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Published in:
IEEE Access

DOI:
10.1109/ACCESS.2023.3311487

Published: 01/01/2023

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Over-the-Air Suppression of Third-Order Intermodulation in a Two-Beam Steered Amplifier-Antenna Array

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This work was supported by Business Finland through the Radio Frequency Sampo Project.

ABSTRACT The effect of load-pull on 3rd order intermodulation (IM3) radiation characteristics of a transmitting active phased array is studied and a general model for predicting the spatial distribution of fundamental tones and intermodulation products is introduced. The used data is obtained from a load pull measured amplifier prototype and a simulated linear antenna array, which are used in co-simulation of the system behavior. The system is optimized for maximum main tone beam powers with a two-tone excitation while satisfying a signal-to-IM3 ratio (S13R) of 40 dB. In this paper, we demonstrate the case, where two separate beams are scanned independently from each other. The used load-pull system model achieves on average an improvement of 10.4 dB for S13R, when compared to traditional small-signal modelling, while decreasing the main beam power densities by only 0.3 dB when compared to traditional small-signal modelling. Optimizing for S13R degrades beam pattern by increasing beamwidths and decreasing sidelobe levels (SLL).

INDEX TERMS Active phased arrays, amplifier, beam-steering, intermodulation, load pull, third-order intermodulation product (IM3).

I. INTRODUCTION Future of 5G wireless communication relies on wide scale on beamforming capable systems. Beamforming requires multiple antenna elements, and thus modern systems will be composed of arrays of active antennas (AA) with amplifiers connected to each antenna element to facilitate the high power and efficiency demands in transmission [1]. Large number of elements, in case of mutual coupling between them, results in systems which are tunable for different needs, but which also exhibit higher non-idealities like non-linearity.

There are currently two trends in designing systems of AA. The traditional way of matching the components separately to 50 Ω is being replaced by the so called active integrated antenna (AiA) concept, in which the amplifier and antenna impedances are designed to match directly [2], [3], [4], [5].

By removing elements between the antenna and amplifier, especially the isolator, losses and complexity can be reduced.

The trend towards maximal utilization of space and integration means that more and more non-idealities need to be taken into account. One such effect is load-pull of the amplifiers connected to individual antenna elements [6], which arises from removing the isolators between amplifiers and antennas as well as tighter spacing of antennas. Load-pull is caused by the active reflections when an antenna array with inter-element coupling is fed. The load-pull effect is dynamic when the array is used for beam steering. Dynamic output impedance makes the single-input amplifier models inaccurate in modern beamforming systems.

In future systems, one transmitter system should simultaneously serve multiple users in adjacent frequency bands using modulated signals while sharing the same radio frequency (RF) amplifiers. This causes intermodulation distortion (IMD), which can hinder user data rates or force the transmitter to be backed off in order to meet, for
example, WLAN standards [7]. Back-off however reduces amplifier efficiency, which is a reason for current popularity to research amplifiers with high back-off efficiencies, like Doherty power amplifiers (DPA) [8].

In a system with multiple single tone beams, IMD can be spatially reduced by using different phase distributions for each frequency to minimize IMD radiation pattern overlapping at the used frequencies [9]. Reduction of IMD in a situation with multiple beams with modulated signals can be done with beams that are narrow by steering the beams to different directions [10]. With modulated signals, individual beams still suffer from IMD caused by their own signals. This IMD cannot be alleviated with pattern configuration alone. In these instances, distortion controlling can be used to disassociate the phase dependency of IMD to the carriers caused by a single signal, which diverges the patterns [11]. A more sophisticated approach is to use digital pre-distortion (DPD), which aims to limit the radiation of IMD completely, by careful control of the input feeds to the amplifiers, while constantly monitoring the output [12]. Present DPD aims to take into account the effect of load-pull by using polyharmonic distortion (PHD) modelling [1], [13], [14] or neural networks [15].

