Nonlinear RF Circuits and Systems Simulation When Driven by Several Modulated Signals

Nuno B. Carvalho, *Senior Member, IEEE*, José C. Pedro, *Senior Member, IEEE*, Wonhoon Jang, and Michael B. Steer, *Fellow, IEEE*

***Abstract*—The simulation of nonlinear RF circuits and systems driven by digitally modulated signals with a large number of carriers is addressed by combining the envelope transient harmonic balance method with the artificial frequency mapping technique. The co-simulation of low-pass equivalent behavioral models with circuit based models is addressed by simulating the overall wireless communication path. Several application examples are considered, in particular, the modeling of complete wireless communications circuits and systems incorporating the radio channel model.**

***Index Terms*—Circuit simulation, communication system nonlinearities, nonlinear distortion, nonlinear systems.**

I. Introduction

The DEMAND for increased data transmission rates in wireless communications while keeping processing power requirements to reasonable levels is driving the proposal of new types of wireless standards[1] that achieve greater spectral efficiency. These standards utilize new modulation formats, require greater bandwidths, and necessitate multicarrier modulation schemes such as orthogonal frequency-division multiplexing (OFDM). OFDM is particularly attractive as it is possible that higher data rates can be achieved than with multiple-input multiple-output (MIMO)-based systems for fixed processing power. Even with MIMO schemes in which multiple propagation paths are utilized to transmit different bit streams between a base station and a terminal unit, the transmitted signal can be modeled as a sum or carriers. Multiuser code-division multiple-access (CDMA) schemes must also be modeled as multicarrier schemes [1]. In these schemes and their projected enhancements, the signal environment consists of a large number of carriers. Finally, we should consider the problem of cosite interference. The RF environment now consists of a large number of differently modulated signals, such as GSM and UMTS, and the coexistence of mobile telephony and position/localization services in the same handset, are imposing new nonlinear RF/microwave simulation challenges. Evolving terminal architectures will relax the RF filters specifications and of great concern is that stopband performance will be limited. In summary, the RF environment is becoming much richer and design will require the handling of a very large number of carriers each of which is digitally modulated.

The simulation of the overall system, from the input bit stream to the output bit stream, is an ideal of RF engineers. The ability to simulate an entire RF system, including the modulator, the power amplifier (PA), the propagation channel, the low-noise amplifier (LNA), and the demodulator will enable an engineer to select each of the components in the system individually in order to optimize the complete link. The overall system goal is minimization of bit error rate (BER) with good spectral efficiency. With the current capabilities, it is not possible to consider the RF environment in its entirety rendering system and circuit simulations to predictions of single-channel impairment such as spectral regrowth captured in measures such as the adjacent channel power ratio (ACPR). What is desired is system-level modeling but with the fidelity achieved in modeling an individual modulated RF carrier. Currently, low-pass equivalent models are used in system simulators but circuit impairments can only be captured poorly. Full fidelity requires circuit- and system-level modeling at the RF frequency. While time-domain simulation would provide the necessary capture, the extremely long simulation times and accumulated numerical error render it inappropriate for modeling digital communication systems. Addressing the system modeling demands of a complete RF system is the focus of this paper.

One of the more important advances in modeling digitally modulated RF signals is the development of the envelope transient harmonic balance (ETHB) techniques [2]–[11], which were initially developed to handle a slowly modulated single RF carrier. It has since been extended in commercial simulators [12] to handle two or more carriers, although no description of the technique is available. What is known is that multitone harmonic balance (HB) is combined with a transient solver. Unfortunately, in this approach, the multirate nature of the problem is kept, and the complexity is still very high. Commercial multitone HB utilizes almost periodic discrete Fourier transforms (APDFTs) or multidimensional Fourier transforms (N-FFTs). Such schemes are practically limited to five or so discrete carriers. One commercial HB implementation using APDFT can handle up to ten carriers but with excessive simulation times. In the various modeling problems outlined, the stimulus is composed of potentially a very large number of unmodulated and modulated RF carriers. Therefore, even

Manuscript received April 1, 2005; revised August 1, 2005. This work was supported in part by the European Union under the Network of Excellence Top Amplifier Research Groups in a European Team—TARGET Contract IS-1-507893-NoE and by the U.S. Army Research Office as a Multidisciplinary University Research Initiative on Multifunctional Adaptive Radio Radar and Sensors under Grant DAAD19-01-1-0496.

N. B. Carvalho and J. C. Pedro are with the Instituto de Telecomunicações, Universidade de Aveiro, 3810 Aveiro, Portugal (e-mail: nborges@ieee.org; jcpedro@ieee.org).

W. Jang and M. B. Steer are with the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC 27695-7243 USA (e-mail: wjang@unity.ncsu.edu; m.b.steer@ieee.org).

Digital Object Identifier 10.1109/TMTT.2005.862713

[1]IEEE 802.11, IEEE 802.15, IEEE 802.16.

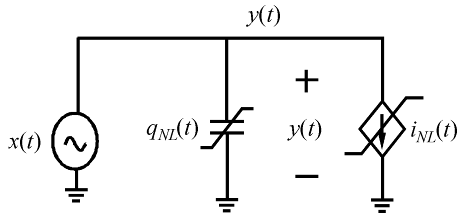

Fig. 1. Nonlinear dynamic circuit example for the illustration simulation techniques.

using a multirate simulator, we no longer would have a single time-domain envelope and frequency-domain carrier, as in ETHB, but a possibly very large series of modulations and carriers. Potentially complex signals with hundreds of carriers would need to be modeled.

The main aim of this paper is to combine the multitone artificial frequency-mapping techniques (AFMTs) [13] with ETHB and so permit rapid and memory-efficient modeling of multicarrier digital communication systems. The work expands upon the outline previously presented [14] with rigorus development presented here. Previously [10], we presented a similar development using three-dimensional (3-D) HB, but the treatment here is completely general. AFMT is capable of modeling an arbitrary number of carriers and we have used it to handle systems with up to 150 noncommensurate tones. The fundamental limit is imposed by ill conditioning of the HB matrices as they become very large. In this paper, we first present the theoretical generalization and integration of the ETHB and AFMT algorithms. The integrated scheme is then applied to several special RF/microwave cases of practical significance: a mixer circuit whose RF input is driven by a modulated signal, a simplified nonlinear amplifier circuit excited by the newly multicarrier modulated signals (OFDM), and, finally, a simulation of a completely RF system including propagation effects. Section II addresses the mathematical formulation underlying this generalization, while Sections III and IV discusses the implementation details. Section V presents the system simulation/circuit approach, while Section VI is devoted to some simulation examples.

