Towards the generation of industrial bundles through a random process under realistic constraints

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Abstract— **To get closer to the reality of aeronautics wire harnesses, we propose to represent a bundle as a non-uniform transmission line by discretizing it into several sections. For each section, positions of conductors are randomized. However this procedure is applied with some geometrical constraints thus resulting in a much more realistic bundle profile. Currents and voltages may be determined on each conductor. Then, we use statistical tools to analyze our results. In order to save computation time, we also propose simplified models for simulation studies of the common mode current.**

Keywords-component; Cable Bundle; Common-mode current; Crosstalk; Multiconductor Transmission Line; Statistical; Random; Weibull; Linear Congruential Generator

I. Introduction

Embedded electric and electronic functions play an increasing role in modern transportation systems. Therefore the number of cable interconnections is still very important even if RF techniques or multiplexing may coexist. These cables are very well known to be potential paths for electromagnetic interference. Since the late 80's, important theoretical work has been done to model multi-conductor harnesses. We may first mention the work done to describe distributions of multiconductor interconnections based on the electromagnetic topology principles [4-8]. This theory splits the complex problem into sub-elementary problems and uses the equations of transmission lines theory to handle calculation of electromagnetic interactions in bundles.

Since the late 90's, modeling the effects of non-uniformity in bundles to consider interlacing has become essential to cope with realistic geometries of cables bundles. Indeed, in aerospace or automotive context, elementary wires inside harnesses which can be up to several hundred meters long are rarely parallel to each other and rarely arranged in a precise order. The authors in [1] describe a way to model the randomness of the arrangement of the cable in a section of wire bundle using the RDSI algorithm. From our side, we propose to describe the bundle as a succession of sections. Each section is defined by the geometry of conductors which may be determined randomly by a different method from [1], taking into account a displacement between the conductors closer to reality. Our goal is to build up a model which is as realistic as possible. This model must constitute a reference for computation of EM interactions inside bundles. Further studies will be then dedicated to the development of less complex representation when possible.

After a presentation of the two methods of bundle generation (Section II), we describe the case study [1] in Section III. Then we implement our model and compare it with results obtained in [1]. In this case study, a voltage is applied on one internal wire. First, the common mode current induced on the bundle is determined (Section IV.A). Then we focus on the crosstalk parameter between conductors of the bundle (Section IV.B). The next step consists in a statistical analysis of results by looking at their distribution function and using the probability distribution of Weibull in Section V. Finally we show in Section VI how a simplified model can reduce the computing time for studying the common mode current with little loss of accuracy.

II. Different models of interlacing cables

A. Model with RDSI algorithm

The method developed in [1] consists in:

- cutting the bundle of cable into sections respecting the constraint shown in [3] where the length of sub-sections remains below $\lambda/10$, λ being the wavelength.
- taking a fixed geometry as in Fig. 1 (a)
- inter-changing conductors numbers associated with these circles in this geometry. These numbers change randomly from one section of the conductor to the next one according to a Gaussian distribution. Consequently a smooth transition between two consecutive sections is achieved. Per unit length L and C matrices are calculated once and appropriate permutations are achieved for each section in order to evaluate currents and voltages on conductors.

B. Model with LCG algorithm

The random generation is done with a pseudo-random algorithm: Linear Congruential Generator (LCG) defined in:

$$x_{n-1} = (a \cdot x_n + c) \cdot \mathrm{mod}(m) \qquad (1)$$

where x_n is the sequence of pseudorandom values (x_0 is the initial value), m the module, a the multiplier and c the increment. It is one of the oldest and most efficient algorithms to generate pseudo-random numbers. It is used mostly for random functions in compilers as ANSI C, Microsoft visual, GCC, Random class API for Java, ...

Our model generates geometric sections of bundles where conductors are randomly placed into a 2-D (x, z) plane (the bundle follows the y-axis) under some constraints. Placement is made by evaluating the neighborhood of each conductor which is randomly chosen. It may however be constrained by a notion of group forcing some conductors to stay nearby, as for example twisted pair. Once this particular neighborhood is determined, we select a conductor randomly and compute also its new coordinates by a random process. The placement must still comply with both, a criterion of proximity which can be adjusted to more or less condensed section, and a constraint of non-overlapping with respect to conductors already placed. Moreover, the conductor is placed in a minimal radius of space. The minimal radius of space is determined by different techniques of barycentric calculations and calculation of maximum distance. Once all conductors placed, a final check enables to ensure that the bundle is at the correct height above the reference ground plane.

