Nonlinear Modeling and Simulation of Active Array Antennas

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Abstract: *This paper presents an overview of active array antennas, system-level nonlinear effects in such antennas, and their modeling and simulation techniques. Influence of nonlinear distortions and interference in active antennas on the overall system performance is considered. Modeling and simulation techniques, which can be applied to active array antennas, are substantially different from those used for circuits and systems. System-level simulation techniques are considered in detail with special emphasis on their application to active array antennas. "Instantaneous" quadrature technique is proposed as an effective tool for numerical simulation of active arrays over wide frequency and dynamic ranges in a computationally-effective way. The validity of this technique is demonstrated through comparison with harmonic balance simulation and measurements. The new Bell Labs ultimate limit for channel capacity and its influence on active array technology and simulation techniques are considered.*

I. Introduction:

For the past 20 years the situation in the area of antenna theory and technology has changed dramatically. One important part of this change is an extensive use of active antennas, especially active array antennas [1-11]. Active antennas in general remain an area of great innovation until now and will remain up to the foreseeable future. Integration of active circuitry into antennas gives a lot of advantages in comparison with conventional antennas, especially at microwave and millimeter-wave frequencies [2, 5-7, 10]. Some of them are the following:

- compensation of increased losses and parasitic coupling at higher frequencies, increase in antenna bandwidth and improvement in impedance matching,
- improvement in sensitivity of receiving antennas; using quasi-optical mixers can also reduce conversion loss in heterodyne receivers; size reduction is also possible,
- active transmitting arrays can be used for spatial power combining techniques that are considered to be very effective for generating high power microwaves and millimeter waves,
- using active circuitry in large phased arrays can eliminate the need for a complex RF distribution network, for a large number of phase shifters and complicated control electronics,
- adaptive antennas that use active circuitry are utilized now in a wide range of applications,
- active antenna arrays find increasingly wider application in mobile communications; the concepts of spatial signal processing and of space-division multiple access (SDMA) based upon the utilization of antenna arrays are introduced and extensively used [6, 43]; 3rd generation mobile communication systems (UMTS) are expected to rely substantially on active array technology,
- the digital beamforming technique is also a very promising one, including mobile communications applications [4]; the concept of a smart antenna is introduced and a lot of research work is done in this area [7, 9, 11],
- present time MMIC technology gives a great impulse to the development of active arrays and their implementation to every-day life, not only military or scientific applications [5, 10].
- very fast progress in the area of active array technology is also expected in future due to the new Bell Labs limit for channel capacity which offers a tremendous increase in bit rates and, at the same time, relies substantially on active array structures [44, 45].

As any other system containing active elements, active arrays suffer from electromagnetic interference (EMI) and distortions caused by nonlinear behavior of the active elements, which can degrade the overall system performance dramatically. Unlike a conventional passive antenna whose parameters are independent of the electromagnetic environment, interfering signals impinging an active antenna can degrade its parameters such as gain, beamwidth, sidelobe level, antenna pattern etc., and can also generate spurious spectral components at the antenna output. The main types of nonlinear effects causing EMI and distortions are the following [4, 12, 13]:

Harmonics generation,
Intermodulation,
Cross-modulation,
Desensitization,
Gain compression/expansion,
Local oscillator harmonics and noise conversion,
Spuriousness in mixers,
Amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) conversion,
Gain and phase sensitivity of amplifiers and mixers to power supply voltages.

Methods of analysis and simulation of nonlinear effects in radio systems and circuits have been developed for a long time and now is quite an established field [12- 16]. Both analytical and numerical techniques are used for this purpose presently with the prevailing use of numerical techniques. Such novel concepts as neural networks and genetic algorithms are actively used in this area in recent times. A number of software analysis and simulation packages are commercially available. At the same time, methods of analysis and simulation of nonlinear effects in antennas are not a well established field. Some work in this area has been done in the past and there is a permanently growing interest for the area now [2, 4, 10, 17-25].

Nonlinear analysis methods used for radio systems and circuits cannot be directly applied to the nonlinear analysis of active array antennas. Why are these methods not appropriate ? Because an active antenna and its circuit components function as a single entity and cannot be split into the passive antenna itself and the active circuit components [2]. In conventional RF systems (with a passive antenna), the antenna and the receiver/transmitter circuits are largely independent, so one could split the entire system into the antenna and the Rx/Tx circuits and, consequently, the analysis is split into the antenna analysis and the Rx/Tx circuit analysis. Thus, an antenna engineer analyzed the antenna and a circuit engineer analyzed the receiver/tramsmitter. And what happens with active arrays ? Since an active array cannot be separated into passive antenna and active circuitry, the antenna engineer and the circuit engineer must work together.

Kirchhoff’s laws and the lumped-circuit approximation are mainly used for the analysis of nonlinear circuits. Radiation effects are ignored. On the contrary, antennas are spatially-distributed structures and radiation effects are of great importance for them. One cannot ignore the radiation effects during the antenna analysis, because radiation is the primary antenna function. EM field equations are used for the analysis of antennas. In order to model and simulate active arrays, new methods of nonlinear analysis should be used, which could combine electromagnetic analysis with nonlinear analysis of active circuits in a computationally-efficient way.

In this paper, we will concentrate our attention on analysis and simulation of active array antennas. We shall outline the active array analysis methods, and some nonlinear effects that are specific to active array antennas. We shall also consider two well-known numerical behavioral-level simulation techniques – the quadrature technique and the discrete technique, as well as their advantages and drawbacks, and proposes the third one – the “instantaneous” quadrature technique that is a combination of two previous ones. We shall also discuss the use of the instantaneous quadrature technique for the nonlinear simulation of active array antennas.

