Antenna Array Inter-Element Coupling impact on Linearization of Active Phased Array

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Abstract—The new generation of 5G mobile and inter-satellite communication systems are using mmWave active phased array (APA) which have up to hundreds of individual analog transmitter and receiver chains and antennas. When moving to high integration scenarios, the isolation between the array and the power amplifiers (PAs) is often removed. Since the array elements are electromagnetically coupled, the waves fed to the antennas are also driving the output ports of the PAs. This effect creates a possible variable load at the output of each PA, depending on steering angle and radiated power at each element in the array. In this system, the behavior of each PA cannot be fully described solely as a function of its input, as it will change according to the coupled signal. In this paper the inter-element coupling of a 4x4 planar patch antenna array and the resulting variation in output impedance of the PA connected to each patch is simulated by using computer simulation tool (CST). The impact of the inter-element coupling has been verified on linearization procedure of the active array.

Index Terms—Power amplifier (PA), digital pre-distortion (DPD), adjacent channel power ratio (ACPR), error vector magnitude (EVM), over the air (OTA).

I. INTRODUCTION

FOR radio links, high power and linear operation are required to achieve high data-rates while maintaining spectral efficiency and low current consumption. To fulfill the latest requirements for high data rate in the 5th generation of mobile and satellite communication, integrated steerable active phased array is a preferred solution [1].

In order to improve the efficiency of the active array, PA needs to operate as close to saturation region as possible. For achieving optimum output power and efficiency, output impedance of the the PA is not necessarily 50 ohm but needs be matched to optimum impedance [2]. In active array each PA is directly connected to an antenna without any isolator in between. Therefore the PAs' outputs impedance get a direct impact from antenna mismatch and the mutual coupling between the antennas [3]. The mismatch and mutual coupling between antenna elements of an array are not easy to foresee by mathematical model but still need to be considered due to their significant impact [4].

As a consequence the waves presents at PA output will travel in both directions and between the antenna elements. Fig. 1

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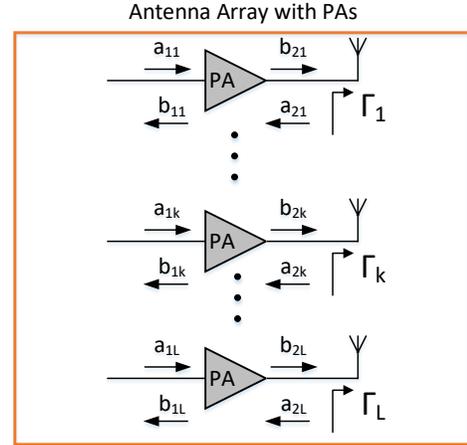Ming Shen, Aalborg University, Department of electronics systems (email: mish@es.aau.dk)

Fig. 1. Conceptual illustration of mutual coupling and reflection coefficients of antenna array including PAs.

shows block diagram of a generic antenna array including L antenna elements where a_{1k} is the incoming signal to the amplifier, b_{1k} is the reflected signal from PA input, b_{2k} is the output from the amplifier, and a_{2k} is the reflected signal from the antenna array at the k'th branch.

There is electromagnetic coupling between the elements of active arrays. Therefore the power injected to one element of the array will be coupled back to other elements and consequently to other PAs outputs. The magnitude of the coupling is dependent on the steering angle and the radiated power level. As illustrated in figure 1, for the k'th element of the array the effective reflection coefficient, (Γ_k), is defined as:

$$\Gamma_k = \frac{a_{2k}}{b_{2k}} = \frac{\sum_{i=1}^{L} Z_{ki} b_{2i}}{b_{2k}} \qquad (1)$$

Where the coupling between the k'th and i'th antennas are defined by the coefficients in scattering matrix, Z_{ki}, which are set by the characteristics of the antenna array. The elements in b_{2i} vector are complex coefficients for the the input to the antenna. Linearity of the active device connected to the k'th element of the antenna is related to the reflection coefficient Γ_k. This parameter is not only dependent on the reflection from the k'th elemnts but also dependent on the coupling from all other elements which is defined as load modulation. The impact of this load modulation on the digital pre-distortion

of the active phased array is described in this paper through simulation and verification.

