Expert System EMC Analysis of Automobile Electronics

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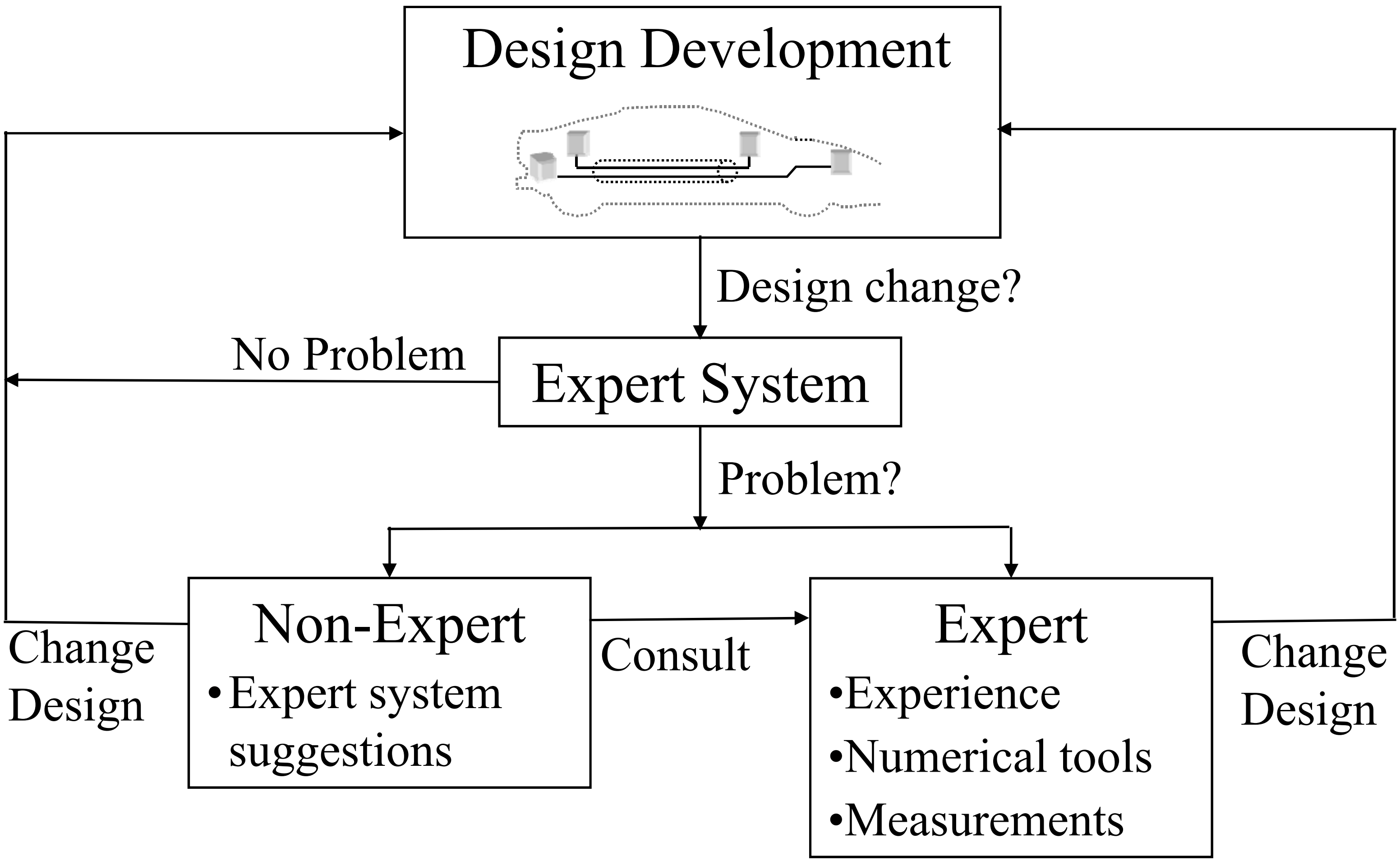
Introduction

- Identifying EMC problems early increasingly important.
  - Increasing complexity
  - "Late" fixes often expensive or impractical
- Early identification is challenging
  - Prototypes expensive and available too late
- Full-wave modeling often impractical
  - Lack of information
  - High system complexity
  - Long simulation time
  - Impact of specific components/structures difficult to assess

Expert System Characteristics

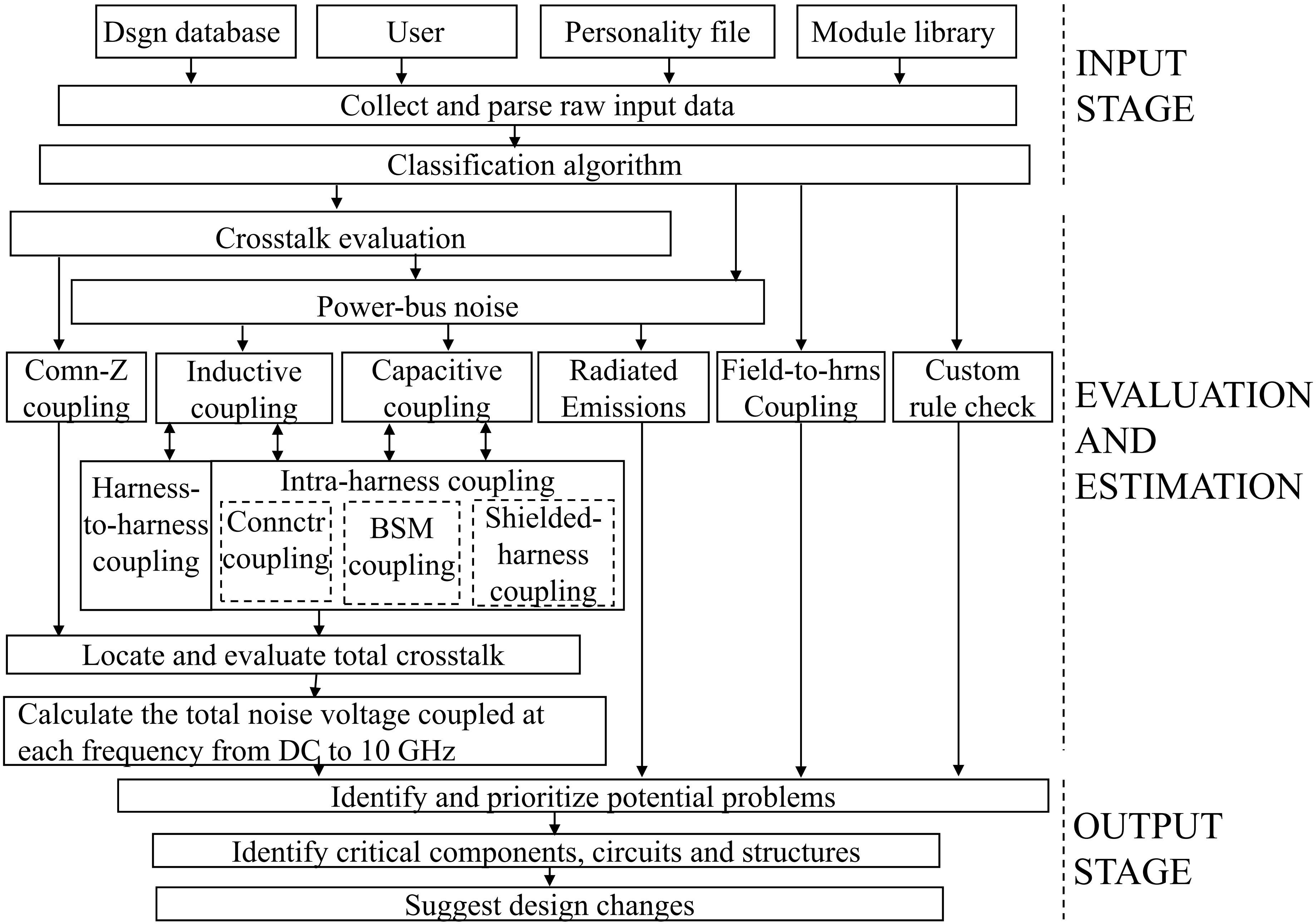
- Expert system is being designed to
  - Apply simplifying approximations and rules of thumb
  - Rapidly perform an analysis and return results accurate enough to determine significant problems and their cause even with incomplete information
  - Help with
    - Wire harness routing
    - Placement of components
    - Radiation and immunity issues
    - Component grounding
    - Test plan formation
  - *Assist* the expert and the non-expert
    - Not replace