II. Theoretical Formulation

In general, an RF circuit (see Fig. 1) can be modeled as a system of ordinary differential equations in time[2]

$$\mathbf{i}\left[\mathbf{y}(t)\right] + \frac{d\mathbf{q}\left[\mathbf{y}(t)\right]}{dt} = \mathbf{x}(t) \tag{1}$$

where $\mathbf{x}(t)$ and $\mathbf{y}(t)$ are the excitation and state-variable vectors, respectively, $\mathbf{i}[\mathbf{y}(t)]$ represents memoryless linear or nonlinear elements, and $\mathbf{q}[\mathbf{y}(t)]$ models memoryless linear or nonlinear charges (capacitors) or fluxes (inductors). In the present case, $\mathbf{x}(t)$ is assumed to be a composite signal where (up to) N different envelope signals modulate N carriers

$$\mathbf{x}(t) = \mathbf{X}_0 + \sum_{n=1}^{N} \left[\mathbf{x}_{m_n}(t)(e^{-j\omega_n t} + \mathrm{e}^{j\omega_n t})\right]. \tag{2}$$

In its highest level of generality, these carriers of frequency ω_n can either be correlated or uncorrelated with each other or with any of the modulating envelopes $x_{m_n}(t)$. If the envelope time and frequency variables, $t_{en} \leftrightarrow \Omega_n$ and $t_{cn} \leftrightarrow \omega_{cn}$, can be considered independent of each other, the stimulus and state vectors become dependent on these $2N$ different time-scales and the nonlinear ODE of (1) is turned into a multirate partial differential equation (MPDE) [15]

$$\begin{aligned}
&\mathbf{i}\left[\mathbf{y}(t_{e1}, t_{e2}, \cdots, t_{eN}, t_{c1}, t_{c2}, \cdots, t_{cN})\right] \\
&\quad + \frac{\partial \mathbf{q}\left[\mathbf{y}(t_{e1}, \cdots, t_{eN}, t_{c1}, \cdots, t_{cN})\right]}{\partial t_{e1}} + \cdots \\
&\quad + \frac{\partial \mathbf{q}\left[\mathbf{y}(t_{e1}, \cdots, t_{eN}, t_{c1}, \cdots, t_{cN})\right]}{\partial t_{cN}} + \cdots \\
&= \mathbf{x}(t_{e1}, \cdots, t_{eN}, t_{c1}, \cdots, t_{cN}).
\end{aligned} \tag{3}$$

This MPDE can now either be solved in the time domain, using a $2N$-dimensional time-marching scheme, in frequency domain using an appropriate HB algorithm, or in any combination of time and frequency using a mixed-mode technique. The mixed-mode approach has proven to be particularly attractive for modeling communications circuits with digitally modulated carriers.

In many multicarrier communication systems, there are only a few master clocks, and, thus, in a large number of situations of practical interest, the number of orthogonal time scales can be significantly reduced from the original $2N$. Furthermore, since the information envelopes are necessarily aperiodic while the carriers are periodic, and the period of the envelopes is several orders of magnitude longer than that of the carriers, in all practical situations, (3) must be solved using a mixed-mode method. In this method, the envelopes are represented by a succession of time samples (eventually separated by constant or dynamic time-steps) and the carriers are described by a vector of complex Fourier coefficients. This naturally leads us to a multidimensional Fourier transform-based harmonic balance algorithm (MDFT-HB) [16], for the simulation of the carriers, and a multidimensional time-step integration for the envelopes. Nevertheless, the use of MDFT-HB is known to be very costly in both simulation time and memory storage, and thus its use is generally prohibitive for situations with more than two modulated carriers.

Following the procedure with the conventional single-modulated-carrier ETHB, the modulated multicarrier signals will thus be represented as a series of envelope time-dependent Fourier coefficients [5]. When such a time-varying envelope frequency-domain representation is substituted into (3), the MPDE becomes

$$\begin{aligned}
&\mathbf{I}(t_{e1}, \cdots, t_{eN}, k\omega_{c1}, \cdots, k\omega_{cN}) \\
&\quad + \frac{\partial \mathbf{Q}\left[\mathbf{Y}(t_{e1}, \cdots, t_{eN}, k\omega_{c1}, \cdots, k\omega_{cN})\right]}{\partial t_{e1}} + \cdots \\
&\quad + jk\omega_{c1}\mathbf{Q}(t_{e1}, \cdots, t_{eN}, k\omega_{c1}, \cdots, k\omega_{cN}) + \cdots \\
&= \mathbf{X}(t_{e1}, \cdots, t_{eN}, k\omega_{c1}, \cdots, k\omega_{cN})
\end{aligned} \tag{4}$$

[2]This expression assumes that any circuit component requiring an impulse response description is represented by an appropriate equivalent circuit model.

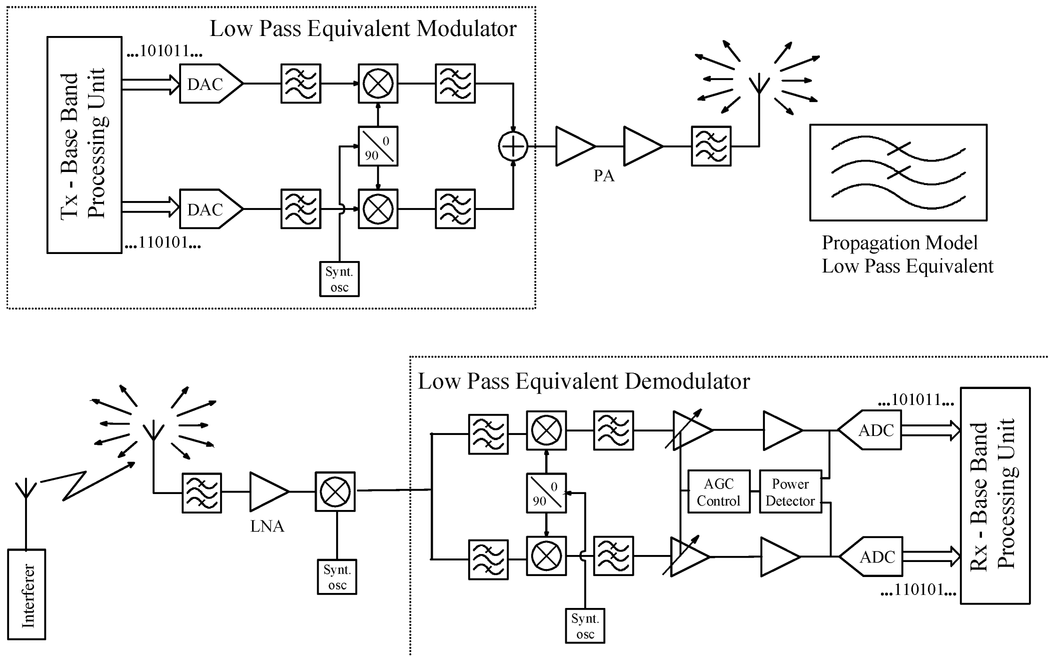

Fig. 2. System to be simulated.

