Interference Study in a Proposed Integrated Multi-beam Active Phased Antenna Array Transmission System for Satellite Communications

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***Abstract*— In this paper, an integrated active phased array multi-beam antenna system model including a nonlinear model of the amplifier and a digital pre-distortion linearizer is introduced and validated by simulation. To investigate nonlinearity effects in a phased-array antenna, a two-beam, three-beam, and five-beam S-band arrays are simulated and the results of the proposed system model are analyzed. The presented model is able to precisely predict the inter-modulation products with an accuracy of 1 dB in power with small fraction of a degree in direction. The effect of integrating a digital pre-distortion linearizer is to enhance the efficiency of antenna array transmission power amplifiers. Therefore, the model can be used as a tool to accurately predict the inter-modulation patterns for multi-beam satellite array applications, avoiding excessive system margin and reducing DC power consumption.**

Keywords- SSP; IM; DSP; DPD; LMS; RLS; IBO.

I. INTRODUCTION

Modern satellite communication payloads require high directivity and multiple beams with large signal bandwidth to satisfy broad-band applications, such as multimedia and voice conferences. Therefore, an active phased array is ideal for such applications, since they can be configured in orbit to provide the bandwidth in demand and increase overall system utilization [1]-[3].

The total transmission quality of a communication satellite using a multi-beam phased-array antenna system is most dependent upon the nonlinear distortion of the Solid State Power Amplifier (SSPA) modules [2]. This distortion brings about Inter-Modulation (IM) interferences. The closer to the compression point in order to have the most power efficiency means more IM product levels that degrade Carrier-to-Interference ratio (C/I) associated with beam steering direction. So, accurate modeling of these IM beams helps to control the IM interference, thus allowing the SSPAs to be operated with minimum back-off since fewer margins are needed. This results in a more efficient array that requires a lower system DC power with reduced mass and cost of the satellite [3].

Inter-Modulation Products (IMPs) in an active antenna array have characteristics that are different from those in lumped active circuits and systems. For multi-beam satellite digital communication systems, signal suppression and IMP interference in amplifiers may degrade the bit-error rate 1 to 5 dB in comparison to passive antennas. The presence of interfering signals may result in an increase of the array beam width, sidelobe level, null depth degradation, as well as changing the null positions [2]. Sandrin [4] previously analyzed the radiating patterns of third and fifth orders IM products of active antenna arrays. In his analysis, he derived the phase gradient for the *m*-th order intermodes and used generic transfer functions for modeling nonlinear characteristics of the power amplifier. His analysis incorporates approximations appropriate for limited field of view arrays (as in the case of an earth-looking antenna on a geosynchronous satellite) and for small percentage bandwidth. Kohls [2] presented simulation and experimental results for KU band arrays. Bessel series function approximation is used to fit the above-mentioned model of a KU-band array for predicting third-order IM product beam patterns. Meanwhile, Maalouf et al. [3] studied IM estimation in an active phased-array theoretically and experimentally.

All of these studies involved narrow band signals. This implies that the amplifier characteristics are frequency independent over the frequency band of interest. However, while having broadband input signals, or systems including wide-band amplifiers and relatively narrow-band components, a frequency-dependent quadrature model is required [5]. Johari et al. [6] introduced an amplifier model with considering frequency-dependent parameters to investigate nonlinearity effects in a phased-array antenna and validate the model by experimental data.

For base stations, the major issue is linearity, as the down-link signal must be highly-linear in order to achieve a small error rate and a good quality of reception in mobile terminals. Power amplification of RF signals faces a problem of achieving high linearity and efficiency at the same time. Efficiency is maximized when a PA operates with a small back-off, i.e., close to the saturation region. However, in this mode of operation, nonlinear distortions are produced, which degrade the system linearity. It means that efficiency and linearity are mutually exclusive requirements. A trade-off between them is usually sought for each particular application [7][8].

Linearization techniques for nonlinear microwave power amplifiers have been around for decades, ranging from analog techniques such as feed forward linearization [8][9] and Cartesian loop feedback correction [8], to digital techniques such as digital pre-distortion linearization [8]-[10].