This paper is organized as follows: Section I is the introduction. Section II is about the numerical modeling of the antenna array with CST Studio. Section III explains the simulation results. Section IV describes the mutual coupling impact on digital pre-distortion and finally, the conclusion of this work is presented in section V.

II. NUMERICAL MODELING OF THE ANTENNA ARRAY WITH CST STUDIO

A 4x4 planar patch antenna array is designed for this simulation. By placing 16 excitation pins and by appropriately phasing of the 16 feeds, a linear polarization with different steering angle can be generated. The substrate is a low-loss Rogers RO4403 with a thickness of 0.406 mm. The 3D geometry and design parameters of the substrate are shown in Fig. 2

An optimization of the patch dimensions and feed position was performed to improve the return loss of each patch to be approximately -25 dB at 28 GHz with sequential excitation. The time domain solver in CST MICROWAVE STUDIO® (MWS) was used with a Hexahedral mesh and a perfect matched layer (PML) boundary condition for the simulation.
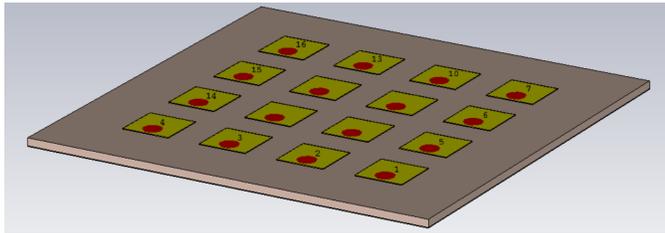
(a)

Name	Expression	Value
pat_sep	= 10.7 * 0.4	4.28
Patch_Width	= Parch_length	2.56
Parch_length	= 2.56	2.56
Ground_Size	= 22	22
Substrate_Height	= 0.406	0.406
Substrate_Size	= Ground_Size	22
Feeding_Point_Lenght	= 0.60	0.60
Feed_Impedance	= 50	50
Feeding_Point_Width	= 0.00	0.00
TT	= 0.035	0.035
Patch_Rotation	= 0	0
pat_num	= 4	4

(b)

Fig. 2. 4x4 planar patch antenna array: (a) Geometry; (b) PCB design parameters.

III. SIMULATION RESULTS

A. Sequential excitation

In the first step the 4x4 patch antenna is driven sequential i.e. one port is exited and all other ports are terminated with 50-ohm impedance. The S-parameters for port 1 with
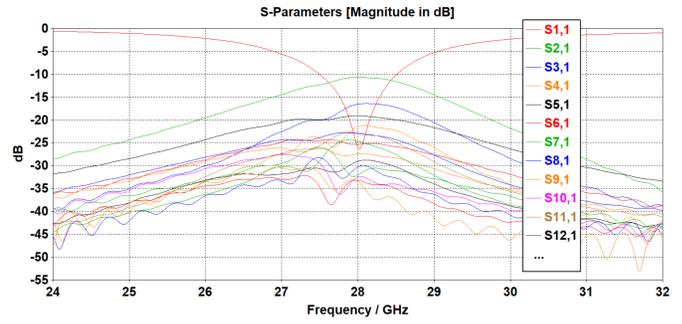

Fig. 3. Sequential S-parameters of each patch while the other 15 patches are terminated with matched impedance.

sequential excitation is shown in Fig. 3 as an example. All other ports behaves almost similar to port 1.

