Estimation of the Statistical Variation of Crosstalk in Wiring Harnesses

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Abstract — **Analyzing interference problems in vehicle wiring harnesses requires fast and accurate methods of approximating crosstalk. Worst-case approximations using lumped element models are fast and easy to use, but run the risk of overestimating problems. Statistical methods that account for the random variation of wire position help prevent overdesign, but are often difficult and time-consuming to apply and lack a clear link between problems and their cause. Here we investigate the use of simple lumped-element models to predict the statistical variation of crosstalk in wire harness bundles. Models are based on lumped-element approximations, where inductance and capacitance values are calculated for a single bundle cross-section, and only the circuit position is varied. Accuracy was evaluated by comparing results to numerical simulations. The method does a good job of quickly predicting the reasonable worst-case values of crosstalk due to inductive or capacitive coupling.**

Keywords: **Approximation methods, crosstalk, modeling, vehicles, harness, statistics.**

I. INTRODUCTION

Electrical systems in automobiles and other vehicles should be evaluated for electromagnetic compatibility (EMC) problems early in the design process. The challenge is developing methods that can account for the considerable complexity of modern vehicle designs while delivering estimates of acceptable accuracy at an acceptable speed. Full-wave numerical models can deliver highly accurate solutions but may require considerable time to simulate and prepare models of geometry. Obtaining accurate models of geometry early in the design process may also be a challenge, since the vehicle geometry may not yet be fully specified. Even when available, there is the additional problem of refining the geometry to a form that allows simulations to be performed in a reasonable amount of time. This refinement process is not always straightforward and often requires considerable human interaction. Accounting for the wide statistical variation in system parameters like the position of wires within a harness, the height of the wires, circuit terminations, and the like only adds to the challenge of calculating results with these tools.

One option for discovering EMC problems early in the design process is to use lumped-element approximations of crosstalk to determine worst-case coupling between circuits [1-3]. The advantage of this approximation is that calculations can be made very quickly with a limited amount of information. This approach has been shown to work well up to several tens of MHz in experiments in an automobile [3], though there is a risk of overestimating the coupling that is *likely* to occur. Experiments have shown worst-case calculations may overestimate crosstalk by as much as 20 dB depending on harness configuration [4].

Avoiding over design requires a statistical approach to analyzing crosstalk between circuits. Several statistical methods for analyzing crosstalk in a wire bundle have been proposed. Work in [4,5] experimentally examined the statistical variation of crosstalk as a function of wire position in the cable harness. The statistical variation in crosstalk was accounted for using a tolerance interval approach. Later work by Ciccolella and Canavero showed these results could be reproduced through simulation using a segmented multiconductor transmission line model, where wire position is varied from one segment to another and many configurations are explored using Monte Carlo methods [6]. Statistical variation can be better determined using methods that smoothly vary the wire path through the harness and that predict crosstalk from untried parameter configurations using interpolation techniques [7]. Such statistical methods have also been extended to predict common-mode radiation from cable harness bundles [8]. Attempts have been made to determine a closed-form expression for the probability distribution function of crosstalk in the harness [9], but so far numerical intervention is still required to calculate results.

For a statistical approach to be effective early in the design process, the approach must be fast and must be able to be applied with a minimum of information. Many existing approaches do not meet either criterion – for example, they may require both considerable information about harness geometry and require numerically modeling crosstalk over tens or hundreds of possible configurations. One method that helps to avoid these pitfalls was proposed by Bellan and Pignari [10]. This technique is based on the statistics of the inductance and capacitance matrix for a single cross-section and shows promise for working well at low frequencies.

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The following paper further explores the work in [10] to investigate the feasibility of this simple method to approximate statistical variation of crosstalk in wiring harnesses and to estimate "reasonable worst-case" coupling. Inductive and capacitive coupling is estimated using lumped-element models. Statistical distribution of crosstalk is estimated by assuming that wires may only take fixed positions within the harness and that crosstalk is dependent on the resulting statistical distribution of inductance and capacitance. The validity of the approach is examined through comparison to simulations made using the Random Displacement Spline Interpolation (RDSI) algorithm [8]. Crosstalk is first estimated using weak-coupling assumptions, where the influence of other circuits in the harness is ignored. The approach is then extended to find limits to possible crosstalk when the influence of other circuits becomes important.

