LinzFrame: A Modular Mixed-Level Simulator with Emphasis on Radio Frequency Circuits

Kai Bittner, Hans Georg Brachtendorf, and Wim Schoenmaker

Abstract *Purpose*: LinzFrame is a circuit and device simulator with emphasis on radio frequency circuits (RF) applications. Slowly changing amplitudes are modulated by a carrier signal at a very high center frequency. These waveforms are referred to as multi-tone signals. RF devices are often distributed elements, i.e. their behavior cannot be adequately represented by terminal voltages and currents.
Design/Methodology: Besides SPICE-like analysis features LinzFrame offers several techniques dedicated to RF circuits. Among them are the multi-tone Harmonic Balance (HB), periodic steady state shooting method, a toolbox for autonomous circuits (oscillators), and multi-rate envelope methods. Besides transient analysis based on the BDF formulas, a toolbox for a spline-wavelet approximation has been developed. This technique combines the advantages of variable time step techniques (such as BDF) with a compact representation of signals by a set of basis functions (such as HB). In contrary to HB a spline-wavelet representation of signals with variable refinements allows for a representation of signals with sharp slew rates without the unwanted Gibbs phenomenon.
In recent time, the simulator has been extended to a circuit-device mixed-level simulator by coupling the circuit simulator to a TCAD simulator. This feature enables the co-simulation of device and circuit levels, where the critical devices are simulated and optimized in full 3D, such as distributed elements.
Originality/Value: LinzFrame enables the holistic (strong) coupling of a circuit and a device simulator, enabling either modeling of the circuit/device as lumped (concentrated) model or as a full 3D model, depending on the needed accuracy. Moreover it circumvents the prohibitive run-time of conventional transient analysis by several multi-rate techniques dedicated to RF circuits/devices.

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1 The LinzFrame Circuit Simulator

The circuit simulator LinzFrame with focus on radio frequency (RF) applications [1, 2] follows a strictly modular concept as depicted in Fig. 1. The simulator kernel employs the Modified Nodal Analysis (MNA). Moreover it comprises an automatic differentiation suite [16] which simplifies the implementation of new models significantly, since partial derivatives w.r.t. the state variables required for the Jacobian calculation for Newton type methods are not coded explicitly [16]. Furthermore, model libraries for linear devices, SPICE transistor models and a stimulus library including modulated sources such as OFDM, FSK, QPSK, QAM, etc., libraries to industry relevant device models such as BSIMx, VBIC, and the Simkit library from NXP Semiconductors (MEXTRAM, MOS9, MOS11, etc.) are available. Hence, the simulator covers the majority of industry standards in circuit simulation. A Laplace model interface allows the incorporation of rational fraction transfer models obtained, e.g., from Model Order Reduction (MOR). The analysis toolbox comprises standard methods such as DC, AC and transient analysis with polynomial and trigonometric multi-step BDFx (MBDFx) methods [3] and an interface to the DASPK simulator [10] for solving higher index differential algebraic equations (DAEs). As an alternative to polynomial multi-step methods, a spline-wavelet transient simulator has been developed by the authors.

