Mixed-mode Simulation of RF Communication Link

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Abstract – **Paper describes techniques and example of mixed level mixed mode simulation of complete communication link. Proposed approach uses co-simulation to compute overall link merits, allowing to simulate digital parts of link using existing commercial digital simulator(s) and RF parts using Modulation Harmonic Balance simulator. Simulation example is presented.**

Keywords – **Harmonic Balance, co-simulation, mixed-level simulation, RF design.**

I. INTRODUCTION

Design of RF link entails significant amount of simulation at different levels. System-level simulation allows estimating design solutions and making first-order estimation of link merits. Basing on system-level design, specifications on constituting blocks are established and those blocks are designed. This outlines to-down "waterfall" design flow. But, most often, such design flow is insufficient, as it does not take into account block interaction and block non-idealities, which may take influence onto complete link merits (like bit or symbol error level, unnecessary RF radiation, etc.). To be sure about system properties, system verification have to be performed, which very often brings to new design iterations.

That laborious iterative approach may be alleviated, providing more information t each level of development, so that designers of each block can estimate behavior of their units in realistic system environment.

Multilevel multi-domain simulation can make sufficient influence onto overall RF system design process, simplifying it and speeding it up. It allows mix on one simulation environment digital and analog subsystems, which usually constitute modern communication systems. Also, such approach helps in simulation of particular analog blocks in system environment, helping out to create proper excitations and estimate reactions. Another one important feature of such approach is ability to match circuit elements in circuit-level simulation to fit system merits.

Many authors paid their attention to this topic [1,2,14]. Similar objectives also can be met using macromodeling, but those approach does not allow to establish links between circuit element values and global merits of communication link.

In following sections co-simulation system implementation is described. It uses discrete complex envelopes technique for system-level simulation and Modulation Harmonic Balance (MHB) technique for circuit-level simulation. Simulation example of circuit-level power amplifier model as a part of system-level communication link model is presented.

II. SIMULATION TECHNIQUES

Complex envelope technique is a most widely used for communication system simulation. According to it, information signal along the system is represented in a form of two orthogonal components – I and Q, which are called inphase and quadrature and considered to be continuous in time. All signal transformations in system blocks (dissipation, filtering, nonlinear distortions, etc.) are considered as transformations of envelope [3].

Convenient representation for envelope components is discrete representation of continuous complex functions. After sampling, reaction of the block to input may be defined as:

$$y_n = \sum_{i=0}^{K} l_i x_{n-i} \qquad (1)$$

for linear blocks or as:

$$y_n = m(x_n, x_{n-1}, .., x_{n-i}, ..) \qquad (2)$$

in more general nonlinear case, where l – linear block response, m – nonlinear block function, i –sample number. If blocks constitute directed graph without loops with incidence matrix A, then resulting system response may be written as:

$$Y_n = A \cdot \begin{bmatrix} m_j(y_n, y_{n-1}, .., y_{n-i}, ..) \\ w_j(n) \end{bmatrix} \qquad (3)$$

where $w_j(n)$ - excitation components at n-th time sample and $m_j()$ - response components, j - component index in a vector.

At circuit level, RF and MW circuits in digital communication links are usually under excitation of complex shape signals with much different time constants. Convenient way to simulate such circuits is modulation (envelope) harmonic balance (MHB) [4,5,13]. MHB equations are formulated simultaneously in time domain w.r.t. "slow" time (information component of excitation) and in frequency domain w.r.t. "fast" component (carrier):

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$$F_k(X_l(t)) \equiv$$

$$I_k(X_l(t)) + \Omega Q_k(X_l(t)) + \frac{d}{dt} Q_k(X_l(t)) + \quad (4)$$

$$+ LX_k(t) + M\{\Omega X + \frac{d}{dt} X_k(t)\} + U_k(t) = 0$$

Here $X_k(t)$ – k-th harmonic component of unknowns X as function of time t, $I()$ – vector-function of nonlinear responses, $Q()$ – vector-function of reactive nonlinear responses, L and M – matrices of linear components of circuit response: resistive and reactive, Ω - frequencies matrix, $U_k(t)$ – free excitation term, k - harmonic number. It is an extension of Harmonic Balance technique [6,7,9].

MHB Eq. (4) can be sampled in discrete moments of time of Eq. (3). That will allow substituting terms of Eq. (4) in Eq. (3) composing equations into one system.