II. WIRE HARNESS MODEL

Crosstalk was calculated using lumped element models. Lumped element models are reasonable when circuits are electrically short. Coupling may occur both due to capacitive and inductive effects. If one knows the impedance of the culprit and victim, one can make a reasonable assumption whether capacitive or inductive coupling will dominate and can estimate crosstalk using only mutual and self-capacitance or mutual and self-inductance. Estimation of the capacitance and inductance can be complicated in a wire-harness bundle due to the inhomogeneity of the medium. One question, then, is whether a reasonable estimate of the statistical distribution of coupling can be made by largely ignoring the influence of other circuits on the coupling between a particular culprit and victim and assuming a nearly homogeneous medium. This assumption greatly simplifies calculations and has generally worked well for worst-case approximations [2]. This possibility will be tested during the following study.

Values of inductance and capacitance for a particular harness cross-section can be calculated from harness geometry. If one knows the statistical distribution of wire positions within the harness, one can calculate the statistical nature of the values of inductance and capacitance, and therefore of the crosstalk [10,11]. A common method is to use a fixed cross-sectional geometry and assume that only the wire position for a particular circuit changes from one distribution to another [8,10]. The advantage of using a fixed cross-sectional geometry is that the inductance and capacitance parameters may be calculated only once, even if wire position changes along the length of the harness. In addition, once the inductance and capacitance parameters are evaluated from the harness, their statistical distribution can be calculated quite readily.

A wire-harness cross section used in this study is shown in Fig. 1. This bundle is constructed from 14 #19 AWG wires. As in [8], the thickness of the PVC insulation is assumed to be the same as the wire radius, the height from the center of the bundle to the return plane is 2 cm, and the length of the harness is 2 m. A particular culprit circuit, M, can be placed in any one wire position, from 1 to 14. A victim circuit, N, can then be placed in any of the remaining 13 positions. The statistical distribution of the inductance and capacitance for this cross-section, then, can be calculated from the statistical distribution of the relative positions of the wires within the harness (for example, the likelihood that two wires lay directly next to one another). Here we assume there is a uniform probability that a circuit will use a particular wire position and the position of one circuit is independent of another. The probability distribution of mutual inductance (or capacitance) can then be determined from the upper-triangle of the inductance (or capacitance) matrix for this cross-section simply by determining the number of times that a particular value of mutual inductance (or capacitance) occurs within this matrix.

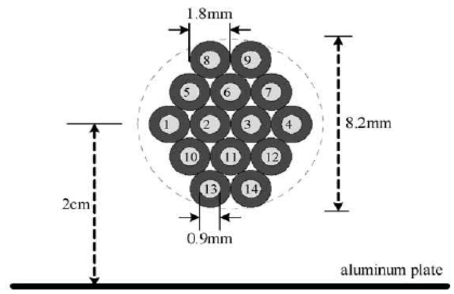

Figure 1. Harness cross section.

In many harnesses, the wires are twisted causing the position of the wires to change along the length of the harness. This variation of position may significantly influence the crosstalk. One method of accounting for this change is to divide the harness into several segments. Circuits are assumed to remain in the same position along each segment of the harness and to take on new positions in adjoining sections. To simplify analysis, circuit positions were assumed to be independent from one section of the harness to another.

III. DISTRIBUTION OF INDUCTANCE AND CAPACITANCE

Ignoring inhomogeneities, the per-unit-length mutual inductance between any two wires, n and m, in the harness can be approximated as

$$l_{nm} \cong \frac{\mu}{4\pi} \ln(1 + \frac{4h_n h_m}{s^2}), \tag{1}$$

where μ is the permeability of the medium, h_n and h_m are the distances from the centers of the wires to the return plane, and s is the distance between the centers of the two wires. Per-unit-length self-inductance can be estimated in a similar manner.