B. Simultaneous excitation

While exiting all ports, the steering angle is shifted horizontally in step of 3 degrees step, ie. 0, ±3, ±6, ±9, ±12 and ±15 degrees by adding appropriate phase shift to the excitation signal to each patch. The combined polar and 3D far-field results with steering angle of 0 degree and 9 degree are illustrated in Fig. 4 and Fig. 5 as examples.
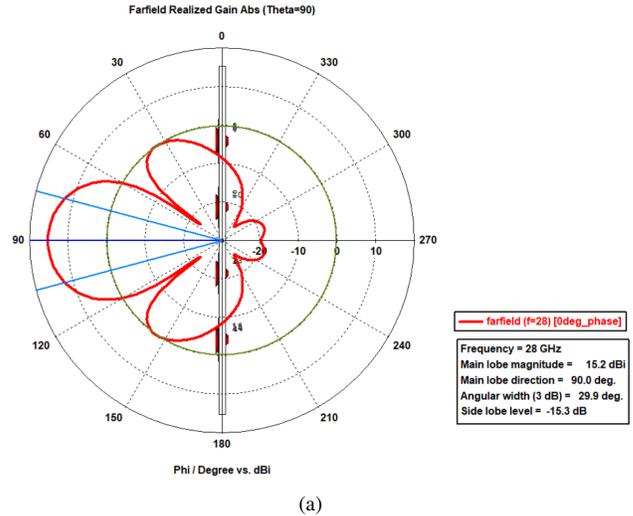
(a)
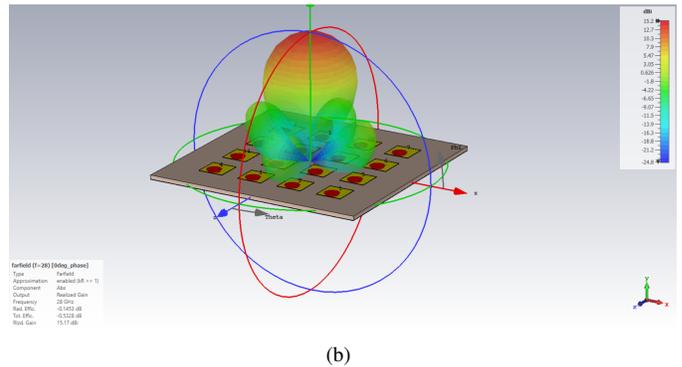
(b)

Fig. 4. Far-field simulation results with steering angle = 0 degree: (a) Polar; (b) 3D.
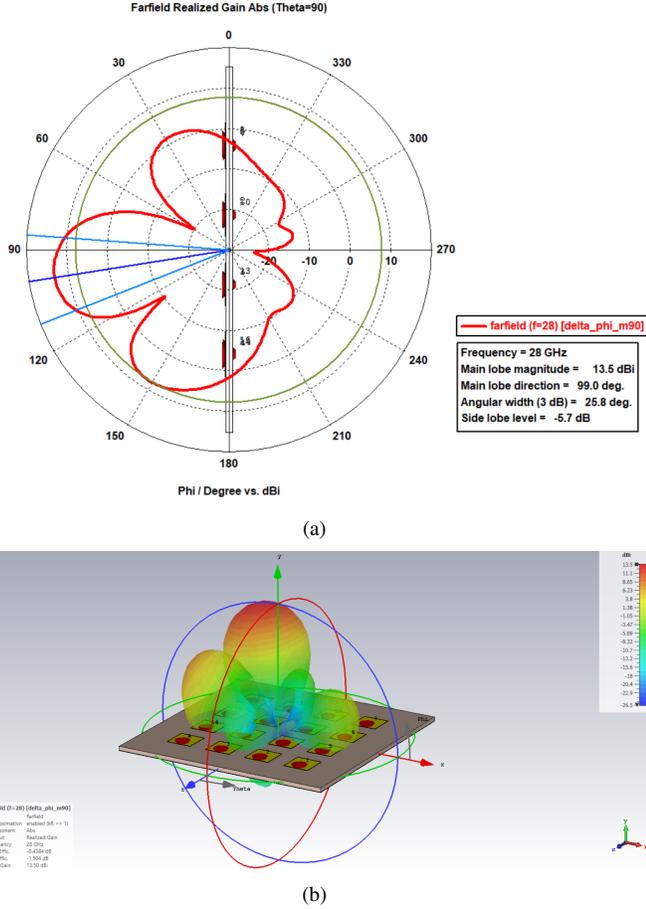
Fig. 5. Far-field simulation results with steering angle = 9 degree: (a) Polar; (b) 3D.

Fig. 6. S-parameter results for each patch, all ports simultaneously exited. (a) Steering angle = 0 degree; (b) Steering angle = 9 degree.

