Digital-Twin Solutions for IC-Package-PCB-Antenna Systems: Correlation-aware Equivalent Circuit Representation Using Eigen-State Formulation

S. Wane[$], W. Saabe[§], D. Bajon[$] , C.-A. Tavernier*, D. Floriot*, P. Eudeline[$], J. Sombrin[$], and T. Gasseling[§]

[$]eV-Technologies, France, contact : *sidina.wane@ev-technologoes.com*

*UMS-RF, France, contact : *Christophe-Antoine.Tavernier@ums-rf.com*

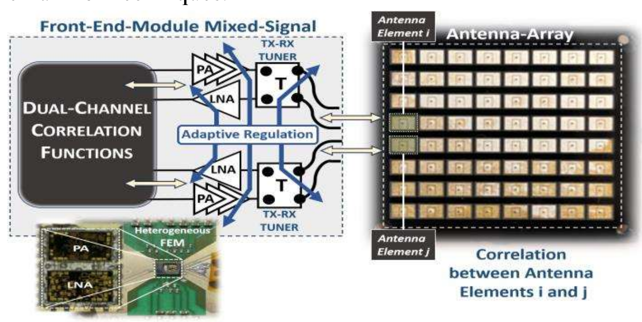
[§]Dassault Systèmes, France, contact: *wissam.saabe@3ds.com*

***Abstract* —A novel Digital-Twin technology platform is introduced for enabling system-level IC-Package-PCB-Antenna co-design, co-simulation and co-verification. The platform, based on *noise* and *correlation-aware* physics-informed behavioral modeling, integrating VISION (IVCAD) software developed by Dassault Systèmes, hosts an innovative SPICE compatible broadband RLC representation of antenna elements. The ability of the platform to account for dynamic impedance loading of antennas by multi-harmonic (MH) nonlinear RF electronics is demonstrated using *energy-efficient* hybrid 3D heterogeneous front-end-module technologies integrating *adaptive biasing* and antenna tuners (*load-aware matching*). The Digital-Twin technology will enable new generations of tooling (*unified EDA & OTA*) where classical Electromagnetic (EM) metrics (*radiation pattern, noise, auto and cross-correlation functions, power-spectral-density*) are extended with wireless-circuit metrics (e.g., *EVM, SNR, ACPR, NMSE*). Unification of EDA and OTA, based on holistic Multiphysics (*EM, Thermal, Mechanical*) approaches, will foster new standards for joint communication and sensing at any time and from anywhere (*remote ubiquitous connectivity*).**

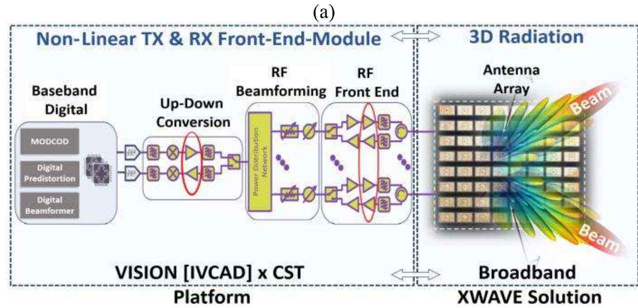
***Keywords* — Digital-Twin, Lab-on-Cloud, Correlation Functions, OTA, EDA, EIRP, TRP, EVM, SNR, ACPR, NMSE.**

I. INTRODUCTION

Joint sensing and communication functionalities are envisioned to be all connected configurable wireless systems encompassing horizontal expansion from ultra-short range to ultra-long range and vertical expansion from terrestrial to satellite networks. The associated test-coverages, relatively to real-world deployment scenarios, will be very challenging to meet in terms of cost and execution time. Digital-Twin (DT) [1] appears as a credible solution for unifying EDA (*design tools*) and OTA (*instruments*) into a coherent platform for reproducing real-world field trials with high fidelity repeatable conditions. The DT, acting as a *digital mirror* of the physical entity or process, can help mimicking complex field trials in controllable and repeatable environmental conditions, enabling the concept of *Virtual-Lab (VL)* with remote seamless access to instrumentations and tools. In combination with secure cloud-based remote testing, VL renders possible real-time hardware evaluations anytime, anywhere with precise monitoring and control of tools, instruments, power supplies, sensors, and peripheral accessories. In providing data-rich insights, golden test patterns deployed in the cloud can be used for accurate verification and validation of real-world test scenarios using *physics-informed* correlation technologies [3]. The resulting *Lab-on-Cloud* imposes stringent requirements on the communication systems in terms of data rate, latency, synchronization, reliability, and security. This calls for innovative holistic *Chip-Package-PCB-Antenna* test and verification methodologies beyond the existing state-of-the art emulation techniques.



