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RAPID SIMULATION OF THE STATISTICAL VARIATION OF

CROSSTALK IN CABLE HARNESS BUNDLES

by

XIANG LI

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2011

Approved by

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ABSTRACT

Accurate assessment of crosstalk problems in cable harnesses requires simulation methods that account for the statistical variation of harness parameters. Methods are proposed to determine the influence of the statistical variation in wire positions, the rate that wires change position (i.e. “twist”), harness height, harness density (i.e. how closely wires are packed) and circuit loads. Methods use a combination of simulation and probability theory. Simulations use the T-parameter method, a rapid simulation technique for harness bundles. Simulation time is further improved by using the mean and variance of crosstalk estimated for fixed harness parameter values to estimate the mean and variance when parameters vary with known probability. The methods can save computation time, since a small number of simulations are required for a relatively small number of fixed parameter values rather than a large number of simulations to predict variation in many parameters.

More importantly, the methods may give better insight into how individual parameters influence the variation of crosstalk than a pure simulation approach, since there is a clear mathematical link between input parameters and the resulting variation in crosstalk. For the cases tested here, results show the mean and variance of crosstalk below 1 GHz can be estimated within a root-mean-square error of 12% when wire position within the harness, wire twist, wire harness density, harness height above the return plane, and load terminations are simultaneously varied.

ACKNOWLEDGMENTS

I express my sincere gratitude to Dr. Beetner for his constant support and guidance throughout the course of my master's degree program. I thank Dr. James Drewniak and Dr. Pommerenke for their research guidance on my work. I thank all the EMC Lab students for their help. I thank my family for their endless love and unconditional supports during my study in US.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

Crosstalk in wire harness bundles varies with changes in the relative position of wires in the bundle, the height of the harness above a return plane, the speed with which wires change position within the harness (e.g. due to twisting of wires within the harness), the density of wires within the harness (i.e. distance between neighboring wires), and with changes in the load terminations. This crosstalk can have a large influence on the performance of the overall system and may vary significantly depending on harness configuration. The harness parameters that determine crosstalk are often random and unknown. Methods to characterize the statistical variation of the crosstalk to account for random changes in these harness parameters are needed.

2. LITERATURE REVIEW

Statistical variation of crosstalk can be estimated using either an analytic-based approach or using simulation. Analytic approaches, as in [1]-[2], are traditionally limited to estimating worst-case or statistically-likely worst case crosstalk, due to the difficulty of the analytic problem. Difficulties can be overcome to an extent by combining analytic results with some simulation [3]. Simulation is performed using a mathematical model of the harness bundle that includes the random parameters. Most proposed simulation methods use variations of multi-conductor transmission line theory (MTL) and Monte Carlo simulation techniques to predict crosstalk within the harness bundle [4]-[5]. Monte Carlo methods estimate statistical variation of crosstalk by constructing a random harness configuration, estimating crosstalk for that configuration, and then repeating this process for many random configurations (several hundred to tens of thousands depending on the number of random parameters and the required accuracy). Changes in the relative position of wires within the harness are modeled in several ways. A standard method is to estimate capacitance and inductance parameters for a "standard" harness segment and then construct SPICE models of the harness using a series of these segments [6]. Wire positions change from one segment to another, though the generic harness cross-section remains unchanged. Changes in position may be abrupt [2] or may be relatively smooth, for example by requiring that positions change slowly according to a pre-defined wire path [6]. Studies suggest that abrupt changes are acceptable so long as the length of the segments is small compared to a wavelength. Crosstalk can be estimated using SPICE, as in [6], or by directly solving multi-conductor transmission line equations [7].

Another method for solving the multi-conductor transmission line problem is using the T-parameter method [8]-[11]. The T-parameter method models a cable bundle as a cascade of equal-length, uniform multi-conductor transmission lines. Each segment is described by a transfer-parameter (T-parameter) matrix. A T-parameter matrix describing the entire harness can be found by multiplying the T-parameters of the individual segments. By changing the characteristics of each segment, it is possible to estimate the statistical characteristics of crosstalk. This technique yields the same results as a SPICE solver or as multi-conductor transmission line equations, but is potentially much faster. Simulation speeds are fast since crosstalk can be found using simple matrix operations and variations in harness parameters can be imposed through simple manipulations of a few characteristic matrices that are calculated only once.

While Monte Carlo simulations can do a good job of predicting the statistical characteristics of crosstalk, there is room for improvement. One shortcoming of Monte Carlo simulations is that results require significant time and computational effort to calculate. A large number of simulations are required to get an accurate result and the number of required simulations grows rapidly with the number of random input parameters. Another shortcoming is that it can be difficult to relate the results of a Monte Carlo simulation to the main causes of crosstalk. The impact of individual parameters is lost in the simulations.

The method proposed in [11] and extended here helps to overcome these limitations by applying probability theory to a limited number of crosstalk simulation results in order to estimate the statistical variation in crosstalk. The mean and standard deviation of crosstalk is estimated for harnesses with fixed heights, wire densities, loads, and twist, while varying the position of wires within the harness. The characteristics of crosstalk found when parameters are fixed are then combined with probability density functions for these parameters to estimate the overall statistical variation of crosstalk when these parameters are random. The advantage of this approach is that requires fewer simulations than the traditional pure simulation technique and, more importantly, that there is a more concrete relationship between the characteristics of crosstalk and the random parameters that influence crosstalk, giving the user a better opportunity to intelligently analyze and correct crosstalk issues.

3. SIMULATION

The following parts introduce the proposed method of combining probability theory and crosstalk simulations to estimate the statistical variation of crosstalk in cable harness bundles. The T-parameter method is given [8] followed by descriptions of methods to account for variations in wire position, harness height, number of twists, harness density and load terminations. Variations are first treated separately, and then an explanation is given how to perform an analysis when all these parameters are varying at the same time. Each section explains both how to use the T-parameter method to account for the variations, as well as how to combine simulations results with probability theory. The accuracy of the proposed method is validated through comparison to results generated with pure Monte Carlo simulations.

3.1. TEST CONFIGURATION

Simulations in the following sections were performed using the harness bundle shown in Figure 3.1. The harness was assumed to contain 14 identical wires, to be 2 m long, and to be above an infinite return plane. Each wire consisted of a perfect conductor with radius 0.45 mm surrounded by an insulator of thickness De = 0.45 mm. The relative dielectric constant of the insulator was 4. The distance between the centers of two wires was give by D, as shown in the figure. For most simulations, the harness was assumed to be tightly packed and D was set to twice the sum of the thickness of the insulator and the radius of the wires, though in later simulations the value of D was varied to simulate loosely packed bundles. The height of the bundle, denoted by H, is defined as the distance between the center of the harness and the return plane. In most simulations, H was set to 2 cm.

The default value of harness termination impedances are listed in Table 3.1. In all simulations, Circuit #2 was considered the generator or culprit circuit. The near end load of Circuit #2 was 10 Ω. The far end load of this circuit was varied so that either inductive or capacitive coupling would dominate. In simulations where inductive coupling dominated, the far end load of Circuit #2 was 100 Ω and Circuit #4 was treated as the victim. In simulations where capacitive coupling dominated, the far end load of Circuit #2 was set to 1000 Ω and Circuit #1 was treated as the victim. The other circuits were terminated with a variety of impedances, similar to other studies of the statistical characteristics of crosstalk [1] [2].

Table 3.1. Load Conditions.

Circuit No.	Near-end (R_{ne}) Ω	Far-end (R_{fe}) Ω
1 (**victim)**	2000	2000
2 (**generator**)	10	R_l
3	100000	10
4 (**victim**)	47	100000
5	1000	47
6	100000	15000
7	15000	15000
8	15000	1000
9	10	10
10	15000	10
11	47	10
12	1000	1000
13	10	15000
14	10	47

Wire positions were varied randomly along the length of the harness in all simulations. The rate that wires changed position was determined by the number of harness segments. By default, the harness was divided into 32 segments (i.e. 32 “twists”) unless otherwise specified.

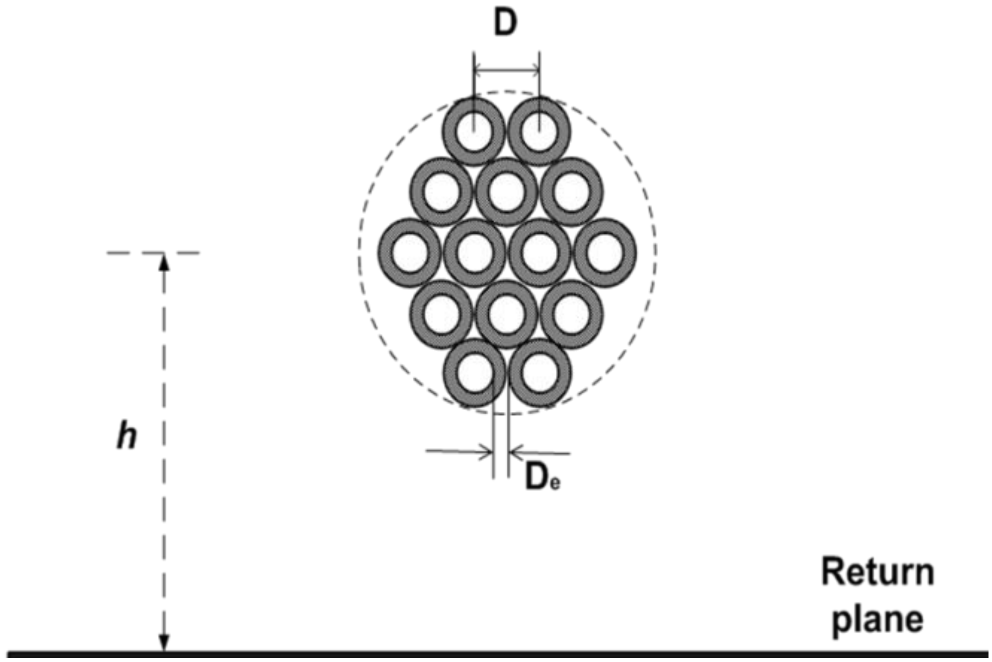


Figure 3.1. 2D cross-section of the harness bundle.

Parameters that were varied randomly include the wire position (P), the number of harness twists (T), harness height (H), load terminations (L) and harness density (D). The probability density functions used to determine the variation of harness density, culprit and victim circuit termination impedance, number of twists, and height are shown in Figure 3.2. These distributions represent sampled Gaussian distributions with different means and standard deviations. Values along the X-axis of Figure 3.2 are shown in Table 3.2. These probability density functions were used to determine parameter variations in all of the following simulations.

Table 3.2. Values Along X-axis.

Variables	V1	V2	V3	V4	V5
Height [cm]	1	2	3	4	5
Number of twists	10	15	20	25	30
Harness Diameter [mm]	1.8	2.1	2.4	2.7	3.0
Rl (load) [Ω]					
(Inductive coupling)	8	9	10	11	12
(Capacitive coupling)	800	900	1000	1100	1200

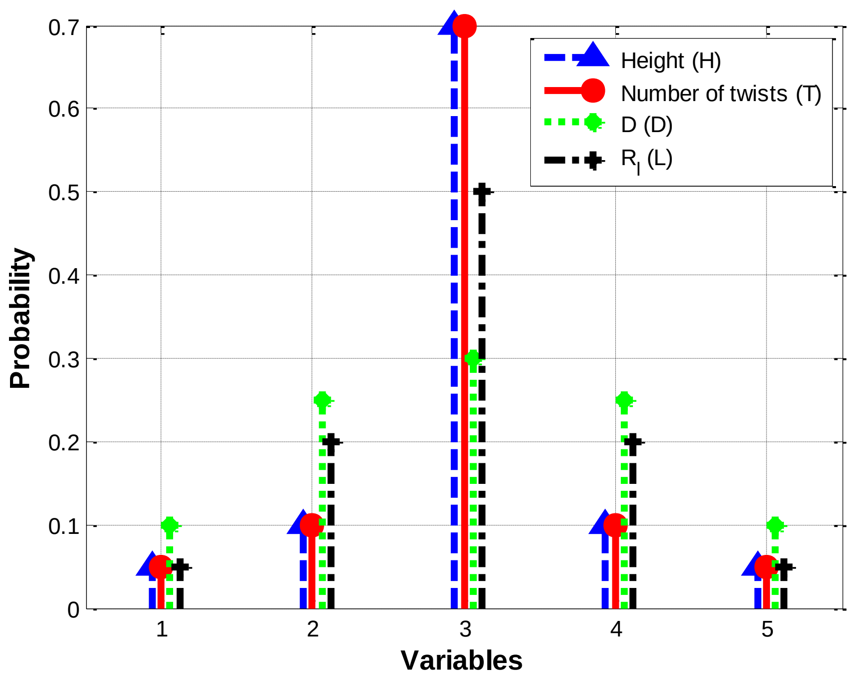


Figure 3.2. Sampled probability density function variables.

3.2. SIMULATION METHODS

Two simulation methods are proposed in the thesis. One is pure simulation method. The other is combined simulation and analytical method. The pure simulation is based on [8]. All the variations in the harness bundle can modeled directly in the simulation. The other one used both simulations and analytical methods. This combined method will be illustrated in the following parts in detail. The advantage of the combined method is that it will reduce the computational resource. The example below will show the advantage of the combined method compared to the pure simulation method.

Suppose that there is a function $Z = 2X + Y^2$. It contains two variables. One is X. The other is Y. They obey the sampled probability function in Figure 3.3.