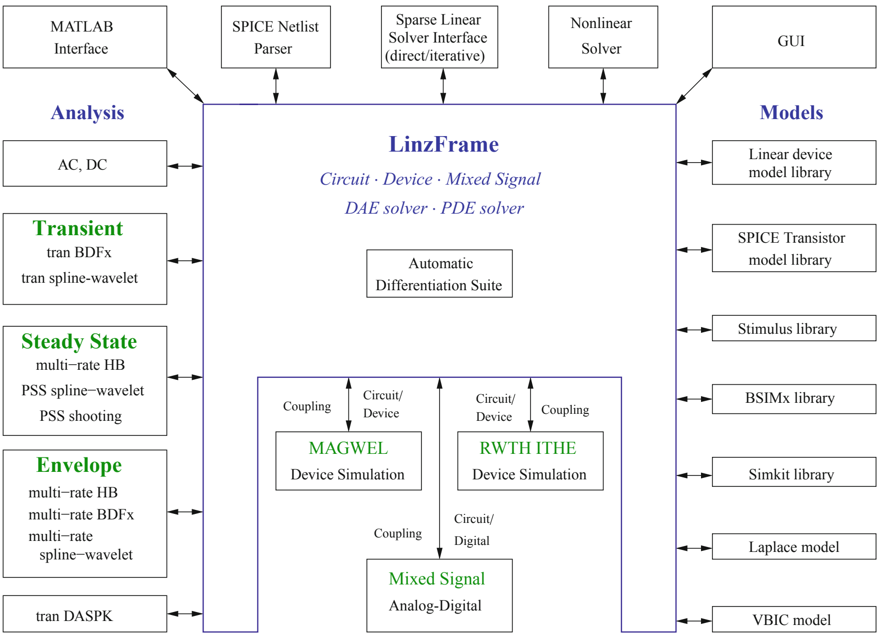


Fig. 1 Overview on the toolboxes of the circuit simulator LinzFrame

Standard transient solvers are prohibitively slow for the simulation of RF circuits. Since the time steps of multi-step integration formulas must be at least a factor of 10 smaller than the reciprocal of the highest relevant frequency, transient simulators come to their limits as the center frequencies become higher. Therefore, multi-rate simulators have been proposed to decouple the slowly varying envelope or baseband signal from the radio frequency modulation. This decoupling enables different techniques and time steps for a compact representation of the waveforms: the baseband signal can be, on the one hand, appropriately represented by multi-step integration methods whereas the periodic RF modulation on the other hand are well approximated by a trigonometric (Fourier) expansion or a spline-wavelet basis.

Several tools for multi-rate simulation [7, 8], such as Harmonic Balance (HB), BDF and spline-wavelet techniques (both algebraic and trigonometric polynomial bases) are therefore incorporated in LinzFrame. The latter technique is superior when strong nonlinearities and/or sharp transients occur, which are efficiently resolved by an adaptive mesh, whereas a trigonometric basis exhibits often the well-known Gibb's phenomenon. Periodic steady state (PSS) methods both for driven and autonomous circuits such as oscillators complete the tool [1–5].

Moreover, interfaces to numerical tools, including damped Newton solvers, homotopy methods [3], several direct sparse linear solvers (e.g. MUMPS, MA48, PARDISO, SuperLU) as well as preconditioned Krylov subspace techniques (e.g. ILUPACK) are available. For a rapid prototyping and test of novel algorithms, a MATLAB interface is at hand.

As part of the European fp7 project nanoCOPS [18, 21], the simulator has been coupled to the commercial EM/device simulator devEM from the company MAGWEL for combined EM-device/circuit simulation [21] as depicted in Fig. 2. The simulator devEM is a full 3D electro-magnetic field and device simulator, which employs as unknowns the scalar and vector potentials $(V, \mathbf{A})$. From Maxwell's equations and the device constitutive equations one obtains a system of partial differential equations (PDEs). The device simulator employs for the spartial discretization of the PDEs the Finite Integration Technique (FIT) [11, 12, 22] resulting in a huge system of ordinary DAEs. The coupling between LinzFrame and devEM is performed holistically [6, 9], that is, LinzFrame—which is the master simulator—has full excess to the Jacobian matrix stamps and the right hand side vector. This enables (damped) Newton methods with enhanced convergence properties than relaxation based techniques also reported in the literature [15]. In another ongoing DFG/FWF project, LinzFrame is coupled with a device simulator from RWTH Aachen university to study plasma oscillations in the THz range [13, 14].