Design Flow with Expert System

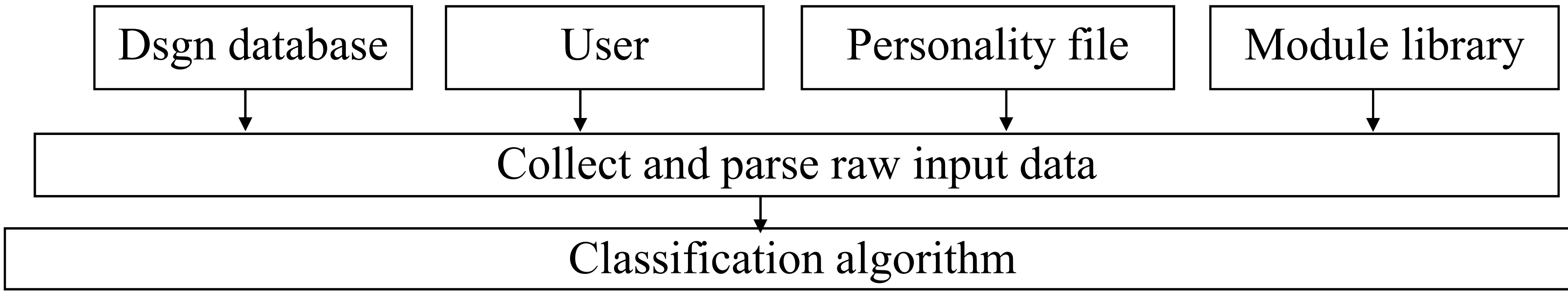


Architecture

Expert System Architecture

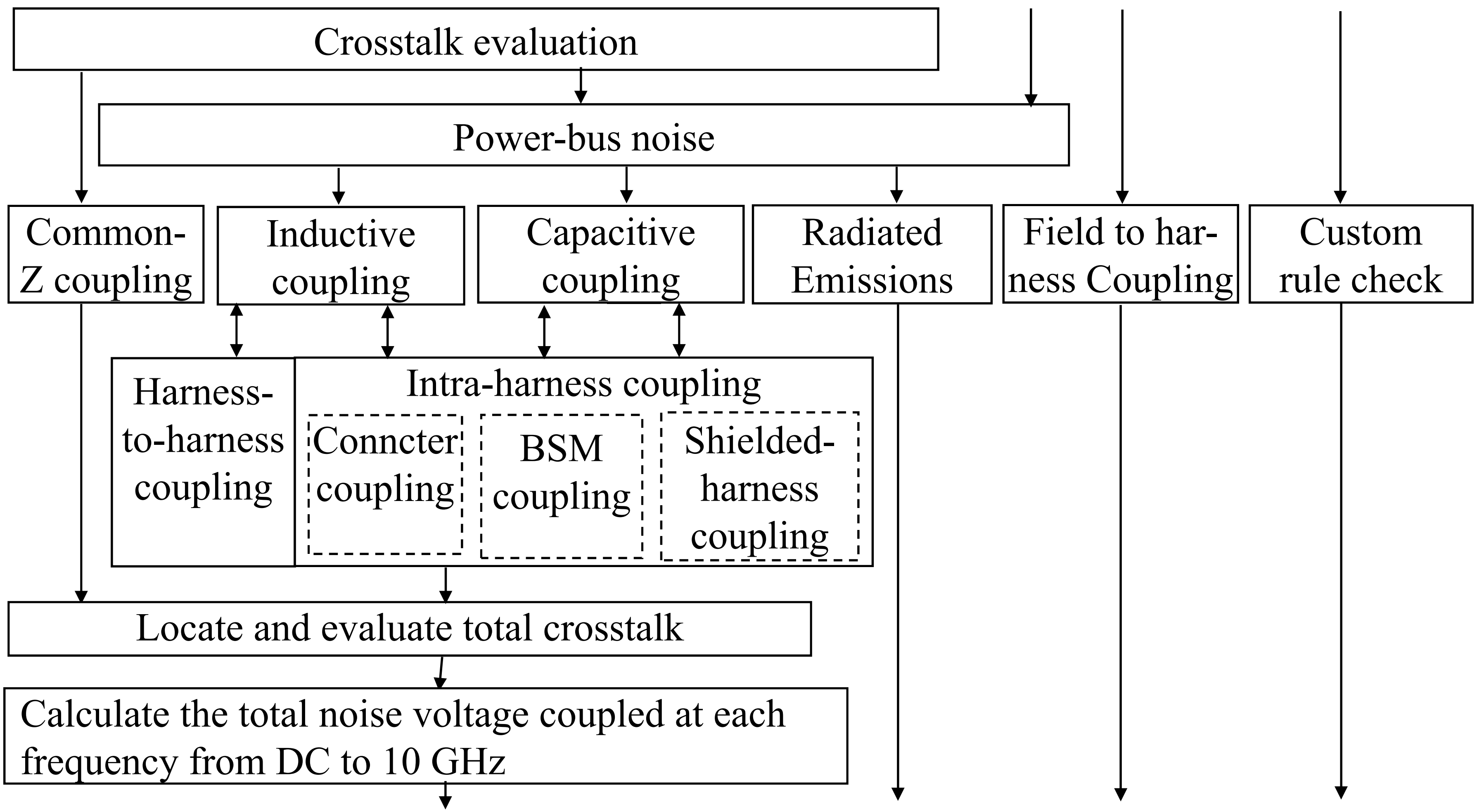


Input Stage



- Automatically gather information required for analysis
- Identify and classify circuits
  - Circuit characteristics determined from design database or inferred from component characteristics or design defaults

Evaluation Stage



Output Stage

Identify and prioritize potential problems

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Identify critical components, circuits and structures

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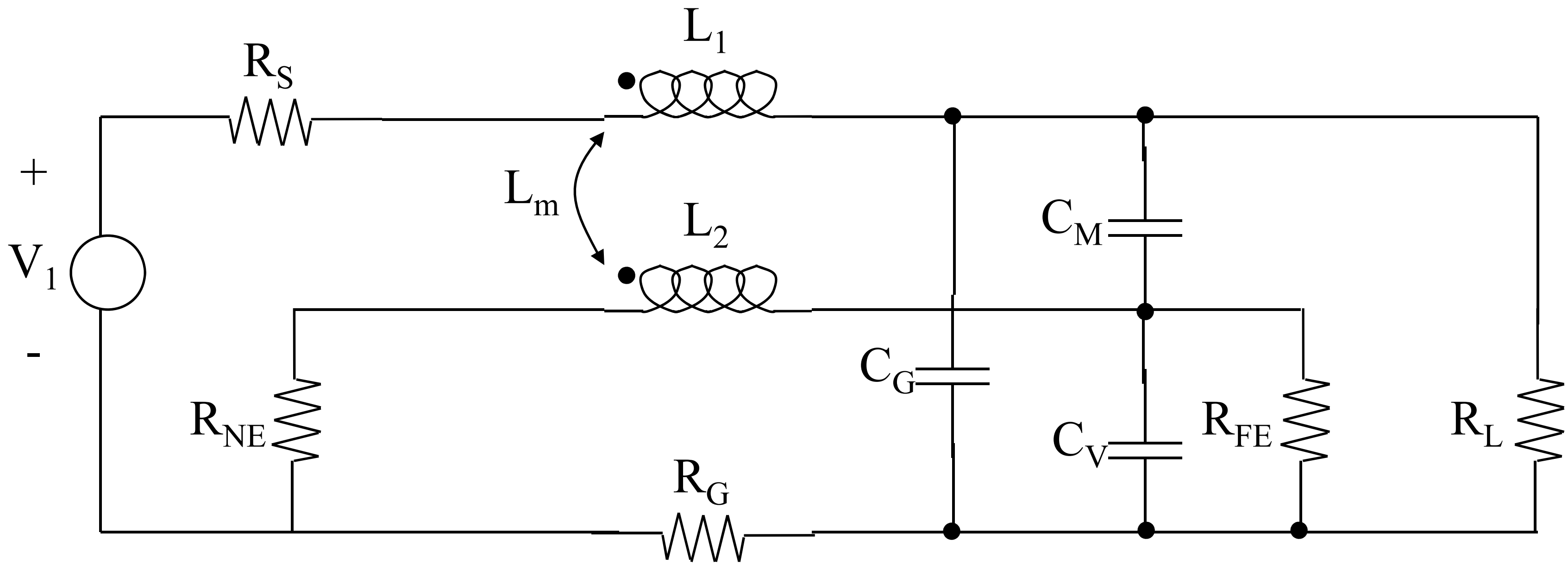
Suggest design changes

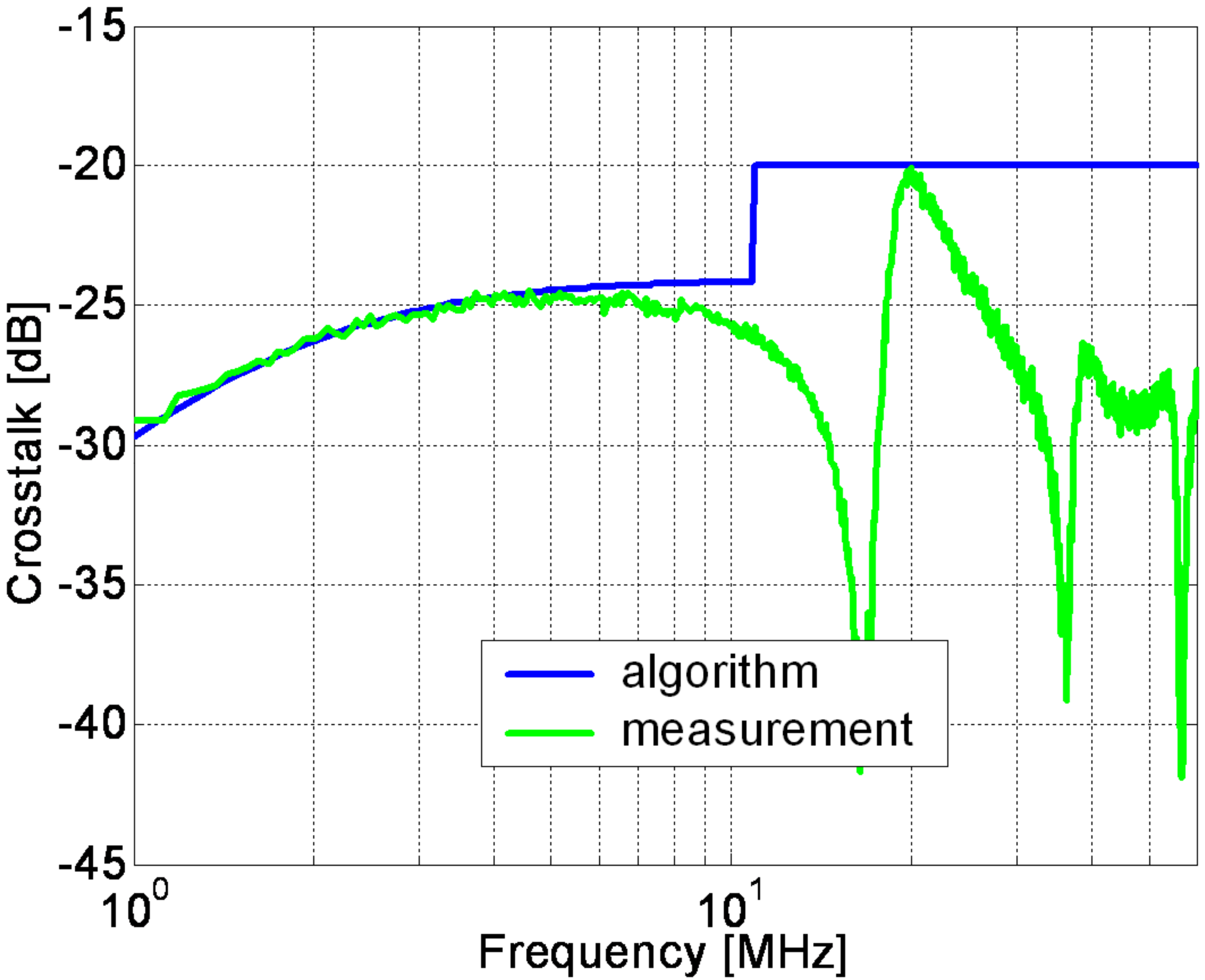
The Algorithms

Crosstalk Algorithms



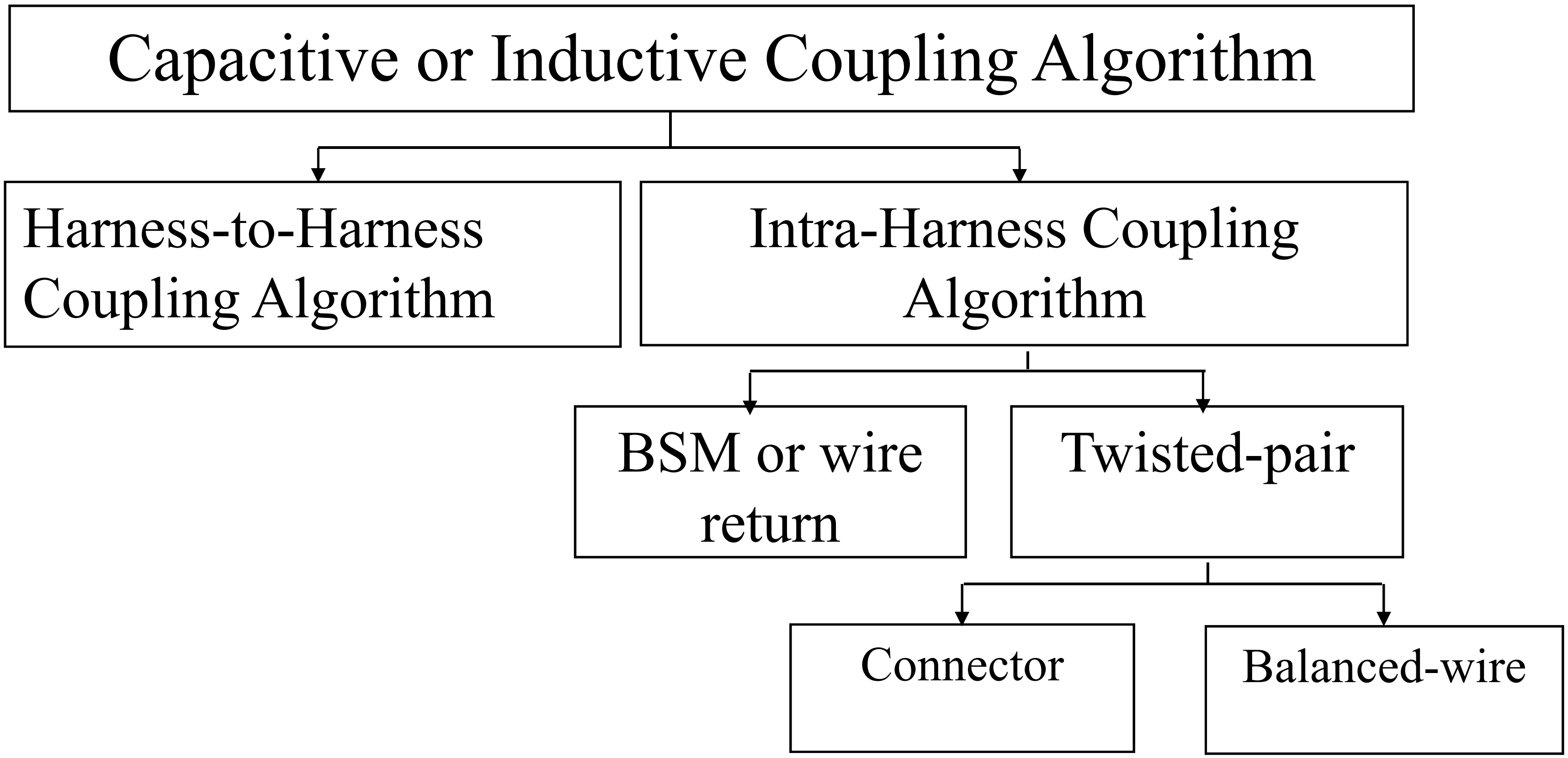
- Based on variations of lumped-element models and simplifications of transmission-line or antenna theory
- Worst-case assumptions

