The Effect of Amplifier Nonlinearities on Directionally Modulated Signals in Phased-Array Transmitters

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***Abstract*—Directionally modulated signals from an antenna allow for the secure transmission of different communication symbols in several directions at the same time. The information required to generate these directionally modulated signals is stored in a vector of relative current weights for each antenna element. In a realistic array environment, these signals must be amplified for transmission. We use these idealized element weights as the input voltages for each element's power amplifier. The integrity of these relative weights through the amplification process is of great importance to the integrity of the transmitted communication symbols. Knowledge of these distortion effects may aid in the implementation of directionally modulated signals in a real array environment. We study the effects of nonlinear amplifier performance on this integrity through a nonlinear circuit simulation platform.**

***Index Terms*—Antenna arrays, nonlinear circuits, modulation, nonlinear distortion**

I. Introduction

The use of phased arrays for directional transmission allows multiple messages to be transmitted in multiple directions at the same frequency and time from the same aperture. In a crowded spectral environment, using the same aperture for multiple, directional transmissions is advantageous, as it allows for more simultaneous users through spatial diversity. However, it is important to examine the collective impact of the array element power amplifier nonlinearities on the directional modulation transmissions as a first step to understanding how to adjust and correct for these inaccuracies.

Directional modulation is demonstrated by Daly as a means for transmitting multiple, distinct messages in different directions using calculated excitations of antenna array elements [1]. Xie shows a method for using the Moore-Penrose pseudoinverse to calculate the excitations in closed form for a directional communications application [2]. McCormick discusses using the same aperture for both radar and communications [3]. Hamza presents an optimization-based approach to perform directional radar out of a wide main beam and directional communications from the angular sidelobes [4].

The impacts of power-amplifier nonlinearities on communication symbol accuracy have long been studied for single-element transmitting devices. For example, Come describes how nonidealities of the transmitter can impact wireless local-area network transmissions using orthogonal frequency division multiplexing (OFDM) [5]. Lin discusses how error vector magnitude can be simulated and measured for power amplifiers used for digital wireless communications [6]. Zou describes how power amplifier nonlinearities can affect Massive Multiple-Input, Multiple-Output (Massive MIMO) systems, specifically examining the effects on the spectrum and on the signal-to-noise-plus-interference ratio (SINR) [7]. Sandrin shows that nonlinearities in the amplifier can cause unwanted spurious beam transmissions in different directions than the original intended beam directions [8]. Mollen calculates that in-band distortion will exist at the intended transmission angles in addition to the unwanted spurious beam angles [9].

The present paper ventures into a new area and examines the distortion of directionally modulated messages due to the element power-amplifier nonlinearities. A simulation setup, consisting of MATLAB with circuit and electromagnetic simulators, is used to perform the examination. The distortion of the directionally transmitted messages due to the element power-amplifier nonlinearities is studied.

II. Application

We study the effects of amplifier nonlinearities on directionally modulated signals in the context of a linear patch antenna array consisting of sixteen elements. Each array element signal is generated by a voltage tone at a frequency of 3.55 GHz. Each tone is amplified, fed through an output impedance matching network, and terminated at its corresponding antenna element. The linear array uses half-wavelength spacing between its elements.

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The directionally modulated signal that we employ is formulated to transmit three communication symbols in three directions. The communication directions are at -30°, -45°, and -60° with respect to boresight. These symbols are encoded with 4-bit phase-shift keying (16-PSK), and their information is encoded exclusively in the relative phase of transmission in the corresponding direction. There are 16 possible phase symbols in the complex plane for this encoding strategy, and the transmitted phase for a symbol must maintain sufficient integrity so as not to be confused with a different symbol upon reception.

III. Simulation Setup

We employ a linear patch antenna array with 16 elements for our simulations. Each element has a transmit chain that consists of a voltage source tone with modifiable magnitude and relative phase, current probes, a power amplifier, an output impedance matching network consisting of an evanescent mode cavity tuner model created by collaborators at Purdue University [10], and an antenna element. Advanced Design System (ADS) from Keysight Technologies was used for circuit simulations, and a nonlinear transistor model from Modelithics was used to simulate the nonlinear device within ADS. Momentum, a 2.5-dimension electromagnetic (EM) simulator housed in the Keysight software package, was used for EM simulations. A third-order ADS harmonic balance simulation was performed to see the simple nonlinearity effects on the transmitted symbols. The power amplifier device is a MWT-173 metal-semiconductor field-effect transistor (MESFET) biased with $V_{GS} = -1.5$ V and $V_{DS} = 4.5$ V. The antenna elements are simulated using a "Momentum RF" EM simulation in order to accurately model EM effects including mutual coupling.