When designing these future systems, more non-idealities should be taken into account at the earliest stages of development. When amplifiers and antennas could previously be designed separately with a constant impedance boundary, present systems need to take into account the dynamic interaction between the two. IMD should also be accounted in this dynamic situation. Behavior of the 3rd order intermodulation products (IM3) has been analyzed in radiation [16], but the effect of load-pull has been ignored. Beam-steering is usually not performed in simulations which take load-pull into account [17].

In this article, we present a method to take into account the amplifier load-pull effect in a transmitting amplifier-antenna system with a two-tone excitation. The model predicts IM3 product and main tone outputs, which are used to calculate radiation characteristics of the system. The model is similar to an iterative method in [18], but it uses directly interpolated measured load-pull data rather than an extracted PHD model.

We then apply the model in simulations to study a four-element transmitting amplifier-antenna and how feed tuning can be used to suppress IM3 interference in main beam directions when the main tones are steered independently from each other. The concept of the suppression is presented in Fig. 1. Optimized results obtained with the system model incorporating load-pull is compared to feeds calculated from the system models using linear and non-linear amplifier models with no load-pull. The results concentrate on field strength in the steer direction in main and IM3 frequencies. Sidelobe levels, beamwidths and power-added-efficiencies (PAE) are reported. To the best of the author’s knowledge, this is the first time a transmitter system has been modelled with load-pull data of an amplifier, which accounts for the IM3 output.

II. AMPLIFIER AND SYSTEM MODELS

The general amplifier-antenna system with $n$ elements is illustrated in Fig. 2. The system consists of an antenna array with RF amplifiers connected to each antenna input. Each amplifier is fed with a two-tone signal and the amplified tones along with the IM3 frequencies are fed into the antenna array. The amplifier output signals $b_2$ couple through the antenna elements back into the outputs of the amplifiers, causing reflected waves $a_2$ according to

$$a_2^k = \begin{bmatrix} a_{2,1}^k \\ \vdots \\ a_{2,n}^k \end{bmatrix} = \begin{bmatrix} S_{11}^k & \cdots & S_{1m}^k \\ \vdots & \ddots & \vdots \\ S_{n1}^k & \cdots & S_{nm}^k \end{bmatrix} \begin{bmatrix} b_{2,1}^k \\ \vdots \\ b_{2,n}^k \end{bmatrix} = St_k b_2^k, \quad (1)$$

where $St_k$ is the $S$-matrix of the antenna array at frequency $f_k$. $a_2$-waves cause load-pull effects in the amplifiers. We therefore model the system by combining the models of the

![Figure 1. IM3 suppression concept. In traditional feeding (top) the IM3 pattern might align with main beams. With system analysis, feeds can be tuned to steer IM3 away from main beam directions (bottom).](image1)

![Figure 2. General amplifier-antenna system.](image2)
antenna and the amplifiers with an iterative algorithm to calculate the system response. In this section, the modelling for separate components and the system are presented. First, the amplifier model is described. Second, the antenna calculations are presented. Last, the iterative algorithm used for calculating the full system output is introduced.

A. AMPLIFIER MODEL
In our previous paper [19], we modelled an amplifier by accounting the effect of load-pull on its operation. An output wave $b^{f}_2$ of a single amplifier with a continuous wave (CW) single-tone excitation is a function $B$ of input wave $a^{i}_1$, output reflected wave $d^{i}_2$ and frequency $f_k$

$$b^{f}_2 = B(a^{i}_1, d^{i}_2, f_k).$$

(2)

A traditional way to model an amplifier under load-pull is to relate the operation of the amplifier to the output reflection coefficient $\Gamma^{f}_2$, but because of the multi-port system and active nature of the reflections in our study, we use $a^{i}_2$. This removes the redundant step of calculating $\Gamma^{f}_2$. $a^{i}_2$ relates to the output reflection coefficient $\Gamma^{f}_2$ with

$$a^{i}_2 = \Gamma^{f}_2 d^{i}_2. \tag{3}$$

In this study, we extend our previous amplifier model (2) to cover two-tone measurement data in order to capture IM3 distortion behavior. The new single amplifier model is a set of functions $B$, which return the output waves $b_2$. Each function in the set is used to calculate output at a single frequency. For amplifier $i$ the set is