Per-unit-length inductance can also be estimated using 2D electromagnetic modeling tools. Values of self- and mutual-inductance were calculated using simple equations like (1) and using a 2D modeling tool for the harness shown in Fig. 1. The two methods yielded very similar results, suggesting that values of inductance can be calculated using (1) and do not require a more sophisticated analysis.

The probability distribution of the per-unit-length mutual inductance for the wire cross-section in Fig. 1 is shown in Fig. 2. The maximum value of mutual inductance is 650 nH/m and the minimum value is 350 nH/m. Probability distributions for the per-unit-length self-inductance can be generated in the same manner.

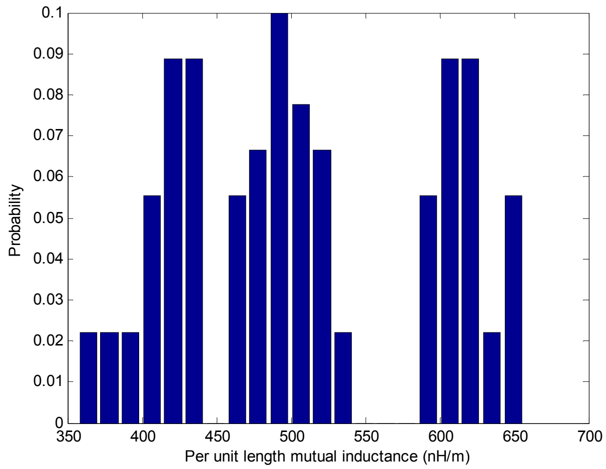

Figure 2. Probability distribution of per-unit-length mutual inductance for a single segment of the wiring harness containing 14 AWG #19 wires 2 cm above a return plane.

Variation in the position of the circuit within the harness can be determined by dividing the harness into separate segments and assuming the circuit takes on a new position within each segment. Assuming the distribution of positions is uniform and independent between segments and that segments are of equal length, the collective distribution of mutual inductance can be found by taking the convolution of the distributions for each segment. That is, if the distribution of per-unit-length mutual inductance is given by the function $f_1(x)$ then the distribution of the "effective" per-unit-length mutual inductance for a harness with two sections is given by:

$$f_2(x) = \int_{-\infty}^{\infty} f_1(x-y) f_1(y) dy .$$

The probability distribution of the effective per-unit-length mutual inductance for the harness in Fig. 1 using 8, 16, or 32 segments (calculated by convolution of the probability distributions in Fig. 2) is shown in Fig. 3. The probability distribution narrows toward the average value of inductance as the number of segments is increased, reducing the probable worst-case mutual inductance. For the case with 32 segments, an effective per-unit-length mutual inductance of 570 nH/m is larger than the effective inductance that will occur in more than 99% of configurations for this amount of twist. The worst-case value of 650 nH/m will only occur rarely when wires change position throughout the harness (on the order of 1 out of 10^{41} configurations for 32 segments).

Values of per-unit-length capacitance were calculated using Q2D for a cross-section of the harness. In this case, calculations of capacitance like (1) using 2-wire models were unable to provide suitable estimates of capacitance within the harness. The probability distribution of mutual capacitance as calculated using Q2D is shown in Fig. 4. The maximum value of mutual capacitance is around 28 pF/m and the minimum value around 4 fF/m.

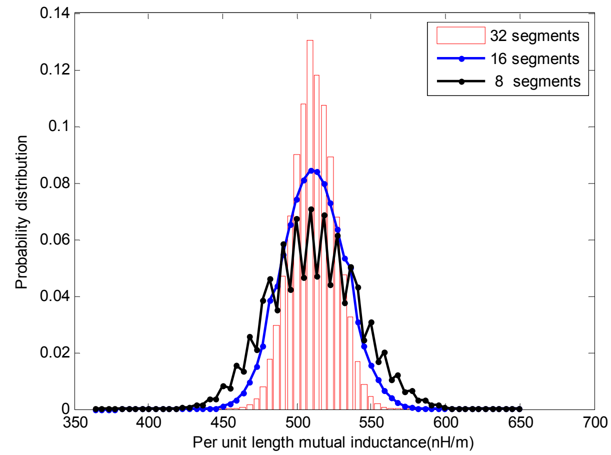

Figure 3. Probability distribution of "effective" per-unit-length mutual inductance for twisted wire bundles containing 14 AWG #19 wires 2 cm above a return plane.

