# The Influence of Electromagnetic Environment on Operation of Active Array Antennas: Analysis and Simulation Techniques

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Keywords: Active arrays; active antennas; multibeam antennas; beam steering; array signal processing; phased arrays; communication system nonlinearities; nonlinear systems; simulation

## 1. Abstract

This paper presents an overview of active array antennas, system-level nonlinear effects in such antennas, and their modeling and simulation techniques. Advantages of active array antennas, in comparison with passive array antennas, are discussed. The influence of nonlinear distortions and interference in active antennas on the overall system performance is considered. Modeling and simulation techniques that can be applied to active array antennas are substantially different from those used for circuits and systems. Analytical and numerical techniques are used for the analysis of active antennas, with the prevailing use of numerical techniques at the present time. Electromagnetic-level and circuit-level simulation techniques are briefly discussed. System-level simulation techniques are considered in detail, with special emphasis on their application to active array antennas. The "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.

## 2. 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. A clear indication of this change is given by review papers on antenna arrays [1-4, 6, 7]. Whereas there is no mention of active arrays (only linear electromagnetic analysis, feeding systems design, etc.) in the first paper, there is some consideration of active arrays in the second one, and there are extensive discussions of active array theory and technology in the others. In general, active antennas remain an area of great innovation, and will remain so in the foreseeable future [3-15]. Integration of active circuitry into antennas gives a lot of advantages in comparison with conventional antennas, especially at microwave and millimeter-wave frequencies [5-14]:

- Active circuitry used within antennas can compensate for increased losses, parasitic coupling, and leakage phenomena at higher frequencies, and can also increase antenna bandwidth and improve impedance matching.
- Active receiving antennas can substantially improve system frequency response and sensitivity due to a reduction in the feed-line loss and, consequently, in the noise temperature, and due to improvement in impedance matching. Using quasi-optical mixers can also reduce conversion loss in heterodyne receivers. Size reduction can also be obtained.
- 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. The efficiency of such combining is much higher than that of waveguide combiners.
- Using active circuitry in large phased arrays can eliminate the need for a complex RF-distribution network, a large number of

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phase shifters, and complicated control electronics. Examples are self-phased and phase-shifter-less arrays that provide a number of advantages when compared to conventional beam-steering techniques [76, 99-105].

- Adaptive antennas that use active circuitry are now utilized in a wide range of applications [9,10,14-25].

- Antenna arrays find increasingly wider application in mobile communications [16, 17, 28-30]. 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. Antenna arrays provide a number of advantages as compared to using a conventional antenna: an increase in channel capacity and spectrum efficiency, a reduction in co-channel interference, delay spread and multipath fading, an improvement in bit-error rate, an increase in transmission efficiency (a reduction in transmitter power or an increase in the service range), and a reduction in outage probability, in handoff rate, and in crosstalk. They also allow one to make dynamic channel assignments and cost-effective implementation. Most of the antenna arrays used for mobile communication applications use active circuitry and, thus, are active arrays.

- The digital beam-forming technique is also very promising, including its use in mobile communications applications [24-34]. The concept of a smart antenna has been introduced, and a lot of research work is being done in this area [36, 37]. Both types of antennas make extensive use of active circuitry.

- Presently, MMIC technology has given a great impulse to the development of active arrays and their implementation in everyday life, as opposed to only military or scientific applications [10-14]. MMIC realization of antenna modules greatly reduces cost, weight, and size, and increases reliability.

As with 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, with parameters that are independent of the electromagnetic environment, interfering signals impinging upon an active antenna can degrade such parameters 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 [28, 38-40]:

- Harmonic generation
- Intermodulation
- Cross-modulation
- Desensitization
- Gain compression/expansion
- Local oscillator harmonics and noise conversion
- Spurious responses 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 this is now quite an established field [38-61]. Both analytical and numerical techniques are now used for this purpose, with numerical techniques prevailing. Such novel concepts as neural networks and genetic algorithms have actively been used in this area, recently [62-65]. A number of software analysis and simulation packages are commercially available [67-69]. At the same time, methods of analysis and simulation for 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 [14, 69-98].

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 [8]. 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 could be split into the antenna analysis and the Rx/Tx circuit analysis. Look at textbooks: they are split into antenna textbooks and Rx/Tx circuit textbooks. Thus, an antenna engineer analyzes the antenna and a circuit engineer analyzes the receiver/transmitter (see Figure 1). And what happens with active arrays? Since an active array cannot be separated into a passive antenna and active circuitry, the antenna engineer and the circuit engineer must work together (see Figure 2).

The analysis of nonlinear circuits mainly uses Kirchhoff's laws and the lumped-circuit approximation. Radiation effects are ignored. To the contrary, antennas are spatially-distributed structures, and radiation effects are of great importance for them. One cannot ignore 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,

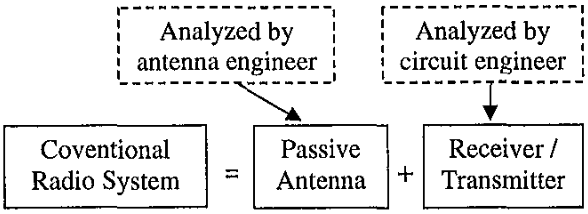

**Figure 1. The analysis of a conventional radio system (with a passive antenna).**

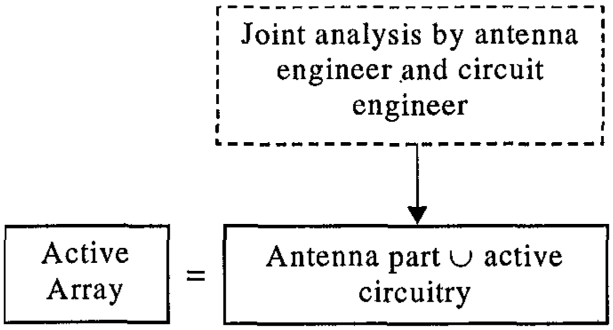

**Figure 2. The analysis of an active array.**

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. Section 3 gives a brief introduction to active arrays currently used in radar and communication applications. Section 4 outlines active array analysis methods. Section 5 discusses some nonlinear effects that are specific to active array antennas, and corresponding analytical and semi-analytical models. Section 6 describes two well-known numerical-behavioral-level simulation techniques–the quadrature technique and the discrete technique, as well as their advantages and drawbacks–and proposes a third one: the "instantaneous" quadrature technique, which is a combination of the two previous techniques. Section 7 discuses the use of the instantaneous quadrature technique for the nonlinear simulation of active array antennas.

### 3. A brief introduction to active arrays

There are many types of active array antennas that are currently used in radar and communication applications. Here, we outline the structures (or block diagrams) of some of them. Block diagrams are very important for modeling and simulation at the behavioral level that is described below. We will consider mainly receiving arrays, but the same principles can be applied to transmitting arrays.

