# Crosstalk prediction on wire bundles by Kriging approach

S. Salio, F. Canavero
Electronics Department,
Politecnico di Torino
Torino, ITALY

D. Lecointe, W. Tabbara
Département de Recherche en Electromagnetisme,
LSS/CNRS-SUPELEC
Paris, FRANCE

**Abstract:** A wide variety of interconnections among electronic devices are performed by means of randomly twisted bundle of wires, particularly for transport and industrial applications. This work examines the crosstalk analysis of such bundles. A new model based on fractals for describing the position of wires winding throughout a bundle is presented. It allows the wires' meandering degree to be tuned simply by means of a parameter (the fractal dimension). It also allows for a statistical analysis of crosstalk because it can simulate independent different realizations of the same interconnection. An efficient multifactor prediction method known as "Kriging" is applied in order to describe the crosstalk as a function of the input factors (cable loads, cable height above the ground plane, etc.) of the cable model. It allows for a drastic reduction in the simulation time insofar as it predicts the crosstalk at untried combinations of the input factors from a small base of input combinations. In comparing the crosstalk simulated using the fractal model with the experimental measurements good agreement was found.

## Introduction

The importance of modeling interconnects in EMC problems is due to their diffusion in all modern electronic devices. Crosstalk on interconnects is a critical phenomenon in modern electronic applications. The crosstalk determination of randomly twisted bundles of wires is very time consuming, since the non-homogeneity of their cross-section requires a repeated 2D approach for the per-unit-length parameters (p.u.l.) calculation along the line (e.g. by moment method), and it requires also repeated determination of crosstalk for taking into account its variability due to the variability of cable realisations.

In this work, the nonuniformity of the bundle is approached by means of a fractal model, whose main feature is to describe the position of a wire throughout a bundle as a realization of a fractal curve [1]. This provides the possibility to tune the wires' meandering degree simply by means of the fractal dimension assigned to the bundle.

It allows also describing an infinite number of different cable realizations determined with the fractal algorithm and then to investigate the crosstalk variability. The efficient approach we suggest in this paper for crosstalk prediction consists in performing a limited number of simulations for a few combinations of the input parameters (loads, height above the ground plane, etc.) and then to predict the crosstalk with the Kriging method at untried combinations of the input parameters. Kriging predictor is suitable for this kind of problems because it provides good accuracy even from a little amount of information [2].

## The fractal model of random bundles of wires

In this Section a new fractal model of random bundles of wires is presented. Fractals are quite an intricate mathematical topic [1] and, therefore, a fractal model of bundles of wires may be seemingly too complicated for describing the winding of wires throughout the bundle. The model currently proposed uses only the Random Midpoint Displacement algorithm (RMD) [3] of the fractal theory which is a recursive method, widely used for generating fractal curves lying in 2-dimensional planes, due to its quickness and simplicity. The advantage of this model with respect to other models currently cited in literature is that it allows for the wires' meandering degree to be tuned simply by means of a single parameter. This improvement is considerable because it allows for simulation of a wide variety of real industrial interconnections. In addition, the fractal model allows for the description of the variability of the cable realizations of a given interconnection and, consequently, the coupling variability.

Let's focus on to the proposed method of building an $n$-wires cable [4]. Let's start with the first wire belonging to the cable. Its 3-dimensional position along the transmission line is described by the composition of two 2-dimensional fractal curves lying in the two orthogonal planes sharing the longitudinal axis of the transmission line. These two fractals in the proposed model have the same fractal dimension. The extremities of the two 2-dimensional fractals are known because they correspond with the $x,y$ positions on the terminations (they have to be input to RMD as starting points of the algorithm).