in which $\mathbf{I}(t_{en}, k\omega_{cn})$, $\mathbf{Q}(t_{en}, k\omega_{cn})$, $\mathbf{Y}(t_{en}, k\omega_{cn})$, and $\mathbf{X}(t_{en}, k\omega_{cn})$ stand for the t_{en} time-varying Fourier components of the currents and charges (or fluxes) of the memoryless nonlinearities, the state variables, and the excitation, respectively. The discretization of (4), using the backward Euler rule, leads to the following system of difference equations in the above Fourier coefficients:

$$\begin{aligned}
&h_{1_i}\cdots h_{N_i}\cdot \mathbf{I}\left(t_{e1_i},\cdots,t_{eN_i},k\omega_{c1},\cdots,k\omega_{cN}\right)\\
&\quad+h_{2_i}\cdots h_{N_i}\mathbf{Q}\left[\mathbf{Y}(t_{e1_i},\cdots,t_{eN_i},k\omega_{c1},\cdots,k\omega_{cN})\right]+\cdots\\
&\quad+h_{1_i}\cdots h_{N_i}\cdot j\boldsymbol{\Omega}_{c1}\mathbf{Q}(t_{e1_i},\cdots,t_{eN_i},k\omega_{c1},\cdots,k\omega_{cN})+\cdots\\
&\ = h_{1_i}\cdots h_{N_i}\cdot \mathbf{X}(t_{e1_i},\cdots,t_{eN_i},k\omega_{c1},\cdots,k\omega_{cN})+h_{2_i}\cdots\\
&\quad\times h_{N_i}\mathbf{Q}\big[\mathbf{Y}(t_{e1_{i-1}},\cdots,t_{eN_i},k\omega_{c1},\cdots,k\omega_{cN})\big]+\cdots.
\end{aligned}\tag{5}$$

The proposed mixed-mode method operates by integrating (5) in a t_{e_i} time-step-by-time-step basis (h_{n_i}), starting from the initial conditions $\mathbf{X}(t_{e1_0},\ldots,t_{eN_0},k\omega_{c1},\ldots,k\omega_{cN})$ and $\mathbf{Y}(t_{e1_0},\ldots,t_{eN_0},k\omega_{c1},\ldots,k\omega_{cN})$ and solving for each of the successive time samples t_{en_i} using a frequency-domain (HB) algorithm. Here, the frequency-domain HB solution for the carriers is efficiently solved using AFMT.

In the above most general formulation, orthogonal time scales were considered for each envelope and carrier signals. However, in many real situations, as in multicarrier modulation formats such as OFDM, the carriers can share the same reference. In most telecommunication systems, even the different envelope bit streams share a common clock reference and bandwidth. This can provide a significant reduction in the problem's dimensionality, which is especially relevant in many practical situations.

III. Multicarrier Implementation

One particular scenario where the number of independent time scales can be significantly reduced is the simulation of circuits excited by an OFDM signal. As this modulation format uses equally separated carriers, the HB analysis can be carried out in a much more efficient manner using an appropriate AFMT technique (AFM-HB) [13]. Furthermore, since all independent carrier envelopes share the same clock time base, the envelope time-step integration can be performed in a synchronous way.

So, a judicious use of AFM techniques allows multidimensional HB to be converted into a one-dimensional (1-D) or sinusoidal HB implementation [13], while the synchronous time-step integration turns the multidimensional time-domain analysis into a 1-D initial condition problem (although still in N different envelopes).

Accordingly, the N-envelope time variables are described by a single t_e time base and discretized in a single time step h_i. The N carriers are represented by a central RF frequency ω_c and a constant carrier separation $\Delta\omega$. After the appropriate AFM transformation, these two frequency-domain variables are mapped onto the harmonics of a single artificial frequency λ, and (5) becomes

$$\begin{aligned}
&h_i\cdot\mathbf{I}\left(t_{e_i},k\lambda\right)+\mathbf{Q}\left[\mathbf{Y}\left(t_{e_i},k\lambda\right)\right]+h_i.j\boldsymbol{\Lambda}\mathbf{Q}\left(t_{e_i},k\lambda\right)\\
&\qquad\qquad = h_i.\mathbf{X}\left(t_{e_i},k\lambda\right)+\mathbf{Q}\left[\mathbf{Y}\left(t_{e_{i-1}},k\lambda\right)\right].
\end{aligned}\tag{6}$$

This demonstrates that any complex OFDM scheme can be simulated using a slightly modified version of the conventional ETHB, combining a conventional sinusoidal HB with a time-step integration engine.

IV. Mixer Implementation

In this case, the number of different uncorrelated signals would lead to three orthogonal variables correspondent to the CW local oscillator (LO) ω_{c2}, the RF carrier ω_{c1}, and its envelope discrete time samples t_{e_i}.

Considering only the frequency-domain representation of the RF carrier and the LO, simulation becomes a two-dimensional (2-D) HB scheme. As before, this can be converted into a sinu-

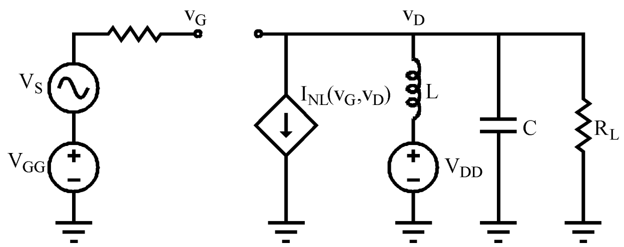

Fig. 3. Nonlinear circuit example.