In these simulations, the adjustable magnitude and phase of the voltage source for each array element are used to generate the ideal directionally modulated signal pattern. These magnitudes and phases are chosen according to a vector of antenna element current weights $\boldsymbol{w}$. These weights contain the information required to transmit the intended communication symbols in their proper directions. We use the Moore-Penrose Pseudoinverse technique, as applied by Xie [2], to generate these weights for a linear array consisting of sixteen elements. These weights are then applied to the voltage tones as the relative input signals to the power amplifiers. The antenna element weight vector is generated using

$$\boldsymbol{w} = [\boldsymbol{H}(\boldsymbol{\theta})^H]^{\dagger}\boldsymbol{r}, \tag{1}$$

where $\boldsymbol{w}$ is the vector of antenna element current weights, $\boldsymbol{H}(\boldsymbol{\theta})^H$ is the Hermetian transpose of the steering matrix, $\dagger$ represents the pseudoinverse operator, and $\boldsymbol{r}$ is the vector of target signals in each specified direction. The steering matrix $\boldsymbol{H}(\boldsymbol{\theta})$ is given by

$$\boldsymbol{H}(\boldsymbol{\theta}) = \frac{1}{\sqrt{M}}\begin{bmatrix} e^{-0jkdsin(\theta_1)} & \cdots & e^{-0jkdsin(\theta_M)} \\ \vdots & \ddots & \vdots \\ e^{-j(N-1)kdsin(\theta_1)} & \cdots & e^{-j(N-1)kdsin(\theta_M)} \end{bmatrix}, \tag{2}$$

where M is the number of signals, N is the number of array elements, and θ_i is the transmission angle with respect to boresight. The magnitude and phase of each element in the weight vector $\boldsymbol{w}$ are used to set the magnitude and phase of the voltage tone for the corresponding element. 4-bit phase-shift keying (16-PSK) was used as the digital modulation of the messages in this study. All voltage tones are then multiplied by a shared scale factor to control the power level presented to the amplifiers. This power level may change the operating behavior of the amplifiers, which is significant when studying their linear or nonlinear behavior. Images describing the ADS simulation setup are shown in Fig. 1-3.

Fig. 1 shows the voltage sources for simulation in ADS. Each voltage source's magnitude and phase can be adjusted independently, along with the aforementioned scaling factor applied equally to all voltage sources. Fig. 2 shows the transmit chain leading to the antenna, including current probes, power amplifier, and output matching network. Fig. 3 shows a portion of the 16-element antenna. The antenna elements are simulated together, using Momentum, to account for effects such as mutual coupling.

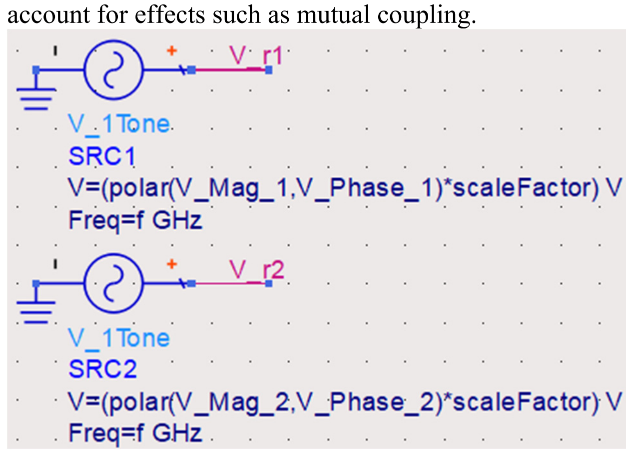

Fig. 1. Two of the 16 custom voltage source tones used for simulation.

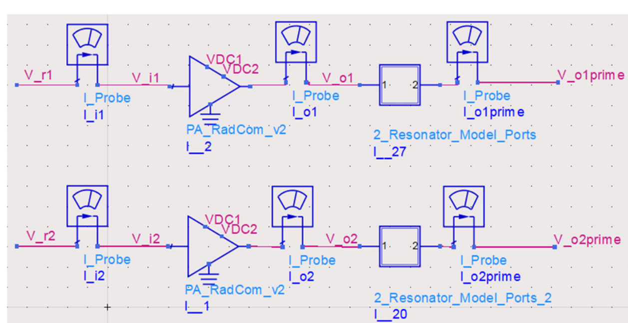

Fig. 2. Two of the 16 transmit chains used for simulation.