Using this process, we obtain a geometry as the one shown in Fig. 1 (b) and a whole bundle as illustrated in Fig. 2. The transition between two successive sections is ensured by a randomly varying parameter in the range limited by the mechanical constraints of conductors inside the bundle. The change of each conductor coordinates fulfills a consistency in the intertwining.

These geometries are then used by a software developed at ONERA, called LAPLACE, to compute the R, L, C, G matrices (per unit length parameters of transmission lines) of each section. These per unit length matrices which entirely describe the bundle from an electromagnetic point of view are included in the CRIPTE [4] software. This software solves the well known BLT equation applied on multi conductor transmission line networks to finally obtain currents and voltages on each elementary conductor [5-8].

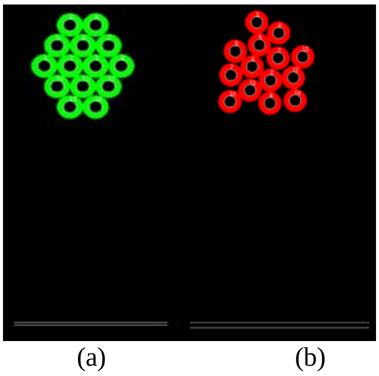


Figure 1. Two dimensional cross section view, article [1] modeling (a) and modeling with LCG algorithm (b)

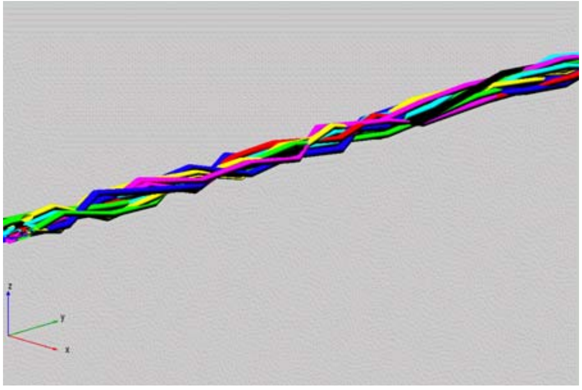


Figure 2. Three dimensional visualization of the bundle with 100 cross sections

III. Description of Case Study – Implementation of Our Model

The cable bundle proposed in [1] is composed of 14 conductors each of diameter 1.8mm and with 0.9mm thick PVC insulation. This cable bundle is 2m long and is placed above an aluminum plane (2.62x1.2m). Each conductor is loaded differently from 10Ω to 100kΩ symmetrically or not. The conductor source is the conductor number 2 on which a voltage generator loaded with 50Ω is applied. Computations are made at 0.31m (P1 position), 0.81m (P2 position) and 1.69m (P3 position) far from the origin on the whole cables bundle as in Fig. 3.

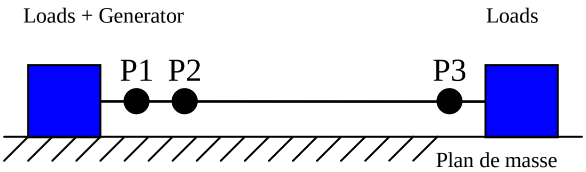


Figure 3. Schematic of the measurement setup

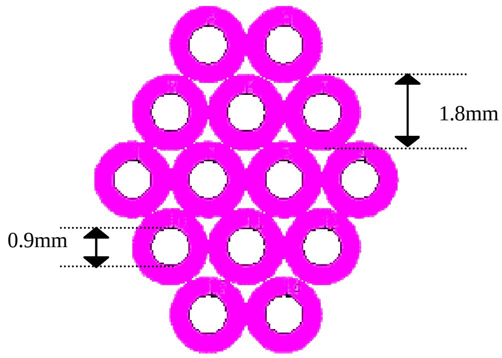


Figure 4. Two dimensional cross section view of article [1]

The first section of the bundle defined in [1] and recalled in Fig. 4 is our initial section geometry for our own generation process. Then we applied our LCG model previously described to generate 100 geometric sections of 0.02m, representing 2m of cable bundle. 40 different bundles have been generated through this random process. Finally we computed currents/voltages on elementary conductors of these 40 generated bundles induced by the voltage generator on conductor number 2 from 100Hz to 1GHz.

