UE Calibration in MIMO Systems

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***Abstract* — The paper describes an antenna path calibration method for (Multiple Input Multiple Output) MIMO systems. In a MIMO system, the RF components used at each transmit/receive antenna path, i.e., uplink versus downlink, do not exhibit similar phase and amplitude responses. Hence, if uplink measurements are used for downlink operations such as beamforming, the incurred distortion results in performance degradation. The proposed scheme relies only on the existing uplink measurements performed by the base-station, and then it provides a feedback to the UE for calibration. It is shown that the overall scheme can be employed for both TDD and FDD systems.**

***Index Terms* — MIMO, antenna, calibration, covariance matrix, reciprocity, LTE, CoMP.**

I. INTRODUCTION

By employing MIMO, the Long Term Evolution (LTE) system brings in a significant improvement in speed and reliability of downlink and uplink traffic. LTE-Advance (LTE-A) has further pushed the envelope by introducing features such as higher MIMO dimensions, Coordinated Multi Point (CoMP) transmission and Carrier Aggregation (CA) [1].

To implement an efficient downlink beamforming, the base-station (eNB) requires an accurate knowledge of the downlink channel. Such information could be provided implicitly or explicitly by the User Equipment (UE) based on the measurements performed on the downlink reference signals. However such approach imposes some delay and overhead on the uplink control channel. In a CoMP scenario, the uplink overhead could grow even further, if the UE attempts to report such information for each transmission point in the CoMP set. An alternative scheme is that the base-station performs measurements on the uplink reference signals and then derives the required channel information for the downlink beamforming. The principal idea behind this approach is derived from the Lorentz reciprocity theorem [2]. In brief, given an alternating current source at point A and a distant point of measurement B, the relationship between the current source and the resulting electric field is maintained if the source is moved to point B and the measurement is performed at point A. An example of such scenario is TDD-based systems where the uplink channel estimation can be used for downlink related functions as long as the round-trip delay is shorter than the channel's coherence time. In FDD-based systems, it is permissible that the uplink covariance matrix can be used for downlink beamforming, if the frequency difference between the uplink and downlink is not significant to cause major change in properties of the channel [3]. In such systems, where uplink measurements are used for downlink operations, receive and transmit RF signal paths need to be properly calibrated as they could exhibit significant amplitude and phase mismatches between the uplink and downlink RF paths of a transceiver [4].

The importance of calibration for CoMP operation in LTE has been discussed in 3GPP, and several solutions have been proposed [5]-[8]. It is broadly accepted that a perfect calibration can be assumed for an eNB, and only UE's are required to be calibrated [5]. This makes sense as base-stations, unlike UE's, can afford the extra hardware/real-estate and the cost to implement self-calibration.

It has been also shown that UE side phase calibration is not necessary, and only amplitude calibration is required [6]. Another important aspect is that even by assuming self-calibration per site, inter-site calibration is vital to achieve CoMP performance gain [8].

In this paper, calibration methods for a MIMO system are proposed. The studied schemes rely only on readily available measurements at eNB. In the section II, the general system model is presented. The proposed UE calibration schemes for single point and distributed MIMO systems are introduced in the section III. The paper is concluded by presenting the simulation results and final remarks.

II. SYSTEM MODEL AND CALIBRATION CONDITION

Figure 1 shows a MIMO transmission model between an eNB and a UE. Matrices $\mathbf{T}_{eNB}$, $\mathbf{R}_{eNB}$, $\mathbf{T}_{UE}$ and $\mathbf{R}_{UE}$ are complex diagonal matrices representing eNB transmitter, eNB receiver, UE transmitter and UE receiver overall gain blocks, respectively.

$$\mathbf{T}_{eNB} = \begin{bmatrix} T_{eNB_1} & & 0 \\ & \ddots & \\ 0 & & T_{eNB_M} \end{bmatrix}, \ \mathbf{R}_{eNB} = \begin{bmatrix} R_{eNB_1} & & 0 \\ & \ddots & \\ 0 & & R_{eNB_M} \end{bmatrix}$$