II. Analysis methods for active arrays:

Since an active array is an integration of active circuitry and an antenna, circuit analysis methods and electromagnetic analysis methods should be used together in this case. A wide variety of methods is applied to circuit/system and electromagnetic problems. In general, all analysis methods that can be applied to active array antennas can be divided into two large groups: (1) analytical methods, and (2) numerical methods. Before computers were introduced into every-day engineering practice, analytical methods had been extensively used. Presently, their range of applications is comparatively small, but, nevertheless, they are still used for some problems. Analytical methods have some advantages over numerical ones: (1) give insight into the system behavior, (2) give understanding of fundamental processes which determine the system operation, (3) allow one to interpret experimental or numerical results, (4) give a general view of the situation within a complex system, (5) approximate analytical or semi-empirical methods are simple and easy-to-use, (6) in general, analytical methods don’t require much computational power.

But they are not very accurate. Some improvements in the accuracy are desirable. And they are not general: each particular phenomenon, each particular system are handled in its own way. Thus far, numerical methods arise. A wide range of numerical methods is presently used for circuit/system and electromagnetic problems. They have a lot of advantages. Some of them are (1) more up-to-date, (2) can take into account more factors and phenomena, (3) in general – more accurate (but there are some exceptions – some semi-empirical analytical methods may be more accurate), (4) can handle wider sets of particular system configurations in a uniform manner. But they require much more computational resources and, consequently, complex systems can not be analyzed due to impractically long analysis times or due to extremely high requirements in computational power.

Everybody should clearly understand which method he/she needs. Sometimes, simple analytical methods would be enough. An example is the analysis of a complex system in an early phase of the design, when there is no detailed information. Numerical methods generally require much more characterization data. So, when there is detailed information and when more accurate results are desirable, numerical techniques are needed. Numerical and analytical methods can be used together to produce a powerful analysis tool. For example, we can analyze the entire communication system by simple analytical methods, and some parts of it – by numerical methods. Computational resources required should also be taken into account during the choice of a method. There is some tradeoff between accuracy on the one hand and computational resources / computational time on the other: lower level methods require more resources and time, but have higher accuracy, higher level methods require less resources and time, but have lower accuracy.

There are several levels of numerical methods which can be used for the active array analysis:

a) those based on fundamental physical laws,
b) those based on circuit theory,
c) system-level methods (or “black box”, or “input-output”, or “behavioral”),
d) multilevel (hybrid) methods that integrate several various-level techniques.

Item “a” works with some limitations, mainly due to limited computer resources: “You can’t solve Maxwell’s equations for a CD player !”. In this case item “b” is needed. But it also works with some limitations by the same reason: you can’t model an entire mobile communication system (several thousands subscribers) or a large active array using circuit-level methods (like SPICE). In this case item “c” is required. A combined use of all these methods can result in a very powerful multilevel analysis tool:

- numerical electromagnetics methods are used for the analysis of distributed (radiating) parts of a system in order to build equivalent input-output transfer characteristics for these parts (for instance, antenna-to-antenna coupling characteristic),
- circuit simulators (like SPICE or harmonic balance) are used for the calculation of input-output transfer characteristics of blocks comprising the system block diagram,
- system (or behavioral) –level methods are used for the analysis of the entire system.

Fig. 1 gives an illustrating example of the hybrid analysis method. This analysis method can also be referred to as macro-modeling because the entire system is modeled using black-box models that are built using electromagnetic and circuit-level simulators.

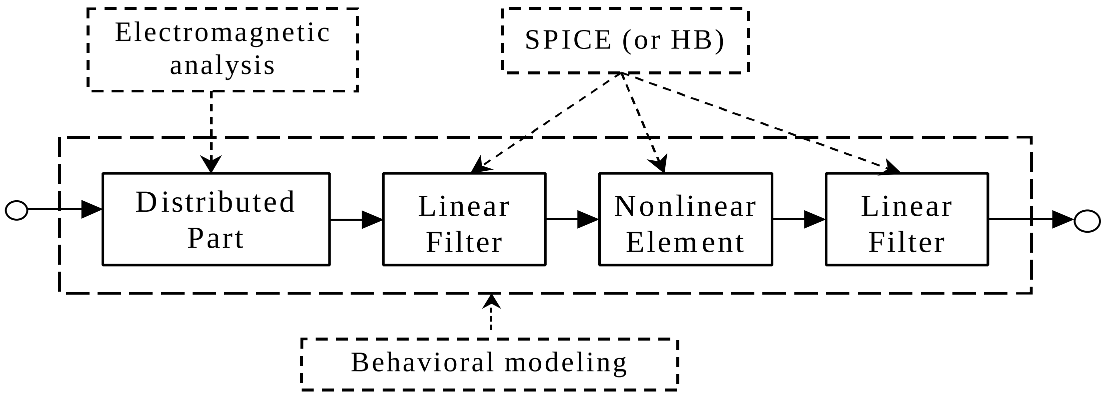

Figure 1. An illustration of hybrid multi-level analysis method.

III. Nonlinear effects in active array antennas:

All main types of nonlinear effects, which are present in active circuit, are also present in active arrays. We constrain our attention here to the system-level nonlinear effects. The most dangerous nonlinear effect in active arrays used in multicarrier communication systems, which has been studied by analytical techniques, is intermodulation generated by power amplifier nonlinearities. This phenomenon has been mainly considered as applied to transmitting active arrays, but many conclusions drawn from these studies can be also applied to receiving active arrays (we should note that the direct application of all results is impossible since the reciprocity principle doesn’t hold for an active array).