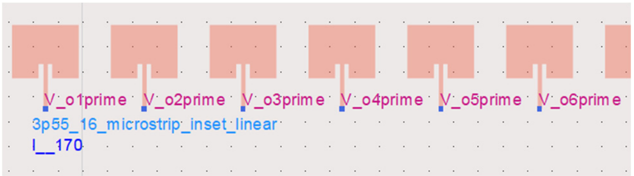

Fig. 3. Six of the 16 antenna elements used for EM simulation

The ideal transmission pattern shape generated by the Moore-Penrose Pseudoinverse technique is shown in Fig. 4. Though the magnitudes of communication beams are not significant to the encoded communication, the antenna distribution pattern is shown to provide a more complete characterization of potential distortion. Applications to other forms of communication where magnitude is important, for example, may find these plots of more interest.

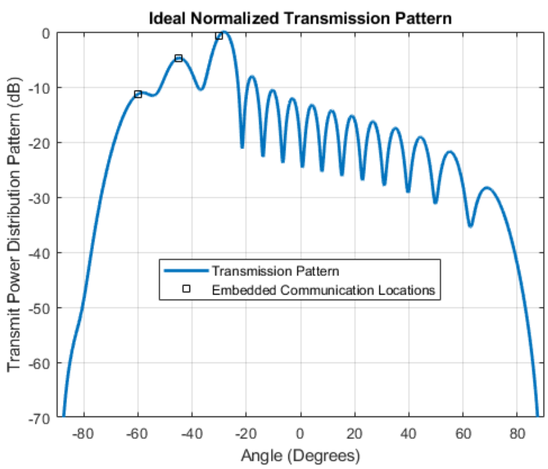

Fig. 4. Ideal directionally modulated transmission pattern, including embedded communication symbols.

For PSK modulations, the phase distortion is of the highest interest, as the symbol information is contained solely in the phases of the directionally received transmissions. An example of an intended transmitted symbol phase diagram is shown in Fig. 5 (this is for Test 1 of the following section), where only phase is shown (magnitude is irrelevant and not shown in this plot due to the PSK modulation). If a transmitted symbol crosses an ambiguity angle from its intended symbol, it will be mistaken for a different symbol. This mistaken symbol corresponds to a symbol error in communication.

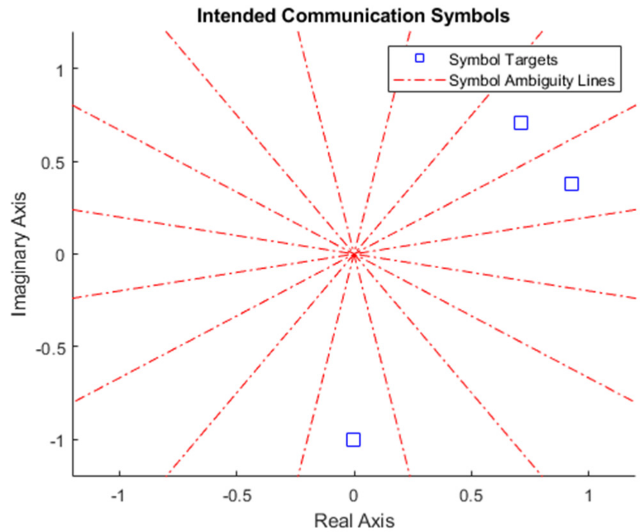

Fig. 5. Intended directionally modulated 16-PSK symbols. Because all symbol information is encoded in the phase of the transmission, all symbols are normalized to a magnitude of 1 for clarity. Dashed lines indicate the ambiguity angles for a 4-bit PSK with 16 possible symbols.

IV. Simulation Results

In order to study the effects of power amplifier nonlinearities on the desired transmission pattern and communication symbols, tests were performed in two regions of amplifier behavior. One of these tests is in the linear operating region of the amplifiers and the other is in the nonlinear operating region. These two tests differ only by the input power values presented to the amplifiers. The test operating in the linear region of the amplifier presents an average available input power of $P_{AVS} = 0.05$ mW. The test operating in the nonlinear region of the amplifier presents an average available input power of $P_{AVS} = 100$ mW.