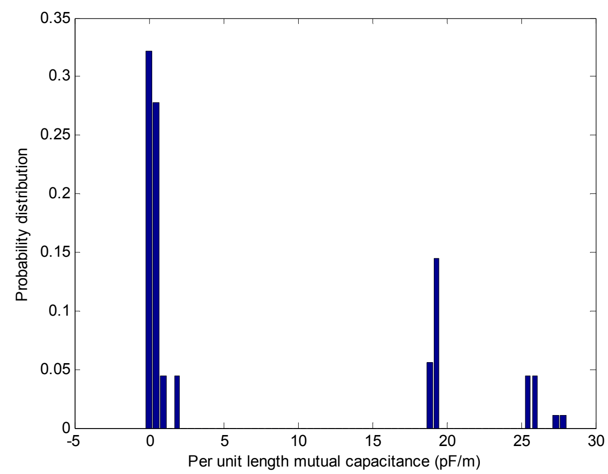

Figure 4. Probability distribution of per-unit-length mutual capacitance for a single segment of a harness containing 14 AWG #19 wires 2 cm above the return plane.

The wide distribution of possible values of mutual capacitance makes it especially important to account for the variation in wire position along the length of the harness [6]. Similar to the inductive coupling case, the bundle was divided into 8, 16, or 32 segments of equal length. Assuming the per-unit-length mutual capacitance between two wires in any segment has a distribution as shown in Fig. 4 and wire positions are independent from segment to segment, the distribution of the effective per-unit-length mutual capacitance over the length of the bundle can be obtained through convolution. The resulting distributions are shown in Fig. 5. Because of the distribution of possible values of capacitance, unlike inductance, increasing the number of segments widens the distribution and moves it to the right, increasing the probable worst-case mutual capacitance. The ratio of likely minimum to maximum values of mutual capacitance, however, is reduced.

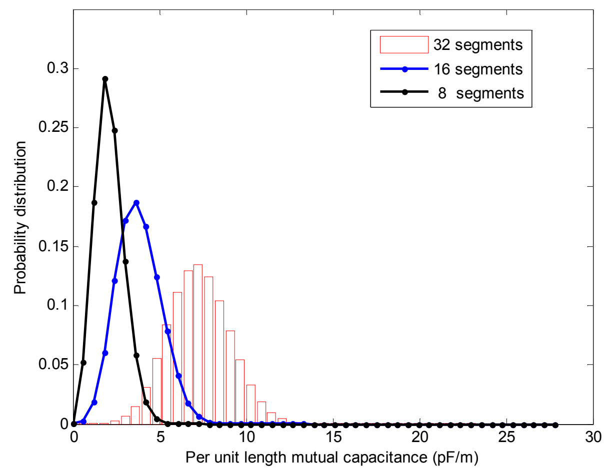

Figure 5. Probability distribution of the "effective" per unit length mutual capacitance for twisted wire bundles containing 14 AWG #19 wires 2 cm above a return plane.

IV. CROSSTALK ASSUMING WEAK-COUPLING

Calculations assuming weak coupling assume that the influence of other circuits has minimal impact on the voltage or current in the culprit or victim circuits. This assumption is typical of many crosstalk calculations.

While values of mutual and self inductance are not independent of one another, the variation in mutual inductance is generally greater and more important to crosstalk than the variation in self inductance, especially when the harness height above the return plane is on the order of the harness diameter or more. In this case, the statistical analysis of inductive crosstalk can be simplified significantly by only considering the variation in mutual inductance and using the average value of self inductance. Using this and the weak-coupling assumption, the far-end inductive crosstalk may be calculated as:

$$xtalk\_ind \cong \frac{jwl_m length}{(R_s + R_L + jwl_{s\_ave} length)} \frac{R_{fe}}{(R_{ne} + R_{fe} + jwl_{s\_ave} length)} \quad (2)$$

where R_s and R_L are the near end and far end loads in the culprit circuit, respectively; R_{ne} and R_{fe} are the near end and far end loads in the victim circuit; l_m is the effective per-unit-length mutual inductance; l_{s_ave} is the average per unit length self-inductance, and the crosstalk is defined as the ratio of the voltage across the victim load to the culprit source voltage (V_{FE}/V_S).