In general, intermodulation products (IMP) in active array antennas have properties substantially different from those in lumped circuits and systems [18]. Spectral and noise properties of an active array differ fundamentally from those of a passive array [19]. For multiple-beam satellite digital communication systems, signal suppression and cochannel IMP interference in amplifiers may result in 1-5 dB bit-error-rate degradation of the system performance relative to that using passive antenna [20]. For multiple-beam mobile satellite communication systems with frequency reuse, an average IMP noise reduction of several dB as compared to single-beam single-amplifier case can be achieved due to spatial dispersion of IMP beams [21]. Comparing with the previous case, we can conclude that the performance improvement depends dramatically on a particular system configuration and an analysis criterion. Presence of external interfering signals may result in an increase of the array beamwidth and sidelobe level [17]. Nonlinear effects in amplifiers and mixers have also a large impact on the operation of adaptive antennas used in mobile communication applications [4, 25]. Nonlinearity of active stages can result in sidelobe level increase, null depth decrease and a change of null positions. Severe requirements to the linearity of active array stages must be applied in order to achieve desired system performance: an IMP-free dynamic range of 60 to 100 dB is required over a wide frequency range [26]. Multipath propagation may have a large impact on the self-phased array operation [24, 27]. In average, a 2 dB increase in the total effective array gain is possible due to the coherent summation of the direct and reflected signals. However, substantial decrease in the gain is possible in some particular cases. Such nonlinear phenomena as harmonic radiation and oscillator phase noise may also substantially degrade the overall system performance [10].

IV. Behavioral-level modeling techniques:

Behavioral-level modeling techniques are very popular presently for modeling complex systems, for example, mobile communication systems with complex digital signals [14, 15, 28, 29]. Further we consider these techniques and their application to active array antennas. Why behavioral modeling for active arrays ? There are at least 3 reasons for it.

1. First of all, a large active array is a very complex system and circuit-level modeling of the array active circuitry would require very large computational resources, if not possible at all.
2. Secondly, real-life spectra are quite complex so single-tone modeling is not adequate (an active array is a nonlinear system, so the superposition principle doesn't hold!). On the contrary, a spectrum comprising many harmonic components (say, from several thousands to several millions) must be modeled. Such parameters as spectral regrowth, adjacent channel power ratio and error vector magnitude should be used for the active array characterization.
3. And finally, it's not enough to model an array alone. The transmitter or receiver connected to this array should also be modeled together with the array in order to get an overall estimation of the system performance, as modeling the array alone may sometimes give incorrect results.

There are two behavioral-level modeling techniques that can be used for the analysis of active arrays in an efficient way. These are the quadrature modeling technique [14, 29] and the discrete technique [30, 31]. A joint use of both of them enables one to overcome drawbacks of each technique when used separately.

The main idea of the quadrature modeling technique is the use of a complex envelope instead of real narrow band signals. For example, a real-life amplitude and phase modulated radio signal can be presented in the following form:

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

where A(t) and φ(t) – are an amplitude and a phase that vary slowly with respect to carrier, ω_0 – is the carrier frequency. Its complex envelope is

$$\overline{A(t)} = A(t) \cdot exp\left[j\varphi(t))\right] = A(t)\cos\varphi(t) + jA(t)\sin\varphi(t) \qquad (2)$$

So, there is not any carrier information in the complex envelope, only modulation information. It's very important from the viewpoint of computational efficiency, but it also limits the technique's capabilities. Amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) conversions (nonlinearities) in a nonlinear stage are characterized using the amplitude and phase transfer factors:

$$K(A_{in}) = A_{out}/A_{in}\,, \quad \Phi(A_{in}) = \varphi_{out} - \varphi_{in} \qquad (3)$$

where A_{in} and φ_{in} are the input signal amplitude and phase. Note that both factors depend on the input amplitude, not on the 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 (3) constitutes the amplitude envelope nonlinearity.

This technique can take into account both AM-AM and AM-PM nonlinearities. The latter is very important for array analysis. Unfortunately, this technique is only valid for narrowband signals and systems. In its present form, it cannot take into account the frequency response of the system, to predict harmonics of the carrier frequency and to simulate multi-carrier systems. Thus, some improvements are desirable.

The basis of the discrete technique is a representation of the system block diagram as linear filters (LF) and memoryless nonlinear elements (MNE) connected in series (or in parallel, or both). This representation reflects characteristic peculiarities inherent to the construction of typical 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. The process of signal passage through linear filters is simulated in the frequency domain using the complex transfer factor of the filter. The process of signal passage through a nonlinear memoryless element is simulated in the time domain using the instantaneous transfer characteristic (not the amplitude one, as in the quadrature technique). The transition from the time domain to the frequency domain and vise versa is made with the use of the direct and inverse fast Fourier Transform (FFT). Polynomial approximation of the transfer characteristic allows one to control the spectrum expansion, avoiding in this way spectrum aliasing (due to using FFT) [32, 33]. The transfer characteristic approximation using Chebyshev polynomials can be also very effective, especially together with the Genetic Algorithm approach [34, 35]. Non-polynomial basis functions can also be used but special measures must be taken in this case in order to avoid the aliasing effect [36]. Frequency converters and mixers can be simulated using 2D nonlinear transfer characteristic models [37]. Simulation of AM, PM and FM detectors is also possible [38-40], what gives possibility to simulate the complete receiving path including digital signal processing at the baseband.

