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Piotr Putek, Rick Janssen, Jan Niehof, E. Jan W. ter Maten,
Roland Pulch, Michael Günther

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Robust optimization of an RFIC isolation problem under uncertainties

Piotr Putek[1,2], Rick Janssen[3], Jan Niehof[3], E. Jan W. ter Maten[1,4], Roland Pulch[2], and Michael Günther[1]

Abstract Modern electronics systems involved in communication and identification impose demanding constraints on both reliability and robustness of components. On the one hand, it results from the influence of manufacturing tolerances within the continuous down-scaling process into the output characteristics of electronic devices. On the other hand, the increasing integration process of various systems on a single die force a circuit designer to make some trade-offs in preventing interference issues and in compensating coupling effects. Thus, constraints in terms of statistical moments have come in a natural way into optimization formulations of electronics products under uncertainties. Therefore, for the careful assessment of the propagation of uncertainties through a model of a device a type of Stochastic Collocation Method (SCM) with Polynomial Chaos (PC) was used. In this way a response surface model can be included in a stochastic, constrained optimization problem. We have illustrated our methodology on a Radio Frequency Integrated Circuit (RFIC) isolation problem. Achieved results for the optimization confirmed efficiency and robustness of the proposed methodology.

1 Introduction

Due to the continuous advances in semiconductor technology, modern mixed-signal and radio frequency (RF) integrated circuits (ICs) show a tendency to increase the integration of various systems on a singe die [3]. This trend in electronics results

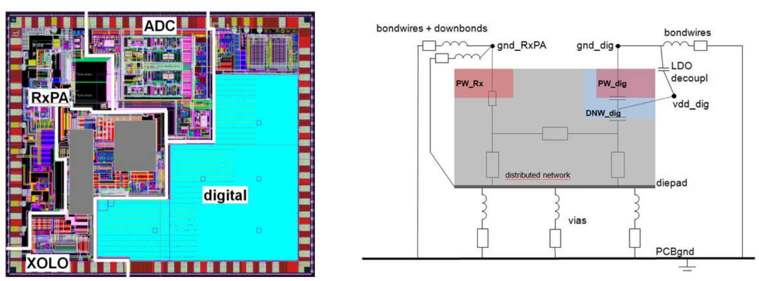
[1]Bergische Universität Wuppertal, Chair of Applied Mathematics and Numerical Analysis, Germany, {putek,termaten,guenther}@math.uni-wuppertal.de,

[2]Ernst-Moritz-Arndt-Universität Greifswald, Institute of Mathematics and Computer Science, Germany, roland.pulch@uni-greifswald.de,

[3]NXP Semiconductors, the Netherlands, {Rick.Janssen,Jan.Niehof}@nxp.com,

[4]Eindhoven University of Technology, Chair of Mathematics and Computer Science (CASA), the Netherlands, E.J.W.ter.Maten@tue.nl,

not only in decreasing material cost but also allows for easier implementation of multiple functions in a compact unit [2]. On the one hand, this complexity gives challenges in the integration of noisy parts, the so-called aggressors, as well as sensitive parts, the so-called victims, the intellectual property blocks (IPs) to provide its proper and interference-free functioning. On the other hand, the integration process has also impact on the failure probability of nanoscale or molecular scale devices associated with yield loss, which can be caused by defects, faults, process variations and design issues [1]. In this respect, the impact of statistical variations in input parameters onto the output characteristics of electronic devices has played an increasingly important role in the predictability and reliability of simulations. Actually, these statistical variations, resulting from manufacturing tolerances of industrial processes, could lead to the acceleration of migration phenomena in semiconductor devices and finally can cause a thermal destruction of devices due to thermal runaway [6, 7]. Moreover, unintended RF coupling, which can occur both as a result of industrial imperfections and as a consequence of the integration process, might additionally downgrade the quality of products and their performance or even be dangerous for safety of both environment and the end users [5]. It should be pointed out, though, that meeting the specification requirements for electromagnetic compatibility standards [4] and issues related to interference between IPs at early design stages allows for avoiding expensive re-spins and for the consecutive decrease of the time-to-market cycle. The ICs designer needs to take special attention to interference issues during all the stages of the product development cycle. Therefore, a structured approach to find an optimal isolation configuration of the IC design needs to be applied.