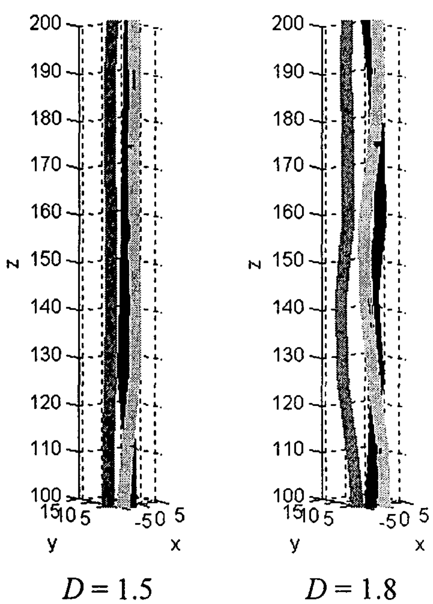


**Figure 1. Examples of random bundles of wires modelled with fractals, for two different values of the fractal dimension *D*.**

In order to build the whole cable the process of generating one wire must be repeated $n$ times. When assembling all the wires belonging to a cable it often happens that one or more wires overlap in one or more cross-sections. For this reason, an ad-hoc algorithm was developed to eliminate the possibility of overlap. In order to prepare this kind of algorithm, the basic constraint is that the conductor

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movements need to be minimized, so that the wires' fractal geometry remains relatively constant during the elimination of overlapping.

Fig. 1 shows two examples of random bundles of wires determined using the fractal algorithm. The figure refers to 1-m long segment of cables having 9 wires and with fractal dimensions 1.5 and 1.8. For a better readability of the figure only three wires are shown. Looking at the figure it is evident that the wires' meandering degree unequivocally depends on the given fractal dimension. The appearance of cables is quite realistic if compared with industrial cables (for example, with bundles of wires assembled on road vehicles).

The determination of a 9-wire bundle takes about ten seconds on a Pentium PC. The CPU time may increase if there is a shortage of space for the wires' movements inside the bundle. In this case, the construction of the cable slows down due to the recurrent call to the anti-overlapping algorithm. At any rate the time required does not exceed the order of minutes even for very complex cable with tens of wires.

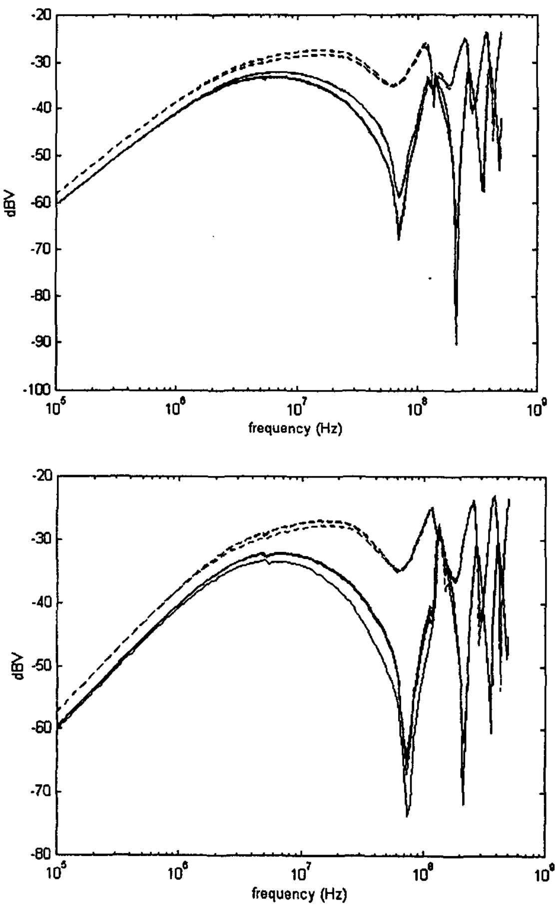


**Figure 2. Direct crosstalk voltage measurements on the right-end termination. Solid and dotted lines refer to two different wires. Top and bottom panels refer to cable heights above the ground plane of 79 and 120 mm, respectively. Loads are 50 Ω. Ten different cable realizations were performed for each height above the ground plane. Many spectra overlap.**

## Experimental validation

This Section deals with the experimental validation of the random bundle of wires model presented above. The experimental measurements cited in the literature are not suitable for validating the present model because they refer mainly to uniform lines and, moreover, because the crosstalk variability of non-uniform lines is not considered.