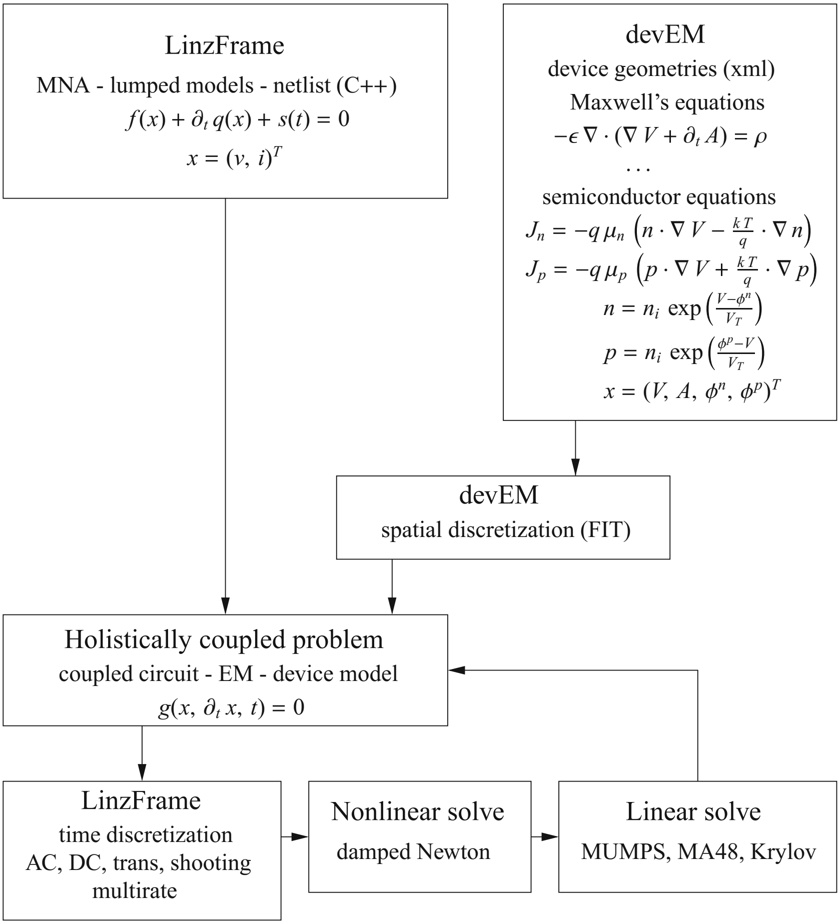


Fig. 2 Concept of the holistic coupling between LinzFrame and devEM

2 Circuit-Device Simulator Coupling

From Kirchhoff's laws, the circuit topology and the device constitutive equations one obtains a system of generally nonlinear DAEs of dimension N

$$\frac{d}{dt}q\big(x(t)\big) + f\big(x(t)\big) - s(t) = 0,\ x(0) = x_0 \tag{1}$$

where $x = (v, i)^T$ is the vector of unknown node voltages (potentials) and some branch currents, $f : \mathbb{R}^N \to \mathbb{R}^N$ the vector sums of currents entering each node and $q : \mathbb{R}^N \to \mathbb{R}^N$ the vector sums of charges and fluxes. Moreover x_0 is the vector of initial conditions and $s(t)$ the stimulus vector, respectively. If s is independent of time, the circuit is autonomous and non-autonomous otherwise.

The electro-magnetic TCAD (EM-TCAD) simulator devEM employs both the scalar potentials V and the vector potential $\mathbf{A}$ such that the magnetic induction is $\mathbf{B} = \nabla \times \mathbf{A}$, and hence $\mathbf{E} = -(\nabla V + \partial_t \mathbf{A})$, where $\mathbf{E}$ is the electric field strength. Furthermore $\mathbf{D} = \epsilon \mathbf{E}$ is the dielectric displacement and $\mathbf{H} = \frac{1}{\mu} \mathbf{B}$ the magnetic field strength. To obtain systems of first-order PDEs in time, the quasi-canonical momentum $\mathbf{\Pi} = \partial_t \mathbf{A}$ is used as an additional degree-of-freedom. The simulator devEM enables both the Coulomb and Lorenz gauge (and a continuous sweep between these two). Exemplarily, the PDEs valid for semiconductors are considered next.

Let N_D, N_A be the donator/acceptor concentrations and n, p the free electron/hole concentrations, respectively. From the standard drift-diffusion equations one obtains

$$-\nabla \cdot (\epsilon\ (\nabla V + \mathbf{\Pi})) = \varrho,\ \varrho = q\ (p - n + N_D - N_A)$$
$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A}\right) = \mathbf{J}_p + \mathbf{J}_n - \epsilon \frac{\partial}{\partial t} (\nabla V + \mathbf{\Pi})$$

where $\mathbf{J}_n$, $\mathbf{J}_p$ are the currents densities of electrons/holes, given by

$$\mathbf{J}_n = -q\ \mu_n\ (n\ (\nabla V + \mathbf{\Pi}) - V_T \cdot \nabla n)$$
$$\mathbf{J}_p = -q\ \mu_p\ (p\ (\nabla V + \mathbf{\Pi}) + V_T \cdot \nabla p)$$

wherein q is the elementary charge, μ_n, μ_p the mobilities of electrons and holes, $V_T = \frac{k_B T}{q}$ the thermal voltage, k_B Boltzmann's constant and T the absolute temperature in Kelvin. The densities of electrons and holes are expressed as

$$n = n_i \exp\left(\frac{V - \phi^n}{V_T}\right), \quad p = n_i \exp\left(\frac{\phi^p - V}{V_T}\right)$$

wherein ϕ^n, ϕ^p are the quasi-Fermi potentials for electrons/holes, respectively. The continuity equation holds for the electrons and holes separately, i.e.,

$$\nabla \cdot \mathbf{J}_n - q \frac{\partial n}{\partial t} = -q\, U(n, p), \quad \nabla \cdot \mathbf{J}_p + q \frac{\partial p}{\partial t} = q\, U(n, p)$$

with net generation rate $U(n, p) = G - R$. devEM employs various generation/recombination models. The system of equations is completed with the gauge condition

$$\frac{1}{\mu} \nabla(\nabla \cdot \mathbf{A}) + \xi\, \epsilon \nabla\, (\partial_t V) = 0$$

For $\xi = 0$ one obtains the Coulomb and for $\xi = 1$ the Lorenz gauge as special cases. Unknowns are the scalar and vector potentials $(\mathbf{A},\ \mathbf{\Pi} = \partial_t \mathbf{A})$ and moreover the quasi-Fermi potentials $(V,\ \mathbf{A},\ \mathbf{\Pi},\ \phi^n,\ \phi^p)^T$.