(a)



(b)

Fig.1. Dual-Channel front-end-module for extraction of noise-aware field-field correlation functions of stochastic signals (a). Multi-physics VISION [IVCAD]+CST+XWAVE Digital-Twin Co-Design & Co-Simulation platform for Chip-Package-PCB-Antenna systems (b).

On the test and verification aspects, contactless (wireless) over-the-air (OTA) industrial (*in-line production*) testing of RF/mmW modules remains extremely challenging. Following these critical challenges, the 3GPP standard [2] defines guidelines for OTA test methods:

- *Direct Far-Field or Indirect Far-Field (e.g. Compact Antenna Test Range, CATR): 3GPP TS 38.141-2 specifies the radiated RF test methods and conformance requirements.*
- *Near-Field to Far-Field Transformation: Key test metrics include Effective Isotropic Radiated Power (EIRP), Total*

Radiated Power (TRP) and Effective Isotropic Sensitivity (EIS), Error Vector Magnitude (EVM) and blocking.

UE (User Equipment) OTA testing requirements covers both FR1 (Sub-6GHz) and FR2 (mmWaves) frequency bands. In FR1 frequency bands, most testing is still through conducted connectivity, this means using RF connectors and cables. UEs in the FR2 frequency bands must be tested through OTA means, as per 3GPP TS 38.101-2. 3GPP TR 38.810 defines OTA testing methodologies for UE RF, UE Radio Resource Management (RRM), UE demodulation requirements, along with the associated measurement uncertainty budgets and the related test tolerances.

In this work, we propose a holistic Chip-Package-PCB-Antenna approach combining VISION (IVCAD) tooling [3] with CST backed up by eV-Technologies XWAVE broadband equivalent circuit representation. The originality of the contribution resides in the following attributes:

1) *Correlation* and *noise-aware* full-transient analysis of Chip-Package-PCB-Antenna systems (see Fig.1(a)) using physics-based broadband eigen-state RLC representation of multi-ports applicable to stochastic signals. The correlation functions support advanced convolution accelerators with *time-scales* below picoseconds.
2) *Digital-Twin* (DT) platform (see Fig.1(b)) for full-transient pulsed-mode TDR/TDT diagnosis of faulty modules enabling ultra-fast testing solutions suitable for industry mass-production requirements.

II. Main Results, Analysis and Discussions

The preliminary validation and verification results are presented for the following frequency bands:

- 24-30 GHz: GaN-GaAs hybrid Front-End-Module.
- 50-70 GHz: 60 GHz Fixed Wireless Access.
- 75-85 GHz: 8 channels 77 GHz car radar modules

For all 3 frequency bands, systematic extraction of near-field correlation functions is conducted using broadband RLC representations. RF testing comprises transmitter and receiver requirements such as maximum output power, modulation performance like Error Vector Magnitude (EVM), sensitivity or the ability to maintain a certain throughput performance in the presence of a blocking signal. RRM testing ensures the efficient use of the available radio resources. For the requirements that are tested, the tests describe the key OTA TX/RX test metrics including the most challenging frequency band: 24 GHz-100 GHz using advanced TDR/TDT nonlinear pulsed waves.

The GaN-based transceiver module (in Fig.1(a)) is controlled using simple terminal commands. Each drain and gate can be individually controlled. The unit can display the drain current for a given gate voltage. An adaptive self-biasing mode can be invoked to automatically adjust the gate voltage to achieve a desired drain bias current for optimal RF performances in RX (S_{ij} in Fig.2(a)) and TX (S_{ij} in Fig.2(b)) based on system-level metrics such as EVM (Fig.2(c)). EVM is used in modern communication standards to measure the overall degradation of the signal due to linear or nonlinear distortions, and to noise, interference and multipath impairments.