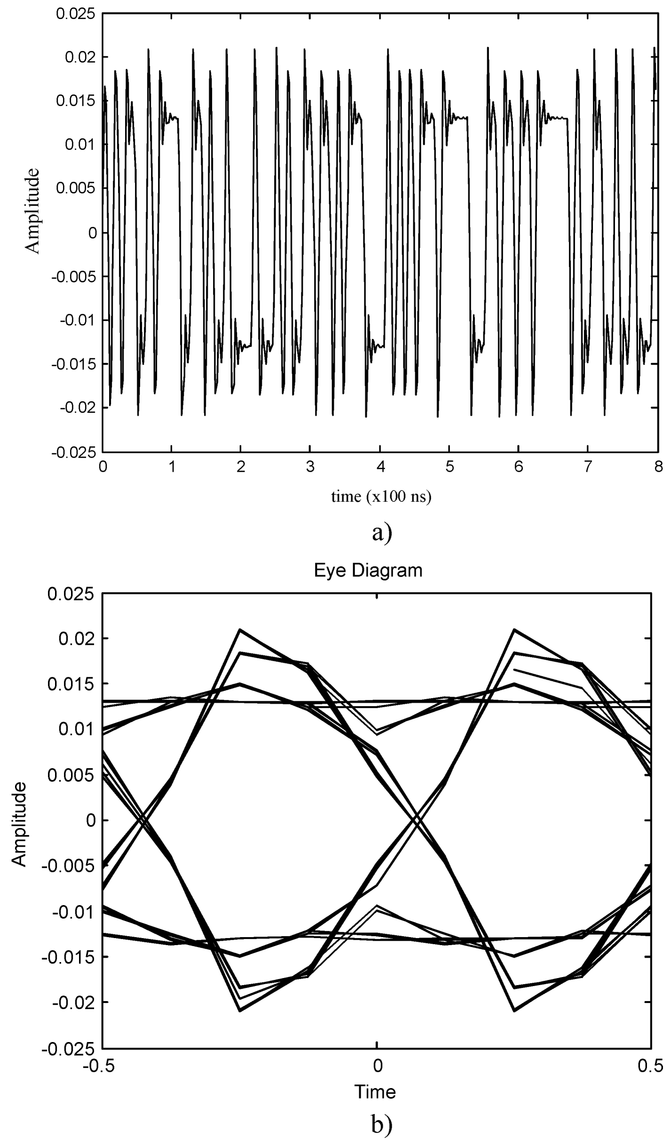

Fig. 4. (a) Input modulation signal waveform. (b) Excitation eye diagram.

soidal HB using a conventional two-tone AFM transform and (5) becomes again simplified to (6).

V. System/Circuit Simulation

Previous sections were devoted to the algorithm implementation details. Nevertheless if the RF engineer is willing to simulate a complete RF system, then he must first divide the envelope exclusive blocks from the ones that operate at RF.

As an example of the application of the proposed scheme to mixed circuit and system simulation consider the block diagram

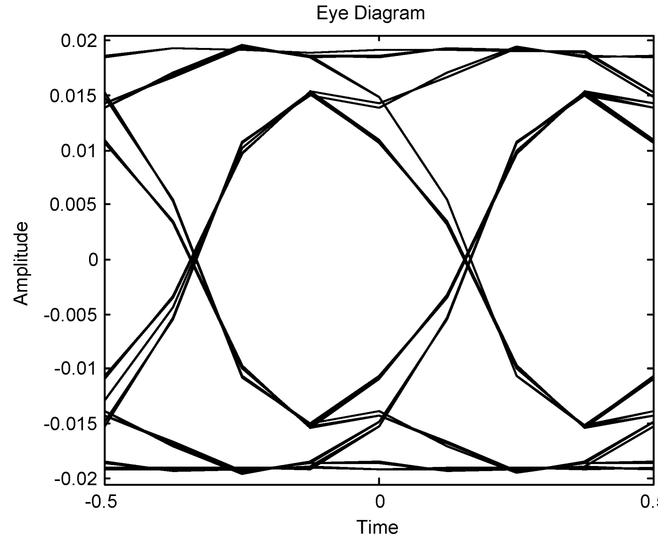

Fig. 5. Output eye diagram at the IF frequency at 100 MHz.

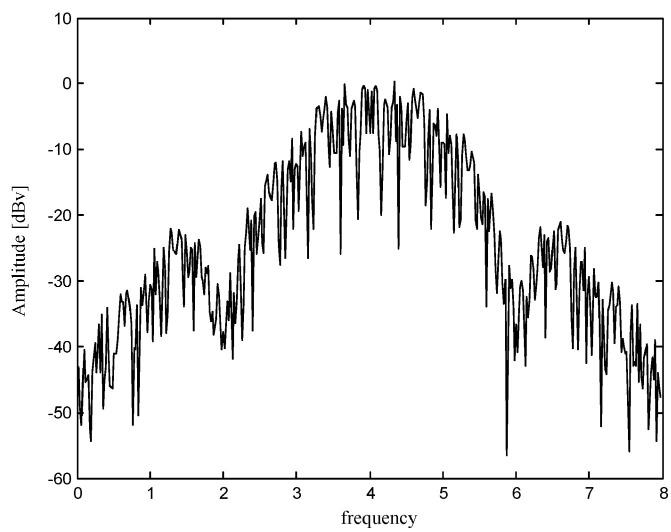

Fig. 6. Simulated output spectrum centered at the IF carrier.

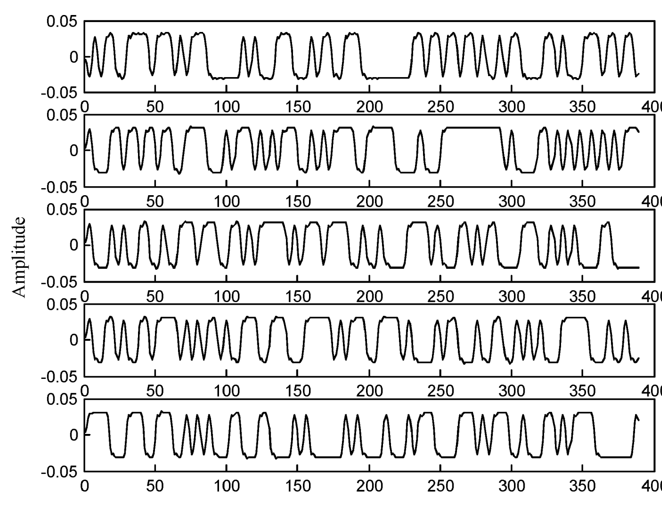

Fig. 7. Output envelope signals at each carrier.

of Fig. 2, then the modulating/demodulating blocks could be considered as low-pass equivalents, while the others should be handled at RF.