Results of the Test 1 operating in the linear region are shown in Fig. 6 and 7. Both the transmission pattern and the phase of transmitted symbols demonstrate good integrity with respect to the ideal signal. The antenna array patterns appear to be similar in shape, with amplifier gain causing the amplified pattern to be higher (Fig. 6), and all directionally transmitted symbol phases fall in the correct symbol regions for the PSK modulation.

Results from a second simulation of the Test 1 transmissions (same transmitted beam directions and symbols), but with amplifiers driven with power levels causing nonlinear operation, are shown in Figs. 8 and 9. Distortion of the array pattern is found when the amplifiers are performing in their nonlinear regions. Fig. 8 shows that the array pattern itself is significantly distorted. This is likely due to spatial intermodulation products, as discussed by Sandrin for multi-beam transmissions [8]. Regarding the in-beam distortion, however, the consequential impact of the power amplifier is phase distortion, as shown in Fig. 9. The actual transmitted phases show more deviations from their intended values than for the linear case, and one of the symbols is misinterpreted, as it falls outside of its intended phase window. As such, it can be concluded that nonlinear power amplifiers can significantly provide "in-beam" distortion of directionally modulated signals, a lesser studied issue with beam transmissions as it relates to power-amplifier nonlinearities, yet a consequential issue.

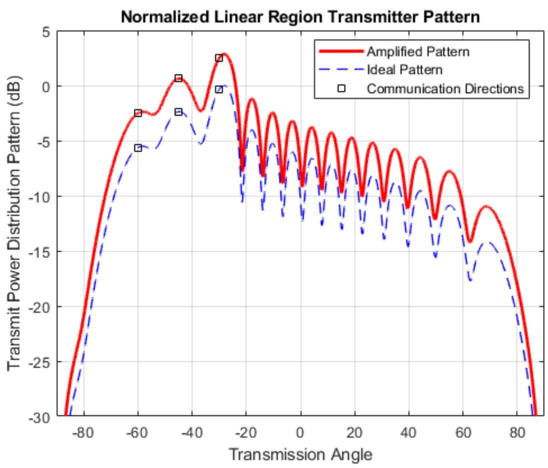

Fig. 6. Linear region transmission pattern. The amplified pattern has very good correspondence to the target transmission pattern.

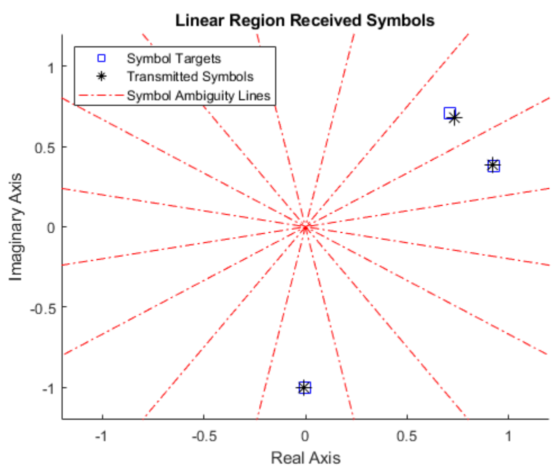

Fig. 7. Linear region communication symbol integrity. All symbols maintain integrity and are transmitted correctly.

Table I shows the results for Test 1, including the transmitted symbol angles for both the linear and nonlinear cases. The intended bit sequence and associated phase are shown for each transmit angle, along with the actual phase achieved in the linear and nonlinear cases. For Test 1, the transmit angle of -45° produced a phase in an undesired symbol bin, producing a symbol of 1110 instead of 1101.

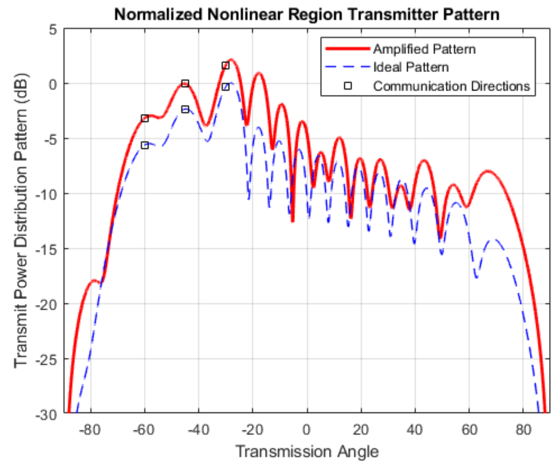

Fig. 8. Nonlinear region transmission pattern. Operation in this region shows distortions from the ideal transmission pattern.