(a) floorplan/domain setup (b) testbench

Fig. 1 Chip architecture with domains indicated [3] (a) floorplan model for isolation and grounding strategies [5] (b) for a RFIC isolation problem.

Our new contribution relies first on incorporating the uncertainty quantification (UQ) analysis into the modeling of electronic devices to provide reliable and robust simulations. Next, the optimization procedure for the compensation of the aggressor impact on the proper operation of the IC system is proposed and applied. Specifically, we focus on the investigation of the coupling path via an exposed diepad, downbonds and bondwires in order to find their optimal configuration, which ensures the minimal influence of the digital noise on the device functioning under uncertainties. To this end, we incorporated our automated optimization procedure in the flow of the floorplanning and grounding strategy [3].

2 Floorplanning and grounding methodology

In order to take the interaction of the ICs with their physical environment into account in the early design phases of a complex RF design, proper floorplanning and grounding strategies need to be applied. Among others, this methodology allows for the identification, quantification and prediction of cross-domain coupling. More precisely, it is based on a high level EM floorplan/circuit simulation model, which consists of the following components: aggressor models, victim models, a package model and an interference testbench [2, 3]. Thus, the overall model of an analyzed device when using this methodology is depicted in Fig. 1 (b), and it includes the following key elements

- *On-chip* including domain regions, padring, sealring, substrate effects,
- *Package* consisting of ground and power pins, bondwires/downbonds, exposed diepad,
- *PCB* containing ground plane, exposed diepad connections.

Among the coupling paths investigated in [3] were a) the exposed diepad and downbonds, b) the splitter cells, c) the substrate d) the air. For our purpose, first each of them has been arbitrarily chosen to be deeply analyzed with respect to a number of model parameter variations including the number of downbonds, the number of ground pins, and the number of exposed diepad vias. In this way, the cross-domain transfer function $\mathbf{y}$ from the digital to the RF domain can be considered here as victims and be included in the optimization procedure as goal functions. In general, when considering a complex harmonic system with a sinusoidal component of $|X|$, an angular frequency ω and a phase $\phi := \arg(X)$ as input to a linear time-invariant system and then its corresponding output as $|Y|$ and $\phi_Y := \arg(Y)$, the frequency response of the transfer function and its phase shift are defined as [8]

$$G(\omega) = \frac{|Y|}{|X|} =: |H(i\omega)|, \qquad \phi(\omega) := \phi_Y - \phi_X = \arg(H(i\omega)). \tag{1}$$

The methodology, briefly described in this section, is based mainly on [2, 3].

3 Stochastic modeling

In order to minimize the RFIC interference issues when considering manufacturing tolerances as input parameter variations in RF products, the key point is to apply stochastic modeling for a floorplan model with grounding strategies. The physical design, shown in Fig. 1 (b), involves on-chip coupling effects, chip-package interaction, substrate coupling, leading to co-habitation issues. Consequently, a direct problem is governed by a system of time-harmonic random-dependent PDEs, derived from Maxwell's equations

$$\begin{cases} \nabla \cdot [\varepsilon(\chi)\nabla\Phi(\chi) + i\,\varepsilon(\chi)\,\omega\mathbf{A}(\chi)] = \rho(\chi) \\ \nabla \times (\nu(\chi)\nabla \times \mathbf{A}(\chi)) = \mathbf{J}(\chi) + \omega^2\,\varepsilon(\chi)\left(\mathbf{A}(\chi) - i\frac{\nabla\Phi(\chi)}{\omega}\right) \\ \nabla \cdot \mathbf{A}(\chi) + i\omega k\Phi = 0 \\ \nabla \cdot \mathbf{J}(\chi) + i\omega\rho(\chi) = 0, \end{cases} \tag{2}$$

equipped with suitable initial and boundary conditions, where the current density $\mathbf{J}$ and the charge density ρ have been additionally defined as

$$\rho = \begin{cases} 0, & \text{on } D_{1,2} \\ q(n - p - N_{\mathrm{D}}), & \text{on } D_3, \end{cases} \tag{3}$$

and

$$\mathbf{J} = \begin{cases} -\sigma(\nabla\Phi + i\,\varepsilon\,\omega\mathbf{A}), & \text{on } D_1 \\ \mathbf{J}_n + \mathbf{J}_p, & \text{on } D_3 \\ 0, & \text{on } D_2. \end{cases} \tag{4}$$