Capacitive crosstalk may be estimated similarly as:

$$xtalk\_cap \cong \frac{R_L}{R_S + jwL_{s\_ave} length + R_L} R_{ne} // R_{fe}\left(jwC_m length\right), \quad (3)$$

where C_m is the mutual capacitance per-unit-length from Fig. 4.

To test how well variation in crosstalk may be estimated using the proposed approach, crosstalk estimated using this method was compared to simulation results generated by the RDSI algorithm [8]. The RDSI algorithm includes a parameter that simulates twist or variation in wire position along the harness length. This parameter was adjusted to correspond to our calculations using approximately 32 independent harness segments. The RDSI algorithm was performed for 273 independent distributions of wire positions and twist.

Figs 6 and 7 show the distribution of inductive crosstalk at 10 kHz and 10 MHz when the culprit and victim circuit were loaded with 50-ohm loads at both the near and far ends so that inductive coupling would dominate and the other circuits were loaded with 1-kohm loads to minimize their influence. While the proposed algorithm did not precisely predict distribution of simulated crosstalk at these frequencies, the results are close. The difference between the probable minimum or maximum crosstalk predicted by the distributions is within about one decibel.

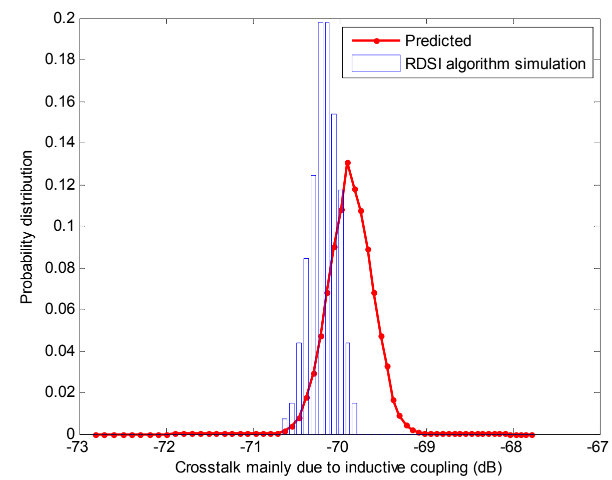

Figure 6. Predicted and simulated probability distribution of inductive crosstalk at 10 KHz (victim, culprit load = 50 ohm, others = 1 kohm).

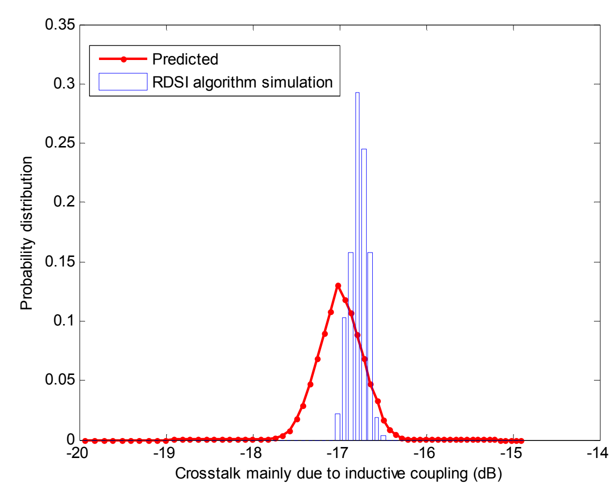

Figure 7. Predicted and simulated probability distribution of inductive crosstalk at 10 MHz (victim, culprit load = 50 ohm, others = 1 kohm).

Figs 8 and 9 show the distribution of capacitive crosstalk at 10 kHz and 10 MHz when all circuits in the harness were loaded with 1-kohm loads at both the near and far ends so that capacitive coupling would dominate. The algorithm did a good job of predicting coupling at 10 kHz, but overestimated results at 10 MHz because the weak coupling assumption no longer applies, as will be shown later.