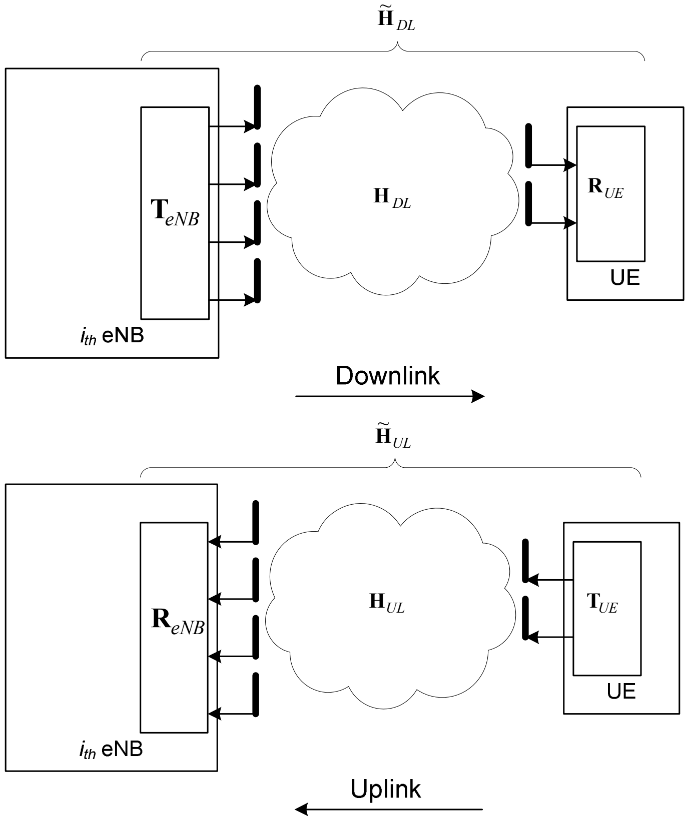

Figure 1- Down link and Uplink TX/RX chain model

$$\mathbf{T}_{UE} = \begin{bmatrix} T_{UE1} & & 0 \\ & \ddots & \\ 0 & & T_{UE\,N} \end{bmatrix}, \mathbf{R}_{UE} = \begin{bmatrix} R_{UE1} & & 0 \\ & \ddots & \\ 0 & & R_{UE\,N} \end{bmatrix} \quad (1)$$

Although the actual uplink and downlink wireless channels are $\mathbf{H}_{UL}$ and $\mathbf{H}_{DL}$, respectively, the effective uplink and downlink channels measured at the receive end of each link are expressed as follows

$$\begin{aligned} \widetilde{\mathbf{H}}_{UL} &= \mathbf{R}_{eNB}\mathbf{H}_{UL}\mathbf{T}_{UE} \\ \widetilde{\mathbf{H}}_{DL} &= \mathbf{R}_{UE}\mathbf{H}_{DL}\mathbf{T}_{eNB} \end{aligned} \quad (2)$$

From (2), in a TDD system, a mismatch of the transmitter and the receiver gain elements in the RF chain of eNB and the UE change the wireless MIMO channel, such that $\mathbf{H}_{UL} \neq \mathbf{H}_{DL}{}^{T}$. Therefore, the channel can no longer be assumed a reciprocal medium. For example in a TDD system, where it generally presumes the reciprocity of the channel within the coherence time, uplink channel measurements cannot be used for downlink beamforming. To eliminate a potential distortion in (2), the calibration condition can be expressed as

$$\begin{aligned} \mathbf{T}_{eNB}\mathbf{R}_{eNB}{}^{-1} &= k_{eNB}\mathbf{I} \\ \mathbf{T}_{UE}\mathbf{R}_{UE}{}^{-1} &= k_{UE}\mathbf{I} \end{aligned} \quad (3)$$

where k_{eNB} and k_{UE} are arbitrary constants.

In a calibrated MIMO system, the ratio of the transmitter gains to the receiver gains is equal to a constant across all the antennas. Thus, in a distributed MIMO system with P participating members, such as CoMP, similar requirements are expected. In other words, the RF paths belonging to different cells shall have equal k_{eNB}'s

$$k_{eNB}{}^{1} = \cdots = k_{eNB}{}^{i} = \cdots = k_{eNB}{}^{P}. \quad (4)$$

III. MIMO Calibration Scheme

The presented estimation methods in this section rely only on basic measurements that are already required for data demodulation at eNB and UE sides. It does not require any specific training signal, and it neither has any impact on the UE hardware design. Also, since the overall amplitude/phase characteristics of the RF components do not change rapidly over time, the rate of the calibration attempts can be very low.