This paper consists of eight sections. In Section II, the used power amplifier model in the integration process is introduced. Then, the mathematical modeling of IM products is calculated in Section III. Next, the model of radiation farfield pattern is considered in Section IV; a digital pre-distortion linearizer is explained in Section V, and finally the functionality of the proposed integrated system is introduced in section VI. The simulated results are presented in Section VII, and conclusions are given in Section VIII.

II. NONLINEAR SSPA MODEL

Using a complex envelope instead of real narrow band signals; thus, there is no carrier information in the complex envelope except the modulation information is the main idea of quadrature modeling technique. This point is important from the viewpoint of computational efficiency. In the SSPA model, its characteristics are modeled with series of Bessel function coefficients [4] because of their ability to quickly converge to the nonlinear characteristics of the amplifier and model the IM products at the output of the amplifier. The mathematical model provides the gain and phase insertion of each carrier and IM component at the output of the SSPA; therefore, it is suitable to incorporate into the antenna phased-array model. Therefore, this method can achieve the necessary accuracy for active phased array systems [4][7].

The nonlinear behavior of the amplifier can be expressed by the following Bessel function series [7]:

$$g(\rho)e^{j\,\varphi(\rho)} = \sum_{s=1}^{L} \beta_s J_1(\alpha\, s\, \rho) \tag{1}$$

where ρ, g(ρ), and $\varphi(\rho)$ denote the amplitude of the input tone and measured AM/AM and AM/PM single-tone characteristics, respectively. J_1 is the Bessel function of the first kind with order 1; β_s, α, and s are the complex number, the real number, and an integer, respectively. The appendix in [7] shows in detail how the parameters s and α are chosen to evaluate β_s, by a linear search method. Once s and α are selected, β_s is calculated to separately satisfy the real and imaginary parts of (1). In particular, the solution to the following two equations uses the least-squares method [7] as:

$$\sum_{k=1}^{z}\left[g_k \cos\varphi_k - \sum_{s=1}^{L} b_{gs} J_L(\alpha s \rho)\right]^2 = \min,$$

$$\sum_{k=1}^{z}\left[g_k \sin\varphi_k - \sum_{s=1}^{L} b_{ms} J_L(\alpha s \rho)\right]^2 = \min \tag{2}$$

where, z is the number of measured sample points during the characterization of the AM/AM and AM/PM behavior of the amplifier. A typical value for the integer z is less than 20, while α is selected such that $1 < \alpha.\, A_{sat} < 2$, where A_{sat} is the saturation voltage of the amplifier. With s and α are fixed, both equations in (2) are quadratic minimization problems in $\beta_{real}\,(s)$and $\beta_{imag}\,(s)$ with known analytical solutions. Equation (2) is solved for several (s, α) pairs, and the solution with the lowest residual error is kept. The final model coefficients are given by $\beta(s) = \beta_{real}\,(s) + \beta_{imag}\,(s)$

III. IM MODELING

This section investigates the effects of IM upon the performance of a K-element planar phased-array antenna satellite communication system. In an array, the input single of the k-th amplifier of the array can be represented by [6]:

$$e(k,t) = \sum_{n=1}^{N} A_{nk}\, e^{-j(2\pi f_n t + \varphi_{nk})} \tag{3}$$

where A_{nk} is the amplitude of the n-th channel at the k-th element, which, in this work, is assumed constant over time, φ_{nk} is the corresponding phase, and f_n is the carrier frequency at the given channel. At the output of the amplifier, the signal is composed of the amplified carriers and IM components that are introduced by the nonlinear amplifier characteristics. The output signal is expressed as [3][6]:

$$e_o(k,t) = \sum_{n=1}^{N} M(L_p)\, e^{j\sum_{n=1}^{N} l_n (2\pi f_n t + \varphi_{nk})} \tag{4}$$

where L_P is a vector member of the set

$$L = \{[l_1, l_2, \dots\dots, l_N],\ \sum_{n=1}^{N}|l_n| = 1, or\ 3\ or\ 5 \dots.\} \tag{5}$$