$$B_i(a^{i}_1, \Gamma^{f}_2) = \begin{bmatrix} B^{i}_1(a^{i}_1, \Gamma^{f}_2, i) \\ B^{i}_2(a^{i}_1, \Gamma^{f}_2, i) \\ \vdots \\ B^{i}_m(a^{i}_1, \Gamma^{f}_2, i) \end{bmatrix} = \begin{bmatrix} b^{i}_1 \\ b^{i}_2 \\ \vdots \\ b^{i}_m \end{bmatrix} = b^{i}_2 \tag{4}$$

where

$$a^{i}_1 = \begin{bmatrix} a^{i}_1^{(1)} \\ a^{i}_1^{(2)} \\ \vdots \\ a^{i}_1^{(m)} \end{bmatrix}, \quad \Gamma^{f}_2 = \begin{bmatrix} \Gamma^{f}_2^{(1)} \\ \Gamma^{f}_2^{(2)} \\ \vdots \\ \Gamma^{f}_2^{(m)} \end{bmatrix}.$$ 

$B$ and $\Gamma^{f}_2$ contain at minimum two elements, the ones corresponding to the input signal. Additional frequencies which affect the amplifiers operation, mainly intermodulation terms and harmonics, could be included as well.

B. ANTENNA MODEL
A single-port antenna is a linear device, which can be described with the frequency dependent matching $S^{s}_{11}$ and the far-field pattern $E^{s}_{1}(\theta, \phi)$. A multi-port antenna has a scattering matrix $S$ and an element far-field patterns $E_{i}(\theta, \phi)$. Adhering with the notation in Fig. 2, $S$-parameters relate the input waves $b^{f}_2$ into the antenna ports to the reflected waves $a^{i}_2$ with (1).

The total electric far field $E^{s}_{\text{tot}}(\theta, \phi)$ is a superposition of all element fields $E^{s}_{i}(\theta, \phi)$ multiplied by the element excitation wave $b^{f}_2$.

$$E^{s}_{\text{tot}}(\theta, \phi) = \sum_{i=1}^{n} E^{s}_{i}(\theta, \phi)b^{f}_2. \tag{5}$$

The corresponding far-field power density $F^{s}(\theta, \phi)$ is calculated by

$$F^{s}(\theta, \phi) = \frac{|E^{s}_{\text{tot}}(\theta, \phi)|^2}{2\eta}, \tag{6}$$

where $\eta$ is the free-space wave impedance.

C. LOAD-PULL SYSTEM MODEL
The system model calculates the power waves inside the system as well as the radiation from the antenna. The algorithm for the calculation is iterative. The reflection coefficients of all amplifiers are affected by the output of all amplifiers, and vice versa. The waves always satisfy (1). The amplifier operation in a coupled system can be solved by iteratively calculating reflections and the output waves from the previous solution, until the waves converge to a stable result. With the solved waves, the radiation from the antenna can be calculated with (5).

At the initial step of the algorithm, $t = 0$, reflection coefficients and waves at the amplifier-antenna interface at all frequencies, i.e., $\Gamma^{f}_2, b^{f}_2$ and $a^{i}_2$, are zero. After the initial step at each subsequent step $t + 1$, $b^{f}_2^{(t+1)}$ are calculated with $\Gamma^{f}_2$ using (4), then $a^{i}_2^{(t+1)}$ are calculated with (1) and new $\Gamma^{f}_2^{(t+1)}$ from the solved $a^{i}_2^{(t+1)}$ and $b^{f}_2^{(t+1)}$ with (3). At the end of the step, if $\max |\Gamma^{f}_2^{(t+1)} - \Gamma^{f}_2^{(t)}| \leq \varepsilon$, the algorithm terminates and the radiation of the antenna is calculated with the converged $b^{f}_2^{(t+1)}$. If $\max |\Gamma^{f}_2^{(t+1)} - \Gamma^{f}_2^{(t)}| > \varepsilon$, then the algorithm continues. Input waves $a^{i}_1$ are kept constant for the iteration. The algorithm is presented in Fig. 3.