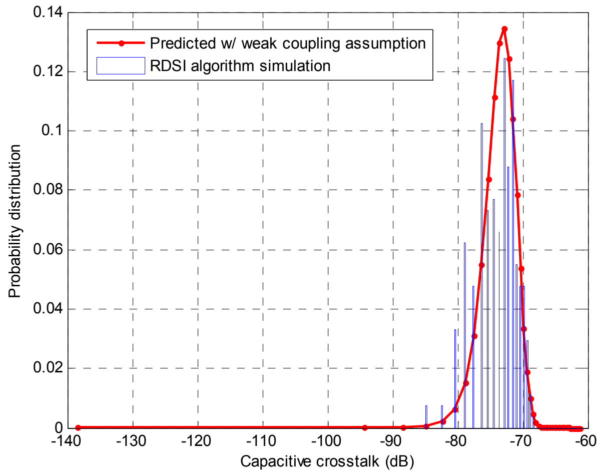

Figure 8. Predicted and simulated probability distribution of capacitive crosstalk at 10 KHz (all circuit loads = 1 kohm).

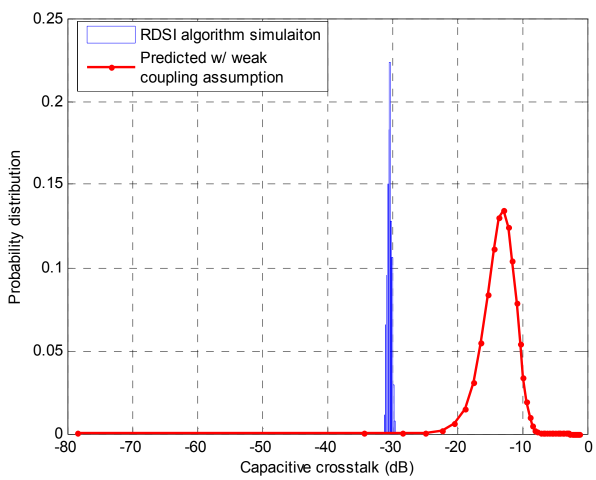

Figure 9. Predicted and simulated probability distribution of capacitive crosstalk at 10 MHz (all circuit loads = 1 kohm).

Using the technique presented here, the "reasonable worst-case" crosstalk can be calculated using the largest value of mutual inductance or capacitance that occurs over some percentage of cases. For example, 570 nH/m is the worst effective per-unit-length mutual inductance that will occur in 99% of cases for the configuration studied here. It will give the worst value of crosstalk in 99% of cases using (2). Figs 10 and 11 compare the reasonable worst-case inductive crosstalk predicted using (2) with the 273 simulation results generated using the RDSI algorithm. Fig. 10 shows crosstalk when the victim and load were terminated with 50 ohms and all other circuits with 1-kohm loads. Fig. 11 shows crosstalk when all circuits were terminated with 50-ohm loads. Because crosstalk only varied by about 1 dB, the 273 simulation results appear like a single curve in the graph. Prediction was performed to 10 MHz, since the lumped element model becomes invalid above this frequency. When other circuits were terminated with 1-kohm loads, the proposed technique estimated the simulated worst-case crosstalk within about 1-2 dB over the entire frequency range. When all circuits were terminated with 50-ohm loads, crosstalk was overestimated above 1 MHz because the weak-coupling assumption no longer applied.

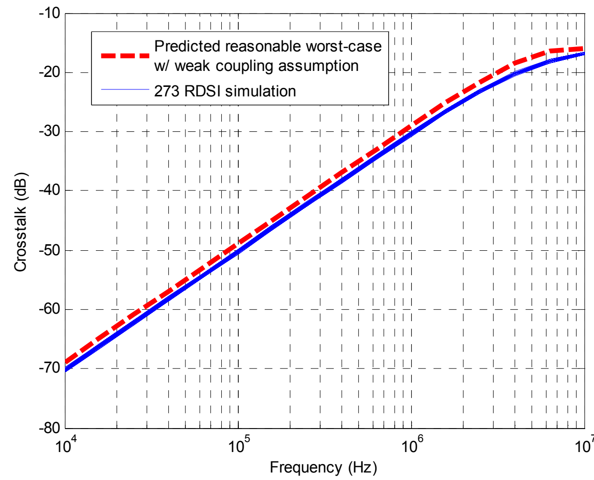

Figure 10. Predicted "reasonable worst case" inductive crosstalk compared to 273 crosstalk simulations using the RDSI algorithm (victim, culprit load= 50 ohm, others = 1 kohm).