where the components that correspond to $\sum_{n=1}^{N}|l_n| = 1$ are carriers, the components that correspond to $\sum_{n=1}^{N}|l_n| = 3$ are third order IM products, and $\sum_{n=1}^{N}|l_n| = 5$ are fifth order IM products. For each index p, there is a unique set of integer number l_1 to l_n. In addition, higher order products are ignored because they are lower than the third order, at least 6 dB [3]. Furthermore, the voltage gain of the p-th component is derived in, and can be expressed as [7]:

$$M(L_p) = \sum_{s=1}^{S} \beta_s \prod_{n=1}^{N} J_{l_n}(\alpha\, A_{nk}\, s) \tag{6}$$

IV. RADIATING ARRAY MODEL

The radiation pattern of the array is modeled analytically as the product of the element pattern and the array factor, assuming identical element patterns over the array and no mutual coupling. These assumptions are relatively accurate for patch elements with distances of 1.5 times greater than lambda, which are considered in the modeling. Furthermore, it is assumed that the fundamental TM10 mode is propagating in the microstrip patch antenna. Here, the radiating elements are modeled in an array environment, and the array factor's farfield radiation patterns are calculated for both the carriers and IM products based on excitation coefficients generated by the IM algorithm. The farfield array factor radiation pattern $P_p(\theta)$ for each component in any spatial direction is given by the coherent sum of the corresponding SSPA output component given in (7), expressed as[6]:

$$P_p(\theta) = M(L_p)\sum_{k=1}^{K}\left\{\exp j\,\frac{2\pi}{\lambda_p}(\cos\varphi_n x_k + \sin\varphi_n y_k)\sin\theta_n\ .\exp j\,\sum_{n=1}^{N} l_n\varphi_{nk}\right\} \qquad (7)$$

where λ_p is the wavelength of the p-th component whose frequency is given by $\sum_{n=1}^{N} l_n f_n$, (x_k, y_k) are the Cartesian coordinates of the array elements, and (θ_n, φ_n) defines the spatial beam directions in spherical coordinates for the n-th beam [3].

V. LINEARIZER MODEL

As processing power has become cheaper and more powerful over the last two decades, mainly due to the great advances in Digital Signal Processing (DSP), digital pre-distortion linearization has become one of, if not the most cost efficient linearization technique available for microwave power amplifiers [8]-[10]. The overall goal is to design a block which compensates for nonlinear effects present in the power amplifier in digital baseband, allowing to utilize digital signal processing techniques to achieve great precision [9]. Prior to designing a digital pre-distorter, a model of the nonlinear microwave power amplifier is often required in order to estimate its inverse. the next step is to estimate the model parameters, either by an direct approach with least squares methods, or by an adaptive or iterative approach, i.e., using an adaptive filter such as the Least Mean Square (LMS) filter [10], or the Recursive Least Square (RLS) filter [10].

The Digital Pre-Distortion technique (DPD) has high efficiency, adaptability and good inter-modulation suppression as it is operated before the power amplifier, which means the signal processing does not consume large power [8]-[10].

The best way to solve this problem is to use the discrete time form of Horison model which takes the following mathematical model [10]:

$$y_n = \sum_{k=0}^{N} f_k(x_{n-k}) \qquad (8)$$

To compensate for the distortions introduced by the amplifier in the amplified baseband signal, it can be shown that according to Horison model (8), there exists an exact inversion [10]. Indeed, from (8), it follows that [10]:

$$f_0(x_n) = y_n - \sum_{k=0}^{N} f_k(x_{n-k}) \qquad (9)$$

It is easy to obtain the inversion system equation as [10]:

$$x_n = \frac{1}{f_0}\left(y_n - \sum_{k=0}^{N} f_k(x_{n-k})\right) \qquad (10)$$

Thus, if there is a reversible function f_0, the analytical model of the form (8), which implies its precise handling (9). These functions can be used to implement the nonlinear characteristics of the linearizer as an inverse of PA model.

In the proposed model the basic functions f_0, f_1, f_2, have been chosen to be spline functions, in particular, piecewise linear splines and the cubic parabola (third degree polynomial).

