

ICESTARS : integrated circuit/EM simulation and design technologies for advanced radio systems-on-chip

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ICESTARS
Integrated Circuit/EM Simulation and Design
Technologies for Advanced Radio Systems-on-chip

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ICESTARS

Integrated Circuit/EM Simulation and Design Technologies for Advanced Radio Systems-on-chip

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Introduction

ICESTARS¹ solved a series of critical issues in the currently available infrastructure for the design and simulation of new and highly-complex Radio Frequency (RF) front ends operating beyond 10 and up to 100 GHz. Future RF designs demand an increasing blend of analog and digital functionalities. The super and extremely high frequency (SHF, 3-30GHz, and EHF, 30-300GHz) ranges will be used to accomplish future demands for higher capacity channels. With today's frequency bands of approximately 1 to 3 GHz it is impossible to realize extremely high data transfer rates. Only a new generation of CAD and EDA tools will ensure the realization of complex nanoscale designs. It necessitates both new modeling approaches and new mathematical solution procedures for differential equations with largely differing time scales, analysis of coupled systems of DAEs (circuit equations) and PDEs (Maxwell equations for electromagnetic couplings) plus numerical simulations with mixed analog and digital signals. In ICESTARS new techniques and mathematical models working in highly integrated environments were developed to resolve this dilemma. The ICESTARS research area covered the three domains of RF design: (1) time-domain techniques, (2) frequency-domain techniques,

¹ICESTARS has received research funding of the European Commission under the FP7 Information and Communication Technologies Programme (ICT), grant agreement number ICT 214911. Website: www.icestars.eu.

and (3) EM analysis and coupled EM circuit analysis.

The ICESTARS consortium comprised two industrial partners (NXP Semiconductors, Infineon Technologies AG), two SMEs (Magwel, AWR-APLAC) and five universities (Upper Austria, Cologne, Oulu, Wuppertal, Aalto), involving mathematicians, electronic engineers, and software engineers.

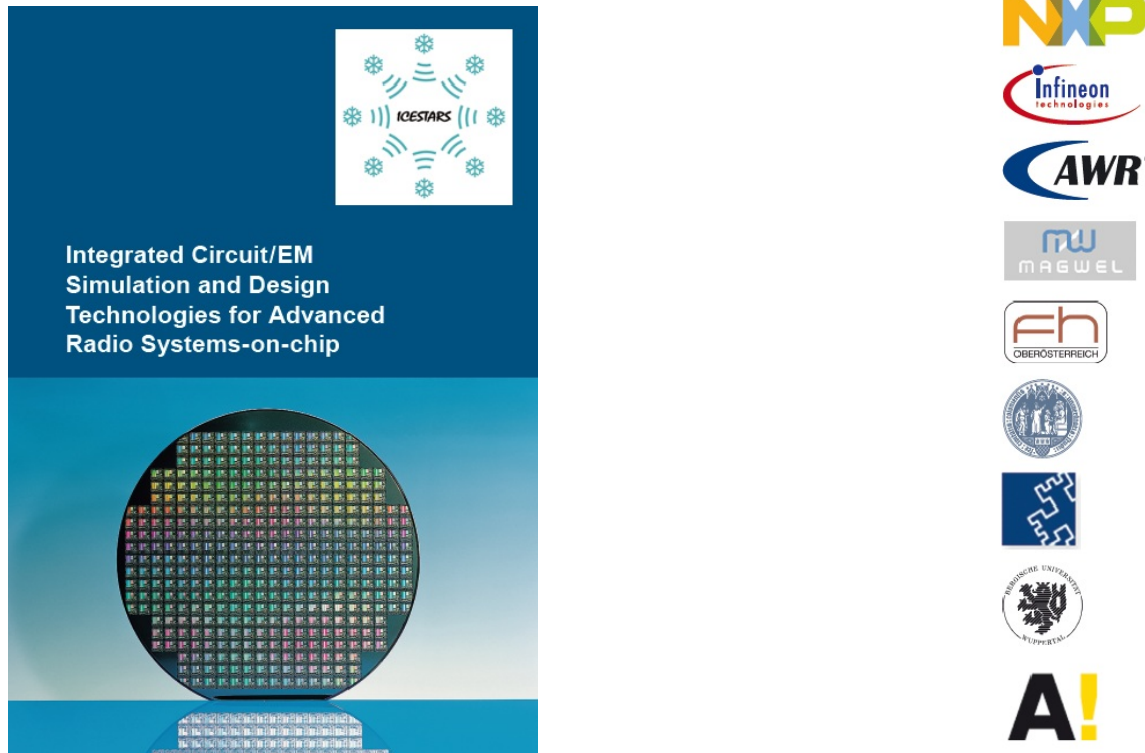


Figure 1: **Left:** The ICESTARS booklet is written for a broad audience. It shows how mathematics is used in a multi-disciplinary project. It is available at <http://www.icestars.eu>. **Right:** Partners overview.