Note that the instantaneous values of input and output signals are used in the discrete technique. Thus, it allows one to carry out simulation over a wide frequency range (for instance, to predict harmonics of the fundamental frequency). It also takes into account the frequency characteristics of the system. It also has drawbacks: it can’t take into account an AM-PM nonlinearity. Thus, some combination of the discrete and quadrature modeling techniques are desirable.

The main idea of the combined technique is to use advantages of both techniques [41, 42]. In order to model signals and systems over a wide frequency range, the instantaneous values of signals must be used, not the complex envelope. In order to model AM-PM conversion, the quadrature modeling structure should be used. Thus, the modeling process consists of the following items:

1. The modeling of linear filters is carried out in the frequency domain (the same as for discrete technique).
2. The modeling of nonlinear elements is carried out in the time domain using the quadrature technique, 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 in the frequency domain is used to calculate the signal amplitude and in-phase and quadrature components (very computationally efficient). In fact, the input signal itself is the in-phase component, and the Hilbert’s conjugate signal is the quadrature- component.

Fig. 2 gives an illustration of the simulation process. An illustration of the nonlinear element modeling is shown on Fig. 3 (note that quasi-memoryless elements appears because no any element can be called “memoryless” if it introduces phase shift). We should point out that that amplitude and instantaneous characteristics are not equal (there is some confusion about this issue in the literature). A system of two integral equations gives relations between the amplitude and instantaneous characteristics:

$$\frac{4}{\pi}\int_0^1 k_I\left(A_{in}t\right)\frac{t^2 dt}{\sqrt{1-t^2}} = K\left(A_{in}\right)\cos\Phi\left(A_{in}\right),\quad \frac{4}{\pi}\int_0^1 k_Q\left(A_{in}t\right)\sqrt{1-t^2}\,dt = K\left(A_{in}\right)\sin\Phi\left(A_{in}\right) \tag{4}$$

where k_I and k_Q – are the instantaneous in-phase and quadrature transfer factors. Note also that using (4) 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 (4) for k_I and k_Q . This can be done using the method of moments. If we use piecewise constant basis functions and a

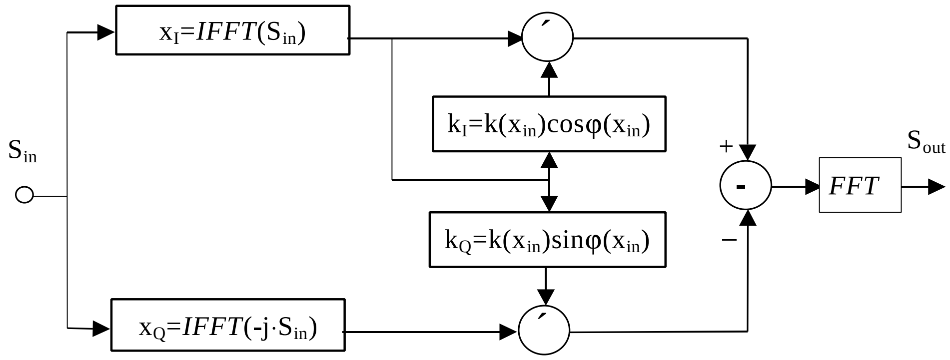

Figure 3. Modeling broadband nonlinear element by the 'instanteneous' quadrature technique.

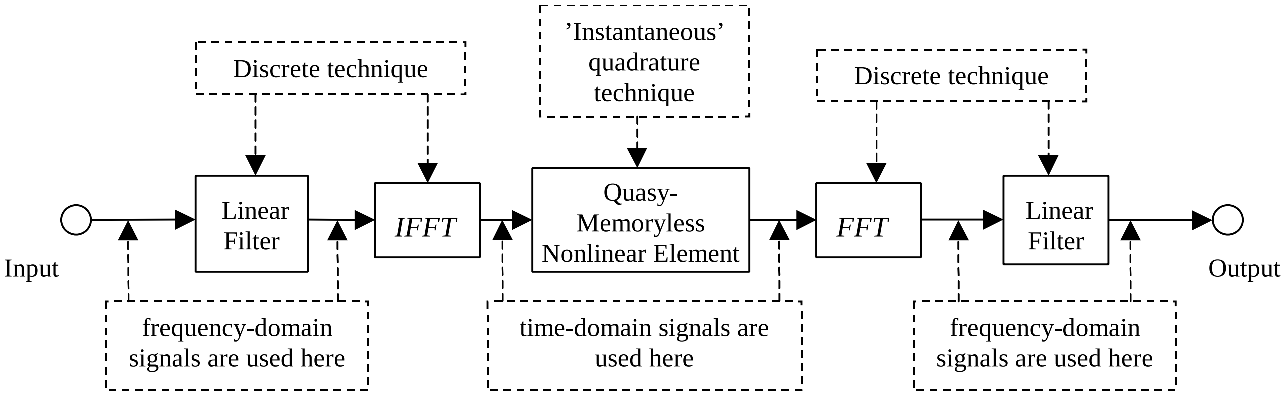

Figure 2. Simulating a single-stage radio amplifier by the 'instantaneous' quadrature technique.

point matching technique, the matrices of these equations appear to be upper triangular ones, so the systems of linear equations can be solved analytically.

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. 4 shows IMPs simulated by our technique (solid line), measured (squares, (a)) and simulated by harmonic-balance technique (squares, (b)). One can note quite a good agreement between behavioral-level simulation from one side, and measurements and harmonic-balance simulation on the other side. In general, the discrepancy is about few dBs except for some special areas, which should be further investigated. Fig. 5 shows harmonics simulated by our technique (solid line), measured (squares, (a)) and simulated by harmonic-balance technique (squares, (b)). There is also quite good agreement between behavioral-level simulation and measurements and harmonic-balance simulation. 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.