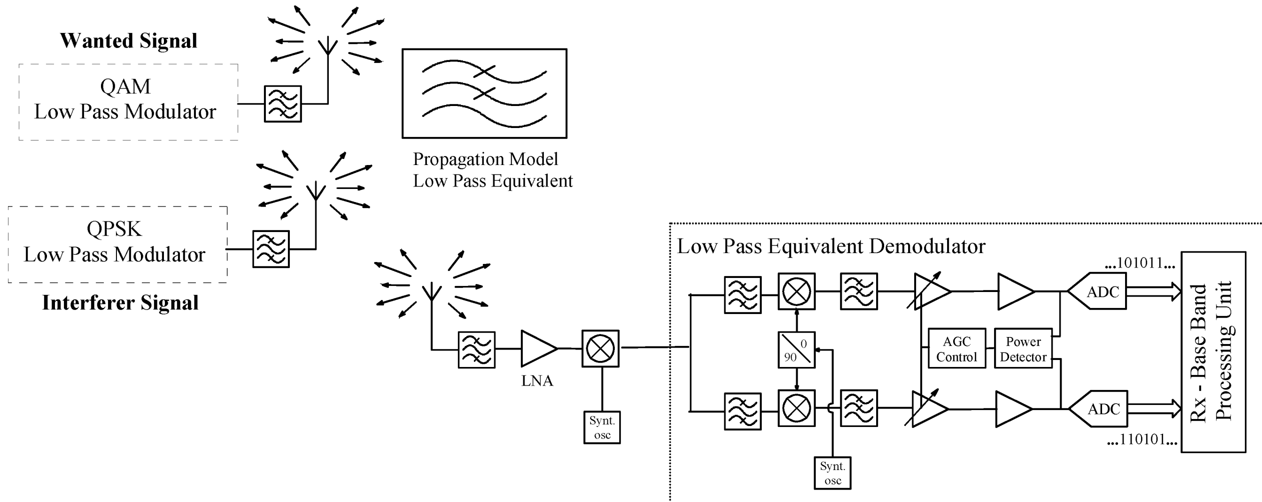

Fig. 8. Super-heterodyne receiver to be simulated in the presence of an interferer.

Thus, implementation of the proposed scheme should first perform a low-pass transient analysis in order to transform the input bits to a complex envelope signal, and then that signal becomes the envelope at time t_1 for one of the channels and the envelope at time t_2 for the other channel. Then, both channels can be sampled at a constant frequency rate and presented to the transient HB engine.

The algorithm would then simulate the common RF blocks at the RF frequency, including propagation models or behavioral- or circuit-level models of the RF amplifiers/mixers. The simulator would then calculate the output complex envelope that would again be fed to the low-pass equivalent of the demodulator. In this way, a complete RF system can be simulated with part of the system described at the circuit level.

In Section VI, a complete RF system will be simulated, thus exemplifying the full capability of the new technique.

VI. Illustrative Application Examples

Two different schemes will be simulated to verify the ideas presented above. First, the response of a microwave circuit will be studied both when working as a mixer and as an amplifier for a multicarrier modulated signal.

Second, a complete wireless communication system will be addressed.

A. Circuit Simulation

The first application of the now proposed algorithm will be the nonlinear circuit of Fig. 3 that it is simply a transfer nonlinearity that drives an output parallel resonant circuit. It can be viewed as a behavioral model or a simplified representation of either an output-tuned FET-based amplifier or gate mixer.

1) Mixer Test: The mixer configuration considered is a gate mixer in which both the RF and LO signals are applied to the gate. It will behave as a down converter. The circuit excitation is the sum of a dc bias voltage V_{GG} plus a binary phase-shift key (BPSK)-modulated RF carrier, and a CW LO, i.e.,

$$v_s(t_e, t_{c1}, t_{c2}) = V_s + v_m(t_e)(\mathrm{e}^{-j\omega_{c1}t_{c1}} + \mathrm{e}^{j\omega_{c1}t_{c1}}) + V_{\mathrm{LO}}(\mathrm{e}^{-j\omega_{c2}t_{c2}} + \mathrm{e}^{j\omega_{c2}t_{c2}}). \quad (7)$$

The RF carrier frequency is at $f_{c1} = 2.1$ GHz, and the LO at $f_{c2} = 2$ GHz while the output bandpass IF filter is centered at 100 MHz. The modulating signal waveform $v_m(t_e)$ is the pseudorandom sequence shown in Fig. 4(a), which corresponds to the eye diagram plotted in Fig. 4(b).

Fig. 5 depicts the output eye diagram of the IF signal, while Fig. 6 presents the resulting simulated spectrum around the IF carrier.

2) Multicarrier Modulated Amplifier Test: In the second case, the circuit of Fig. 3 was biased, and the output filter tuned, so that it behaves as an amplifier. The input excitation is a multicarrier (five-tone) modulated signal centered at 2 GHz and with a frequency separation of 100 kHz. Each of the five carriers is modulated by a different envelope signal. Thus, the excitation is

$$v_s(t_{e1}, \ldots, t_{e5}, t_c) = V_s + v_{m1}(t_{e1})(\mathrm{e}^{-j\omega_{c1}t_{c1}} + \mathrm{e}^{j\omega_{c1}t_{c1}}) + \cdots + v_{m5}(t_{e5})(\mathrm{e}^{-j\omega_{c5}t_{c5}} + \mathrm{e}^{j\omega_{c5}t_{c5}}) \quad (8)$$

where $\omega_{c_n} = \omega_{c1} + n\Delta\omega$. Fig. 7 presents the output envelope of each fundamental carrier.

B. RF Circuit/System Simulation

The end-to-end communication system presented in Fig. 8 will now be studied considering the complete link, including radio-channel propagation degradation. The proposed simulation provides analysis of an RF system that uses a super heterodyne receiver and accounts for the degradation of the symbol error rate (SER) caused by an interferer present at the image frequency.

The signal at Channel 1—which is the sought signal—is a 16-quadrature amplitude modulation (16-QAM) signal and that in channel 2—which is the unwanted signal at the image frequency—is quadrature phase-shift keying (QPSK) modulated.

The modulation blocks are implemented via their low-pass equivalents and are responsible for the envelopes of each of the RF carriers.

The propagation channel will be modeled by the COST-231 Hata Model, which is dependent on the frequency, distance, and height of each antenna [17]–[19].

The receiver's LNA and mixer were considered at the circuit level, since they both present nonlinear behavior with long-term memory effects, and enough low-pass equivalent models of sufficient accuracy do not exist for such circuits.

Since the super-heterodyne structure uses an LO for down conversion, a third carrier is considered as the LO. Thus, the system has two complex envelope signals beyond the three RF carriers.

Finally, the demodulator will also be implemented as a low-pass equivalent model.

In this case, the input driving signal of our simulator will be

$$\begin{aligned} v_s(t_{e1}, t_{e2}, t_{c1}, t_{c2}, t_{c3}) &= V_s + v_m(t_{e1})(\mathrm{e}^{-j\omega_{c1}t_{c1}} + \mathrm{e}^{j\omega_{c1}t_{c1}}) \\ &\quad + v_m(t_{e2})(\mathrm{e}^{-j\omega_{c2}t_{c2}} + \mathrm{e}^{j\omega_{c2}t_{c2}}) \\ &\quad + V_{\mathrm{LO}}(\mathrm{e}^{-j\omega_{c3}t_{c3}} + \mathrm{e}^{j\omega_{c3}t_{c3}}). \end{aligned} \tag{9}$$

The interferer was first set at a power that was low enough that no interference results from the nonlinear part of the super-heterodyne receiver. Fig. 9 presents (a) the corresponding constellation diagram, (b) the time-domain envelope, and (c) the corresponding spectrum of the input and output signals. In the previous case, no distortion and no errors were seen as expected.