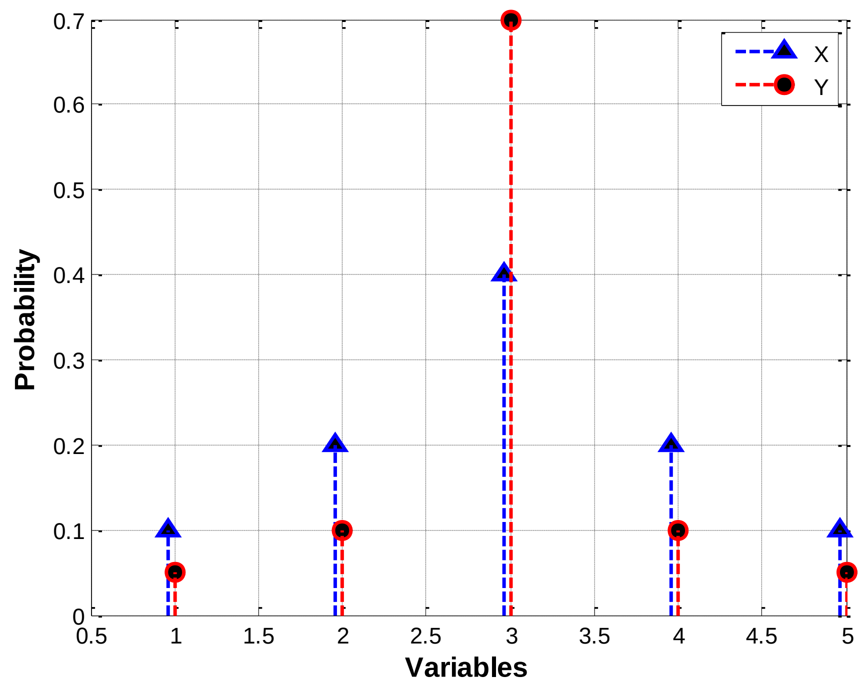


Figure 3.3. Sampled probability density functions of X and Y.

At first, μ_z and σ_z^2 is estimated using Monte Carlo method, varying both X and Y for 100,000 random values of X and Y. These valued are supposed to be true values of the mean value and variance of Z.

A second test is done. μ_z and σ_z^2 is estimated when Y varies and X is kept as a constant at each sampled value, using 1000 samples of Y. The errors are defined as $\frac{\mu_{z,true} - \mu_{z,x}}{\mu_{z,true}}$ and $\frac{\sigma^2_{z,true} - \sigma^2_{z,x}}{\sigma^2_{z,true}}$, which are 1% and 4%.

Repeat simulations use Monte Carlo with both X and Y varying. When the simulation number is 10,000 the error is 1% for mean and 4% for variance

The mean value and variance also is estimated, when X varies and Y is kept as a constant at each sampled value, using 1000 samples of X. The errors are defined as $\frac{\mu_{z,true} - \mu_{z,y}}{\mu_{z,true}}$ and $\frac{\sigma^2{}_{z,true} - \sigma^2{}_{z,y}}{\sigma^2{}_{z,true}}$, which is 0.03% and 0.7%.

Another simulation used Monte Carlo method with both X and Y varying. When the simulation number is 20,000 the error is 0.08% for mean and 0.6% for variance.

The follow table shows that the combined method will save a lot of simulation times compared to the pure simulation method to achieve errors on the same level.

Table 3.3. Comparison of simulation times between pure simulation and combined methods.

Variations	Method	Simulation times
X	Pure simulation method	20,000
	Combined method	1000
Y	Pure simulation method	10,000
	Combined method	1000

3.3. VARIATION IN HEIGHT

Most harness simulations vary only the position of wires along the harness, but height also changes as illustrated in Figure 3.4. Because the height of the harness will influence the per-unit length RLGC parameters associated with the S-parameter matrix, one reference S-parameter matrix is not sufficient to describe the whole harness bundle. Different S-parameter matrices are needed to represent different heights. The number of reference S-parameter matrices needed depends on how closely one wants to model the height.

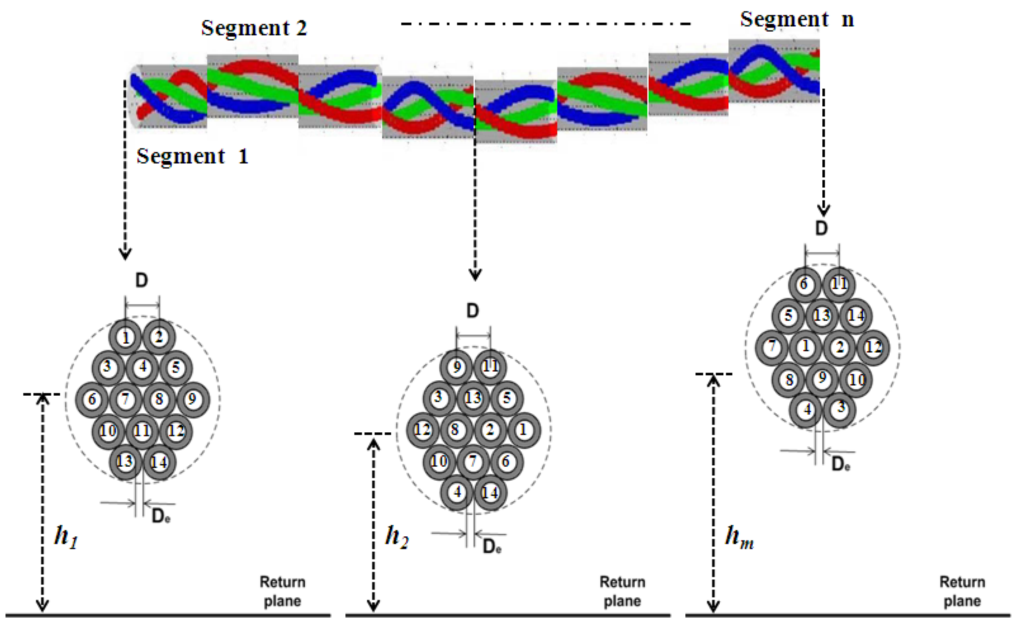


Figure 3.4. The height of the harness above the return plane changes randomly.

3.3.1. Pure simulation method. The pure simulation is based on the method proposed in [8]. Random variations in height can be modeled by calculating S-parameter matrices for a few given heights, then randomly choosing one reference matrix (one height) to represent each segment. The probability that a particular S-parameter matrix is chosen should depend on the probability distribution for height along the cable bundle. Random variation in wire position can be simulated by switching rows and columns of the reference matrix as before. In order to generate a random number according to the known sampled probability density function, the method in is used. The flow chart of the code is shown in Figure 3.5.

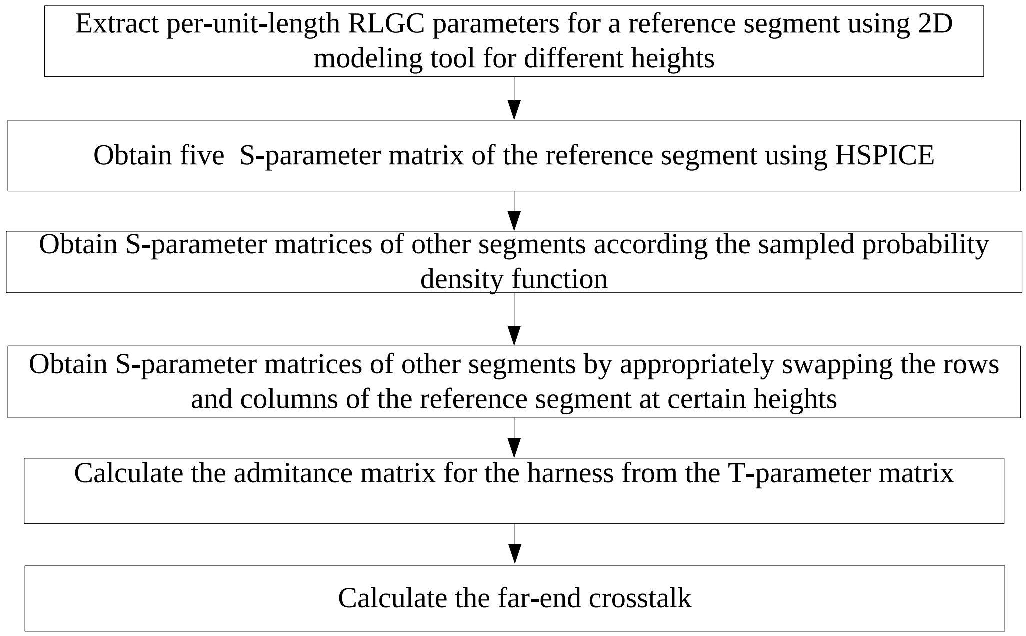


Figure 3.5. Flow chart of the pure simulation method for variations in height.

3.3.2. Combined simulation and analytical method. The method is illustrated in the following example. The probability density function for height was assumed to be Gaussian and was then sampled and normalized as shown in Figure 3.2. Five different heights (1 cm, 2 cm, 3 cm, 4 cm and 5 cm) between the center of the harness bundle and the return plane were modeled.

Crosstalk was simulated for 200 harness configurations. For each configuration, a reference S-parameter matrix describing each segment height was chosen randomly according to the probability density function for height. Wire positions were varied by randomly switching rows and columns of the S- parameter matrix as mentioned earlier. The estimated mean and variance of crosstalk is shown in Figure 3.6. and Figure 3.7.

While the statistical variation of crosstalk in harness bundles with random height and wire position can be estimated by simultaneously varying both parameters over many simulations, it might also be estimated by performing simulations where only wire position is varied and height is fixed. The mean value of crosstalk when both height and wire position are varied, μ_c, is given by:

$$\mu_c = E\{C\} = \int \mu_{c|H} P(H) dH \tag{1}$$

where $E\{C\}$ is the expected value of crosstalk, *C*, *H* is the height of the harness bundle, $\mu_{c|H}$ is the mean value of crosstalk at a given height, and *P(H)* is the probability of the harness being at a given height. The average value of crosstalk can be found by integrating the average value of crosstalk at fixed heights, times the probability of each height occurring in the harness.

The variance of crosstalk, $\sigma_c{}^2$, when both harness height and wire position are varied is given by:

$$\sigma_c{}^2 = E\{(C-\mu_c)^2\} = E\{C^2\} - \mu_c{}^2 \tag{2}$$

$E\{C^2\}$ is given by:

$$E\{C^2\} = \int E\{C^2 \mid H)\} P(H) dH \tag{3}$$

The variance of crosstalk at a fixed height is

$$\sigma_{c|H}{}^2 = E\{C^2 \mid H\} - \mu_{c|H}{}^2 \tag{4}$$

so that

$$E\{C^2 \mid H\} = \sigma_{c|H}{}^2 + \mu_{c|H}{}^2 \tag{5}$$

By substituting equation (5) into equation (3),

$$E\{C^2\} = \int (\sigma_{c|H}{}^2 + \mu_{c|H}{}^2) P(H) dH \tag{6}$$

and equation (2) becomes

$$\sigma_c{}^2 = \int (\sigma_{c|H}{}^2 + \mu_{c|H}{}^2) P(H) dH - \mu_c{}^2 \tag{7}$$

The variance of crosstalk when both height and position change randomly can thus be obtained from the mean and variance of crosstalk obtained for fixed harness heights.

To test the viability of using equation (1) and equation (7), these equations were applied to the same configurations used by the pure simulation approach in Figure 3.6. and Figure 3.7. The mean and standard deviation of crosstalk was found when only varying wire position for each of the heights indicated in Table 3.2. The estimated values of crosstalk when both wire position and height are changing are shown in Figure 3.6. and Figure 3.7.(inductive coupling dominating) and Figure 3.8 and Figure 3.9. (capacitive coupling dominating) where they are compared to simulations made when all parameters were varied simultaneously.

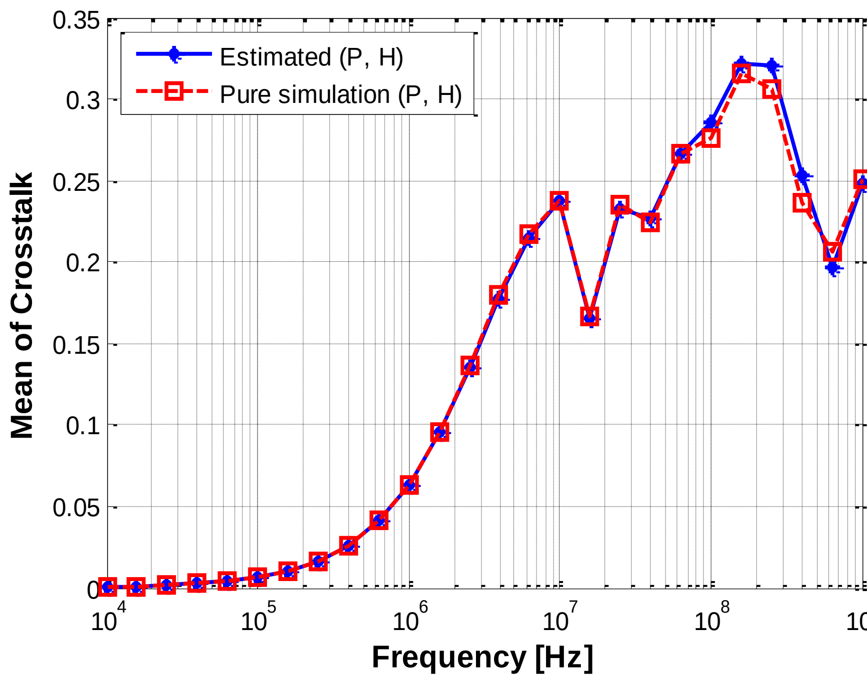


Figure 3.6. Mean value of crosstalk inductive coupling dominating when varying wire position (P) and harness height (H) as estimated using equation (4) and as simulated while varying both parameters (RMS difference 8%).

