Inter-cell Antenna Calibration for TDD CoMP Systems

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Abstract

Coordinated Multi-Point (CoMP) transmission is a promising technique to suppress inter-cell interference, especially for TDD system which can easily get downlink channel information at evolved NodeB (eNB) through channel reciprocity. However, mismatches of radio frequency (RF) transmitter and receiver might affect channel reciprocity, thus make antenna calibration become a crucial issue. Intra-cell antenna calibration has already been studied for single cell systems. In this paper, an inter-cell antenna calibration method is proposed for TDD CoMP systems to efficiently compensate these mismatches. Differences between the inter-cell phase information feedback from users and that calculated based on uplink channel are used to get the mismatch coefficients. Simulation results demonstrate the proposed method can well compensate the RF channel mismatch, and TDD based CoMP technology can greatly improve the average and cell-edge spectral efficiency compared to the traditional cellular systems.

1. Introduction

The performance gain derived from multiple input multiple output (MIMO) is limited due to inter-cell interference (ICI) from neighboring cells [1]. Therefore, coordinated multi-point (CoMP) transmission which can suppress ICI as well as increase spectral efficiency has been introduced into LTE-Advanced system [2]. In TDD system, downlink channels can be obtained at evolved NodeB (eNB) side by estimating uplink sounding reference signals (SRS) through channel reciprocity. However, due to the mismatch of radio frequency (RF) transmitter and receiver, channel reciprocity can be applied only in the spatial propagation channel. Thus, the reciprocity of complete MIMO channel which is combined of the propagation channel and the RF front-end contributions will be destroyed.

So far, various reciprocity calibration methods have been proposed to compensate the mismatch of RF transmitter and receiver [3-6]. For single cell MIMO, intra-cell antenna calibration algorithms were introduced in [3]. Intra-cell calibration adjusts the RF coefficients of all the antennas to a constant value, which does not affect the performance of single cell MIMO system. Thus it could be well used for single cell MIMO. However, it cannot be used in CoMP system since the antennas needed to be calibrated belong to different cells. For CoMP system, "over-the-air (OTA) calibration" schemes were proposed in [4-6], calibration coefficients were calculated by comparing the full feedback downlink channel information and the uplink channel estimated through SRS. However, in order to get accurate information for calibration, large overhead for compressing the downlink channel information would be needed.

In this paper, we propose an inter-cell antenna calibration scheme for TDD CoMP system by exploiting inter-cell phase information feedback, to improve the feedback efficiency as well as ensure the performance gain of CoMP. Assuming the RF coefficients of intra-cell antennas have already been adjusted to a constant value, then eNBs calculate inter-cell mismatch coefficients based on the uplink channel and the feedback inter-cell phase information. This will keep all antennas involved in CoMP transmission have the constant RF characteristic. Joint transmission algorithms, such as Zero-forcing (ZF), block diagonalization (BD) and multiuser eigenmode transmission (MET) [7-8], which take advantage of the channel reciprocity, could be applied at the cooperative eNBs to further mitigate the ICI. We demonstrate through system level simulation that the proposed scheme can well compensate the RF transmitter and receiver mismatch, and TDD based CoMP technology can greatly improve the average and cell-edge spectral efficiency compared to the traditional cellular systems.

The rest of this paper is organized as follows. Section 2 describes the general antenna calibration model. The inter-cell antenna calibration scheme for TDD CoMP systems is presented in Section 3. System level simulation results are given in section 4, and the paper is concluded in section 5.

2. Antenna Calibration Model

Consider a downlink MIMO system with m transmit antennas and n receive antennas. Assume the coordination is performed among M adjacent cells which named a CoMP cooperating set. Within each set, joint transmission using the shared information such as scheduling and channel state information (CSI) is performed at eNB side to cancel ICI.

In TDD system, channel reciprocity could be used to get downlink channel information at eNB side. However, in real system, the RF of each antenna needs two sets of circuits to complete the transmission and reception, respectively, as shown in Fig. 1. In the model, $\boldsymbol{H}$ denotes propagation channel response, 'T' and 'R' denote transmitter and receiver, respectively. It is difficult to guarantee the two sets of the RF end circuits having the same characteristics, due to the hardware implementation error and the nonlinear distortion of the amplifier. Besides, the characteristic response of each RF circuit varies with the environment (temperature, humidity, etc.). Thus, the baseband signal is multiplied by different coefficients while passing through the transmission and reception circuits, which will cause the channel reciprocity error.

