Intra-Array Coupling Estimation for MIMO Transceivers Utilizing Blind Over-The-Air Measurements

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***Abstract*— A new technique for the estimation of coupling between array elements in MIMO transceivers is presented. The estimation method is founded on subsequent transmission and over-the-air (OTA) reception between the array elements, when the transmitter's characteristics are unknown. The method enables accurate on-line characterization of the behavior of the array in terms of coupling for a complete system with PAs and antennas connected. The method is validated via OTA measurements on a four-element array in a MIMO transmitter configuration. The results demonstrate that the estimated couplings with the proposed technique are similar to the ones obtained from S-parameter measurements with deviations reflecting the operation with antennas and PAs connected. The proposed intra-array coupling estimation facilitates practical OTA measurement-based modeling and linearization of MIMO transmitters.**

***Keywords*— MIMO transmitter, mutual coupling, crosstalk, antenna coupling, power amplifier, behavioural modeling.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) technology will continue to play a vital role in next-generation wireless systems, e.g., the fifth generation wireless networks (5G). Large-scale antenna arrays (also called massive MIMO) seem to be the most promising physical layer solution for meeting the ever-growing demand for high spectral efficiency [1].

Large-scale MIMO arrays are typically deployed with high integration and using low-cost components, and hence, they are prone to different hardware impairments such as cross-talk between the transmit antennas and power amplifier (PA) nonlinearities which distort the transmitted signal. In order to avert the performance degradation due to these impairments, it is essential to have mechanisms for predicting the output of the MIMO arrays. Such prediction mechanisms are mandatory for performance evaluation and more importantly, for the adoption of proper compensation techniques such as digital predistortion (DPD) schemes [2].

In conventional MIMO systems, the prediction mentioned above is carried out with the aid of bulky couplers which feed the transmitted radio frequency (RF) signal in each branch to observation receivers [3]. However, in large-scale MIMO systems with up to several hundreds of transmission paths, employing conventional observation receivers with couplers would be overly expensive and too complicated for implementation. This has motivated attempts for alternative solutions, one of which is the use of over-the-air (OTA) observation receivers. For instance, the authors in [4] propose a DPD technique for linearizing the analog beamforming array by relating the far-field received signal at the observation receiver antenna to the input signal to the array. For general spatial multiplexing MIMO systems (i.e., where different data streams are transmitted at different antennas), OTA measurement-based modeling of the array is a more complex task. Hausmair *et al.* [5] introduce a solution where a few observation receivers are placed at the array performing the OTA measurements whose received signals are used for extracting the PA models and accordingly, identifying the DPD coefficients. However, this solution relies on the assumption that the propagation channel between the transmitter antennas and the observation receivers are known. As an extension to the scheme proposed in [5], in this paper, we introduce a novel intra-array coupling estimation technique. We consider an array of transceivers where at each transceiver, both the transmitter and receiver are connected to the same antenna port (see Fig.1). Our proposed technique relies on reciprocity of propagation channels in time-division duplex (TDD) mode where coupling coefficients are estimated via consecutively transmitting from different antennas and receiving the signals by the other antennas. We validate the effectiveness of the proposed solution experimentally by comparing the estimated coupling coefficients with antenna S-parameters. The proposed technique serves as an on-the-fly estimation approach, and since the impedance mismatch and reflection effects are taken into account, it provides a more accurate characterization of the couplings with respect to the S-parameters. As a result, the estimated intra-array couplings facilitate practical modeling and linearization of the arrays using OTA measurements.

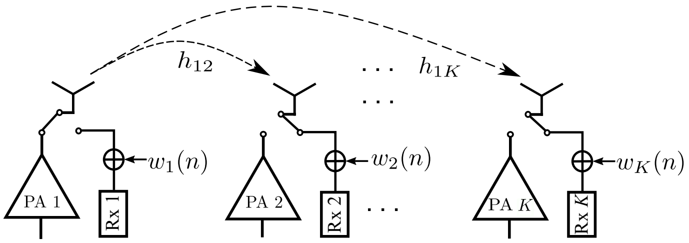

Fig. 1. Block diagram of a MIMO system with K transceivers.