The resulting F-parameters for each patch while all patches are simultaneously exited is illustrated in Fig. 6. The S-parameters for e.g. patch number one of the array is calculated by simulation tool as following:

$$S_1 = \frac{b_1}{a_1} = \frac{\sum_{i=1}^{16} S_{1i}a_i}{a_1} \qquad (2)$$

where a_1 is the exited signal into antenna and b_1 is the reflected signal from the antenna array. This is equivalent to the reflection coefficient in (3). As it is shown in Fig. 6 for the case of 0 degree beam steering at 28 GHz frequency, taking patch number 13 as worst performed, the reflection coefficient is -8 dB, where it changes to -2.5 dB in case of 9 degree beam steering. This change of 5.5 dB varies the PA's output impedance and obviously impacts into the calibration and linearization procedure for whole array.

IV. MUTUAL COUPLING IMPACT ON DIGITAL PRE-DISTORTION

In section I the impact of mutual coupling between the antennas at PAs' outputs has been discussed and there is shown that the impedance presented at the output of each PA depends on the mutual coupling between antennas. In order to improve the efficiency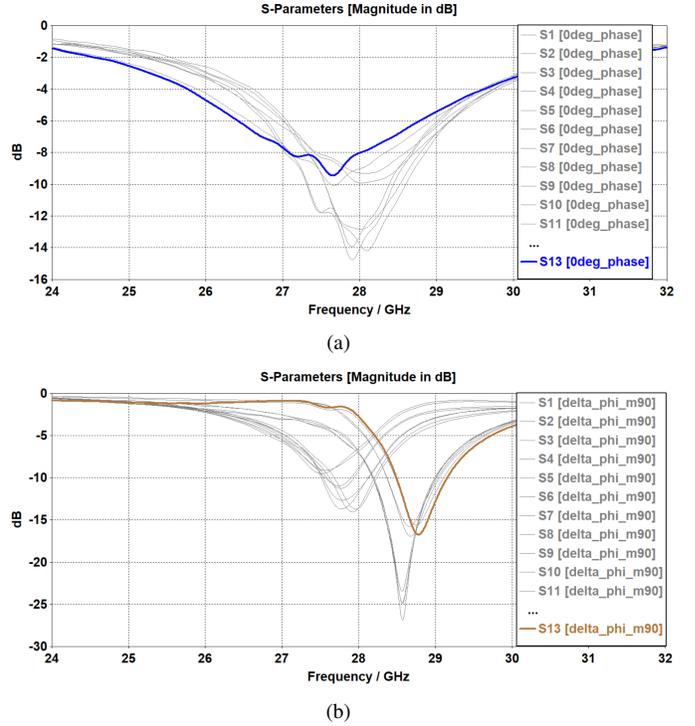 of transmitter, normally the PA is driven to compression which on the other hand results into increase of 3rd order inter-modulation which is magnified by adjacent channel leakage ratio (ACLR). Digital pre-distortion is often used as a method to keep the magnitude of ACLR as low as possible while driving PA into compression. In [5], [6] and [7] an investigation for improving ACLR by using digital pre-distortion of the main beam has been demonstrated.

A. Measurement setup

The block diagram of the measurement setup for the 4x4 array is shown in Fig. 8. and the actual measurement set-up is illustrated in Fig. 7. The input source for the measurements is a 3 GHz LTE10 signal, compliant with the 3GPP downlink orthogonal frequency-division multiplexing (OFDM) modulation with a peak to average power ratio of 10.6 dB from the signal generator. For up-conversion, an unmodulated signal of 12.5 GHz has been frequency doubled to 25 GHz and fed into a power divider in order to be used as local oscillator (LO) signal for both up-conversion and down-conversion. The 28 GHz signal is fed to an AMOTECH A0404 which includes four Anokiwave AWMF-0158 [8]. This device integrates 16 branches of attenuators and phase shifters plus PAs and 16 patch antennas in a 4x4 active phased array.