Here, $\chi := (x, f, \boldsymbol{\xi}) \in D \times D_{\mathrm{F}} \times \Xi$ with $D = D_1 \cup D_2 \cup D_3$ being a bounded domain in $\mathbb{R}^3$, composed of regions such as metal, insulator and semiconductor, respectively. $D_{\mathrm{F}} \ni (f_1, \ldots, f_n)$ represents the frequency spectrum and Ξ is a multidimensional domain of physical parameters. The electric conductivity σ, and the permittivity ε are independent of the magnetic vector potential $\mathbf{A}$; Φ denotes the scalar electric potential; $\mathbf{J}_n$ and $\mathbf{J}_p$ are electron and hole current densities, where n and p represent electron and hole concentrations; N_{D} refers to the doping concentration, k is a constant that depends on the scaling scenario, and $\omega := 2\pi f$ denotes an angular velocity.

Furthermore, in order to find the solution of an integral equation formulation of (2), ADS/Momentum from Keysight Technologies, which employs the Methods of Moments (MoM) [10], has been used. Therein, the concept of Green functions is used to model the proper behavior of the substrate [9]. In our simulations, the Quasi-Static Mode is used, which provides accurate electromagnetic simulation performance at radio frequencies for the geometrically complex and electrically small designs. As output of these simulations, S-parameters can be generated for general planar circuits, which contains sufficient information to characterize each individual component. Additionally, the application of the ADS tool, allows for modeling the behavior of RF passive component by a frequency independent lumped model [**?**]. Hence, the lumped model can be further employed to speed up the electrical performance for an RFIC optimization problem.

4 Uncertainty quantification analysis

For the UQ analysis, a type of the SCM in conjunction with the PC expansion has been used. Following the methodology developed in [11], some parameters $\boldsymbol{\xi} \in \Xi$ in the model (2) were replaced by random variables $\boldsymbol{\xi} = (\xi_{\mathrm{dwnbond}}, \xi_{\mathrm{exp}}, \xi_{\mathrm{Xolo}}, \xi_{\mathrm{RxPa}})$:

$\Omega \rightarrow \mathbb{R}$ defined on the probability triple $(\Omega, \mathscr{F}, \mathbb{P})$. Furthermore, we assume that a joint density function $g : \Xi \rightarrow \mathbb{R}$ exists and let y be a square integrable function. Then, a response surface model of y can be obtained by a truncated series of the PC expansion, see [11],

$$y(f, \boldsymbol{\xi}) \doteq \sum_{i=0}^{N} v_i(f) \Phi_i(\boldsymbol{\xi}) \tag{5}$$

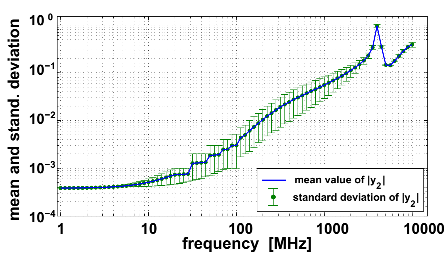
with a priori unknown coefficient functions v_i and predetermined basis polynomials Φ_i with the orthogonality property $\mathbb{E}[\Phi_i \Phi_j] = \delta_{ij}$[1] (Kronecker delta). Therein, $\mathbb{E}$ is the expected value, associated with $\mathbb{P}$. Specifically, we have applied a pseudo-spectral approach with the Stroud formula of order 3 [6, 7] for the calculation of the unknown coefficients v_i. The basic concept of this method is first to provide the solution at each quadrature node $\boldsymbol{\xi}^{(k)}$, $k = 1, \ldots, K$ of the deterministic problem, defined by the system (2). Next, the multi-dimensional quadrature rule with associated weights w_k allows for computing

$$v_i(f) \doteq \sum_{k=1}^{K} y\left(f, \boldsymbol{\xi}^{(k)}\right) \Phi_i\left(\boldsymbol{\xi}^{(k)}\right) w_k, \tag{6}$$