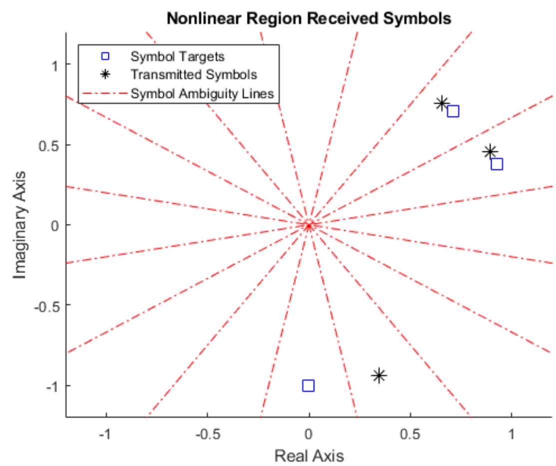

Fig. 9. Nonlinear region communication symbol integrity. In this test, one transmitted communication symbol is mistaken for another. This communication symbol is in the -45° direction.

TABLE I: TEST 1 INTENDED AND SIMULATED TRANSMIT SYMBOL PHASE VALUES FOR LINEAR AND NONLINEAR AMPLIFICATION

Transmit Angle (°)	Bits	Symbol Phase (°): Intended	Symbol Phase (°): Linear	Symbol Phase (°): Nonlinear	Nonlinear Pass/Fail
-30	0010	45	42.87	48.93	Pass
-45	1101	-90	-90.61	-69.70	Fail
-60	0001	22.5	22.71	26.90	Pass

To communicate effectively, an array must be able to transmit any user-defined combination of communication symbols. We therefore also test a different combination of communication symbols (Test 2) and evaluate the effect of amplifier distortion on their integrity. The communication directions remain unchanged; however, the target symbols for each communication direction have changed. Results for the new symbol combination from power amplifiers operating in their linear regions are shown in Figs. 10 and 11. Fig. 10 shows that the beam pattern integrity is maintained. Fig. 11 shows that all three transmitted PSK symbols have phases within their intended phase windows.

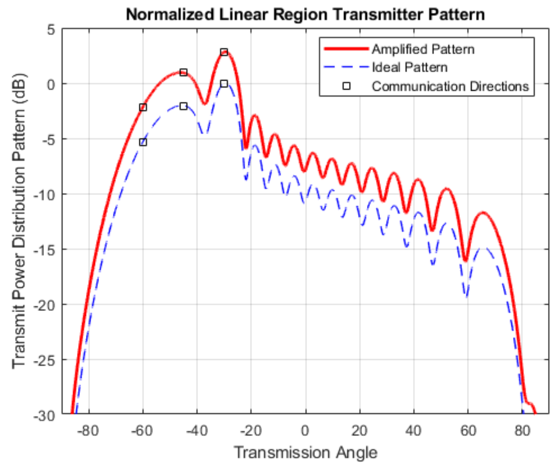

Fig. 10. Linear region amplifier effect on the transmission pattern including the second set of communication symbols. The linear region of the amplifiers reproduces the ideal pattern accurately.

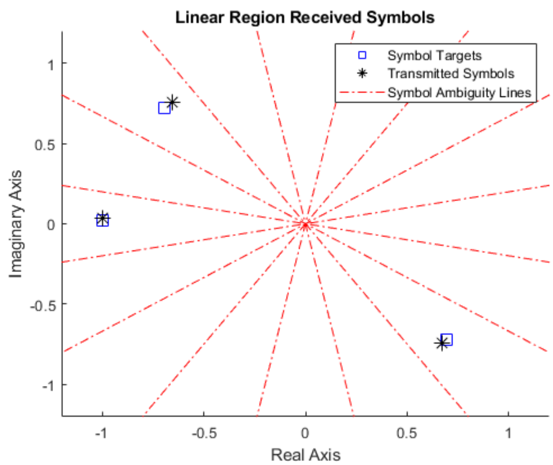

Fig. 11. Amplifier effect on the second set of communication symbols. In the linear region the communication symbols maintain integrity.

Figs. 12 and 13 show the array pattern and transmitted symbol phases when the power amplifiers are driven into nonlinearity. Fig. 12 shows that the array pattern is distorted. Fig. 13 shows that two of the three transmitted message symbols fall out of their intended phase windows and will be misinterpreted. While the third symbol falls within the intended phase window, it is very close to the boundary.