V. The use of the 'instantaneous' quadrature technique for the active array analysis:

The 'instantaneous' quadrature technique uses advantages of both techniques it is comprised of. It can predict both AM-AM and AM-PM conversion over a wide frequency range and over a wide dynamic range, taking into account frequency dependence of the characteristics. Thus far, a large active antenna array having a complex structure (for example, a DBF array whose every channel includes in fact its own receiver) can be analyzed on a PC in a reasonable time taking into account (a) nonlinearity in amplifier and mixers, including harmonics, intermodulation products, spurious responses of receivers, (b) frequency responses of filters and matching networks, (c) complex spectrum of real-world signals, (d) presence of complex-spectrum interfering signals, (e) characteristics of radiating structures using an electromagnetic simulator.

(a) **(b)**

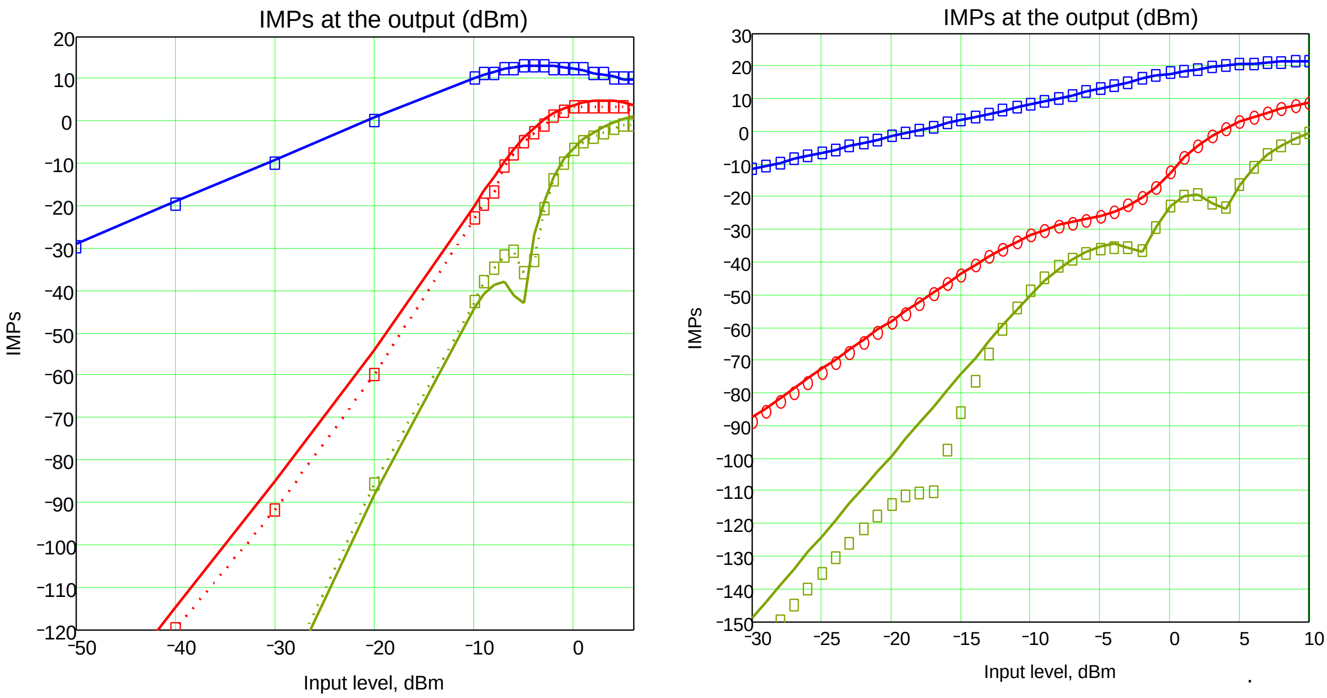

Figure 4. (a) fundamental, 3rd and 5th order IMPs (solid line – simulated, squares – measured) for 2 stage MMIC amplifier; (b) fundamental, 3rd and 5th order IMPs (solid line – behavioral-level simulation, squares – Harmonic Balance simulation) for single-stage microwave transistor amplifier.