Calculation of Crosstalk

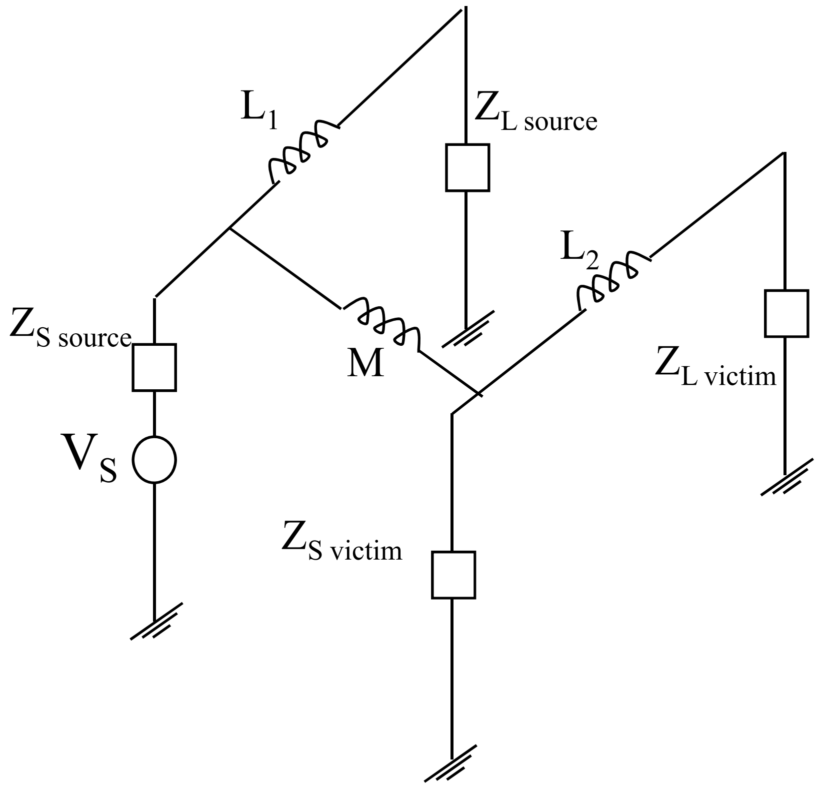


Inductive and Capacitive Coupling (Low Frequency)

Inductive and Capacitive Coupling



Inductive Coupling (Low Frequency)



$V_{NOISE} = I_{culprit} * \omega * M_{TOTAL} * [Z_L / (Z_L + Z_S)]_{victim}$ (continuous wave)

or

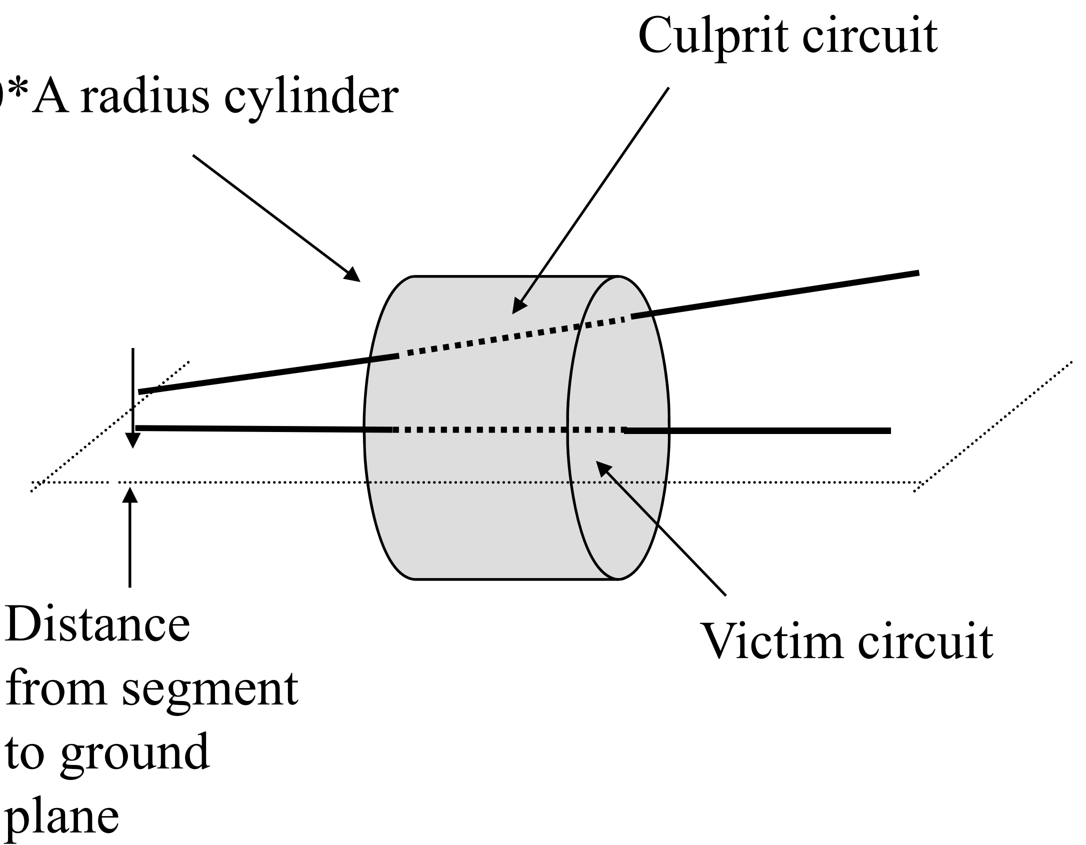
$V_{NOISE} = \Delta I_{culprit} / t_{rise/fall} * M_{TOTAL} * [Z_L / (Z_L + Z_S)]_{victim}$ (transients)

Inductive Coupling Algorithm

- Identify circuits (loops)
- Calculate inductive coupling if
  - Culprit circuit is classified as R2 or R3 (high noise)
  - Victim circuit is classified as S2 or S3 (highly sensitive)
  - Impedance of culprit circuit < 400 ohms
- Calculate intra-harness inductive coupling for circuits that share the same harness
- Calculate harness-to-harness inductive coupling for circuits in different harnesses.
- Sum coupled noise from all sources
- Evaluate result

Identification of Segments

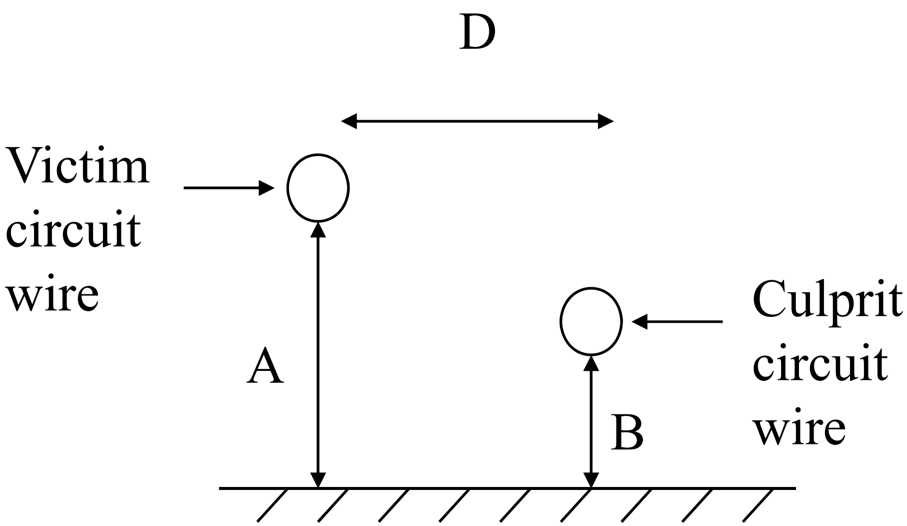
$$M = k\sqrt{L_1 L_2}$$



- Harness divided into 10 cm segments
- Significant coupling assumed possible within 10X distance to return

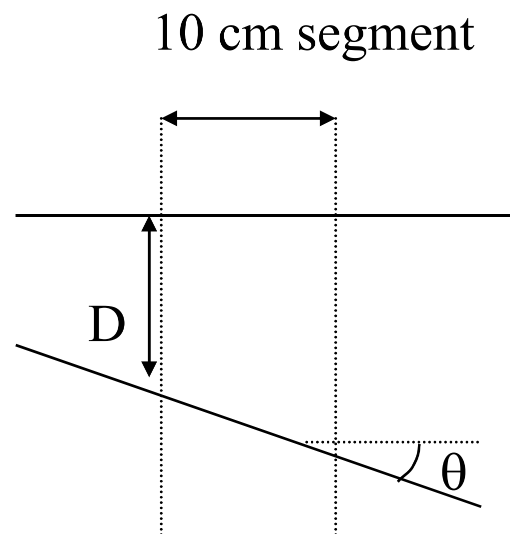
Harness to Harness Coupling (Low-Frequency)

Cross-section



Configuration of wires above signal return plane

Top view

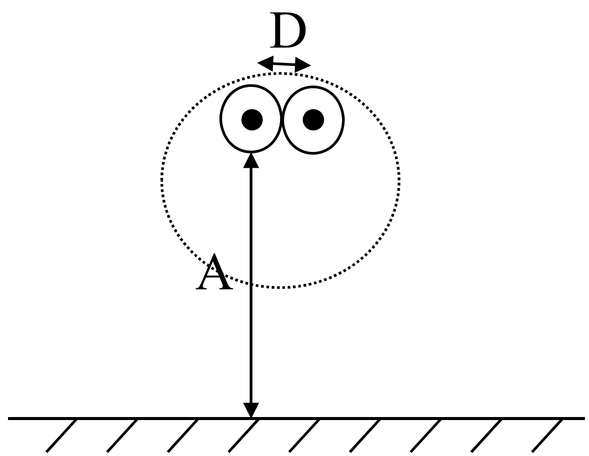


Angle calculated between segments and included in calculation of mutual inductance

Mutual inductance for segment is

$$M_{segment} = \frac{\mu_0}{4\pi} * \cos\theta * \ln(1 + 4*A*B/D^2) * (10\text{ cm})$$