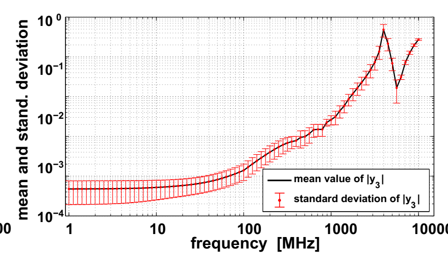
which represents an approximation of the exact projection of $\mathbf{y}$ onto the basis polynomials. Finally, the moments are approximated by, cf. [11],

$$\mathbb{E}\left[\mathrm{y}(f,\, \boldsymbol{\xi})\right] \;\doteq\; \mathrm{v}_0(f), \quad \mathrm{Var}\left[\mathrm{y}(f,\, \boldsymbol{\xi})\right] \;\doteq \sum_{i=1}^{N} |\mathrm{v}_i(f)|^2 \tag{7}$$

assuming $\Phi_0 = 1$. Additionally, in order to investigate the impact of each uncertain



(a) $y_2 = |\mathrm{CplXolo}|$



(b) $y_3 = |\mathrm{CplRx}|$

Fig. 2 Mean and standard deviation values of the cross-domain transfer functions calculated for an investigated floorplan model under input variations of 0.2 for every parameter.

parameter on the output variation, the variance-based sensitivity analysis has been applied. This analysis has been provided by the approximation of the Sobol indices using the PC expansion v_k via [12]

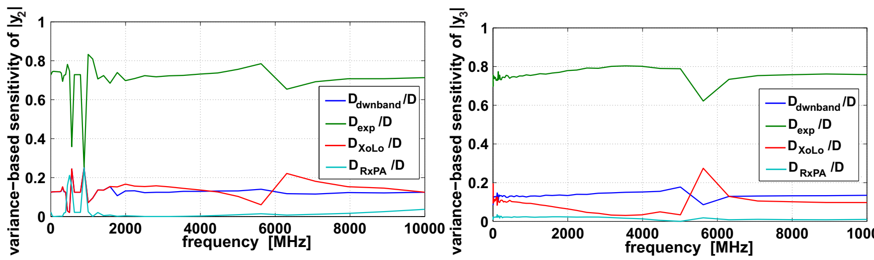
[1] For an orthogonal system of basis polynomials a normalization can be done straightforward, e.g., [11]

$$D \approx \sum_{|k|=1}^{M} v_k^2, \quad D_{i_1 \cdots, i_S} \approx \sum_{|k| \le M, k \in L} v_k^2. \tag{8}$$

with $L := \{k | k_i \ge 1, i \in \{i_1, \ldots, i_S\}; k_j = 0, j \notin \{i_1, \ldots, i_S\}\}$. Here D and $D_{i_1 \cdots, i_S}$ denote the total and partial variances, while the Sobol indices are defined by

$$SU_{i_1, \ldots, i_S} := D_{i_1, \cdots, i_S} / D. \tag{9}$$

The result for the UQ analysis in terms of statistical moments has been depicted in Fig. 2. The global sensitivity coefficients, shown in Fig. 3, allow for identifying the most influential parameters.



(a) variance-based sensitivity for y_2 (b) variance-based sensitivity for y_3

Fig. 3 Global sensitivity analysis performed for an investigated floorplan model under input variations of 0.2 for every parameter.

5 Robust optimization problem

Finally, when considering statistical moments, an optimization problem constrained by stochastic PDEs can be reformulated into the robust single objective optimization problem [7] as follows

$$\begin{aligned} \min_{\boldsymbol{\xi}} \quad & \mathbb{E}\left[F(\boldsymbol{\xi})\right] + \eta \sqrt{\mathrm{Var}\left[F(\boldsymbol{\xi})\right]} \\ \text{s.t.} \quad & \mathbf{K}\left(\boldsymbol{\xi}^{(k)}\right)\{\mathbf{A}, \Phi\}^{(k)} = \mathbf{f}^{(k)},\ k = 1, \ldots, K, \\ & p_{\max_\ell} \le p_\ell \le p_{\min_\ell}, \ell = 1, \ldots, P, \end{aligned} \tag{10}$$

where $\mathbf{K}$ and ξ denote the mass/stiffness matrix and a vector of optimized parameters, respectively. The random-dependent functional reads as

$$F(\boldsymbol{\xi}) = \sum_{i=1} w_i \int_\Gamma |g_i(\boldsymbol{\xi})|^2 \mathrm{d}\mathbf{x}. \tag{11}$$