IV. NUMERICAL RESULTS – PHYSICAL ANALYSIS

A. Analysis of the common mode current

The objective is, here, to compare our LCG algorithm to the one proposed in [1]. Therefore, for physical analysis, we represent the maximum, average and standard deviation of the common mode current for the 40 bundles modeled on the entire frequency range at the measurement point P1 (Fig. 5).

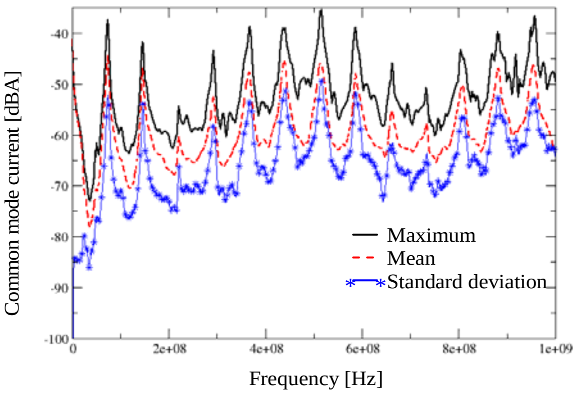


Figure 5. Accumulated maximum, average and standard deviation common mode current from 40 simulations at point P1

First of all, we find the same behavior as in [1] with similar resonance frequencies but with slightly higher levels which could be explained by the numerical scheme used in our case to solve the BLT equation. We note that in Figure 5, the maximum and average common mode current have quite the same magnitude in low frequency, before the resonant domain. This is confirmed by a very low standard deviation 45 dB lower than the average up to 50MHz. With increasing frequency, when the bundle becomes resonant, the standard deviation compared to the average is much more important. It shows that in that frequency range the common mode current depends on the bundle internal geometry.

Fig. 6 illustrates the variation of the common mode current at points P1, P2 and P3 computed on one sample of the bundle among the 40 generations.

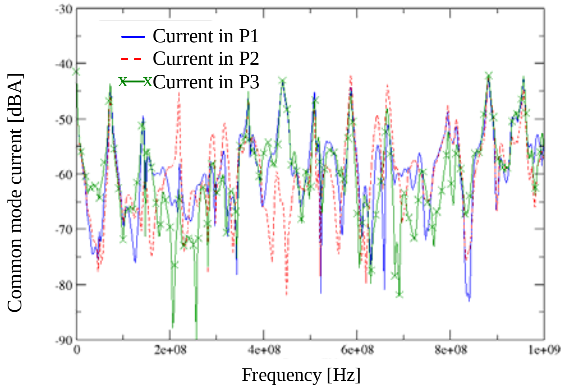


Figure 6. Simulated common mode current at point P1, P2 and P3 with the same bundle realization

In Fig. 6, we observe that the frequency response of the common mode current strongly depends on the measurement position and the distance from the source. We can note some symmetry of the measurement points P1 and P3 looking at the resonance and antiresonance frequencies associated to these distances. For example, at 450MHz we find an antiresonance in P3 and a resonance in P1. Again the behavior of the curves is similar to the one observed in [1].

B. Analysis of crosstalk

In the following description, we are interested in determining the crosstalk between an arbitrary wire (2) and another wire (3) which are randomly placed in the bundles described above. The crosstalk parameter between conductor i and conductor j is defined by:

$$H(f) = \frac{V_j(f)}{V_i(f)} \qquad (2)$$

where $V_j(f)$ is the induced voltage on wire j while $V_i(f)$ is the applied voltage on wire i.

In our case, this crosstalk has been evaluated between conductor 2 (on which the voltage generator is applied) and conductor 3 for 16 generations of bundles as in [1]. These results are presented in figure 7.