Fig. 10 presents the situation when the interferer has a power level that degrades the reception of the desired signal.

As can be seen from Figs. 10 and 11, the interferer severely degrades the reception of the QAM signal because of nonlinear effects associated with the nonideal LNA and mixer circuit models. In particular, constellation points associated with RF amplitudes have disappeared [see Fig. 10(a)]. That is, outlying constellation points were demodulated as other points in the constellation diagrams were interpreted this way as symbol errors. Fig. 11 presents the degradation of the SER due to the rise in power of the interferer. The implication here is that the modulation scheme should adapt to the presence of the large interferer to reduce demands on forward error correction (FEC) codes and maintain low frame error rates.

To the best of the authors' knowledge, the proposed method constitutes an optimal compromise between computation accuracy and efficiency for simulating multicarrier digital communication systems. An alternate envelope-level simulation using low-pass equivalent models would have its accuracy compromised by the lack of appropriate behavioral models of the LNA and the mixer. If a time-marching simulator were used with modulated RF carriers, the simulation time would be prohibitive, because of the extremely different time scales (of the RF carriers and the base-band envelopes) common to this type of telecommunication system. Indeed, the only viable alternative seems to be cosimulation via a combination of envelope-level and modulated-RF carrier-level analysis through a multicarrier/multi-envelope harmonic balance simulation scheme. Also, in this respect, the use of AFMT harmonic balance can provide an enormous advantage in computation efficiency.

In order to show the benefits in simulation speed provided by the presented combination of the multicarrier/multi-envelope engine with the AFMT-based harmonic balance solver, we have also compared its results with an ETHB scheme implemented by a well-known commercial simulator. The comparison was conducted for excitations of increasing complexity and was composed of two to six modulated carriers.

Fig. 12 presents the simulation time measured from the two simulation environments.

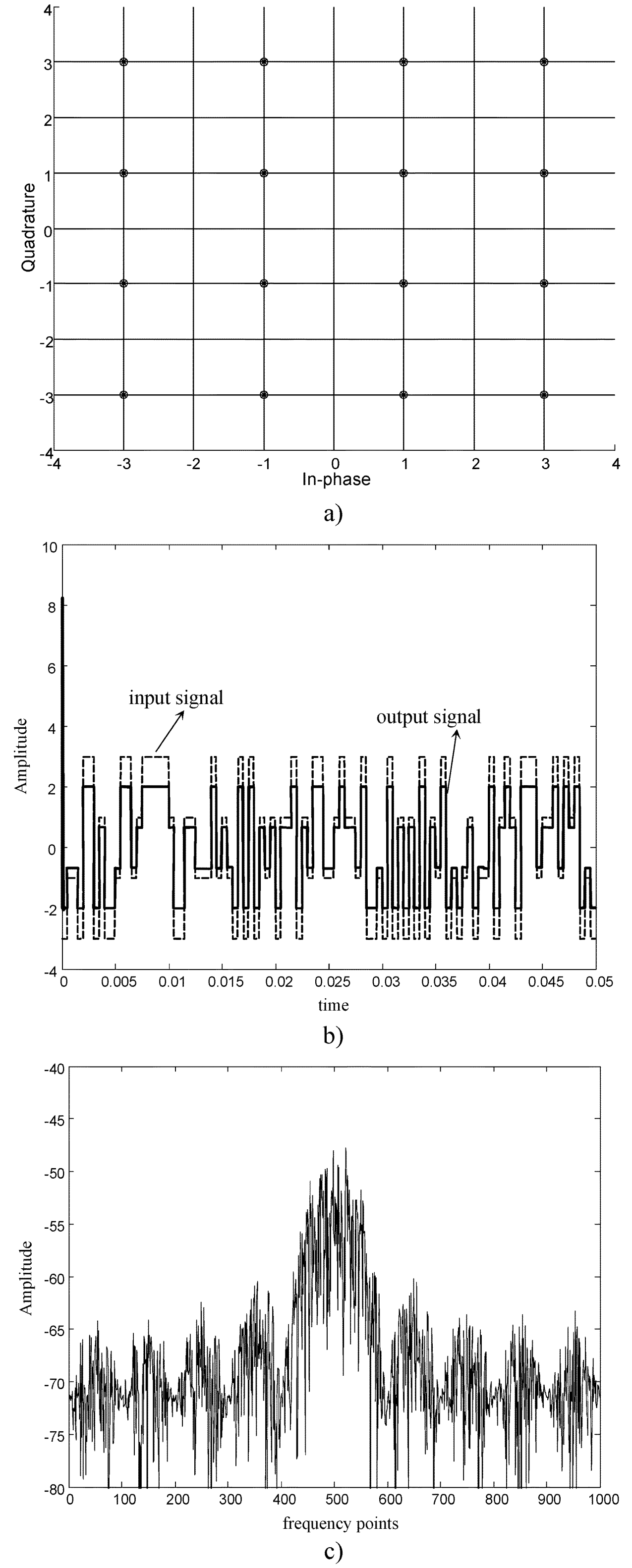

Fig. 9. (a) Constellation diagram (circles: input diagram; crosses: output diagram) and (b) time-domain envelope (dotted line: input signal; solid line: output signal) of (c) output and input signals and spectrum of the output signal.