VI. INTEGRATED SYSTEM MODEL

A functional block diagram of the proposed integrated active phased antenna array transmission system is shown in Figure 1. It consists of M radiating elements, M Solid State Power Amplifiers (SSPAs), and N independent beamformer channels and M attenuators and phase shifters for each beamformer. The proposed integrated model functionality can be described briefly as following:

- Antenna array radiating elements: form the antenna aperture and consist of a set of identical near-omni-directional radiators (dipole, slot, horn, waveguide), usually located in the form of right-angled or skew-angled nodes;
- Power amplifier modules: are usually implemented in the form of electric vacuum or solid-state devices, which are connected directly to the antenna elements in order to eliminate the need for RF feeder line at a high power level, and thereby significantly reduce the high-frequency loss;
- Linearizer module: is responsible for the transmission factor adjustment (the gain and the phase) of each power amplifier module via linearization of PA characteristics, which in turns achieves a higher efficiency performance due to the enhancement of power losses, which are generated by IM signals;
- The central microprocessor: determines the complex coefficients of transmission channels in accordance with a predetermined shape and position of the antenna array pattern in the space, which are determined by beam pattern control unit and simultaneously an adaptive monitoring of PAs outputs is achieved via a command control program within the linearizer module. The output signals are multiplied with the vector of coefficients that take into account the internal state of the system (failures, amplitude and phase calibration) for correction of antenna array pattern;
- Modulator: adaptive phased antenna array emitted signals can be modulated in the excitation stage or at PA elements;

- Beam pattern control unit: generates the necessary distribution of amplitudes and phases of the input signals to the array radiation elements. This system comprises a set of power amplifiers, a set of phase shifters and a set of matching circuits. Each radiator element is connected in series with the matching circuit, power amplifier and phase shifter to form a single adaptive phased array channel. Usually, all channel elements are combined into a unitary structure which is called a module;
- Amplitude and phase control unit: generates the required phase and amplitude distribution of excitation signals. Usually it consists of a set of controlled delay lines or phase shifters, and attenuators;
- Input power distribution unit: can be implemented in a passive or active forms. Passive type is based on the parallel, serial, or other multilevel scheme by using different types of power dividers (feeder excitation) or by the optical system (spatial excitation). Active type is intended to be included at different levels (stages) of cascaded amplifiers. Active types are used in cases when the excitation power is not sufficient to excite all PAs of adaptive phased array system, or when it is required to build an array by using the same active devices, i.e., unifying or standardizing them;
- Matching devices, such as impedance transformers and non-dissipative stubs, which have been installed to reduce the reflection losses from the antenna array radiators in the scan mode (or changing the array radiation pattern) and providing stable operating conditions at PAs outputs;
- Non-reciprocal devices - valves or circulators can be installed for isolation PAs and radiators;
- In addition, the construction of any adaptive phased array systems may include some other units such as; power supply, functional check control and cooling units, where the construction of adaptive phased antenna array system are mainly based on three factors: the location of the phase shifters in each transmitter sub-channel, the number of distribution systems, and the presence of cascaded PA conversion (frequency multiplication stages).