(a) **(b)**

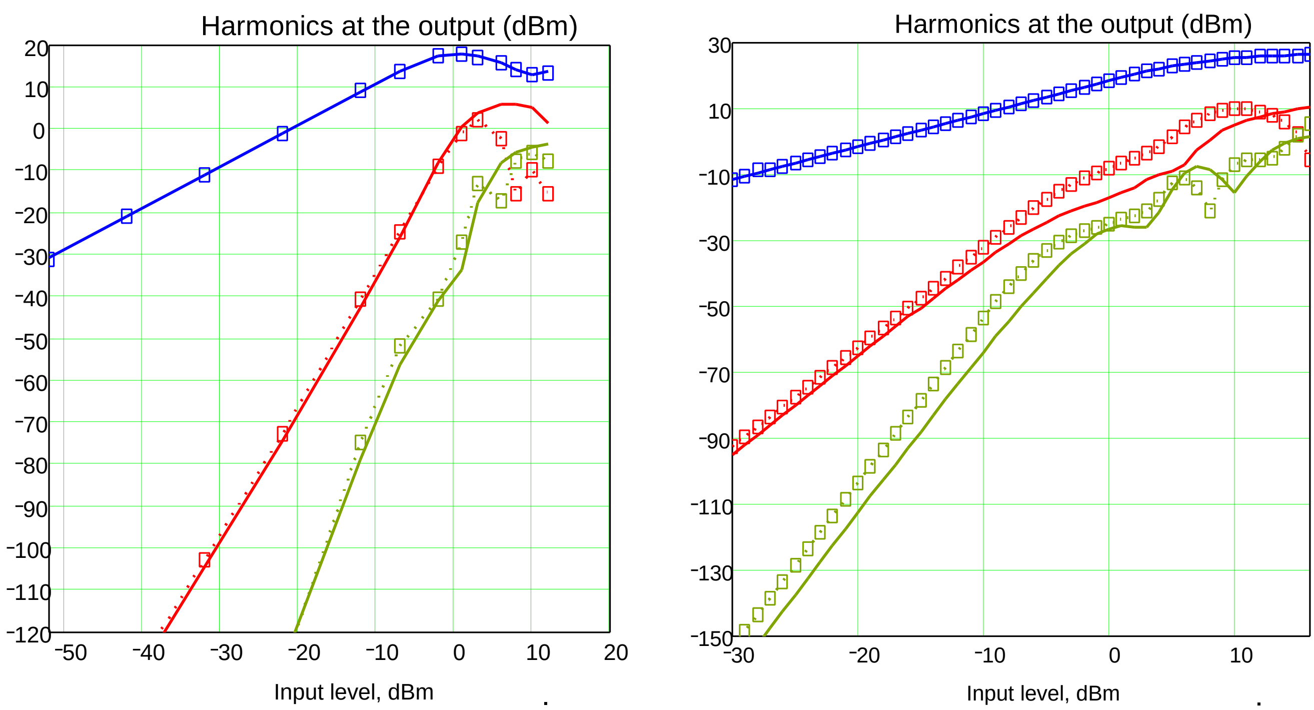

Figure 5. (a) fundamental, 3rd and 5th harmonics (solid line – simulated, squares – measured) for 2 stage MMIC amplifier; (b) fundamental, 3rd and 5th harmonics (solid line – behavioral-level simulation, squares – Harmonic Balance simulation) for single-stage microwave transistor amplifier.

The instantaneous quadrature technique gives us the possibility to simulate such active array characteristics as the following: (a) array pattern at the fundamental frequency in large signal mode (beamwidth, direction, sidelobe level), (b) influence of an interfering signal on the array pattern at the fundamental frequency, (c) array patterns at intermodulation frequencies (beamwidths, number of main intermodulation beams and their directions, sidelobe levels), (d) such phenomena as desensitization, local oscillator noise conversion and cross-modulation should can also be studied.

The identification of nonlinear interference sources is also possible [31]. Multi-level simulation can be carried out using the instantaneous quadrature technique in a natural way (see, for example, Fig. 1). The instantaneous quadrature technique requires more computational resources as compared to the quadrature technique since signal sampling as done at the carrier frequency. Nevertheless, computational resources required are not so high as for circuit-level simulators (using harmonic balance, for instance) or some hybrid techniques that also use circuit-level simulation.

VI. New Bell Labs Layered Space-Time (BLAST) architecture & active array simulation:

New Bell Labs Layered Space-Time (BLAST) architecture of a communication system proposed recently [44, 45] allows tremendous increase in the channel capacity as compared to the traditional one that is limited by well-know Shannon's limit. Hundreds of bits/Hz/second capacity is expected (as compared to few bits/Hz/second offered by traditional approaches) when multi-element array antennas are used. Block diagram of such a system is shown on Fig. 6. Its main idea is to split between channels not only the carrier but also the information (thus, each channel transmits its own information bits). Fig. 7 shows the channel capacity for a traditional system with antenna array and for BLAST architecture.

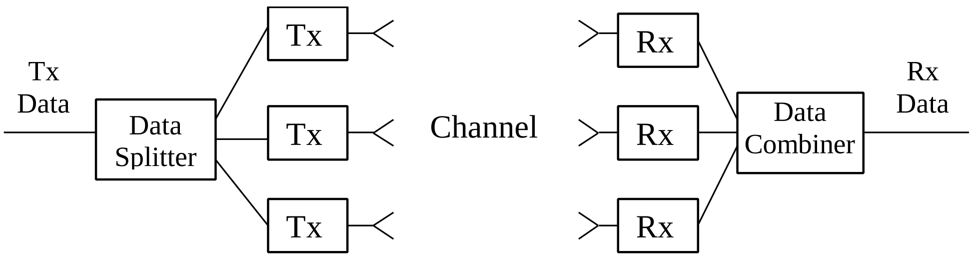

Figure 6. Bell Labs Layered Space-Time communication architecture.