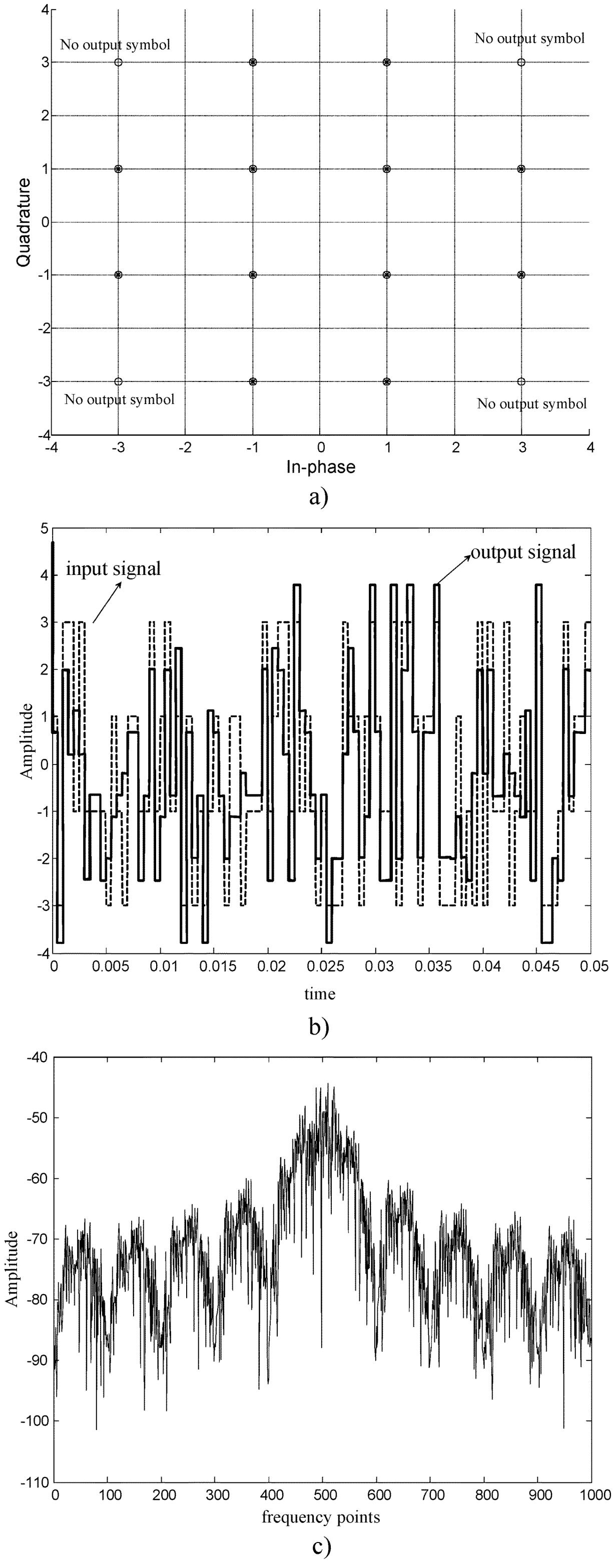

Fig. 10. (a) Constellation diagram (circles: input diagram; crosses: output diagram) and (b) time-domain envelope (dotted line: input signal; solid line: output signal) of (c) output and input signals and spectrum of the output signal of the high-power interferer.

As can be seen from this figure, the advantage in using our simulation machine is unquestionable for a number of modulated carries higher than four. Note, for example, that although our simulator requires simulation times on the order of 100–300 s for three to six modulated carriers, the commercial engine requires 100–25 000 s for three to five carriers, while it takes an unacceptable amount of time for more then five carriers.

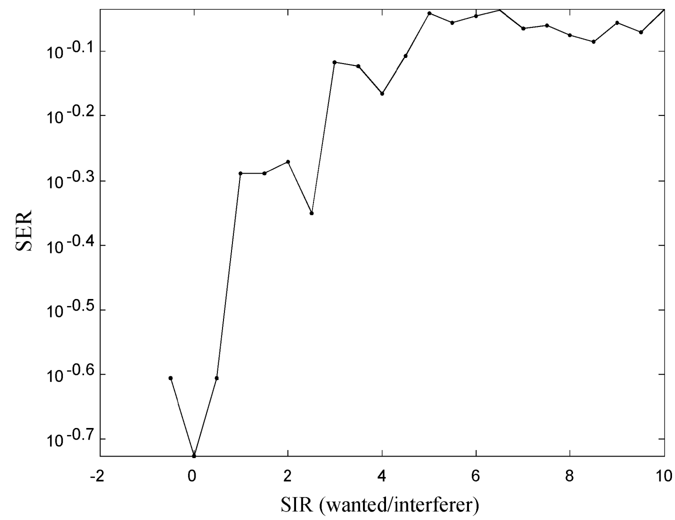

Fig. 11. SER versus signal-to-interference ratio.

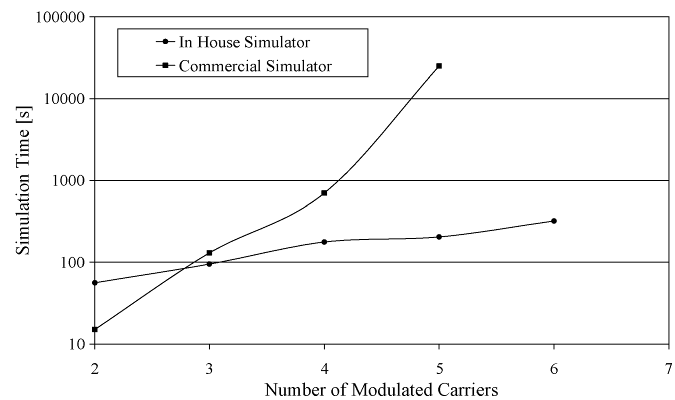

Fig. 12. Simulation time comparison between the proposed algorithm and a commercial simulator.

VII. Conclusion

In this paper a method combining multi-envelope transient harmonic balance algorithm with AFMT was proposed. The method presented here reduces the number of independent time and frequency variables required in an analysis. The algorithm takes advantage of particular properties of the stimulus to couple a conventional 1-D time-step integration scheme with an HB employing the artificial frequency mapping techniques. To illustrate the methods capabilities, three examples of practical relevance in the microwave and wireless fields were studied: a mixer driven by a CW LO and modulated RF signal; an amplifier excited by an OFDM digital modulated multicarrier signal; and a complete wireless system. The technique presented is capable of handling an arbitrarily large number of carriers.

The technique presented in this paper allows the designer to optimize the complete wireless chain simultaneously. Moreover, the designer can focus on the optimization key system parameters of SER rather than on intermediate and inadequate measures of subsystem performance.

REFERENCES

[1] R. Nee and R. Prasaad, *OFDM Wireless Multimedia Communications*. Norwood, MA: Artech House, 2000.

[2] D. Sharrit, "New method of analysis of communication systems," in *MTT-S Nonlinear CAD Workshop*, Jun. 1996.

[3] V. Rizzoli, A. Neri, and F. Mastri, "A modulation-oriented piecewise harmonic-balance technique suitable for transient analysis and digitally modulated signals," in *Proc. 26th Eur. Microw. Conf.*, Prague, Czech Republic, Sep. 1996, pp. 546–550.

[4] E. Ngoya and R. Larchevèque, "Envelope transient analysis: a new method for the transient and steady-state analysis of microwave communications circuits and systems," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Francisco, CA, Jun. 1996, pp. 1365–1368.