Here, g_i are real-valued functions, which yield the frequency response of transfer functions defined by using potentials shown on Fig. 1 (b) are defined as

$$y_2 = |\mathrm{CplXolo}| := \frac{|\mathrm{gnd\_xolo}-\mathrm{PCBgnd}|}{|\mathrm{Vdd\_dig}-\mathrm{gnd\_dig}|}, y_3 = |\mathrm{CplRx}| \quad := \frac{|\mathrm{gnd\_rx}-\mathrm{PCBgnd}|}{|\mathrm{Vdd\_dig}-\mathrm{gnd\_dig}|}. \tag{12}$$

Due to the insensitivity of $y_1 = |\mathrm{CplADC}|$ w.r.t. the input variations, the response functions denoted as y_2 and y_3 have been used for the optimization purposes.

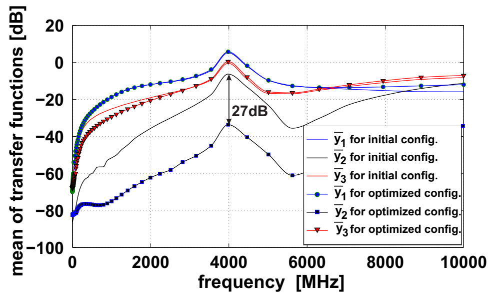
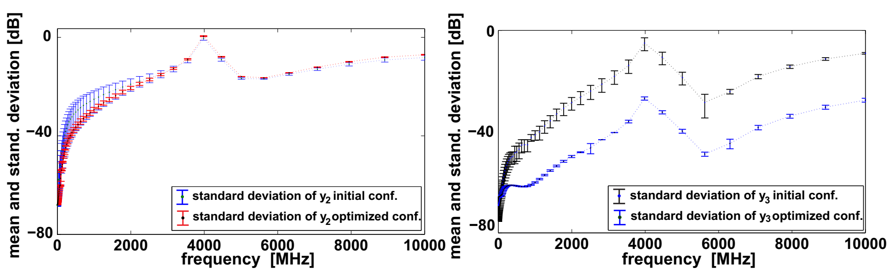


Fig. 4 Result for stochastic optimization of an RFIC problem.

6 Numerical example & Conclusions

A model shown schematically in Fig.1 has been implemented and simulated in Momentum within the frequency range from 1MHz-10GHz. An algorithm for the UQ



(a) $y_2 = |\mathrm{CplXolo}|$ (b) $y_3 = |\mathrm{CplRx}|$

Fig. 5 Mean and standard deviation before and after optimization.

analysis was implemented in python using the DAKOTA v.6.2 library [14]. The least squares nonlinear optimization problem has been solved in every iteration using the normal equation method and the Tikhonov regularization [13] in the MATLAB 2010b. The final result of the robust optimization has been presented in Figs. 4 and 5. Table 1 includes the information about the error indicator. The impedance $\bar{\mathbf{z}}_0(\omega) := [10 + \mathrm{i}\omega 2.0e^{-8}, 0.1 + \mathrm{i}\omega 1.0e^{-8}, 20 + \mathrm{i}\omega 4.0e^{-7}, 16.67 + \mathrm{i}\omega 3.33e^{-7}]\,\mathrm{m}\Omega$ has been assumed as the starting point. The optimized configuration of impedance $\bar{\mathbf{z}}_4(\omega) := [9.37 + \mathrm{i}\omega 1.87e^{-8}, 0.13 + \mathrm{i}\omega 1.38e^{-8}, 25 + \mathrm{i}\omega 5e^{-7}, 0.36 + \mathrm{i}\omega 7.22e^{-9}]$ mΩ has been found in the 4th iteration.

Both the mean values and standard deviations have been reduced significantly. However, the application of the Pareto front method instead of the average weighted method might yield the optimal solution in the sense of Pareto due to competing objective functions y_2 and y_3. This is considered as a further direction of our research.

Table 1 Relative error in [%] calculated for the particular functions before and after optimization.

quantities	for y_1 in [%]	for y_2 in [%]	for y_3 in [%]	for all functions in [%]
mean value	12.41	7.64	-94.99	-24.67
standard deviation	-90.49	-78.22	-98.77	-91.20

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