Highlight I: New time-domain techniques

Traditional RF algorithms were developed at a time when the analog and digital parts were not integrated on the same die. Present RF circuits feature a sharp increase in digital content with analog parts up to the essential analog parts being increasingly replaced by their digital counterparts. The sharp drop in performance of existing RF simulators to deal with these multiscale signals (especially speed, memory requirements and robustness) necessitates the development of novel algorithms capable to efficiently simulate RF circuits comprising signals with steep slopes as well as multirate (multitone) circuits.

Wuppertal and Infineon developed wavelet-based algorithms for mixed analogue/digital simulations. A prototype of an adaptive wavelet method, based on a B-spline Galerkin method, was tested in Infineon's in-house circuit simulator. MUMPS² was used as sparse direct linear solver. Convergence problems encountered on circuits exhibiting hysteresis behavior were solved via a novel time interval splitting approach. The developed wavelet-based method exhibits higher accuracy on a smaller time grid compared to traditional TR-BDF initial value solvers (which combine the Trapezoidal Rule and

²<http://graal.ens-lyon.fr/MUMPS/>

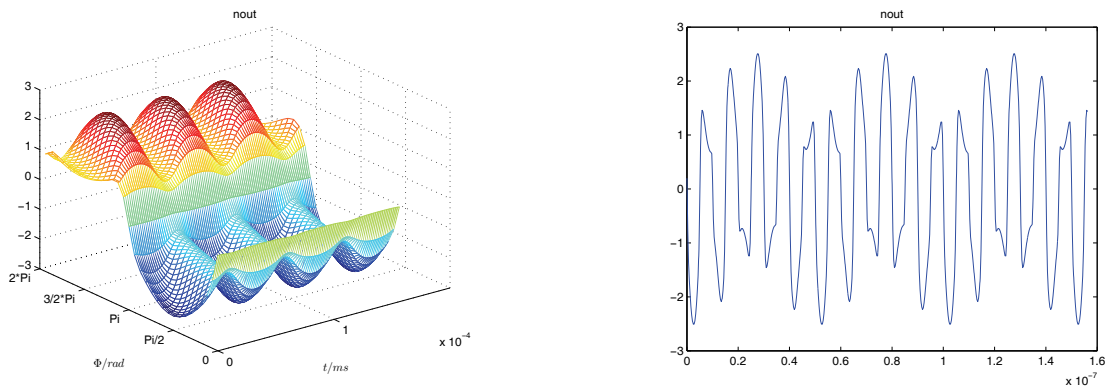


Figure 2: **Left:** Multi-time solution for a downlink mixer derived by applying multirate techniques. **Right:** Reconstructed circuit solution obtained from the multi-time solution. This is more efficient than to solve the circuit solution directly.

the 2nd order Backward Differentiation Formula). A very high potential for further optimization exists and the development will be continued beyond the projects end.

For multirate problems different time scales appear. An emerging technique here is to write the equations as a multirate PDE (MPDAE) in independent time directions. The solution of the original problem can be reconstructed by following characteristics of the PDE solution. No commercial vendor of software exploits this technique yet. A wavelet collocation multirate method is now available as a MATLAB/Octave code in the Demonstrator Platform that resulted from the EU MRTN COMSON project. In addition a prototype of a wavelet envelope method based on periodic wavelets expansion in combination with Galerkin discretization was tested in Infineon's in-house circuit simulator. It was built on top of the new wavelet method.

The Universities of Upper Austria and Wuppertal and NXP focussed on Multirate Envelope Methods. A novel finite difference (FD) scheme has been implemented and validated. It involves envelope steady state calculation and mixed time-frequency techniques. The results are superior to existing techniques for high-Q oscillators. The methods have been validated with the Harmonic Balance (HB) envelope method as reference, both on a test suite and on third party designs. A special envelope method was the Sweep Following Method. Here a scalar differential equation for the phase function $a(t)$ can be defined that provides an optimal time splitting. In one of the time directions large time steps can be made. The method has been generalized and yet applies to forced oscillators (driven by external sources) and to autonomous oscillators (free-running).