### 3.1 Simple receiving active phased array

The block diagram of this array is different from that of a conventional phased array, in that low-noise amplifiers are used in each channel [6, 25] (see Figure 3). Channel signals are first amplified, before the phase shifters and combiner, to compensate for network losses. This provides a better noise performance and impedance matching, and a wider frequency band, as compared to the conventional phased array.

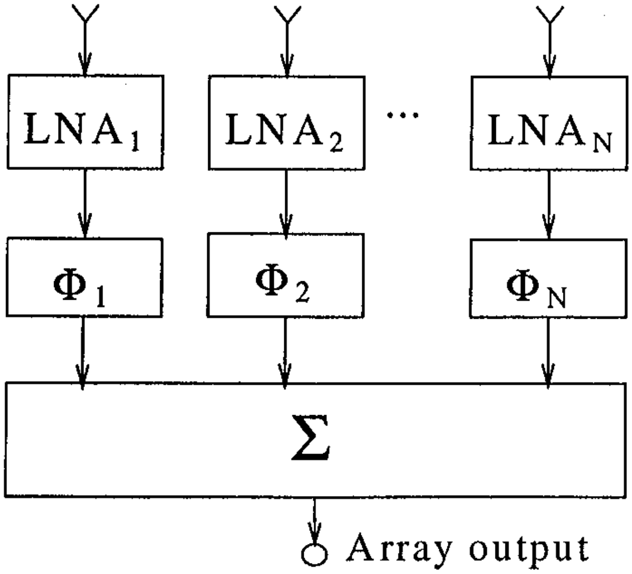

**Figure 3. A block diagram of a simple active-phased-array: $A_1$–$A_N$ are low-noise amplifiers; $\Phi_1 - \Phi_N$ are phase shifters; $\Sigma$ is the combiner.**

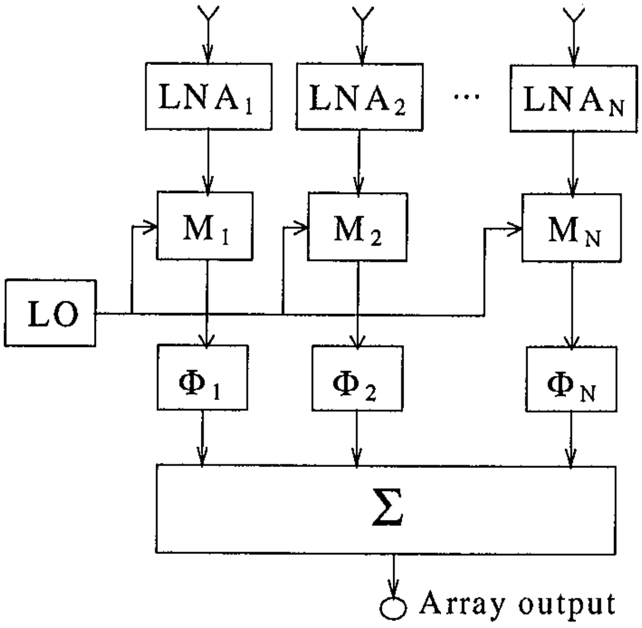

**Figure 4. An active phased array with IF combining: $A_1$–$A_N$ are low-noise amplifiers; $M_1$–$M_N$ are mixers; LO is the local oscillator; $\Phi_1 - \Phi_N$ are phase shifters; $\Sigma$ is the combiner.**

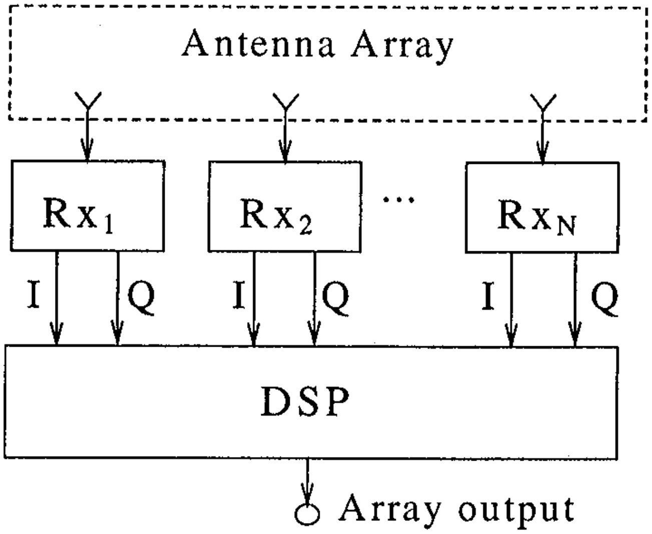

**Figure 5. A block diagram of a DBF array: $Rx_1$–$Rx_N$ are receivers; DSP is the signal processor; and I and Q denote the in-phase and quadrature signals.**

### 3.2 Active receiving array with combining at the intermediate frequency

In this array, the signal is down-converted prior to being fed to the phase shifters and the combiner (see Figure 4). Thus, all the feed network operates at a lower frequency (IF instead of RF), which simplifies the feed-network design and reduces losses. LNAs [low-noise amplifiers] can be excluded from the block diagram or, alternately, can be inserted after mixers, thus operating at the intermediate frequency. Active phased arrays of other kinds are also used for many applications [22-27].

### 3.3 Digital beam-forming array

A digital beam-forming (DBF) array is an integration of antenna technology with digital-signal-processing (DSP) technology. Digital beam-forming allows one to use not only frequency-domain or time-domain signal processing, but also spatial-domain processing. In general, a DBF array (see Figure5) consists of three main components: the antenna array, the digital receivers (or transmitters, in the case of a transmitting array), and the digital signal processor [25-29].

In the digital beam-forming array, the incoming signals are received, detected, and transformed into digital form at each array channel. The digital signal processor is used to extract the spatial-domain data from the incoming signals.

This technology has a lot of advantages when compared to conventional phased arrays [28-34]:

- A number of independent beams can be formed without degradation in signal-to-noise ratio
- All of the information arriving at the array is accessible to the signal processor
- Beams can be assigned to individual users
- Adaptive beam-forming can be easily implemented with improved adaptive nulling
- Real-time antenna-system calibration can be implemented, resulting in ultra-low sidelobes
- The beam-former algorithm can be easily upgraded by changing software

We further consider a number of receiver structures used in DBF arrays [28-34].

### 3.3.1 Single-conversion receiver

In this receiver (see Figure 6), the incoming signal is amplified by a LNA, and down-converted directly to baseband by two mixers ($M_I$ and $M_Q$). Two channels are used, in-phase and quadrature-phase channels, in order to process phase as well as amplitude information. After the mixers, baseband signals are filtered by low-pass filters, and amplified by video amplifiers up to a level sufficient for analog-to-digital converters.