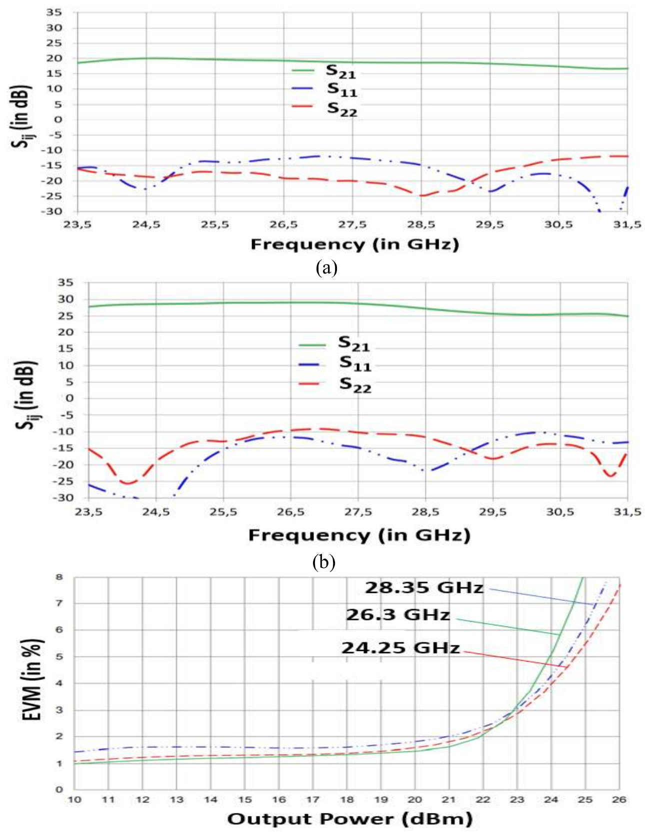


Fig.2. Gain and Return-Loss against frequency in RX (a) and TX (b) modes. Error Vector Magnitude (c) versus output power at 24.25GHz, 26.3GHz and 28.35GHz without DPD for 256 QAM modulation.

The classical method for EVM (Error Vector Magnitude) computation is to compute vector errors between received (y_n) and ideal (x_n) symbols and then to compute a root-mean-square of the magnitude of these vectors for all symbols in a frame. All these computations [5] can be done in the following steps by replacing the optimum gain by its value and using the covariance between ideal **x** and received **y** symbols vectors.

$$e_n = y_n - \gamma\, x_n \tag{1}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|e_n|^2} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|y_n - \gamma x_n|^2} \tag{2}$$

$$\gamma = \frac{\sum_{n=1}^{N} y_n x_n^*}{\sum_{n=1}^{N} x_n x_n^*} \tag{3}$$

The optimum gain is computed by using autocorrelation and cross-correlation of ideal and received symbols.

$$\cos\theta = \frac{\left|\sum_{n=1}^{N} y_n x_n^*\right|}{\sqrt{\sum_{n=1}^{N} y_n y_n^* \sum_{n=1}^{N} x_n x_n^*}} = \frac{|\langle y,x\rangle|}{\|y\|\|x\|} \tag{4}$$

$$EVM = \sqrt{\frac{1}{\cos^2\theta} - 1} = \tan(\theta) \tag{5}$$

The flexibility offered by FPGA platforms enables versatile control and monitoring of the radiation properties, the polarizations, the frequency band, the Direction of Arrival (DoA). $E_1(\theta,\varphi)$ and $E_2(\theta,\varphi)$ being the radiation patterns of antenna 1 and 2 respectively, the envelope cross-correlation between the two antennas is given by the following expression which can be linked to the general theory of coherence [4]:

$$\rho(\omega) = \frac{\left|\int_{4\pi} d\Omega\, E_1(\theta,\varphi) \,.\, E_2^*(\theta,\varphi)\right|}{\sqrt{\int_{4\pi} d\Omega |E_1(\theta,\varphi)|^2}\sqrt{\int_{4\pi} d\Omega |E_2(\theta,\varphi)|^2}} \qquad (6)$$