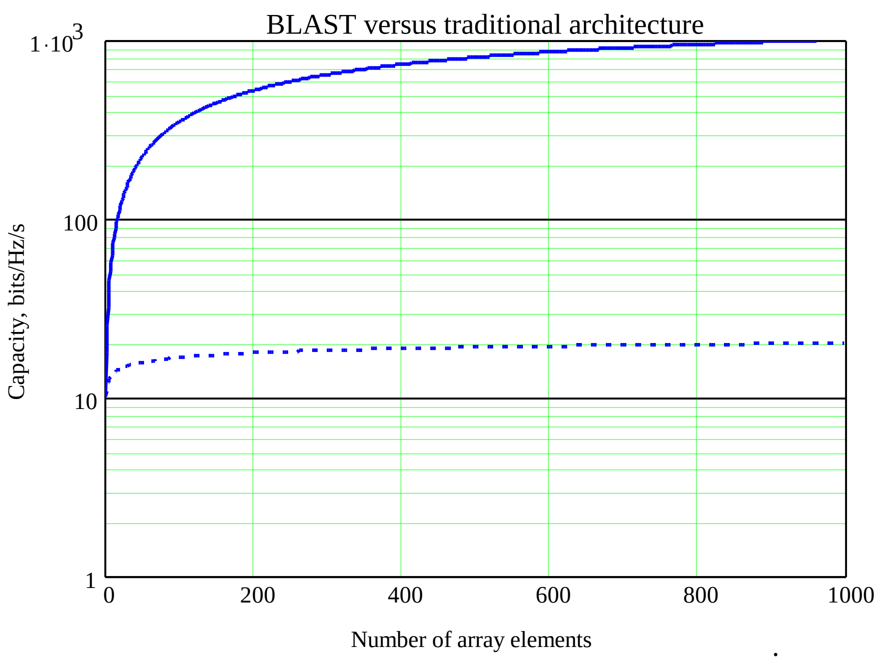

Figure 7. BLAST channel capacity (solid line) versus traditional channel capacity (dashed line).

Such a tremendous increase in the channel capacity will stimulate in future, without any doubts, widespread use of such systems. At the same time, as one may see from Fig. 6, BLAST architecture relies substantially on active array technology (it is impossible in principle to use a passive array for such an architecture) and works in multi-signal and multipath environment where the potential for interference in active elements is very big. Thus, special attention must be paid to nonlinear behavior of active elements in the design process. Behavioral-level simulation techniques seem to be a very effective design tool in such a case, especially when used together with hybrid multi-level analysis approach (see Fig. 1).

VII. Conclusion:

Active array antennas find increasingly wider applications due to a number of advantages they offer as compared to passive antennas, especially in microwave and millimeter wave frequencies. However, they suffer from electromagnetic interference and distortions that can degrade the overall system performance dramatically. Analytical techniques were used in the past for the analysis of active array antennas. Many interesting results were obtained using these techniques. Presently, numerical techniques are widely used for this purpose, which can provide more robustness and better accuracy. Behavioral-level simulation techniques were considered in detail. The "instantaneous" quadrature technique was proposed as an computationally-effective tool for simulation of active array antennas over wide frequency and dynamic ranges. Development of a multi-level simulation technique, which could combine electromagnetic, circuit and system-level analysis methods, is strongly desirable.

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References:

[1] D. I. Voskresenskij, V. L. Gostyuhin, K. G. Klimachev, "On-board solid-state active phased arrays," Izvestia Vuzov. Radioelectronica (Radioelectronics and Communications Systems, Allerton Press Inc.), 31, 2, 1988, pp.4-14.

[2] C. W. Pobanz, T. Itoh, "Active integrated antennas," in W.R. Stone (ed.), The review of radio science 1993-1996, Oxford University Press, 1996, pp.305-333.

[3] Proceedings Of ESA Workshop on Active Antennas (COST Action 245), 27-28 June 1996, Noordwijk, The Netherlands.

[4] J. Litva, T. K.-Y. Lo, Digital Beamforming in Wireless Communications, Boston, Artech House, 1996.

[5] E. Brookner, "Major advances in phased arrays: parts I and II," Microwave Journal, 40, 5&6, 1997, pp. 288-294&84-92.

[6] L. C. Godara, "Application of antenna arrays to mobile communications, part I: performance improvement, feasibility, and system considerations," Proc. of IEEE, 85, 7, July 1997, pp.1031-1060.

[7] Proceedings of Workshop on Smart Antenna Design and Technology (COST Action 260), Dubrovnik, Croatia, 11-12 Dec. 1997

[8] N. Fourikis, Phased Array-Based Systems and Applications, New York, John Wiley & Sons, 1997.

[9] M. Reudink, "Cellular network design and smart antenna systems," Proceedings of 1998 IEEE Radio and Wireless Conference (RAWCON'98), Colorado Springs, CO, Aug. 9-12, 1998, pp.19-22.

[10] P. S. Hall, "Progress in active integrated antennas," Proceedings of 28th European Microwave Conference, 6-8 Oct., Amsterdam, 1998, pp.735-740.

[11] Proceedings of 1998 Int. Symp. On Advanced Radio Technologies, Boulder, CO, Sep. 9-11, 1998.

[12] 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.

[13] S. A. Maas, Nonlinear Microwave Circuits, Norwood, MA, Artech House, 1988.

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

[15] F. M. Gardner, J. D. Baker, Simulation Techniques: Models of Communication Signals and Processes, New York, John Wiley & Sons, 1997.

[16] T. A. Fjeldly, T. Ytterdal, M. Shur, Introduction to device modeling and circuit simulation, New York, Wiley & Sons, 1998.

[17] I. Ya. Kremer, V. I. Vladimirov, V. I. Karpuhin, Modulating Interference and Radio Signal Reception, Moscow: Sviaz, 1972.

[18] W. A. Sandrin, "Spatial distribution of intermodulation products in active phased array antennas", IEEE Transactions on Antennas and Propagation, 21, 11, Nov. 1973, pp.864-868.

[19] S. C. Iglehart, "Noise and spectral properties of active phased arrays", IEEE Transactions on Aerospace and Electronic Systems, 11, 6, Nov. 1975, pp.1307-1315.

[20] A. S. Acampora, "Digital error rate performance of active phased array satellite systems," IEEE Transactions on Antennas and Propagation, 26, 6, Nov. 1978, pp.833-842.