Intra-Harness Coupling (BSM Return)

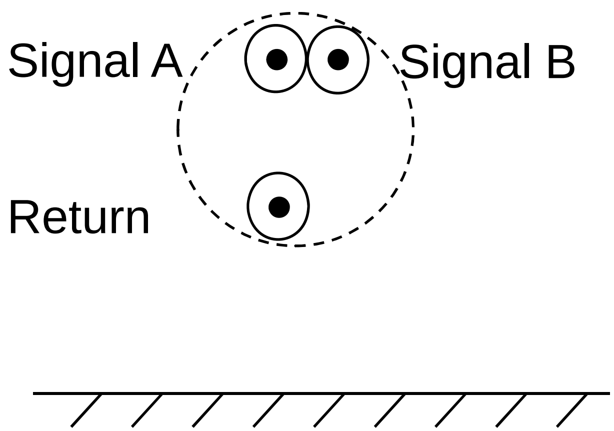


- Segment harness into 10 cm lengths
- Determine the height of the circuits, A , above BSM.
- Assume worst case coupling – the two circuits lie right next to each other with spacing D = insulation thickness.
- Mutual inductance for segment

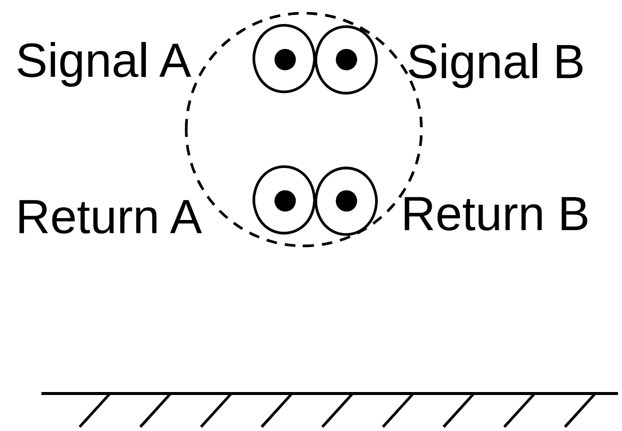
$$M_{segment} = \frac{\mu}{4\ \pi} \ln\left(1 + 4{*}A^2/D^2\right) {*}(10\ \text{cm})$$

Intra-Harness Coupling (Other Configurations)

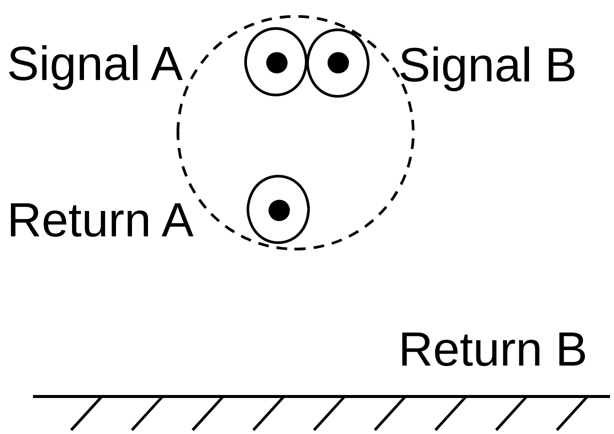
Common wire return



Separate return wires

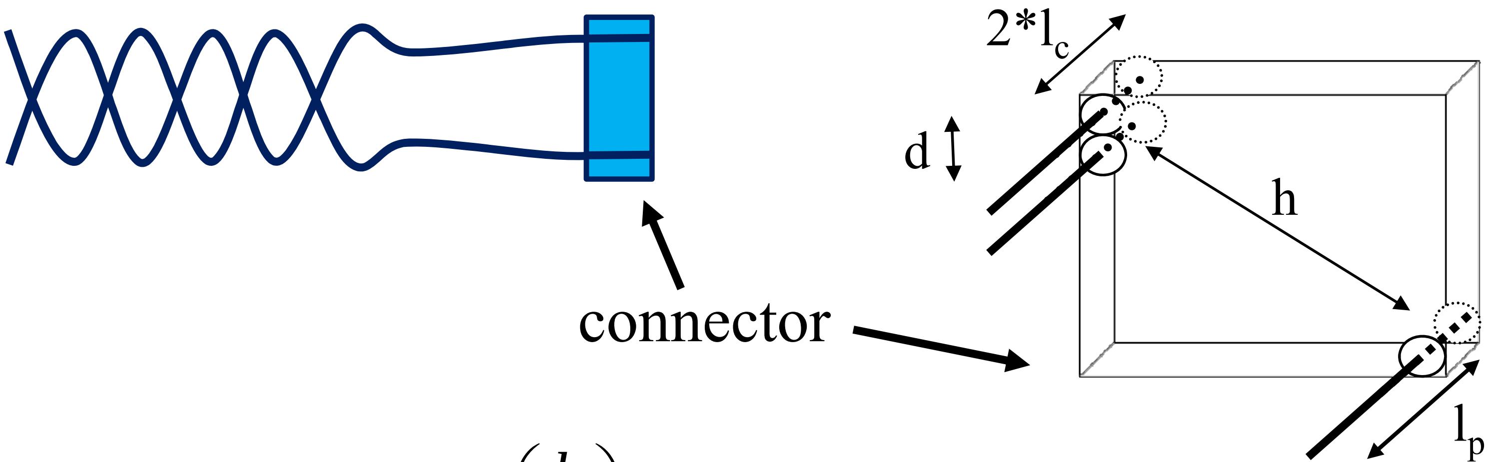


Wire + body return



Algorithms generally assume worst-case wire positions

Coupling to/from Twisted Pairs

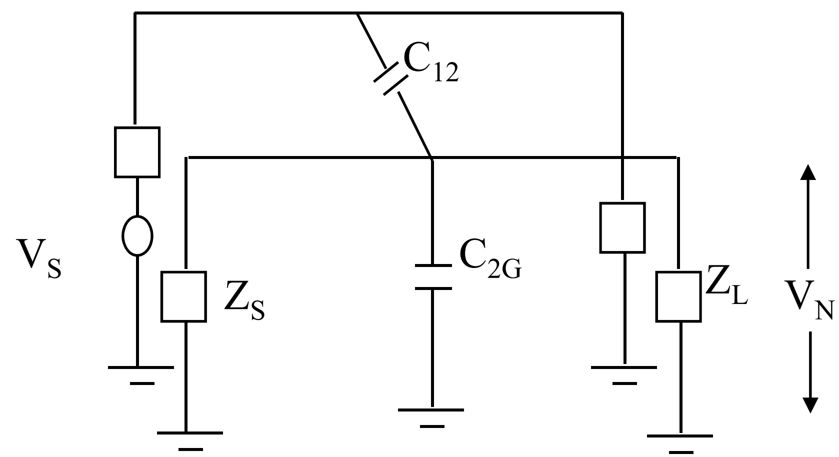


$$M_{connector} \approx \frac{\mu}{2\pi} \ln\left(\frac{h}{d}\right)\left(l_p + l_c\right)$$

- Wires are untwisted at connectors.
- Coupling is assumed to be due to position of wires/pins within connector, length of connector, and length of pigtail to connector

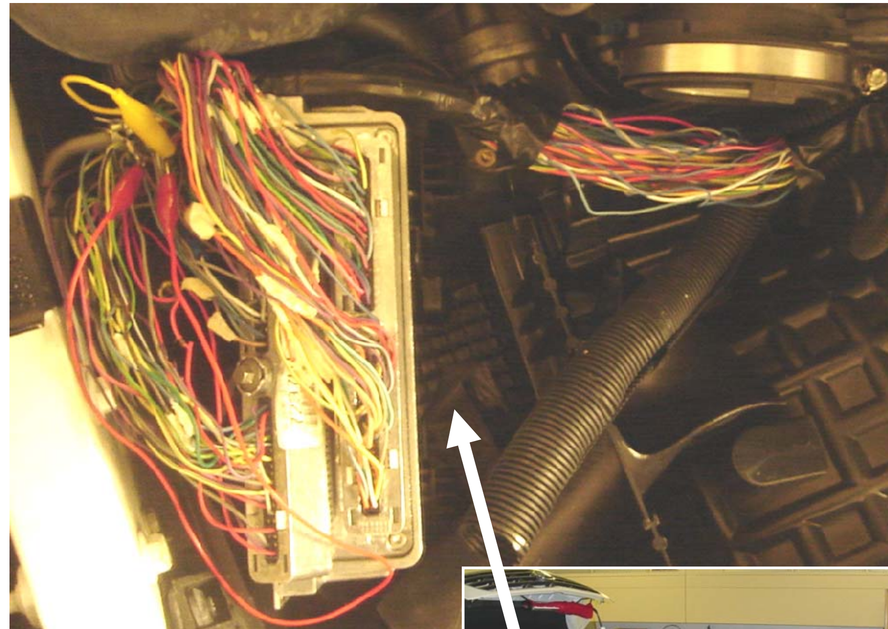
Capacitive Coupling

- Predicts noise due to electric field coupling
  - Calculate mutual capacitance between circuits
  - Calculate capacitance to ground
  - Calculations differ for:
    - intra-harness coupling
    - harness-to-harness coupling
  - Calculate noise voltage for transient and continuous signals