Estimated and simulated results match well. The means estimated by the two approaches had a root-mean-square (RMS) difference of 8%. The RMS difference between the variances was 15%. Inductive coupling dominates in these figures, but a similar match was obtained when capacitive coupling dominated, where the RMS difference between the means was 3% and was 8% between the variances.

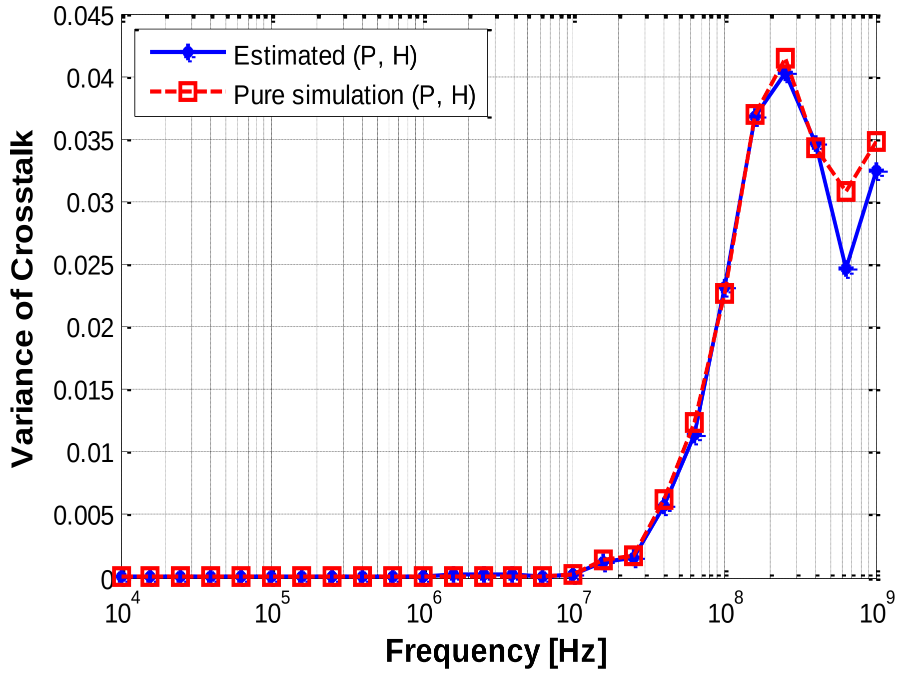


Figure 3.7. Variance of crosstalk inductive coupling dominating when wire positions (P) and varying height (T) as estimated using equation (4) and as simulated while varying both parameters (RMS difference 15%).

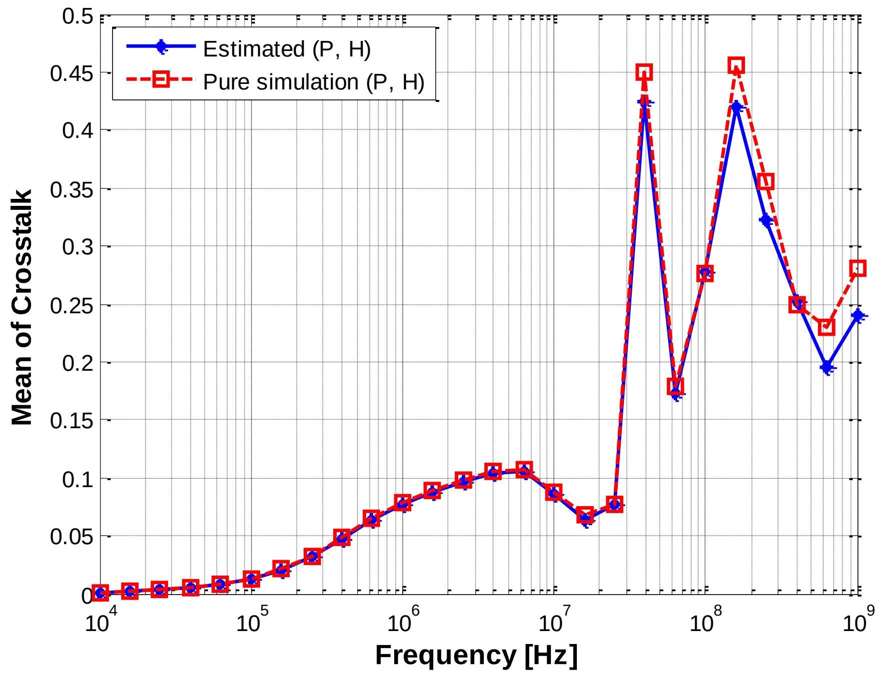


Figure 3.8. Mean value of crosstalk capacitive coupling dominating when varying wire position (P) and harness height (H) as estimated using equation (4) and as simulated while varying both parameters (RMS difference 3%).

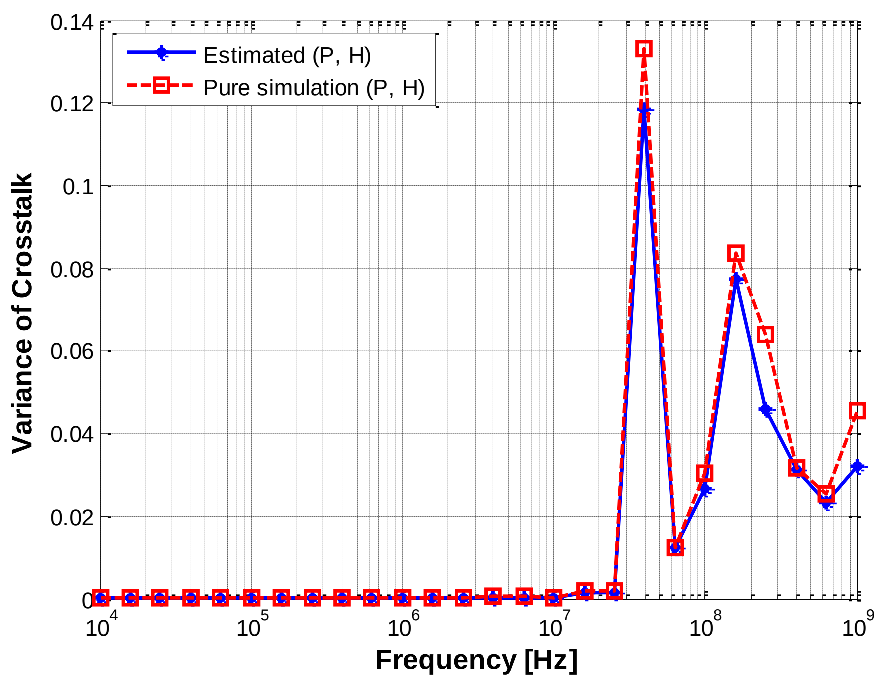


Figure 3.9. Variance of crosstalk capacitive coupling dominating when wire positions (P) and varying height (T) as estimated using equation (4) and as simulated while varying both parameters (RMS difference 8%).

3.4. VARIATION IN NUMBER OF TWISTS

The number of twists – that is, the number of times wires change position along the harness length – varies depending on the manufacturing process. Variations in the number of twists can be modeled by varying the number of segments used to model the harness.

3.4.1. Pure simulation method. The Random variations in number of twists can be modeled by defining different number of segments. The other processing is similar to that of the variation in height. The flow chart of the code is shown below.

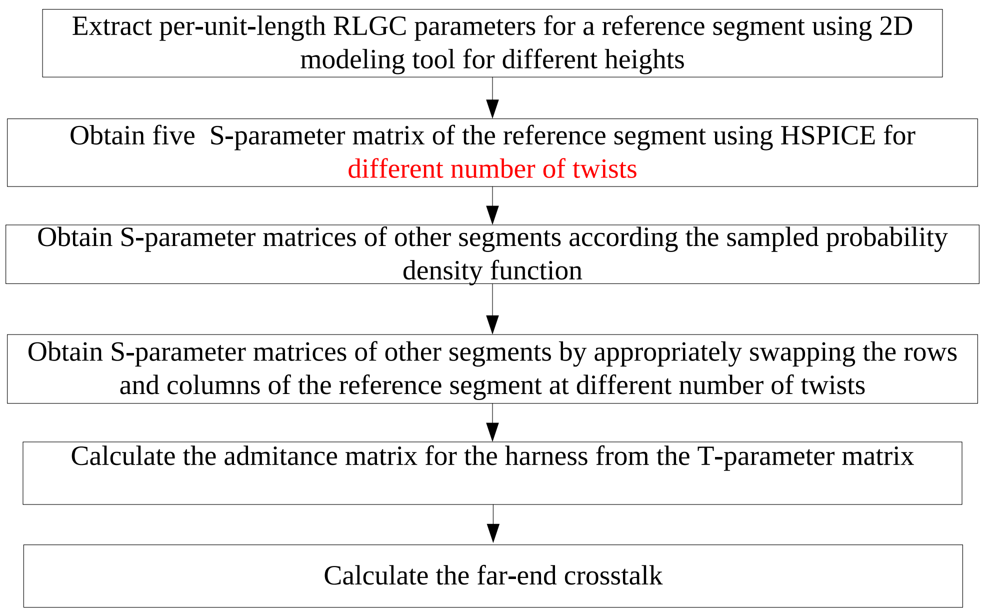


Figure 3.10. Flow chart of the pure simulation method for variations in height.

3.4.2. Combined simulation and analytical method. Analytically, variation in crosstalk caused by variations in both twist and position can be found using the same approach shown in equation (1) and equation (7); however, a simpler calculation may be possible. In [12] it was shown that at low frequencies, the mean and variance of crosstalk with only a single twist (single segment) could be used to estimate the mean and variance when there were many twists as

$$\mu_{N-segments} \approx \mu_{1-segment} \tag{8}$$

and

$$\sigma^2{}_{N-segments} \approx \frac{\sigma^2{}_{1-segment}}{N_s} \tag{9}$$

where N_s is the number of wire twists, $\mu_{N-segments}$ and $\mu_{1-segment}$ and $\sigma^2_{N-segments}$ and $\sigma^2_{1-segment}$ are the average and variance of crosstalk when using N-segments and using one segment, respectively.

According to equation (8) and equation (9), the mean values of the crosstalk of the different number of segments should be the same and the variance will decrease when the number of the segments increases. The results are shows in Figure 3.11. through Figure 3.14.

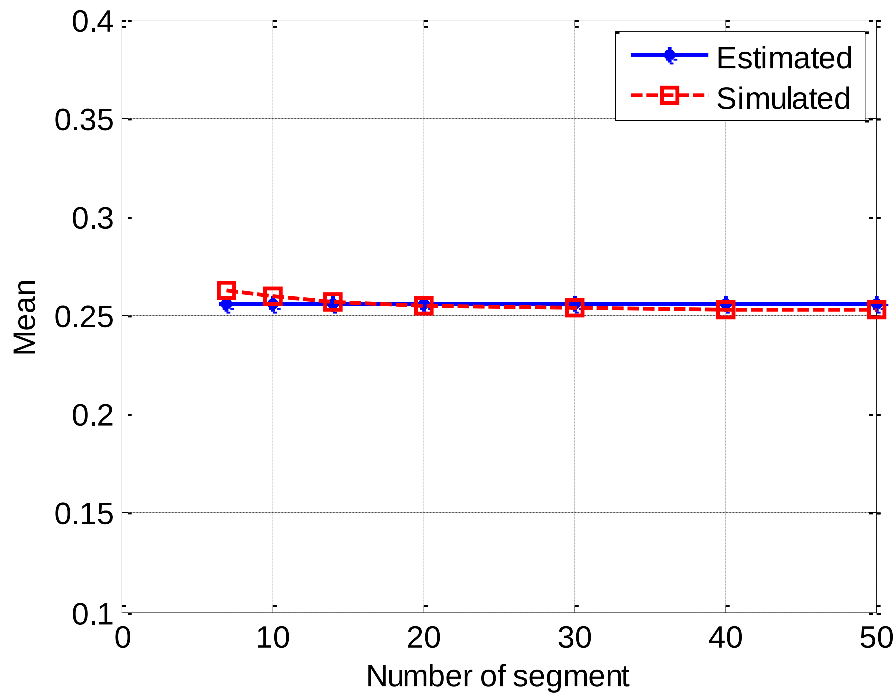


Figure 3.11. Mean value of crosstalk at 10 MHz when varying number of twists, for two circuits where inductive coupling dominates (RMS error 3.57%).