Highlight II: Frequency-Domain Techniques

Simulation methods and algorithms were developed that scale well with the component count, the number of frequencies, and the number of unknowns arising in an Harmonic Balance analysis. A Tensor Method from the Trilinos solver package of Sandia National Laboratories was tested in solving the HB equations in the APLAC solver of AWR-APLAC. Hierarchical iteration of the HB Jacobian with a hierarchical GMRES (splitting lower and higher frequency components) was developed in the APLAC simulator as well. In addition a new one-dimensional sampling mapping for N-tone HB analysis ($N > 4$) has been developed, which speeded up HB 10...100x. Also an improved circuit matrix partitioning and reordering technique was derived resulting into 10x speed up. An adaptive frequency

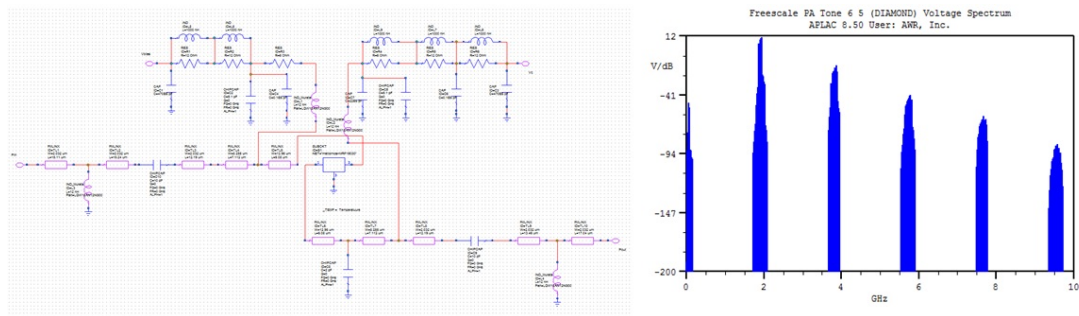


Figure 3: Power amplifier circuit with LDMOS transistor and its 6-tone HB voltage spectrum at amplifier output.

technique in the HB analysis in APLAC now allows to dynamically change the number of harmonic components during the the analysis. This greatly improved the accuracy of the spectrum voltages and currents and of the oscillation frequency. A detection of increased nonlinearity allows to change the preconditioner. This greatly improved the robustness of the methods. A diagnostic tool provides information on the violators, preventing HB convergence, to the designers.

Aalto University and NXP developed techniques to increase robustness for the special HB oscillator analysis (then also the oscillation frequency is an additional unknown). A new method for generating an initial guess for the oscillation frequency and amplitude and for all node voltages can be based on a limited Transient Analysis. It includes a kick and adaptivity for the oscillation start-up. In NXP's simulator Pstar an Accelerated Poincaré Map-method was implemented: it applies subspace techniques and vector extrapolation to sequences of initial values, allowing for superconvergence. NXP and TU Eindhoven developed a new improved Newton method with an adaptive gauge equation, exploiting modern generalized eigenvalue methods.

Volterra-on-HB (VoHB) simulation was developed at the University of Oulu. The algorithm was further extended and refined and now runs in APLAC via an AIF interface. It works at a Voltage-Controlled Current-Source level, making it independent of the type of device modeling and the number of devices. Added are functionalities for characterizing difficult devices and recognizing linear devices. When needed frequency sampling improves fitting. An almost real time harmonic sweep over a Smith chart can be made. The main contributors in the design (components or nonlinearities) to harmonic distortion are detected, thus allowing to improve the design.