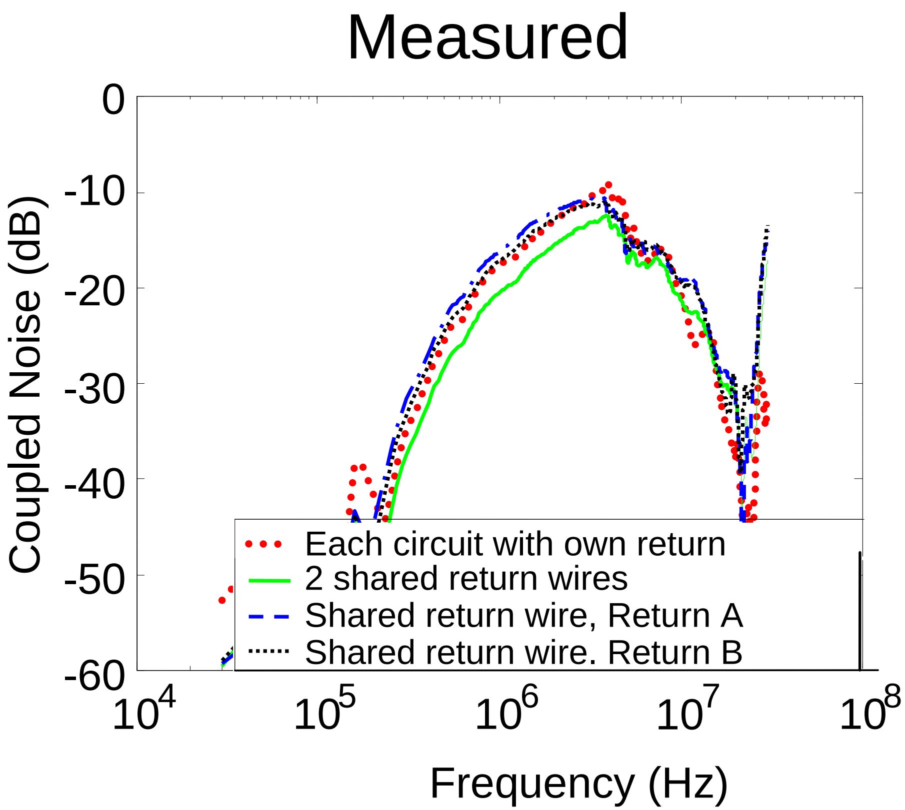


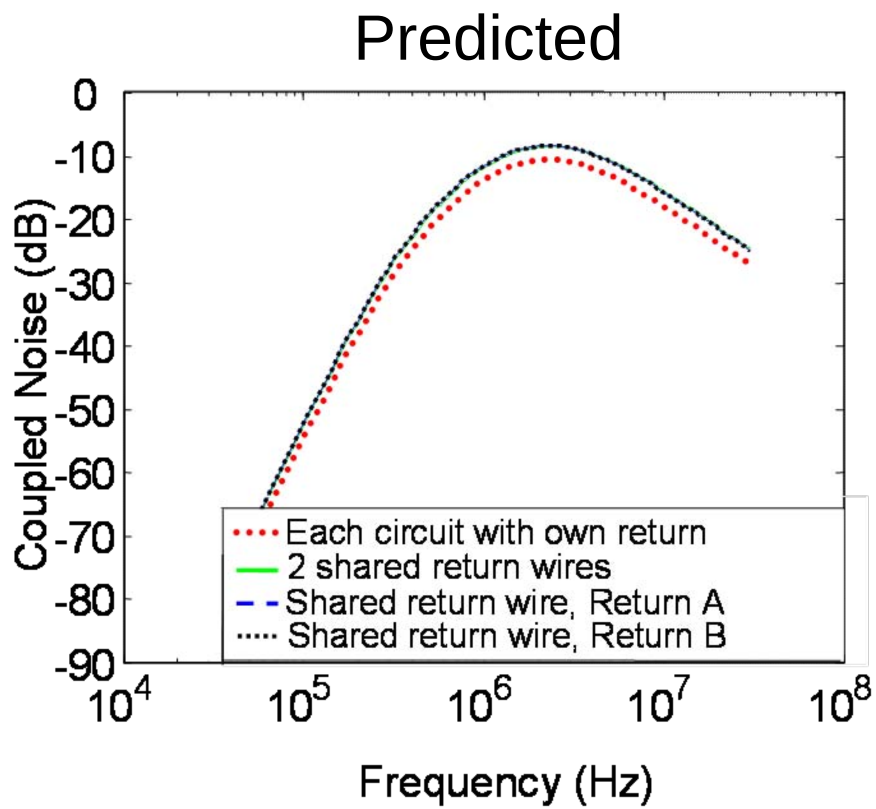
Validation

- Crosstalk was measured and predicted in passenger and engine compartment
  - Used real and imposed load impedances
- Configurations:
  - Separate return wires
  - Shared return wire
  - Body surface metal (BSM) return
  - BSM and wire return
  - Combination of BSM and wire return
  - Twisted pair



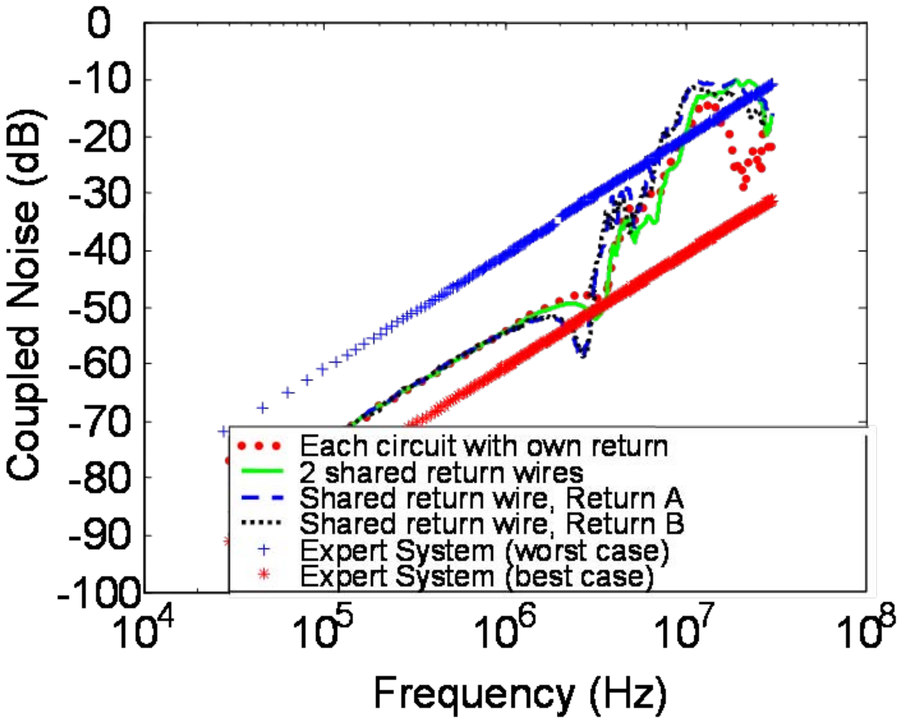
Inductive Coupling

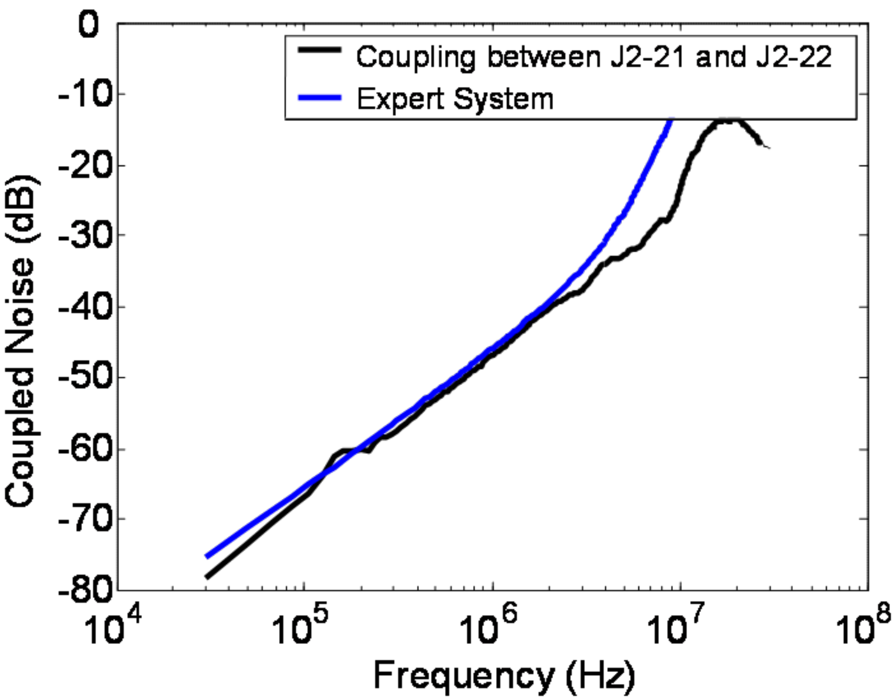




- Low-frequency estimates reasonable to 10-20 MHz
- Worst-case estimates overestimated measurements by a few dB to 10-15 dB