II. SYSTEM MODEL

The block diagram of a TDD MIMO system, which typically utilizes a switch to alter between the transmit and the receive mode, is presented in Fig. 1. When an intra-array transmission of a pilot signal vector $\boldsymbol{s} \in \mathbb{C}^{N\times 1}$ is performed, the several building blocks of the base station (BS) transmitter, the propagation channel and the BS receiver blocks are mathematically modeled as

$$\boldsymbol{y}_{ij} = r_i h_{ij} f_{t_j}(\boldsymbol{s}) + \boldsymbol{w}_{ij}, \tag{1}$$

where r_i is the complex coefficient which models the hardware response of the receiver in the ith receive chain from RF-to-baseband and function $f_{t_j}(\boldsymbol{s})$ describes the possibly nonlinear hardware response of transmitter in the jth transceiver chain from baseband-to-RF. The term h_{ij} is in complex form and represents the reciprocal propagation channel between the jth transmit antenna and the ith receiver antenna due to the mutual coupling between the antenna elements. Note that this coupling is equivalent to S-parameters if the transmitter and receivers are well matched to 50 Ω, while in a real physical system when the impedance match is not precise, h_{ij} does not necessarily represent S-parameters. Finally, the vector $\boldsymbol{w}_{ij} \in \mathcal{CN}(0, N_0)$ is the additive white Gaussian noise at the receiver. While the r_i and f_{t_j} are varying slowly in time due to changes of temperature, etc., in physical RF components, we consider these terms constant and deterministic with respect to the symbol duration. For a BS equipped with K antennas, the intra-array couplings are estimated by exploiting the reciprocity of the propagation channels between all antenna pairs in a TDD system, i.e., $h_{ij} = h_{ji}$. Assume without loss of generality that the propagation channel and receiver hardware response are combined and collectively form the coupling coefficient. In the following section, a framework for estimation of coupling coefficients c_{ij}, where $c_{ij} = r_i h_{ij}$ is presented.

III. PROPOSED INTRA-ARRAY COUPLING ESTIMATION

We start the coupling estimation by listening with multiple receivers to the same transmit signal. Based on (1), for the signal transmitted from antenna j, and received by the ith and pth receivers, the following equation holds, if the observations are noiseless

$$\boldsymbol{y}_{ij}\lambda_{ij} = \boldsymbol{y}_{pj}\lambda_{pj}, \quad i, p \neq j, \tag{2}$$

where $\lambda_{ij} = 1/(r_i h_{ij})$. Accordingly, in the presence of observation noise, a natural approach is to minimize the following cost function

$$J(\boldsymbol{\lambda}_j) = \sum_{i,p=1}^{K} \parallel \boldsymbol{y}_{ij}\lambda_{ij} - \boldsymbol{y}_{pj}\lambda_{pj} \parallel^2, \quad i, p \neq j, \tag{3}$$

for the jth transmitter where $\boldsymbol{\lambda}_j = [\lambda_{1j}, \ldots, \lambda_{Kj}]$ excluding the term λ_{jj} [6]. Without loss of generality, we assume that the receiver characteristics are similar. Thus, the parameters λ_{ij} are reciprocal. The validity of this assumption is discussed and examined in Section IV-C. To provide a robust and computationally efficient algorithm, we propose a joint estimation method where the superposition of individual cost functions is obtained as

$$J_{\text{tot}}(\boldsymbol{\lambda}) = \sum_{j=1}^{K} J(\boldsymbol{\lambda}_j). \tag{4}$$

The $J_{\text{tot}}(\boldsymbol{\lambda})$ is a real-valued function of parameters λ_{ij} and λ_{ij}^*. Thus, the condition for optimality can be found by setting the partial derivative with respect to λ_{ij}^* to zero and treating λ_{ij} as an independent variable [7]. In other words, by solving

$$\frac{\partial J_{\text{tot}}(\boldsymbol{\lambda})}{\partial \lambda_{ij}^*} = 0, \quad \forall i, j = 1, \ldots, K \quad i \neq j, \tag{5}$$

the optimal estimation of $\boldsymbol{\lambda}$ is obtained. In matrix form, this can be written as

$$\boldsymbol{\Psi}\boldsymbol{\lambda} = 0, \tag{6}$$

where the vector $\boldsymbol{\lambda} = [\boldsymbol{\lambda}_1^T, \ldots, \boldsymbol{\lambda}_K^T]^T$ and the matrix $\boldsymbol{\Psi} \in \mathbb{C}^{2M \times M}$ where $M = K(K-1)/2$, is presented in (7).