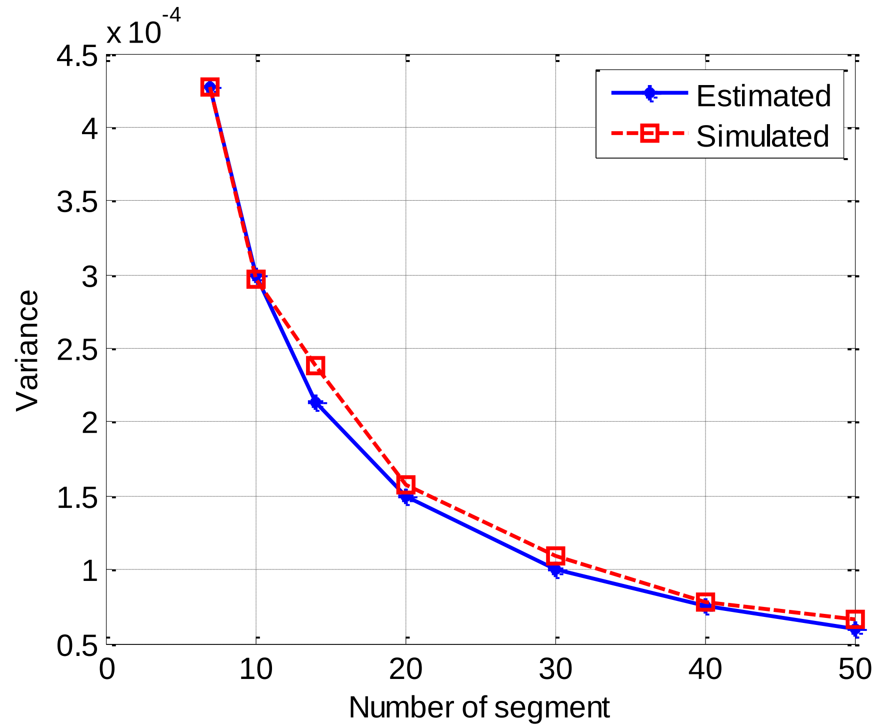


Figure 3.12. Variance of crosstalk at 10 MHz when varying number of twists, for two circuits where inductive coupling dominates (RMS error 6.46%).

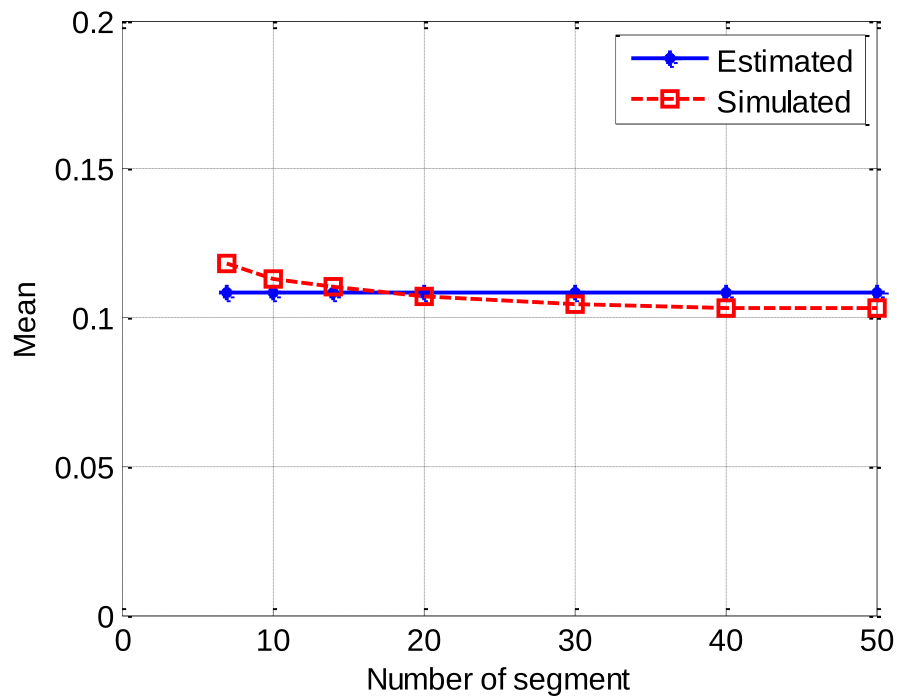


Figure 3.13. Mean value of crosstalk at 10 MHz when varying number of twists, for two circuits where capacitive coupling dominates (RMS error 12.8%).

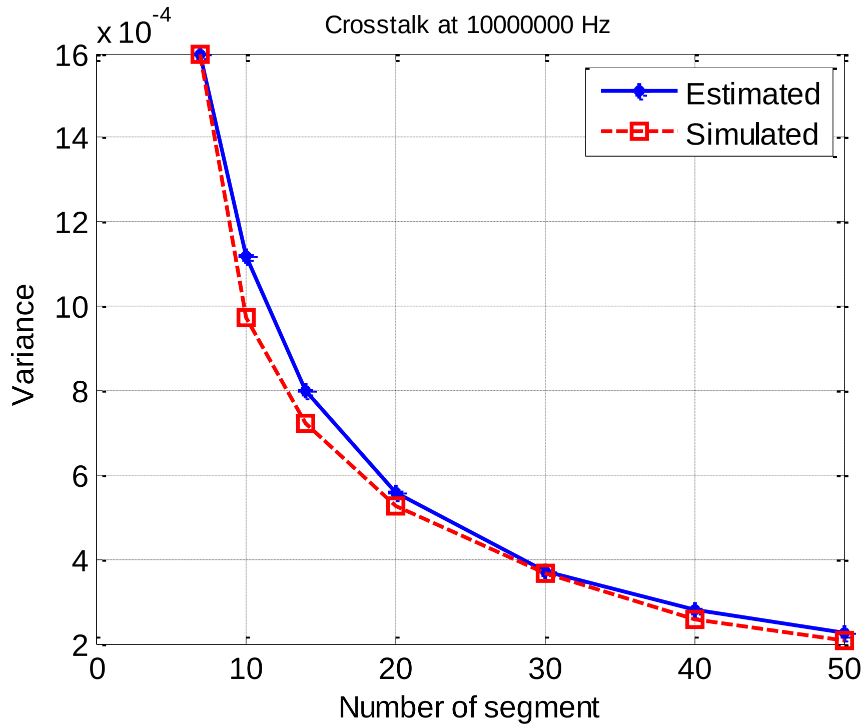


Figure 3.14. Variance of crosstalk at 10 MHz when varying number of twists, for two circuits where capacitive coupling dominates (RMS error 10.6%).

Three sets of simulations were performed to estimate the mean and variance of crosstalk when both wire position and twist were random parameters. In one set of simulations, crosstalk was estimated using the T-parameter method for many harnesses where both the number of twists and wire position was random within each harness. In the second set of simulations, the variation in crosstalk was simulated for fixed values of twist, and the overall variation in crosstalk (when twist was random) was estimated using equations like equation (1) and equation (7) (but for twist). In the third set of simulations, mean and variance of crosstalk for fixed values of twist was estimated using equation (8) and equation (9) from simulated values of the mean and variance of a harness with a single twist. The overall variation in crosstalk (when twist was random) was then estimated using equation (1) and equation (7). Results are shown in Figure 3.15 and Figure 3.16.

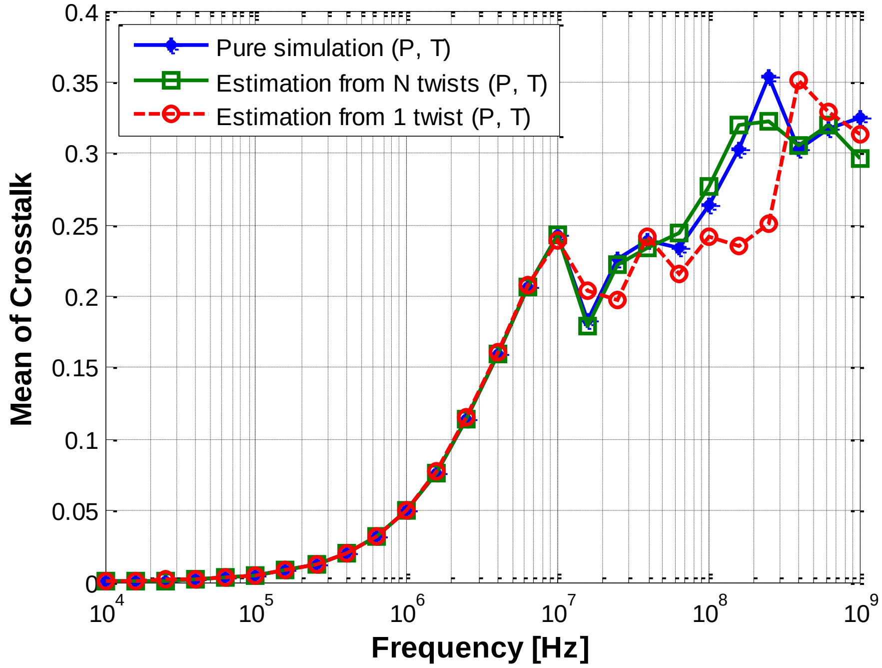


Figure 3.15. Mean value of crosstalk when varying wire position (P) and number of twists (T) where inductive coupling dominates.

While the mean value of crosstalk could be estimated well up to 1 GHz using simulations of a harness with only one twist, the approximation for variance broke down when the harness became electrically large, in this case up to around 20 MHz. Below 20 MHz, the mean was estimated with an RMS difference of 10% compared to the pure simulation approach and the variance was estimated with an RMS difference of 5%.

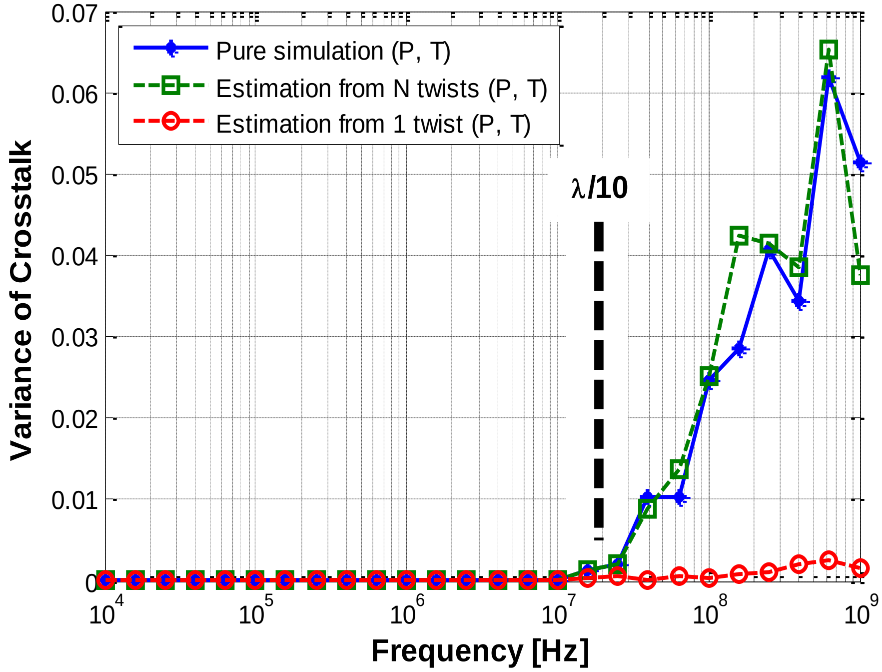


Figure 3.16. Variance of crosstalk when varying wire position (P) and number of twists (T) where inductive coupling dominates.

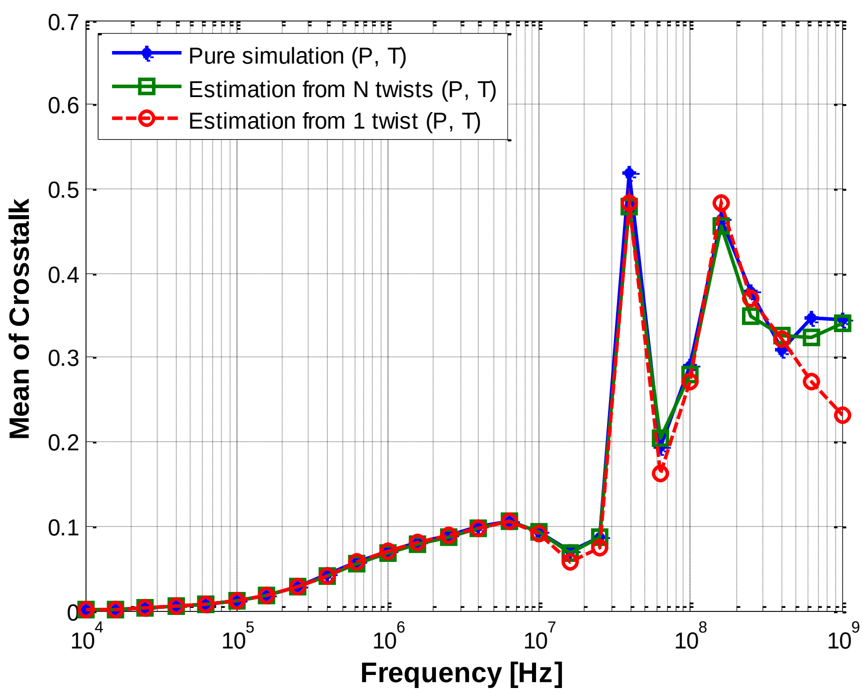


Figure 3.17. Mean value of crosstalk when varying wire position (P) and number of twists (T) where capacitive coupling dominates.