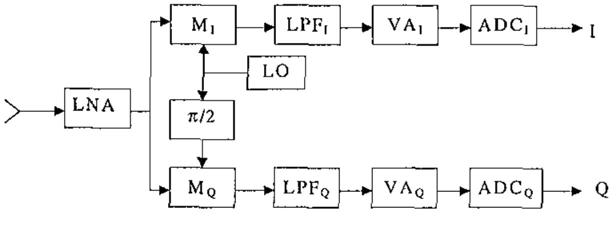

**Figure 6. A block diagram of a single-conversion receiver: LNA is the low-noise amplifier; M denotes the mixers; LO is the local oscillator; LPF denotes the low-pass filters; VA denotes the video amplifier; ADC denotes the analog-to-digital converter; and I and Q denote the in-phase and quadrature signals.**

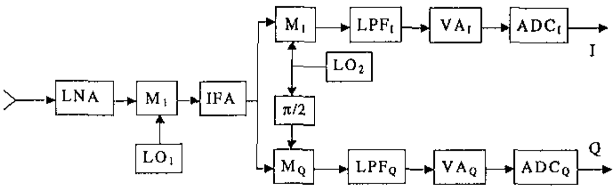

**Figure 7. A block diagram of a double-conversion receiver (the notation is the same as in the caption of Figure 6).**

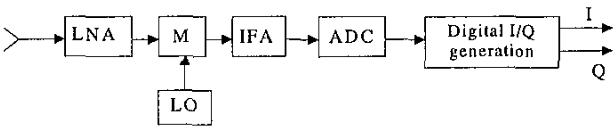

**Figure 8. A block diagram of an IF sampling receiver (the notation is the same as in the caption of Figure 6).**

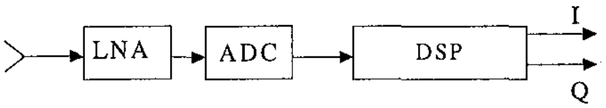

**Figure 9. A block diagram of a software receiver (the notation is the same as in the captions of Figure 5 and 6).**

### 3.3.2 Double-conversion receiver

The primary difference presented by this receiver (see Figure 7), as compared to the previous one, is the use of an IF chain. The incoming signal is down-converted to IF and amplified by an IF amplifier, prior to down-conversion to baseband. The performance of this receiver is much better than the previous one [28].

A triple-conversion receiver allows one to further improve the performance. Nevertheless, all these receivers have a common deficiency: pure match and performance of I/Q channels that deteriorates the overall array performance dramatically. Thus, an IF-sampling receiver structure has been introduced, in order to overcome this drawback.

### 3.3.3 IF sampling receiver

In this receiver (see Figure 8), analog-to-digital conversion is made at the intermediate frequency, so that converting the signal to baseband is performed in the digital domain. Digital coherent phase detection is used to generate I/Q signals and, thus, the I/Q channel-matching problem is overcome.

### 3.3.4 Software receiver

The software-receiver architecture has become very popular in recent times [30, 35]. In a software receiver (see Figure 9), analog-to-digital conversion is used as close to the antenna as possible. Thus, all RF and IF signal processing and coherent detection are made in the digital domain, using special software for DSP. This allows for increased flexibility, multi-band and multimode operation, etc. However, it requires very high speed analog-to-digital conversion. High-speed digital signal processors are also required for practical realization of the software-receiver structure.

### 3.4 Self-phased arrays

Another kind of active array with signal processing is a self-phased array [22, 76, 99-105]. The use of a self-phase structure gives many advantages, in particular because there is no need for phase shifters and complicated control electronics, since array phasing is done using analog signal-processing techniques. Here, we consider only some of the self-phased array structures.

### 3.4.1 Self-phased array using a pilot signal

The block diagram of this array is shown in Figure 10. It consists of antenna elements, self-phasing units, and a summer. A self-phasing unit structure is shown in Figure 11. Thus, the only difference from the conventional phased array structure is that self-phased units are used instead of phase shifters. The principle of the self-phased array operation is that a one-tone pilot signal is radiated on the transmitting side, together with the primary signal. A mixer is used in the self-phasing unit in order to down-convert the primary signal to an intermediate frequency that is equal to the difference between the primary and pilot signal frequencies. Thus, channel signal combining is done at the intermediate frequency. But phases of IF signals in all channels are equal, because the primary and pilot signals travel the same path, and their frequencies are chosen to be close [76, 100]. Thus, array phasing is done automatically, without any need for phase shifters and control electronics.

Unfortunately, the performance of the simple self-phasing unit shown in Figure 11 is not very good. Besides, the pilot signal amplitude must be large enough to make the mixer operate properly. So, a more-complicated scheme, shown in Figure 12, is used [76]. A voltage-controlled oscillator is used in this unit, in order to generate the pilot signal used in the mixer for conversion to IF. A phase-locked loop is used, in order to control the pilot-signal phase, and to improve the noise performance (the bandwidth of the phase-locked loop is chosen to be very narrow). The noise performance of this scheme is reported to be much better than that of the previous one [76].

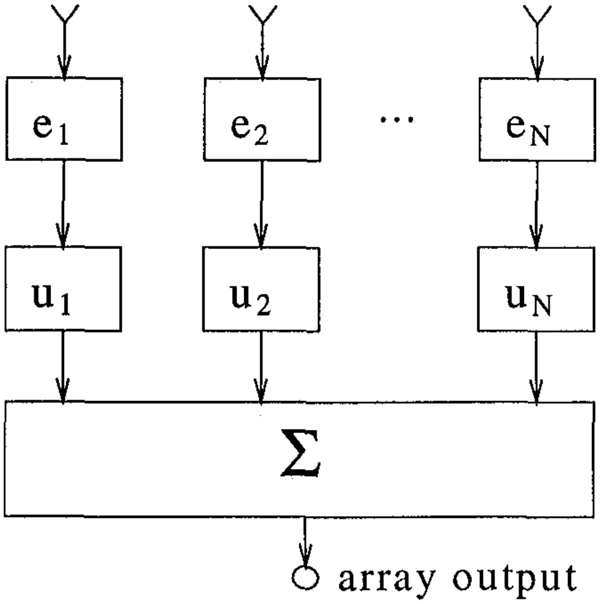

**Figure 10. A block diagram of a self-phased array: $e_1$–$e_N$ are the antenna elements; $u_1$–$u_N$ are the self-phasing units; and Σ is the summer.**