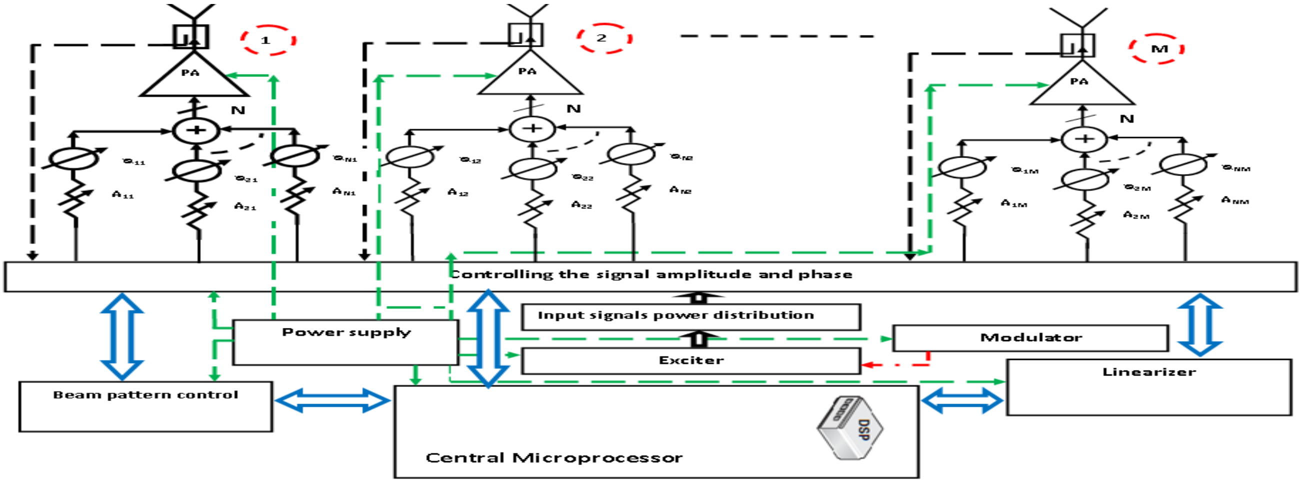
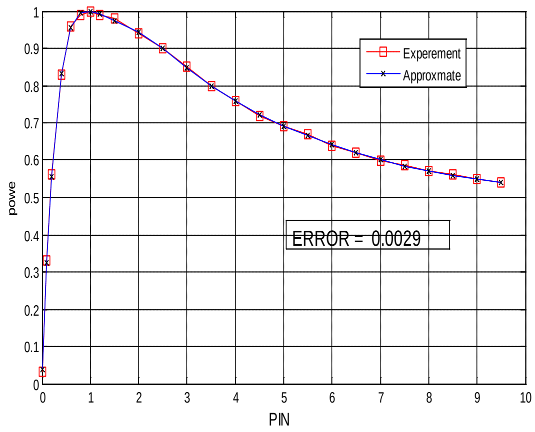


Figure 1. Scheme for the construction of transmission channels of digital active phased antenna array (DAPAA) systems

VII. SIMULATION RESULTS

In this paper, a five-beam S-band array has been studied, which is comprised of sixteen patch antenna elements in a *1x16* configuration. The amplifier characterization is described by measuring the single tone AM/AM and AM/PM of a subset of the SSPAs with frequency *3.5* GHz to represent the nonlinear response of the PA element. Then, the amplifier is modeled as described in Section II with ten terms of Bessel function series. The agreement between the measured and predicted amplitude and phase characteristics is shown in Figure 2.



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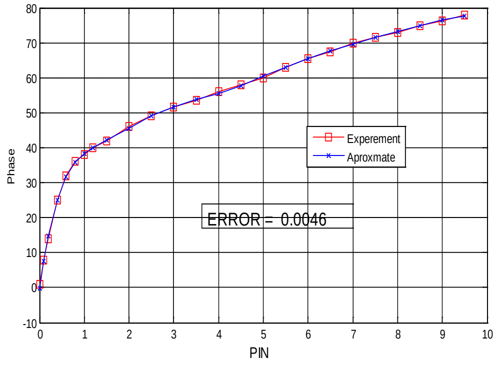
(a)



(b)

Figure 2. Predicted and measured power amplifier characteristics (a) AM / AM characteristics (b) AM / PM characteristics

After PA modeling, the array is fed by five different tones 3500 MHz, 3450 MHz, 3475 MHz 3525 MHz, and 3550 MHz, which are steered in directions [-50°, -25°, 0°, 25°, 50°], such that each PA excitation power is set at 0 dB total power Input Back-Off (IBO) to represent the nonlinear operation of predicted frequency components in the compressed region. Figure 3 shows the predicted two components on the same graph (carrier component as well as the third order IM-32 component) when the array is fed to be operated at 0 dB IBO in Cartesian diagram and Figure 4 represents them in polar diagram.