Envelope correlation as function of S-parameters for loss-less coupled antenna is :

$$\rho(\omega) = \frac{|S_{11}^*(\omega)S_{12}(\omega)+S_{21}^*(\omega)S_{22}(\omega)|}{\sqrt{1-|S_{11}(\omega)|^2-|S_{21}(\omega)|^2}\sqrt{1-|S_{22}(\omega)|^2-|S_{12}(\omega)|^2}} \qquad (7)$$

The loss-factor normalization appearing in the denominator of equation (7) is introduced to comply with the definition in equation (6) involving radiation patterns. When η_1 and η_2 denote the radiation efficiencies of antenna 1 and 2, equation (7) can be re-written as :

$$\rho^{\eta_1-\eta_2}(\omega) = \frac{\rho(\omega)}{\sqrt{(1-\eta_1)}\sqrt{(1-\eta_2)}} \qquad (8)$$

Reverberation chambers (RC), referenced [6] in Fig.3(a),(b), are seen as a medium that facilitates energy-aware probabilistic formulations of stochastic EM field-field correlations. In Fig.3(c), RC-based OTA measurement of the FEM transceiver in TX mode is compared to classical connectorized measurement approach showing excellent agreement. Based on the proposed broadband RLC extraction approach, the thermal noise received by an antenna can be represented by a noise source embedded in the real part of the antenna radiation impedance using the Nyquist theory [7]. The noisy load can be obtained using a noiseless load in series with an idealized stochastic voltage generator. The total noise power accessible at the input to the receiver, assuming conjugate impedance match between the antenna and the receiver, equals P_{Noise}:

$$P_{Noise} = \left(T_{System} + T_{Antenna}\right)kB \qquad (9)$$

In (9), $T_{Antenna}$ represents the equivalent antenna noise temperature, T_{System} being the receiving system noise temperature referred to its input. k is the Boltzmann's constant and B is the receiving system measurement bandwidth. T_{System} can be linked to the receiving system input Noise Figure (NF):

$$NF = 10log_{10}\left(1 + T_{System}/290\right) dB \qquad (10)$$

In (10), 290 K is the standard noise source temperature.

From equations (9) and (10), stochastic formulations can be derived for extracting statistical variations of antenna noise temperatures based on load-aware correlations (Fig.3(d)). Broadband EM-Thermal RLC extraction solution, compliant with *Kirchhoff's laws* and incorporating both radiation and diffusion effects in a unified energy-aware representation, is used for *noise matching efficiency* that quantifies the effect of mutual coupling in antenna arrays. The validity of the proposed network representation is extended to higher frequencies demonstrating excellent agreement with 3D full-wave EM simulations. Fig.4 presents extracted broadband RLC models valid in full range from DC to 140 GHz for Fixed Wireless Access (FWA). Fig.5 shows time-domain transient analysis of 4 channels transceiver radar module operating at 77 GHz.