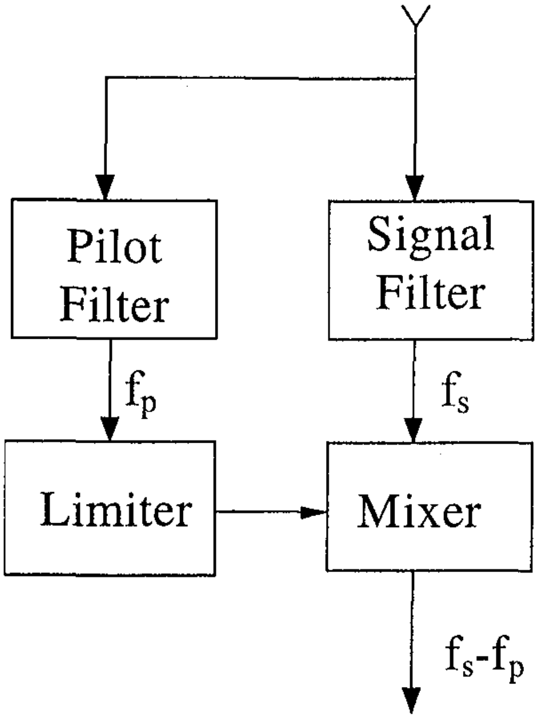

**Figure 11. The self-phasing unit structure: $f_s$ and $f_p$ are the primary signal and pilot frequencies.**

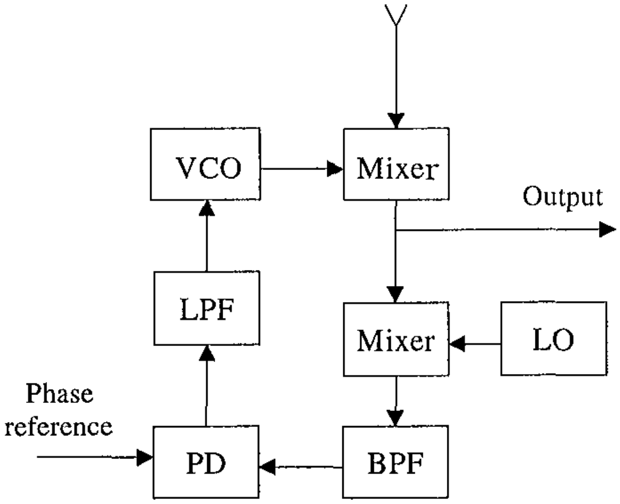

**Figure 12. A more-advance structure for the self-phasing unit: VCO is the voltage-controlled oscillator; LPF is the low-pass filter; BPF is the bandpass filter; PD is the phase detector; and LO is the local oscillator.**

### 3.5 Simple two-element adaptive antenna

A wide variety of adaptive antennas is presently used in different applications, in order to improve the system performance

[11, 12, 18-26]. Since the number of specific structures is almost countless, we consider here a simple two-element structure, in order to demonstrate how active elements are implemented there.

The block diagram of a simple adaptive antenna is shown in Figure 13 [26]. It consists of elementary antennas, two mixers and low-pass filters, a phase shifter and attenuator, and a summer. Two mixers and low-pass filters are used in order to calculate the correlation between the output and the second elementary-antenna output, and to control the attenuator and phase shifter. These are used to suppress the strong interfering signal at the first elementary-antenna output by subtracting the output signal of the second antenna with corresponding attenuation and phase shift. Analog signal-processing circuitry can be used instead of the attenuator and the phase shifter. Down-conversion to IF can be used in each elementary-antenna channel [23].

### 3.6 BLAST architecture: new technology of wireless communications

The new Bell Labs Layered Space-Time (BLAST) architecture of a communication system, proposed recently [127-129], allows a tremendous increase in the channel capacity in a rich multipath environment. Hundreds-of-bits/Hz/second capacity is expected (as compared to a few bits/Hz/second, offered by traditional approaches) in certain applications (indoor communication, local-area networks, etc.), when multi-element antenna arrays are used. A block diagram of such a system is shown in Figure 14. The main idea is to split not only the carrier but also the information (and thus, each channel transmits its own information bits) between channels, and to exploit rather than suppress multipath propagation in this way. This system uses signal processing very effectively, not only in time dimension, but also in the spatial dimension. Such a tremendous increase in the channel capacity will stimulate widespread use of such a system in the future, without any doubts.

As one can see from Figure 14, the BLAST architecture relies substantially on active-array technology (it is impossible, in principle, to realize such a system using passive arrays), and operates in a rich multi-signal and multipath environment. Thus, the linearity requirement for the receive and transmit paths must be very high, in order to avoid system performance degradation due to their nonlinear behavior.

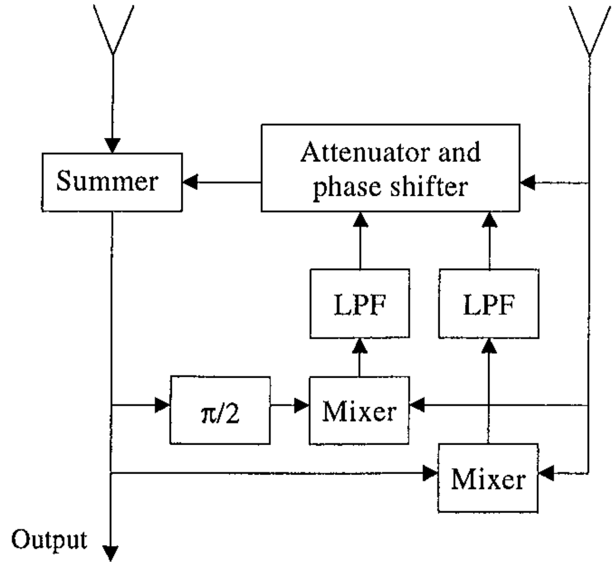

**Figure 13. A block diagram of a simple two-element adaptive antenna.**

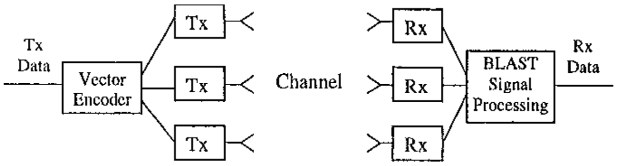

**Figure 14. The Bell Labs Layered Space-Time (BLAST) architecture.**

As we can see from the considerations given above, a lot of active circuitry is used in antenna arrays, in order to improve their performance. Active circuitry is integrated into the antenna structure in such a way that it is inseparable from the entire antenna structure, and must be analyzed together with the antenna. Appropriate analysis methods should be used for the modeling and simulation of such antennas.

## 4. 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 [38-65, 69-116]. In general, all analysis methods that can be applied to active array antennas can be divided into two large groups:

1. Analytical methods

2. Numerical methods

### 4.1 Analytical methods

Before computers were introduced into everyday engineering practice, analytical methods were extensively used [1, 38-40, 49, 50, 69-75, 98, 99]. Presently, their range of applications is comparatively small, but, nevertheless, they are still used for some problems [38, 48, 76, 77, 79, 80, 83, 85-88, 90, 91, 94, 95, 111]. Analytical methods have some advantages over numerical methods:

- They give insight into the system behavior
- They give understanding of fundamental processes that determine the system operation
- They allow one to interpret experimental or numerical results
- They give a general view of the situation within a complex system
- They approximate analytical or semi-empirical methods and are simple and easy-to-use
- 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 is handled in its own way. Thus, numerical methods arise.