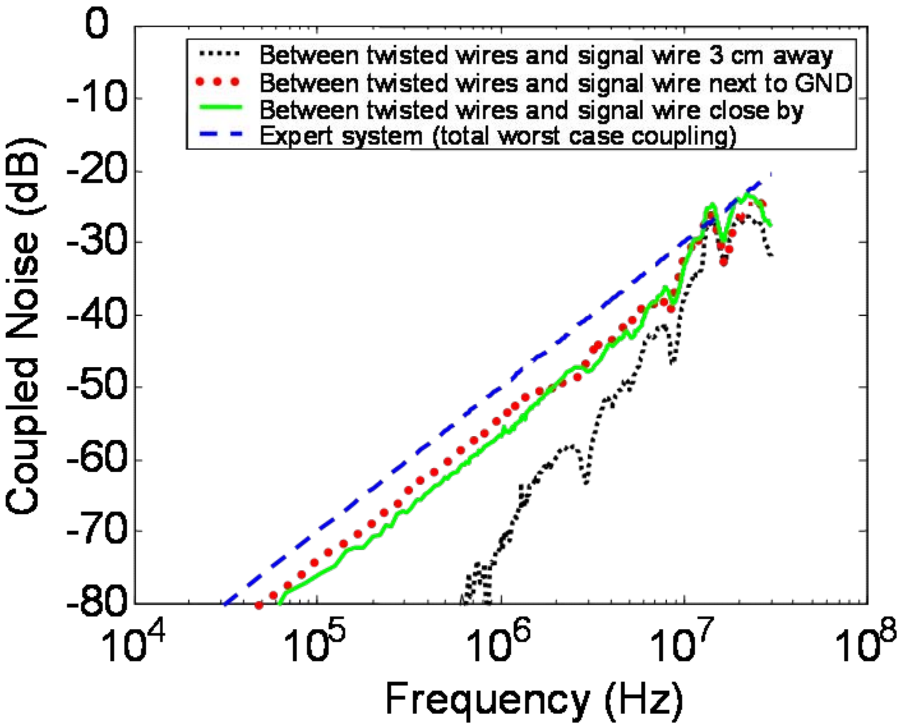
Capacitive Coupling

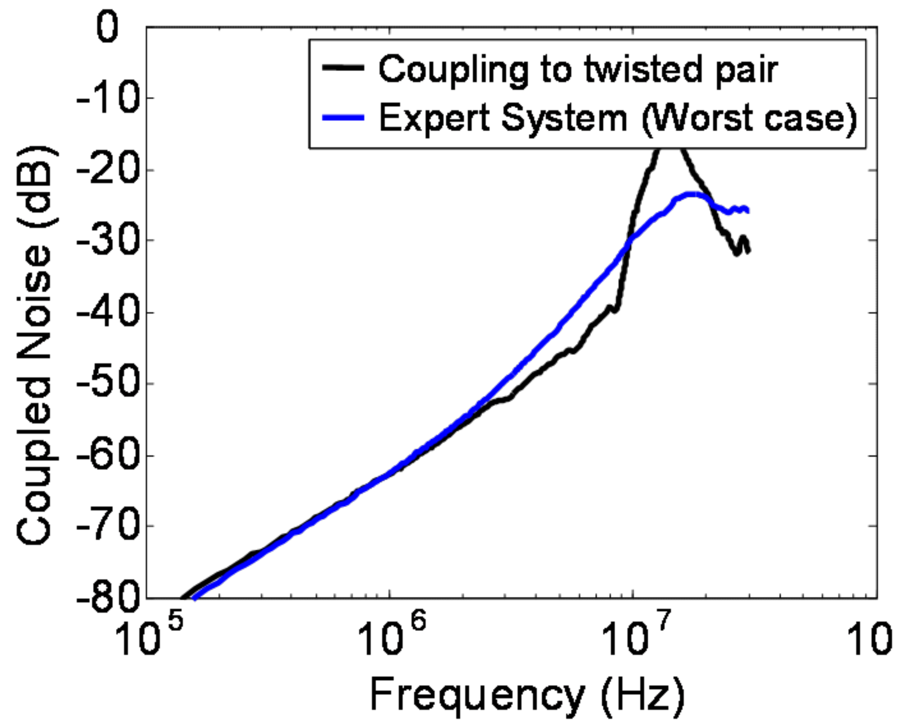




- Worst-case estimates overestimated measurements by a few dB to 10-15 dB

Twisted Pair

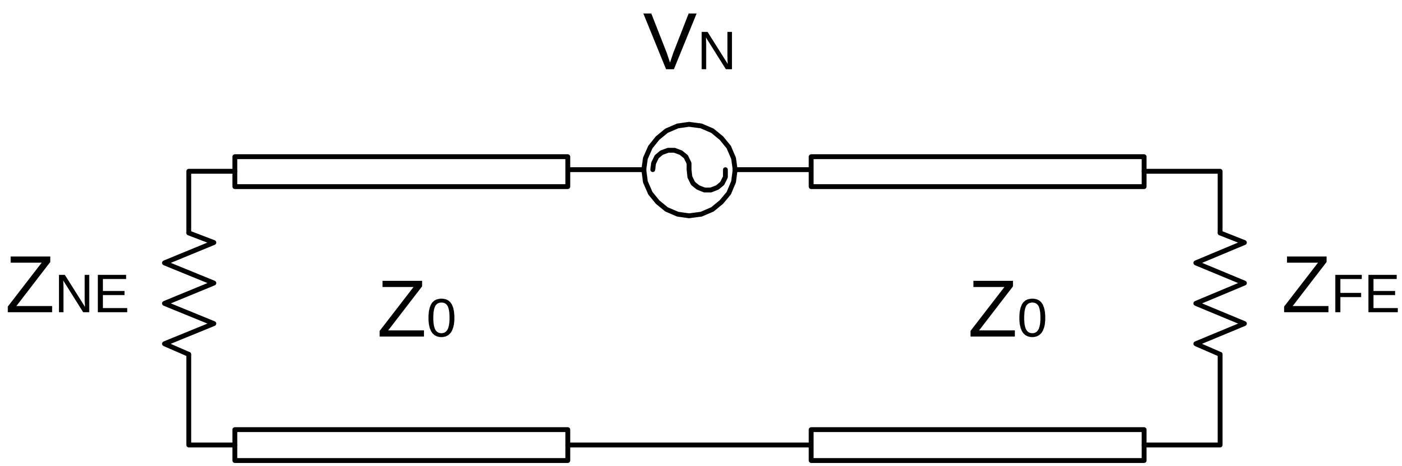




- Expert system algorithms overestimated results by a few dB to several dB

High-Frequency Crosstalk

Prediction at High Frequencies



Multi-conductor transmission-line models required when the circuit is electrically large, but calculations too complex for an expert system

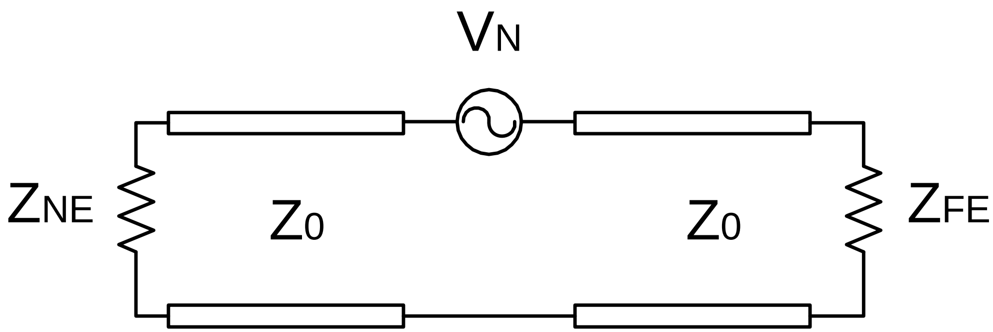
Prediction at High Frequencies

- Simplify crosstalk formulas by assuming:
  - Transmission line geometry is uniform along length
  - Homogeneous medium
  - Defining maximum crosstalk as:

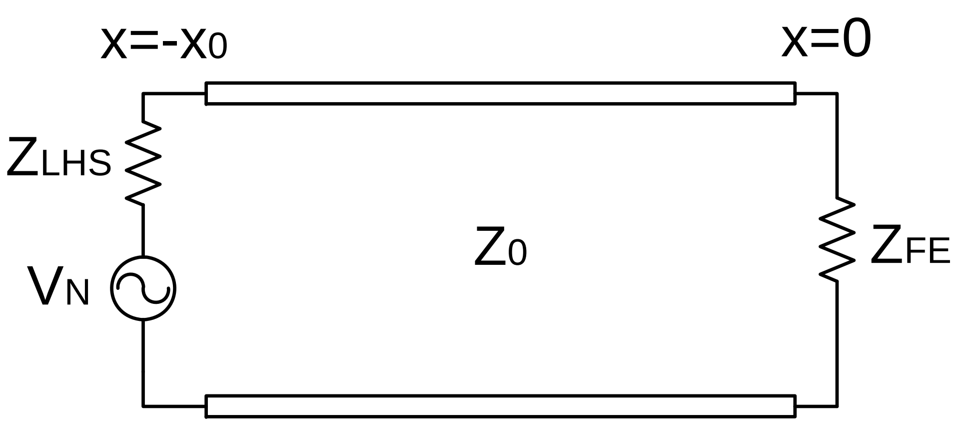
$$X = \frac{V_{2MAX}}{V_{1MAX}}$$

High-Frequency Coupling

The maximum voltage on the culprit circuit will couple to victim at some location



The noise voltage will drive the victim's transmission line



Simplified formulas

Maximum crosstalk is approximately:

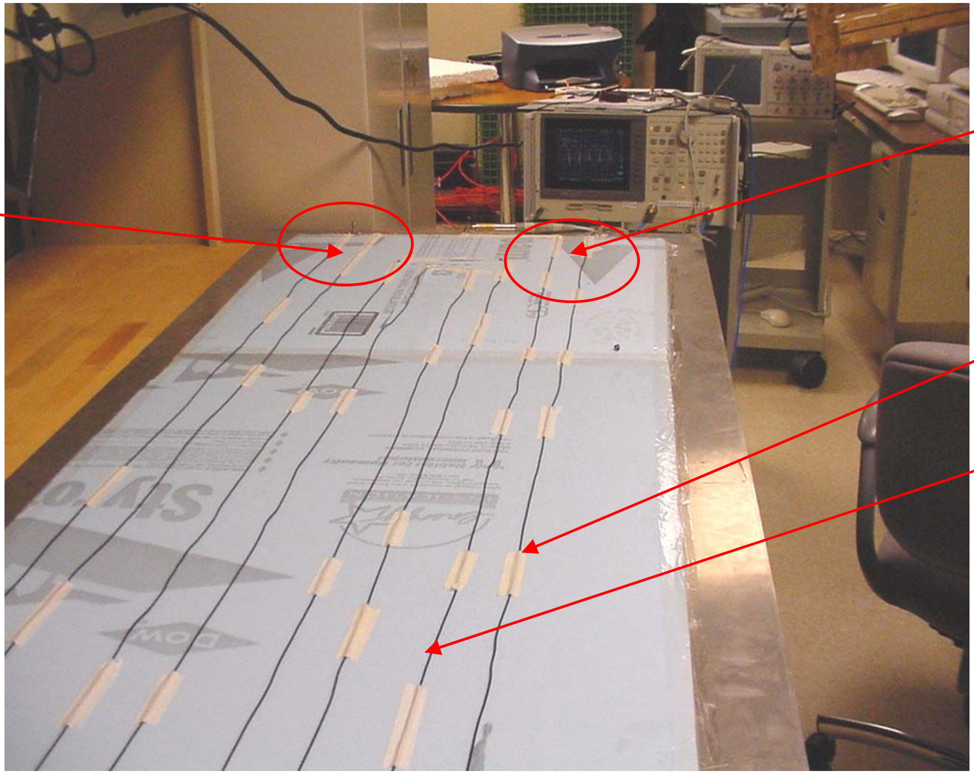
$$X_{MAX} = \frac{C_m}{C_m + C_{22}} \frac{(1+|\Gamma_{NE}|)(1+|\Gamma_{FE}|)}{2(1-|\Gamma_{NE}||\Gamma_{FE}|)}$$

or

$$X_{MAX} = \frac{l_m}{l_{11}} \frac{(1+|\Gamma_{NE}|)(1+|\Gamma_{FE}|)}{2(1-|\Gamma_{NE}||\Gamma_{FE}|)}$$