The solution to (6) is obtained up to a multiplicative complex constant. In order to eliminate this ambiguity, we introduce a reference transceiver within the array with known transmitter characteristic, f_{t_r}. By listening to the transmitted signal $\boldsymbol{s}$ from reference transceiver, parameters of λ_{ir} can be estimated directly by minimizing a linear least squares (LS) cost function, and by reciprocity, we have $\lambda_{ir} = \lambda_{ri}$. Hence, the array $\boldsymbol{\lambda}$ parameters can be solved as a function of $\boldsymbol{\lambda}_r$, allowing for absolute estimation of $\boldsymbol{\lambda}$. The first $(K-1)$ columns of $\boldsymbol{\Psi}$ associate with the elements of vector $\boldsymbol{\lambda}_r$. Thus, the solution of (6) yields an estimate of λ_{ij} as a factor of λ_{ir}. When antenna 1 acts as the reference antenna, we solve $\tilde{\boldsymbol{\lambda}} = [\boldsymbol{\lambda}_2^T, \ldots, \boldsymbol{\lambda}_K^T]^T$ as

$$\tilde{\boldsymbol{\lambda}} = -(\tilde{\boldsymbol{\Psi}}_2^H \tilde{\boldsymbol{\Psi}}_2)\tilde{\boldsymbol{\Psi}}_2^H \tilde{\boldsymbol{\Psi}}_1 \boldsymbol{\lambda}_1, \tag{8}$$

where $\tilde{\boldsymbol{\Psi}}_1$ is a matrix containing the first $(K-1)$ columns of $\boldsymbol{\Psi}$, and the remaining columns of $\boldsymbol{\Psi}$ form the matrix $\tilde{\boldsymbol{\Psi}}_2$.

IV. EXPERIMENTAL VALIDATION

To validate the proposed intra-array coupling estimation technique, we conduct experiments using a simple four-element MIMO system operating at 2.12 GHz.

$$\boldsymbol{\Psi} = \begin{bmatrix} \parallel \boldsymbol{y}_{21} \parallel^2 & -\boldsymbol{y}_{21}^*\boldsymbol{y}_{31} & 0 & 0 & \cdots & \cdots & 0 \\ -\boldsymbol{y}_{31}^*\boldsymbol{y}_{21} & \parallel \boldsymbol{y}_{31} \parallel^2 & 0 & 0 & \cdots & \cdots & 0 \\ \parallel \boldsymbol{y}_{21} \parallel^2 & 0 & -\boldsymbol{y}_{21}^*\boldsymbol{y}_{41} & 0 & \cdots & \cdots & 0 \\ -\boldsymbol{y}_{41}^*\boldsymbol{y}_{21} & 0 & \parallel \boldsymbol{y}_{41} \parallel^2 & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & \cdots & \cdots & \cdots\ 0 & & \parallel \boldsymbol{y}_{(K-2)K} \parallel^2 & -\boldsymbol{y}_{(K-2)K}^*\boldsymbol{y}_{(K-1)K} \\ 0 & \cdots & \cdots & \cdots\ 0 & & -\boldsymbol{y}_{(K-1)K}^*\boldsymbol{y}_{(K-2)K} & \parallel \boldsymbol{y}_{(K-1)K} \parallel^2 \end{bmatrix} \tag{7}$$

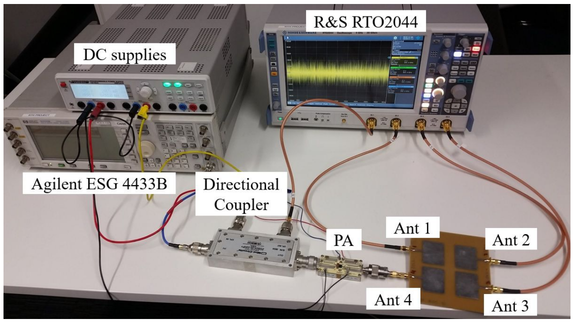

Fig. 2. Experimental measurement setup for OTA coupling estimation.