### 4.2 Numerical methods

A wide range of numerical methods is presently used for circuit/system and electromagnetic problems [40-48, 51-68, 72, 77, 78, 84, 89, 92, 93, 97, 106-116]. They have a lot of advantages. Some of these are:

- They are more up-to-date
- They can take into account more factors and phenomena
- They, in general, are more accurate (but there are some exceptions: some semi-empirical analytical methods may be more accurate)
- They can handle wider sets of particular system configurations in a uniform manner

But, they require many more computational resources and, consequently, complex systems cannot be analyzed, due to impracticably long analysis times, or due to extremely high requirements in computational power.

### 4.3 When to use analytical and numerical methods

Everybody should clearly understand which method he/she needs. Sometimes, simple analytical methods will 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.

The 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.

### 4.4 The use of numerical methods

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

a.) Those based on fundamental physical laws (Maxwell's equations, etc.) [107, 110-115]
b.) Those based on circuit theory [43, 44, 47, 48, 50, 52, 54, 58, 59, 62, 64, 65]
c.) System-level methods (or "black box," "input-output," or "behavioral" methods) [40-42, 51, 52, 55-57, 60, 61, 117-125]
d.) Multilevel (hybrid) methods that integrate several techniques at various levels [46, 72, 78, 89, 90, 92, 93, 97, 106, 108, 109]

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 this also works with some limitations, for the same reason: you can't model an entire mobile communication system (several thousands of subscribers) or a large active array using circuit-level methods (like *SPICE*). In this case, item "c" is required.

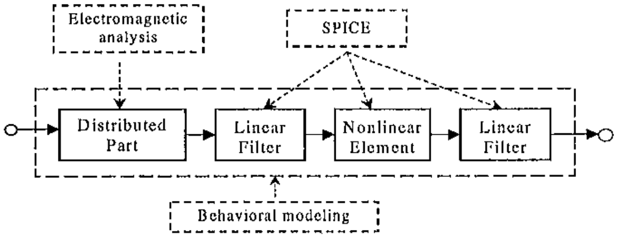

**Figure 15. An illustration of a hybrid multi-level analysis method.**

A combined usage of all of 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, the antenna-to-antenna coupling characteristic)
- Circuit simulators (like *SPICE*) 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

Figure 15 gives an illustrating example of the hybrid analysis method. This analysis method can also be referred to as macromodeling, because the entire system is modeled using black-box models that are built using electromagnetic and circuit-level simulation.

## 5. Nonlinear effects in active array antennas

As was mentioned in the Introduction, all the main types of nonlinear effects, which are present in active circuits, 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 multi-carrier communication systems that has been studied by analytical techniques is intermodulation generated by power-amplifier nonlinearities. This phenomenon has been mainly considered as applied to active transmitting arrays, but many conclusions drawn from these studies can be also applied to active receiving arrays (we should note that the direct application of all results is impossible, since the reciprocity principle doesn't hold for an active array).

The main results obtained in this area can be summarized as follows [69-71, 74-77, 83-88, 98, 126]:

1. Intermodulation-product (IMP) beams have a direction different from those of the main beams at fundamental frequencies, even if the IMP and fundamental frequencies are the same. The shape of these beams is determined by the shape of the main beams, the IMP frequencies, and the direction of IMP beams. Element-to-element variations in amplifier characteristics have, in general, a larger impact on IMP beams than on the main beam. For amplitude-modulated signals, IMP beams produced

by spectral components of the same signal have the same direction as the main-beam direction for this signal [69].

2. The width of an IMP beam is determined by the array geometry and excitation, the fundamental frequency, the IMP order, and the IMP beam direction. Several beams may exist for the same IMP in a receiving array. If no IMP beams exist in the visible region, the system-interference immunity greatly increases. The number of IMP beams and the conditions of their existence have been determined [85-88].

3. A statistical analysis of IMPs at the active array output shows that the instantaneous values of different IMPs are non-correlated random magnitudes, when two single-tone signals with independent initial phases, distributed uniformly on the interval $[-\pi, \pi]$, are at the array input. Thus, the output IMP noise power equals the sum of the powers of all IMPs [85, 88].

4. The spectral and noise properties of an active array differ fundamentally from those of a passive array. Additive random noise of array channels is radiated according to the element pattern, rather than according to the array pattern. Consequently, the noise density of the active array in the main lobe is considerably reduced as compared to the passive array, and is considerably higher in the far-sidelobe region for a low-sidelobe design. The array does not preserve its amplitude-modulated or phase-modulated character outside the main array lobe. In a pulsed system (radar), the line spectrum follows the array pattern for frequencies close to the carrier, but follows the element pattern for frequencies far from the carrier [70].

5. For multiple-beam satellite digital-communication systems, signal suppression and co-channel IMP interference in amplifiers may result in a 1-5 dB bit-error-rate degradation of the system performance, relative to that using a passive antenna [71].

6. For multiple-beam mobile satellite communication systems with frequency reuse, an average IMP noise reduction of several dB, compared to the single-beam single-amplifier case, can be achieved, due to spatial dispersion of the IMP beams [75, 126]. Comparing this with the previous item, we can conclude that the performance improvement depends dramatically on a particular system configuration and an analysis criterion.

7. In a DBF radar, the array nonlinear distortion signals can be reduced due to the array effect. Thus, the specifications of receiver nonlinearities can be relaxed [74].

8. The presence of external interfering signals results in an increase of the array beamwidth and sidelobe level [98].

Passive IMPs, generated by slight nonlinearities in the beamforming network or the multiplexer, can also substantially increase the noise level, degrading the overall system performance [83].

Nonlinear effects in amplifiers and mixers also have a large impact on the operation of adaptive antennas used in mobile communication applications [28, 80, 81]. The nonlinearity of active stages can result in sidelobe-level increase, null-depth decrease, and a change of null positions. Severe requirements on 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 [81]. Comparing this to item 7, we can conclude that the impact of active-stage nonlinearity on the overall system performance depends dramatically on a particular system type and configuration.

Multipath propagation may have a large impact on the self-phased array operation [76, 91, 94, 95]. In average, a 2 dB increase in the total effective array gain is possible (depending on the path-length difference), due to the coherent summation of the direct and reflected signals. However, a substantial decrease in the gain is possible in some particular cases.

Such nonlinear phenomena as harmonic radiation and oscillator phase noise have also been studied [14, 90].

## 6. Behavioral-level modeling techniques

Behavioral-level modeling techniques are currently very popular for modeling complex systems, for example, mobile communication systems with complex digital signals [40-42, 52, 63, 117-125]. Furthermore, we consider these techniques and their application to active array antennas.