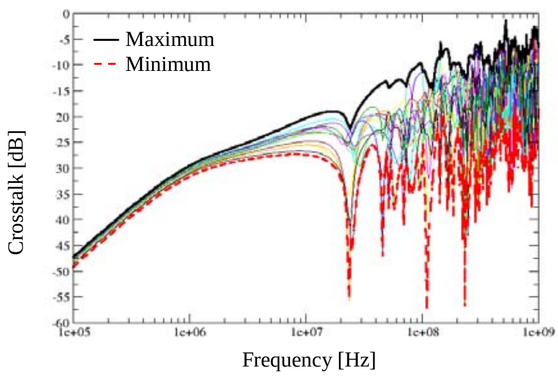


Figure 7. Near-end crosstalk between wire 3 and wire 2 for 16 generations of bundles

The two curves above and below represent the maximum and minimum results among the 16 generations of bundles in

Fig. 7. We note that in low frequency up to 1MHz, we have a slope of 20dB/decade explained by the inductive coupling between both conductors. Above 1MHz, the random position of the conductors, the nature of the bundle and capacitive effects become increasingly important which causes more deviation in the frequency response.

V. STATISTICS FOR COMMON MODE CURRENT

In order to better understand the results, it is necessary to go through a statistical analysis of the results of simulations of different bundles. Statistical analysis must be the most general as possible, we use a distribution law of Weibull. The probability density function of the Weibull law is defined by:

$$f(x) = a \cdot b \cdot (x^{(b-1)}) \cdot e^{(-a \cdot x^{b})} \qquad (3)$$

where a is a scale parameter, b, the shape parameter and X the random value under analysis. Rayleigh, exponential or even Gaussian distributions appear as particular cases of this Weibull distribution with specific values of a and b. The determination of these two parameters can be made by several methods. One of them is based on the maximum likelihood method and is detailed in [2,9,10]. By applying this method, we obtain a system of two equations with two unknowns:

$$N = a \cdot \sum_{i=1}^{N} x_i^{\,b}$$
$$N + b \cdot \sum_{i=1}^{N} \ln(x_i) + a \cdot b \cdot \sum_{i=1}^{N} (x_i^{\,b} \cdot \ln(x_i)) = 0 \qquad (4)$$

where N is the number of simulations and Xi are the current values for the simulations to a specific frequency.

Fig. 8, 9 and 10 illustrate the pdf probability distribution function (pdf) and the cumulative distribution function (cdf) assuming a Gaussian law as in [1] and the proposed Weibull law derived from our samples of computed common mode currents on the 40 generated bundles at respectively 506MHz, 528MHz, 550MHz. These frequencies have been chosen because they are respectively located at the top, middle and bottom of a resonance peak. All curves are normalized for increased readability of the figures.

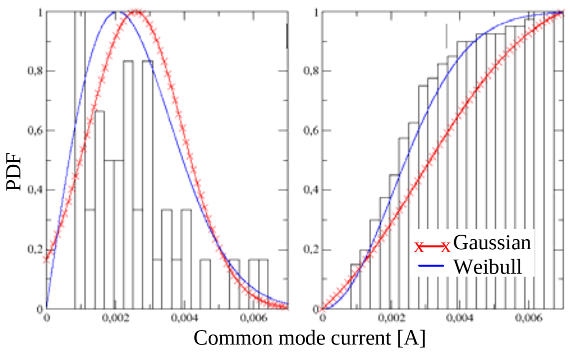


Figure 8. Analytical probability density functions and the histograms at 506MHz. The number of simulation is 40.

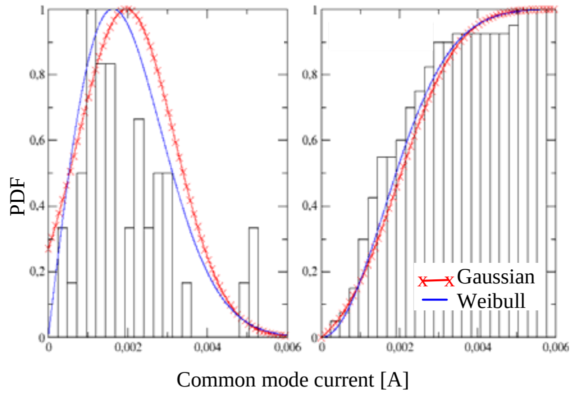


Figure 9. Analytical probability density functions and the histograms at 528MHz. The number of simulation is 40.