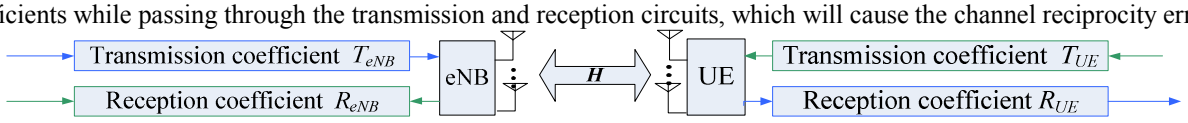

Figure 1. Illustration of RF circuits mismatches

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The downlink channel at UE side ($\boldsymbol{H}_{DL}$) can be denoted as : $\boldsymbol{H}_{DL} = \boldsymbol{R}_{UE} \cdot \boldsymbol{H} \cdot \boldsymbol{T}_{eNB}$, where $\boldsymbol{R}_{UE}$ and $\boldsymbol{T}_{eNB}$ are diagonal matrix, the diagonal elements represent the reception coefficient on each antenna of the UE and the transmission coefficient on each antenna of the eNB, respectively. The uplink channel derived through SRS channel estimation ($\boldsymbol{H}_{UL}$) is : $\boldsymbol{H}_{UL} = \boldsymbol{R}_{eNB} \cdot \boldsymbol{H}^T \cdot \boldsymbol{T}_{UE}$, where superscript T indicates the transpose, and propagation channel $\boldsymbol{H}$ is reciprocity. However, the downlink channel obtained using channel reciprocity at eNB side ($\widehat{\boldsymbol{H}}_{DL}$) is not equal to the actual downlink channel ($\boldsymbol{H}_{DL}$), which can be given as

$$\widehat{\boldsymbol{H}}_{DL} = \boldsymbol{H}_{UL}^T = \boldsymbol{T}_{UE} \cdot \boldsymbol{H} \cdot \boldsymbol{R}_{eNB} = \boldsymbol{T}_{UE} \cdot \boldsymbol{R}_{UE}^{-1} \cdot \boldsymbol{H}_{DL} \cdot \boldsymbol{T}_{eNB}^{-1} \cdot \boldsymbol{R}_{eNB} = \boldsymbol{C}_{UE} \cdot \boldsymbol{H}_{DL} \cdot \boldsymbol{C}_{eNB} \tag{1}$$

where $\boldsymbol{C}_{eNB} = diag(c_{UE,i})$, $(1 \le i \le n)$ and $\boldsymbol{C}_{eNB} = diag(c_{BS,j})$, $(1 \le j \le m)$ represent the mismatch of transmission and reception circuits for the i-the antenna of UE and the j-th antenna of eNB.

In order to enable channel reciprocity, calibration of the antennas at both eNB and UE sides will be needed. The target of antenna calibration is to keep all antennas involved in CoMP transmission have the constant RF characteristic by multiplying a compensation factor to each transmission and reception circuit.

$$\varphi_{eNB,j} \times c_{eNB,j} = a, \quad \varphi_{UE,i} \times c_{UE,i} = b, \tag{2}$$

where $\varphi_{eNB,j}$ and $\varphi_{UE,i}$ denote the compensation factor for the j-th antenna of eNB and the i-th antenna of UE. Besides, both a and b are constants. Actually, the UE side RF transmitter and receiver mismatch has limited impact on the performance of CoMP system, proved in [4]. Therefore, antenna calibration only at eNB side can obtain most of the performance gain of channel reciprocity in practice.

3. Inter-cell Antenna Calibration Scheme

In this section, an inter-cell antenna calibration scheme using inter-cell phase information feedback is proposed to improve the feedback efficiency and ensure the performance gain of CoMP. Since amplitude mismatch has little impact on system performance [4], we only focus on the phase mismatch coefficient. Assuming RF coefficients of intra-cell antennas have already been adjusted to a constant value $\widehat{\boldsymbol{H}}_{kDL} = \boldsymbol{H}_{kUL}^T = \alpha_k \boldsymbol{H}_{kDL}$, where subscript '$k$' $(1 \le k \le M)$ represents the k-th eNB and α_k represents the constant RF characteristic for the k-th eNB after intra-cell antenna calibration. Thus, the downlink channel matrix from the cooperating set can be expressed as $\widehat{\boldsymbol{H}}_{DL} = [\widehat{\boldsymbol{H}}_{1DL} \quad \cdots \quad \widehat{\boldsymbol{H}}_{MDL}] = [\alpha_1 \boldsymbol{H}_{1DL} \quad \cdots \quad \alpha_M \boldsymbol{H}_{MDL}]$. Since removal of the constant value α_1 has no impact on performance, the downlink channel is equivalent to:

$$\widehat{\boldsymbol{H}}_{DL} = \left[\boldsymbol{H}_{1DL} \quad \cdots \quad \frac{\alpha_M}{\alpha_1} \boldsymbol{H}_{MDL}\right] = [\boldsymbol{H}_{1DL} \quad \cdots \quad \theta_M \boldsymbol{H}_{MDL}] \tag{3}$$

where θ_k represents the inter-cell mismatch coefficient of the k-th eNB. The detailed procedure of the proposed inter-cell antenna calibration scheme is described below.