Why behavioral modeling for active arrays? There are at least three 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 possible at all.

2. Second, 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 IMP level, second- and third-order intercept points, spurious-free dynamic range, etc. have been used for the characterization of the impact of nonlinearity on the analog system performance [38-40]. For modern digital systems, another set of parameters is used: spectral re-growth, adjacent-channel power ratio, error-vector magnitude, etc. [52, 117-119]. Consequently, simulation techniques must be capable of predicting these parameters. The computation time and computer resources for a circuit-level simulator would be unreasonable.

3. 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, since modeling the array alone may sometimes give incorrect results. An illustrative example is a wideband active array connected to a narrowband receiver. Spectral components outside the receiver's bandwidth don't degrade the overall system performance.

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 [40-42, 117, 118] and the discrete technique [121-124]. A joint use of both of them gives even more advantages. Since both these techniques are behavioral- (or system-) level techniques, they use a representation of the system by an equivalent block diagram, so they are so-called block-model techniques.

### 6.1 The quadrature modeling technique

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

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

where $A(t)$ and $\varphi(t)$ are an amplitude and a phase that vary slowly with respect to the carrier, and $\omega_0$ is the carrier frequency. Its complex envelope is

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

So, there is not any carrier information in the complex envelope, only modulation information. This is very important from the viewpoint of computational efficiency, but this also limits the technique's capabilities. Two terms on the right-hand side in Equation (2) constitute the in-phase and quadrature-phase low-pass signals:

$$X_I(t)=A(t)\cos\varphi(t),\ X_Q(t)=A(t)\sin\varphi(t). \qquad (3)$$

The output signal of a bandpass nonlinear stage is

$$y(t)=K\left[A_{in}(t)\right]A_{in}(t)\cos\left[\omega_0 t+\varphi_{in}(t)+\Phi(A_{in}(t)\right], \qquad (4)$$

where $A_{in}$ and $\varphi_{in}$ are the input amplitude and phase. A nonlinear stage is characterized by its amplitude- and phase-transfer factors:

$$K(A_{in})=\frac{A_{out}}{A_{in}},\quad \Phi(A_{in})=\varphi_{out}-\varphi_{in}. \qquad (5)$$

$K(A_{in})$ represents the AM-AM (amplitude-to-amplitude) conversion in the nonlinear elements, and $\Phi(A_{in})$ represents AM-PM (amplitude-to-phase) conversion. Note that both factors depend on the input amplitude, not on the instantaneous value of the signal. This is due to the bandpass representation of signals and system stages (actually, low-pass equivalents of both are used). Thus, Equation (5) constitutes the amplitude envelope nonlinearity.

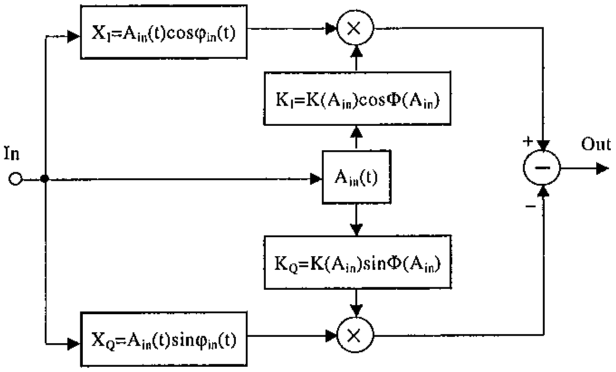

**Figure 16. A schematic diagram of modeling bandpass nonlinearity using a quadrature technique.**

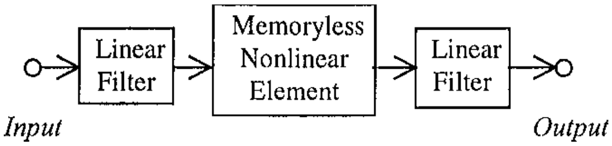

**Figure 17. A block diagram of a single-state radio amplifier in the discrete technique representation.**

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

$$\begin{aligned} K_I(A_{in})&=K(A_{in})\cos\Phi(A_{in}),\\ K_Q(A_{in})&=K(A_{in})\sin\Phi(A_{in}). \end{aligned} \qquad (6)$$

The output low-pass signal is expressed as

$$Y(t)=K_I(A_{in})X_I(t)-K_Q(A_{in})X_Q(t). \qquad (7)$$

The modeling process can be illustrated by the scheme shown in Figure 16. 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 also cannot take into account the frequency response of the system. Thus, some improvements are desirable. Such improvements will be discussed in Section 6.3.

### 6.2 The discrete technique

The basis of the discrete technique is a representation of the system block diagram as linear filters (LF) and memory-less nonlinear elements (MNE), connected in series (or in parallel, or both). For example, Figure 17 shows a single-stage radio amplifier represented in this way. Input and output filters can model input and output matching networks.

This representation reflects characteristic peculiarities inherent to the construction of typical amplifying and converting stages. The utilization of the model with memory-less nonlinearity is not a significant limitation of 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,

$$S_{out}(f_n)=S_{in}(f_n)K(f_n), \qquad (8)$$

where $S_{out}(f_n)$ is the signal spectrum at the filter output, $S_{in}(f_n)$ is the signal spectrum at the filter input, $K(f_n)$ is the complex transfer factor of the filter, and $f_n$ are sample frequencies. It is necessary to use an appropriate sampling technique in order to get a sampled spectrum.

The process of signal passage through a nonlinear memoryless element is simulated in the time domain using

$$u_{out}(t_k) = F\left[u_{in}(t_k)\right], \tag{9}$$

where $u_{out}(t_k)$ is the instantaneous value of the signal at the memory-less nonlinear element output, $u_{in}(t_k)$ is the same for the memory-less nonlinear element input, $t_k$ are sample points in time, and $F$ is the instantaneous transfer characteristic of the nonlinear element. Expansion in Chebyshev polynomials can be very effectively used for the approximation of the measured or circuit-level simulated transfer characteristic. Non-polynomial basis functions (Bessel functions) can also be used, but special measures must be taken in this case in order to avoid spectrum aliasing (due to using an FFT).

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). Figure 18 gives an illustration of the modeling process.

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 is desirable.

### 6.3 The combined "quadrature + discrete" ("instantaneous") technique

The main idea of the combined technique is to use advantages of both techniques. 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 the 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 using the 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.

Figure 19 gives an illustration of the modeling process. An illustration of the nonlinear element modeling is shown in Figure 20.

We should point out that amplitude (envelope) and instantaneous characteristics are not equal (there is some confusion about this issue in the literature):

$$k(x_{in}) \neq K(A_{in}), \quad \varphi(x_{in}) \neq \Phi(A_{in}). \tag{10}$$

A system of two integral equations gives relations between the amplitude and instantaneous characteristics:

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

Note that using Equation (11), only the even parts of $k_I$ and $k_Q$ 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, so the systems of linear equations can be solved analytically.

