Experimental Investigation of Decoupling Effect on the Nonlinearity of Power Amplifiers in Transmitter Array

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Abstract – In a practical compact massive multiple-input multiple-output (MIMO) transmitter array, each antenna or subarray is connected to an independent power amplifier (PA) with a modest power capacity in order to avoid the challenging demand of high-power capacity of a single PA for the whole array and to facilitate the power dissipation of the transmitter array. In this case, there is simply not enough space for an isolator between the antenna and the PA. As a result, the array mutual coupling changes the load impedances of the PAs and thus further increases the MIMO transmitter’s nonlinearity. In this work, the decoupling effect on the transmitter array’s linearity is investigated experimentally by using an array prototype with PAs. The mutual coupling of the array can be effectively suppressed using a hybrid decoupling structure. Two continuous-wave (CW) signals at different frequencies are injected into the PAs, and the output signal of each PA is measured via a coupler. The measured results show that with effective mutual coupling reduction, the PA interference is greatly suppressed by up to 16 db and the amplitude of the desired signal is enhanced by up to 10 db.

Index Terms – mutual coupling, nonlinearity, power amplifier, transmitter array.

I. INTRODUCTION

The massive multi-input multi-output (MIMO) has been one of the key enablers for current and future wireless communications [1], [2]. Reduction of the power consumption and improvement of the transmitter linearity in a massive MIMO system has become a research hotspot. By configuring a large number of channels and antenna elements, the massive MIMO technique brings great performance enhancement, yet also introduces many thorny problems. Among them, the problem of nonlinear distortion of the power amplifiers (PAs) is particularly prominent [3]-[6]. The PAs are important modules in a MIMO transmitter array. In a practical MIMO transmitter array, each antenna or subarray is connected with an independent power amplifier (PA) with a modest power capacity instead of using a single PA with high-power capacity to feed the whole array. In this way, the transmitter can be more robust and cost-effective, and the multi-PA scheme also facilitates the power dissipation in the transmitter front-end. Moreover, for a compact massive array, there is not enough space for an isolator between the antenna and the PA. As a result, the mutual couplings between the elements in a MIMO array will change the active port impedance, resulting in mismatch between the antenna and the PA. In the presence of mutual coupling, the outputs of the PAs will interfere with each other, increasing the nonlinearity of the PA.

Figure 1 shows a schematic model of a MIMO transmitter array with PAs. Each element in the array is connected with a PA. The incident wave in the i-th PA (a₂,i) is dependent on the mutual couplings between antenna elements and the reflected wave in j-th PA (b₂,j), as mathematically described in (1). In other words, the mutual coupling changes the load impedances of the PAs, resulting in deteriorations of the PA efficiency and linearity.

\[ a_{2,i} = \sum_{j=1}^{N} s_{i,j} b_{2,j}, \]  

(1)

where the \( s_{i,j} \) is the S-parameter between i-th and j-th element.

Various PA behavior models have been proposed to optimize the linearity [7] where the PA parameters are characterized by signal-tone or multi-tone excitation in measurements [8], [9]. A DC behavior was extended to a PA model [5] to predict the linearization and efficiency of PA in the presence of mutual coupling. A 4×1 array with 4 PAs was designed in [6], and the spectral results at the PA output were given to show the spectral regrowth with/without mutual coupling. Nonlinear
In this paper, an antenna array prototype with a removable decoupling structure is connected with PAs. The PA output signals with and without array decoupling are measured. The experimental results show that the mutual coupling not only deteriorates the linearity but also creates strong interference. More importantly, it is shown that with effective array decoupling, both interference and spurious signals are greatly suppressed, and the desired signal is enhanced. To the best knowledge of the authors, this is the first experimental work demonstrating the decoupling effect on the linearity of a transmitter array.

II. COUPLING SUPPRESSION IN MIMO ARRAY

The MIMO array used in the test is a 4×4 base station (BS) array with a 57-mm horizontal inter-element spacing (0.38λ₀, where λ₀ is the free space wavelength at center frequency of 2.0 GHz) and a 117-mm vertical inter-element spacing (0.75λ₀). The four dual-polarized elements in each array column are combined using a power divider into one subarray with two antenna ports (for the ±45° polarizations), which is a typical BS array configuration.