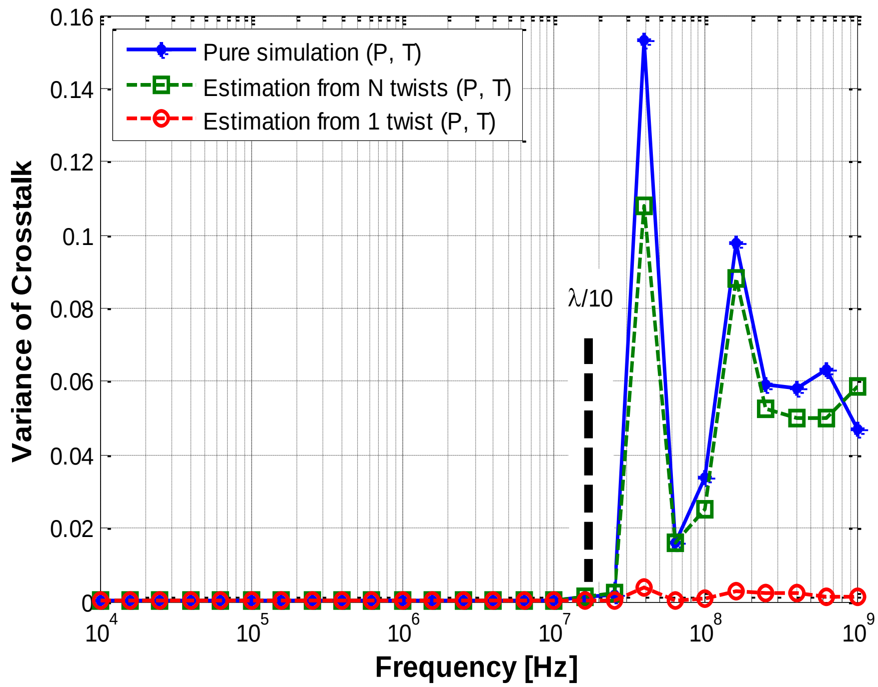


Figure 3.18. Variance of crosstalk when varying wire position (P) and number of twists (T) where capacitive coupling dominates.

3.5. VARIATION IN HARNESS DENSITY

A harness may be packed either loosely or tightly by the assembly operator or may be tight only at certain locations, for example where there are wire ties.

3.5.1. Pure simulation method. Variations in wire density can be handled similar to variations in harness height: by estimating S-parameter matrices for segments with different harness densities and randomly assigning a matrix (a density) to each segment. The flow chart is shown in Figure 3.19.

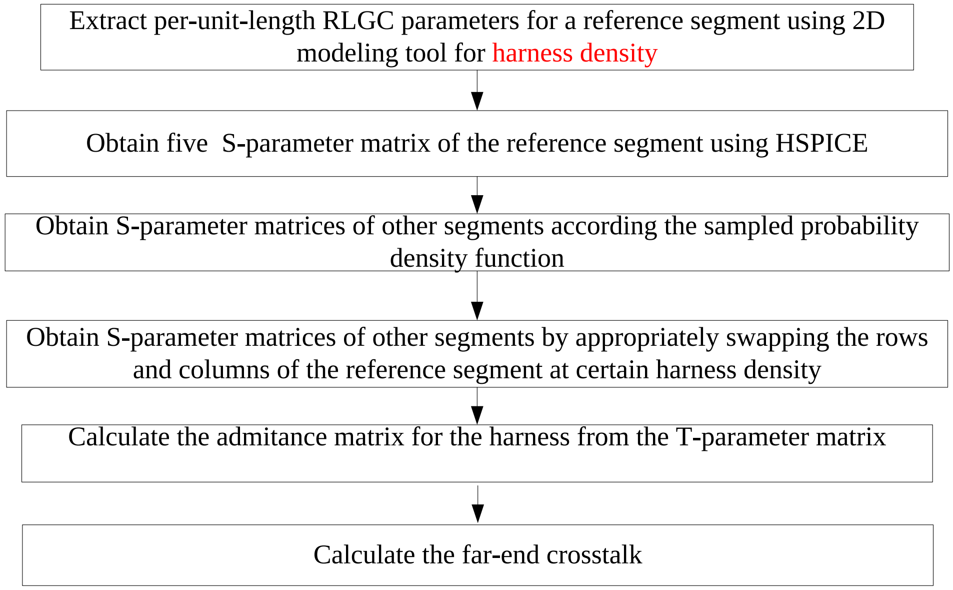


Figure 3.19. Flow chart of the pure simulation method for variations in harness density.

3.5.2. Combined simulation and analytical method. Harness density can be accounted for analytically using equations like equation (1) and equation (7) written for density rather than height:

$$\mu_c = \int \mu_{c|D} P(D) dD \tag{10}$$

$$\sigma_c^{\,2} = \int (\sigma_{c|D}^{\,2} + \mu_{c|D}^{\,2}) P(D) dD - \mu_c^{\,2} \tag{11}$$

where $\mu_{c|D}$ and $\sigma_{c|D}^2$ are the mean and variance of crosstalk at a given harness density, *D*, and *P(D)* is the probability of that density occurring. Figure 3.20. and Figure 3.21.show the mean and standard deviation of crosstalk for a harness where wire position and density varied randomly along the harness length, as calculated using a pure simulation approach and as calculated using equation (10) and equation (11). Results match closely, with an 8% RMS difference between the means and 14% RMS difference between the variances. Figure 3.20. and Figure 3.21.show results when inductive coupling dominated. When capacitive coupling dominated (in Figure 3.22. and Figure 3.23.), the RMS difference was 9% between the means and 14% between the variances.

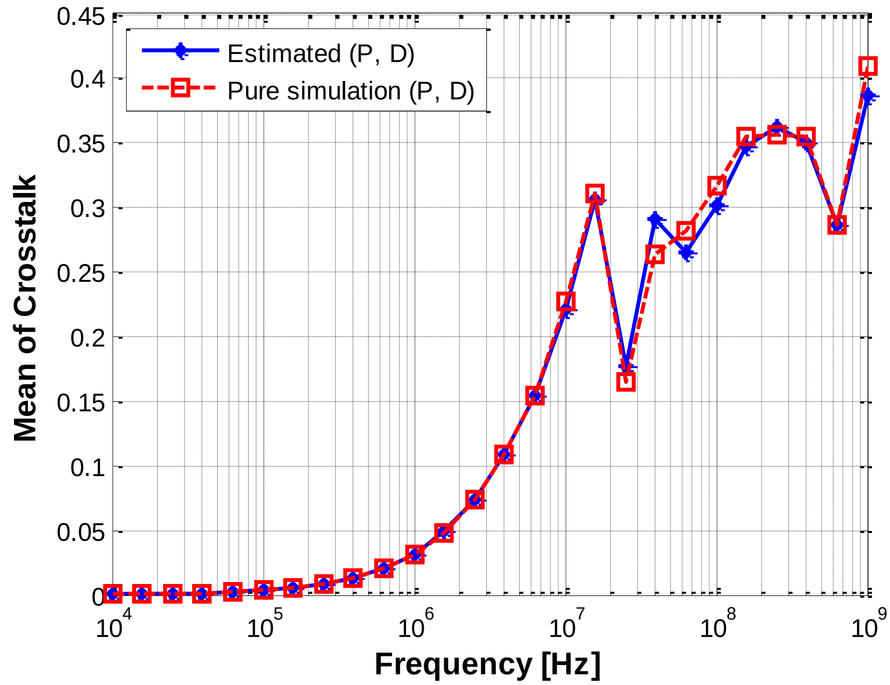


Figure 3.20. Mean value of crosstalk when varying wire position (P) and harness density (D) (RMS difference 8%)(inductive coupling dominating).

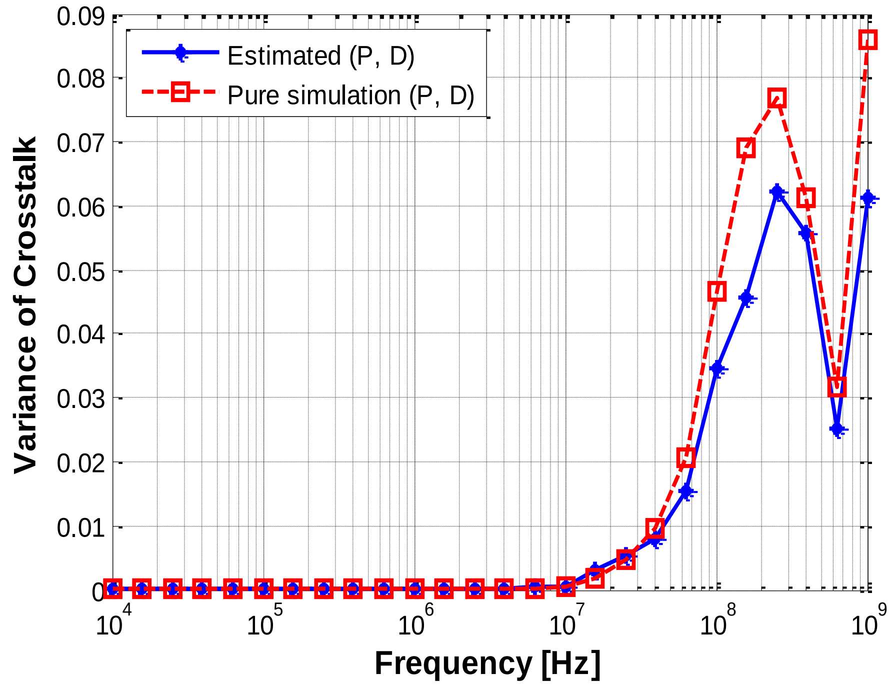


Figure 3.21. Variance of crosstalk when varying wire position (P) and harness density (D) (RMS Difference 14%) (inductive coupling dominating).

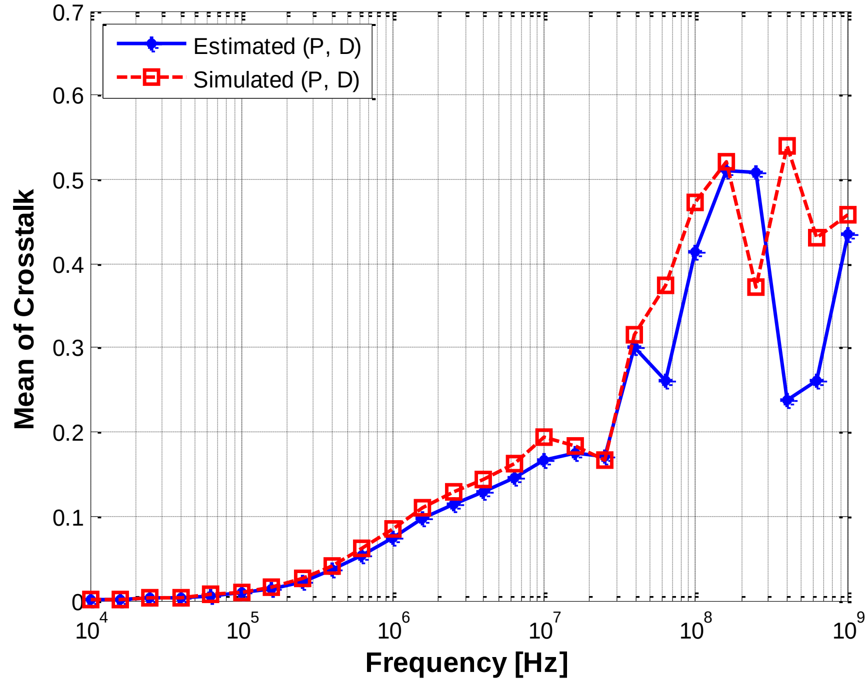


Figure 3.22. Mean value of crosstalk when varying wire position (P) and harness density (D) (RMS difference 9%)(capacitive coupling dominating).

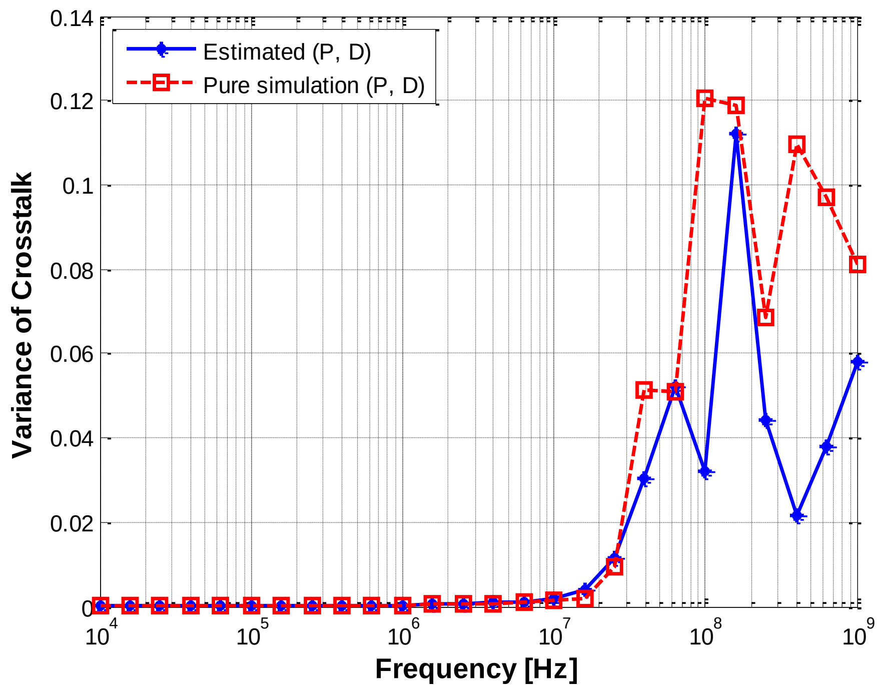


Figure 3.23. Variance of crosstalk when varying wire position (P) and harness density (D) (RMS difference 14%) (capacitive coupling dominating).