Considering equation interaction, let us allow Eqs. (1) and (2) to be coupled only via their stimuli $w_j(n)$ and $U_k(t_n)$. So, any $y_{n,j}$ value of vector Y_n at (1) can be assigned to $U_k(t_n)$ and any $X_k(t_n)$ can be assigned to $w_j(n)$. Please, note that both values are complex, as both represent complex amplitudes. This simplifies consideration and shows how each part of combined task can be simulated with own specific solver.

III. CO-SIMULATION SYSTEM IMPLEMENTATION

Two ready-made components were chosen to build co-simulation system: Matlab/Simulink [10] and Rincon [11]. Simulink was chosen for its extendibility using common programming language like C/C++ and ready-to-use communication and DSP libraries. Rincon implements MHB and allows circuits to be defined with VHDL-AMS/FD [8,9,11] – extension of VHDL-AMS language, with frequency-domain modeling capabilities. In addition, it can be integrated with external tools via pipe interfaces.
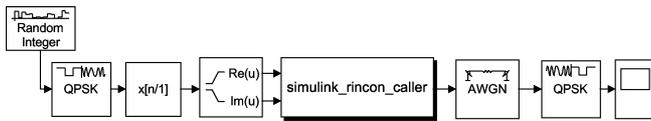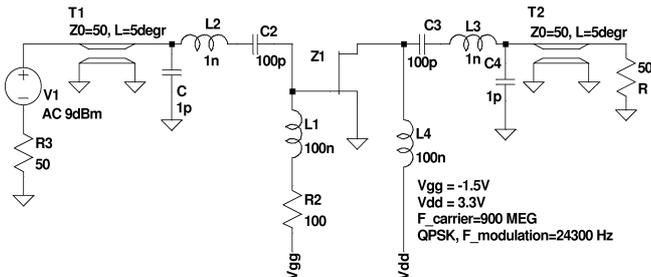

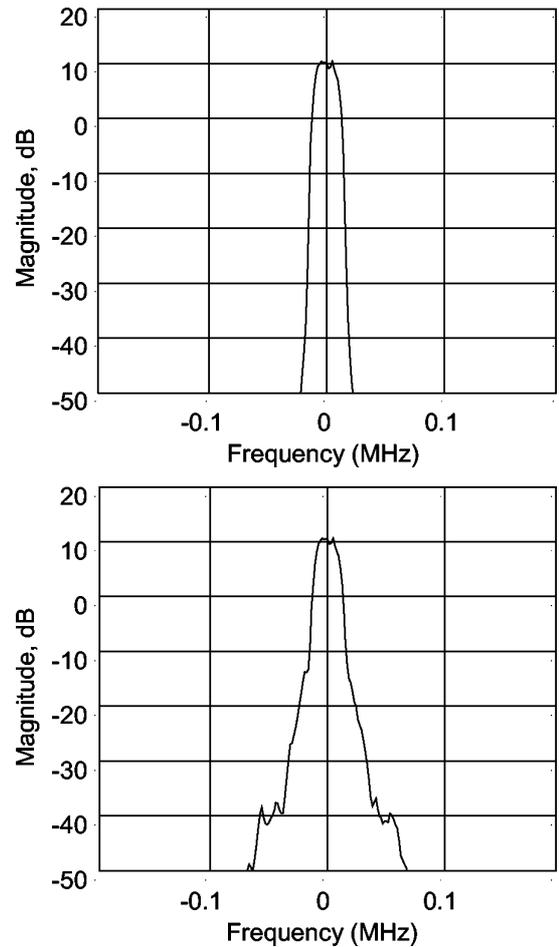Fig. 1. QPSK Link

Fig. 2. Amplifier schematic

Fig. 3. Input and output amplifier spectra.

Simulink's capability to extend components using C or C++ programming languages was used to code interface part, which arranges simulators interaction. Simulink - Rincon interaction is built such way, that Rincon is considered as one of the discrete Simulink blocks with fixed signal sampling frequency. Simulink also is used to perform results visualization, as any circuit variable inside Rincon is available in Simulink. Rincon, in turn, get stimuli envelopes, simulates circuit and returns data back to Simulink. Circuit element values, harmonics numbers and additional data can be passed into Rincon as function parameters.