1) UEs obtain the actual downlink channel information $\boldsymbol{H}_{kDL}$ by estimating CSI reference signal (CSI-RS).
2) UEs report codebook based inter-cell information (take advantage of $\boldsymbol{H}_{kDL}$) to serving eNB using N-bit feedback.

We use phase difference between downlink channels to indicate the inter-cell information. For instance, the singular vector can be used as the channel direction of different eNBs. Considering feedback overhead, codebook could be used for phase difference quantization and denotes as $\boldsymbol{W}_t = [w_{t1} \quad \cdots \quad w_{tM}]^T, (1 \le t \le 2^N)$, where w_{tk} is the phase difference between the k-th eNB and the reference eNB. The codebook should be maintained at both eNB and UE sides. The principle of codebook selection is trying to make downlink channels from different coordinated eNBs coherent combining, thus the algorithm could be:

$$\boldsymbol{W}_{DL} = \arg\max_{W_t} \left\| \boldsymbol{V}_{1DL} w_{t1} + \cdots + \boldsymbol{V}_{MDL} w_{tM} \right\| \tag{4}$$

where $\boldsymbol{W}_{DL}$ indicates the optimal codebook chosen by UE, $\|\cdot\|$ is Frobenius norm and $\boldsymbol{V}_{kDL}$ represents the direction of the downlink channel $\boldsymbol{H}_{kDL}$. Assuming eNB 1 as the reference eNB, thus $w_{t1} = 1$.

3) eNBs acquire the uplink channel information $\boldsymbol{H}_{kUL}$ by estimating SRS.
4) eNBs derive the another type of inter-cell information taking advantage of $\boldsymbol{H}_{kUL}$.

Phase difference of uplink channel could be used to indicate inter-cell information at eNB side. Since $\boldsymbol{W}_t$ is also maintained at eNB, it could also be used in quantization. The codebook selection algorithm should be the same as that at UE side:

$$\boldsymbol{W}_{UL} = \arg\max_{W_t} \left\| \boldsymbol{V}_{1UL} w_{t1} + \cdots + \boldsymbol{V}_{MUL} w_{tM} \right\| \tag{5}$$

where W_{UL} indicates the optimal codebook chosen by eNB, and $\boldsymbol{V}_{kUL}$ represents the direction of the uplink channel $\boldsymbol{H}_{kUL}$.

5) eNBs could compare $\boldsymbol{W}_{UL}$ with $\boldsymbol{W}_{DL}$ to get inter-cell uplink and downlink mismatch coefficients φ_k,

$$\varphi_k = {w_{UL}(k)} \big/ {w_{DL}(k)} \tag{6}$$

where $w_{UL}(k)$ is the k-th element of $\boldsymbol{W}_{UL}$, represents the uplink channel phase difference between the k-th eNB and the reference eNB. $w_{DL}(k)$ is the k-th element of $\boldsymbol{W}_{DL}$, represents the downlink channel phase difference between the k-th eNB and the reference eNB.

6) eNBs derive weighted inter-cell uplink and downlink mismatch coefficients $\bar{\varphi}_k$ considering all of the φ_k obtained from different UEs in both time and frequency domain. One simple weighting method is average.

7) eNBs compensate the channel reciprocity using $\frac{1}{\bar{\varphi}_k}$. After calibration, the downlink channel obtained at eNB side is:

$$\hat{\boldsymbol{H}}_{DL} = \left[\boldsymbol{H}_{1UL}^T \quad \cdots \quad \frac{1}{\bar{\varphi}_M}\boldsymbol{H}_{MUL}^T\right] = \left[\boldsymbol{H}_{1DL} \quad \cdots \quad \frac{\theta_M}{\bar{\varphi}_M}\boldsymbol{H}_{MDL}\right] \tag{7}$$

Due to quantization loss, there would be residual phase mismatch $\frac{\theta_M}{\bar{\varphi}_M}$ after antenna calibration. With inter-cell and intra-site antenna calibration, the residual phase mismatch $\frac{\theta_M}{\bar{\varphi}_M}$ could be controlled at an acceptable level, and the channel reciprocity can be well used to get CoMP performance gain in TDD system.