Experimental measurements specifically intended to validate the fractal model of bundle of wires were thus conducted on a cable made of seven 1-m long wires created in the laboratory where the measurements were carried out. Since the cable was suspended without supports, very light wires were chosen to reduce the effect of gravity and the difficulties in keeping them parallel to the ground plane. The wires were forced to stay in a cylindrical volume all along the line by circular staples set 20 cm apart. The radius of such an imaginary cylinder was nearly the one defined by the wires on the terminations. The cable wires had the following characteristics:

- dielectric diameter: 0.9 mm
- conductor diameter: 0.45 mm (7 x 0.15 mm)
- dielectric: PVC (filotex KY3 0-03)

The source was a 1Vpp sinusoidal signal (with a 50-Ω generator output resistance) over a frequency range 1 kHz to 500 MHz, positioned on the left-end termination.

Two set-ups with respective cable heights of 79 and 120 mm above the ground plane were considered. This distance was measured between the ground plane and the centre of the cable.

The results of experimental measurement are reported in Fig 2. The top panel refers to the cable located 79 mm above the ground plane and the bottom panel refers to the cable located 120 mm above the ground plane. Both configurations were lightly perturbed by hand 10 times in order to reproduce 10 different cable realizations. The crosstalk voltage was measured on the right-end termination of two different wires.

A discussion of the measurement errors is given, because the nominal set-up is affected by a number of uncertainties. First of all, the characteristics of the dielectric are not accurately known. Any nominal dielectric thickness is incorrect because the wire thickness changes along the cable; also, the dielectric constant is generally known in terms of typical values for the material in use (e.g., PVC). Another area of uncertainty arises from the circular staples hung on the cable. Their diameter is only roughly known because they were manually put in place but their effect on the crosstalk is the most relevant among those mentioned, because they determine the closeness of wires (the investigation conducted with simulations has shown that this error can reach several dB). These effects are certainely dominant with respect to the intrinsic uncertainty of measurements due to the electronic intrumentation used.

A comparison between measurements and simulation is discussed with reference to Fig. 3 showing the simulation results of the set-up with height above the ground plane 79 mm and 120 mm; for both configurations, 50-Ω loads are considered. Each configuration has been simulated for 50 cable realizations with fractal dimension 1.05. This value has been chosen based on the smoothness of the wires in the experimental set-up. It seemed the most appropriate.

The comparison of measurements of Fig. 2 with simulations of Fig. 3 reveals that over low frequencies, simulations overestimate the experimental crosstalk on both wires by about 1 dB. Simulations overestimate the experimental crosstalk variability, as well. In general, a good agreement between simulations and experimental measurements has been found, if considering the uncertainty of the experimental set-up. The underestimation of crosstalk variability that affects the entire spectrum is not a severe problem. An improvement of the validation would be obtained by repeating the experimental measurements for more different cable realizations (the cable was perturbed by simple manipulations, whose effect is not clearly identifiable, although this was the only practical method available).