[5] J. C. Pedro and N. B. Carvalho, "Simulation of RF circuits driven by modulated signals without bandwidth constraints," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Seattle, WA, Jun. 2002, pp. 2173–2176.

[6] M. Condon and E. Dautbegovic, "A novel envelope simulation technique for high-frequency nonlinear circutis," in *Proc. 33rd Eur. Microw. Conf.*, Munich, Germany, Oct. 2003, pp. 619–622.

[7] E. Ngoya, J. Sombrin, and J. Rousset, "Simulation des circuits et systémes: méthodes actuelles et tendances," in *Séminaires Antennes Actives et MMIC*, Arles, France, Apr. 1994, pp. 171–176.

[8] D. Sharrit, "Method for Simulating a Circuit," U.S. Patent 5 588 142, May 12, 1995.

[9] S. Sancho, A. Suarez, and J. Chuan, "General envelope-transient formulation of phase-locked loops using three time scales," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 4, pp. 1310–1320, Apr. 2004.

[10] N. B. Carvalho, J. C. Pedro, W. Jang, and M. B. Steer, "Nonlinear simulation of mixers for assessing system-level performance," *Int. J. RF Microw. Computer-Aided Eng.*, to be published.

[11] V. Rizzoli, A. Neri, F. Mastri, and A. Lipparini, "Modulation-oriented harmonic balance based on Krylov-subspace methods," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 1999, pp. 771–774.

[12] Agilent, Advanced Design System 2002, 2002.

[13] J. C. Pedro and N. B. Carvalho, *Intermodulation in Microwave and Wireless Circuits*. Norwood, MA: Artech House, Aug. 2003.

[14] N. B. Carvalho, J. C. Pedro, W. Jang, and M. B. Steer, "Simulation of nonlinear RF circuits driven by multi-carrier modulated signals," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2005, pp. 801–804.

[15] J. Roychowdhury, "Analyzing circuits with widely separated time scales using numerical PDE methods," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 48, no. 5, pp. 578–594, May 2001.

[16] V. Rizzoli, C. Cecchetti, and A. Lipparini, "A general-purpose program for the analysis of nonlinear microwave circuits under multitone excitation by multidimensional Fourier transform," in *Proc. 17th Eur. Microwave Conf.*, Rome, Italy, Sep. 1987, pp. 635–640.

[17] "Digital mobile radio toward future generation systems," European Communities, COST Action 231, Final Tech. Rep. EUR 18 957, 1999.

[18] Y. Oda, K. Tsunekawa, and M. Hata, "Advanced LOS path-loss model in microcellular mobile communications," *IEEE Trans. Veh. Technol.*, vol. 49, no. 6, pp. 2121–2125, Nov. 2000.

[19] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 1999.

Nuno B. Carvalho (S'92–M'00–SM'05) was born in Luanda in 1972. He received the Diploma and Doctoral degrees in electronics and telecommunications engineering from the Universidade de Aveiro, Aveiro, Portugal, in 1995 and 2000, respectively.

From 1997 to 2000, he was an Assistant Lecturer with the Universidade de Aveiro, and is currently is an Associate Professor. He is also a Senior Research Scientist with the Instituo de Telecomunicacoes, Universidade de Aveiro. He was a Scientist Researcher with the Instituto de Telecomunicacoes, during which time he was engaged in different projects concerning nonlinear computer-aided design (CAD) and circuits. He coauthored *Intermodulation in Microwave and Wireless Circuits* (Artech House, 2003). His main research interests include CAD for nonlinear circuits and design of RF-microwave PAs. He has been a reviewer for several magazines.

Dr. Carvalho is a member of the Portuguese Engineering Association. He is a reviewer for the IEEE TRANSACTIONS ON MICROWAVE THEORY and TECHNIQUES. He was the recipient of the 1995 Universidade de Aveiro and the Portuguese Engineering Association Prize for the best 1995 student at the Universidade de Aveiro, the 1998 Student Paper Competition (third place) presented at the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS) and the 2000 Institution of Electrical Engineers (IEE), U.K. Measurement Prize.

José C. Pedro (S'90–M'95–SM'99) was born in Espinho, Portugal, in 1962. He received the Diploma and Doctoral degrees in electronics and telecommunications engineering from the Universidade de Aveiro, Aveiro, Portugal, in 1985 and 1993, respectively.

From 1985 to 1993, he was an Assistant Lecturer with the Universidade de Aveiro, and a Professor since 1993. He is also a Senior Research Scientist with the Instituo de Telecomunicacoes, Universidade de Aveiro. His main scientific interests include active device modeling and the analysis and design of various nonlinear microwave and optoelectronics circuits, in particular, the design of highly linear multicarrier power amplifiers and mixers. He coauthored *Intermodulation Distortion in Microwave and Wireless Circuits* (Norwood, MA: Artech House, 2003) and has authored or coauthored several papers appearing in international journals and symposia.

Dr. Pedro is a reviewer for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS). He was the recipient of the 1993 Marconi Young Scientist Award and the 2000 Institution of Electrical Engineers (IEE) Measurement Prize.

Wonhoon Jang received the B.S. degree in electronics from Kyungpook National University, Daegu, Korea, in 1997, and is currently working toward the Ph.D. degree in electrical engineering at North Carolina State University, Raleigh.

From 1997 to 1999, he was with LG Precision Company, Kumi, Korea, where he was involved with military radios. His current research interests include nonlinear RF/microwave system analysis and modeling.

Michael B. Steer (S'76–M'82–SM'90–F'99) received the B.E. and Ph.D. degrees in electrical engineering from the University of Queensland, Brisbane, Australia, in 1976 and 1983, respectively.

He is currently the Lampe Family Distinguished Professor of Electrical and Computer Engineering, North Carolina State University, Raleigh. In 1999 and 2000, he was a Professor with the School of Electronic and Electrical Engineering, The University of Leeds, where he held the Chair in microwave and millimeter-wave electronics. He was also Director of the Institute of Microwaves and Photonics, The University of Leeds. He has authored approximately 300 publications on topics related to RF, microwave and millimeter-wave systems, high-speed digital design, and RF and microwave design methodology and circuit simulation. He coauthored *Foundations of Interconnect and Microstrip Design* (Wiley, 2000).

Prof. Steer is active in the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). In 1997, he was secretary of the IEEE MTT-S. From 1998 to 2000, he was an elected member of its Administrative Committee. He is the Editor-in-Chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (2003–2006). He was a 1987 Presidential Young Investigator (USA). In 1994 and 1996, he was the recipient of the Bronze Medallion presented by the Army Research Office for "Outstanding Scientific Accomplishment." He was also the recipient of the 2003 Alcoa Foundation Distinguished Research Award presented by North Carolina State University.