The inter-cell antenna calibration scheme exploiting inter-cell phase information feedback is shown in Fig. 2.

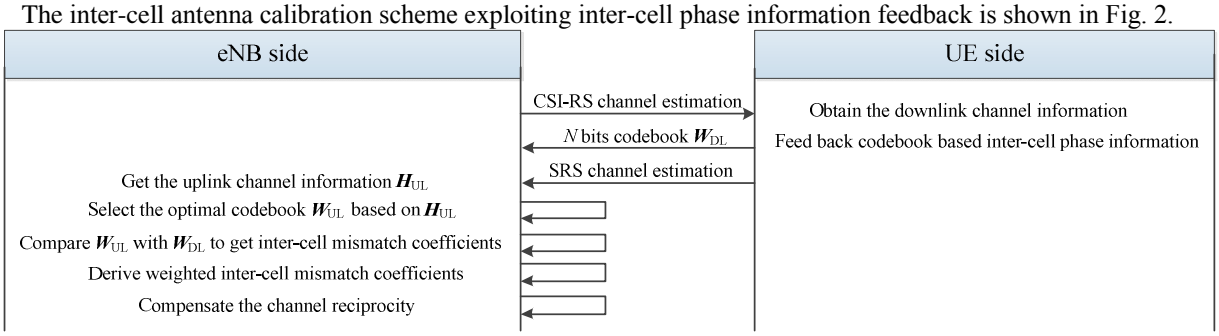

Figure 2. Inter-cell antenna calibration scheme

4. Simulation Results

In this section, the performance of the proposed inter-cell antenna calibration scheme is analyzed. With the inter-cell antenna calibration, the coordinated transmitter further adopts transmit precoding to mitigate the ICI. Various algorithms such as ZF, BD and MET can be utilized. Here, we take BD for instance. The results can be divided into two parts. The first part shows the residual mismatch of RF channels after exploring the proposed calibration scheme. The second part compares the performance of CoMP with the proposed inter-cell antenna calibration and the traditional cellular TDD system.

4.1 Simulation Assumptions

Calibration at the UE side is hard to implement in real system, and the impact due to UE side RF mismatch is inconspicuous. Therefore, we assume the amplitude and phase mismatches for UE are subject to uniform distribution with the maximal value of 3dB and 360 degrees, respectively. For simplicity, we just illustrate the calibration implemented between 2 eNBs, and all eNBs involved in CoMP transmission can be iterated calibrated.

The simulation method is described as follow:

1) Preset an initial inter-cell phase mismatch coefficient θ_{init}.
2) eNB k calculates the phase mismatch coefficien φ_k related to each UE using the proposed scheme.
3) eNB k obtains the weighted phase mismatch coefficient $\bar{\varphi}_k$ considering all of the φ_k.
4) eNB k compares $\bar{\varphi}_k$ and θ_{init} using $|\bar{\varphi}_k - \theta_{init}|$, and the difference could be used to indicate the performance of the proposed inter-cell antenna calibration scheme.

Assuming 4-bit feedback is implemented, thus the codebook maintained at both eNB and UE side can indicate 2^4 phases from 0 to 360 degrees. The codebook is:

$$\begin{bmatrix} x & y \end{bmatrix} = \begin{bmatrix} 1 & e^{j\vartheta} \end{bmatrix},\ \vartheta = 360^\circ / 2^4 \times i,\ (i = 1, 2, \cdots, 2^4) \tag{8}$$

The detailed parameters for system level simulation are listed in Table I.

TABLE I. SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
Layout	3-sectorized hexagonal grid with 7 cells and wrap-around	Ave. Num. of users per sector	10
Deployment scenario	ITU Urban Micro (UMi)[9]	User distribution / UE speed	Uniform / 3 km/h
Bandwidth	20 MHz	Traffic model	Full Buffer
eNB / UE antenna number	8 / 2	Channel estimation	Ideal

4.2 Residual Phase Mismatch after Antenna Calibration

To show the performance of the proposed inter-cell calibration scheme more intuitively, the probability of residual phase mismatch $|\varphi_k - \theta_{init}|$ related to each individual UE is described in Fig.3.

