NUMERICAL MODELING OF NONLINEAR INTERFERENCE AND DISTORTIONS FOR WIRELESS COMMUNICATIONS

Sergey L. Loyka

Belorussian State University of Informatics & Radioelectronics, P. Brovki Str. 6,
Minsk 220027, Belarus, e-mail: sergey.loyka@ieee.org

Nonlinear interference and distortions have a profound impact on wireless communication system operation, especially under conditions of severe electromagnetic environment (overcrowded spectrum, strong interfering signals, multipath and multi-signal environment etc.). In this paper, we propose a new behavioral-level simulation technique – the "instantaneous" quadrature technique, which can be employed for the EMC/EMI analysis of wireless systems in a computationally-efficient way taking into account nonlinear effects (over wide dynamic and frequency ranges) and, secondly, we discuss how to apply the instantaneous quadrature technique to simulating wireless receivers and transmitters for EMC/EMI problems.

1. INTRODUCTION

Exponential increase in the number of wireless communication systems and in the complexity of their design greatly increases the risk of intra- and inter-system interference and distortions, which can degrade the system performance drastically, especially under conditions of over-crowded spectrum and limited space available (antenna towers, indoor communications, closely-located handheld phones etc.). Even carefully-made frequency planning does not guarantee the absence of interference in any scenario. Some possible kinds of nonlinear interference and distortions for wireless communication systems are the following [1, 2]:

1. Spurious radiation of transmitters: harmonics and sub-harmonics, intermodulation products (IMP), noise etc. Note that the intermodulation radiation can be caused by an external signal (from a nearby transmitter) as well as by several carriers (in CDMA systems, for example) in the transmitter's power amplifier.
2. Spurious responses of receivers: adjacent, image and intermediate frequency (IF) channels.
3. Nonlinear behavior of receivers may also cause the performance degradation (desensitization, IMPs, local oscillator noise and harmonics conversion etc.).

Analytical and semi-empirical methods were extensively used in the past for the analysis of these effects [1, 2]. Those methods were quite simple and allowed one to get some insight into the system operation. However, the accuracy of those methods is rather poor. Besides, the analysis of complex systems (present-day wireless systems) is rather difficult to do by the old methods.

Thus, nonlinear numerical methods should be used for these problems. System-level analysis (when one or even several systems are to be analyzed at the same time) requires for behavioral-level techniques [3] because circuit-level methods can not be applied due to very high demand for the computational resources.

2. QUADRATURE MODELING TECHNIQUE

The quadrature modeling technique is the most popular tool for behavioral-level nonlinear modeling and simulation of active stages of communication circuits and systems [3, 4]. This technique was introduced in early 1970s for nonlinear modeling and simulation of traveling wave tube amplifiers used in satellite communications [5]. The main idea of the quadrature modeling technique is the use of a complex envelope instead of real narrowband signals [3-5]:

$$x(t) = A(t)\cos\left(\omega_0 t + \varphi(t)\right) = Re\left\{A(t)\cdot \exp\left[j\cdot(\omega_0 t + \varphi(t))\right]\right\} \quad (1)$$

where $A(t)$ and $\varphi(t)$ – are amplitude and phase that vary slowly with respect to carrier (amplitude and phase modulation), ω_0 – is the carrier frequency. Its complex envelope is

$$\overline{A(t)} = A(t)\cdot \exp\left[j\varphi(t)\right] \quad (2)$$

So, there is not any carrier information in the complex envelope, only modulation information (only the first harmonic zone is taken into account). It's very important from the viewpoint of computational efficiency, but it also limits the technique capabilities – only narrowband analysis is possible because the frequency response is assumed to be flat over the simulation bandwidth. The output signal of a bandpass nonlinear stage is

$$y(t) = K(A_{in}(t))\cdot A_{in}(t)\times \cos\left(\omega_0 t + \varphi_{in}(t) + \Phi(A_{in}(t))\right) \quad (3)$$

where A_{in} and j_{in} are the input signal amplitude and phase. A nonlinear stage is characterized by its envelope amplitude and phase transfer factors:

$$K(A_{in}) = \frac{A_{out}}{A_{in}}, \quad \Phi(A_{in}) = \varphi_{out} - \varphi_{in} \qquad (4)$$

$K(A_{in})$ represents envelope amplitude-to-amplitude (AM-AM) nonlinearity, and $F(A_{in})$ represents envelope amplitude-to-phase (AM-PM) nonlinearity. Note that both factors depend on the input signal amplitude, not on instantaneous value of the signal. It's due to the bandpass representation of signals and system stages (actually, lowpass equivalents of both are used). Thus, equation (4) constitutes the envelope nonlinearity.