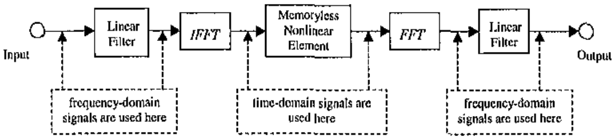

**Figure 18. A block diagram of modeling a broadband nonlinearity by the discrete technique.**

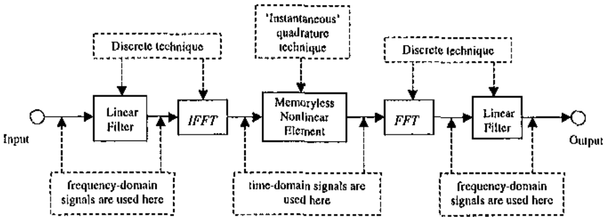

**Figure 19. A block diagram of modeling a single-state radio amplifier by the "instantaneous" quadrature technique.**

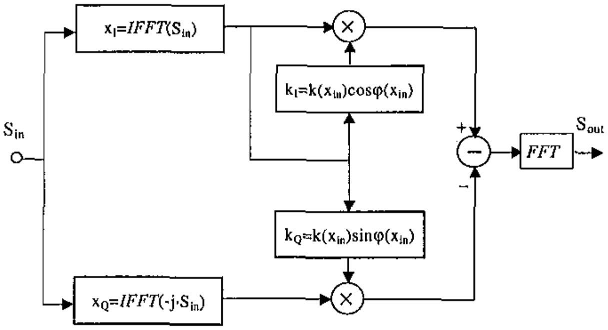

**Figure 20. A block diagram of modeling a broadband nonlinear element by the "instantaneous" quadrature technique.**

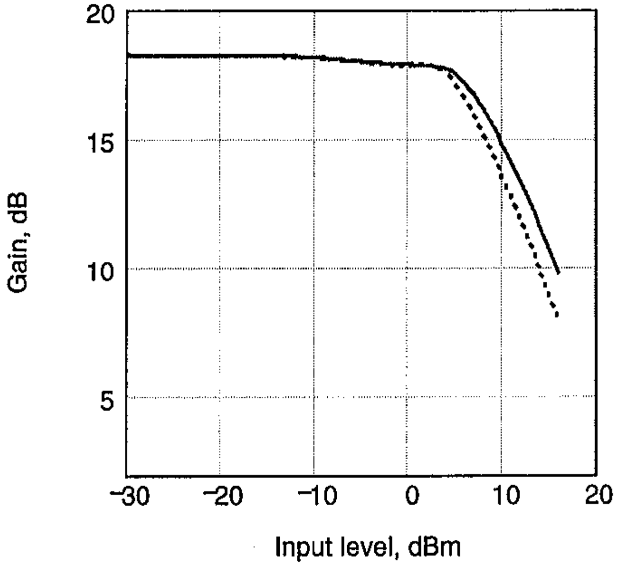

**Figure 21. The envelope (solid line) and instantaneous (dotted line) gains as functions of the input level.**

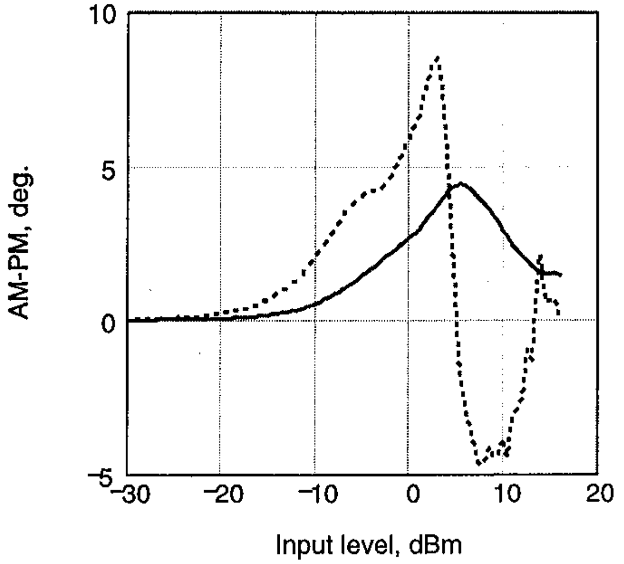

**Figure 22. The envelope (solid line) and instantaneous (dotted line) AM-PM characteristics as functions of the input level.**

For some nonlinear elements, a lot of sample points should be used to discretize the system of Equation (11), in order to achieve a high dynamic range in the analysis. Computational efficiency can be improved in this case in two ways: (1) to solve the system not for the entire amplitude range, but separately for the small-signal range (using a large number of points) and for the whole range (using a small number of points); or (2) to use other basis and weighting functions.

Below, we give some simulation examples for microwave amplifiers. Figures 21 and 22 show gain (AM-AM) and output-signal relative phase (AM-PM) versus input-signal level for a single-stage transistor microwave amplifier. These were simulated by the harmonic-balance (HB) technique (the HP Advanced Design System was used [66]). Note that amplitude and instantaneous characteristics differ (this is especially true for the AM-PM characteristic). Furthermore, we shall consider HB simulation results as a reference, because their accuracy is, in general, better (since the HB simulation is a circuit-level simulation; we should note, however, that it also has a lot of limitations, especially for nonlinear problems). Instantaneous characteristics were calculated using Equation (11). Figure 23 shows fundamental tone and IMP levels at the amplifier output (a two-tone input signal was used), which were simulated by the instantaneous quadrature technique (see Figures 19 and 20) and by the HB technique. Agreement between HB simulation and the technique proposed is very good, except for fifth-order IMP in the small-signal area (<−12 dBm), which requires further investigation. We should point out that the dynamic range of the simulation is very high (from −150 dBm up to 20 dBm, i.e., 170 dB). The instantaneous quadrature technique is also very computationally efficient: the simulation time for this technique was only a few minutes, and for the HB technique it was more than five hours. This difference becomes even larger for a larger number of input tones (for, say, 100 input tones, the HB simulation would last for years, and the simulation time of the instantaneous quadrature technique does not depend on the number of input tones).

Figure 24 shows the gain of a microwave monolithic integrated circuit (MMIC) amplifier versus the input signal level (AM-AM). The amplitude (envelope) gain was measured, and the instantaneous gain was calculated using Equation (11). The AM-PM characteristic was not taken into account, due to its small values. Figure 25 shows fundamental tone and harmonics at the amplifier output, which were measured and simulated by the instantaneous quadrature technique. This figure illustrates the capability of this technique to perform simulation over a wide frequency range (to predict harmonics), and over a wide dynamic range, at the same time.