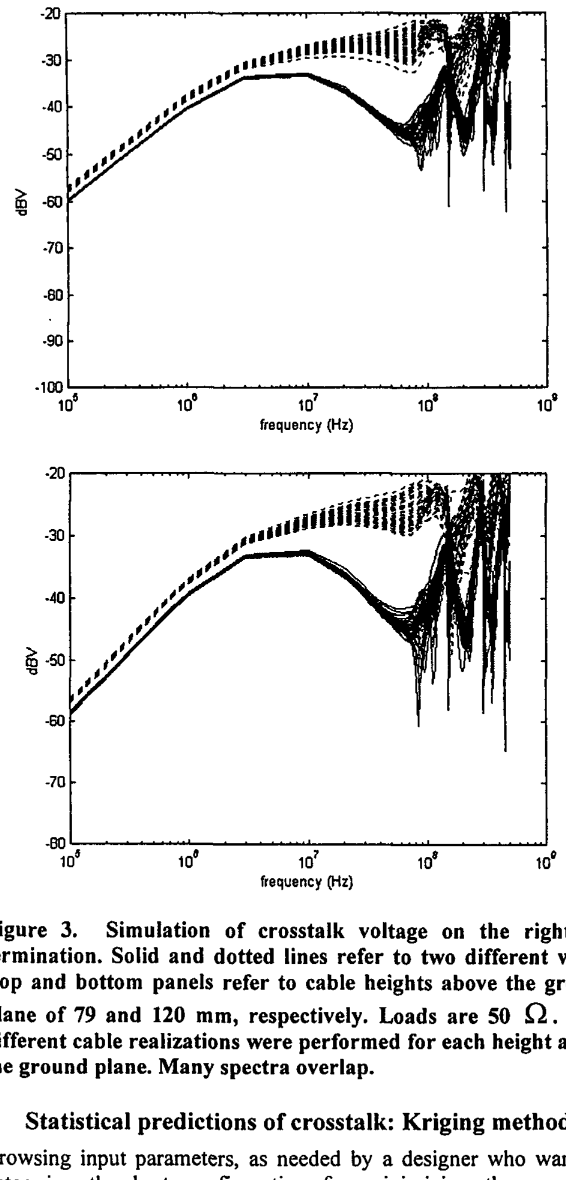


**Figure 3. Simulation of crosstalk voltage on the right-end termination. Solid and dotted lines refer to two different wires. Top and bottom panels refer to cable heights above the ground plane of 79 and 120 mm, respectively. Loads are 50 $\Omega$. Fifty different cable realizations were performed for each height above the ground plane. Many spectra overlap.**

## Statistical predictions of crosstalk: Kriging method

Browsing input parameters, as needed by a designer who wants to determine the best configuration for minimizing the crosstalk, requires an endless amount of time primarily due to the following factors:

- the number of parameters associated with an interconnect (loads, geometric characteristics of the cable, etc.) is very high with respect to other kind of EMC problems. For instance, a 10-wires cable has about 50 parameters.
- for each combination of parameters, a large number of simulations has to be performed in order to describe the statistic of crosstalk; the analysis of a single cable realisation is meaningless.
- the amount of time required to calculate the p.u.l. parameters increases greatly as the number of wires increases. For example, the p.u.l. parameters' determination for a 10-wire line with 64 cross-sections takes several minutes on a Pentium PC.

It turns out that an efficient crosstalk predictor for untried combination of parameters is necessary in order to reduce the total simulating time. The Kriging multifactor prediction method is the approach suggested and applied in this paper. The method was developed in the 1960's for geostatistics problems and then later successfully employed in the fields of mining, meteorology, and hydrology ([2] and references therein).

The Kriging predictor combines a regression model with a stochastic process. It provides excellent interpolations when data points are smooth but is not particularly efficient with fast varying data-points (a typical problem of all interpolating methods). The Kriging approach provides also account for the uncertainty of its predictions. Thus it is straightforward to improve the global accuracy of one's predictions by adding data-points to the regions where the uncertainty of predictions is relatively high.

**Application to a 9-wire cable**

In this section the crosstalk analysis of a 9-wire bundle is performed using the Kriging predictor. The loads, the wires' twisting degree and the cable height above the ground plane are the varying parameters. Several source-observable combinations are considered.

The cable analyzed is a 9-wire 2-m long bundle of wires located above a perfect conducting ground plane. The characteristics of the wires are as follow:

- diameter of the conductors: 1.5 mm
- diameter of the dielectric jackets: 2.3 mm
- relative dielectric constant of the dielectric jackets: 2.6
- relative dielectric constant of the surrounding medium: 1 (air)

The cable crosstalk is calculated as a function of the height above the ground plane, the loads, the frequency, the fractal dimension, the number of the excited wire and the number of the disturbed wire. The crosstalk is simulated for a few combinations of the input factors just listed. The choice of these combinations is crucial since they have to bring to the predictor as much information as possible. The general rule (as for any predictor) is that one has to choose the points where the observable changes more rapidly. The Kriging predictor has the strength to give the uncertainty of predictions and then, if necessary, it is straightforward to add up information exactly where it is missing.

Three configurations that differ for the height above the ground plane are considered. The first configuration has its bundle centre located 7.3 mm above the ground plane. The second and the third configurations have the height of the bundle centre at 12.3 and 22.3 mm, respectively. The three heights considered are not equally distanced in order to model accurately the effect of the ground plane.

Resistive loads all of the same value are placed between the wire terminations and the ground plane (diagonal loads). Four cases are considered: 10, 100, 1000, and 10000 $\Omega$. The only exception is that of the excited wire, where a 50-ohm resistance is placed as output resistance of an ideal sinusoidal 1-V generator.