In the quadrature modeling technique, in-phase and quadrature envelope transfer factors are used

$$\begin{aligned} K_I(A_{in}) &= K(A_{in}) cos\Phi(A_{in}) \\ K_Q(A_{in}) &= K(A_{in}) sin\Phi(A_{in}) \end{aligned}, \qquad (5)$$

and output lowpass signal is expressed as

$$Y(t) = K_I(A_{in}) X_I(t) - K_Q(A_{in}) X_Q(t) \qquad (6)$$

Two independent channels (in-phase (I) and quadrature (Q)) are used for the simulation. In this way this technique takes into account both the AM-AM and AM-PM nonlinearities. This nonlinear model is sometimes called a memoryless nonlinearity [3]. Strictly speaking, this nonlinearity is not a memoryless one because there is a phase shift (AM-PM), thus the output depends on the input at some past instants (however, there is indeed no any frequency dependence in this model). The input of the quadrature nonlinearity is also shifted by $-\pi/2$ and this operation is not a memoryless one (in fact, it is the Hilbert Transform that is an integral transformation [3]). Consequently, this channel and the entire quadrature structure are not memoryless ones. However, we can still use the term "memoryless" in the sense that the transfer factors K_I and K_Q depend on the input signal amplitude A_{in} at the same instant only.

At the present time, this technique is mainly used for the simulation of solid-state power amplifiers. It has many advantages: it allows one to simulate the power amplifier with a digitally-modulated input signal using a PC in reasonable time and, consequently, to predict adjacent channel power ratio (ACPR), power spectral regrowth (PSR) and error vector magnitude (EVM). The technique can also predict IMPs and gain compression/expansion. The permissible number of input tones and the analysis dynamic range are quite large. However, the main drawback of the quadrature modeling technique is that it is a narrowband one, so it can not take into account frequency response, to predict harmonics of the carrier frequency and even-order nonlinear products, or to model the bias decoupling network effect [6]. This effect limits the analysis accuracy even for narrowband signals and systems [6]. The quadrature modeling technique also uses an explicit representation of the modulated signal, so multiple-carrier signals can not be simulated in a direct way. Thus, some improvements are desirable.

3. DISCRETE TECHNIQUE

The discrete technique was introduced in 1980s for the nonlinear simulation of a RF/microwave receiving path taking into account nonlinear interference and distortions [7-11]. It also accounts for the spurious receiver channels (adjacent, image, local oscillator noise etc.), IMPs and harmonics, gain compression/expansion etc. The main application of this technique was to EMC/EMI analysis in a group of RF/microwave systems. An important advantage of the discrete technique is that instantaneous values of the signals are used during the analysis, not the complex envelope.

The basis of the discrete technique is a representation of the system block diagram as linear filters (matching networks) and memoryless nonlinear elements (active elements) connected in series (or in parallel, or both) [7-11]. Input and output filters model input and output matching networks. This representation reflects characteristic peculiarities inherent to the construction of typical RF amplifying and converting stages. The utilization of the model with memoryless nonlinearity is not a significant limitation on the method. Non-zero memory effects can partially be factorized at the level of input or output filters, that is, this representation is equivalent with respect to the simulation of the "input-to-output" path. Signal passage through a linear filter is simulated in the frequency domain using the complex transfer factor of the filter,

$$S_{out}(f) = S_{in}(f) \cdot K(f), \qquad (7)$$

where $S_{out}(f)$- is the output signal spectrum, $S_{in}(f)$ – is the input signal spectrum, $K(f)$ - is the filter complex transfer factor, and f - is frequency. An appropriate sampling technique is required in order to sample the spectrum. Signal passage through a nonlinear memoryless element is simulated in the time domain using the instantaneous transfer function of the element,

$$u_{out}(t) = F[u_{in}(t)], \qquad (8)$$

where $u_{out}(t)$ - is instantaneous value of the output signal at time instant t, $u_{in}(t)$ - is the same for input signal, F - is an instantaneous transfer function of the nonlinear element. This function can be calculated using the measured or circuit-level simulated AM-AM characteristic [9-10].