B. Measurements procedure

The steps of the measurements are:

- A vector signal generator is used to sample the 10 MHz bandwidth signal with a sampling rate of 100 MHz and 1E5 samples of I and Q data are recorded.
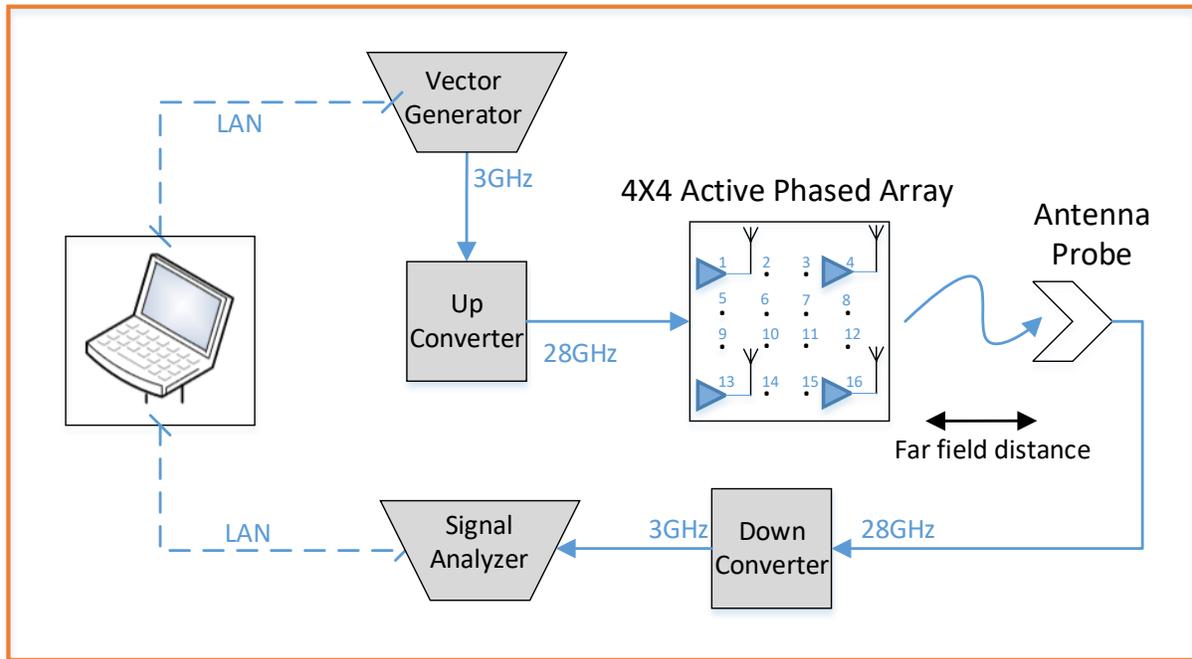
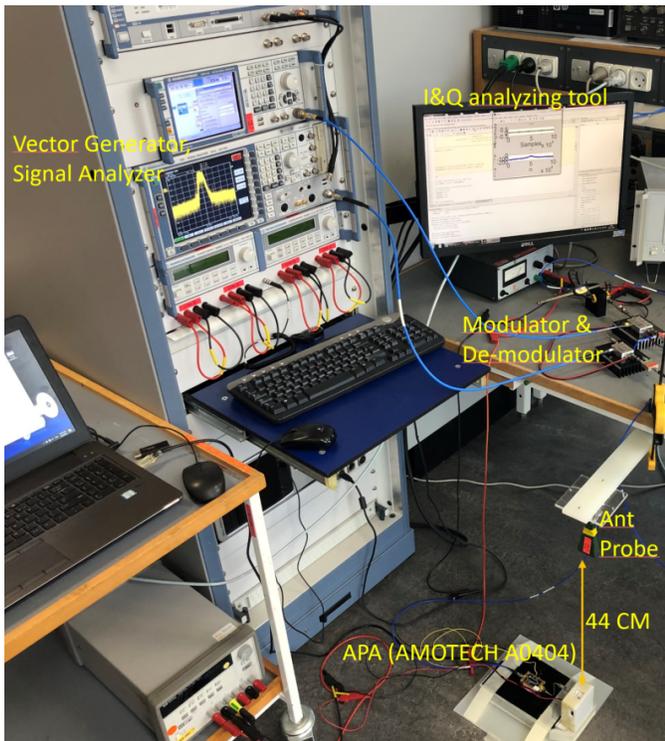Fig. 7. The block diagram of the measurement setup for the 4x4 array. The far field distance is 48 cm.

