Book of abstracts of the 7th International Conference on Advanced Computational Methods in Engineering, ACOMEN 2017
18–22 September 2017.

Stochastic Framework to Quantify Variability and Uncertainty in Wireless Links

Marco Rossi[1], **Dries Vande Ginste**[1] **and Hendrik Rogier**[1]

[1] *Dept. of Information Technology, Ghent University-imec*

e-mails: marco.rossi@ugent.be, dries.vandeginste@ugent.be, hendrik.rogier@ugent.be

Abstract

A stochastic framework is described to quantify the statistical distribution of the overall performance of wireless links. A generalized polynomial chaos expansion relates this distribution to variations in geometry and uncertainty in orientation and position of the receive and transmit antenna. A non-intrusive stochastic testing procedure is applied to evaluate the uncertainty on the efficiency of a wireless power transfer system.

Key words: statistics, generalized polynomial chaos, stochastic testing, electromagnetic theory

1 Stochastic framework

In a wireless link, the antenna geometries, positions and orientations will be random variables x_k. Therefore, the system performance y will be statistically distributed. Our aim is to calculate this probability density function (PDF) $d\mathcal{P}^y$, given the statistically independent input distributions $d\mathcal{P}^{x_k}$ describing the antenna variability and uncertainty. Let $\boldsymbol{x}$ be the vector containing all input random variables. To determine $d\mathcal{P}^y$, we approximate the relationship $y = f(\boldsymbol{x})$ by the generalized polynomial chaos (gPC) expansion

$$y \approx f^P(\boldsymbol{x}) = \sum_{\boldsymbol{l}=0}^{L} y_{\boldsymbol{l}}^{\boldsymbol{x}} \boldsymbol{\phi}_{\boldsymbol{l}}^{\boldsymbol{x}}(\boldsymbol{x}), \tag{1}$$

with $\boldsymbol{l} = [l_1, \ldots, l_K]$ a multi-index and with $l_1 + \ldots + l_K \leq L$. The set of expansion polynomials $\boldsymbol{\phi}_{\boldsymbol{l}}^{\boldsymbol{x}}(\boldsymbol{x})$ is composed of products of orthogonal polynomials $\phi_{l,k}(x_k)$, such that the Cameron-Martin theorem guarantees exponential convergence to $y = f(\boldsymbol{x})$. To determine the coefficients y_k^X, we enforce (1) in a set of testing points chosen according to the stochastic testing procedure [1].

The stochastic framework is now applied to quantify the uncertainty on the wireless power transfer efficiency PTE= $\eta_{\text{link}} \cdot \eta_{\text{match}} \cdot \eta_{\text{rect}}$ in a wireless power transfer (WPT) link between an MI-212-1.72.45 GHz horn antenna (transmit power 10 dBm at 2.45 GHz) and a dual-polarized textile patch antenna [2] at a distance d. A fast radiative near-field formalism [3] first computes the WPT link efficiency η_{link}, for arbitrary positions of transmitter and receiver. On the latter antenna, a rectifier, voltage doubler and matching network deliver DC power. Harmonic balance simulation in ADS, yields the matching efficiency η_{match}, and the voltage doubler and rectifier efficiency $\eta_{\text{rect}} = P_{\text{inc}}/P_{\text{DC}}$, with $P_{\text{inc}} = \eta_{\text{match}} \cdot P_{\text{RX}}$ and $P_{\text{DC}} = V_{\text{out}}^2/R_L$.

The transmit antenna being a standard gain horn, we concentrate on random variations in dimensions and permittivity of the receive antenna. The radiation impedance $Z_{\text{RX}} = Z^{re} + jZ^{im}$ and the coefficients of the spherical harmonics expansion of the antenna pattern are expressed as gPC expansions as a function of length L, width W and relative permittivity ϵ_r. These parameters are then used to evaluate the radiative near-field link, following [3], and to calculate the wireless link efficiency η_{link} and the received power P_{RX}. The stochastic analysis accounts for random variations in the position (x, y) and rotation (θ, ϕ) of the receive antenna. The effect of all random variables on the overall PTE of the WPT system is given by

$$\text{PTE} = \sum_{\boldsymbol{l}_7=0}^{L_{\text{PTE}}} y_{\boldsymbol{l}_7}^{\boldsymbol{x}} \phi_{\boldsymbol{l}_7}^{\boldsymbol{x}}(\mathbf{x}^{\text{WPT}}) \tag{2}$$

with $\mathbf{x}^{\text{WPT}} = [L, W, \epsilon_r, d, x, y, \theta, \phi]$ the vector of all random variables in the link. More details of the method are described in [2]

2 Results

Consider a WPT link between the standard gain horn and a rectenna on a substrate of thickness 3.94 mm and permittivity $\epsilon_r = 1.5259$ at 2.45 GHz with patch length $L = 45.3854$ mm and width $W = 44.4516$ mm, at a distance $d = 0.6$ m. L, W and $\epsilon_r$vary as independent Gaussian random variables with standard deviations $\sigma_L = 0.1628$ mm, $\sigma_L = 0.1268$ mm and $\sigma_{\epsilon_r} = 0.03190$. Antenna positions d, x, y and orientation angles θ and ϕ vary as Gaussian random variables with standard deviations $\sigma_d = 16.66$ mm, $\sigma_y = \sigma_x = 6.66$ mm and $\sigma_\theta = \sigma_\phi = 10°$. A median PTE of 0.6% is obtained, with the PTE being larger than 0.5% in 75% of the cases. The two-stage approach, where first stochastic antenna models are constructed based on full-wave simulations and then incorporated into the statistical radiative near-field link model to evaluate the distribution of the PTE reduces the simulation time to about 22 min. In contrast, a single gPC expansion directly applied to model the overall PTE requires more than 2 h. A validation based on the Monte Carlo method requires more than 41 h, since 10000 realizations need to be evaluated through full-wave simulations.

References

[1] P. Manfredi, D. Vande Ginste, D. De Zutter, and F. Canavero, "Generalized decoupled polynomial chaos for nonlinear circuits with many random parameters," *"IEEE Microw. Guided Wave Lett."*, vol. 25, no. 8, pp. 505–507, 2015.

[2] M. Rossi, G.-J. Stockman, H. Rogier, and D. Vande Ginste, "Stochastic analysis of the efficiency of a wireless power transfer system subject to antenna variability and position uncertainties," *Sensors*, vol. 16, no. 7, 2016.

[3] G. J. Stockman, H. Rogier, and D. Vande Ginste, "Efficient modeling of interactions between radiating devices with arbitrary relative positions and orientations," *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 6, pp. 1313–1321, Dec 2014.