The array has an operation band of 1.7-2.2 GHz. Due to the close horizontal inter-subarray spacing, the array suffers mutual coupling up to −15 dB. Different decoupling techniques have been reported in previous works, e.g., decoupling metasurfaces [12–14], decoupling resonators [15], defected ground structure [16], and dielectric decoupling superstrate [17,19]. In order to increase the decoupling bandwidth, a hybrid decoupling method has been designed to reduce the mutual couplings down to −30 dB at the center frequency. Figure 2 shows the coupling wave and decoupling mechanism between a two-element array. As shown in Fig. 2(b), both the neutralization board and metal baffle are applied to the array. The neutralization board is suspended above the antenna to produce a reflective wave that is opposite in phase to the coupling wave, reducing the mutual coupling between elements. The metal baffle is placed between the two antennas to suppress the propagation of the space electromagnetic wave. Detailed description about the BS array and the decoupling method can be found in [19].
that both the co-polarization and cross-polarization coupling between adjacent antennas (subarrays) has a significant reduction across the whole frequency band. The mutual couplings between adjacent elements are reduced to below −20 dB within 1.7-2.2 GHz, and the couplings at the center frequency point are less than −30 dB with a reduction of 15 dB.

III. MODEL DESCRIPTION OF POWER AMPLIFIER

Figure 5 shows the configuration of the PA module used in the experimental test. This PA module contains two identical PA channels, i.e., channel A and channel B. Each channel includes a coupled port at the PA output. The coupled port can be considered as a coupler, whose power is about 40 dB lower than that of the output. The signal characteristics of the PA’s output can be inferred by observing the output signal from the coupled port.

The output load-pull impedance of the PA and the corresponding waveform are shown in Figs. 6 (a) and (b), respectively. The parasitic parameters of the transistor are de-embedded during simulation and test, which means that the results are obtained from the intrinsic current source plane ($I_{gen}$ plane). The PA is biased with a gate voltage ($V_{GS}$) of −3.2 V, corresponding to a Class-F condition. The drain voltage ($V_{DS}$) is 10 V. The fundamental impedance of $Z(f_0)$ is kept within nearly 50 Ohms from 2.03 GHz to 2.17 GHz, the corresponding second harmonic impedance $Z(2f_0)$ and the third harmonic impedance $Z(3f_0)$ are located at short and open, respectively, as shown in Fig. 6(a). Under these impedances matching conditions, the drain voltage is approximately square wave, and the drain current is nearly half-wave rectified sinusoidal, which verifies the operation as Class-F mode [22], as shown in Fig. 6(b). The measured results of the PA are shown in Figs. 6(c) and (d). From 2.03 GHz to 2.17 GHz, the power added efficiency (PAE) is higher than 72%. The output power is larger than 30 dBm with a power gain larger than 11 - dB. Figure 6(d) depicts the Pout, PAE and Gain performances within 10 -dB input-power range at the center.
frequency of 2.1 GHz. The proposed PA is operating at the nearly $P_{-3}$ point when $P_{in}$=20 dBm.

Case 2: The input signal frequencies are set to $f_1$ = 2.13 GHz (inject to PA$_1$) and $f_2$ = 2.08 GHz (inject to PA$_2$) with 15-dBm amplitude.

Case 3: The input signal frequencies are set to $f_1$ = 2.10 GHz (inject to PA$_1$) and $f_2$ = 2.13 GHz (inject to PA$_2$) with 10-dBm amplitude.