III. SIMULATED SYSTEM STUDY
With the general system model in Section II, we perform an example system level simulation study using a load-pull measured amplifier prototype and an EM-simulated antenna array. The used components are only examples, and not chosen because of particular qualities. The system diagram is presented in Fig. 4. The objective of the study is to lower IM3 radiation interference in a situation, where the two main tones are steered independently from each other. This reduction is
done by tuning the feeds $a_1$ into the amplifiers. The study is performed at 2.5 GHz frequency with a 10 MHz tone spacing, making the main tones $f_1 = 2.495$ GHz and $f_2 = 2.505$ GHz. The corresponding IM3 frequencies are $f_3 = 2.485$ GHz and $f_4 = 2.515$ GHz.

This section is organized as follows. First, the system structure, the measured amplifier prototype, and the simulated antenna array, are presented. Second, the performance metrics used to evaluate the system are introduced. Third, the optimization target and reference methods used to calculate optimal feeding amplitudes and phases are described. Finally, the load-pull data used to model amplifier outputs are discussed.

### A. SYSTEM SETUP

The studied example system is a four-element transmitting amplifier-antenna array. Four amplifiers are directly connected to the inputs of a 4-element linear array. The input waves $a_1$ of the amplifiers can be tuned in order to control the radiation patterns of the system. The phases $\psi_{ij}$ of $a_{1,i}$ into a single amplifier can be chosen independently. The amplitude $A_{1,i}$ of $a_{1,i}$ are the same, making $a_{1,i}$

$$a_{1,i} = \begin{bmatrix} a_{1,i} \\ a_{1,i} \\ a_{1,i} \\ a_{1,i} \end{bmatrix} = A_{1,i} \begin{bmatrix} \exp(j\psi_{1_{i1}}) \\ \exp(j\psi_{1_{i2}}) \\ \exp(j\psi_{1_{i3}}) \\ \exp(j\psi_{1_{i4}}) \end{bmatrix}. \quad (7)$$

The inputs to different amplifiers can be chosen independently.

The used amplifier prototype is Freescale Semiconductor class A MMG38151BT1 mounted on a test board made of FR-4. The prototype is shown in Fig. 5. The measured power-to-the-load ($P_L$) for main tones and IM3 as well as IM3-to-carrier are plotted in Fig. 6. OIP3 of the measured
amplifier is 25.2 dBm and $P_{1dB}$ is 14 dBm. Fig. 7 presents the measured powers of $b_2$-waves of main tones and IM3 products, as well as the IM3-to-carrier levels for these powers when main tone impedances are swept over the Smith chart. Typically contour plots are drawn for $b_2$-waves, but because $b_2$-waves are the waves exciting the radiated fields, we have opted to plot the parameter more prominent for this study.

The array used in this study is a 4-element linear array with patch antenna elements and matching circuits at element ports. Fig. 8 illustrates the array geometry and a single element size. Fig. 9 shows the matched antenna S-parameters for the first and second elements, as well as the ideal matching circuits at the element ports. Symmetrical S-parameters are excluded. The matching circuit is used to match the antenna elements when combined into an array, and it is identical for all elements. The element patterns in the plane of the array for elements 1 and 2 are shown in Fig. 10.

B. OPTIMIZATION GOAL AND REFERENCES

The optimization goal has two targets. First, to keep signal-to-IM3 ratio (SI3R) in the main beam directions $\theta^f_k$ above a predefined limit for both main tone frequencies.
The definition of SI3R is

$$\text{SI3R}^{f_1/2} = \frac{F^{f_1/2}(\theta^{f_1/2})}{\max(F^{f_3}(\theta^{f_3/2})), F^{f_4}(\theta^{f_4/2})},$$  

(8)

where \(f_3\) and \(f_4\) are the IM3 frequencies. Second, while maintaining the SI3R above the limit, optimization maximizes \(F^{f_1/2}(\theta^{f_1/2})\) of the frequency with lower radiated power density.