A. *Measurement Setup*

A four-element, 2.12 GHz FR4 microstrip patch antenna array was used for the experiments. The antenna S-parameters for this array were measured by a four-port vector network analyzer (VNA) and used to evaluate the accuracy of the estimated couplings. For a perfect 50 Ω match between PA and the antenna, the estimated coupling coefficients will be the same as the S-parameters. However, in a real physical setup, we expect to see a deviation in the coupling coefficients from S-parameters due to the impedance mismatch.

An OFDM test signal with 5 MHz bandwidth and peak-to-average power ratio (PAPR) around 8.5 dB was created in Matlab and used to excite the transmitter. The array presents approximately similar characteristics within this bandwidth, which allows a scalar representation of the coupling as in (1). The measurement setup is shown in Fig. 2. There were several iterations of the experiment. In each instance, one antenna was transmitting, and three other antennas were listening. Therefore, each antenna acted both as a transmitter and as a receiver during this experiment, which emulated a TDD MIMO system. The test signal was sent at a carrier frequency of 2.12 GHz using a signal generator (Agilent ESG4433B).

In order to have access to the transmitted signal with the correct phase, the signal generator output was fed to a directional coupler. The coupled path was measured and represented the transmitted signal, i.e., $\boldsymbol{s}$. This signal is only used for the estimation of $\boldsymbol{\lambda}_r$. The direct path of the coupler was used to excite the PA and the antenna connected to the PA. The received signals by three receiver antennas were then captured. A four-channel 4 GHz oscilloscope (Rohde&Schwarz RTO2044) was used to simultaneously capture the transmitted signal $\boldsymbol{s}$, and the received signals from three receiver antennas. The captured signals were processed at a baseband sampling frequency of 25 MHz.

Antenna 1 in the array was considered as the reference antenna, i.e., $r = 1$. Reference antenna was connected directly to the reference plane, i.e., coupler output, whenever it was transmitting. Therefore, it can be assumed that $f_{t_1}(\boldsymbol{s}) = \boldsymbol{s}$. where $r_i h_{ij}$ is obtained LS approach. For this configuration, λ_{12}, λ_{13} and λ_{14} were estimated. The coupling coefficients related to λ_{23}, λ_{24} and λ_{34} are the targeted couplings to be estimated with the proposed technique.

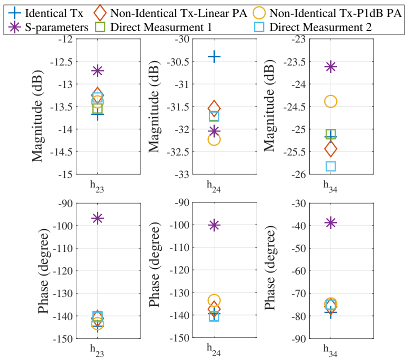

Fig. 3. Magnitude (dB) and Phase (degree) of the coupling coefficients corresponding to different configurations.

B. *Impact of Different Transmitter Configurations on Coupling Estimation*

The proposed coupling estimation technique eliminates the influence of the characteristics of the transmitters in each path. Three different scenarios were tested to prove the consistency of the estimated coupling, irrespective of the transmitter characteristics. First, each of the transmit antennas were connected directly to the direct path of the coupler, hereby referred to as the *Identical Transmitters* case. Second, three class AB PAs (BLP7G22S-10P) were connected to antenna 2, 3 and 4. This is referred to as the *Non-Identical Transmitters* case. To emulate different transmitter characteristics, the PAs were driven with a different back-off level in range 13-15 dB where PA responses are linear. Impedance mismatch between the PA output and antenna and mutual coupling between the antenna elements results in reflections toward the PA output introducing nonlinear distortion that can significantly change the PA behavior [8]. At low power, the effect of the reflected signal is negligible. In the third case, to study the effect of nonlinear distortion and impedance mismatch on the robustness of the coupling estimation, the PAs were driven at the 1-dB compression point (P-1dB).

Estimated coupling gains and phases are presented in Fig. 3 for different transmitter configurations which are, *Identical Transmitters*, *Non-Identical Transmitters* with linear PAs, and *Non-Identical Transmitters* with P-1dB PAs. The single-frequency S-parameters at 2.12 GHz presents the couplings at 50 Ω match. The maximum variation in the magnitude of estimated coupling was obtained for the coupling coefficient related to h_{34} which is 1 dB. The variation of 1 dB in measurement setup is an acceptable margin due to the measurement setup connections have been changed in each measurement iterations to emulate a MIMO TDD system. Thus, the estimated coupling coefficients for different transmitter types show a good persistence.