Highlight III: Coupling of circuit simulation and EM simulation

The ever increasing miniaturization of future circuits realized in the physical modeling necessitates the simulation of electromagnetic circuits an entirely new mathematical approach. At higher frequencies parasitics effects are difficult to model. EM simulation is commonly used to accurately model such structures. However, when circuits include the use of lumped components such as transistors, diodes, and capacitors, most engineers abandon EM as being too difficult to set up and run large multi-port problems. The ICESTARS expertise in circuit-EM simulation provides algorithms to simulate RF designs covering a nonlinear performance of circuits and an EM-accurate modeling of distributed components, thereby taking full advantage of the accuracy of EM simulation and the generality of non-linear simulation. When coupled to a circuit or to the nonlinear PDEs for a semiconductor device a real overall time integration should be made. Cologne and Magwel set up a mathematical framework and

formulated the equations for the transient solver and the proper boundary conditions in the EM-circuit coupling. An in depth mathematical problem analysis led to the new pseudo-canonical momentum approach (a new variable in the EM solver). Furthermore a set up has been developed for addressing high frequency effects that becomes highly efficient in the THz regime. A transient field for an octo-shape inductor of NXP with 300K dofs was calculated.

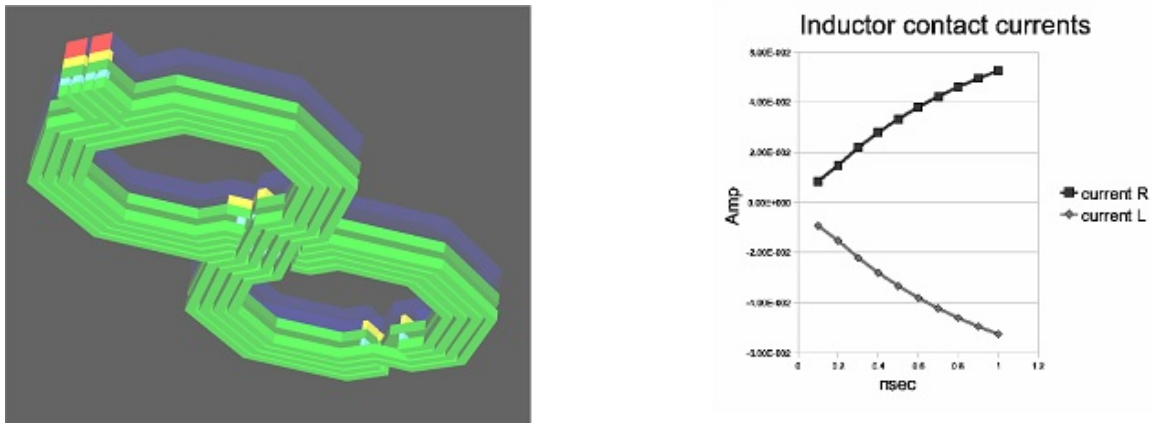


Figure 4: **Left:** Layout of the octo-shaped inductor. **Right:** currents in the transient regime at the contacts.

A holistic EM-circuit coupling was obtained via an accurate contact variables description. Only at a contact the EM and circuit meet. Cologne and Magwel developed a coupled circuit-EM solver using python/C++/Cython technology. A transparent interface model was formulated. The MECS DAE-solver of Cologne (Python) collects the circuit equations, while contributions from as well as equations for the EM-devices are provided by the simulator of Magwel (C/C++); the interface uses Cython. The whole system is solved directly in a monolithic way using a BDF time integrator and a linear solver that combines the sparse direct solver MUMPS with the iterative solver SAMG³. The solver is fully operational for metal/insulator structures. If semiconductors are present then the Cython communication currently is too slow to be of practical use. A solution (pointer communication to dedicated assembling parts) has been found but has not (yet) been programmed. An adaptive time integration for coupled EM circuit simulation was demonstrated on a Voltage Controlled Oscillator (netlist with 5 resistors, 6 capacitors, 4 inductors, 3 Voltage Sources, 1 Current Source, 6 MOSFET devices) generating a 1.8 GHz frequency.

Epilogue

The public deliverables and non-confidential project presentations are available on the public website www.icestars.eu. Here also pointers to further publications can be found. A special deliverable is a project booklet that summarizes the project outcomes for a broad audience. We maximized visibility at major scientific conferences where users/industry attended in a significant number, like DAC-2010, EuMW 2009 (Rome) and ESSDERK 2010 (Sevilla). For mathematicians and developers of simulation software two Mini-Symposia were organized at ECMI-2010 (Wuppertal) and several presentations were given at SCEE-2010 (Toulouse). Both ECMI and SCEE proceedings will appear

³<http://www.scai.fraunhofer.de/en/business-research-areas/numerical-software/products/samg.html>

in the ECMI Series for Mathematics in Industry of Springer. Finally, journal publications were made in IEEE MTT, IEEE TCAD and in journals for mathematicians.

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