Three cable fractal dimensions are considered: 1, 1.1, and 1.5. The fractal dimensions are not equally distanced in order to accurately describe the transition between a uniform cable (with fractal dimension 1) and a non uniform cable (with fractal dimension greater than 1).

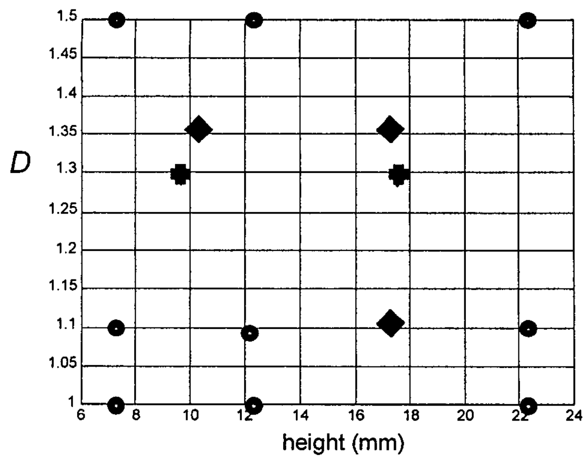


**Figure 4. Experiment design for a two-parameter Kriging prediction. The originally planned data-points are represented by circles and the points added for reducing Kriging variance are shown as diamonds. The test-points are represented by crosses.**

The number of configurations analyzed is 72. This number rises from the combination of three fractal dimensions (1, 1.1 and 1.5), three heights of the cable above the ground plane (7.3, 12.3, and 22.3), four loads (10, 100, 1000, and 10000 $\Omega$), and two excitations (wire #1 and #2). When a configuration involves a non-uniform cable (fractal dimension greater than 1), 50 simulations are carried out on 50 different cable realizations obtained using the fractal algorithm.

The observable is the spectrum of voltage on all wires (both left and right terminations). Such voltage spectrum is an extremely rough function of the frequency in the region affected by multiple resonance. Since the Kriging approach is fitted to smooth curve interpolations, the frequency cannot be used as a prediction factor. On the other hand, the frequency is a fundamental parameter for the crosstalk. In order to overcome this difficulty, one can consider a few significant points of the spectrum and apply the Kriging interpolator to each one. For this reason we note that the crosstalk spectrum shows a typical behaviour that can be separated in two bands independent of the specific configuration and cable realization considered. Over low frequencies, the crosstalk increases with the frequency with a slope of 20 dB/decade. In this band it is sufficient to provide crosstalk at a specific frequency, since providing crosstalk at a greater number of frequencies would be redundant. Over high frequencies, picking up short and simple information on crosstalk is more complicated, because of the multiple resonances affecting the crosstalk that make the spectrum extremely rough. Over this band, the minima produced by the resonances are not of practical interest, whereas the crosstalk envelope and its maximum are of great practical interest.

As mentioned in the discussion above, in this work three characteristics of the crosstalk are provided: its amplitude at 101 kHz (low frequency); its mean envelope over the band 100 MHz to 500 MHz (high frequency), and its maximum amplitude over the band 100 MHz to 500 MHz (high frequency)

### Experiment design

Let's begin by considering an experiment in which the height above the ground plane and the fractal dimension are the browsing input factors. The terminal loads are fixed at 10 $\Omega$ and the excited and disturbed wires are #1 and #2 respectively. The possible combinations of the input factors are represented by circles in Fig. 4, that represents the entire domain in which the Kriging interpolator is used to predict the crosstalk voltage. Clearly Kriging provides a general good prediction when the voltage is much greater than its variance. If there are domains where this condition is not verified then some additional data points must be provided, because nearby there is a shortage of information. The additional points required for this experiment are indicated in Fig. 4 by diamonds.