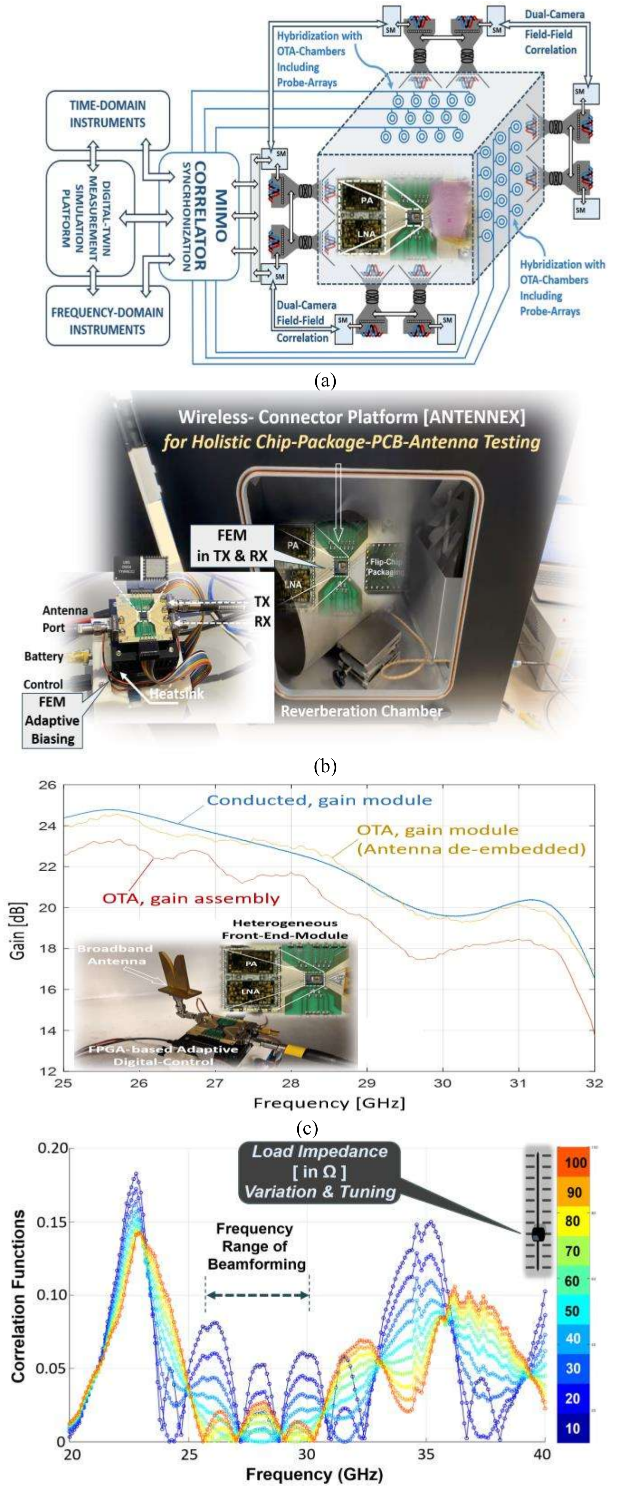


Fig.3. Digital-Twin (a) unification [1] of measurement and modeling. Reverberation Chamber (RC) for wireless (b) testing [6] of Chip-Package-PCB-Antenna systems accounting for multiphysics EM-Thermal-Mechanical constraints. Contactless measurement of FEM gain (c) as function of frequency compared to conducted measurement. Correlation functions (d) as function of impedance loading conditions.

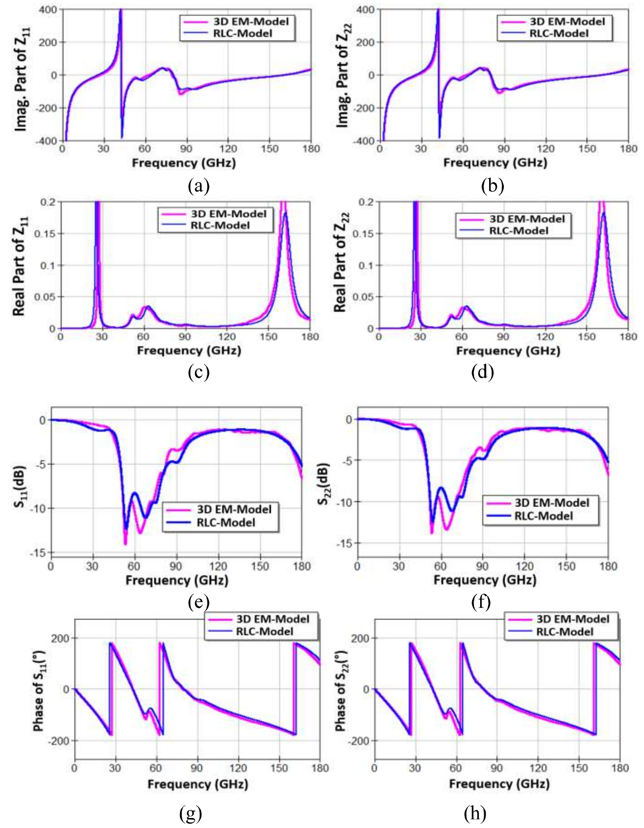


Fig.4. Broadband (*DC-180 GHz*) SPICE compatible RLC-synthesis versus 3D full-wave analysis of (a): Z_{11}-Imaginary-Part, (b): Z_{22}-Imaginary-Part, (a): (c): Z_{11}-Real-Part, (d): Z_{22}-Real-Part, (e): S_{11}Magnitude, (f): S_{22} Magnitude (g): S_{11}Phase, (h): S_{22} Phase.