Table II summarizes the Test 2 results. In Test 2, the transmissions of 1000 and 1110 failed in the nonlinear case, with the intended 1000 transmission resulting in 1001, and the intended 1110 transmission resulting in 1101.

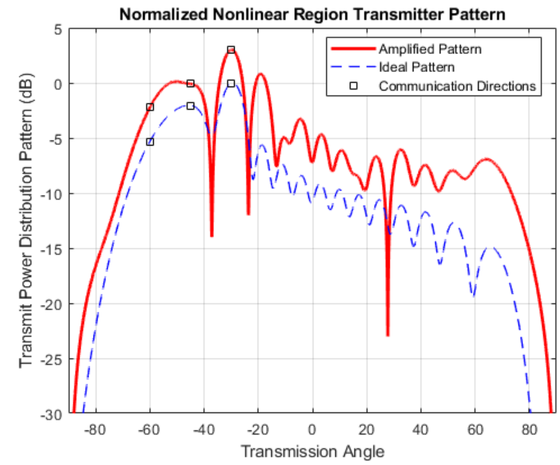

Fig. 12. Nonlinear amplifier effect on the transmission pattern for the second set of communication symbols. The transmission pattern does demonstrate distortion from the ideal pattern.

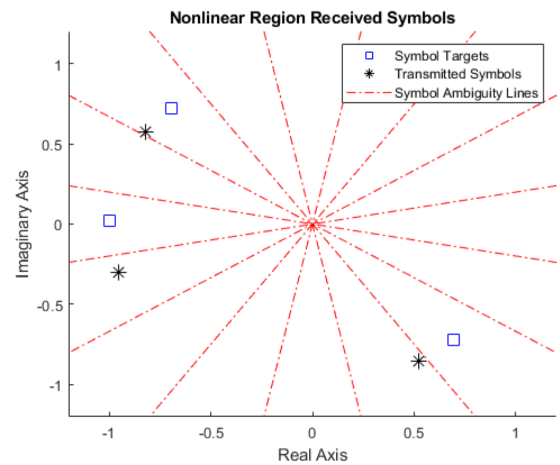

Fig. 13. The effect of nonlinear amplifier performance on the second set of communication symbols. In this test two symbols are transmitted incorrectly, namely the communication symbols in the -45° and -60° directions relative to boresight.

TABLE II: TEST 2 INTENDED AND SIMULATED TRANSMIT SYMBOL PHASE VALUES FOR LINEAR AND NONLINEAR AMPLIFICATION

Transmit Angle (°)	Bits	Symbol Phase (°): Intended	Symbol Phase (°): Linear	Symbol Phase (°): Nonlinear	Nonlinear Pass/Fail
-30	0110	135	130.77	144.94	Pass
-45	1110	-45	-47.79	-58.40	Fail
-60	1000	180	177.90	-162.66	Fail

These tests on two different sets of communication symbols both demonstrate similar effects of amplifier nonlinearities. When amplifiers operate in their linear regions, both the transmission pattern and the communication symbol integrity are maintained. As amplifiers operate in their nonlinear regions, however, both the transmission patterns and the transmitted symbols are distorted, significantly degrading directional communication accuracy.

Given this demonstration that in-beam distortion of even phase-modulated signals occurs, future work should be performed that should examine how the induced distortion errors in the transmitted messages can be corrected. Both predistortion and impedance tuning methods may be useful for linearizing the power amplifiers, allowing the originally intended transmission currents to excite the antennas, permitting the appropriate directionally modulated signals to be transmitted in the indicated directions.

V. Conclusions

Undesirable effects of power-amplifier nonlinearities on the integrity of directionally modulated signals transmitted from phased arrays have been observed in a simulation study. Even on PSK signals, where amplitude is unimportant, the distortion on the transmitted phase of the signals can be significant, based on the observed amplitude and phase distortions of the currents entering the element antennas. Significant distortions to the ideal signals can lead to severely degraded communication effectiveness. Further study is warranted to develop more detailed analysis of the translation of individual element nonlinearities to the overall directional modulated transmissions, and to assess possible solution mechanisms that can maintain system efficiency while linearizing performance in a way that provides the desired transmissions. Useful techniques may include predistortion (for linearization) or impedance tuning techniques to optimize power gain while limiting distortion. Both predistortion [11] and impedance tuning [12] have been demonstrated as successful approaches to resolve out-of-beam distortions in array multi-beam transmissions, and may also be able to improve signal integrity in intended transmission directions.

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