A. Calibration by reporting the channel estimate

The effective uplink channel measured at the eNB can be presented by

$$\widetilde{\mathbf{H}}_{UL} = \mathbf{R}_{eNB}\mathbf{H}_{UL}\mathbf{T}_{UE} \quad (5)$$

where $\mathbf{H}_{UL}$ is the actual channel. Since $\mathbf{H}_{UL} = \mathbf{H}_{DL}{}^{T}$, and $\widetilde{\mathbf{H}}_{DL} = \mathbf{R}_{UE}\mathbf{H}_{DL}\mathbf{T}_{eNB}$, then we can rewrite the equation for the effective uplink channel as

$$\widetilde{\mathbf{H}}_{UL} = \mathbf{R}_{eNB}\left(\mathbf{T}_{eNB}{}^{-1}\widetilde{\mathbf{H}}_{DL}{}^{T}\mathbf{R}_{UE}{}^{-1}\right)\mathbf{T}_{UE} \quad (6)$$

Assuming perfect calibration at the eNB that is $\mathbf{T}_{eNB}\mathbf{R}_{eNB}{}^{-1} = k_{eNB}\mathbf{I}$, then

$$\widetilde{\mathbf{H}}_{UL} = k_{eNB}{}^{-1}\widetilde{\mathbf{H}}_{DL}{}^{T}\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE} \quad (7)$$

From there,

$$\mathbf{T}_{UE}\mathbf{R}_{UE}{}^{-1} = k_{eNB}\left(\widetilde{\mathbf{H}}_{DL}\widetilde{\mathbf{H}}_{DL}{}^{T}\right)^{-1}\widetilde{\mathbf{H}}_{DL}\widetilde{\mathbf{H}}_{UL} \quad (8)$$

Then, the gain imbalance for the UE can be estimated by

$$\Lambda = \left(\widetilde{\mathbf{H}}_{DL}\widetilde{\mathbf{H}}_{DL}{}^{T}\right)^{-1}\widetilde{\mathbf{H}}_{DL}\widetilde{\mathbf{H}}_{UL} \quad (9)$$

Thus the correction matrix can be shown as:

$$\mathbf{G} = \mu\Lambda^{-1} \quad (10)$$

Therefore, a UE can estimate its correction matrix, if the eNB shares the uplink channel estimates with the UE. The scheme discussed in this section is applicable for TDD operation if the exchange of the information occurs within the coherence time of the channel.

B. Calibration by reporting the covariance matrix

The estimated uplink covariance matrix can be expressed as

$$\begin{aligned}\widetilde{\mathbf{\Phi}}_{UL} &= E\left\{\widetilde{\mathbf{H}}_{UL}{}^{H}\widetilde{\mathbf{H}}_{UL}\right\} \\ &= \mathbf{T}_{UE}{}^{H} E\left\{\mathbf{H}_{DL}{}^{T\,H}\mathbf{R}_{eNB}{}^{H}\mathbf{R}_{eNB}\mathbf{H}_{DL}{}^{T}\right\}\mathbf{T}_{UE}\end{aligned} \tag{11}$$

Since $\mathbf{H}_{DL} = \mathbf{R}_{UE}{}^{-1}\widetilde{\mathbf{H}}_{DL}\mathbf{T}_{eNB}{}^{-1}$, then the uplink covariance matrix can be re-written as

$$\widetilde{\mathbf{\Phi}}_{UL} = \left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right)^{H}\mathbf{E}\left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right) \tag{12}$$

$$\mathbf{E} = E\left\{\widetilde{\mathbf{H}}_{DL}{}^{T\,H}\left(\mathbf{R}_{eNB}\mathbf{T}_{eNB}{}^{-1}\right)^{H}\left(\mathbf{R}_{eNB}\mathbf{T}_{eNB}{}^{-1}\right)\widetilde{\mathbf{H}}_{DL}{}^{T}\right\} \tag{13}$$

Assuming perfect calibration at eNB, $\mathbf{T}_{eNB}\mathbf{R}_{eNB}{}^{-1} = k_{eNB}\mathbf{I}$, then the uplink covariance matrix can be further simplified and expressed in terms of downlink covariance matrix.