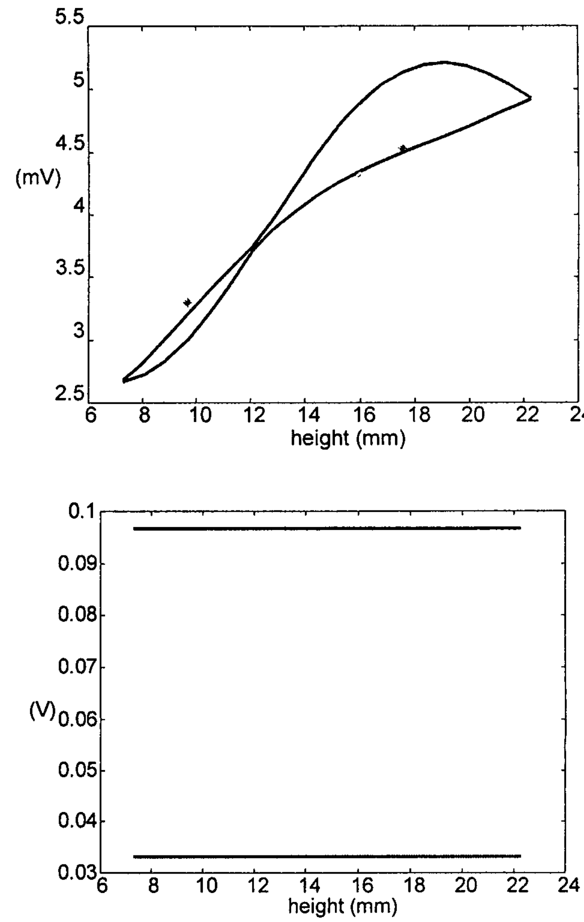


**Figure 5. Test of Kriging predictions: the top panel refers to the mean crosstalk at 101 kHz, and the bottom panel refers to the maximum crosstalk over the 100-500 MHz band. In each panel the band between the two curves represents the interval mean voltage +/- standard deviation *vs.* height above ground, for fixed fractal dimension (D=1.29). The '*' represents the exact value at test points.**

The crosstalk prediction obtained with Kriging for this experiment is tested at two points with fractal dimension 1.29 and heights above the ground plane 9.67 and 17.56, respectively. These test points are represented by crosses in Fig. 4. The test points chosen are far away from the data points in order to check the Kriging prediction for the worst case. For these two test points the crosstalk is simulated and the results are compared with the Kriging predictions in Fig. 5. If the voltage of test points falls between the prediction +/- the standard deviation, then Kriging is working properly.

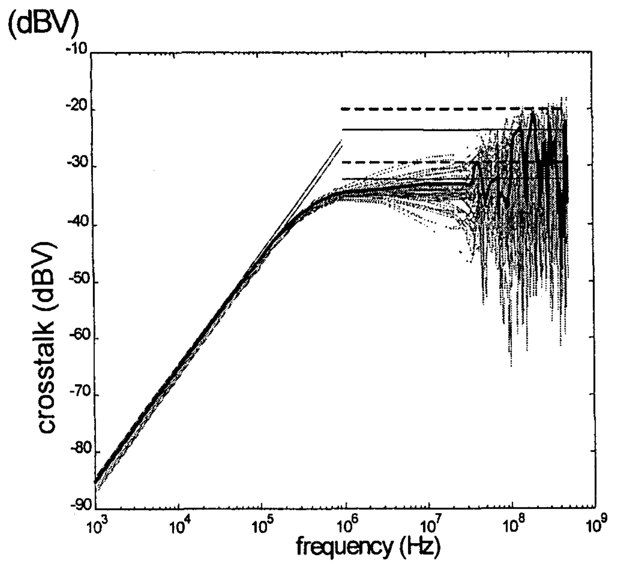


**Figure 6. Comparison between Kriging predictions and simulations. The fractal dimension was 1.29 and height above the ground plane was 17.56 mm. The light lines represent the crosstalk simulated on 50 different realizations of the cable considered. The bold line represents their mean. The two thin solid lines over low frequencies represent the prediction of the mean crosstalk provided by Kriging +/- one standard deviation. The two thin solid horizontal lines represent the Kriging prediction of the mean envelope of crosstalk over high frequencies +/- one standard deviation. The two thin dotted horizontal lines represent the Kriging prediction of the mean maximum of crosstalk +/- one standard deviation.**

For the second test point, the whole spectrum is reconstructed according to the Kriging prediction for low and high frequencies and it is compared with the real spectra obtained simulating 50 cable realizations (Fig. 6). The boundary given by the Kriging predictions is a good estimate of the average simulated envelope and of the maximum of crosstalk.