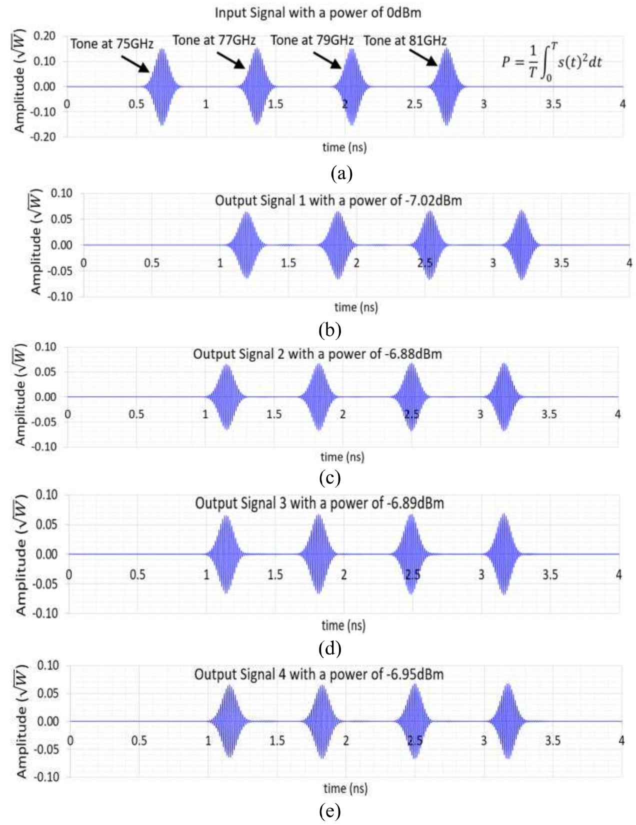


Fig.5. Broadband time-domain full-transient pass-fail testing of car-radar module in 4-Channels (*labelled 1,2,3,4*) pulsed modes (TX & RX). The 4-Channels are split in TX mode and combined in RX mode. Stochastic load-aware variations are captured in SPICE compatible RLC representations.

III. Conclusion

We have introduced novel *correlation* and *noise-aware* Digital-Twin technology that unifies modeling and measurement into a coherent platform enabling holistic Chip-Package-PCB-Antenna co-design, co-simulation and co-verification. The resulting platform offers accurate and parameterizable characterization of antennas physical design parameters based on innovative SPICE compatible EM-Thermal aware broadband RLC representation. The capability of the XWAVE RLC representation to account for dynamic impedance loading of antennas by multi-harmonic (MH) nonlinear RF electronics is demonstrated through several practical applications using heterogeneous front-end-modules (FEMs) hosting energy-efficient *adaptive-biasing* co-designed with antenna-in-package (AiP) solutions. This leads to *correlation-based* noise matching efficiency that qualifies effects of *mutual couplings* on active front-end phased-arrays wide-band performances. Linking system temperature to noise and correlation considerations will open new avenues for *camera-free* high-accuracy non-contact *imaging* thermometers. The Digital-Twin technology platform enables new generations of OTA testing systems where classical EM metrics (*radiation pattern, EIRP, TRP, Power-Density*) can be extended with wireless-circuit metrics (*noise, MIMO correlations, EVM, AM-PM distortions, entropy*). Cognition-ready signal processing, backed-up by correlation technologies in time and frequency domains, will benefit from *physics-informed* AI-powered algorithmic solutions for pushing system-level *unified* co-simulation (EDA) and co-verification (OTA) to their ultimate performances.

Acknowledgment

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