$$\begin{aligned}\widetilde{\mathbf{\Phi}}_{UL} &= \left|k_{eNB}\right|^{-2}\left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right)^{H} E\left\{\widetilde{\mathbf{H}}_{DL}{}^{T\,H}\widetilde{\mathbf{H}}_{DL}{}^{T}\right\}\left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right) \\ &= \left|k_{eNB}\right|^{-2}\left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right)^{H}\widetilde{\mathbf{\Phi}}_{DL^{T}}\left(\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}\right).\end{aligned}$$

Due to the diagonal structure of the term $\mathbf{R}_{UE}{}^{-1}\mathbf{T}_{UE}$,

$$\left|\left(\mathbf{T}_{UE}\mathbf{R}_{UE}{}^{-1}\right)_{ii}\right| = \left|k_{eNB}\right|\left(\frac{\widetilde{\mathbf{\Phi}}_{UL\,ii}}{\widetilde{\mathbf{\Phi}}_{DL^{T}\,ii}}\right)^{1/2} \tag{15}$$

the UE amplitude imbalance can be estimated as

$$\left|\Lambda\right| = \left(\frac{\widetilde{\mathbf{\Phi}}_{UL\,ii}}{\widetilde{\mathbf{\Phi}}_{DL^{T}\,ii}}\right)^{1/2} \tag{16}$$

where $(\cdots)_{ii}$ represents the $i_{th}i_{th}$ element of the corresponding matrix. Due to the phase cancellation during the evaluation of the covariance matrix, the phase imbalance estimation involves an ambiguity that cannot be resolved. However, as noted before, amplitude calibration is sufficient to perform UE calibration [6]. Therefore, a UE can estimate its correction matrix, if the eNB shares the estimate of the covariance matrix of the uplink channel with the UE. The scheme proposed in this section is relevant for both FDD and TDD operation.

IV. Performance Evaluation

Figure 2 demonstrates the overall procedure for UE calibration. The performance of the proposed schemes is evaluated. The 3GPP case 1 [9] model is used for the generation of the downlink raw channel data for a 4×2 MIMO configuration. The accuracy of the algorithm is evaluated by measuring the estimation error of the imbalance matrix by using the MIMO correlation metric [10] defined as

$$e = 1 - \frac{tr\left(\mathbf{A}\widetilde{\mathbf{A}}\right)}{\left\|\mathbf{A}\right\|_{F}\left\|\widetilde{\mathbf{A}}\right\|_{F}} \tag{17}$$

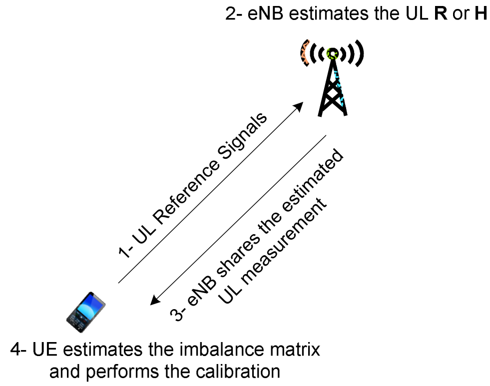

Figure 2- UE Calibration procedure

where $\mathbf{A} = \left|\Lambda\right|_{Actual}$ and $\widetilde{\mathbf{A}} = \left|\Lambda\right|_{Estimated}$. The correlation metric provides an estimate of the error between the estimated and the actual imbalance matrices.

To characterize the performance of the calibration algorithm; the estimation error is measured by assuming two different uplink SNR of 5, 15, 25 and 35 dB, and then the downlink SNR is swept over a wide range of -5 to 20 dB.

As demonstrated in Figures 3-(a-d), both methods results in very low estimation errors. Using either scheme, the accuracy of the estimation methods seems reasonable even at low SNR region. The R-based scheme that relies on sharing of the uplink covariance matrix performs almost an order of magnitude better than the H-based scheme that uses the uplink channel estimate.

Another aspect to consider is the uplink feedback overhead requirement. It is also worth mentioning that due to the symmetric structure of the covariance matrix, there is less number of values needed to be transmitted for the R-based scheme. Therefore, the scheme that relies on sharing the covariance matrix has the extra advantage of demanding less capacity from the downlink feedback channel.

Due to the almost static nature of the phase and amplitude imbalances of the RF components, the required update rate of the calibration parameters can be assumed infrequent. Therefore, the calibration process can be performed either periodically every several radio frames or once at the session start up.