This study uses two reference methods in calculating the feeding weights to compare to weights calculated with the load-pull included model. System behavior with all weights is finally evaluated with the load-pull model. The first reference is a linear reference (later LIN), which can only take into account the behavior at the main tones. LIN feeds \(a_1\) are driven at constant input power, \(P_{\text{tot}} = -2\) dBm and only phases are tuned when feeding weights are calculated with LIN. The phases are calculated from array geometry similar to the progressive phase shift. LIN cannot predict IM3 patterns. It is only used as a base line for main tone patterns and unpredicted SI3R levels.

The second reference used to calculate the weights is a non-linear case (later NLIN). NLIN uses the amplifiers measured response when the load is matched. This effectively takes into account the AM-AM distortion as well as the IM3 output levels. NLIN adjusts phases \(\varphi\) and amplitudes \(A\) freely in order to keep SI3R levels above the optimization target threshold. The model lacking the ability to take the load-pull effect into account in the system behavior will lead to greater inaccuracies in poorly matched cases.

Optimization with the load-pull accounted system model (later LP) and NLIN are done with a genetic algorithm. The input phase resolution for the three cases is \(5^\circ\) and the input power resolution is 0.5 dB.

**C. LOAD-PULL DATA MODELLING**

In this study, we are limiting the number of \(\Gamma_2\) frequencies affecting the amplifiers to two main tones \(f_1\) and \(f_2\). Also, the MT2000 two-tone load-pull does not contain phase information of the output waves \(b_2\) but only the output powers \(P_{\text{out}}\).

As the output phases \(\varphi_{b_2}\) are required for calculating the beam steering, we calculate them analytically. We assume no AM-PM distortion, making \(\varphi_{b_2}\) at main tones be same as the input phases \(\varphi_{a_1}\)

$$\varphi_{b_2,i} = \varphi_{a_1,i}^{f_1/2}.$$  

(9)

Similarly, the IM3 phases are calculated analytically from the main tone phases with the relation

$$\varphi_{b_{2,i}}^{f_3/4} = 2\varphi_{a_1,i}^{f_1/2} - \varphi_{a_1,i}^{f_2/4},$$  

(10)

where \(f_3\) and \(f_4\) are the lower and higher IM3 frequencies, respectively. With the separation of phase and powers, the amplifier load-pull models for \(b_{2,i}\) used in this study are

$$b_{2,i} = \begin{bmatrix} b_{2,i}^{f_1} \\ b_{2,i}^{f_2} \\ b_{2,i}^{f_3} \\ b_{2,i}^{f_4} \end{bmatrix} = \begin{bmatrix} B_i^{f_1}(p_{1,i}, \Gamma_{2,i}) \exp(j\varphi_{b_{2,i}}^{f_1}) \\ B_i^{f_2}(p_{1,i}, \Gamma_{2,i}) \exp(j\varphi_{b_{2,i}}^{f_2}) \\ B_i^{f_3}(p_{1,i}, \Gamma_{2,i}) \exp(j\varphi_{b_{2,i}}^{f_3}) \\ B_i^{f_4}(p_{1,i}, \Gamma_{2,i}) \exp(j\varphi_{b_{2,i}}^{f_4}) \end{bmatrix}.$$  

(11)

AM-PM can usually be ignored when operating amplifiers in the linear region. Near compression, where efficiency is higher, non-linearities including AM-PM are more profound, and should be taken into account when possible. Disregarding AM-PM can effect sidelobe levels and nulls, but has lower impact on main beams. The general model described in Section II takes AM-PM into account and can be used in high compression, even though our case study does not accommodate that.

**IV. RESULTS**

The system described in Section III is analyzed when the two main tone beams are independently steered from \((\theta, \phi) = (60^\circ, 0^\circ)\) to \((\theta, \phi) = (60^\circ, 180^\circ)\) on the H-plane. The beams are scanned in \(15^\circ\) steps and all combinations of beam steer directions are simulated. The used SI3R level for the optimization goal of NLIN and LP is 40 dB.