2.1 Discretization

The spatial discretization is done on an (un)structured grid using a variation of the Finite Integration Technique [12, 17, 22].

LinzFrame on the other hand is the master simulator which performs the time discretization and step size control. Besides multi-step integration formulas, specifically for radio frequency applications a multi-rate technique has been developed which decouples the slowly varying envelope or baseband signal in time scale τ and RF time scale t from the carrier signal. The underlying ordinary DAE system (1) is reformulated by a system of partial DAEs, i.e.

$$\tfrac{\partial}{\partial \tau} q\big(\hat{x}(\tau, t)\big) + \omega(\tau)\, \tfrac{\partial}{\partial t} q\big(\hat{x}(\tau, t)\big) + i\big(\hat{x}(\tau, t)\big) = \hat{s}\big(\tau, t\big)$$

where $\omega(\tau)$ is an estimate of the instantaneous frequency [19]. The signal $\hat{x}$ is assumed to be periodic in its second argument, that is $\hat{s}(\tau, t) = \hat{s}(\tau, t + P)$ with normalized period $P = 1$. The characteristic curves of the PDE are given by

$$\big(t,\ \Omega_\theta(t)\big), \quad \Omega_\theta(t) = \theta + \int_0^t \omega(s)\, ds, \quad \theta \in [0,\ P]$$

parametrized by θ. The solution of the underlying problem (1) is obtained along a specific characteristic curve through the origin, i.e. $\theta = 0$. A comprehensive documentation on the multi-rate PDE method can be found, e.g., in [1, 3, 20].

3 Results

3.1 Mixer Circuit

The mixer circuit with differential RF and oscillator inputs is depicted in Fig. 3. The input signals operate in the GHz range, whereas the center frequency of the output signal at a low intermediate frequency in the MHz range. Therefore, mixers are typical examples for which the multi-rate technique is superior compared with a classical transient analysis. Figure 4 exhibits the solution of the multi-rate PDE. The solution of the underlying ordinary DAE is obtained along a characteristic curve through the origin (not depicted in figure). One can observe sharp transients at the switching times of the mixer. Hence, an expansion of the waveforms by a trigonometric series (as in Harmonic Balance) leads to both the Gibb's phenomenon