## 7. The use of the "instantaneous" quadrature technique for active array analysis

As we can see from the block diagrams of typical active arrays (see Section 3), and from the block diagrams of the simula-

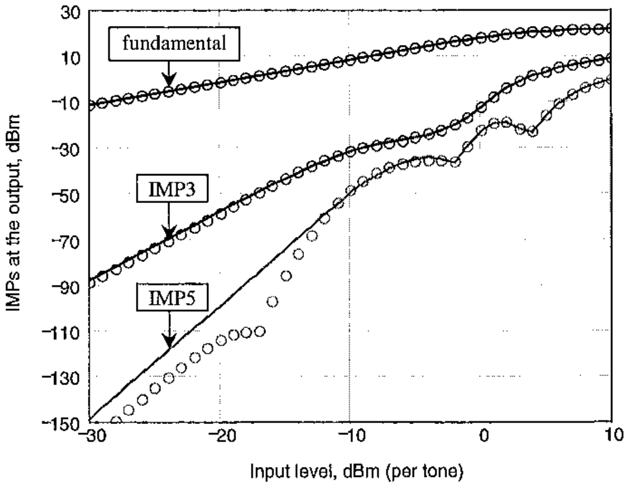

**Figure 23. The fundamental tone, third-, and fifth-order IMPs at the amplifier output as functions of the input level (solid line: instantaneous quadrature technique; circles: HB technique).**

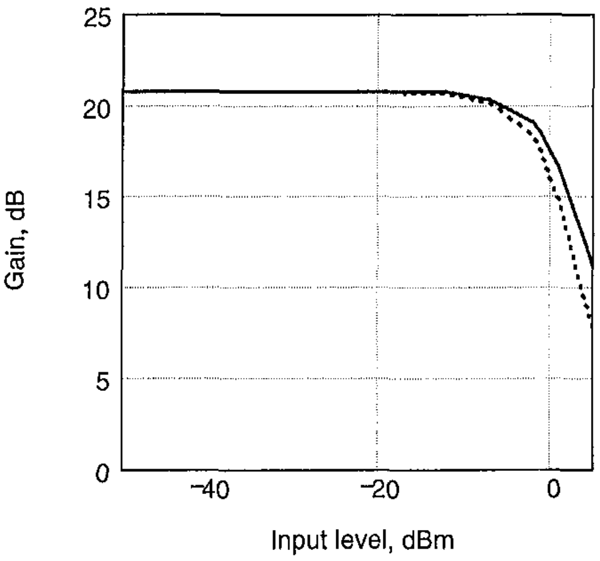

**Figure 24. The envelope (solid line) and instantaneous (dotted line) gains as functions of the input level.**

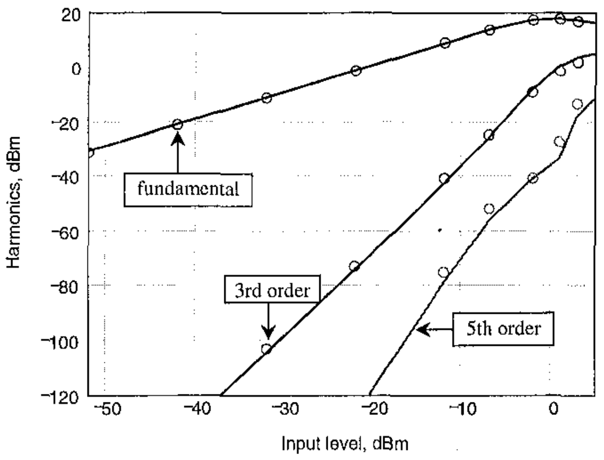

**Figure 25. The fundamental, third-, and fifth-order harmonics at the amplifier output as functions of the input level (solid line: instantaneous quadrature technique; circles: measurements).**

tion process done by the instantaneous quadrature technique (see Section 6), this technique is very well suited for the simulation of active array antennas at the system level.

The "instantaneous" quadrature technique uses advantages of both of the techniques of which it is comprised. It can predict both AM-AM and AM-PM conversion over a wide frequency range and over a wide dynamic range, taking into account the frequency dependence of the characteristics.

A large active antenna array having a complex structure (for example, a DBF array, every channel of which includes, in fact, its own receiver) can be analyzed on a PC in a reasonable time taking into account:

- Nonlinearity in amplifier and mixers, including harmonics, intermodulation products, spurious responses of receivers
- Frequency responses of filters and matching networks
- The complex spectrum of real-life signals
- The presence of complex-spectrum interfering signals
- The characteristics of radiating structures using an electromagnetic simulator

The instantaneous quadrature technique gives us the possibility to simulate such active array characteristics as the following:

- The array pattern at the fundamental frequency in large-signal mode (beamwidth, direction, sidelobe level)
- The influence of an interfering signal on the array pattern at the fundamental frequency
- Array patterns at intermodulation frequencies (beamwidths, number of main intermodulation beams and their directions, sidelobe levels)
- Such phenomena as desensitization, local-oscillator noise conversion and cross-modulation can also be studied.

The identification of nonlinear interference sources, as well as modeling a detector taking into account its imperfections, are also possible [117, 118]. Baseband signal processing can also be modeled. Multi-level simulation can be carried out using the instantaneous quadrature technique in a natural way (see, for example, Figure 15).

The instantaneous quadrature technique requires more computational resources when compared to the quadrature technique, since signal sampling is done at the carrier frequency. Nevertheless, the computational resources required are not as high as for circuit-level simulators (using harmonic balance, for instance) [43, 44, 58], or as some hybrid techniques that also use circuit-level simulation [66, 125].

Computational efficiency can be further improved in several ways:

1. If only harmonic levels are of interest, the modulating spectrum can be omitted during the simulation, thus reducing substantially the number of sample points
2. Transformation to a frequency lower than the carrier can be made in such a way that no distortions are introduced in the RF and IF parts of the spectrum (thus, down-conversion is modeled correctly); harmonics are omitted in this case
3. If both harmonics and the modulating spectrum are of interest, a multi-step simulation can be made: step 1 is used for simulation of harmonics, and step 2 is used for simulation of the modulating spectrum

## 8. Conclusion

Active array antennas are finding increasingly wider applications, due to a number of advantages they offer when compared to passive antennas, especially at 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. Numerical techniques which can provide more robustness and better accuracy are now widely used for this purpose.

Behavioral-level simulation techniques were considered in detail in this article. 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 very desirable.

### 9. Acknowledgment

The author would like to thank Prof. F. Gardiol and Prof. J. Mosig for many helpful discussions, and Mr. J. F. Zurcher for help with measurements. The financial and technical support of this work by the Swiss Government and by the Electromagnetism and Acoustics Laboratory of Swiss Federal Institute of Technology, Lausanne, are also appreciated.

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