VII. Conclusion

In an un-calibrated MIMO system, if uplink measurements are used for downlink operations such as beamforming, the incurred distortion results in performance degradation. Two schemes based on sharing the uplink covariance or uplink channel estimates are proposed for UE MIMO calibration. The simulation results indicate that an accurate estimate of the imbalance matrix can be obtained by either approach. However, the scheme that employs the covariance matrix is

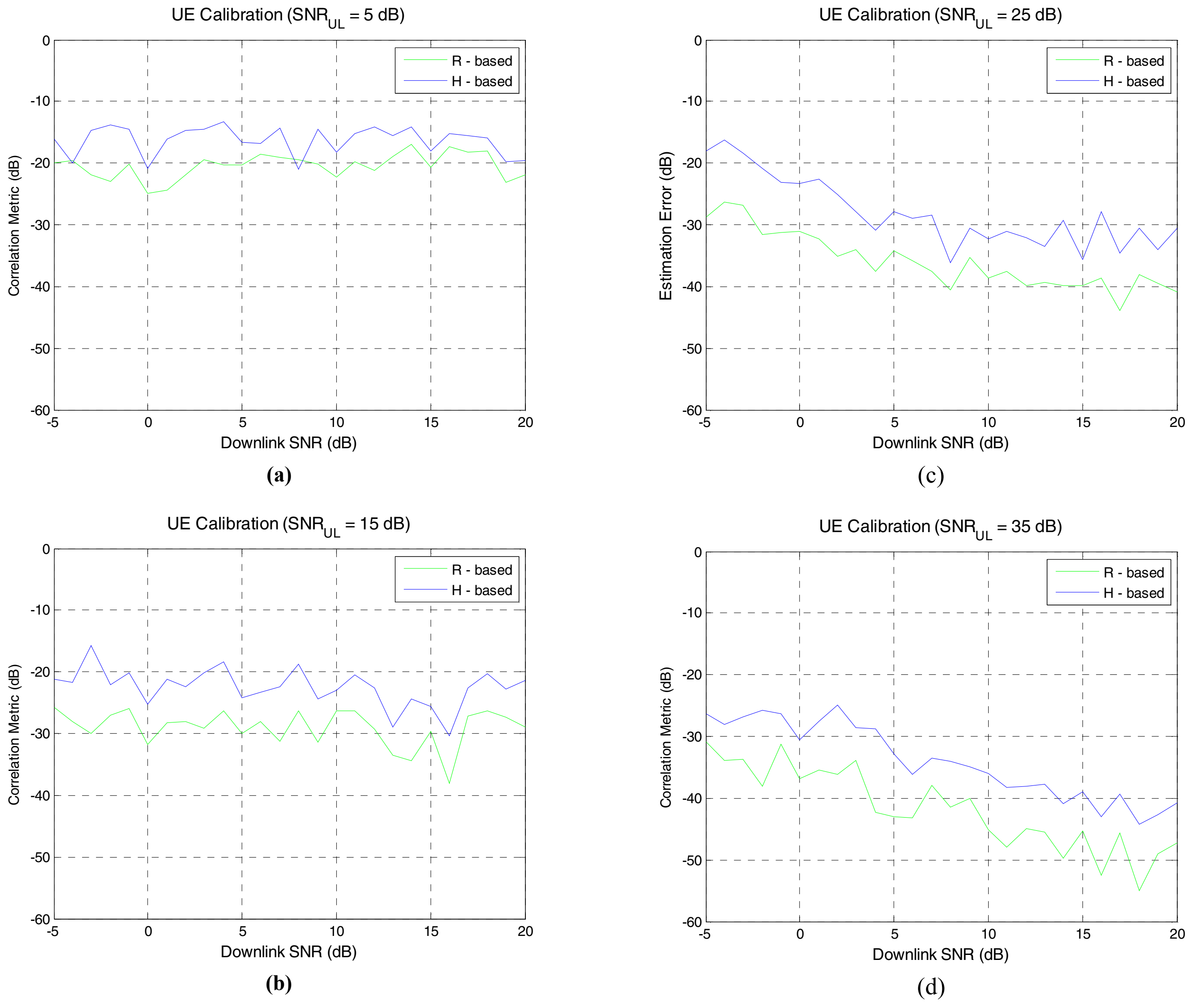

Figure 2- Estimation Error of the correction matrix

preferred due to better performance and less impact on downlink feedback overhead.

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