Thus, the simulation is made over a wide frequency range. The technique allows one to predict harmonics and even-order nonlinear products, to take into account frequency response and to analyze multi-carrier systems. Both these techniques (the quadrature modeling technique and the discrete technique) are very computationally efficient as compared to circuit-level techniques (HB technique or SPICE), and still have a circuit-level accuracy in many cases. However, the discrete technique does not take into account AM-PM

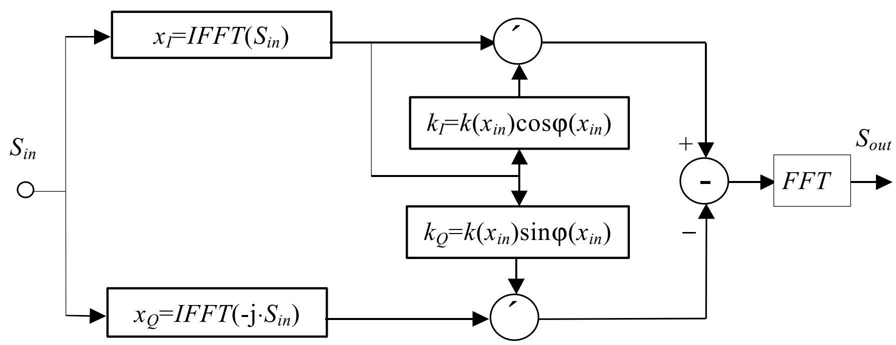

Figure 1. Modeling broadband nonlinear element by the ‘instanteneous’ quadrature technique.

nonlinearity that limits substantially the analysis accuracy.

4. "INSTANTANEOUS" QUADRATURE TECHNIQUE

Here we propose to combine the quadrature modeling technique and the discrete technique in order to build the combined “instantaneous” quadrature modeling technique which can model the circuit or system behavior over wide frequency and dynamic ranges taking into account both AM-AM and AM-PM conversions. In order to model signals and systems over a wide frequency range, the instantaneous values of the signals must be used, not the complex envelope. In order to model the AM-PM conversion, the quadrature modeling structure should be used for the nonlinear element modeling. Thus, the modeling process consists of the following items:

1. Linear filters are modeled in the frequency domain (the same as for the discrete technique).
2. Nonlinear elements are modeled in the time domain using the quadrature structure, but the instantaneous signal values are used, not the complex envelope.
3. The transform from the frequency (time) domain to the time (frequency) domain is made by IFFT (FFT) (very computationally efficient).
4. The Hilbert transform [3] is used to calculate in-phase and quadrature components,

$$x_Q(t) = \hat{x}(t) = \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau\,,\ x_I(t) = x(t), \qquad (9)$$

where $x_I(t)$ and $x_Q(t)$ – are instantaneous in-phase and quadrature components of the signal, $\hat{x}(t)$ is the Hilbert-conjugate signal of $x(t)$. In fact, we use the Hilbert Transform in the frequency domain to calculate the quadrature components because it does not require numerical integration and, thus, is much more computationally efficient:

$$x_Q(t) = IFFT(-j \cdot S(\omega)) \text{ for } \omega \geq 0,$$
$$S(\omega) = FFT(x(t)) \qquad (10)$$

where S(ω) – is the signal’s spectrum. The signal itself is the in-phase component, and the Hilbert’s conjugate signal is the quadrature component.