IV. QPSK LINK SIMULATION

To demonstrate the abilities of implemented co-simulation system, model of communication link with QPSK modulation (Fig. 1) has been simulated. Link starts with random number generator, and then follows QPSK modulator (block from Simulink toolbox), raised cosine filter, power amplifier, AWGN channel and demodulator. Power amplifier, being represented at circuit level, has been co-simulated with the whole system. Schematic of power amplifier is presented at Fig. 2. It is one-transistor MESFET power amplifier with reactive load. Input and output passive

circuits model matching circuits and interconnections. Schematic is shown with input source and load.

Simulink S-function ("simulink_rincon_caller") performs all necessary initializations, starts separate process of circuit simulation using Modulation Harmonic Balance technique and performs required communication: input data for circuit-level simulation are got from Simulink and, after simulation, are returned to it. That is performed for each step of Simulink simulation cycle. 16 points per transmitted digit are used in simulation.

Simulation results are presented at the following figures. Spectrum at input and output of amplifier is presented at Fig. 3 to show regrowth due to amplifier nonlinearities. Signal trajectories before and after amplifier are shown at Fig. 4 and eye diagrams are shown at Fig. 5. Inphase and quadrature components at amplifier input and output are shown at Fig.6. Figure illustrates channel interaction due to amplifier nonlinearity.

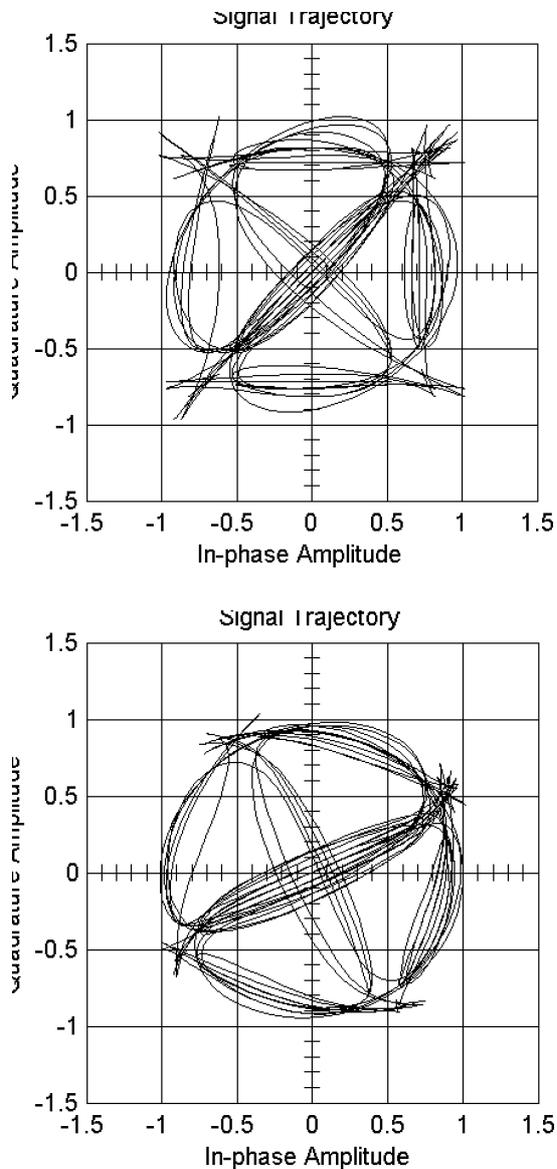Amplifier schematic was taken from [12].