A consistent offset in the phase of the estimated coupling coefficients and the measured S-parameters phase is observed. The difference in phase is mainly due to the fact that the reference plane of the S-parameters is at the connector, while the estimated couplings reference plane is at the measurement instrument input, i.e., the oscilloscope channels.

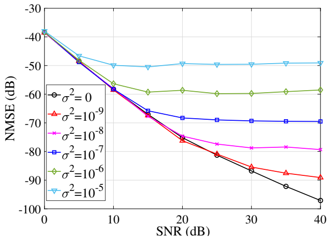

Fig. 4. NMSE of estimated couplings vs. SNR for different levels of receiver similarities.

C. Impact of Receiver Characteristic Dissimilarity on Coupling Estimation

For a real physical system, the assumption of perfect similarity in receiver characteristics does not hold. A receiver model was developed to study the effect of dissimilarity in receiver characteristics. In this model, the difference between the receivers is modeled as a stochastic variable and presented as

$$r_i = r(1 + \epsilon_i), \quad i = 1, \ldots, K, \tag{9}$$

where $\epsilon_i \in \mathcal{CN}(0, \sigma^2)$ is a complex random variable representing the gain deviation relative to the nominal receiver r. The variance of ϵ_i determines the mismatch between the receivers. For $\sigma^2 = 0$ the receivers are identical. Simulation results for different variances of ϵ_i are presented in Fig. 4. In this simulation, the S-parameters from the previous experiment were used as the propagation channel. An arbitrary complex constant value was assigned to nominal r. By introducing different variances of ϵ_i distinct gains for r_i were generated. The proposed estimation technique was used to find an estimation of $r_i h_{ij}$. The estimated couplings were compared to the given values of $r_i h_{ij}$ and the normalized mean square error (NMSE) values were calculated. The NMSE in this figure represents the accuracy in estimation of $r_3 h_{34}$. The error floor is exactly in line with theoretical expectations.

Our assumption for similar receiver characteristics is examined through direct measurement 1 and 2. In these two measurements, the transmitter and receiver antennas were swapped such that their functions were reversed. The couplings $r_i h_{ij}$ and $r_j h_{ji}$ are found, when $f_{t_j}(\boldsymbol{s}) = \boldsymbol{s}$, i.e., the *Identical Transmitters* setup. For a known block of transmitted signal $\boldsymbol{s}$, an LS approach was used to find the aforementioned couplings. The reciprocity of the propagation channel, i.e., $h_{ij} = h_{ji}$, indicates that any difference between the pairs of $r_i h_{ij}$ and $r_j h_{ji}$ are due to receiver differences.

Direct measurement 1 is taken to estimate $r_2 h_{23}$, $r_2 h_{24}$, $r_3 h_{34}$, while direct measurement 2 represents $r_3 h_{32}$, $r_4 h_{42}$, $r_4 h_{43}$. It can be inferred from Fig.3 that the magnitude of coupling between the third and the fourth antenna estimated via direct measurement 1 and 2 has the highest difference. This can be interpreted as the existence of a dissimilarity between r_3 and r_4. However, the divergence of the estimated couplings for h_{34} via three different transmitter configurations, is still in an acceptable range of 1 dB.

V. CONCLUSION

A new technique to estimate the intra-array channels in MIMO transceivers has been presented. The method relies on a simple sequence of transmitting and receiving of a signal without further calibrations being involved in the procedure. The estimated channels present the behavior of the complete system, i.e., transmitter and receiver are connected to the antenna with impedance mismatches and antenna coupling causing reflections between the array elements and the PA. With our proposed method, as the system end-to-end behavior changes, we can update the channel coefficients. With the aid of the estimated channel coefficients, the modeling and linearization of the MIMO arrays are facilitated using OTA measurements. Such solutions are important considering the current trend towards large-scale MIMO transmitters.

Future work will include the extension of this work, whereby using the estimated channels, the PA models be obtained. The extracted model will then be used for linearization of MIMO array using DPD technique.

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