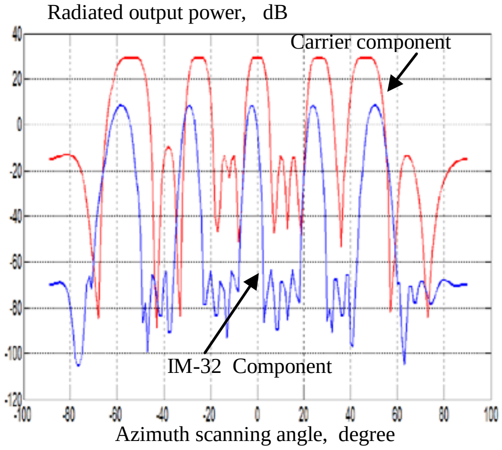


Figure 3. Five beams antenna array patterns of both carrier component and IM-32 component in cartesian diagram

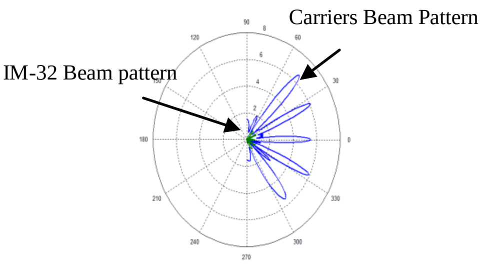


Figure 4. Five beams antenna array patterns of both carrier component and IM-32 component in polar diagram

The linearizer characteristics based on having the inverse of the predicted PA model by using Horison model is shown in Figure 5. Both distorted carrier component and the linearized one are shown in Figure 6 to represent models integration output.

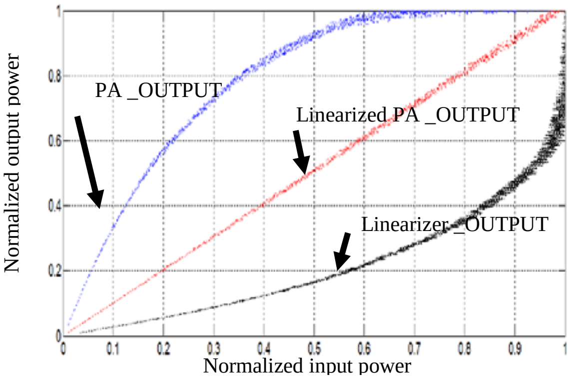


Figure 5. Linearizer effect on power amplifier response

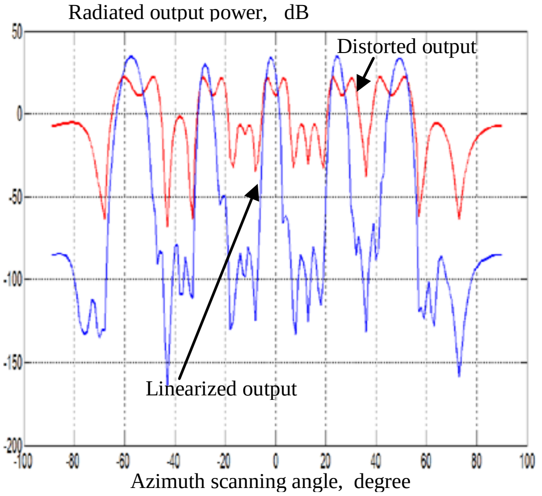


Figure 6. Model integration (distorted carrier component as PA output and its linearized form as linearizer output)

VIII. CONCLUSIONS

A main goal in an active transmitter array is to drive the amplifiers to be as saturated as possible (for optimal efficiency). In this paper, an sixteen-element integrated S-band phase array system is simulated by the Shimbo nonlinear amplifier model [7] and digital pre-distortion linearizer model based on getting PA inverse by using Horison model. Also, the array farfield parameters, side lobe, and IM patterns are considered in the proposed integrated model. This analysis presents that IM interference can be predicted accurately, which enable controlling its effects in multi-beam phased-array satellite system. Hence, it reduces the necessary excessive margin. Therefore, with this reduction, the transmission power consumption will be decreased, and consequently, satellite power consumption and mass will be reduced.

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