Fig. 8. Measurement set-up.

- The vector signal generator uses these recorded I and Q data to generate a modulated signal at 3 GHz. After up-conversion by external mixer to 28GHz, the signal is fed to the active phased array and received by observation

antenna. A down-conversion mixer is used for converting the 28 GHz signal to a 3 GHz signal, which is sampled by a vector signal analyzer and converted to the baseband I and Q data.

- After time-alignment by cross-correlation, the recorded input and output I and Q data are used in memory polynomial model.

- The memory polynomial model uses a nonlinearity order of 8 and a memory depth of 8 for generating the pre-distorted signal.

- A modulated 28 GHz RF signal based on the pre-distorted I and Q data is generated and inserted to the active array.

- Output power and ACLR of the 28 GHz signal are measured by the signal analyzer to quantify the linearization performance.

C. Measurements results

Each element of the antenna array is exited by a phase shifter and a PA. The main beam of the array has been shifted from θ = -78 to +78 degrees in approximately 5 degrees step using the code-book and software tools of AMOTECH AAiPK428GC-A0404 (using AWMF-0158 [8]). The used evaluation board for test is shown in Fig. 9.

An observation receiver is placed in far-field to capture the steered beam. The placement of the observation receiver antenna has been kept fixed at maximum received signal at θ = 0 degree at X-Y coordinate system. The measurement is done for both horizontal and vertical steering angles of the main beam. The measurement result is shown in Fig. 10. The magnitude of the beam captured by the fixed antenna probe is varying by changing the beam direction as expected.
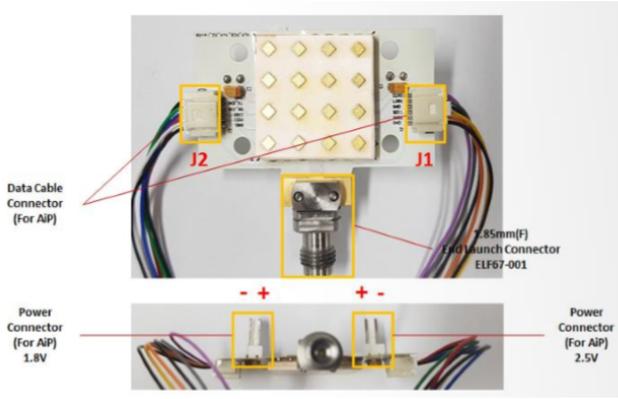
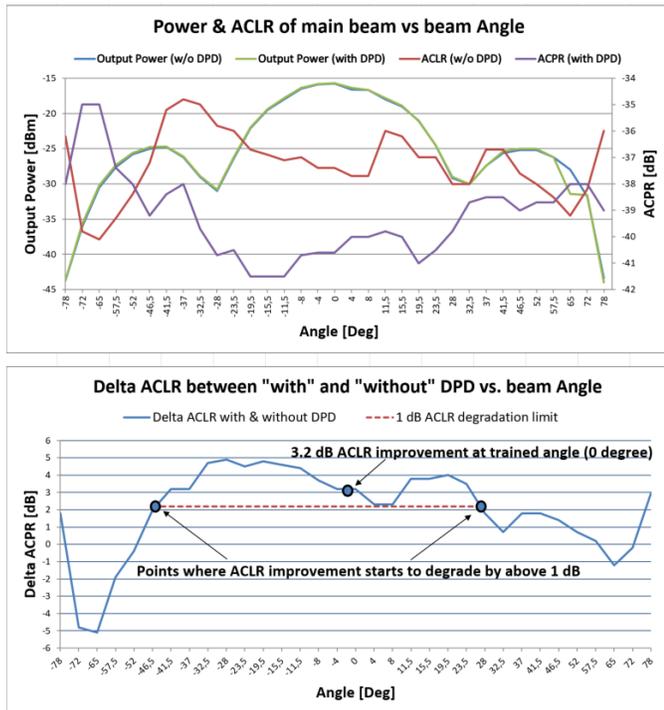Fig. 9. AAiPK428GC-A0404 [9] evaluation board used for measurements.