Experimental setup

Far end



Near end

Victim circuit

Culprit circuit

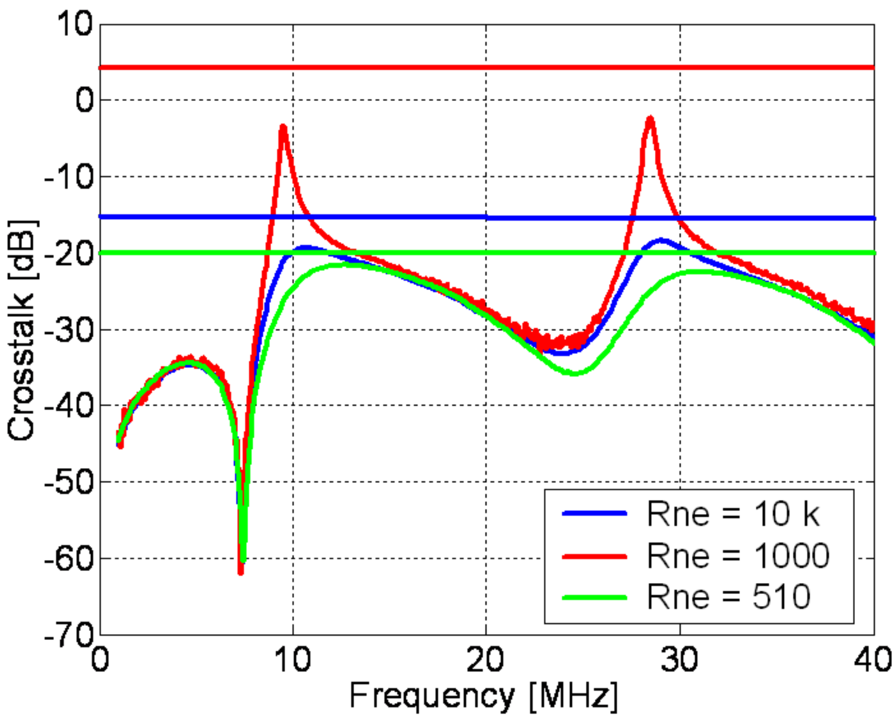
Wire length: 7.5 m

Wire radii: 0.8 mm, 20#

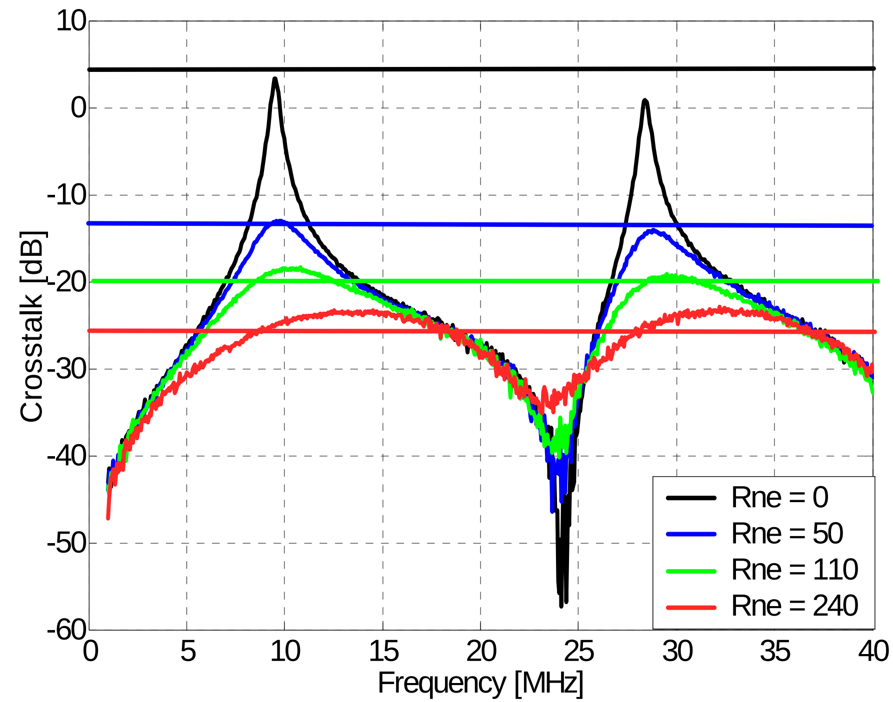
Height : 1.5 cm

Distance: 5 cm

Experimental results



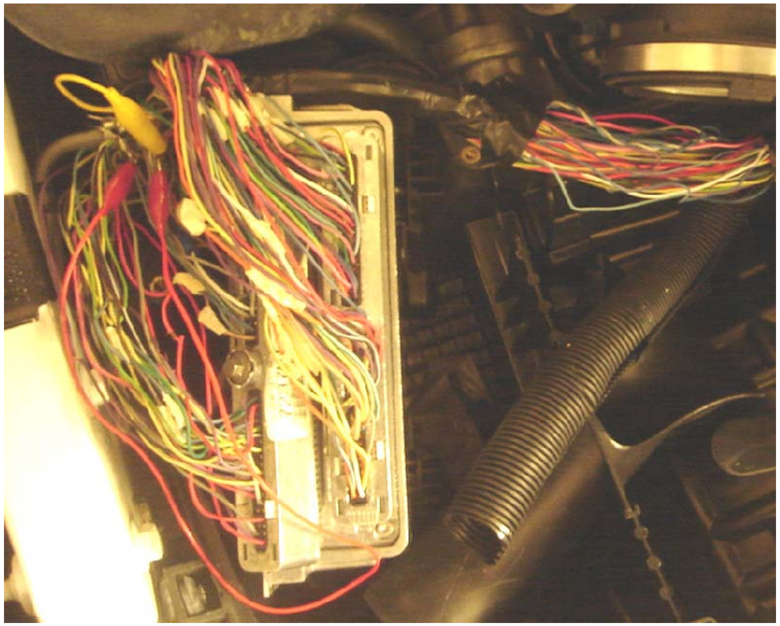
$R_S = 50\Omega$ $R_L = 0\Omega$ $R_{FE} = 0\Omega$

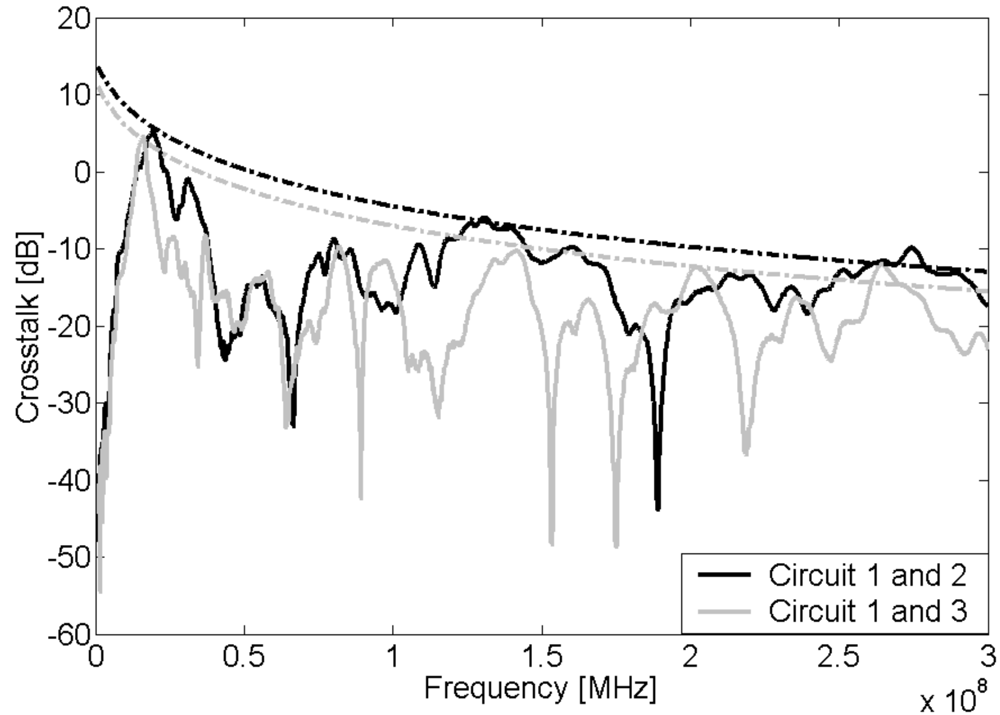


$R_S = 50\Omega$ $R_L = 0\Omega$ $R_{FE} = 10k\Omega$

The difference between the estimated and measured maximums are less than 6 dB

In-Vehicle Verification

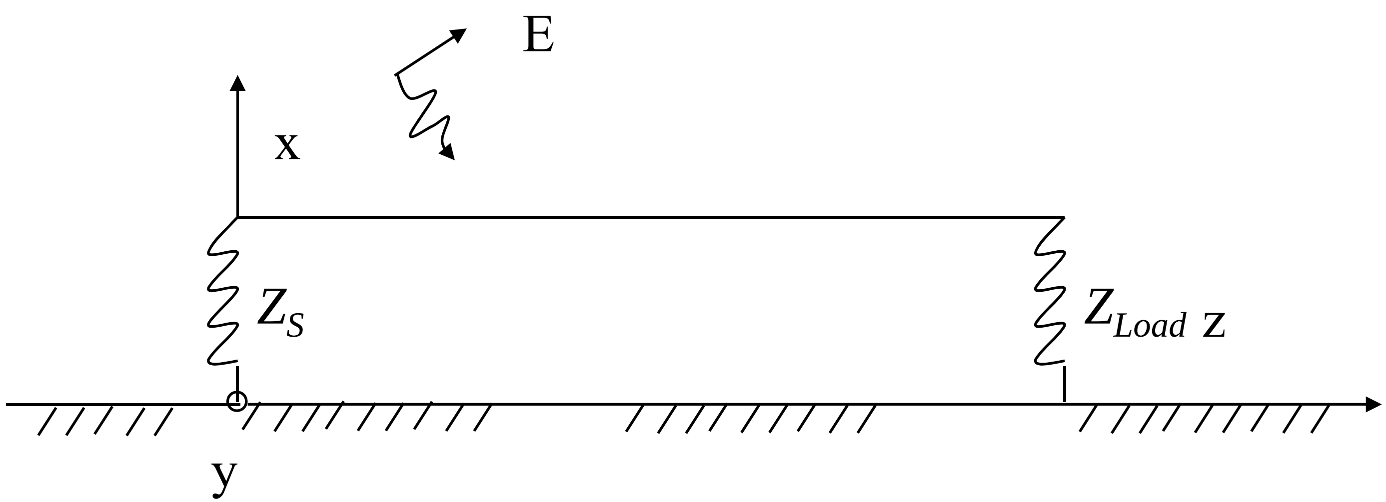




The approximation did a reasonable job of predicting maximum crosstalk in the vehicle

Radiated Emissions and Field-to-Harness Coupling

Radiated Emissions and Field-To-Harness Coupling



$$V_{Load} = E_{Ext} \times Gain$$

- Predict radiated emissions from circuits and coupling to circuits from an external field
  - Gain of circuit estimated using transmission line and antenna theory

Gain ($S < \lambda/4$)

$$Gain = \frac{2Z_{Load}H}{D}[Z_0(1-\cos(\beta S)+jZ_S\sin(\beta S)]$$

$$D = (Z_0Z_S + Z_0Z_{Load})\cos(\beta S) + j(Z_0^2 + Z_SZ_{Load})\sin(\beta S)$$

Where, H is the wire height over ground plane, S is the length of the wire, Z_0 is the characteristic impedance of the transmission line, Z_S and Z_{load} are source and load impedance respectively.

Gain ($s \geq \lambda/4$)

$Z_S > 300$ ohms:

$$Gain = \frac{2Z_{Load}Z_S H}{Z_0^2 + Z_S Z_{Load}}$$

$Z_S < 300$ ohms and $Z_{Load} < 300$ ohms:

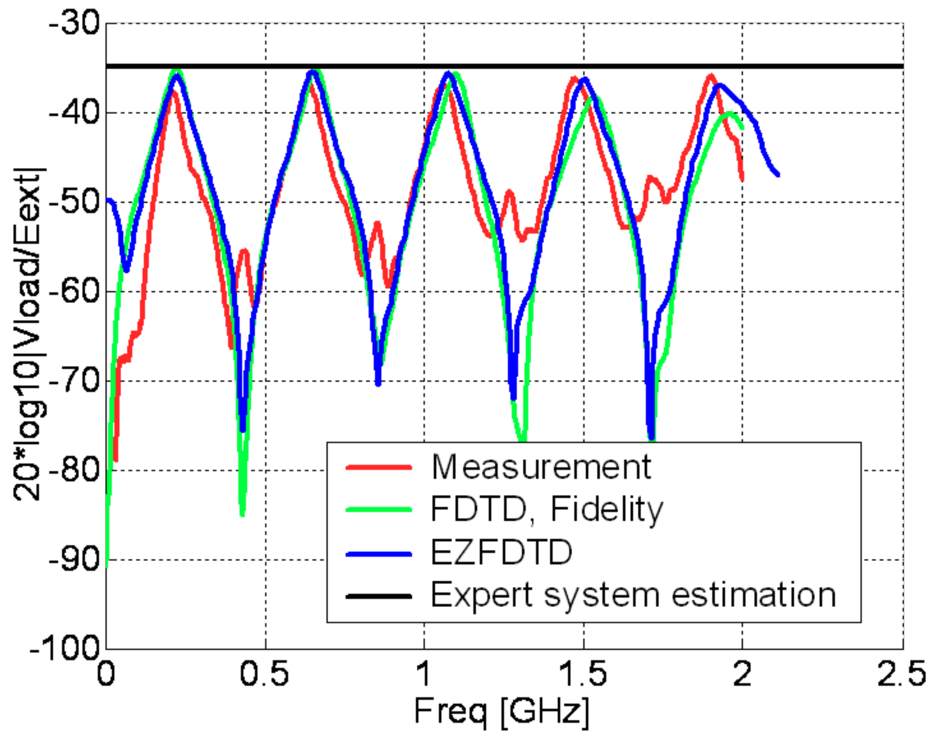
$$Gain = \frac{4Z_{Load}H}{Z_S + Z_{Load}}$$

$Z_S < 300$ ohms and $Z_{Load} > 300$ ohms:

$$Gain = \frac{2Z_{Load}Z_0 H}{Z_0^2 + Z_S Z_{Load}}$$

Verification

Top view of circuit

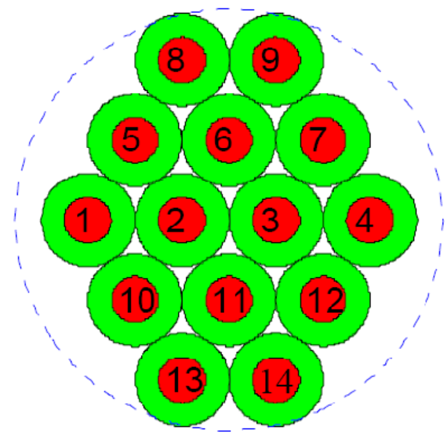


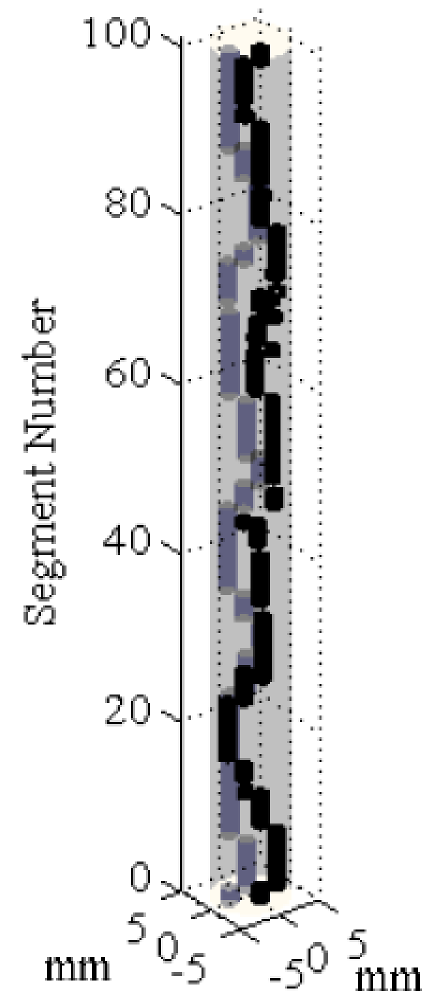
Algorithms were verified experimentally and through simulation