Example patterns for a single steer combination for the three different feeding cases LIN, NLIN, and LP are...
TABLE 1. Input feed powers $P_{in,i} = |a_{f1,i}|^2/2$ and phases $\phi_{f1,i}$ for the example patterns.

<table>
<thead>
<tr>
<th>Case</th>
<th>LIN</th>
<th>2.495 GHz</th>
<th>2.505 GHz</th>
<th>2.495 GHz</th>
<th>2.505 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P_{in}$ (dBm)</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>Phase (°)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE 2. Amplifier $b_{2}$-wave output powers $P_{out,i} = |b_{f2,i}|^2/2$ for the example patterns.

<table>
<thead>
<tr>
<th>Case</th>
<th>LIN</th>
<th>2.495 GHz</th>
<th>2.505 GHz</th>
<th>2.495 GHz</th>
<th>2.505 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P_{out}$ (dBm)</td>
<td>10.6</td>
<td>10.5</td>
<td>10.5</td>
<td>10.6</td>
<td>10.5</td>
</tr>
<tr>
<td>$f$</td>
<td>2.485 GHz</td>
<td>2.515 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P_{out}$ (dBm)</td>
<td>-14.1</td>
<td>-13.9</td>
<td>-14.0</td>
<td>-14.0</td>
<td>-15.9</td>
</tr>
<tr>
<td>$f$</td>
<td>2.485 GHz</td>
<td>2.515 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P_{out}$ (dBm)</td>
<td>-11.5</td>
<td>12.6</td>
<td>11.7</td>
<td>12.8</td>
<td>11.6</td>
</tr>
</tbody>
</table>

For the LIN pattern, all four beams collimate in the same direction resulting in a S13R of 24.6 dB. As IM3 output powers decrease 2 dB/dB faster than main tone outputs when input power is decreased, input powers should be decreased by 8 dB to achieve S13R target level of 40 dB with LIN. The decrease would directly translate to main tone beam powers, and they would be lowered by 8 dB. LIN manages to decrease S13R dramatically by slightly steering off the main beams from the steer direction, while increasing the input powers. The steer is to different directions as to exploit the relation between IM3 and main tone phase products. The total power input to amplifiers is larger with LIN than with LIN, as can be seen in Table 1, but they have not increased evenly. S13R requirement of 40 dB is not met by LIN or NLIN, whereas LP has met the requirement. LP has also increased the power density of the main tones by 0.6 dB compared to LIN. Both NLIN and LP suffer from a general pattern degradation, with sidelobe levels increasing by around 6 dB and 5 dB, respectively. In addition, the half-power beamwidth increases slightly for both. The maximum IM3 $F$ has increased by around 5 dB for NLIN and 14 dB for LP.

The normalized S13R of the simulated cases are shown in Fig. 12. The plot is normalized to 40 dB level, which was shown in Fig. 11. Corresponding powers and phases of the input feeds and amplifier output powers are shown in Tables 1 and 2, respectively. Output phases are omitted from Table 2, as they are analytically calculated from input phases with (9) and (10).
used as the optimization target for SI3R. In the LIN results, two main tones having the same phase shift is seen in a diagonal area where SI3R is below $-10$ dB. This causes all the beams, main and IM3, to collimate, as the IM3 phase shifts have the same value to main tones, as can be verified with (10). Furthermore, there are multiple points in the LIN results, $(\theta^{f_1}, \theta^{f_2}) = (15^\circ, 15^\circ)$ for example, where the normalized SI3R is above $0$ dB. In these directions, the phase shifts of IM3 products form nulls in main tone directions. NLIN achieves SI3R above the goal of $40$ dB in most of the directions. There are certain directions, however, where the ignored load pull in NLIN modelling causes the SI3R to drop below the limit. This could effectively be tackled by having a marginal increase in the goal to accommodate the final error to keep SI3R above the wanted level. LP achieves the required limit in all directions for both $f_1$ and $f_2$ simultaneously.