### IV. MEASUREMENT SETUP AND RESULTS

#### A. Measurement setup

The BS array with and without the decoupling structure [19] is used to illustrate the decoupling effect on the linearity of the transmitter array. Two adjacent subarray ports of the same polarization are connected with two PAs (i.e., PA$_1$ and PA$_2$), while the rest of the subarray ports are terminated with 50-Ohm loads. Figure 7 shows the photo and schematic diagram of the measurement setup. Two continuous-wave (CW) signals with different frequencies from two signal generators are fed to the PAs. The PAs are fed by DC power supply where the DC voltage is 10 V. The coupled port of the PA is connected to a spectrum analyzer in order to observe the interference and nonlinearity of the PAs when loaded with the BS array with and without the decoupling.

The array without decoupling corresponds to the spectrum of high mutual coupling, and the array with decoupling corresponds to the spectrum of low mutual coupling.

Denote the two frequencies of the CW waves as $f_1$ and $f_2$, respectively. Three signal cases with different frequencies and amplitudes are used to illustrate the decoupling effect on the PA output spectrum.

*Case 1:* The input signal frequencies are set to $f_1$ = 2.05 GHz (inject to PA$_1$) and $f_2$ = 2.08 GHz (inject to PA$_2$) with 20-dBm amplitude.

*Case 2:* The input signal frequencies are set to $f_1$ = 2.13 GHz (inject to PA$_1$) and $f_2$ = 2.08 GHz (inject to PA$_2$) with 15-dBm amplitude.

*Case 3:* The input signal frequencies are set to $f_1$ = 2.10 GHz (inject to PA$_1$) and $f_2$ = 2.13 GHz (inject to PA$_2$) with 10-dBm amplitude.

#### B. Measured Spectrum of PA

The PA$_2$ output spectra for case 1 with (wi. dec.) and without decoupling (w.o. dec.), are shown in Fig. 8(a). If there were no mutual coupling or PA nonlinearity, the output spectrum from PA$_2$ should only contain the frequency of $f_2$ = 2.09 GHz. In the presence of mutual coupling and PA nonlinearity, however, the output spectrum from PA$_2$ contains multiple frequencies, as shown in Fig. 8(a). The interference signal at $f_1$ = 2.05 GHz with an amplitude of $-21.8$ dBm is mainly due to the array mutual coupling. In addition, two spurious signals at 2.13 GHz and 2.17 GHz are observed due to the PA nonlinearity in the presence of mutual coupling. After the decoupling structure [cf. Fig. 3] is applied to the BS array, the mutual coupling is reduced by 15 db (i.e., from
The interference and spurious caused by nonlinearity are suppressed, such as the interference signal at 2.10 GHz is reduced from −26.1 dBm to −33.8 dBm, the spurious signal at 2.16 GHz is almost completely eliminated, while the amplitude of the desired signal at $f_2 = 2.13$ GHz increases from −25.9 dBm to −15.6 dBm.

Table 1 summarizes the comparison of PA$_2$ output spectrum in the array with and without decoupling in three cases, all of which increase the desired signal amplitude and suppress interference and spurious signals.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement of desired signal / dB</td>
<td>6.8</td>
<td>4.1</td>
<td>10.3</td>
</tr>
<tr>
<td>Suppression of interference / dB</td>
<td>16.1</td>
<td>11.6</td>
<td>7.7</td>
</tr>
</tbody>
</table>

The results in Table 1 are for PA$_2$. The output results of PA$_1$ are similar, as shown in Fig. 9. After the mutual coupling in the array is reduced, the output spectrum result of PA$_1$ is that the desired signal is enhanced and
the interfering signal is suppressed. Table 2 shows the suppression level of interference signal for different amplitudes. When the amplitude of the input signal varies from 20 db to 10 db, the coupling reduction can bring obvious interference suppression effect.

V. CONCLUSION

A measurement-based characterization of the decoupling effect on the PA linearity in a transmitter array has been conducted in this paper. The experimental results show that the mutual coupling not only deteriorates the linearity, but also produces strong interference. For three cases with different frequencies and amplitudes, the desired signal could be improved by 4-10 db, and the spurious and interference signals could be suppressed by 7-16 db. It was demonstrated experimentally that decoupling could improve the PA linearity, reduce the interference, and enhance the desired signal in the transmitter array. Sci. China Inf. Sci.

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REFERENCES


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