Let's now consider the 3-factor experiment design. The additional input factor is the load imposed on the cable terminations (the other two are, of course, the height above the ground plane and the fractal dimension). In order to obtain accurate predictions, the loads are measured using a logarithmic scale. The observable is the voltage spectrum on the right end of wire #2. Fig. 7 shows the resulting three-dimensional space where Kriging is applied, the position of the 48 data points, and the two planes chosen to graphically depict the Kriging predictions of the observable.

Being impossible to represent the predicted voltage in a 4-D space, the predictions are reported in the two planes having fixed fractal dimension 1.26 and fixed height above the ground plane of 15.19 mm. These two planes are represented in Fig. 7 by bold lines. The predictions (Fig. 8 and 9) show good accuracy because the standard deviation of predictions is less then 1/10 of the predictions themselves.

The results obtained using the Kriging interpolator with three input factors are tested in three points that differ according to the loads imposed on the line terminations. The loads are 42.8, 545, and 4833 $\Omega$, respectively. These three points have a common height above the ground plane (15.19 mm) and a common fractal dimension (1.26).

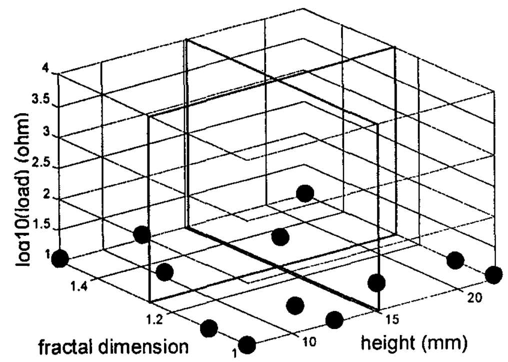


**Figure 7. Three-dimensional space for Kriging application. The circles represent data points. For the clarity of the representation, the circles are reported only in the first plane having 10 Ω loads. Bold lines represent the two planes in which Kriging predictions are graphically reported in Fig. 8 and 9.**

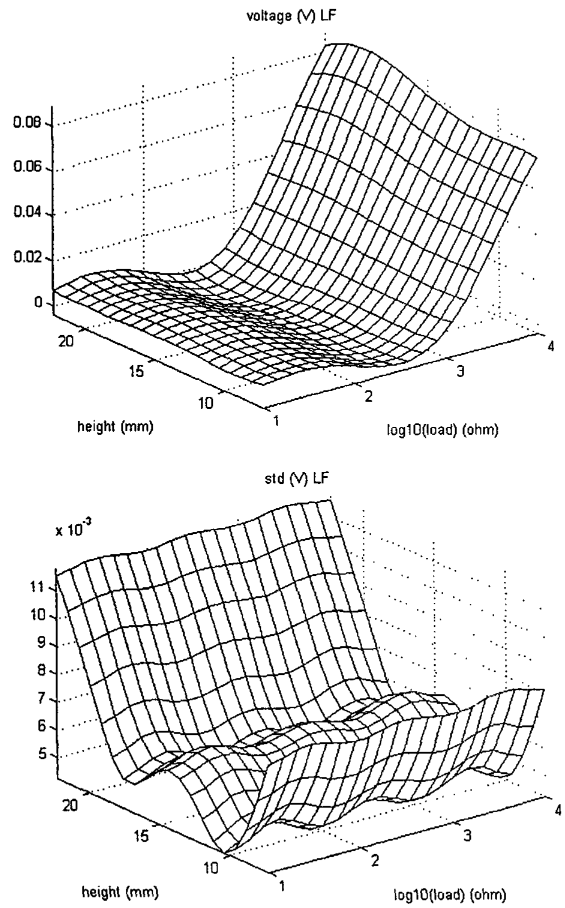


**Figure 8. Kriging predictions for fixed fractal dimension 1.26 as function of the loads and the cable height above the ground plane. The top plate represents voltage, and the bottom one shows standard deviation of the voltage.**