[21] K. G. Johannsen, "Scan beam antenna intermodulation improvement due to spatial dispersion", IEEE Transactions on Aerospace and Electronic Systems, 23, 4, July 1987, pp.543-557.

[22] Ya. S. Shifrin, A. I. Luchaninov, "The theory of antennas with nonlinear elements: state-of-the-art," Izvestia Vuzov. Radioelectronica (Radioelectronics and Communications Systems, Allerton Press Inc.), 39, 9, 1996, pp.5-16.

[23] S. L. Loyka, "Characteristics of receiving intermodulation channel of active array antennas," International Journal of Electronics, 80, 4, 1996, pp. 595-602.

[24] S. L. Loyka, "Influence of Pilot Signal on Directivity of Self-Phased Arrays Under Conditions of Multipath Propagation," IEEE Transactions on EMC, 40, 1, 1998, pp.12-18.

[25] H. Xue, M. Beach, J. McGeehan, "Non-linearity effects on adaptive antennas", IEE International Conference On Antennas and Propagation, 4-7 April 1995, pp.352-355.

[26] H. Xue, M. A. Beach, J. P. McGeehan, "Linearised transceivers for mobile communications base stations using adaptive array antennas", IEE Conference On Radio Receivers and Associated Systems, 26-28 Sep. 1995, pp. 208-211.

[27] P. V. Brennan, "An experimental and theoretical study of self-phased arrays in satellite mobile communications," IEEE Trans. on Antennas and Propagation, 37, 11, Nov. 1989, pp.1370-1376.

[28] J. F. Sevic, M. B. Steer, A. M. Pavio, "Nonlinear analysis methods for the simulation of digital wireless communication systems," Int. Journal of Microwave and Millimeter-Wave Computer-Aided Engineering, 6, 3, 1996, pp.197-216.

[29] J. Staudinger, "Applying the Quadrature Modeling Technique to Wireless Power Amplifiers," Microwave Journal, 40, 11, Nov. 1997, pp.66-86.

[30] S. L. Loyka,. V. I Mordachev, "Computer-aided nonlinear simulation at the system level," Proc. of 5th Int. Conf. on EMC/EMI (INCEMIC'97), Hyderabad, India, Dec. 3-5, 1997, pp. 93-98.

[31] S.L. Loyka, V. I. Mordachev, "Identification of Nonlinear Interference Sources with the Use of the Discrete Technique," IEEE Int. Symp. on EMC, Denver, Colorado, Aug. 24-28, 1998, pp.882-887.

[32] I.D. Cheremisinov, S.L. Loyka, Polynomial Models of Radio System Nonlinear Stages for the Discrete EMC Analysis, 8th International Crimean Conference "Microwave & Telecommunications Technology" (CriMiCo 98), Crimea, Ukraine, Sep. 14-17, 1998, pp.408-409.

[33] I.D. Cheremisinov, S.L. Loyka,. V.I. Mordachev, Synthesis of the polynomial model of nonlinear elements based on intermodulation dynamic ranges, Proc. of 3rd Inter. Confer. on Telecommunications in Modern Satellite, Cable and Broadcasting Services (TELSIKS'97), Oct. 8-10, Nis, Yugoslavia, 1997, pp. 519-522.

[34] S.L. Loyka, A Canonical Representation of Nonlinear Transfer Functions for Behavioral-Level Simulation, to be published

[35] S.L. Loyka, New Method for Nonlinear Transfer Function Approximation, Electronics Letters, vol. 35, No. 10, 13th May 1999, pp.789-791.

[36] I.D. Cheremisinov, S.L. Loyka, Estimation of FFT aliasing impact on the accuracy of discrete EMC analysis, Intern. Conference on New Information Technologies for Science and Industry, 24-27 Nov., Minsk, Belarus, 1998.

[37] I.D. Cheremisinov, S.L. Loyka, 2D polynomial models of mixers and analog multipliers for discrete EMC analysis, Intern. Conference on New Information Technologies for Science and Industry, 24-27 Nov., Minsk, Belarus, 1998.

[38] S.L. Loyka, Nonlinear EMI Simulation of an AM-Detector at the System Level, IEEE Trans. on EMC, 1998, submitted for publication

[39] S.L. Loyka, Detector Simulation with the Use of the Discrete Technique, 14th Intern. Wroclaw Symp. on EMC, Poland, Wroclaw, June 23-25, 1998, pp.311-315.

[40] S.L. Loyka, Simple Formula for AM-Detector Transfer Factor, Electronics Letters, vol.35, No. 2, pp.126-127, 21st Jan. 1999

[41] S.L. Loyka, Numerical Simulation of Nonlinear Interference in Radio Systems (Invited paper), the 26th URSI General Assembly, Aug. 1999, accepted for presentation.

[42] S.L. Loyka, A New Behavioral-Level Simulation Technique for RF/Microwave Applications, to be published.

[43] P. Howard, W. Slingsby, Linear amplifiers for adaptive antenna basestations, Microwave Engineering Europe, April 1999, pp.35-40.

[44] P.W. Wolniansky, G.J. Foschini, G.D. Golden, R.A. Valenzuela, V-BLAST: An Architecture for Realizing Very High Data Rates over the Rich-Scattering Wireless Channel (Invited paper), Proc. ISSSE-98, Pisa, Italy, Sep. 29, 1998.

[45] G.J. Foschini, M.J. Gans, On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas, Wireless Personal Communications, vol. 6, No. 3, March 1998, pp. 311-335.