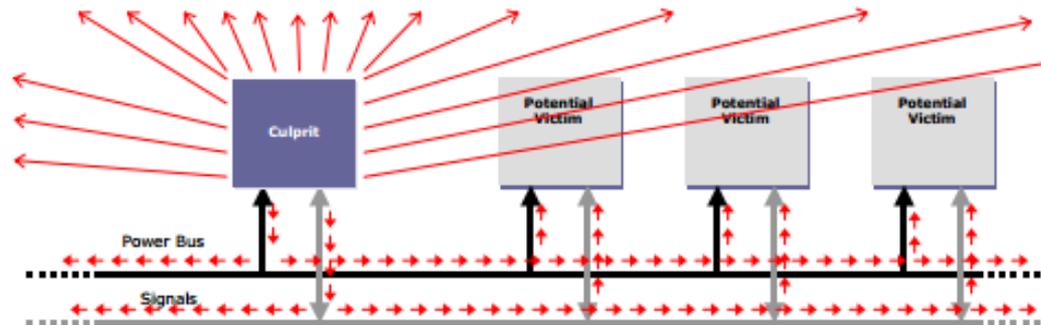
Figure 12. PC board component configurations.

# Integração de Sistemas

## System Partitioning/Guidelines



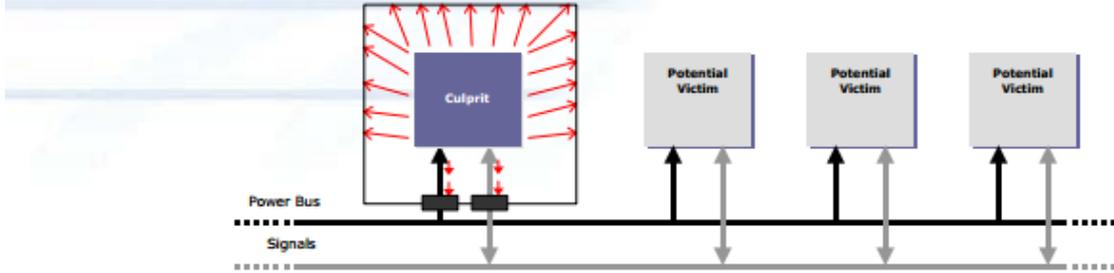
- ◆ Minimize interconnections between WRAs/LRUs
- ◆ Minimize the distribution of analog signals
- ◆ Control interference at the source



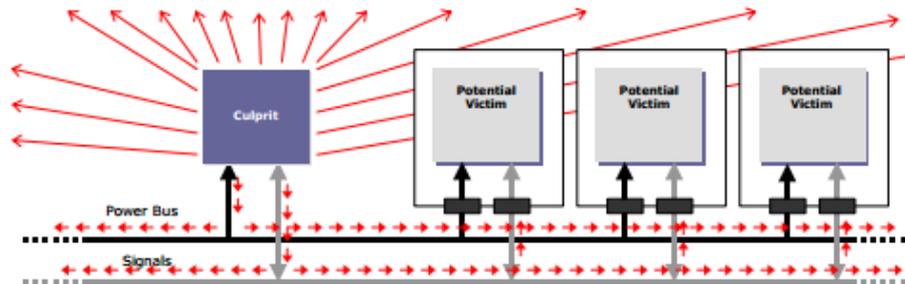
# Integração de Sistemas

## Control Interference at the Source

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



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



# Referências Bibliográficas



PAUL, C. **Introduction to Electromagnetic Compatibility**. 2ª ed. Wiley, Janeiro de 2006.

OTT, H. **Electromagnetic Compatibility Engineering**. Wiley, Agosto de 2009.

LAWSON, A. **A Beginners Guide to EMC**. Apresentação da TÜV SÜD Product Service.

COLOTTI, J. **EMC Design Fundamentals**. Apresentação da Telephonics – Command System Division, 2003.

EMC Research Group at Michigan State University. **Notas de aula de ECE407: Electromagnetic Compatibility**. Disponíveis em:

<http://www.egr.msu.edu/em/research/goali/notes/>. Acessado em 02/07/2014.

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