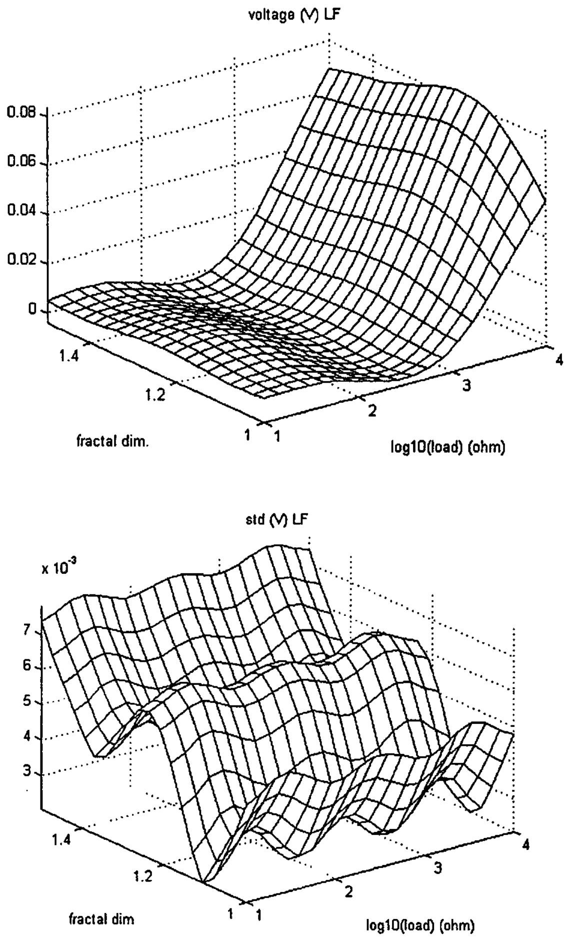


**Figure 9. Kriging predictions for fixed height (15.19 mm) above the ground plane as function of the loads and the cable fractal dimension. The top plate represents voltage, and the bottom one represents standard deviation of the voltage.**

Considering Fig. 7 these three points belong to the line orthogonal to the plane determined by the height and the fractal dimension axes. The test results are shown in Fig. 10.

Kriging estimator was used also for high frequency predictions and accurate results were gained as well.

The results obtained show somewhat less accuracy as compared to the 2-dimensional predictions. This is due to fact that the experiment design is voluntary and is based on a small amount of information in order to test the Kriging performance. In fact, it takes into account loads ranging from 10 Ω to 10 kΩ, and only four load values (10, 100, 1000, and 10000 Ω) were given as input to Kriging. It is interesting to note that, in this case, the prediction is acceptable with only a small amount of information given to the predictor.

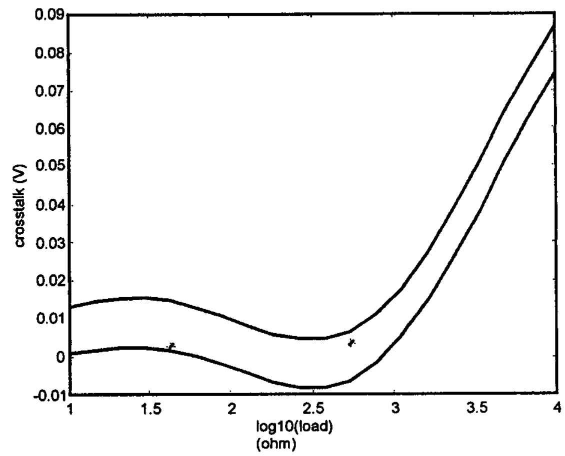


**Figure 10. Test of Kriging results of the 3-dimensional experiment design. The band between the two curves represents the interval mean voltage +/- one standard deviation. The symbol '*' represents the test points.**

## Conclusion

The focus of this work is now moved to the necessity for designers of interconnects to be given the possibility of assessing in real time the effects of cable parameters variability, in order to find the best configuration which minimizes the crosstalk. Designers cannot repeat the crosstalk simulation for a large number of combinations of input parameters due to the long amount of time required. A very efficient multifactor prediction method known in the literature as the "Kriging predictor" has been applied to minimize the number of simulations of a cable and to predict the crosstalk at untried combination of the input parameters. The Kriging predictor combines a regression model with a stochastic process and it also provides the variance of its predictions. This method has been used in predicting the crosstalk on a 9-wire cable as a function of the cable height above the ground plane, the cable loads, and the cable fractal dimension (i.e. 3-dimensional predictions). The results have highlighted the usefulness of this method insofar as it has provided very accurate predictions even though based on very little information.

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