Fig. 10. Impact of beam angle on linearization.

However due to load mismatch while changing steering angle, the ACLR varies significantly.

During linearization of the active array, it is desired to keep the coefficients of the trained digital pre-distorted signal unchanged as long as possible since a new training is costly due to power consumption. However this experiment shows that a single trained DPD is not sufficient for maintaining a low ACLR in a wide range of steering angles. To avoid an ACLR improvement be degraded by more than 1dB across the steering angle, a new training after approximately ±28 degree shift of the main beam is required. For allowing only 0.5 dB degradation, a new training after approximately 5 degrees shift of the main beam is required which is a hard limit and requires many several training during beam steering.This can be explained as the effect of mutual coupling of the highly integrated antennas in the array as the simulation results in

section III also has indicated.

V. CONCLUSION

This paper shows a methodology for modeling the active phased array and the behavior of the steering beam when there is no isolation between the PAs and the patches of a active antenna array. Simulation results showing a clear change of the reflection coefficient of each patch antenna of the active array due to the mutual coupling among the antenna elements. This variation of input impedance of each element of antenna array results into change in output power and efficiency of the PAs since these parameters are mainly determined by the output impedance conditions. Simulation results in this paper shows that it is possible to magnify the input impedance of each patch of the array while all elements are exited simultaneously and it is possible to predict the behavior with strongly correlated signals.

The simulated effect has been validated by measurement on 4x4 active phased array. The mutual coupling affects, among others, the linearization of active array using digital pre-distortion. Since the load impedance of each PA is changing by the steering angle and because the pre-distortion algorithm cannot predict the loading condition then it affects the performance of the algorithm. This is illustrated in section III where a new training after approximately ±28 degree shift of the main beam is required.

REFERENCES

[1] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millimeter-wave beamforming as an enabling technology for 5g cellular communications: Theoretical feasibility and prototype results," *IEEE communications magazine*, vol. 52, no. 2, pp. 106–113, 2014.

[2] S. Crips, "RF power amplifiers for wireless communications, artech house," 1999.

[3] Zahidul Islam Shahin, et. al, "Efficient dpd coefficient extraction for compensating antenna crosstalk and mismatch effects in advanced antenna system," Department of Electrical and Information Technology LTH, Lund University SE-221 00 Lund, Sweden, 2017.

[4] C. A. Balanis, *Antenna theory: analysis and design*. John wiley & sons, 2016.

[5] F. Jalili, M. H. Nielsen, M. Shen, O. K. Jensen, J. H. Mikkelsen, and G. F. Pedersen, "Linearization of active transmitter arrays in presence of antenna crosstalk for 5g systems," in *2019 IEEE Nordic Circuits and Systems Conference (NORCAS): NORCHIP and International Symposium of System-on-Chip (SoC)*. IEEE, 2019, pp. 1–5.

[6] F. Jalili, F. F. Tafuri, O. K. Jensen, Y. Li, M. Shen, and G. F. Pedersen, "Linearization trade-offs in a 5g mmwave active phased array ota setup," *Ieee Access*, vol. 8, pp. 110 669–110 677, 2020.

[7] M. Alizadeh, P. Händel, and D. Rönnow, "Behavioral modeling and digital pre-distortion techniques for RF pas in a 3× 3 mimo system," *International journal of microwave and wireless technologies*, vol. 11, no. 10, pp. 989–999, 2019.

[8] Anokiwave, "Awmf-0158 28 ghz silicon 5g tx/rx quad core ic," https://www.anokiwave.com/products/awmf-0158/index.html, 2019.

[9] Amotech, "A 5G antenna that implements beam-steering with a 4 x 4 antenna element and 8 x 8 antenna," 2020.