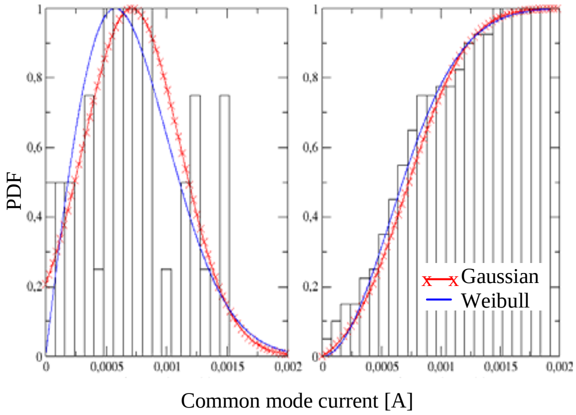


Figure 10. Analytical probability density functions and the histograms at 550MHz. The number of simulation is 40.

The Weibull distribution law overlaps fairly well on the numerical results on all figures. The Weibull distribution law with appropriate parameters is statistically preferred to explain the results of simulations. For the three frequencies, we have these parameters:

a=0.77 and b=2.05 for 506 MHz

a=0.84 and b=1.74 for 528 MHz

a=0.81 and b=1.79 for 550 MHz

Since the Weibull law is a two-parameter function it appears that some other distribution laws appears to be specific cases of this function. Thus, a Rayleigh law is in fact a Weibull law with parameters a=0.78 and b=2. So with these estimations of a and b for 506 MHz, the distribution is probably well approximated with the Rayleigh law.

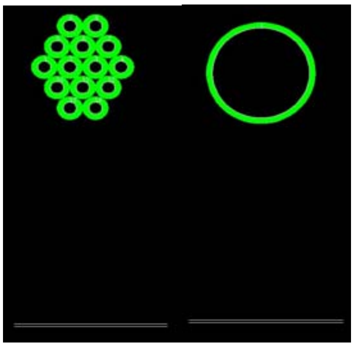
We have also performed a Kolmogorov-Smirnov test with a Massey criterion corrected for Weibull Law [2] to check the validity of the law to the data representation. For a risk threshold set at 1%, if we look at the maximum difference between the theoretical and experimental distribution function, we get a value below this maximum distance with this threshold of risk. We can therefore conclude that the Weibull distribution law could be an acceptable candidate for this process.

VI. SIMPLIFIED MODELS

We saw in the previous paragraphs that the computation of common mode currents is based on the evaluation of RLCG matrices. Here, each of the 40 generated bundles is described by 100 geometries (100 cross sections). In other words, 4000 geometries must be generated and therefore 16000 matrices computed. For all models/simulations on this entire set of 40 bundles, the computation lasts 8h to determine all the RLCG matrices. The calculations are performed on a computer with a 3.4GHz processor and 1GB of RAM. One way to decrease this computing time is to simplify the geometric model to reduce the number of RLCG matrices to compute.

The first possible simplification consists in generating multiple uniform bundles which single section is randomly created. We obtain for 40 bundles, only 160 matrices.

The second model consists in reducing the 14 conductors to one equivalent conductor which diameter is equivalent to the whole bundle diameter with a thick dielectric equal to one of the14 conductors, as shown in Fig. 11 (a).



(a) (b)

Figure 11. Two dimensional cross section view, with equivalent model (b) and with RDSI model (a)

A. *Common mode current*

Fig. 12 shows the average current mode common computed:

- on the 40 bundles with non-uniform discretization as in section III,
- on the 40 bundles discretized by a single random geometry
- and the equivalent conductor. For this equivalent conductor, the extremities loads are supposed to be the 14 initial loads in parallel. The equivalent source generator to apply is derived from a Thevenin equivalent model.

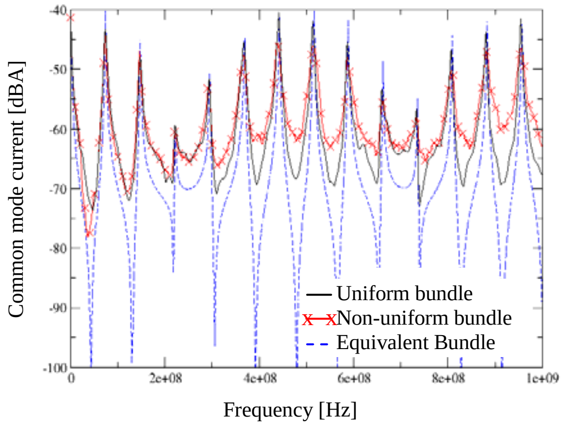


Figure 12. average common mode current

The average common mode computed on the bundle discretized by 100 sections and the average common mode current computed on 40 single geometries are very close to each other in low frequency. With increasing frequency, we can note that there are some discrepancies which can be explained by the low number of uniform bundles included in the average and by the effects of the interfaces between two sections not included in the uniform bundle. However the deviation is rather small (about 20dB below the two averages), this model represents fairly well the bundles discretized by 100 sections. The calculation time for 40 simulations is about 1 hour that is 1/10th of the initial computation time. The result is almost equivalent.