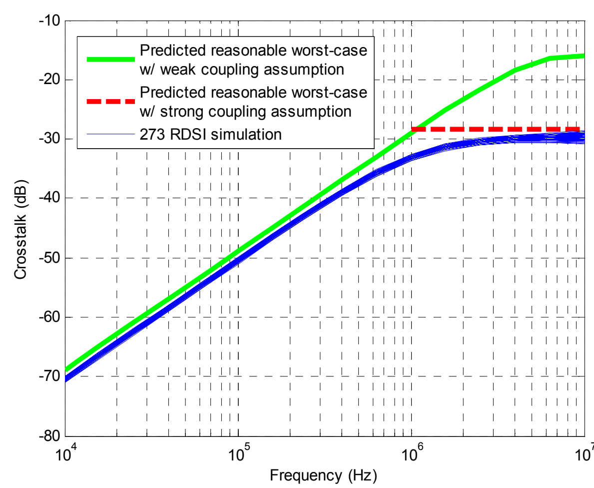

Figure 11. Predicted "reasonable worst case" inductive crosstalk compared to 273 crosstalk simulations using the RDSI algorithm when the influence of other circuits is important (all circuit loads = 50 ohm).

Similar comparisons for the reasonable worst-case estimate of capacitive crosstalk are shown in Fig. 12 and 13. Fig. 12 shows crosstalk when all circuits where terminated with 1-kohm loads. Fig. 13 shows crosstalk when the culprit and victim were terminated with 1-kohm loads and all other circuits were terminated with 50-ohm loads. The proposed technique again works well up to 1-2 MHz, but begins to fail above this frequency as the weak-coupling assumption breaks down.

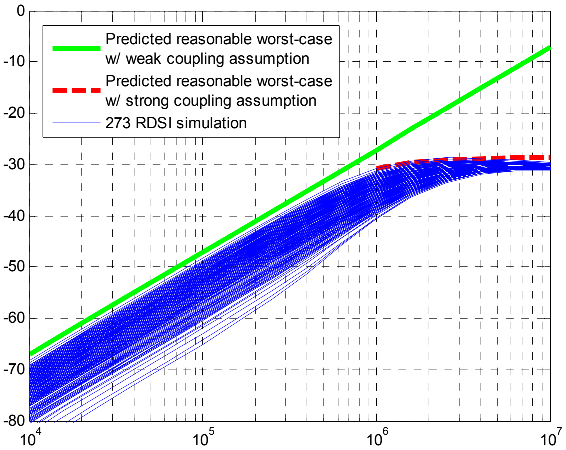

Figure 12. Predicted "reasonable worst case" capactive crosstalk compared to 273 crosstalk simulations using the RDSI algorithm when the influence of other circuits is important (all circuit loads = 1 kohm).

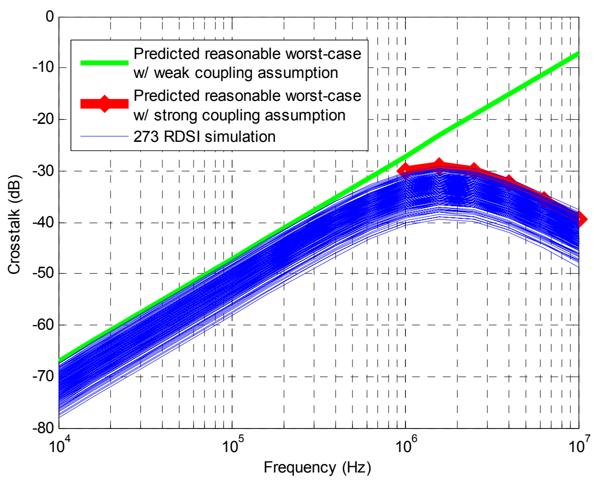

Figure 13. Predicted "reasonable worst case" capacitive crosstalk compared to 273 crosstalk simulations using the RDSI algorithm when influence of other circuits could be ignored (victim, culprit load= 1 kohm, others = 50 ohm).