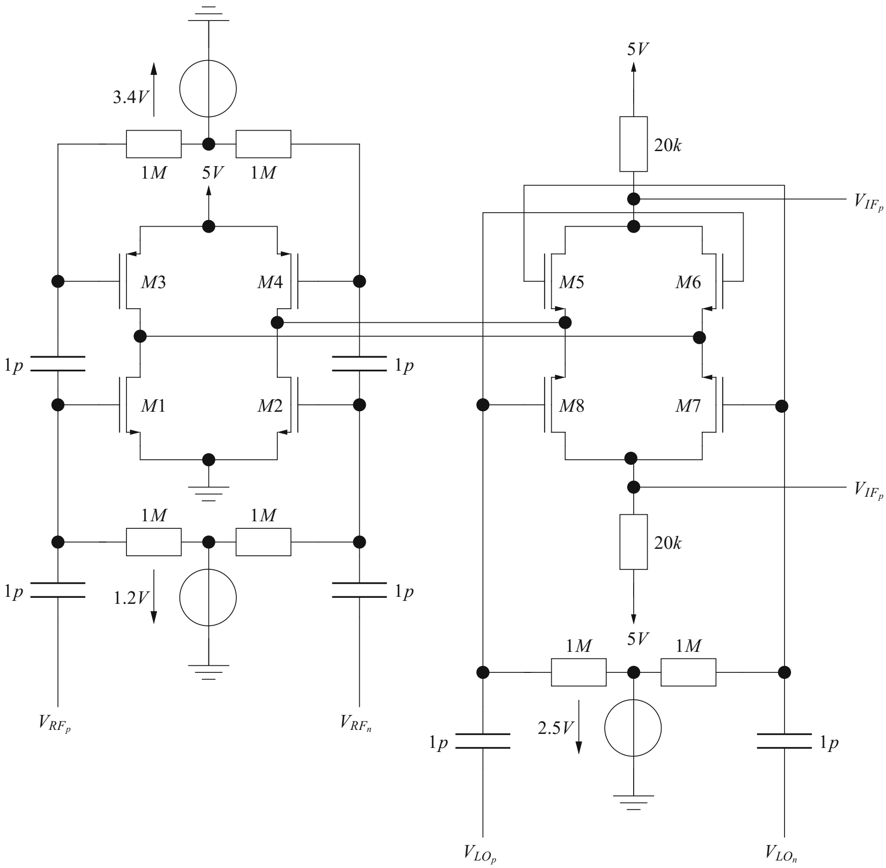


Fig. 3 Gilbert folded mixer circuit

and a large number of Fourier coefficients, making this approach inefficient. Instead, a spline-wavelet expansion based on compact basis functions are superior in capturing sharp transients.

3.2 Coupled Circuit-Device Simulation

Figure 5a depicts a power stage circuit with an on-chip balun for a band I application at a center frequency $f_c = 1–9$ GHz. The power stage operates in differential mode, that is all signals occur with ± signs. Since the source, e.g. the signal coming from the antenna, and output signals are single ended, a first balun, operating at a low power input signal, together with a matching circuit is required. The critical device in the design is the balun at the output of the power stage since it is driven by

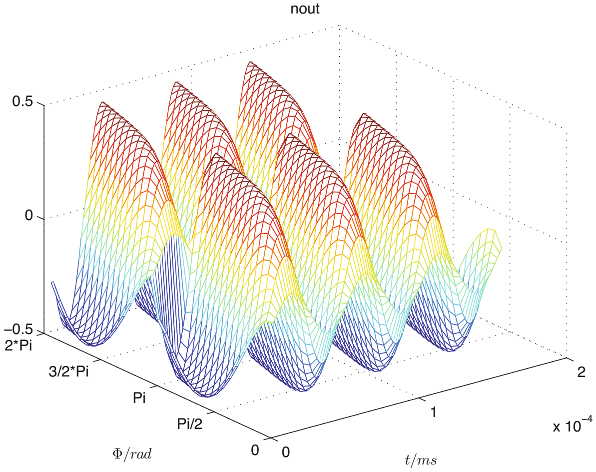
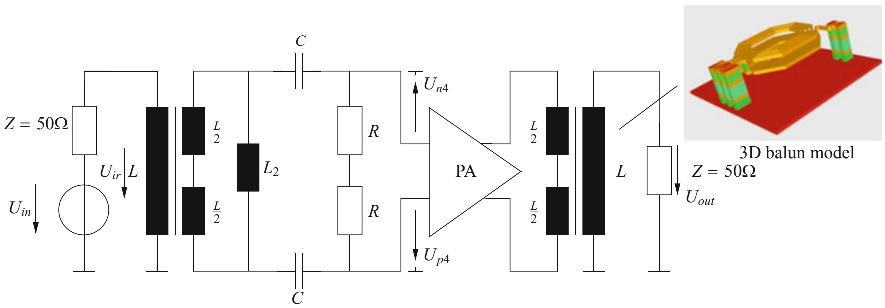
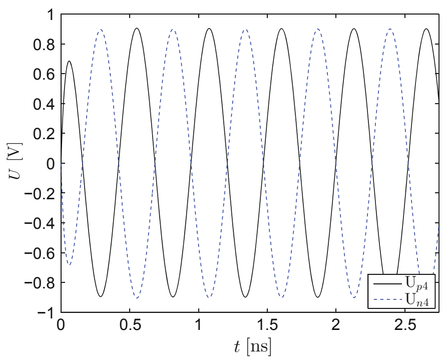


Fig. 4 PDE solution of the mixer circuit depicted in Fig. 3



(a)



(b)

Fig. 5 Balun driver circuit and differential output signal. (**a**) Circuit schematic. (**b**) PA differential output signal a large input power. It is therefore modeled as full 3D device and simulated by the devEM TCAD solver. The remaining circuit's devices are simulated as lumped models. The balun is fabricated in bismaleimide-triazine (BT) technology with four layers. Figure 5b depicts the differential voltages waveforms at the input of the balun.

4 Conclusions

LinzFrame is a modular circuit simulator with emphasis on Radio Frequency circuits and devices. It has been holistically coupled both to the EM simulator devEM from MAGWEL NV and in an ongoing research project to the device simulator from RWTH Aachen for the development of novel devices for THz applications, enabling circuit-device mixed-level analysis.

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