3.6. VARIATION IN LOADS

3.6.1. Pure simulation method. Variation in harness loads can significantly influence crosstalk. The load parameter is totally different from other parameters. The pure simulation method is shown in Figure 3.24.

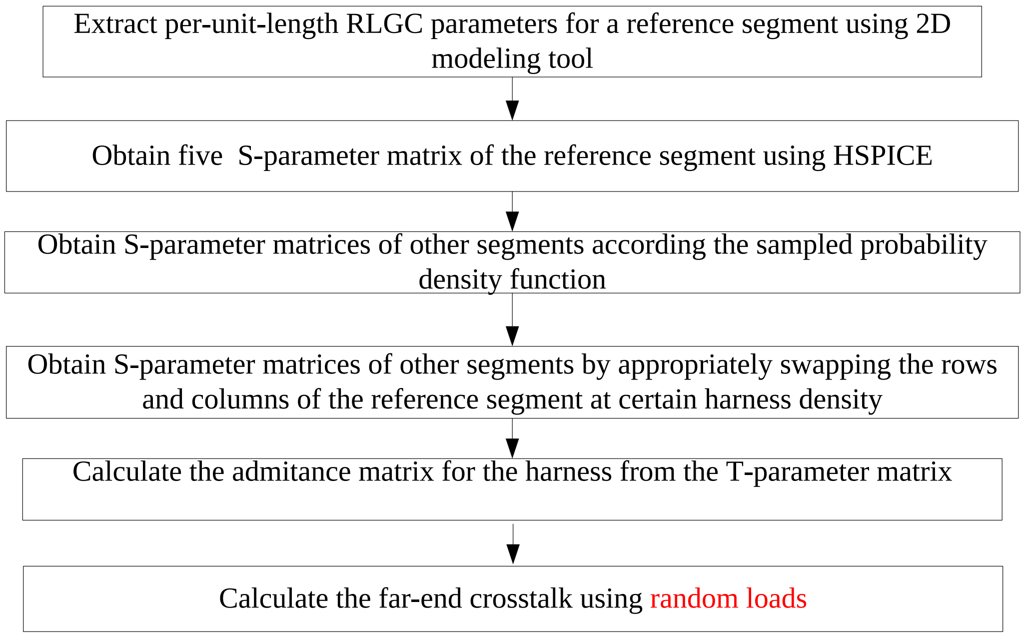


Figure 3.24. Flow chart of the pure simulation method for variations in loads.

3.6.2. Combined simulation and analytical method. As with other parameters, variation in crosstalk when loads are varied can be estimated as:

$$\mu_c = \int \mu_{c|L} P(L) dL \tag{12}$$

$$\sigma_c^{\,2} = \int (\sigma_{c|L}^{\,2} + \mu_{c|L}^{\,2}) P(L) dL - \mu_c^{\,2} \tag{13}$$

where $\mu_{c|D}$ and $\sigma^2_{c|D}$ are the mean and variance of crosstalk with a given load, *L*, and *P(L)* is the probability of that load occurring. Simulations of crosstalk were performed when the load impedance of the culprit circuit was varied as well as the position of wires within the harness. Comparison between results from a pure simulation when inductive coupling dominated show an RMS difference between the means of 4% and an RMS difference between the variances of 6%. When capacitive coupling dominated, the RMS difference between the means was 6% and was 15% between the variances.

3.7. VARIATION IN MULTIPLE PARAMETERS

3.7.1. Variation in heights and number of twists. According to equation (8) and equation (9), the mean and variance of the crosstalk for a different number of twists can be estimated from the mean and variance found for a 1-segment harness. Variation in both height and twist, then, can be accounted for by simulating crosstalk in a harness with a single segment (one twist), repeating the simulation for multiple heights, then estimating mean and variance of crosstalk for variations in height and twist using equation (1), (7), (8), and (9). Three sets of simulations were performed to test the ability to estimate statistical variation of crosstalk when varying both height and twist. In one set of simulations, crosstalk was estimated using the T-parameter method for many harnesses where the number of twists were random for each harness, wire position within each segment was random, and the height of each segment was also random. The probability density functions for height and number of twists are shown in Figure 3.2. Estimated mean and variance are shown in blue in Figure 3.25. and Figure 3.26.

A second set of simulations was performed to estimate mean and variance of crosstalk for harnesses with a fixed number of twists and a fixed height, but random wire positions at each segment. All combinations of height and twist indicated from the probability density functions for height and twist in Figure 3.2 were simulated. The mean and variance when all parameters varied was estimated from the probability density functions in Figure 3.2 and using equation (1) and equation (7) only. The estimated mean and variance is shown in red in Figs. 10 and 11. This method does a good job of predicting the mean and variance of the crosstalk up to 1 GHz. The RMS errors in the mean and variance are 8% and 15% respectively.

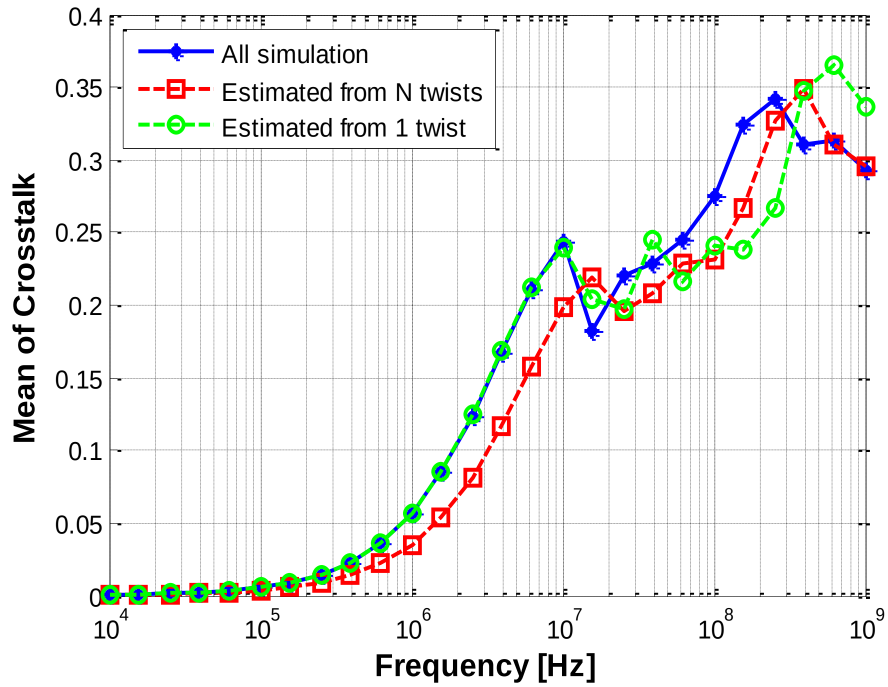


Figure 3.25. Mean value of for two circuits where inductive coupling dominates with both height and number of twists changing for 2 m harness (blue-All parameters varied in simulation, red-Estimate from simulations performed for fixed parameter values, green-Estimated from simulations of only 1 twist).

In the third set of simulations, mean and variance of crosstalk was estimated for harnesses with a single twist and for the fixed heights indicated in Figure 3.2. Mean and variance when both height and twist are random were estimated using the probability density functions in Figure 3.2 and using equation (1), (7), (8), and (9). The estimated mean and variance is shown in green in Figure 3.25. and Figure 3.26.

These results indicate that equation equation (8) works well to high frequency (1 GHz as shown here), but equation (9) is suitable only when the harness is electrically small. When the harness is electrical small (up to 20 MHz), equation (8) and equation (9) were able to predict the mean and variance of crosstalk with an RMS error of 8% for the mean and 12% for the variance.

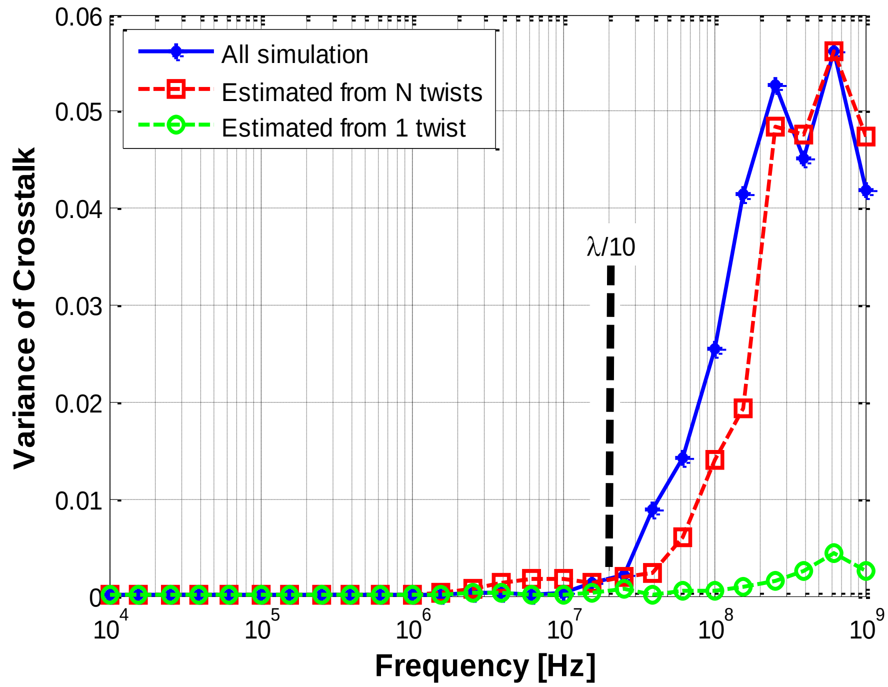


Figure 3.26. Variance of crosstalk value of for two circuits where inductive coupling dominates with both height and number of twists changing for 2 m harness (blue-All parameters varied in simulation, red-Estimate from simulations performed for fixed parameter values, green-Estimated from simulations of only 1 twist).

3.7.2. Variation in number of twists and loads. The previous results showed estimates of variation in crosstalk when two parameters were varied: wire position and either height, twist, density, or load. Simultaneous variation of all these parameters can be found similar to equation (1) and equation (7) as:

$$\mu_c = \int\int\int\int \mu_{c|H,T,D,L} P(H)P(T)P(D)P(L)dH\,dT\,dD\,dL \tag{14}$$

$$\sigma_c^{\ 2} = \int\int\int\int (\sigma_{c|H,T,D,L}^{\ \ 2} + \mu_{c|H,T,D,L}^{\ \ 2}) \bullet P(H)P(T)P(D)P(L)dH\,dT\,dDdL - \mu_c^{\ 2} \tag{15}$$

where $\mu_{c|H,T,D,L}$ and $\sigma^2_{c|H,T,D,L}$ are the mean and variance given fixed values of height, twist, density, and load and each random parameter is assumed to be independent. Presumably, $\mu_{c|H,T,D,L}$ and $\sigma^2_{c|H,T,D,L}$ would be found through simulation for the case where only wire position is varied, since it is difficult to assign wire position to an "average" value.

Equations (14) and (15) require estimates of $\mu_{c|H,T,D,L}$ and $\sigma^2_{c|H,T,D,L}$ for each combination of height, twist, density, and load that are part of the calculation (e.g all combinations of values in Table 2). If the equation for crosstalk were a simple addition or multiplication, the contribution of each element could be separated out and the number of required simulations could be reduced dramatically. For twist, this is possible at low frequencies using equations (8) and (9). Height, density, and position are difficult to separate out, since they impact crosstalk through mutual capacitance or inductance, which is generally a complicated function of these variables. The impact of loads, however, might reasonably be separated from the impact of height, density, position, and twist.

Crosstalk can approximately be given as the product of two functions, one associated with the harness loads and the other with parameters that determine coupling like height, density, twist, and wire position. For example, at low frequencies crosstalk between two circuits due to inductive coupling is given by an equation like

$$Crosstalk \approx j\omega M \frac{1}{Z_S + Z_L} \frac{Z_{FE}}{Z_{FE} + Z_{NE}} \tag{16}$$

The first term, $j\omega M$, is determined by height, density, twist, and wire position. The second term is determined by harness loads. The function will, of course, be much more complicated at high frequencies, but in general crosstalk can approximately be separated into the product of two functions as

$$Crosstalk \approx f_1(other\ parameters) \bullet f_2(loads) \tag{17}$$

where f_1 is a function of parameters like height, twist, density, and wire position that determine how energy is coupled and f_2 is a function of the load terminations. If variations in the loads are independent of variations in the other parameters and crosstalk is given by a multiplication of the two random functions, f_1 and f_2, then the mean and variance of crosstalk when all parameters are varied is given by [13]:

$$\mu_{c,all} = \mu_{f1,other}\mu_{f2,load} \tag{18}$$

$$\begin{aligned}\sigma^2_{c,all} &= (\sigma^2_{f1,other} + \mu^2_{f1,other})(\sigma^2_{f2,load} + \mu^2_{f2,load}) - \mu^2_{f1,other}\mu^2_{f2,load} \\ &= \sigma^2_{f1,other}\sigma^2_{f2,load} + \sigma^2_{f1,other}\mu^2_{f2,load} + \sigma^2_{f2,load}\mu^2_{f1,other}\end{aligned} \tag{19}$$

where $\mu_{c,all}$ and $\sigma^2_{c,all}$ are the mean and variance of crosstalk when all the parameters vary, $\mu_{f2,load}$ and $\sigma^2_{f2,load}$ are the mean and variance *of the portion of the crosstalk given by function* f_2 when only the loads vary, and $\mu_{f1,other}$ and $\sigma^2_{f1,other}$ are the mean and variance *of the portion of the crosstalk given by function* f_1 when other parameters (height, density, position, and twist) are varied.