V. CROSSTALK ASSUMING STRONG COUPLING

Calculations using weak-coupling assumptions begin to fail when the coupling to the rest of the harness significantly loads the culprit and victim circuits. This loading can be accounted for in the limit by assuming strong coupling. For inductive coupling, when strong coupling applies, all circuits besides the culprit can be thought of as a single (strongly coupled) circuit. For the case where each potential victim has a similar load, crosstalk to this circuit from the culprit can be approximated as:

$$xtalk\_ind \cong \frac{1}{2N}$$

where N is the number of potential victim circuits. This limit is shown in Fig. 11 and does a good job of predicting reasonable worst-case crosstalk above 1 MHz when the weak-coupling assumption does not apply.

A similar approximation can be applied to estimate capacitive coupling. In Fig. 12, where all circuits are loaded with 1k-ohm loads on both ends, the culprit circuit is heavily loaded by the harness above 1 MHz because $Z_{harness} + 1/jwC_{o\_avg}length << R_L$, where $Z_{harness}$ is the parallel combination of all the circuits in the harness except the culprit and C_{0_ave} is the average value of the per-unit-length capacitance between one wire and all the other wires plus the return plane. The approximation $1/jwC_m length >> R_{ne} // R_{fe}$ does not apply either. To a rough approximation, one can think of the culprit as coupling to all the potential victims, who are shorted in parallel. In this case, the crosstalk from the culprit to the victim is approximately:

$$xtalk\_cap \cong \frac{Z_{harness}}{R_S + \left(Z_{harness} + 1/jwC_{o\_avg}length\right)}.$$

When the other circuits in the harness are loaded with 50-ohm loads, both conditions $Z_{harness} + 1/jwC_{o\_avg}length << R_L$ and $1/jwC_m length >> R_{ne} // R_{fe}$ apply from 1-10 MHz. In this case crosstalk can be approximated by accounting only for the loading on the culprit and victim circuits:

$$xtalk\_cap \cong \frac{R_L // Z_x}{R_S + jwL_{s\_ave}length + R_L // Z_x} \frac{R_{ne} // R_{fe} // Z_x}{R_{ne} // R_{fe} // Z_x + \dfrac{1}{jwC_m length}},$$

where $Z_x = \dfrac{1}{jwC_{o\_avg}length}$.

These limits are plotted in Figs 12 through 13 and do a good job of predicting the reasonable worst-case crosstalk when the weak-coupling assumption does not applies.

VI. DISCUSSION AND CONCLUSIONS

The relatively simple method of calculating inductive and capacitive coupling in a wire harness bundle suggested here is able to predict the reasonable worst-case crosstalk well up to 10 MHz. Below 1 MHz, the reasonable worst-case is predicted well using a weak-coupling assumption. Above 1 MHz, the reasonable worst-case is predicted well using approximations that assume strong-coupling.

The technique presented here for estimating statistical variation in crosstalk shows promise both as a means of improving the speed of estimating crosstalk as well as a means of improving the understanding of the major causes. Results suggest that the variation in crosstalk from inductive coupling will generally be small and the variation from capacitive coupling will be large, as seen in earlier studies [4]. The insensitivity of inductive coupling to wire position indicates that a statistical analysis may not be required – at least for the case studied using a return plane rather than a return wire. For this case, a worst-case analysis that ignored the contribution of the other wires would have given a result within a few dB of the reasonable worst-case found here. The wide distribution of mutual capacitance with position indicates that a statistical analysis of wire position is appropriate when capacitive coupling dominates. 2D numerical models may be required to find the capacitance values in many cases. One should also carefully consider the influence of twist (i.e. movement within the harness) for capacitive coupling, as the amount of twist can significantly influence the reasonable worst-case value of mutual capacitance. For both inductive and capacitive crosstalk, the loading influence of the harness must be taken into account at higher frequencies.

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