Accounting for Statistical Variation

Accounting for Statistical Variation

- Statistical analysis may prevent over design, but must be fast for application in an expert system
- Evaluate simple statistical methods for expert system
  - Monty Carlo and approximate methods

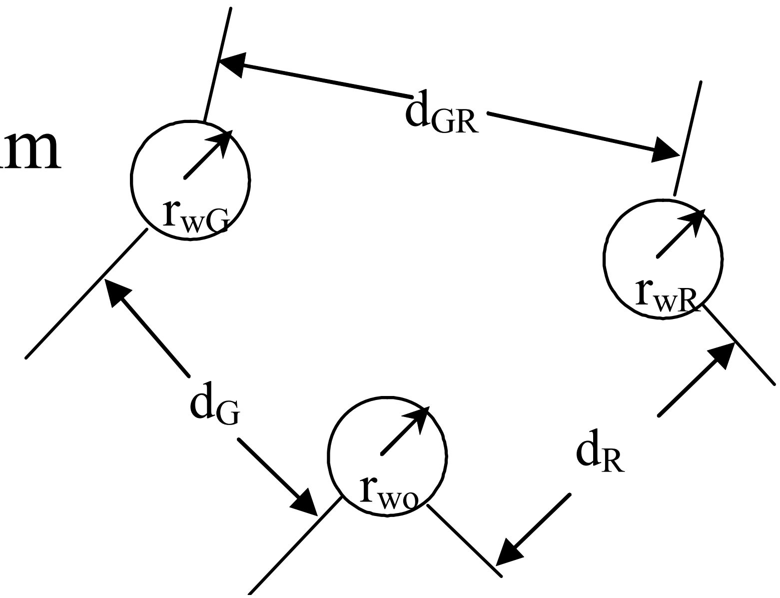




Pictures from S. Sun, J. Drewniak, and D. Pommerenke, “Common-mode radiation resulting from hand-assembled cable bundles on automotive platforms,” *Proceedings of the 2006 IEEE International Symposium on EMC,* vol. 2, pp. 298-303, Aug. 2006.

Example

- Using Monte Carlo methods for 3 cm diameter harness, r_w=0.5 mm
  - Average distance = 11 mm
  - Variance = 8.7 mm
- For two circuits sharing a return:

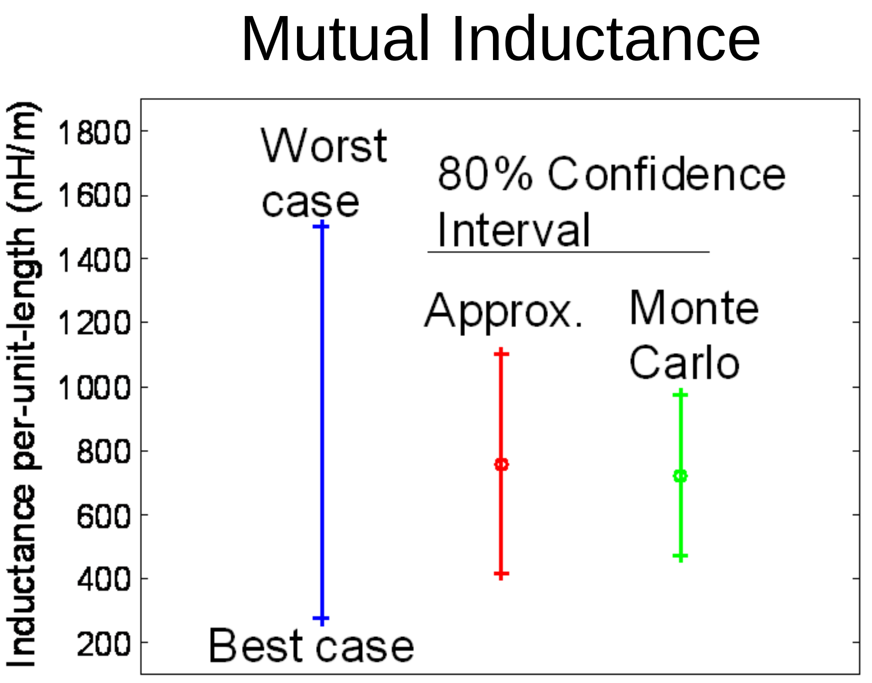


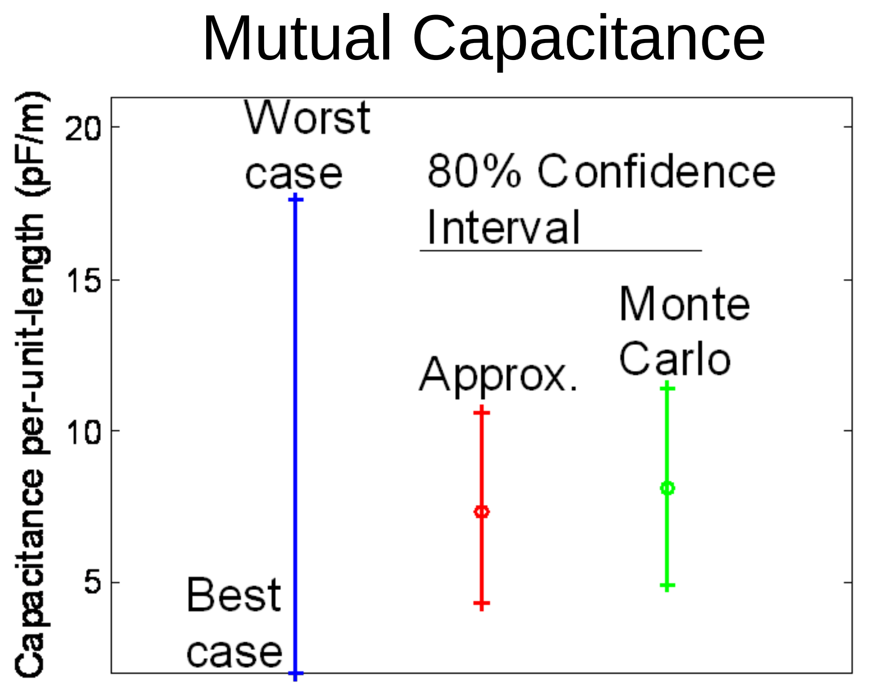
$$\overline{l_m} \approx \frac{\mu_0}{2\pi} \ln\left(\frac{\overline{d_G}\,\overline{d_R}}{\overline{d_{GR}} r_{w0}} \right)$$

$$\sigma_{l_m} \approx \sqrt{\left[\frac{d(l_m)\sigma_{d_G}}{d(d_G)} \right]^2 + \left[\frac{d(l_m)\sigma_{d_R}}{d(d_R)} \right]^2 + \left[\frac{d(l_m)\sigma_{d_{GR}}}{d(d_{GR})} \right]^2}$$

- Capacitance calculated similarly

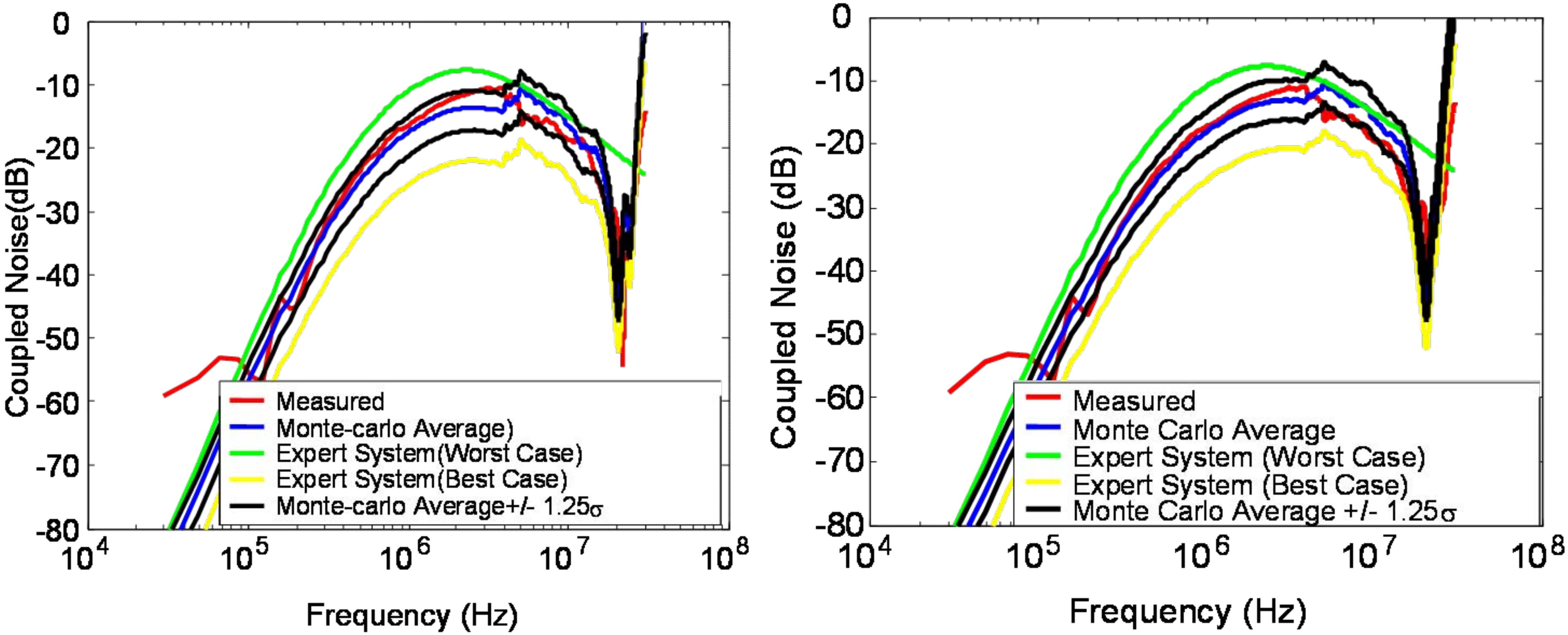
Example (cont.)





- The approximate method gave about the same confidence interval as the Monte Carlo estimate
- Worst case was 5-12 dB outside confidence interval

Comparison to Measurements



- Estimated values were typically near to the expected average, within the 80% confidence interval

Conclusions

- An expert system can improve EMC early in the design
  - Fast
  - Works with limited information
  - Quantifies contribution of specific structures/modules/etc
- Based largely on “reasonable” worst-case estimates
  - Generally accurate to within a several dB to 10-30 MHz
  - Estimates maximum coupling within about 6 dB at higher frequencies
- Simple methods can be used to apply statistical analysis