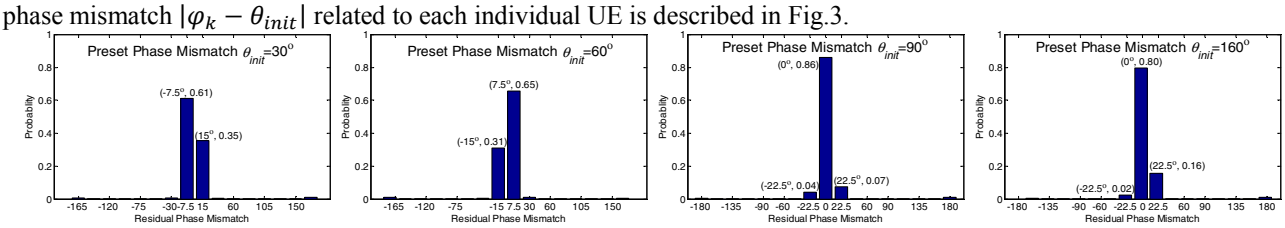

Figure 3. Residual phase mismatch after antenna calibration

With numbers of calibration coefficients related to different UEs, each eNB calculate a weighted antenna calibration coefficient $\bar{\varphi}_k$considering all φ_k in time, frequency and multi-user domain. There are many methods to get $\bar{\varphi}_k$, two of them are listed below and the residual phase mismatches in different preset phase mismatch coefficients are shown in TABLE II according to the simulation results shown in Fig. 3.

TABLE II. RESIDUAL PHASE MISMATCH

Methods to get $\bar{\varphi}_k$	Preset inter-cell phase mismatch			
	30°	60°	90°	160°
Average all of the φ_k of each UE	1.2°	-0.7°	1.8°	2.4°
Average some φ_k with the probability greater than q (e.g. q=10%)	0.7°	0.3°	0.7°	1.2°

From TABLE II, we can see that the proposed inter-cell antenna calibration scheme has the ability to limit the residual mismatch of RF channel within 5 degrees with 4-bit feedback.

4.3 The Performance Comparison

We assume the inter-cell phase mismatch coefficient is subject to uniform distribution with the maximal value of 10 degrees considering implementation error in system level simulation. Proportional Fair (PF) scheduling [10] is used to select two users for every scheduling resource. MIMO in traditional cellular system, ideal CoMP with no antenna RF mismatch and CoMP with the proposed scheme are evaluated, and the spectrum efficiency is shown in TABLE III.

Form TABLE III, we can observe that CoMP with the proposed inter-cell antenna calibration scheme only has 1% and 2% performance loss in average and cell-edge, compare to the ideal CoMP. Besides, CoMP with the proposed scheme outperforms the traditional MIMO system by 29% and 54% in average and cell-edge, respectively.

The cumulative distribution function (CDF) curves of the average user signal to interference and noise ratio (SINR) are illustrated in Fig. 4, which compared the SINR of MIMO, ideal CoMP and CoMP with the proposed inter-cell antenna calibration. From Fig. 4, we can observe that the SINR of CoMP outperforms that of MIMO by about 5dB. The CDF curves of ideal CoMP and CoMP with the proposed scheme has little difference while SINR is lower than 20dB. When SINR is higher than 20dB, the difference is larger; however, it has little impact on throughput due to the limitation of MCS.

TABLE III. SPECTRUM EFFICIENCY FOR MIMO AND COMP

Schemes	Average cell SE (bps/Hz/cell)	Cell-edge SE (bps/Hz/cell)
MIMO	3.77	0.124
Ideal CoMP	4.91	0.194
CoMP with the proposed scheme	4.85	0.191

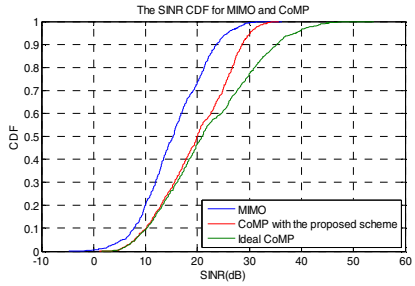

Figure 4. The SINR CDF for MIMO and CoMP

5. Conclusions

In this paper, inter-cell antenna calibration for CoMP TDD system is analyzed. We propose an inter-cell antenna calibration scheme by exploiting inter-cell phase information feedback, to improve the feedback efficiency as well as ensure the performance gain of CoMP. Assuming intra-cell antennas' RF coefficients have already been adjusted to a constant value, then the eNBs calculate inter-cell mismatch coefficients and keep all antennas involved in CoMP transmission have constant RF characteristic. Joint transmission which takes advantage of the channel reciprocity is applied at the cooperative eNBs to further mitigate the ICI. System level simulation results demonstrate that the proposed scheme can limit the residual mismatch of RF channel within 5 degrees with 4-bit feedback, and CoMP with the proposed scheme can improve the average cell spectral efficiency by 30% compared to the traditional cellular TDD system.

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