Fig. 13 shows the far-field power patterns $F$ of the simulated cases normalized to LIN maximum. LIN is behaving as expected, main tones reducing smoothly with the steer angle, with $-3$ dB steer range being approximately $43^\circ$ for both frequencies. With NLIN and LP, the behavior is more erratic. LIN has generally SI3R at levels of $-5$ dB below the wanted $40$ dB, so NLIN and LP have that much to improve. This SI3R improvement naturally leads to $F$ decreasing as a trade-off, as mentioned previously. The trade-off is however lessened with NLIN and LP, compared to just limiting amplifier input powers evenly. NLIN decreases generally over $1$ dB, but less than $3$ dB, whereas LP typically decreases less than $1$ dB. On average, taking load-pull into account yields approximately $1$ dB increase in $F$ when SI3R is limited, when comparing NLIN and LP. In a few directions, $(\theta^{f_1}, \theta^{f_2}) = (-15^\circ, 15^\circ)$ as the most prominent one, $F$ increases with NLIN and LP when compared to LIN. In this mentioned direction, LIN meets the SI3R requirement and exceeds it by $5$ dB. In this situation, NLIN and LP have a chance to optimize $F$ while decreasing SI3R and still adhere to the limit.

In Figs. 14 and 15 the sidelobe levels (SLL) and half-power beamwidths of the main tones are compared with the simulated cases. LIN SLLs decreases smoothly with the steer angle, whereas NLIN and LP SLL suffer from uneven feeding. As a specific example, in Fig. 11 is the situation where both main tones point towards broadside. The maximum SLL for LIN, NLIN and LP are $-10.8$ dB, $-4.8$ dB and $-7.1$ dB, respectively. Generally, it can be said, that for both NLIN and LP, the SLL has increased in the areas where SI3R needs considerable improvement compared to LIN. For example, the diagonal where main tones collimate with LIN, both NLIN and LP have increased the SLL level. Half-power beamwidths
of NLIN and LP are not as much effected, when compared to LIN. Generally, the beamwidths increase by 1° or 2°, the broadside direction being most effected. In Fig. 16 is the power-added-efficiency (PAE) of the system with NLIN and LP compared to LIN. PAE for the system is calculated with

\[
\text{PAE}_{\text{SYS}} = \sum_{i=1,2} \frac{P_{\text{OUT}, \text{TOT}}^i - P_{\text{IN}, \text{TOT}}^i}{P_{\text{DC}}},
\]

where \(P_{\text{OUT}, \text{TOT}}^i\) and \(P_{\text{IN}, \text{TOT}}^i\) are the total output and input powers at the main tones and \(P_{\text{DC}}\) is the DC power used by the amplifier. PAE of LIN is almost constant being 8.5% on average with a variation being within 0.1% over whole steer range and thus not plotted. Generally, neither NLIN or LP do not improve PAE drastically, change to LIN being mostly within 1%. The lack of change is accounted to the fact that LIN is driven quite close to compression, which is very close to the highest attainable efficiency.

Table 3 summarizes the findings in our case study. Whereas NLIN and LP both take IM3 into account in operation, NLIN cannot be used in co-designing modern amplifier-antenna systems for the lack of modelling the effects of load-pull. LP on the other hand requires more complex measurements to achieve modelling of amplifiers to account dynamic reflections in a coupled antenna array.

V. CONCLUSION

We have shown that by taking into account the load-pull effects of an amplifier, the amplifier-antenna performance can be improved in respect to radiated IM3 distortion. Considering only the IM3 and main tone behavior of the amplifiers without load-pull can cause an error in SI3R of 2.5 dB even with −20 dB active reflection magnitudes. Taking the load-pull into account increases SI3R generally by 10.3 dB while decreasing main beams by 0.3 dB, whereas equal traditional feeding would require the main beam powers to decrease by 5 dB to achieve the same SI3R improvement. The modelling of load-pull effect in a transmitter system could enable tackling integration problems in an early stage of system design, and allow making changes to components before prototyping.

REFERENCES


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