With the equivalent conductor model, we find similar behavior including the same resonance frequencies. We retain most information but with patterns of more important antiresonance due to the idealization of our model in the resolution of the BLT equation [5-8]. The calculation time is 5 minutes on the same computer used previously. So depending on the nature of information sought, we can reduce the computing time in using equivalent models for common mode currents.

B. *Crosstalk current*

It would nevertheless be interesting to see if such a simplified model is applicable to evaluate the currents on one of the 14 conductors of the bundle. Fig. 13 and Fig. 14 represent maximum, average and standard deviation of the current on a conductor free, for the initial randomized section bundle and the equivalent randomized uniform bundle respectively.

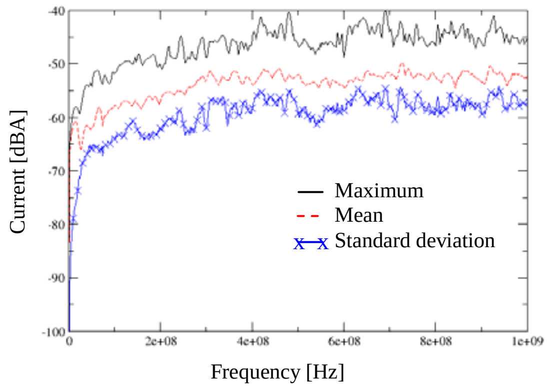


Figure 13. Accumulated maximum, average and standard deviation of 40 simulations non-uniform bundle current on wire 3

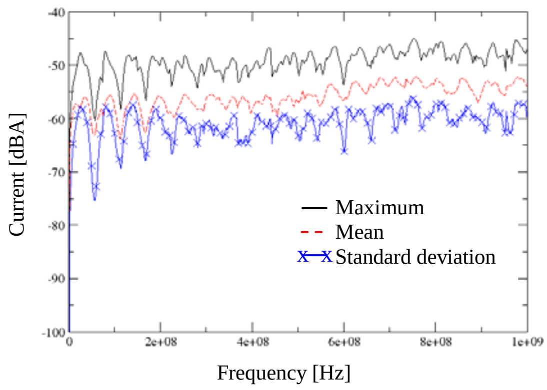


Figure 14. Accumulated maximum, average and standard deviation of 16 simulations uniform bundle current on wire 3

We note that the initial bundle and the uniform bundle give different results for average current. There could be 2 reasons for that. First the number of simulated uniform bundles may be not high enough. Second the inherent non uniform structure of the actual bundle may explain this different behavior. These hypothesis will be investigated in a near future. However, a low standard deviation with respect to average appears in Fig. 13 for frequencies below 50MHz. It indicates the similarity of results in low frequency whatever the non-uniform bundle achieved. Therefore a simple model would still be valid in a quasi-static regime. In Fig. 14, we can observe antiresonance frequencies which are specific of the simplified model of uniform bundles. These results enable to glimpse the limits of this simplified model compared to the phenomena that we want to observe.

VII. Conclusion

In this paper, we have presented a model of random bundles based on the random placement of conductors in space within the constraints of interface between sections. This model has been developed in order to match as closely as possible the fine details of the geometry of industrial bundles. It is intended to be a reference model before validating further possible simplification. We have first carried out a comparison with the RDSI model developed by authors of [1]. This model is based on the modified number of conductors from section to section and therefore could appear as a simpler model. It turns out that we find common mode currents comparable to those of the article [1]. In that very specific case, it is even possible to further simplify further the way of evaluating the common mode current. I may be indeed evaluated with uniform bundles. Looking at crosstalk results, our model and the RDSI model are comparable. A final conclusion would require further investigation and experimental studies.

Additional work is also necessary to establish simplified models to correctly reproduce crosstalk phenomena.

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