5. A system of two integral equations is used in order to convert the envelope transfer function into the instantaneous ones:

$$\begin{aligned} &\frac{4}{\pi}\int_0^1 k_I(A_{in}t)\frac{t^2 dt}{\sqrt{1-t^2}} = K(A_{in})\cos\Phi(A_{in}) \\ &\frac{4}{\pi}\int_0^1 k_Q(A_{in}t)\sqrt{1-t^2}\,dt = K(A_{in})\sin\Phi(A_{in}) \end{aligned} \qquad (11)$$

where k_I and k_Q – are the instantaneous in-phase and quadrature transfer factors. Note also that using (11) only the even parts of the transfer factors can be calculated. In order to find the odd parts, some additional characteristics should be used (for instance, the second harmonic transfer factor). As a rule, the amplitude transfer characteristics can be measured or simulated using a circuit-level simulator, thus we need to solve equations (11) for k_I and k_Q . This can be done using the method of moments. If we use piecewise constant basis functions and a point matching technique, the matrices of these equations appear to be upper triangular ones, so the systems of linear equations can be solved analytically (this semi-analytical approach speeds up computations substantially).

Fig. 1 gives an illustration of the nonlinear element modeling. It should be noted that the transfer function of the quadrature channel is not a usual transfer function in a conventional sense: it depends not only the input of the quadrature nonlinearity (x_Q) but also on the input of the entire structure (x_{in}) i.e., in fact, on the input of the in-phase nonlinearity (x_I). Consequently, we cannot use the usual methods of the transformation of the envelope transfer function into the instantaneous one [5]. At the same time, the transfer function of the in-phase channel is a usual transfer function and those methods can be applied in this case.

If one whishes to simulate even-order nonlinear products, then odd parts of the instantaneous transfer factors must be determined. It can be done using the second-order envelope characteristics (second harmonic zone AM-AM and AM-PM functions or second-order IMP at the output for the two-tone input):

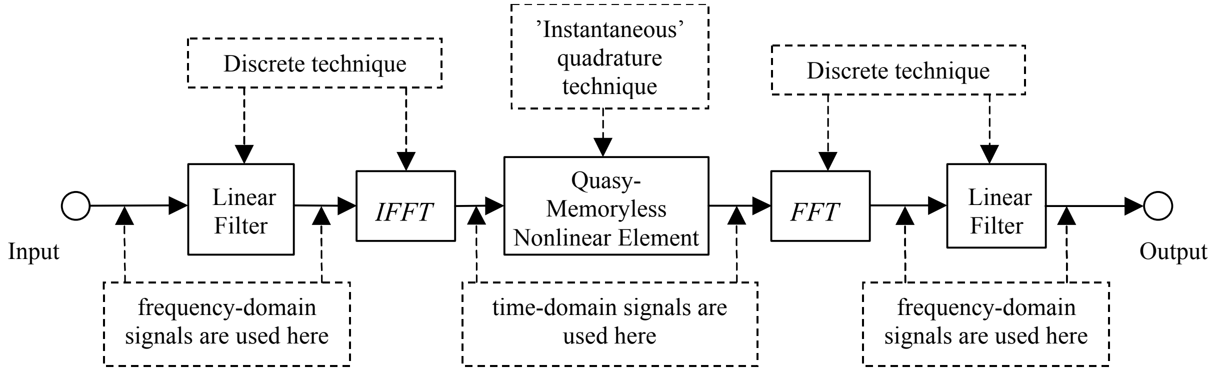

Figure 2. Simulating a single-stage radio amplifier by the 'instantaneous' quadrature technique.

$$\begin{aligned} \frac{4}{\pi}\int_0^1 k_I(A_{in}t)\frac{t\left(2t^2-1\right)}{\sqrt{1-t^2}}dx &= K_2\left(A_{in}\right)cos\left(\Phi_2\left(A_{in}\right)\right) \\ \frac{8}{\pi}\int_0^1 k_Q(A_{in}t)t\sqrt{1-t^2}\,dx &= K_2\left(A_{in}\right)sin\left(\Phi_2\left(A_{in}\right)\right) \end{aligned} \tag{12}$$

where $K_2(A_{in})$ is the second-order envelope transfer factor and $\Phi_2(A_{in})$ is the second-order AM-PM characteristic. We can solve the integral equations (12) using the traditional method of moments approach. But, as practical experience shows, it requires even more sample points than for the even parts. Thus, it is much efficient to use the semi-analytical approach proposed above.