The parameters $\mu_{f1,other}$, $\sigma^2_{f1,other}$, $\mu_{f2,load}$ and $\sigma^2_{f2,load}$ cannot be determined independently for the general case, but one can determine them indirectly from two sets of simulations. In the first set of simulations, loads are held to their average value and other parameters (wire position, height, number of twists and density) are allowed to change randomly. In these simulations for crosstalk, the average value of the function f_2 will take on its average value when loads vary, $\mu_{f2,load}$, and the variance of f_2 is zero (since the standard deviation of the load is zero in this case). For these simulations, the mean and variance of crosstalk are given by equations (18) and (19) as

$$\mu_{c,other,1} = \mu_{f1,other}\mu_{f2,load} \tag{20}$$

$$\sigma^2_{c,other,1} = \sigma^2_{f1,other}\mu^2_{f2,load} \tag{21}$$

where $\mu_{c,other,1}$ and $\sigma^2_{c,other,1}$ are the mean and variance of crosstalk in simulation (or calculation) 1, when the load is held constant and other parameters are varied. The terms $\mu_{c,other,1}$ and $\sigma^2_{c,other,1}$ can be calculated strictly through simulations or a combination of simulations and calculations, as shown earlier.

In the second set of simulations, the parameters determining coupling (height, number of twists, density, etc) are held to their average value and loads are allowed to change randomly. In this case, the average of function f_1 remains at $\mu_{f1,other}$ and the variance is zero. For these simulations, the mean and variance of crosstalk are then given by equations (21) and (22) as

$$\mu_{c,load,2} = \mu_{f1,other}\mu_{f2,load} \tag{22}$$

$$\sigma^2_{c,load,2} = \sigma^2_{f2,load}\mu^2_{f1,other} \tag{23}$$

where $\mu_{c,load,2}$ and $\sigma^2_{c,load,2}$ are the mean and variance of crosstalk in simulation 2, when only the load is varied.

From equations (18)-(23) it can be shown that the mean and variance when all parameters vary can be calculated from the two simulation results as:

$$\mu_{c,all} = \mu_{c,other,1} = \mu_{c,load,2} \tag{24}$$

$$\sigma^2_{c,all} = \frac{\sigma^2_{c,other,1}\sigma^2_{c,load,2}}{\mu_{c,other,1}\mu_{c,load,2}} + \sigma^2_{c,other,1} + \sigma^2_{c,load,2} \tag{25}$$

The advantage of calculating mean and standard deviation in this way is that a crosstalk estimate is not needed for every combination of loads, height, wire position, twist and harness density. One set of estimates only needs the loads at their average position, while varying the other parameter. The second set of estimates only varies the loads while the other parameters are set at their average value.

One challenge to using equations (24)-(25) is that it is difficult to set wire positions in the harness to an "average" value. This issue can be resolved by performing two simulations to estimate this "average" case, one where both load and position are changing and one where only position changes. The mean does not change, as shown in (24). The variance for this "average" case is made using calculations similar to equations

(18)-(25). From equation (25), the standard deviation when both wire position and load are varied, $\sigma^2_{c,wirepostion+load}$, is given by:

$$\sigma^2_{c,wirepostion+load} = \frac{\sigma^2_{c,wireposition,3}\sigma^2_{c,load,2}}{\mu_{c,wireposition,3}\mu_{c,load,2}} + \sigma^2_{c,wireposition,3} + \sigma^2_{c,load,2} \qquad (26)$$

where $\mu^2_{c,wireposition,3}$ and $\sigma^2_{c,wireposition,3}$ are the mean and variance of crosstalk found when only wire position was varied. The variance when only load varies and wire position is at its average value is then:

$$\sigma^2_{c,laod,2} = \frac{(\sigma^2_{c,wirepostion+load} - \sigma^2_{c,wireposition,1})}{\dfrac{\sigma^2_{c,wireposition,1}}{\mu^2_{c,wireposition,1}} + 1} \qquad (27)$$

This value can be used in equation (25) to estimate overall variation in crosstalk.

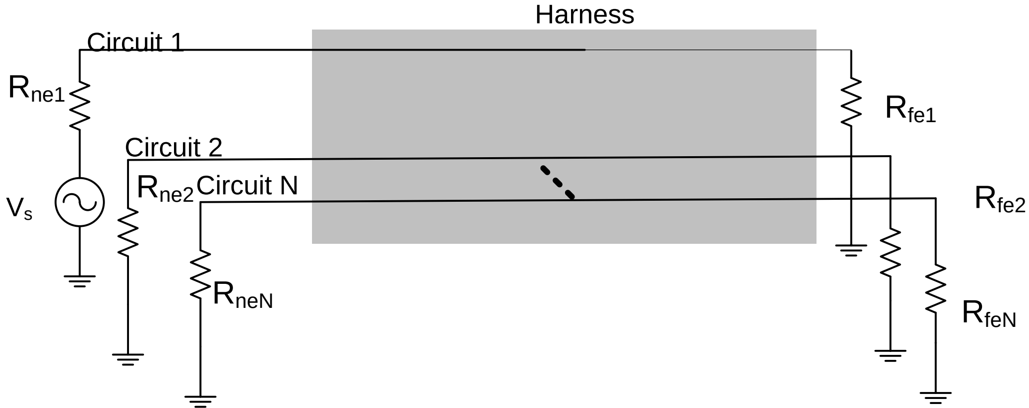
There are several procedures that one can use to estimate variation in crosstalk when several parameters are varying. Twist can be accounted for using equations (8) and (9) or simulations can be performed for each expected number of twists. Variation in loads can be simulated separately from variations in other parameters and results combined using equations (24), (25), and (27). Another option is to perform simulations for all expected combinations of parameter values and estimate overall crosstalk variation using equations (14) and (15).

Four sets of simulations were performed to test the ability of the proposed methods to accurately estimate the statistical variation of crosstalk when many parameters were varied. In the first set of simulations, crosstalk was estimated for many harnesses where wire positions, harness height, number of twists, load, and harness density were all varied randomly from one harness to another. In the second set of simulations, simulations were performed on harnesses with a single twist and fixed values of harness height, load, and harness density. Variations in twist were accounted for using equations (8) and (9).

1) Pure simulation method

   All the variations are directly simulated based on T-parameter method.

2) Combined simulation method (from 1 twist) shown in Figure 3.27.



Estimate μ,σ of crosstalk for 1-segment harness when wire position varies and height, harness density and load fixed for all the configurations

↓

Estimate μ,σ of crosstalk for N-segment harness when wire position varies and height, harness density and load fixed for all the configurations

↓

Estimate μ,σ of crosstalk when wire position, height, number of twists and harness density vary according to equations (1)(7)(10)(11)

↓

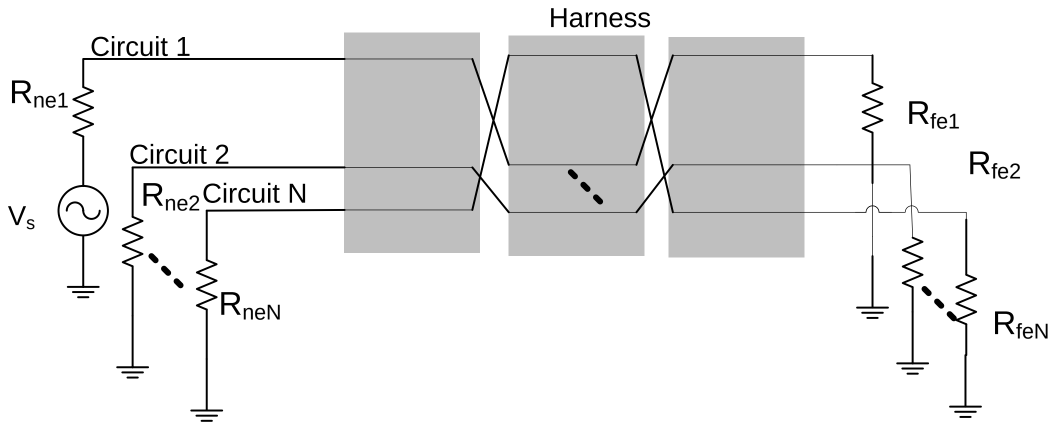
Estimate μ,σ of crosstalk when wire position and load varies with height, number of twists and harness density fixed at mean values

↓

Estimate μ,σ of crosstalk for harness when wire position, height, harness density, twist and load varies equations (23)(24)

Figure 3.27. An approach for estimating mean and variance based on simulations of harnesses with a single twist and with different fixed values of height, loads, and harness density.

3) Combined simulation method (from N twist) using equations (14) and (15) shown in Figure 3.28.



Estimate μ,σ of crosstalk for 1-segment harnesses where wire position varies and height, harness density and load fixed. Estimate for each combination of height, harness density when loads are set to their average value and estimate for each combination of loads when height and harness density are set to their average value.

↓

Estimate μ,σ of crosstalk for multi-segment (twist) harnesses using equations (8)(9) for each number of expected twists.

↓

Estimate μ,σ of crosstalk when wire position, height, number of twists and harness density and loads according to equations (14)-(15)

Figure 3.28. An approach for estimating mean and variance based on simulations of harnesses with N twist and when separately accounting for variations in loads.

4) Combined simulation method (from N twist) using equations (24), (25) and (27) shown in Figure 3.29.

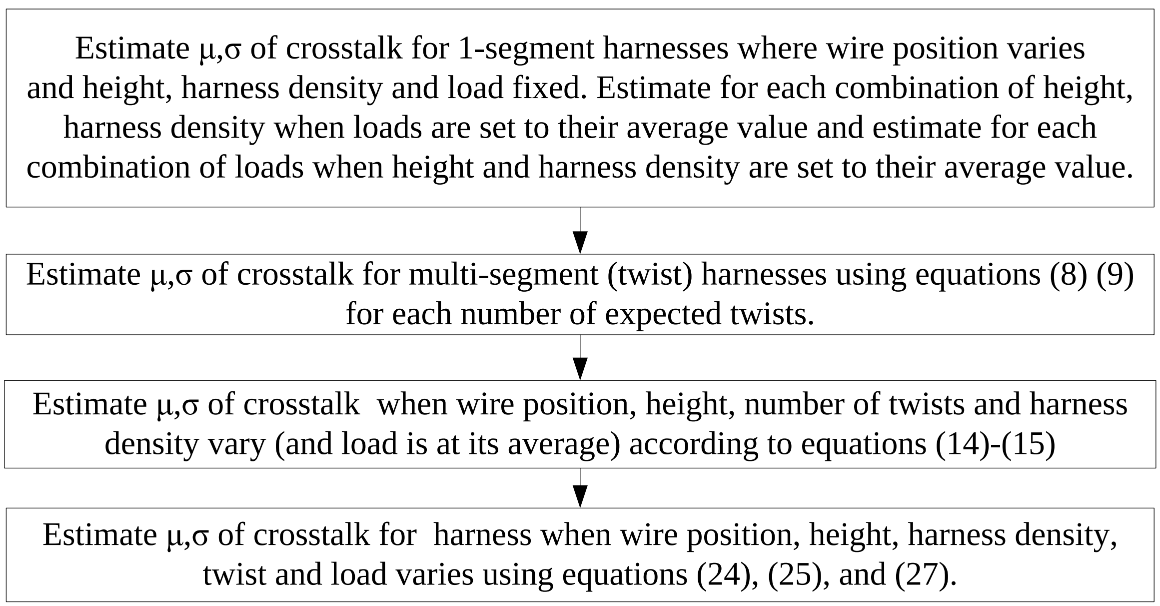


Figure 3.29. An approach for estimating mean and variance based on simulations of harnesses with N twist and when separately accounting for variations in loads using equations (24), (25) and (27).

Mean and variance when both loads and twist are random were estimated using the probability density functions in Figure 3.2 and using equations (24), (25), and (27). The comparison of estimated mean and variance is shown in Figure 3.30. and Figure 3.31.