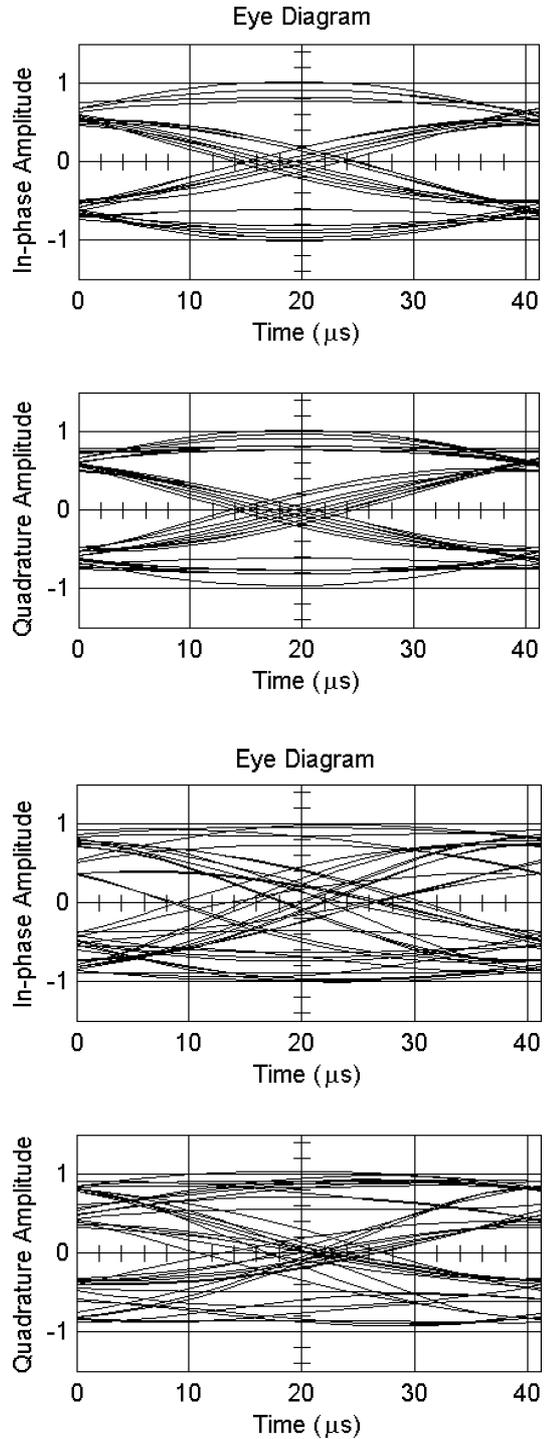Fig. 4. Signal trajectories after filter and after amplifier.

Fig. 5. Eye diagrams after filter and after amplifier.

V. CONCLUSION

Principles of implementation of multilevel mixed-mode co-simulation environment for communication link simulation are discussed. Viable methods are considered for different levels of representation and ways of their interaction are presented. New implementation based onto proposed approach for co-simulation is described, which allows usage models of different levels. Results are illustrated with mixed-level mixed-mode simulation
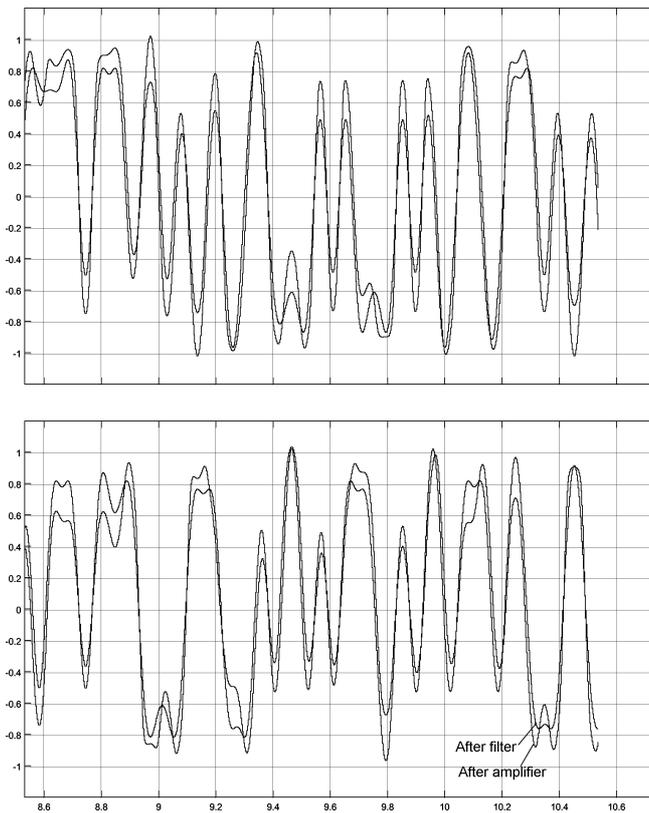
Fig. 6. Normalized inphase and quadrature components before and after amplifier, time is in ms.

example, which includes power amplifier operated under complex modulated signals in QPSK RF communication link. Example allows visualizing signal impairments caused by amplifier nonlinearities.

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