5. APPLYING INSTANTANEOUS QUADRATURE TECHNIQUE TO WIRELESS SYSTEMS

Let us now consider the simulation of typical wireless subsystems/systems using the instantaneous quadrature technique. Fig. 2 illustrates the simulation of a single stage RF amplifier (either power or low noise). The input and output filters model the matching networks, and the quasy-memoryless nonlinear elements model the amplifier nonlinearity (both AM-AM and AM-PM). Using this approach, we may simulate other RF and IF stages (like mixers and IF amplifiers) and even detectors [11] in a computationally-efficient way. Further, using the black-box approach, we may simulate the entire subsystem/system operation under real-world conditions and signals.

The simulation of a wireless transmitter using the instantaneous quadrature technique is quite straight-forward: we do it in the same way as for the quadrature modeling technique. The power amplifier is considered to be the main source of interference and distortions in this case (however, other stages can also be simulated). The simulation of a wireless receiver is not so simple because many its components can contribute to the overall interference and distortions. Thus, we consider (i.e. simulate) the receiver block diagram step by step: low-noise amplifier, local oscillator plus mixer, IF filter and IF amplifier, detector and baseband signal processing part. It should be noted that (i) frequency response is taken into account in every stage, and (ii) detector simulation is possible using the technique proposed that enables us to go further to the simulation of baseband signal processing.

Thus, the instantaneous quadrature technique can be used for the EMC/EMI simulation of an entire wireless communication system over wide frequency and dynamic ranges.

6. TECHNIQUE VALIDATION

In order to validate the technique proposed, extensive harmonic-balance simulations as well as measurements of microwave solid-state amplifiers have been carried out. Fig. 3 shows IMPs simulated by our technique (solid line) and measured (squares). One can note quite a good agreement between behavioral-level simulation and measurements. In general, the discrepancy is about few dBs except for some special areas, which should be further investigated. Fig. 4 shows harmonics simulated by our technique (solid line) and measured (squares). Behavioral-level simulation and measurements agree quite well in this case too. The discrepancy is rather large for several special areas, which should be further investigated. Note also that the analysis is made over wide dynamic range (130-180 dB) and wide frequency range (harmonics!). Thus, these results seems to be very satisfactory taking into account that the problem is a nonlinear one. Accuracy of even-order nonlinear products prediction is slightly worse but still satisfactory for practical purposes.

7. CONCLUSION

In this paper, we have presented the instantaneous quadrature technique as an efficient tool for behavioral-level simulation of wireless circuits and systems for EMC/EMI problems. This techniques combines the advantages of both the quadrature modeling technique and the discrete technique and, consequently, gives one possibility to simulate the circuit/system nonlinear performance over wide frequency and dynamic ranges. This technique should be used on the frequency planning phase in order to avoid possible system performance

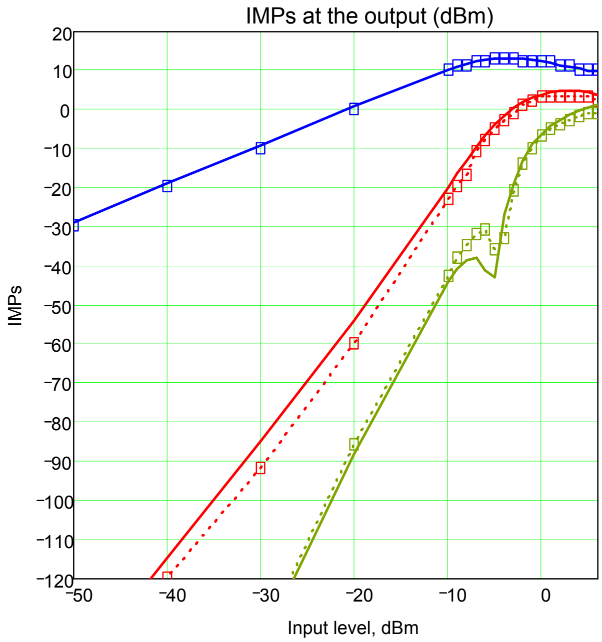

Figure 3. Fundamental, 3rd and 5th order IMPs (solid line – simulated, squares – measured) for 2 stage MMIC amplifier.