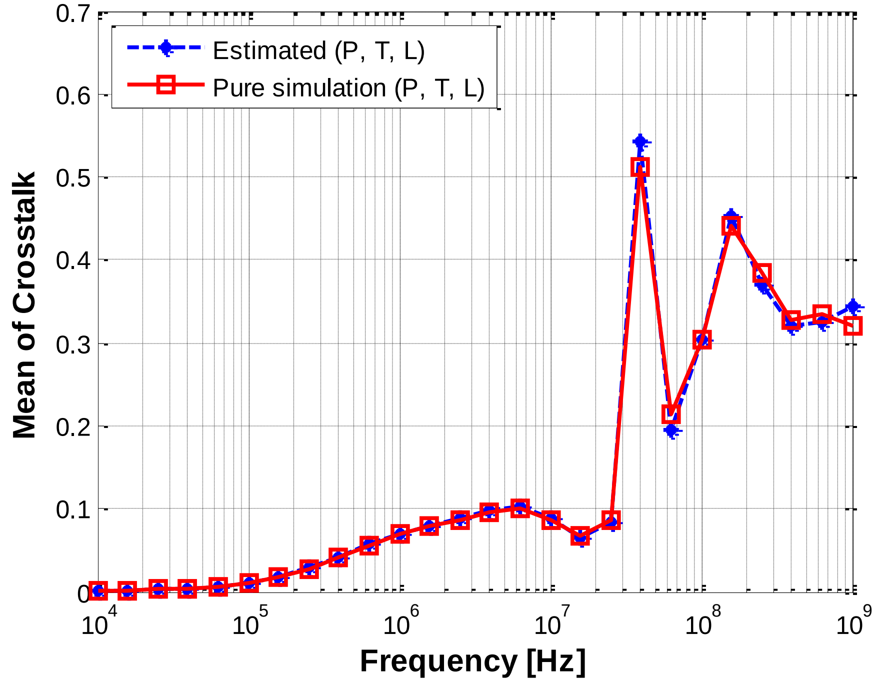


Figure 3.30. Mean value of crosstalk when varying load, twist and wire positions, for two circuits where inductive coupling dominates (RMS difference 4%).

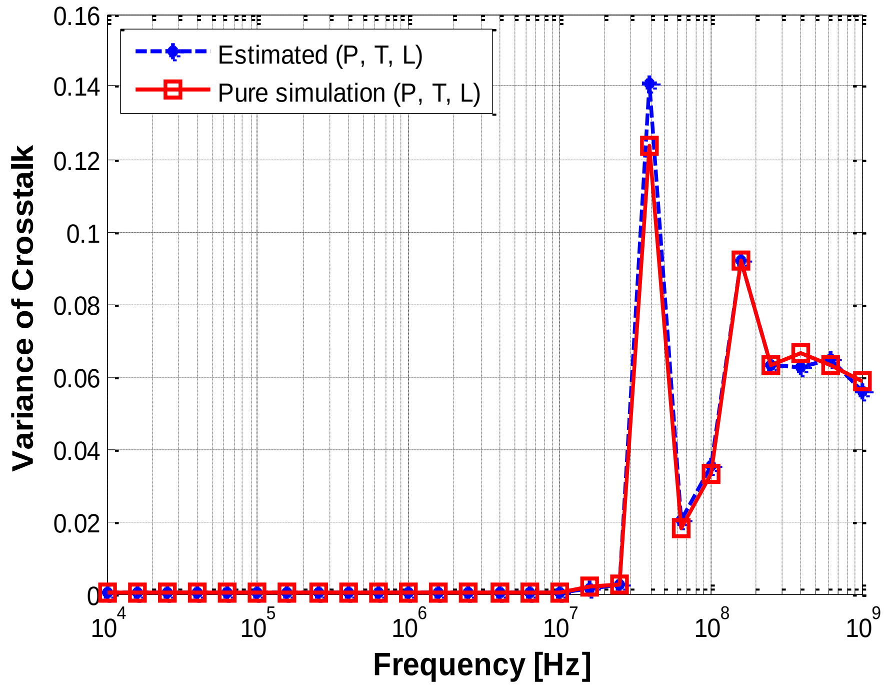


Figure 3.31. Variance of crosstalk when varying load, twist and wire positions, for two circuits where inductive coupling dominates (RMS differnence 5.84%).

The RMS difference between the means of the estimate and pure simulation is 4% and between the variances is 6%. Inductive coupling dominated for these results but similar results were found for capacitive coupling. The RMS difference was 6% between the mean values and 15% between the variances.

Variations in load were accounted for separately using equations (24), (25), and (27). In the third set of simulations, simulations were performed on harnesses with multiple twists. Variations in load were accounted for separately using equations (24), (25), and (27). In the last set of simulations, simulations were performed for each combination of harness height, load, number of twists, and harness density indicated in Table 3.2. and overall variation in crosstalk was estimated strictly from equations (11) and (15). The comparison of estimated mean and variance is shown through Figure 3.32. to Figure 3.35.

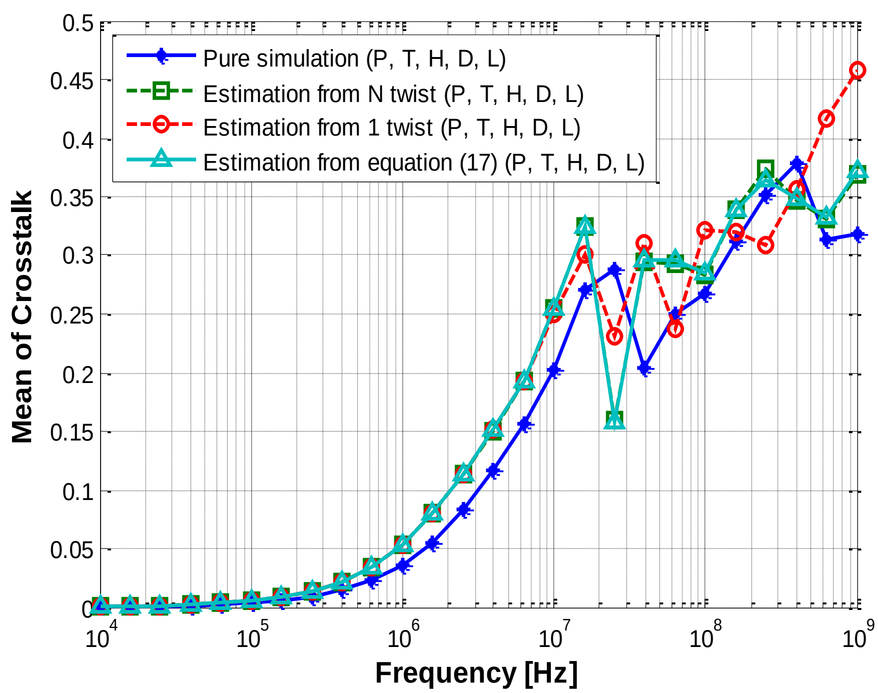


Figure 3.32. Mean value of crosstalk when varying wire position (P), number of twists (T), harness height (H), harness density (D), and harness far_end loads of generator (L).

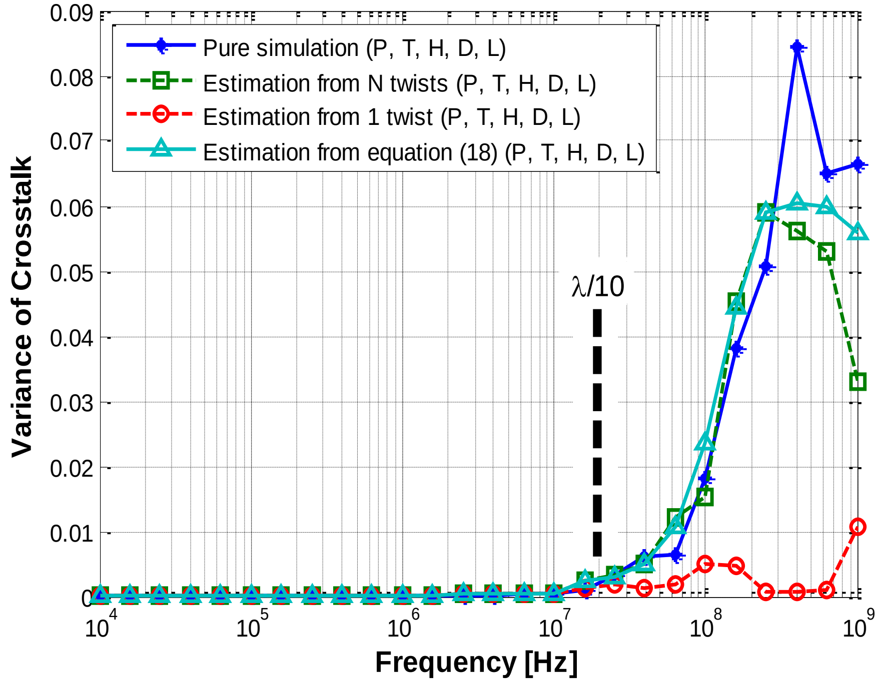


Figure 3.33. Variance of crosstalk when varying wire position (P), number of twists (T), harness height (H), harness density (D), and harness far_end loads of generator (L).

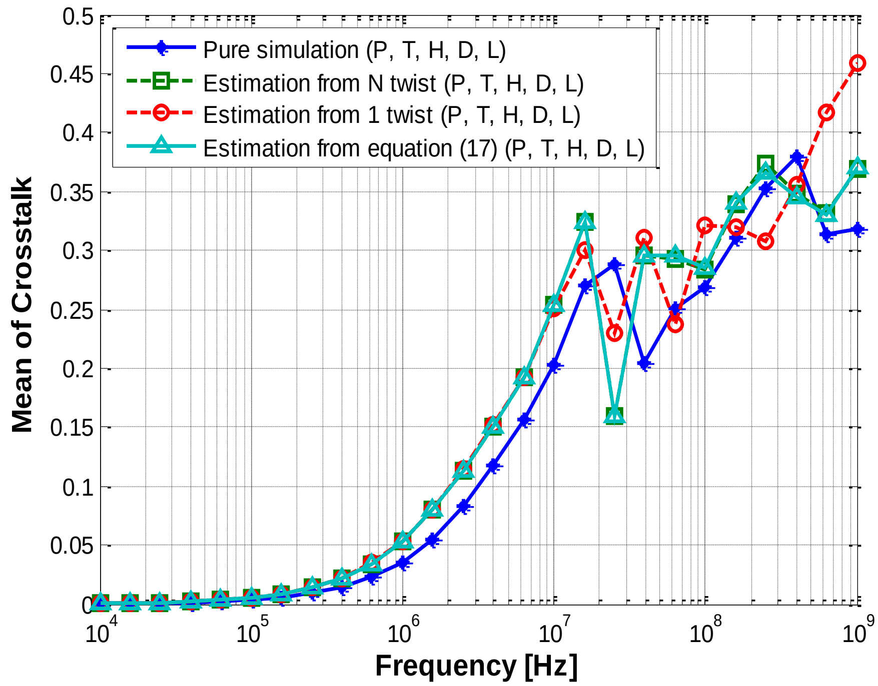


Figure 3.34. Mean value of crosstalk when varying wire position (P), number of twists (T), harness height (H), harness density (D), and harness near_ end loads of generator (L).

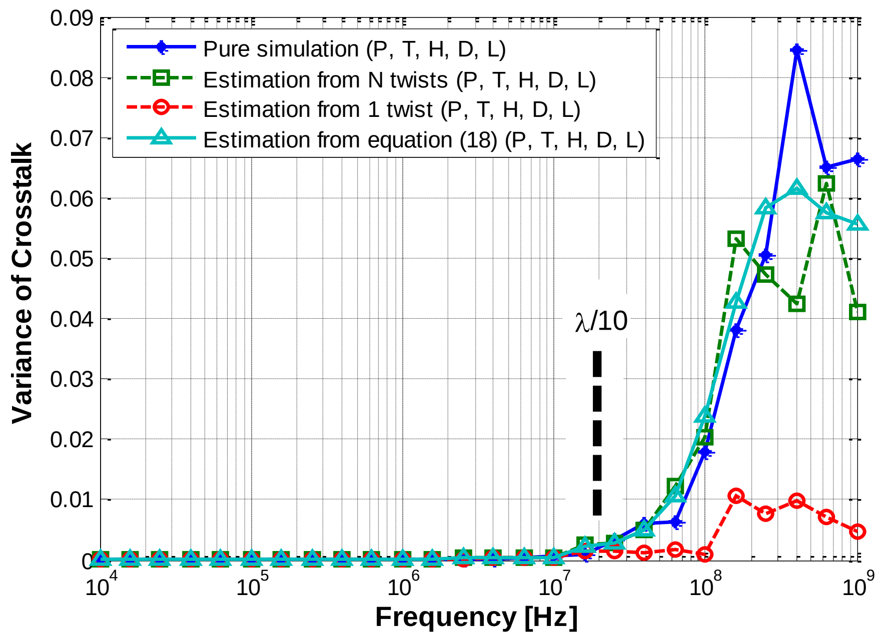


Figure 3.35. Variance of crosstalk when varying wire position (P), number of twists (T), harness height (H), harness density (D), and harness near_end loads of generator (L).

4. CONCLUSION

The T-parameter method, which approximates the cable as cascaded segments of multi-conductor transmission lines, can be used to quickly estimate statistical variation in crosstalk in cable-harness bundles without sacrificing accuracy. The accuracy of the T-parameter method was verified by comparing its results with results from a conventional SPICE analysis of the entire harness that had previously been tested against experimental data. Both methods gave the same result, but the T-parameter method was approximately 300 times faster than the SPICE analysis.

Methods to estimate statistical variations in crosstalk were also presented to account for random variations in harness height, harness density, number of twists and loads. Statistical variations in crosstalk can be estimated using only the T-parameter method or using a combination of simulations for the mean and variance of crosstalk for specific values of the random variables along with probability density functions for those variables. Variations in twist can be estimated well at low frequencies based on results from a harness with no twists (a single segment). Variations in loads can be separated from variations in other parameters and combined to estimate overall crosstalk when all parameters vary. The main advantages of these approaches is that they allow fewer simulations to obtain an accurate result and, more importantly, that they give a closer link between variation in crosstalk and the parameters that cause that variation than could be obtained using strictly Monty Carlo methods.

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