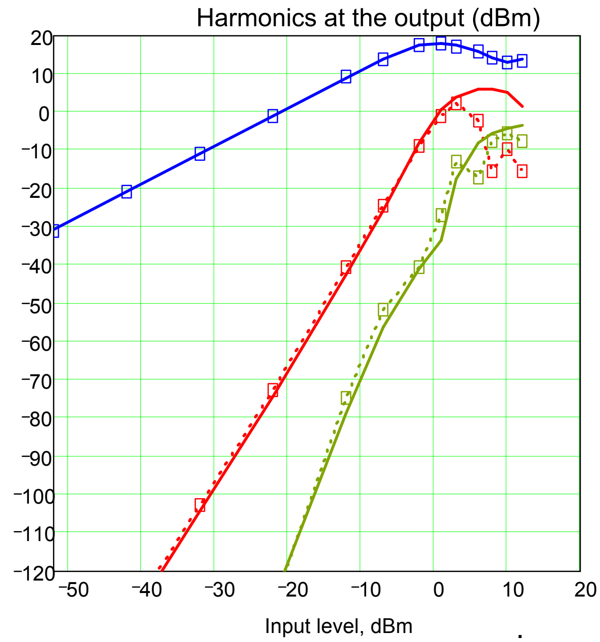

Figure 4. Fundamental, 3rd and 5th harmonics (solid line – simulated, squares – measured) for 2 stage MMIC amplifier.

degradation on the implementation phase and to ensure reliable and high-quality communication.

8. REFERENCES

[1] D.R.J. White, "*A Handbook Series on Electromagnetic Interference and Compatibility*", Don White Consultants Inc., Germantown, Maryland, 1971-1973.

[2] J. Gavan, “Principles of Radio System and Relevant EMI Environmental Effects, Analysis and Computation,” in R. Perez (ed.), *Handbook on Electromagnetic Compatibility*, New York, Academic Press, 1995.

[3] M.C. Jeruchim, P. Balaban, K.S. Shanmugan, *Simulation of Communication Systems*, Plenum Press: New York, 1992.

[4] J. Staudinger, “Applying the Quadrature Modeling Technique to Wireless Power Amplifiers,” *Microwave Journal*, vol. 40, No. 11, Nov. 1997, pp.66-86.

[5] A. R. Kaye, D. A. George and M. J. Eric, “Analysis and compensation of bandpass nonlinearities for communications”, *IEEE Transactions on Communications*, vol. 20, No. 11, Nov. 1972, pp.965-972.

[6] J. Staudinger, Behavioral Analysis Method Applied to the Design & Simulation of Linear Power Amplifiers, *RAWCON’98 Workshop “Modeling and Simulation of Devices and Circuits for Wireless Communications”*, Colorado Springs, CO, Aug. 9-12, 1998.

[7] V.I. Mordachev “Express analysis of electromagnetic compatibility of radio electronic equipment with the use of the discrete models of interference and Fast Fourier Transform”, *Proc. of IX Inter. Wroclaw Symp. on EMC*, Poland, Wroclaw, 1988, Part 2, pp.565-570.

[8] S. L. Loyka and V. I. Mordachev, “Identification of Nonlinear Interference Sources with the Use of the Discrete Technique,” *IEEE EMC Symp.*, Denver, Colorado, Aug. 24-28, 1998, pp.882-887.

[9] S.L. Loyka, "Numerical Simulation of Nonlinear Interference in Radio Systems (Invited paper)," *The 26th URSI General Assembly*, Toronto, Canada, Aug. 13-21, 1999.

[10] S.L. Loyka, "The Influence of Electromagnetic Environment on Operation of Active Array Antennas: Analysis and Simulation Techniques," *IEEE AP Magazine*, 1999, accepted for publication.

[11] S.L. Loyka, Nonlinear EMI Simulation of an AM-Detector at the System Level, *IEEE Trans. on EMC*, 1999, accepted for publication.

BIOGRAPHICAL NOTE

Dr. Sergey L. Loyka was born in Minsk, Republic of Belarus on August 6, 1969. Since 1995 he is a Senior Researcher of the EMC Laboratory, Belorussian State University of Informatics and Radioelectronics. Dr. Loyka is a member of the New York Academy of Sciences and of the IEEE. He has over 60 publications in the area of EMC, active antenna arrays, wireless communications, nonlinear circuit analysis and computer-aided modeling and simulation.